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EXPLORATION OF THE AKUTAN GEOTHERMAL RESOURCE AREA

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ABSTRACT

Gas geochemistry from geothermal fumaroles on Akutan Island, Alaska, indicates that geothermal reservoir temperatures could approach 572 °F (300 °C), and probably consists of a brine liquid overlain by a small steam cap. Fluids produced by core holes show evidence of chemical re-equilibration to lower temperatures, with cation geothermometry providing a range from 392-464 °F (200-240 °C). Geochemistry of hot spring fluids shows evidence of equilibrating at still lower temperatures. These data support a model with a high-temperature upflow system in the vicinity of the fumaroles that transitions to a lower temperature outflow zone that mixes with meteoric water and connects to hot springs 12,000 ft (3600 m) from the fumarole. This model is supported by MT resistivity data.

Exploratory drilling targeted the outflow zone with two core holes 9,200 and 12,000 ft (2800 and 3600 m) from the fumarole. The farther core hole encountered expected fluid temperatures of 360 °F (180 ^{o}C) at 613 ft (186 m). Static temperature profiles suggest that the 360 °F zone is drawn from a nearby fault zone not located directly below the well. Alteration mineralogy in the two core holes suggests that the rocks were at temperatures greater than 469 °F (250 °C) in the geological past and have cooled to present temperatures. The integrated interpretation of core mineralogy, temperature logs and MT resistivity suggests that the part of the outflow encountered by the wells has insufficient volume and too close a connection to cooler water to support commercial development, although the higher risk of cooling during exploitation as a result of either cold water influx from near-surface aquifers or injection breakthrough might be offset by flexibility in lower cost shallow wells. Targeting the area of the fumarole field with an 8000 ft (2500) m directional well would have the highest probability of encountering commercial production at Akutan. This target is likely to be >430 ^{o}F (>220 °C) and could be as hot as 570 ^{o}F (300 °C).

INTRODUCTION

The volcanic Aleutian Islands of Alaska have long been considered a promising setting for geothermal energy resources. Akutan Island, in the eastern portion of the Aleutian chain (Fig. 1) holds one of the most commercially viable geothermal prospects in the state, Hot Springs Bay Valley (HSBV). The HSBV resource is approximately 4 miles (six kilometers) northeast of the only population centers on Akutan Island, the City of Akutan (COA) and Trident Seafoods Processing facility. Combined, these two entities have a peak energy demand of ~7-8 MWe. This demand is currently being met through diesel generators and heaters, consuming ~4.2 million gallons of diesel annually. In 2008, the base cost of power in the City of Akutan was $0.323/kWh (Kolker and Mann, 2009).

Initial exploration of the geothermal potential of this area began in 1979 (Motyka and Nye, 1988; Motyka et. al., 1993). In the summer of 2009, the City of Akutan initiated a more detailed study of the full HSBV area (Kolker and Mann, 2009; Kolker et al., 2010), and in 2010, based on the results of the 2009 efforts, two thermal gradient (TG) wells were drilled in the floor of the main valley.

Geologic Setting and Background Data

Akutan Volcano is the second-most active volcano in the Aleutians subduction zone, with 32 historic eruptions (Simkin and Siebert, 1994; Newhall and Dzurisin, 1988; Miller et al., 1998; Richter, 1998). An initial volcanic hazard review indicated that the proposed geothermal development area was unlikely to be directly impacted by eruption activity, excepting ash fall that might cause temporary closure (see Waythomas et. al., 1998).

The HSBV lies approximately 2.3 miles (3 km) to the NE of Akutan Volcano, and is composed of two linear, glacially carved valleys (the SE-trending Fumarole Valley and the NE-trending Hot Spring Valley; Fig. 1; Richter et. al., 1998).

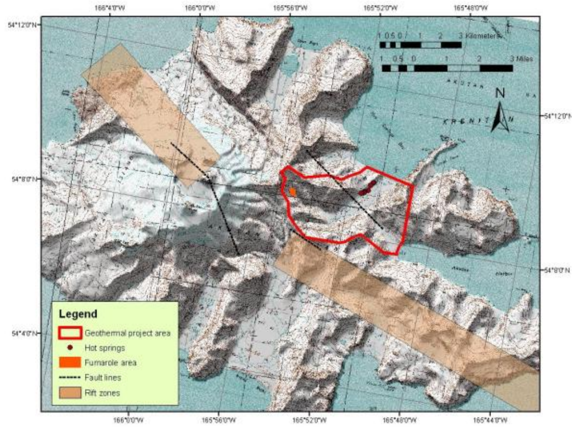


Fig. 1. Topographic map of Akutan Island, showing the geothermal project area and pertinent geologic features. Hot Springs Bay Valley (HSBV) is a L-shaped topographic low that lies at the center of the geothermal project area.

Five groups of hot springs with more than 10 vents have been identified in lower HSBV (Fig. 1 and 2). Temperatures of the hot springs range from 129 to 205 °F (54 to 96 °C); and some have been reported as boiling. A fumarole complex exists at the head of HSBV to the west of the hot springs and covers an area of approximately 1600 ft^2 (500m^2). Kolker et. al. (2010) indicate gas geothermometry of reservoir fluid of 518 °F (270 °C) and higher at the fumaroles, and that these fluids are re-equilibrating to lower temperatures along the outflow path feeding the hot springs. The silica geothermometry of the hot springs indicate 275 °F (~135 °C) fluid, while cation geothermometry provides up to 374 ^{o}F (190 ^{o}C). Another fumarole field is located at the summit of the active volcano ~2.5 miles (~4 km) to the west of Fumarole Valley.

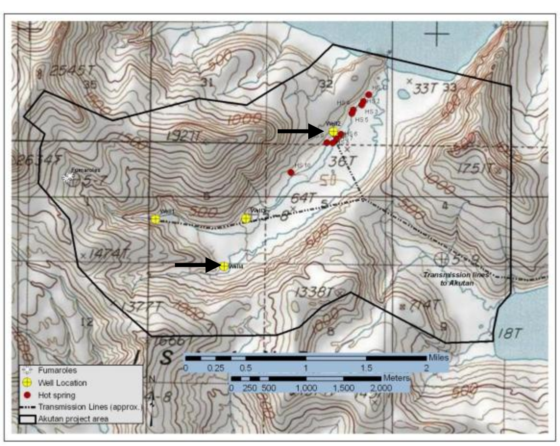


Fig. 2. Map of the Akutan Geothermal area, showing the four candidate exploration well locations that were considered for the 2010 program. The two holes drilled in 2010 are marked with black arrows.

The two valley sections are joined at right angles, suggesting structural control of glacial flow. Soil geochemical anomalies (Arsenic, Mercury, and Carbon Dioxide) at the junction of the Fumarole Valley and the HSBV also suggest that the valley junction is structurally controlled and was initially interpreted as a potentially important locus of geothermal fluid flow (Kolker et al, 2010). These structural features parallel regional fault patterns associated with subduction stresses and volcanic processes on Akutan, providing the large-scale permeability for deep magma migration and storage (Lu et. al., 2000; John Power, pers. comm.). These structures are likely to be important in the control hydrothermal upflow and outflow. One mapped fault cuts near-perpendicularly across HSBV (Fig. 2). All of the hot springs are topographically lower than the fault's surface trace, consistent with geochemical indications that they outflow from an upflow near the fumarole.

MT Resistivity

Kolker et. al., (2010) show that the MT resistivity pattern of the Akutan geothermal prospect includes a low resistivity, low permeability clay zone, caps a higher resistivity, higher temperature, permeable geothermal reservoir. The resistivity values of >20 ohm-m within most of the low resistivity zone between the fumarole and hot springs at Akutan, however, are higher than in the smectite zone of most developed geothermal fields, although a local pattern of alteration near the hot springs is more conventional, with a <600ft (<200 m) thick, 5-15 ohm-m zone interpreted as a smectite clay cap overlying a higher resistivity geothermal outflow. Kolker et. al., (2010) interpret the shallow >20 ohm-m layer between the fumarole and the hot springs as either an unusually high fraction of dense lavas causing weak alteration, or relict alteration that formed at higher temperatures and has experienced only minor retrograde alteration to smectite clay. The most serious limitation in the MT survey is the lack of station coverage in the area near the fumarole and a large part of a likely direct outflow path to the hot springs due to steep topography and inclement weather.

TEMPERATURE GRADIENT DATA

Core Hole Drilling

In 2010, two small-diameter temperature gradient ("TG") core holes were drilled in the floor of HSBV (black arrows in Fig. 2). Well TG-2 was sited to test the outflow aquifer(s) and was drilled to a Total Vertical Depth (TVD) of 833 ft (254 m). Between

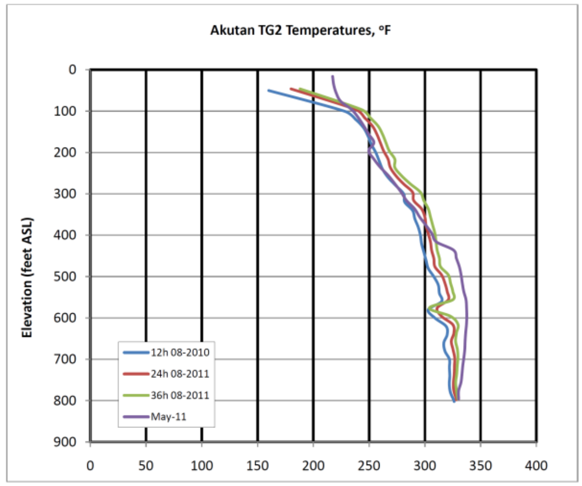
585 and 587ft (178 and 179 m), a highly permeable zone, apparently a highly fractured and vesicular lava flow top, flowed geothermal fluid at 359 °F (182 °C). Well "TG-4" was sited at the southern part of the junction between the two perpendicular valleys, to test the size and extent of the outflow zone. Reaching the planned depth of 1500 ft (457 m), this well did not encounter substantial fluid flow. This suggests that its location is outside the margins of the outflow zone, vertically or horizontally (or both). However, the well did encounter a shallow temperature gradient high enough to imply close proximity to a geothermal source. Further details on these wells can be found in Kolker et. al. (2010).

End-of-Drilling Logs

After TD was reached, three P/T logs were recorded at 12, 24, and 36 hours after circulation ended for each well. For every run, stops were made in 20 foot increments. Both wells show very high shallow temperature gradients, which is consistent with their proximity to the shallow outflow zone (Figs. 3a, b). Following production, TG-2 shows a drop in temperature occurring just above the casing shoe at 603 ft (181 m), corresponding to the hot fracture zone between 585 and 587 ft (178 and 179 m) that was cemented in. The apparent cooling is likely the result of drilling fluid and cement injected across that entire area. TG-4 shows a relatively rapidly increasing temperature gradient until ~900 ft (274 m), transitioning to a slowly increasing temperature gradient from 900 ft -1500 ft. An injection test performed on well TG-4 suggested that the well has generally poor permeability.

TG-2 Equilibrated Temperature Log

The equilibrated temperature survey for TG-2 was taken nine months after well completion. The equilibrated log shows a distinctly different shape from the end-of-well temperature build-up profiles Fig. 3a. Among the new features to note are: (1) The well was bleeding while the log was run, resulting in a minor steam or two-phase section in the upper 60-70 ft (20-25 m); (2) Apparent cooling of the well since shut-in is noticeable in the upper 400 ft (122 m). This probably reflects a trickle of water down-flowing from around 200 ft (61m) measured depth (MD) and exiting into the formation at about 415 ft (126m) MD. It can only be a trickle of water because the water is heating up as it flows down behind the casing; (3) The highest temperatures occur in the permeable zone near 585 ft MD (415 ft / 126 m elevation), with a temperature reversal of about 9 °F (5 °C) below the permeable zone to the bottom of the well.



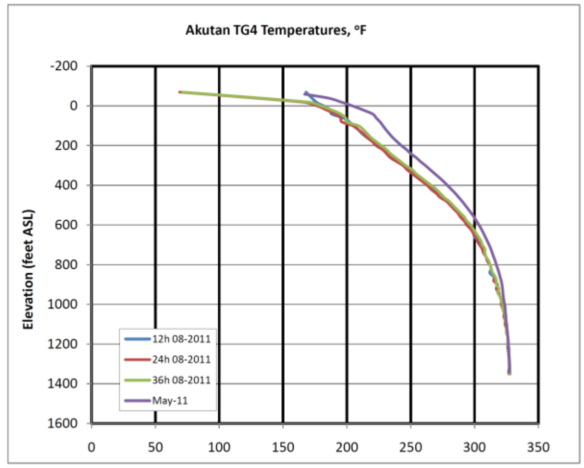


Figure 3. End-of-drilling temperature curves and equilibrated temperature curves. The end-of-drilling surveys were taken 12 hours. 24 hours, and 36 hours after circulation; the equilibrated profile was obtained 9 months later. (a) temperature curves for TG-2; (b) temperature curves for TG-4.

The new data shows that the permeable zone at 585ft MD (415 ft/ 126 m elevation) has thermally recovered since drilling. Notably, the static temperatures measured in this permeable zone are about 338 °F (170 °C), which is lower than the 359 °F (182 °C) temperature measured in this zone when the well was flowing. Since the MRT reading is supported by the silica geothermometry, it is likely that the well was drawing in higher temperature fluids from an adjacent permeable zone when it was producing.

TG4 Equilibrated Temperature Log

Unlike TG-2, the equilibrated temperature profile from TG-4, run about 8 months after well completion, differs very slightly from the end-of-drilling temperature profile (Fig. 3b). The new profile shows that the top 800 ft (244 m) of well TG-4 heated up slightly, but the bottom temperatures remained extremely close to those measured during the end-of-well surveys. This is not surprising in light of the fact that that well was relatively impermeable and exhibits a temperature profile that shows heating primarily from conduction for the upper 800 ft (244 m). By contrast, the bottom of the hole is approaching an isothermal gradient. This suggests that the conductive heating is from the side (either from a shallow outflow zone at some lateral distance, or from a sub-vertical heat source somewhere nearby), and not from a hot aquifer below.

P/T Data Analysis

Although TG-2 flowed geothermal fluid at 359 °F (182 °C) during drilling, the equilibrated temperature logs show a maximum temperature of 338 °F (165 °C) with a reversal at the bottom of the hole. This implies that the 359 ^{o}F fluid was not circulating in the immediate vicinity of TG-2 but rather was "pulled in" from elsewhere due to the pressure drop caused by flowing the well. A likely scenario is that the productive subhorizontal fracture at 585 ft (178 m) in TG-2 is connected to a subvertical fracture dipping west (see Figs. 1, 2). When the subhorizontal fracture was produced, the subvertical one became a temporary conduit for fluids in the outflow zone. It is unlikely that the source of the 359 °F (182 °C) fluid is directly below Well TG-2 because of the temperature reversal recorded in the equilibrated log.

A comparison of the static temperature profiles in TG-2 and TG-4 shows the difference between the shape of a convectively heated outflow profile in TG-2, and a conductively heated temperature profile in TG-4 (Figs. 3a, b). Also, the temperatures in the upper 800 ft (254 m) of TG-4 are generally lower than in TG-2, indicating that TG-4 is further from the outflow path. No strong conclusions can be drawn from the temperature profiles as to whether additional high temperature permeable zones underlie either well, but it appears unlikely based on the shape of the bottom of both well profiles.

The 359 °F (182 °C) temperature measurement during drilling of TG-2 is consistent with silica geothermometry. If the well was producing fluids that were higher than its static measured temperature, this suggests that TG-2 was drilled on the margins of a permeable and hotter outflow path. The higher temperature fluids drawn into TG-2 during the flow test suggest that the production zone is in proximity to the higher temperature zone but that it has a relatively low volume. The slight temperature reversal of about 9 °F (5 °C) below the permeable zone is consistent with the geologic model that the thermal features in HSBV are sourced from a vertically restricted lateral outflow from a geothermal reservoir located further west, or possibly north.

FLUID CHEMISTRY AND THERMOMETRY

Fluid from well TG-2 was collected from the entry zone at 585 -587 ft (178-189m) MD during a well discharge and from production zones between 603 ft (184m) and 833 ft (245m) MD. Air assist was used to collect fluid samples from well TG-4 due to poor permeability conditions. New gas chemical data are from samples obtained from the fumaroles in 2010. All other analyses used in geothermometry calculations and chemical modeling were obtained from past reports (Motyka and Nye, 1988; Motyka et. al., 1993; Symonds et. al., 2003; Kolker and Mann, 2009; Kolker et. al., 2010).

Chemistry

Chemical analyses of the hot springs water shows that they are derived from a dilute, near-neutral Na-Cl reservoir brine. The Akutan hot springs show slightly elevated HCO_3 and SO_4 concentrations, suggesting mixing along the outflow path with dilute, steam-heated near-surface waters. Hydrogen and oxygen isotopic data shows that the hot spring waters are derived from local meteoric water.

The chemistry of the fumarole gases demonstrates some magmatic affiliation. Gas plots show that the gases are well-equilibrated and likely to be derived from a high temperature neutral chloride reservoir. In addition, the gas concentrations in the flank fumaroles imply that some fraction of gas is derived from equilibrated steam, indicating the presence of a localized steam cap in the reservoir. The chemistry of the fumaroles are consistent with an equilibrated geothermal system associated with an andesitic stratovolcano (Giggenbach, 1991). In comparison, the gas from the summit fumarole originates from a more oxidizing environment and exhibits high H_2S concentrations. These all suggest a magmatic affiliation for the summit fumarole steam but only a minor magmatic influence in the Fumarole Valley features that are consistent with a neutral geothermal reservoir.

Geothermometry

Using silica and Na, K, Ca, and Mg concentrations of the hot spring and well fluids, we have estimated the temperature of last equilibration along the outflow path to be ~338 °F (~170 °C) and ~392 °F (200 °C) for the two samples from TG-2, following the calculation methodologies of Powell and Cumming 2010). This temperature is similar to the estimated entry temperature of 359 °F (182 °C) at 585-587 ft (178-179 m) MD in well TG-2 (Kolker et al, 2010). Cation concentrations in hot spring and well discharge analyses show that the springs and well fluids are mixed or partially equilibrated fluids. This is commonly observed along outflow paths where the fluids are re-equilibrating to lower temperatures and mixing with near surface waters with elevated Mg concentrations.

The data from the entry at 585 ft (178 m) MD in core hole TG-2 and from the hot springs nearest TG-2 suggest that the fluids originate in a deeper reservoir with temperatures in the range of 428-464 °F (220-240 °C; Fig. 4).

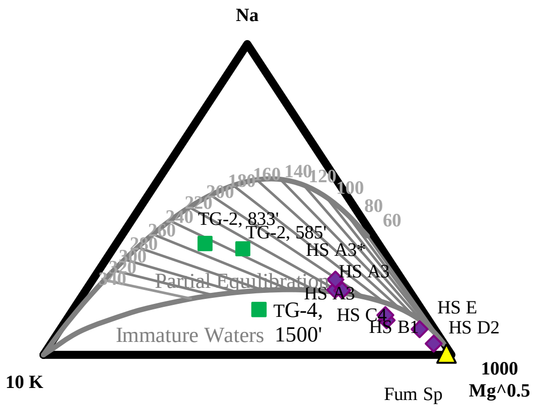


Fig. 4. Na-K-Mg geothermometry plot for samples obtained from the Akutan hot springs and temperature gradient holes. Green squares =well fluid; purple diamonds=hot spring fluid; yellow triangle=fumarole condensate.

This compares to a temperature of 412 °F (211 °C) estimated from the Na-K-Ca geo-thermometer for the well discharge. Geothermometers that apply Na, K, Ca, and Mg concentrations tend to partially re-equilibrate to lower temperatures in the outflow zone, and so the deep reservoir temperature is likely to exceed 464 °F (240 °C).

Geothermometry estimates from Fumarole Valley fumarole gases exhibits very good consistency, indicating an origin from a mature, equilibrated neutral chloride reservoir. The gas geothermometry consistently suggests reservoir temperatures of 518-572 °F (270-300 °C), as shown, for example, in the Car-Har plot (Fig. 5)

Geochemical Model

The new geochemical data set confirms the previous interpretations of the resource distribution in HSBV. The hot springs represent a shallow outflow from a high temperature neutral chloride reservoir that exists further west. The chemistry of the hot springs indicates that they have experienced significant mixing with cooler, dilute near surface meteoric waters. The lack of evidence for mixing of air-saturated meteoric water in the Fumarole Valley fumarole gases support an interpretation of a nearby upflow zone. Geothermometry of the well discharges and the fumarole gases indicate a likely deep reservoir temperature of at least 464 °F (240 °C) based on Na/K geothermometry, with temperatures possibly as high as 572 °F (300 °C) in the reservoir based on gas geothermometry. The geochemical data do not provide any constraints on the reservoir boundaries to the west nor on the reservoir volume within the outflow area.

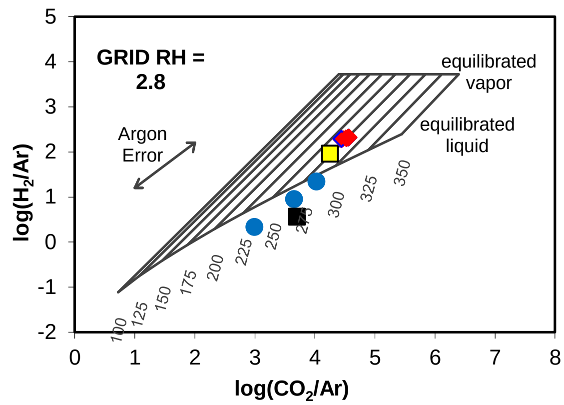


Fig. 5. CAR-HAR geothermometry plot for the Akutan fumarole gases. Red diamonds represent samples collected in 2010, squares from Symonds et al. (2003; yellow=HSBV fumarole, black=summit), and blue circles samples from Motyka and Nye (1988). The Motyka and Nye samples are the poorest quality, showing depletion in H_2 and higher levels of air contamination.

The non-condensable gas data from the fumaroles suggest that a steam cap may overlie the deep brine reservoir. The chloride hot springs in HSBV represent shallow outflow from the reservoir. The outflow becomes diluted by mixing with cool meteoric waters, especially in the near surface environment. Thus, the new geochemical data from the fumarole and well TG-2 are very consistent with the geochemical outflow models suggested by Kolker et al. (2010).

CORE DATA

In addition to full lithologic logs recorded at the drill site, core extracted from wells TG-2 and TG-4 was analyzed at Western Washington University in Bellingham, WA. The goal of the laboratory analysis was to determine the hydrothermal history of the HSBV. Determination of specific mineral species was conducted through XRD, SEM, and petrographic observations, whole rock XRF analysis (conducted at Washington State University) and qualitative assessment of permeability.

Rock Types and Primary Mineralogy

There are four main lithologies present in the Akutan core: basalt, andesite, ash tuff, and lithic-rich basalt. The most common lithology in the core is basalt lava, which appears to be subareal in nature and typically contains plagioclase, clinopyroxene, rare olivine and primary apatite. Ash tuffs are fine grained rocks lacking phenocrysts, with groundmass phases of plagioclase microlites, glass, and alteration minerals (see below). In TG-2, these units are <3 ft (1 m) thick. In TG-4, which is ~2 miles (3.2 km) closer to Akutan Volcano, similar units are as thick as 60 ft (18 m), although correlations between individual units was not possible. Units of lithic basalt are composed of multiple different rock types in a crystalline matrix. At this time, the origin of this lithology is unknown.

Secondary Mineralogy, Mineral Paragenesis, and Hydrothermal History

The core rocks in general appear to be only weakly altered. Flow margins are characteristically rich in vesicles and fractures, and thus tend to be more altered and more readily brecciated than the main body of the lava. Heavy Fe-oxidation was observed between flow layers. Alteration minerals occurred interstitially, in fractures, vesicles, and contact zones.

Alteration assemblages in both wells are dominated by chlorite, zeolites, epidote, prehnite and calcite, and this propylitic alteration appears to have happened multiple times in both wells. The presence of adularia in specific locations in both wells indicates higher temperature and permeability conditions existed at some point in the past. The presence of kaolinite in TG-2 indicates argillic alteration with lesser extent and intensity. Illite was identified in both wells, although much more sparsely in TG-2.

Within the most recent propylitic alteration event in TG-2, the sequence of zeolite formation shows a classic trend toward higher temperatures with depth (Seki et. al., 1969b; Wood, 1994). It is possible that this trend will continue below the base of the well (833 ft / 254 m MD). Figure 6a shows that some higher-temperature minerals (illite, epidote, prehnite, wairakite and adularia) occur in regions that are currently much colder than expected for these minerals. This suggests that the TG-2 region underwent higher temperature alteration (>469 ^{o}F/ 250 ^{o}C) in the past. The presence of these higher-temperature minerals at unexpectedly shallow depths further suggests that a significant portion of this older alteration sequence has been removed through erosion, possibly glacial. Overprinting of these minerals by lower-temperature alteration assemblages indicates the sampled region has since returned to a lower-temperature alteration regime with reduced permeability.

The pattern of alteration in TG-4 is more complex than TG-2 (Fig. 6b), but still records multiple propylitic alteration events.

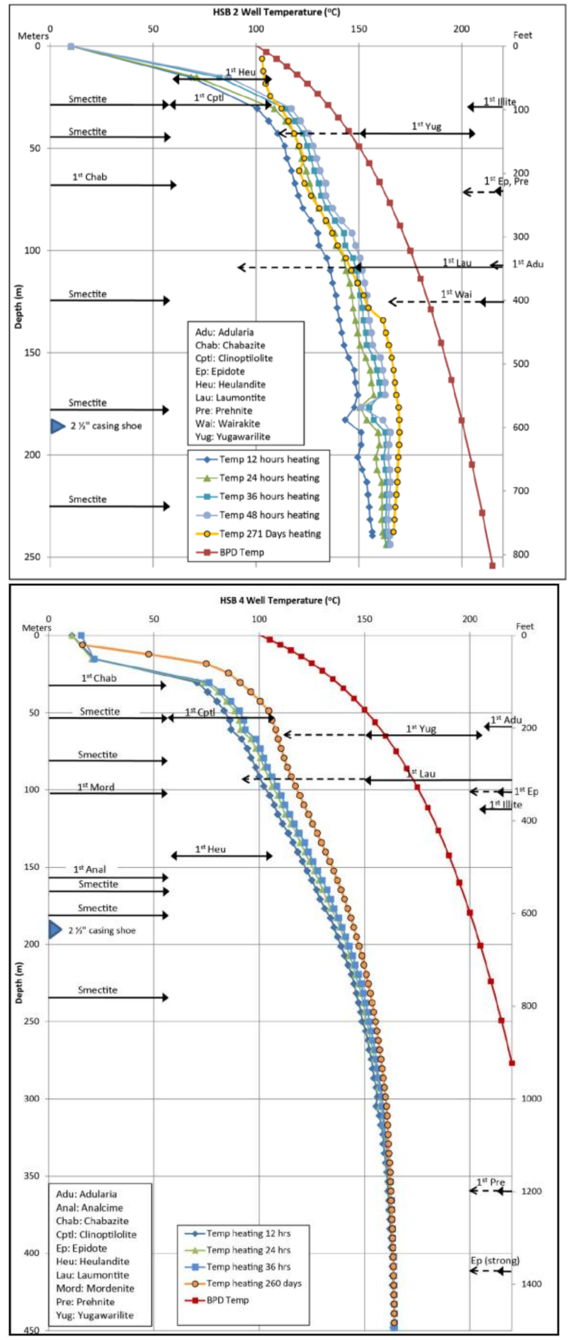


Fig. 6. First occurrence of indicator minerals with depth in core from wells TG-2 (a) and TG-4 (b). Horizontal arrows indicated formation temperature ranges for each mineral. Dashed lines indicate published values; solid lines indicate the most commonly reported minimum temperatures.

While the alteration patterns are somewhat different from those observed in TG-2, they may still be related to the same thermal histories. The most recent alteration event may have been stronger in the TG-2 region, overprinting more completely the alteration sequence observed in TG-4.

Both cores show an alteration sequence progressing from an early propylitic event, a narrow band of adularia-bearing propylitic alteration, followed by a later propylitic event. The trend from moderate propylitic to high-temperature adularia-forming alteration and back to moderate propylitic indicates that the shallow portion of the HSB field has reached its thermal peak and has cooled moderately. Additionally, many of the higher temperature minerals occur at depths much shallower than reported in other geothermal fields. Thus is it likely that 1) this region was hotter than it is currently, and 2) the uppermost portion of the rock column has been removed by glacial erosion.

Permeability and Porosity of Well Rocks

The primary lithologies do not lend themselves to high primary permeability. The abundance of isolated vugs filled with secondary minerals indicates that fluid flow through microscopic intergranular networks has been important, but flow rates are likely very low. Vug filling is especially common in fine-grained, detrital deposits (e.g., ash tuff), but clay alteration and fracture mineralization by carbonates and zeolites reduces permeability in these rocks.

The primary fluid pathways appear to be associated with brittle fracturing and lithologic contacts, based on the abundance and degree of alteration and secondary mineralization. Highly vesicular lava flow tops have high porosity and, when collapsed, can have high permeability, although this was not observed in the core. The majority of alteration and secondary mineralization occurs along fractures, however. This is particularly evident in the ash tuffs, in which the lack of large crystals allows the units to fracture at prescribed orientations (0^o, 30^o, 45^o, 60^o and 90^o). The majority of these fractures have secondary mineralization associated with them, and some of the larger fractures contain relatively large amounts of clays and other secondary minerals. Because the tuff is more susceptible to clay alteration, these fractures can seal before major secondary mineralization becomes intense. However, these units are thin in the wells, so may not have significant control over the overall fluid flow.

The occurrence of the mineral adularia helps to elucidate the nature of the permeability beneath HSBV. Although adularia occurs in all lithologies in the HSBV cores, the restriction of adularia to fractures highlights the importance of secondary permeability, as it does in many fields worldwide. Adularia is strongly associated with zones that once had high permeability but each occurrence of adularia in the core is in veins that are now thoroughly sealed by mineralization. Therefore, the waxing of a higher temperature system and subsequent waning has apparently reduced the permeability in the HSBV outflow system.

Evidence for large scale structures was not encountered in Akutan geothermal wells. A number of brecciated zones were observed in TG-4, but most were "sealed" with secondary mineral deposits and therefore probably do not represent active faults. Minor slickensides observed in cores could be related to a possible normal fault on the SW side of the valley near TG-4.

CONCEPTUAL MODELS

Two conceptual models of the Akutan Geothermal Resource have been presented in previous works (Kolker et al, 2010), both of which describe the Akutan geothermal system as a single resource comprised of two distinct features: a high-temperature (>500 °F / >240 °C) upflow zone located at depth somewhere proximal to the fumaroles, and a lower-temperature outflow aquifer (~360-390 °F / 180-200 °C). Two alternative outflow pathways are either along the L-shaped path of HSBV (Fig. 7) or along a northern trajectory from the fumaroles to the hot springs (Fig. 8).

Conceptual model 'CM1' (Fig. 7), follows the HSBV path. This model was initially preferred because the flow paths followed major structural features. There are several lines of evidence, however, that reduce the likelihood that this model is accurate. The downhole temperature profile in TG-4 shows little evidence for conductive heating from below, requiring that the hot upflow region be significantly displaced both vertically and horizontally from TG-4. Additionally, for this model to fit the observed downhole temperature profiles in both wells, the outflow along HSBV can only be very thin (vertically constrained low-permeability) and restricted to the shallow subsurface.

Temperature differences between fluids flowed from the permeable zone (585-587 ft MD in TG-2) during drilling (359 °F; 182 °C) and after equilibration (338 °F; 165 °C) provide additional arguments against CM-1. First, the hottest fluids must have been "pulled in" laterally from a nearby source, and CM-1 does not allow for such hot fluids to be so rapidly available at TG-2,as these temperatures would be ~3 km distant (Fig. 7b). Second, Conceptual model 1 'CM1' does not resolve the location of a hotter outflow resource of 360-392 °F (180-200 °C), for which there is a substantial amount of geochemical evidence. Additionally, the rapidity with which this hotter fluid was drawn in during such a short test implies that the 338 °F (165 °C) permeable zone in TG-2 must be restricted in volume and at a higher natural pressure than the 359 °F (182 °C) adjacent reservoir.

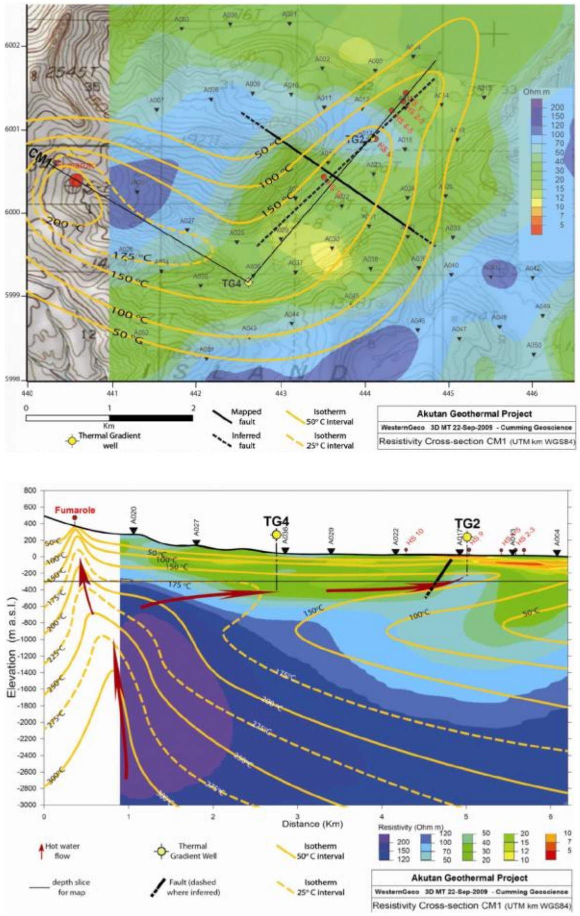


Fig. 7 Map view of Conceptual model CM1; shallow outflow following HSBV. Isotherm contour placement is based on downhole temperature data, chemical geothermometry, hot springs and fumarole locations and MT resistivity data. (a) Map view, with resistivity values for 984 ft (400 m) depth. Angled black line "CM1" corresponds to the profile trace in (b). (b) Profile view of CM1, MT resistivity data based on 3-D inversion model. Black line at 400 m refers to depth slice for resistivity values shown in (a).

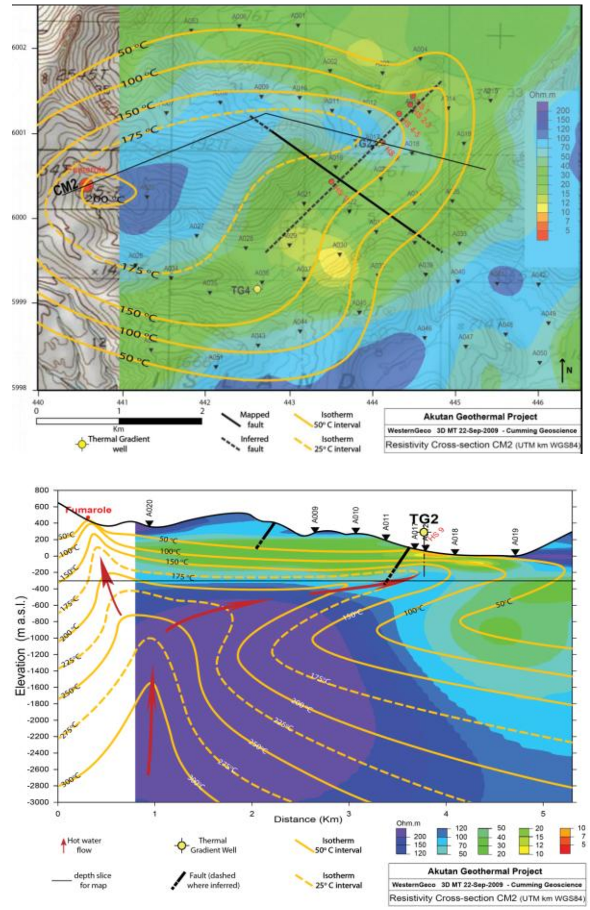


Fig. 8 Conceptual model CM2; shallow outflow north of HSBV. Isotherm contour placement is based on downhole temperature data, chemical geothermometry, hot springs and fumarole locations and MT resistivity data. (a) Map view, with resistivity values for 984 ft (400 m) depth. Angled black line "CM2" corresponds to the profile trace in (b). (b) Profile view of CM2, MT resistivity data based on 3-D inversion model. Black line at 400 m refers to depth slice for resistivity values shown in (a).

In conceptual model 2 'CM2' (Fig. 8), the shallow outflow path takes a northerly trajectory from the fumarole to the ENE towards the hot springs, circumventing HSBV altogether. This model appears more likely based on several lines of reasoning: 1) the temperature profile for TG-4 shows no evidence for being along an outflow path, implying that outflow feeding the hot springs is laterally distal; 2) a low-resistivity clay cap appears to form a dome pattern around the northerly outflow path, which is consistent with the interpretation that the HSBV is near, but not in, the main outflow path of geothermal fluids (Figs.7a and 8a); and 3) the isotherm contours on the CM2 profile (Fig. 8b) are slightly more typical of an outflowing geothermal system.

Both models suggest that producing the outflow resource entails more risk because much of the data suggest low permeability conditions in the HSBV. In addition to the well behavior and alteration patterns observed in the core discussed above, there is no well-developed clay cap to indicate that a large, very permeable reservoir volume at ~360-390 °F (180-220 °C) exists under HSBV. The lack of widespread surface alteration, geochemical, and ground temperature anomalies (Kolker and Mann 2009) in HSBV are consistent with this interpretation. Additionally, the chemical composition of the hot springs fluids suggests that outflow fluids become extensively mixed with cooler meteoric waters near the surface, raising concerns about cold water influx into the outflow system with production.

Both models also suggest that the upflow zone could be an extremely attractive development target. Geochemical data from the fumaroles suggest that the area lies fairly near an upflow zone from the reservoir that a steam cap may overlie the upflow, and that reservoir temperatures could approach 570 °F (300 °C) within the upflow. The deep reservoir probably consists of a brine liquid capped by a small two-phase region (steam cap). Resistivity data suggest that the upflow reservoir is situated in brittle rocks, implying propylitic alteration regime and a good possibility of high permeability.

CONCLUSIONS

The Akutan geothermal resource can be divided into an upflow zone and one or more outflow zones. While the conceptual models of the outflow resource have downgraded its potential for development, geochemical data from the fumaroles significantly upgrades the upflow resource as a drilling target. Studies of alteration minerals in the core suggest that the outflow region has reached a thermal maximum and is in a cooling phase. The presence of a thin clay cap, high resistivity values, and high temperature minerals occurring at surprisingly shallow depths in the outflow region suggest the uppermost portion of the outflow region may have been eroded, possibly due to glaciation. Alteration and secondary mineralization in the outflow region has resulted in "self-sealing" of permeable structures, and the outflow resource discovered by TG-2 is likely to have significant permeability limitations. The peak outflow resource temperature of 359 °F (182 °C) discovered during slimhole exploratory drilling in 2010 appears to reflect fluid "pulled in" from a nearby source. A temperature reversal at the bottom of the stabilized TG-2 profile reduces the possibility that a hotter or more voluminous reservoir would be encountered by drilling deeper at that location. New geochemical data from well fluid and fumaroles indicates that the upflow region of the Akutan system, in the vicinity of the fumaroles at the head of Fumarole Valley, is >428-572 °F (220-300 °C), near-neutral chloride system with minor volcanic affinity and a steam cap. Thus, the greatest probability of successful development is in this region.

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