Akutan Geothermal Area Exploration Results and Pre-Drilling Resource Model

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Keywords: Akutan, Alaska, exploration, magnetotellurics, gravity, mapping, geophysics, Aleutians, volcanic, structure

Abstract: In August 2012, the City of Akutan completed an exploration program to further characterize the geothermal resource and to select drilling targets in the geothermal resource area on Akutan Island near Hot Springs Bay Valley. The exploration program included geologic mapping, a magnetotelluric (MT) survey, and a gravity survey. The program built on previous exploration, which included an MT survey, a geologic reconnaissance field study, soil and soil gas geochemical surveys, a satellite remote sensing study, a review of existing hot springs geochemistry data, drilling of two temperature gradient wells, and development of a conceptual model. The culmination of the 2012 work was to use 3D visualization of the data to advance the conceptual model and select deep drilling targets. Access requirements were taken into account in selection of the surface locations; underground targets will be reached using directional drilling.

Introduction and Background

Hot Springs Bay Valley (HSBV), on the Island of Akutan in the east Aleutians, has been a source of interest for geothermal development since at least the mid-1970's. In 2008, the City of Akutan established an exploration program to define the geothermal resources of HSBV (Figure 1). The island community and the Trident Foods fish processing plant, located in Akutan Bay adjacent to the City, have a nominal 7MW peak electrical demand that is currently met by diesel-fired generators. A developed geothermal resource would be used to offset or supplant the diesel consumption.

An initial conceptual model of the resource was developed in 2009 from a resistivity model created from MT data gathered in the valley, and from reevaluation of fluid chemistry data from the hot springs. The initial model led to the selection of four drilling targets for temperature gradient drilling (Kolker et al., 2010b).

Figure 1: Akutan Island and Hot Springs Bay Valley location map. Red dots indicate active hot springs and fumaroles.

Two of the four selected targets were drilled during the summer of 2010. Wells TG2 and TG4 were drilled with the intention of intersecting the shallow outflow of the resource, sampling reservoir fluids, and measuring subsurface temperatures in order to improve resource data and establish the extent of the resource. TG2, drilled to depth of 254 m (833'), is located on the northeast side of the study area, adjacent to the hot springs near the mouth of HSBV. A highly permeable, over-pressured interval was encountered at 178 m (585') with a down-hole temperature of 182°C (359°F). . TG4 is located toward the head of HSBV on the south side of the valley, and was drilled to 457 m (1500'). TG4 showed a high temperature but no significant permeability. Both wells are located outside of the main reservoir, as indicated by a lack of extensive alteration (Kolker et al., 2011).

Subsequent to the 2010 core drilling, exploration work included core sample analysis, the acquisition of aerial photographs of HSBV, creation of a digital elevation map of the valley, and chemical analysis of the fumarole gases and hot spring waters. During this time, the existing project data was integrated into an updated conceptual model of the geothermal system, which postulates that the upflow of the geothermal system is in the vicinity of a fumarole field in uppermost HSBV at an elevation of about 447 m (1400’). The model describes an upflow-outflow system wherein upflow occurs under the fumarole area and outflow reaches the surface at the hot springs area toward the mouth of HSBV. Unfortunately, there was a shortage of geophysical and structural data of the area around the fumarole field to more conclusively support this model, as the majority of work done to that point had been focused on the valley floor and around the hot springs near the bay (Kolker et al., 2012).

In order to more firmly delineate the reservoir and minimize resource risk, the City of Akutan instituted a program of work for 2012. The first part of this work was to develop a strategy that would supplement the existing exploration data, acquire additional data through fieldwork, and then integrate all data into a robust conceptual model to minimize resource development risk. The second part was to analyze the results of this work, verify the suitability of the area for development access, and to identify at least one primary and two secondary drilling targets to be confirmed in a drilling phase of the project.

Geologic Mapping

There was a need for additional geological mapping of the highlands region adjacent to the fumarole field. In addition to the field mapping, the geological team was able to accomplish regional fault mapping with air photos and satellite imagery that provided broader context for the interpretation of the structural framework of the HSBV area. Approximately 25 km^2 were field mapped in 2012 and include all of HSBV, the upper half of the adjacent Long Valley, and along the northeastern flank of Akutan volcano. Faults and fractures were analyzed to constrain kinematic evolution of the region and evaluate the local strain and stress fields. The extent of hydrothermal alteration and surface manifestations were also mapped in detail for integration with the geophysical and structural geology data sets to define the patterns of activity.

Stratigraphic Framework

In the Hot Springs Bay Valley – Long Valley (HSBV-LV) area, four principal late Tertiary and Quaternary stratigraphic units were distinguished, and include from oldest to youngest: 1) ~1.4-3.3+ Ma basalt and basaltic andesite volcaniclastic deposits, lava flows, and dikes (QTv); 2) ~0.3-0.6 Ma andesite plugs (Qbai); 3) ~0.5 Ma to present deposits of the Akutan volcano (Qv); and,4) Holocene post-glacial surficial deposits (Figure 2). The oldest unit (QTv) is the most extensive unit in the HSBV-LV area and throughout the island, essentially acting as basement to the modern day Akutan volcano. This unit is composed of a heterogeneous mix of mafic lava flows, volcaniclastic deposits, tuffs, and dikes that were erupted and intruded from various on and off island sources. In upper HSBV and upper Long Valley, volcaniclastics dominate QTv while the walls of lowermost HSBV are dominated by lava flows. The present Mt. Akutan volcanic edifice (Qv) is estimated to have started forming ~0.5 Ma and has been very active throughout the Holocene and historic time, with extensive Holocene deposits 40 to 60 m thick, prograding out over the late Pleistocene glacial erosion surface (Richter et al., 1998). Several ~0.3-0.6 Ma basaltic plugs (Qbai) and sills intrude upper Long Valley and the drainage divide area between Long Valley and HSBV. These plugs range in size from tens of meters to nearly 1 km across, and intrude an area 1-2 kmwide by nearly 4 km long, elongate northwest-southeast. Based on age and proximity, these intrusions are probably a satellite center of the Akutan volcano (Richter et al., 1998).

Figure 2: Geologic map of HSBV modified from Hinz and Dering, 2012. Orange rectangle corresponds to the outline of Figure 3, which delineates the area where the most intense alteration is present.

Structural Framework

Akutan Island is cut by a widely distributed array of moderately to steeply dipping normal, oblique-slip, and strike-slip faults (Hinz and Dering, 2012). Strike lengths of faults range from tens of meters up to ~5-6 km. These faults have three primary general orientations including E-W, WNW, and NE-strikes. The WNW-striking faults are the most pervasive, and are exposed over much of the island. The WNW and E-W-striking faults are characterized by overlapping arrays of fault segments only partially connected by linkages. All three of these fault orientations, E-W, WNW, and NE, come together and intersect in the HSBV area. The majority of the mapped faults in the HSBV-LV area were interpreted as southward dipping, with down-to-the-south dip-slip or oblique-slip motion. Cumulative offset was identified for only two faults, both ~5 km long, one within HSBV and one south of Akutan Harbor, with maximum observed vertical stratigraphic offset only reaching a few tens of meters of offset along each fault. Most of the faults exposed across Akutan Island are only observed cutting the ~1.4-3.3 Ma QTv 'basement' rocks. Even though the Akutan volcano started forming ~0.5 Ma, its flanks are covered by late Pleistocene and Holocene units that would obscure any middle Pleistocene faults, if present. Holocene scarps were observed along several WNW-striking faults across Akutan Island, including one fault near the southern drainage divide of HSBV, the only fault scarp within the HSBV drainage area.

Hydrothermal Alteration and Surface Manifestations

It has long been known that the HSBV geothermal system consists of two primary surface manifestations, a ~4 km-long NE alignment of hot springs in lower HSBV and a tight cluster of fumaroles in upper HSBV (Motyka and Nye, 1988). In addition to the main cluster of fumaroles, a series of discontinuous hydrothermally altered outcrops and active surface manifestations were distinguished in this study across upper HSBV within an area ~1.5 km wide by 3.5 km long, elongated N-S. Alteration and active surface manifestations are conspicuously absent in the central part HSBV. A fossil geothermal system was discovered in upper Long Valley, directly adjacent to the active geothermal system in HSBV.

All of the alteration and surficial manifestation features show preferential concentration within the three primary drainages of upper HSBV, delineated as areas A, B, and C in (Figure 3). Areas A and B are elongate WNW-ESE and area C is elongate E-W. Specific mapped features include areas of moderate and strong intensity argillic alteration, ferricrete spring deposits, native sulfur and sulfate deposits, hot and warm springs, fumaroles, and boiling mud pots. In upper HSBV, nearly all the active hot springs, fumaroles, and boiling mud pots are concentrated in area B. Only one warm spring was found in area A, and one other in area B. Of particular note, silica in any form was not identified in association with any of the areas of alteration in upper HSBV, except up-slope of the fumaroles near the drainage divide with Long Valley, where the silica was interpreted as being associated with the ancestral Long Valley geothermal system.

In lower HSBV, over three dozen hot and warm springs emanate through Holocene alluvium in an ~4km-long, NE-trending alignment that stretches from near the midpoint of lower HSBV all the way to the ocean, and follows within ~100 m of the north side of the valley. Small amounts of silica sinter in some of these springs have been noted by previous researchers (e.g., Kolker, 2011). However, in contrast to upper HSBV, fumaroles, native sulfur deposits, or argillic alteration of the bedrock have not been identified in lower HSBV.

The style of alteration and associated sulfidation observed in upper HSBV is consistent with Motyka and Nye's (1988) interpretation that the surface manifestations are directly fed by gases and steam boiling off a reservoir at depth. The boiling of a reservoir at depth also fits the observed absence of silica in the upper HSBV area, because in this model the silica remains in the residual liquid when the reservoir fluids boil to steam. The presence of silica sinter locally associated with some of the hot springs in lower HSBV, and lack of observed fumaroles, imply that these hot springs are fed by outflow from the reservoir, not condensate. Although separated by an area devoid of alteration and active surface manifestations in the central HSBV, similarities in geothermal fluid chemistry between upper and lower HSBV imply that both areas are connected to the same reservoir and are part of a single geothermal system (Kolker, 2011).

Figure 3: Detail of bedrock alteration, surficial geothermal manifestations, faults, and dikes mapped in upper HSBV. Black oval B is the most altered area, followed by areas A and C (from Hinz and Dering, 2012).

MT Survey

The 2009 MT survey showed a resistivity structure similar to that found in other economically viable geothermal systems, consisting of a low resistivity layer capping the moderately resistive geothermal reservoir. This layered effect in geothermal systems is created by the intensity of rock alteration relative to its position in the system. Higher-grade propylitic alteration typically found within the geothermal reservoir has a resistivity range of 10-60 ohm-meters. The 'clay cap' consists primarily of smectite transitioning to illite as depth and temperature increase. The cap exhibits lower resistivity, typically <10 ohm-m. This clay cap model is often used in the interpretation of MT data for geothermal exploration to infer the size of the potential resource. Because the 2009 survey was limited to lower elevations within HSBV, there was not enough data to determine the extent of the clay cap under the fumarole field. The 2012 MT survey was an extension of the 2009 survey to cover the area of the primary surface expression of the geothermal resource at the fumarole field.

MT Methods

Three different array types were deployed in the course of the survey to conform to the ground conditions, topography and physical limitations. Most of the 22 sites were acquired using one of two arrays, either a 400-meter array or a Double-L array, both described below. A Telluric-MT array was deployed at one site. This refers to a site measuring only the electric (telluric) fields. An approximate impedance tensor is obtained at Telluric-MT sites by substituting a set of horizontal magnetic fields measured concurrently at another survey area site. The MT stations for both the 2009 and 2012 surveys are shown in Figure 4.

Measurements for the 400-meter array used six electric-field receiver dipoles (4 Ex and 2 Ey) of 100-meter length with a pair of magnetic-field antennas (Hy and Hx) located in the center of the spread. Measurements for the Double-L array used four electric-field receiver dipoles (2 Ex and 2 Ey) of 50-meter length, with a pair of magnetic-field antennas. Measurements for the Telluric-MT site used only the four electric-field receiver dipoles (2 Ex and 2 Ey) of 50-meter length without orthogonal horizontal magnetic sensors.

MT time-series were simultaneously recorded with two to five synchronized receivers each day of acquisition. Time series data were acquired in three frequency bands for scheduled time periods. MT processing was completed using an integrated set of proprietary Zonge software programs. Overall, during the survey, natural source signal strengths were sufficient to get acceptable, usable quality data over nearly all of a frequency range extending from 0.008 to 256 Hertz.

Figure 4: Station locations for 2009 (squares) and 2012 (circles) MT surveys.

MT Modeling

The 2009 MT survey data and the additional sites collected in 2012 were combined into a 2D fence model. Merging of the two datasets for use in the Zonge 2D MT modeling software required impedances from both surveys be rotated to a common x-axis azimuth and interpolated to a common set of frequencies. The 2D fence model has cell dimensions of 100 meters horizontal and 25 meters vertical at the surface. The vertical cell dimensions increase at rate of 1.2 per cell downward to a total active model depth of 13 km. The fence model is clipped at 2 km depth to remove the deeper, less reliable results from the inversion. The frequency range used was 0.1 Hz to 10000 Hz. The data were fit to the combined Transverse Magnetic and Transverse Electric (TM +TE) modes with a static adjustment. Relatively strong horizontal smoothing was imposed on the model to identify layering as opposed to single station resistivity features.

The synthesis of a 3D volume model from 2D inversions is both science and art. Each modeling approach will produce visible differences in model details, but major features in all well-executed models should be similar. Results from the hybrid TM+TE with static fitting were compared with the 2009 3D model, a determinant fence, and standard TM and TE sections. The hybrid approach was found to be more effective at generating a 2D fence with the desired resolution and stability of resistivity values across modeling area.

Refined spatial interpolation procedures were used to extend the 2D fence model to a continuous 3D voxel model. The procedures maintained the resolution of the shallow layers between stations and blended the deep resistivity values based on the constraining physics. The resulting 3D voxel model has been instrumental to defining the areas where geothermal fluids may be circulating and for defining targets for future drilling. The model conforms to the domed and layered model of a geothermal system, with an upper conductive layer (clay cap) underlain by a zone of intermediate resistivity of 50-100 ohm-m, and a resistive core defined by resistivity values above 160 ohm-m; an image of the 3D result is shown in Figure 5. The geothermal resource is expected to be found in the zone of intermediate resistivity.

Figure 5: Image of the 3D model of the MT data from the HSBV geothermal area. The cornercut view looks northeast and shows the yellow-green 32 ohm-m iso-surface.

In the HSBV resource, the expected clay cap is underdeveloped, as evidenced by resistivity values that are higher than expected, 10-40 ohm-m, as opposed to 10 ohm-m or less. The cause of the lack of development can be explained by one or more of the following: (1) the system rapidly evolved to higher temperatures and has cooled, with a retrograde alteration that has higher resistivity; (2) the system is immature and alteration as just begun; or, (3) the system is old and eroded. None of these explanations preclude the presence of a geothermal system but require consideration in the data interpretation. In this case, there is sufficient proof of commercial grade heat from the TG drilling, active tectonics to promote fracturing, and sufficient fluid sources to indicate that there is likely a small but active geothermal system, despite the elevated resistivity values.

In looking at the interpreted data set, the conductive layer (defined here as resistivity values ≤40 ohm-m) varies in thickness, averaging 250 m (820’) thick, with a maximum thickness of about 500 m (1640’). The layer encompasses the majority of the highlands portion of the field area. The top of this conductive layer reaches the surface in the area surrounding the fumaroles, which is expected given the intensity of alteration in the exposed rock. It is thin or absent in the field area directly to the north and east of the fumarole area. This correlates well with the locations of intense alteration as described in the geologic map.

Gravity Survey

A gravity survey was chosen for its low incremental cost adjunct to deploying the MT survey, low cost per station, ability to cover the entire field area in the 2-week time frame for exploration, and the high potential for a direct relationship to the MT data for interpretation. A gravity survey measures density differences in the subsurface, revealing faults, fractures, dense intrusive bodies, and altered rock zones that can be conduits or hosts for the geothermal reservoir. Other techniques were considered, including induced seismicity, ground magnetics, controlled-source AMT, InSAR, and an aeromagnetic survey. These were each eliminated based on budget, feasibility or questionable potential benefit to the overall data set.

Gravity Survey and Processing Methods

A total of 217 gravity stations were acquired, with station spacing of 150 m in the center of the area of interest, and 300 m at the edges. GPS data were acquired for three to five minute sessions at each station during simultaneous acquisition at a fixed GPS base station located in the City of Akutan for easy access. Thirteen stations were repeated to verify measurement precision.

The processing of gravimeter readings to the Complete Bouguer Anomaly was made using the Gravity and Terrain Correction software version 7.1 for Oasis Montaj by Geosoft LTD of Toronto, Canada. The observed gravity is the gravitational acceleration, in milligals, that is determined by relative measurements made in a loop from a gravity base, after the meter readings have been corrected for instrument height, instrument scale factor, instrument drift and earth tides. The observed gravity is a function of position (geographic latitude and elevation) and variations in the density of the subsurface material. A series of corrections were made to the observed gravity to remove the variation caused by position so that the variations caused by subsurface density distribution remain. These corrections include a latitude correction, a two-part elevation correction (free-air and Bouguer), a Bullard B correction, and a correction for the effect of the topography directly surrounding the station. All of these corrections are included in the Complete Bouguer Anomaly presented in Figure 6.

Figure 6: Complete Bouguer anomaly for the HSBV geothermal area.

Gravity Survey Results

The primary result of the gravity survey was the creation of a gravity based pseudo-basement interface model. This was created using the USGS horizontal-density-sheet edge solutions and an assumed basement density. The value of the pseudo-basement resides in its shape and its gradient, which indicate significant variations in the basement's relief and/or density. Figure 7 shows the 3D model resistivity at -1000 m (-3281’) elevation. The high resistivity basement is in dark blue. The contours of the gravity pseudo-basement elevation are overlain on this map. The gross match of the shapes of the high resistivity basement and the pseudo-basement elevation contours increase the likelihood that the deep thermal source is associated with an intrusive complex contained within the study area. Additionally, the gravity and MT data together indicate that an intrusive feature is present at -1000 meters (-3281’) elevation, or approximately 1500 m (4921’) depth. The high density of this body suggests that it is less altered than the surrounding formation, and has thus far been resistant to fluid intrusion and breakdown. It likely represents a boundary to the geothermal system.

It is suspected that the body is a magmatic intrusion related to the modern-day Akutan volcano. The steep density gradient along the margin of this body is a promising area to encounter fractures resulting from the fluid and mechanical forces imposed during the intrusion event(s). The surface manifestations of the geothermal reservoir at the western side of the field area do not extend to the south or southeast of the gravity high. This provides further evidence that this dense body may be a controlling factor on the extent of the reservoir.

Figure 7: MT Resistivity model slice at -1000m elevation (in color) with contours of pseudo-basement interface. This shows a gross match in shape to a dense resistive basement, interpreted as an intrusive body.

Discussion

The lavas, volcaniclastic rocks, and intrusions mapped at the surface cannot explain the gravity maximum under HSBV. The coincidence of a resistive (>160 Ohm-m), dense body may result from a gabbroic intrusion or intrusive complex that tops out around 1500 m (4921') depth. We infer that the intermediate resistivity range of 50 to 100 Ohm-m that comes closest to the surface, coincidently with the fumarole area, corresponds to the reservoir, and that the reservoir is rooted in the highly fractured margins of the intrusion and adjacent country rock, similar to the exposed roots of the ancestral Long Valley system. We also suggest that age and erosion has contributed to the reduced clay cap since we know that some of the bedrock in upper HSBV has undergone strong intensity argillic alteration prior to the Holocene. Three fault networks intersecting in HSBV create numerous steeply plunging fault intersections that visibly relate to the distribution of alteration and active features at the surface, and probably contribute to reservoir permeability.

Based on the results of the 3D geophysical interpretations, the location of the most active and extensive surface manifestations, and the numerous steeply plunging fault intersections, we infer that center of the active system is probably located directly below the fumarole field. From the combined evidence, the resource model presented following the 2009 exploration work and 2010 drilling has been substantiated. Based on these findings, several well targets have been selected that will intersect the resource beneath the fumarole area, with the elevation of the resource between 30 m and 792 m (100' and 2600') below mean sea level, based on the MT model. The intermediate resistivity layer from this model is expected to be the host of the geothermal reservoir. The well targets chosen intersect this this resistivity layer between the low resistivity layer (clay cap) at its thickest part and the high resistivity core (intrusive body) at the point where it comes closest to the surface. From the proposed accessible location at the surface, the wells will need to be drilled directionally to between 500 m and 1250 m (1640 and 4100') vertical depth (Figure 8). It is between these depths that the wells are expected to intersect permeable fractures.

Figure 8: 3D resistivity model, with geologic cross section showing two of three proposed well trajectories that will intersect the geothermal resource, as defined by resistivity values and prevalence of fracturing and alteration at the surface. View is to the north.

Conclusion

The combined evidence of past and present assessments strongly supports the presence of a high-temperature geothermal reservoir in the western highlands above HSBV, in the vicinity of the fumarole field. The conceptual models presented in 2010 and 2011 were substantiated and significantly enhanced by the 2012 work. This refined model describes heated fluids circulating close to the surface through a network of fractures created by regional and local tectonics and the coincident intrusions. The fumarole field is formed by fluid emanating at the surface, after being partially condensed by passing through a shallow surface aquifer composed of meteoric water. The hot spring area is still considered a surfacing of the outflow of the resource. Additional numerical modeling and statistical analysis of temperature distribution is underway that is intended to further refine the conceptual model to better define the outflow path and reduce drilling risk (Ohren et al., 2013).

The next step to advancing the geothermal project at Akutan will be to drill wells capable of penetrating the geothermal reservoir, followed by long-term production testing. Drilling a slim well sufficient to test the resource will require fixed costs that could reach two-thirds to three-quarters the cost of drilling a full-size production well. If a slim well succeeded in finding the resource, it would still be necessary to drill a production well toward the same target. Therefore, the wells are planned to be of production size and grade, as the high expense of mobilizing drilling equipment to Akutan makes prolonged exploratory drilling impractical. Three wells sites and target locations have been selected: two for production and one for injection. The sites have been selected to drill directionally, intersect numerous fractures and faults identified in the 2012 field study, and penetrate the mid-range resistivity layer thought to be the host of the geothermal reservoir.

Acknowledgements

The research team would like to thank Mayor Joe Bereskin and the residents of the City of Akutan for their hospitality and assistance during the 2012 fieldwork season. We would also like to acknowledge the assistance of Rich Koehler of the Alaska Division of Geological and Geophysical Surveys. Amanda Kolker, Pete Stelling, and Bill Cumming have all been a tremendous source of guidance and continuity. Ray Mann and Bob Kirkman of RMA Consulting Group have provided invaluable knowledge of the ins-and-outs of operating in the Aleutians.

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