Dacite Melt at the Puna Geothermal Venture Wellfield, Big Island of Hawaii

**William Teplow[1], Bruce Marsh[2], Jeff Hulen[1], Paul Spielman[3],
Mike Kaleikini[4], David Fitch[1], and William Rickard[5]**

**[1]Consulting Geologist
[2]Dept. Earth & Planetary Sci., Johns Hopkins University
[3]Ormat • [4]PGV • [5]Resource Group**

Keywords

Dacite magma, Puna Geothermal Venture, EGS, Kilauea Lower East Rift Zone

ABSTRACT

During the drilling of injection well KS-13 in 2005 at the Puna Geothermal Venture (PGV) wellfield, on the island of Hawaii, a 75-meter interval of diorite containing brown glass inclusions was penetrated at a depth of 2415 m. At a depth of 2488 m a melt of dacitic composition was encountered. The melt flowed up the wellbore and was repeatedly redrilled over a depth interval of ~8 m, producing several kilograms of clear, colorless vitric cuttings at the surface. The dacitic glass cuttings have a perlitic texture, a silica content of 67 wgt.%, are enriched in alkalis and nearly devoid of mafic minerals with the exception of rare pyroxene phenocrysts and minor euhedral to amorphous magnetite. The melt zone is overlain by an interval of strong greenschist facies metamorphism in basaltic and dioritic dike rock. The occurrence of an anhydrous dacite melt indicates a rock temperature of approximately 1050ºC (1922ºF) and sufficient residence time of underlying basaltic magma to generate a significant volume of highly differentiated material. Heat flux from the magma into the overlying geothermal reservoir is ~3830 mW/m^2, an order of magnitude greater than for mid-ocean ridges. The geologic conditions at PGV combine tensional tectonics with magmatic temperatures at readily drillable depths (<2500 m).

Introduction

Commercial geothermal development in the Kilauea Lower East Rift Zone (KLERZ) on the island of Hawaii (Figure 1) commenced in 1976 when the State of Hawaii well HGP-A was drilled to a depth of 1968 m. The well encountered a low-permeability resource with a maximum temperature of 356°C. The well powered a three-MW power plant from 1981 to 1989 and was subsequently plugged and abandoned after the plant was shut down. Beginning in 1981 various commercial developers drilled several geothermal exploration wells in the area surrounding HGP-A. In 1989 Ormat Technologies, Inc. of Reno Nevada, acquired the 500-acre Puna Geothermal Venture (PGV) lease containing three steam-dominated production wells located adjacent to the HGP-A site (Figure 2, overleaf).

The PGV subsidiary of Ormat drilled several production and injection wells and went into commercial production with a 30 MW geothermal power plant in 1993. The power plant has operated continuously since that time with new production and injection wells being drilled from time to time to maintain full power plant capacity. In 2005 during the routine drilling of injection well KS-13, the most recent well to be drilled in the PGV wellfield, magma of dacitic composition was encountered at a depth of 2488 m below surface. High drill string torque occurred at that depth and 8 meters of hole were lost when the bit was picked up. The hole was cleaned out repeatedly without

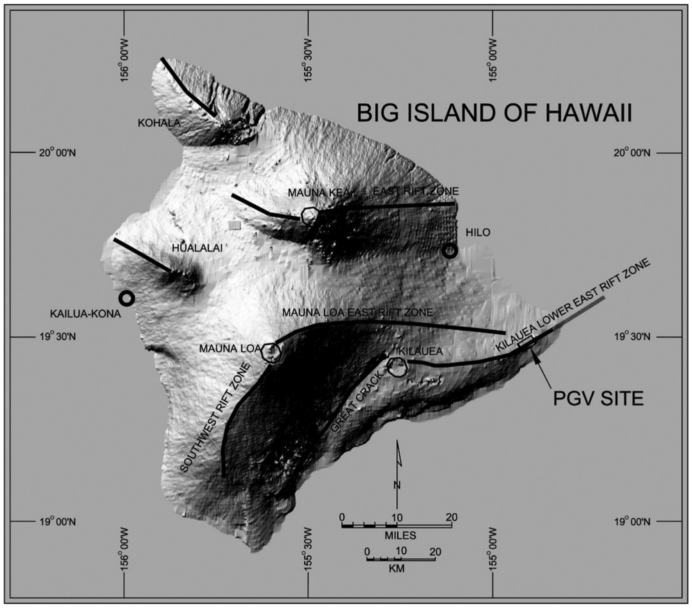

Figure 1. PGV Location Map and Big Island Volcanic Rift Zones.

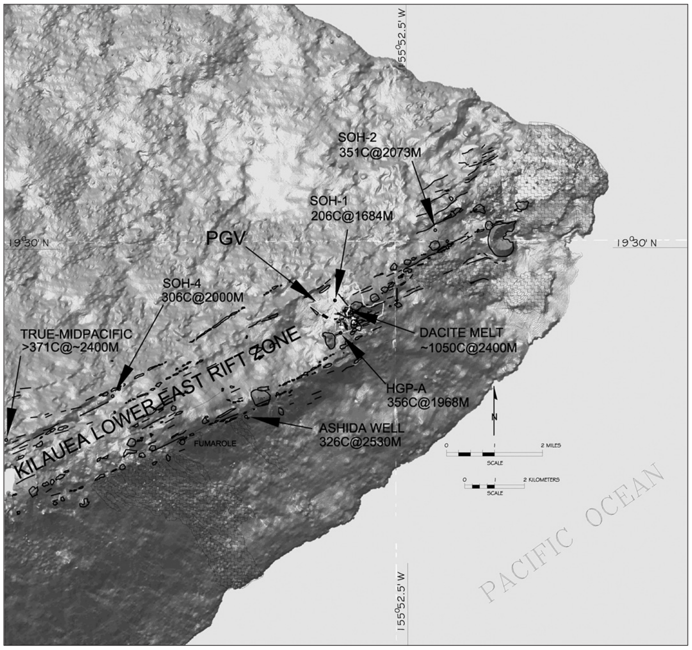

Figure 2. PGV Site and Geologic Setting, KLERZ.

progress beyond the original total depth (TD). Each time the drill string was raised and set back on bottom, the string took full weight-on-bit several meters above the original TD. Several kilograms of felsic glass cuttings were generated in this manner. The cuttings were circulated to surface and a bulk sample of the dacite glass was collected. This paper discusses the geologic setting for the dacite magma, its mineralogical and chemical characteristics, an estimate of temperature based on the magma chemistry and flow characteristics in the wellbore, and the possibility for commercial exploitation of this heat source.

Geologic Setting

The Puna Geothermal Venture wellfield is located in the Kilauea Lower East Rift Zone (KLERZ) (Figure 2).

The KLERZ is characterized by a system of active but currently quiescent basaltic vents, fractures, pit craters and cinder cone lineaments with a width of two kilometers to the west of the PGV wellfield and a width of 1 kilometer to the east of PGV (Moore and Trusdell 1991). Eighty percent of the KLERZ is covered by basalt flows younger than 500 years. The most recent eruption in the KLERZ took place in 1955 in the vicinity of PGV and in 1960 in Kapoho area six kilometers to the east. The PGV lease block is seismically active with 6-12 events occurring daily with typical magnitudes ranging from -1 to 2. The microearthquake activity has remained relatively constant both before and after start of power production and injection in 1993. Likewise, the natural subsidence rate within the PGV property has remained relatively constant at approximately 1 cm/yr since the beginning of measurements by the USGS in 1958.

KS-13 Targeting and Drilling History

KS-13 was targeted and drilled as an injection well in the central part of the PGV lease block. It was drilled in August-October, 2005 to a depth of 2488 m (Figure 3). The open-hole segment consisted of a 10-9/16 inch (25.88 cm) hole drilled directionally with mud motor and MWD to TD. The well was targeted to cross two eruptive lineaments, the 1955 eruptive fissure and the adjacent cinder cone lineament (Figure 3). Lost circulation occurred at 1521, 1562, 1691, 2001, 2077, and 2191 m MD. Micronized cellulose was added to the mud to regain partial to full returns after each loss zone.

High torque occurred at 2488 m TVD and 8 m of hole was lost when the bit was picked up. The hole was cleaned out repeatedly without progress. Several kilograms of clear, colorless glass was circulated in bottoms-up samples and collected at the shaker screens. While reaming, the drill string became stuck in hyaloclastite fill and was shot off at 2253 m and abandoned in place due to the very low probability of successful recovery. The well was completed as an injector with perforated liner, set on the top of hyaloclastite fill at 2124 m.

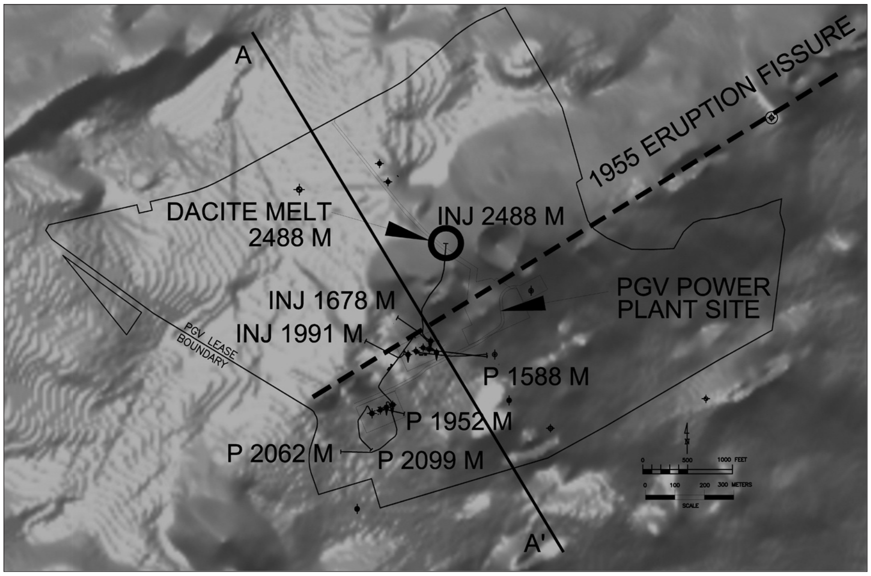

Figure 3. PGV Wellfield and Location of Dacite Melt.

Upon completion, KS-13 was developed using cold water injection and surging with a hydrostatic bailer and by swabbing. The well is currently the primary injection well for the project, taking 189 liters/second at a wellhead pressure of 29 bar.

Mineralogy of the KS-13 Dacite Glass and Host Rock

Twenty-eight selected cuttings samples from well KS-13 were examined in detail using a Zeiss Stemi stereozoom microscope with wide-field optics and high-intensity fiber-optic illumination. The samples span the measured-depth interval 1890 m to 2528 mMD. Emphasis for this work was on lithology, hydrothermal alteration and mineralization, and evidence of structural or hydrothermal rock rupture. Of particular interest were the two deepest cutting samples (from 2480 to 2488 m TVD) which appeared to be dominated by felsic glass.

Lithology

Seven rock types appear to dominate the 28 cuttings samples from KS-13: (1) Microdiorite or microdiabase; (2) sparsely porphyritic olivine-pyroxene basalt; (3) basaltic tuff [hyaloclastite]; (4) andesite or basaltic-andesite tuff; (5) diorite or quartz diorite; (6) an unusual "glass-globule" andesite; and (7) glassy dacite porphyry, in essence, a vitrophyre. Also present in some samples are small amounts of hydrothermally altered cataclasite (indurated fault gouge and breccia) as well as hydrothermal veinlets and veinlet fragments.

The texture of the KS-13 microdiorite/microdiabase, some of which contains minor amounts of interstitial quartz, indicates that it is intrusive. The basaltic hyaloclastite is a vitric-lithic variety that is invariably and intensely hydrothermally altered. Dark brownish-gray, the "glass-globule andesite" is a glassy to microcrystalline rock that contains disseminated globules—as well as angular clasts—of deep grayish-brown translucent glass.

Glassy dacite porphyry, or vitrophyre, accounts for most of the two deepest samples. The vitrophyre consists mostly of white to colorless to very light gray, translucent to transparent, pumiceous to perlitic glass, in which are embedded small, fresh plagioclase laths and equally unaltered microcrystalline magnetite.

Hydrothermal Alteration

The nature and intensity of hydrothermal alteration in the 28 KS-13 cuttings samples varies with rock type and/or depth. The hyaloclastite is ubiquitously and uniformly altered to a "soapy"-textured mixture of clay (saponite?) and other, unidentified secondary phases. All samples of the microdiorite/microdiabase retrieved from below 7550 ft depth are weakly to strongly altered to chlorite, sericite, and fibrous to acicular tremolite or actinolite. Traces of talc may also be present. Much of the dacite porphyry/vitrophyre appears unaltered, but about 10% of the cuttings of this rock are weakly altered to whitish clay.

Likely Dacite Glass Diferentiation and Segregation Mechanism

In oil of a refractive index of 1.54 the dacite glass appears colorless (Figure 4) and contains about 5-8 vol% crystals of plagioclase (dominant phase), Fe-Ti oxide (i.e., 'magnetite'), orthopyroxene, and apatite. Each of the crystalline phases is euhedral, well-formed and hence in equilibrium with the melt, and not due to quenching attending drilling. There is no sign of vesiculation and the glass is generally unstructured, but there are patches of swirled or perhaps incipient spherulite which may reflect a combination of shear due to the drill bit action during rapid quenching from contact with drilling mud.

Magma Temperature

The temperature of the dacite magma can be inferred in two ways. The first is to calculate the full crystallization history beginning with a dry magma of a composition the bulk rock (Table 1). This thermodynamic calculation uses the well-known MELTS software (e.g., Ghiorso et al., 1994) to find the sequence of crystallization and the increase in crystallinity with decreasing temperature (see Figure 5, overleaf). Matching the visually estimated crystallinity (i.e., 5-8 vol.%) to that computed gives a temperature of about 1050°C. The second method uses the same software to match the measured glass composition to the composition of melt from a parent basalt undergoing protracted crystallization. The parent basalt composition chosen is that of the 1955 eruption on the East Rift, which occurred in this area and is the most likely parent of this dacite (Dr. T.L. Wright, pers. comm., March, 2008). Matching the K2O concentration in the residual melt of the parent basalt to that measured in the bulk dacite also gives

Table 1.

Sample	KS-13 Dacite 2844 m	Chilean oceanic ridge	Spreading center, S. Pacific	Kilauae basalts 418 samples avg.
Rock Type	dacite glass	dacite	dacite glass	basalt
Location	PGV	45.9198°S, 75.9148°W	38.0918°S, 111.0027°W	East Rift Zone
Data Source	Actlabs	Sherman, 1997	Hekinian, 1997	Thornber *et al.*, (2002)
SiO2	67.33	64.81	64.03	51.06
TiO2	0.585	0.87	1.13	3.95
Al2O3	12.01	15.84	13.26	12.44
FeOT	5.18	3.99	8.6	13.15
MnO	0.086	0.06	0.18	0.19
MgO	2.29	1.92	1.34	5.04
CaO	2.49	4.6	4.33	9.4
Na2O	4.03	4.22	3.28	2.72
K2O	2.76	2.17	1.17	0.82
P2O5	0.11	0.17	0.33	0.43

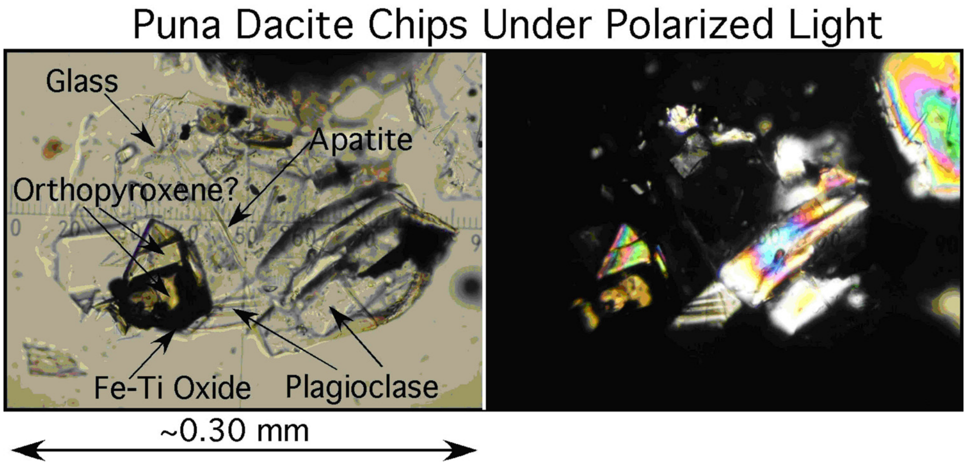

Figure 4. Photomicrographs of Puna Dacite in oil. Plain polarized light (left) and under crossed Nicols (right) when the glass appears opaque.

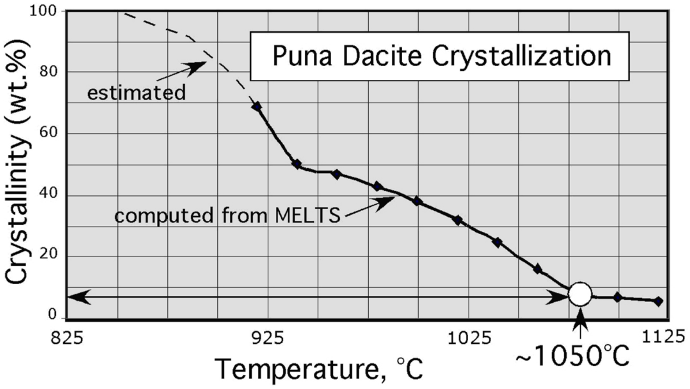

Figure 5. Crystallization of Puna Dacite as calculated from MELTS. The increase in overall crystallinity with decreasing temperature.

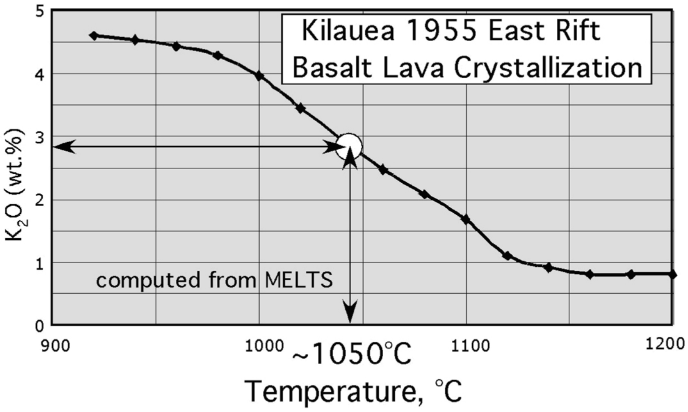

Figure 6. Crystallization of the 1955 Kilauea basalt as a parent to the Puna Dacite ,showing the increase in potash in the residual melt with increasing crystallization and decreasing temperature.

a temperature of about 1050 °C (see Figure 6). An overall check on this result is available by comparing the dacite composition to the observed compositions of interstitial melts extracted from Alae, Makaopuhi, and Kilauea Iki lava lakes (e.g., Wright and Okamura, 1977; Wright and Peck, 1978; Helz, 1987). From these works, the dacite melt estimated temperature could be slightly higher (~1065°C), reflecting the slightly different parent basalt initial composition.

Magma Viscosity

The flow of the dacite magma up the drill hole (25.88 cm diameter) can be used to estimate the viscosity of the magma. This is done by calculating the time necessary for melt of a given viscosity to flow under a given pressure gradient a given distance up the drill hole. The melt was observed to flow upward approximately 5.5.m in a few minutes. The most elusive part of the calculation involves estimating the pressure gradient driving the flow. The lithostatic load at this depth, based on the hole depth (~2.54 km), is about 0.65 kilobars, which is assumed to act (see below) over a characteristic distance of about 2 m to give a characteristic pressure gradient. Using the well-known results for Hagan-Poiseuille flow in a pipe, yields a characteristic viscosity of 3.8 x 10^7 poise. An independent calculation from the MELTS software using only melt composition, temperature, water content (zero), and crystal content gives an almost identical estimate of 3.16 x 10^7 poise.

The thermal residence time or time of solidification of the dacite as it flows up the drill hole was also calculated using the method as described above. This time is 30-60 minutes depending on how much cooling is assumed. This is far longer than the 'few minutes' observed before the magma came to rest, presumably by solidification, in the open drill hole. This suggests that the upflowing magma, in effect, caps itself not by cooling through the lateral walls, but by cooling and solidification of the leading front, which undergoes quenching against the stream of cool drilling mud impinging on the top of the melt in the drill hole.

Magma Origin and Size

Lavas of this composition are unknown on Hawaii, although a small rhyodacite flow of broadly similar composition has been observed on Oahu (Bauer et al., 1973). Dacites and rhyolites are fairly common on some oceanic islands like Iceland and Rapa Nui (Easter Island) and are thought to come about through reprocessing of earlier basaltic materials containing isolated lenses of silicic differentiates (e.g., Gunnarson et al., 1998). Silicic lenses or silicic segregations are found in most basaltic sill-like bodies and can vary in size from a few cm to over a meter in thickness and many meters in length. The segregations themselves form from a gravitational instability that promotes internal tearing within the upper solidification front of intrusions undergoing cooling and progressive solidification (Marsh, 1996; 2002). In essence, at higher crystallinities (i.e., >~40 vol.%) the upper solidification front is highly interconnected in a trellis or chicken-wire network of crystals and due to its weight it becomes unstable, forming tears or gashes that are filled with local residual melt. At slower cooling rates associated with sills, these lenses can become over a meter thick and 50-60 m long. This is the most likely source of the Puna dacite. Drilling has encountered an unusually large lens.

A second possibility is that one or more lenses have collected and flowed into a common region. This is possible if the parent basaltic body is not horizontal but is dipping. Open fractures with large apertures (2-5 meters) have routinely been encountered in the PGV wellfield at depths ranging from 1500 m to 2000 m. These fractures constitute the prolific productions zones which are exploited for power production. They typically lie along the footwall of near-vertical diabase (fine grained gabbro) dikes. These large-aperture fractures are located within a vertical distance of 500 m from the dacite magma body and may represent a tectonic feature that would provide the host volume for the differentiating dacite magma (Figure 8).

Size and Age of the Parent Body

If the basalt parent to the Puna dacite is, indeed, the 1955 Kilauea basalt, then the parent intrusion has been sustained in a partially molten state for about 50 years. This time places a minimum characteristic thickness on the parent body of about 100 meters. That is, a first order solution to the heat conduction equation shows that the time (t) for a sheet of half thickness (L) to cool by 15% is given by $t \sim L^2/k$, where k is the thermal diffusivity (~10-2 cm^2/s), which suggests the minimum equivalent sheet thickness 100 m.

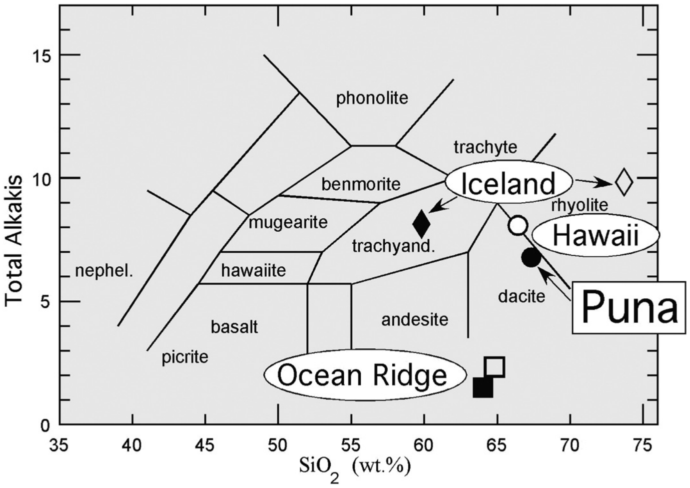

Figure 7.

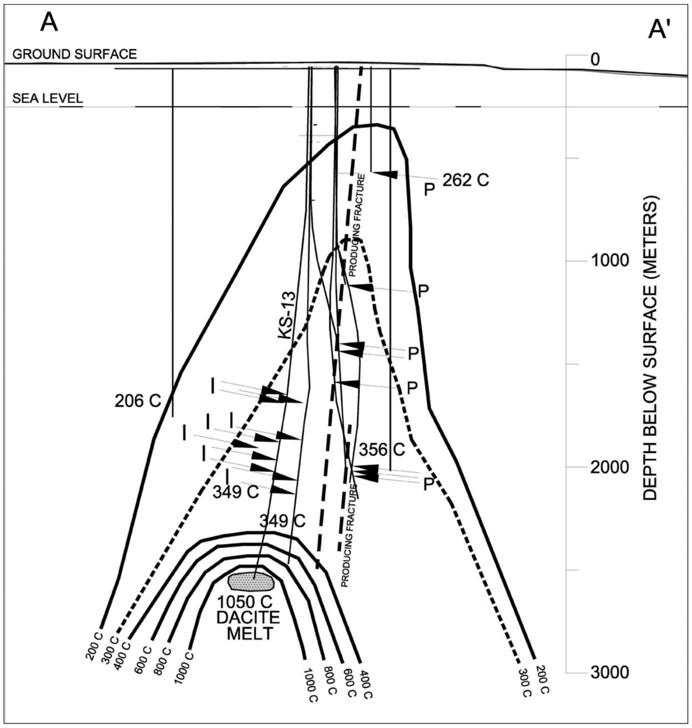

Figure 8. Thermal Cross Section A-A', P = Production zone; I = Injection zone.

This estimate is consistent with the longevity of the Kilauea Iki lava lake, which formed in 1959. The lake is about 125 m thick, and, from its drilling history, is certainly still partially molten (e.g., Helz, 1987). The initial eruption and filling temperature was about 1200 °C at which point crystallization began and crystallization ends at about 900°C. The lateral extent of sheet-like bodies, which is the likely form of the parent body, is on the order of 1 km (perhaps several km) and will be roughly circular in plan form.

Comparison to Other Oceanic Dacites

As mentioned already, although silicic magmas are almost unknown in the Hawaiian Islands, they are much more common on many oceanic islands, especially on islands where sustained magmatism allows reprocessing of the existing volcanic/plutonic pile. A simple comparison of the silica and potash contents of the Puna dacite with dacites and rhyolites from Iceland (Gunnarson et al., 1998), mid-ocean ridges (Sherman, 1997; Hekinian, 1997) and the Oahu rhyodacite lava (Bauer, 1973) is shown by Figure 7. Ocean ridge silicic rocks are generally much lower in potash and soda and Icelandic silicic rocks are most often richer in both silica and total alkalis. Overall, the Oahu lava is similar to the Puna dacite.

Heat Flux

A temperature cross section A-A', transverse to the KLERZ in the PGV wellfield, is shown in Figure 8. The inferred temperature of the dacite, 1050 C, is separated by 526 m of rock from the deepest permeable zone in KS-13 with a temperature of 356 C. The thermal gradient through this impermeable rock section is ~700ºC/526 m = 1.331 ºC/m. The calculated conductive heat flux from the magma upward into the deepest zone of hydrothermal circulation is given by k*(dT/dZ)=2.9 * 1.33 = 3.83 W/m^2 = 3830 mW/m^2 (thermal conductivity k=2.9 $W{*}m^{-1}{*}{}^{o}C^{-1}$ for basalt). This heat flux is an order of magnitude greater than the average heatflow of 270-290 mW/ m^2 typical for the mid-ocean ridges (Sclater and Fracheteau, 1970), 140 mW/m^2 for the Imperial Valley (Lachenbruch et al 1985) and 118 mW/m^2 for the Battle Mountain High of the Basin and Range Province.

References

Bauer, G.R., Fodor, R.V., Husler, J.W. and Keil, K., 1973, Contributions to the mineral chemistry of Hawaiian rocks III. Composition and mineralogy of a new rhyodacite occurrence on Oahu, Hawaii. Contrib. Min. Pet. 40, 183-194.

Davis, Earl E, David S. Chapman, Craig B. Forste1996, Observations concerning the vigor of hydrothermal circulation in young oceanic crust, Journal of Geohysical Research, VOL. 101, No. B2, pp. 2927–2942,

Fedotov, S. A., V. M. Sugrobov, I. S. Utkin, and L. I. Utkinab, 2007, On the Possibility of Using Heat Stored in the Magma Chamber of the Avachinsky Volcano and the Surrounding Rock for Heat and Power Supply, Journal of volcanology and Seismology, vol. 1, No. 1 pp.28-41.

Ghiorso, M.S., Hirschmann, M., and Sack, R.O., 1994, MELTS: software for thermodynamic modeling of magmatic systems. EOS, Trans. Amer. Geophys. Union, 75, 571.

Gunnarsson, B., B. D. Marsh, and H.P. Taylor,Jr. 1998. Geology and petrology of postglacial silicic lavas from the SW part of the Torfajokull central volcano, Iceland. J. Volcanology and Geotherm. Res. 83, 1-45.

Hekinian, R., Stoffers, P., Devey, C.W., Ackerman, D., Hemond, C., O'Connor, J., Binard, N., Maia, M., 1997, Intraplate versus ridge volcanism on the Pacific-Antarctic ridge near 37 degrees S – 11 Degrees W JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. B6, PAGES 12,265–12,286, 1997

Helz, R.T., 1987, differentiation behavior of Kilauea Iki lava lake, Kilauea Volcano, Hawaii: An overview of past and current work. Geochemiccal Society Special Publication 1, 241-258.

Lachenbruch, Arthur H.; Sass, J. H.; Galanis, S. P., 1985, Heat flow in Southernmost California and the origin of the Salton Trough, Journal of Geophysical Research, Volume 90, Issue B8, p. 6709-6736.

Marsh, B.D., 1996. Solidification fronts and magmatic evolution, Mineralogical Magazine, v. 60, 5-40.

Marsh, B. D., 2002, On Bimodal Differentiation by Solidification Front Instability in Basaltic Magmas, I: Basic Mechanics, Geochimica et Cosmochimica Acta, v66, 2211-2229.

Moore, Richard and Frank Trusdell, 1991, Geologic Map of the Lower East Rift Zone of Kilauea Volcano, Hawaii, Miscellaneous Investigations Series Map I-2225.

Sclater, John G., Jean Francheteau (1970) The Implications of Terrestrial Heat Flow Observations on Current Tectonic and Geochemical Models of the Crust and Upper Mantle of the Earth,Geophysical Journal International 20 (5) , 509–542

Sherman, S.B., Karsten, J.L., Klein, E.M., 1997, Petrogenesis of axial lavas from the southern Chile ridge: major element constraints. Jour. Geophys. Res., 102, 14963-14990.

Tsutomu Murase, and Alexander R. McBirney, 1973, Properties of Some Common Igneous Rocks and Their Melts at High Temperature,*GSA Bulletin*; November 1973; v. 84; no. 11; p. 3563-3592.

Wilcock, William S.D., John R. Delaney (1996) Mid-ocean ridge sulfide deposits: Evidence for heat extraction from magma chambers or cracking fronts?, Elsevier Earth and Planetary Science Letters 145, pp. 49-64.

Wright, T.L. and Okamura, R.T., 1977, Cooling and crystallization of tholeiitic basalt, 1965 Makaopuhi lava lake, Hawaii. U.S.G.S. Prof. paper 1004, 78 p.

Wright, T.L. and Peck, D.L., 1978, Crystallization and differentiation of the Alae magma, Alae lava lake, Hawaii. U.S.G.S. Prof. paper 935-C, 20p.