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A GEOTHERMAL RESOURCE FOR ERITREA, AN ENERGY-POOR AFRICAN NATION

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SUMMARY - Eritrea badly needs electrical energy to power an emerging economy. Geothermal resources associated with volcanoes may be able to provide the energy needed to launch this new nation's development plans. We have undertaken a pre-drilling assessment of the geothermal potential of Alid volcanic center as a step toward realizing this possibility.

Alid volcanic center is a 700-meter-tall structural dome astride the axis of a crustal spreading center (the Danakil Depression) in eastern Eritrea. This mountain has many fumaroles whose gas compositions suggest an underlying hydrothermal system of about 250°C or hotter. Many of the volcanic rocks at Alid are rhyolite, which suggests an upper crustal silicic magma reservoir beneath the mountain. The growth of this magma reservoir probably produced the structural dome by arching up overlying rocks. The process of dome formation and the ongoing crustal spreading probably produced and help maintain permeability in the hydrothermal system.

1. INTRODUCTION

Eritrea, Africa's newest nation, has a weak economy and little infrastructural framework to improve the country's status. One measure of the economy's weakness is that, in terms of annual per capita electrical-energy use, Eritrea may be the poorest African nation. Conventional indigenous energy resources are scarce or lacking. Given the generally arid to semi-arid climate, hydroelectric power is not a viable option. No coal resources are known, and although current exploration is underway, no petroleum or natural gas resources have been identified, either on land or on the continental shelf along the Red Sea. However, volcano-related geothermal energy of potential electrical grade occurs within the Danakil Depression, a crustal spreading center that transects the eastern lowlands part of Eritrea near the Red Sea (Fig. 1). Within this depression, a mountain called Alid has long been recognized as the site of a potential geothermal resource of electrical grade because (1) it is the focus of geologically young rhyolitic volcanism within a background of spreading-related basaltic volcanism and (2) it is the site of many fumaroles (U.N.D.P., 1973). This paper reports initial results of a current exploration program whose principal objective is to define the potential of the hydrothermal system beneath Alid to be developed to generate electricity.

The Danakil Depression is a subaerial segment of the crustal-spreading system that is opening to form the Red Sea. A once-continuous basement terrain of Precambrian granitic and metamorphic crust was rifted apart when the Arabian Plate separated fiom Africa during initial spreading. Parts of this basement complex are widely exposed in a belt near and parallel to the Red Sea coast **of** the Arabian Peninsula and in the Eritrean and Ethiopian highlands southwest of and adjacent to the Danakil Depression. Precambrian rocks also crop out in the Danakil Alps (Fig. 1). The distribution of Precambrian exposures provides a framework for structural reconstructions of the region. Of local significance, a hydrothermal system beneath Alid may be mostly within Precambrian rocks, which are exposed at the east-central summit area of Alid and in the horsts immediately adjacent to the Danakil Depression (locally **known as** Alid Graben) near Alid.

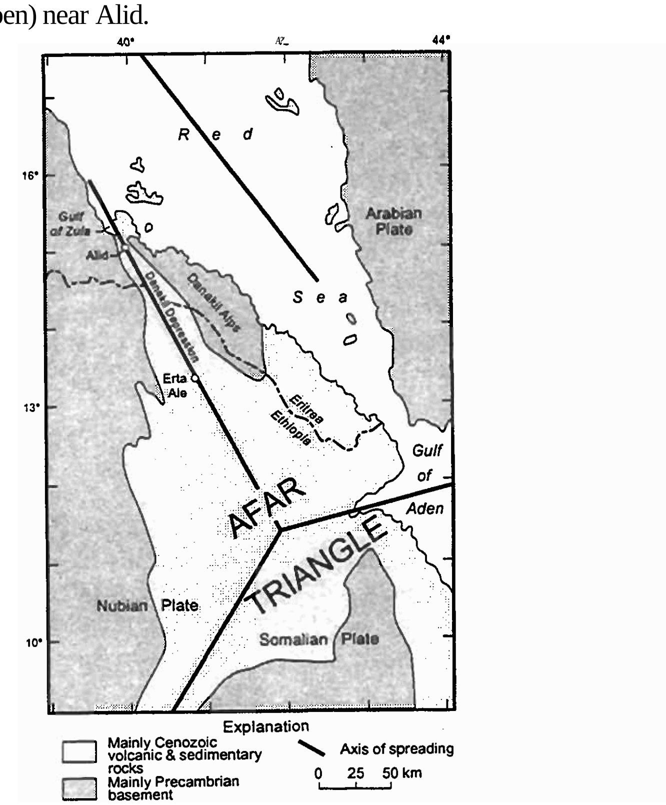

Figure 1. Simplified plate-tectonic map of the Afar Triangle region. Modified from figures in Barberi and Varet (1977).

2. BACKGROUND

Most of the Danakil Depression was uncharted scientifically until as recently as the 1960s. However, by the end of the 1960s, much reconnaissance work had been completed within the Afar Triangle and its Danakil Depression offshoot (C.N.R.-C.N.R.S., 1973). These mid-20th century studies almost completely bypassed Alid, even though Alid has long been known as the site of many geothermal manifestations (U.N.D.P., 1973). Nonetheless, some of the earlier workers concluded that Alid is a volcano with a summit caldera (Barberi *et al.*, 1970; C.N.R-C.N.R.S., 1973).

The results of our field examination indicate that Alid is a structural dome upon which a volcanic vent is superposed and that Alid's pseudo-caldera depressed summit area is fundamentally the result of gravitational collapse over the highly distended crest of the structural dome, rather than collapse caused by the geologically instantaneous removal of a large volume of melt from a magma reservoir in the upper crust. In spite of this non-volcano geologic model, the results of our field and laboratory studies to date suggest that the geothermal potential of Alid and adjacent area is high.

3. SETTING AND STRUCTURE OF ALID

The northernmost part of the Danakil Depression is informally known as the Alid graben. This graben is about 15 km wide and asymmetrical in cross section. The western structural and topographic boundary of the graben is a several-kilometer-wide zone of east-dipping normal faults, expressed as an eroded and stepped escarpment. Across this fault zone, Precambrian basement rocks of the adjacent horst rise from 300 meters to 2,500 meters elevation. The eastern structural and topographic boundary is marked by a steep and abrupt 300-meter-high west-dipping normal-fault escarpment. Precambrian rocks are locally exposed at the base of this scarp and are unconformably overlain by a post-Miocene sequence of intercalated sedimentary and volcanic deposits.

Alid is a slightly elliptical mountain astride the structural axis of the graben (Fig. 2). The major axis of this mountain is about 7 kilometers long perpendicular to the graben, and the minor axis is about 5 kilometers long parallel to the graben. Alid rises roughly 700 meters above a field of Quaternary basaltic lava flows that lap unconformably against the north and south flanks of the mountain. As noted above, Alid is not a volcano in the classical sense of a constructional accumulation of volcanic deposits erupted from a single vent or several closely spaced vents, but rather is primarily a structural dome (Fig. 3). For purposes of following descriptions, we subdivide the domed rocks, from oldest to youngest, into **1** Precambrian basement; **2** interlayered sedimentary deposits and lava flows (the "sedimentary sequence"); and **3** basaltic and rhyolitic lava flows (the "lava shell").

The outermost flanks of the dome consist of several tens of meters of basaltic, andesitic and rhyolitic lava flows (the lava shell). At the base of the dome, the flows dip as steeply as 65 degrees, decreasing to about 20 degrees high up on the dome. All dips are radially outward. The low viscosity of basaltic magma precludes the possibility that the flows of the lava shell were emplaced in their present steeply dipping orientations.

Bedding in the underlying "sedimentary Sequence" is conformable with the orientation of flows that make up the lava shell. The sedimentary component of the sequence consists of fine-grained locally fossiliferous epiclastic deposits of a shallow intertidal environment and beds of anhydrite indicative of shallow-water to evaporitic conditions. The volcanic component of the sedimentary sequence includes basaltic lava flows and pillow lavas that locally change abruptly upward into subaerial lavas. Thus, rocks of both the lava shell and sedimentary sequence must have been domed after they accumulated in a horizontal, or nearly horizontal, orientation along the sometimes flooded floor of Alid graben.

The **3-km** by 2-km summit region of the dome is depressed about 200 meters below a discontinuous topographic rim formed by the truncated edges of rocks of the lava shell and sedimentary sequence. Most outcrops within the eastern two-thirds of this depression are rotated landslide blocks of the lava shell and sedimentary sequence. Apparently, rocks along the top of the growing dome were strained laterally until they broke and collapsed downward and inward to form something akin to a chaotic keystone graben at the apex of the dome. Erosion that accompanied and followed formation of the dome has breached the eastern half or so of the depressed summit region of the mountain and cut down to Precambrian basement, an inlier of crystalline rocks first recognized by Dainelli and Marinelli (1912). The rest of the depressed summit region has internal drainage, and this basin may be the landform that influenced Barberi *et al.* (1970) and Beyth (1994) to describe Alid as being crowned by a caldera. In addition, the westernmost third of the summit region was modified when a post-doming vent there produced voluminous deposits of rhyolite pumice, accompanied by near-vent subsidence that formed a local closed basin within the larger closed basin.

How does a structural dome form in an environment of crustal extension? A likely answer is that a body of low-density silicic magma intruded into the upper crust and domed overlying rocks to form Alid. The rhyolite pumice mentioned in the preceding paragraph is interpreted as having been erupted from this inferred upper crustal magma body. The presence of high-density Precambrian schists at the core of Alid may have facilitated gravity-driven dome formation.

The rhyolite pumice is the youngest volcanic deposit that we recognize as having been erupted from within the area

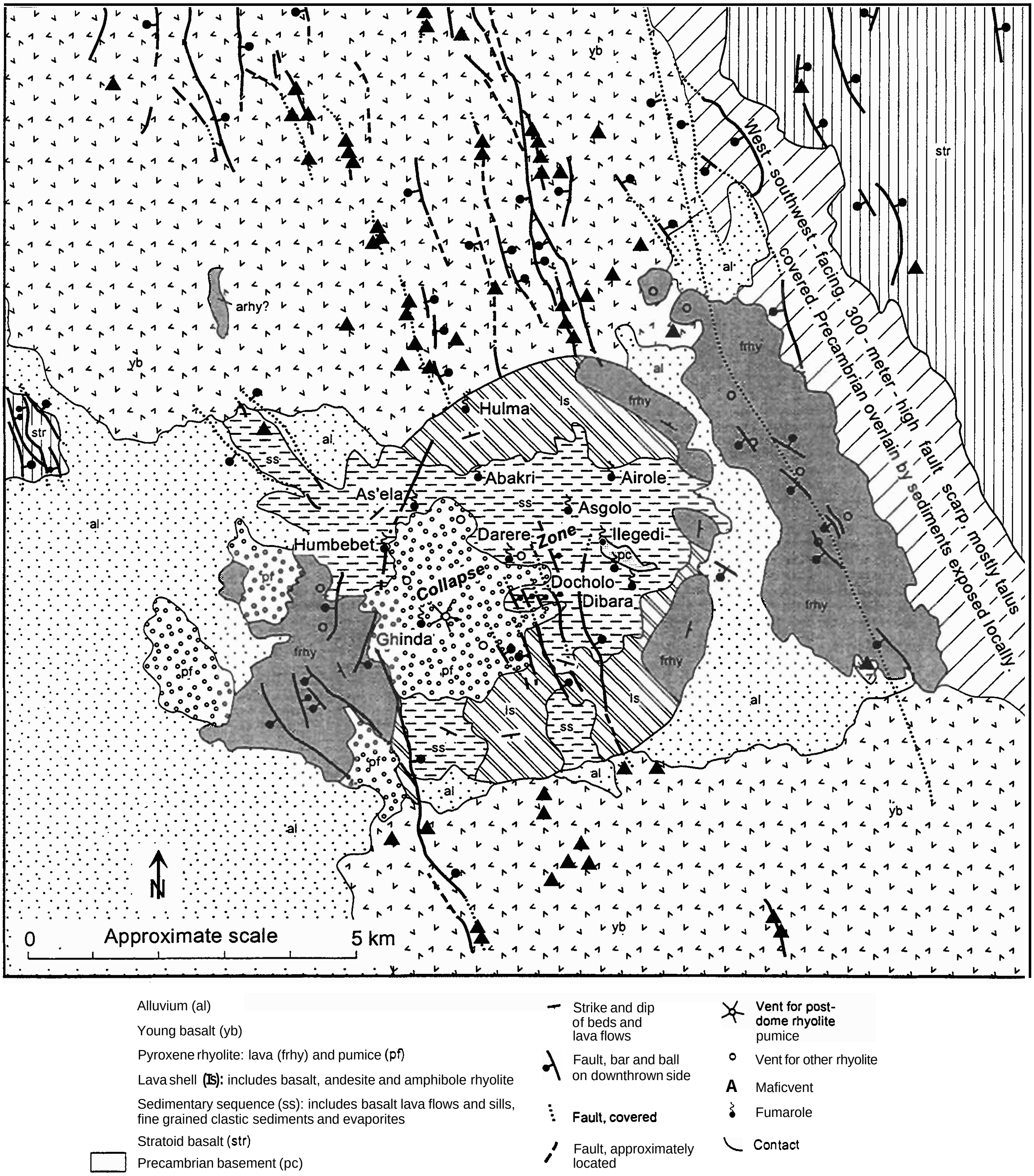

***Figure** 2. Generalized geologic map of Alid volcanic center. Because map was traced from lines on aerial photograph, the scale is approximate and varies somewhat across the area. Note small outcrop of Precambrian basement in the east-central part of Alid. Though it seems quite unlikely in view of the distribution of Precambrian rocks in the horsts adjacent to Alid graben, the possibility that the Precambrian exposure on Alid is simply a detached block within younger rocks should be considered.*

of the dome. Though now seen only as erosional remnants, this pumice once blanketed most, or perhaps all, of the structural dome and extended outward kilometers from the dome's base. The rhyolite pumice unconformably overlies all dome-forming rock units. Moreover, canyons eroded into the flanks of the dome are

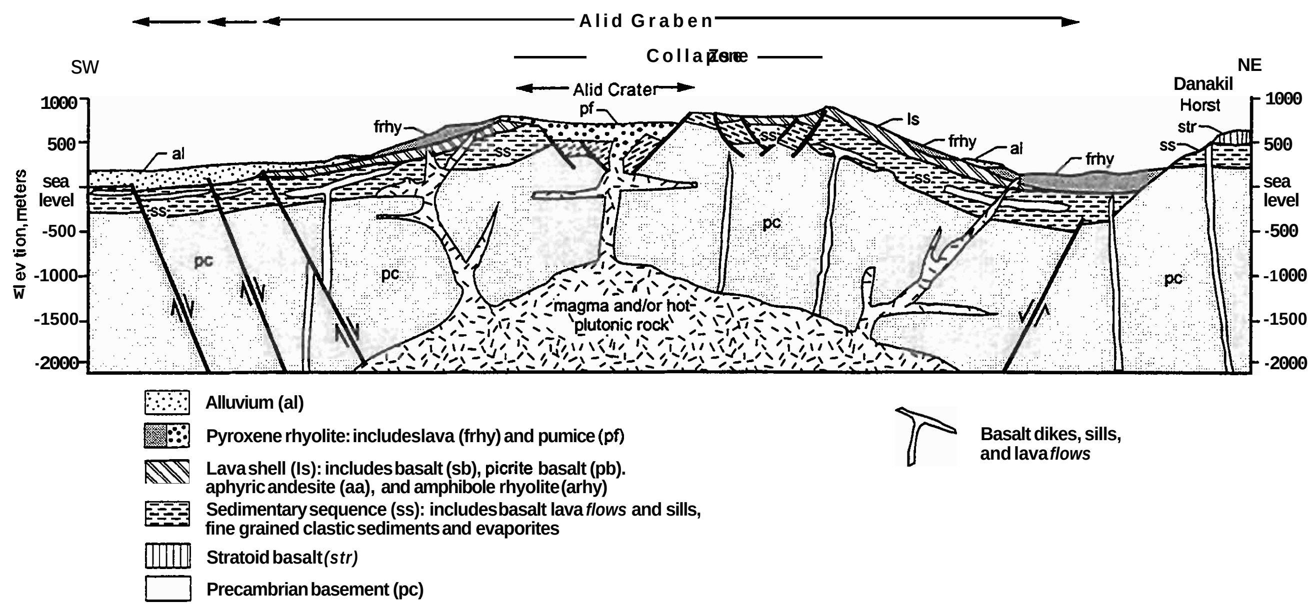

***Figure 3.** Schematic NE-SW cross section through Alid. Because no accurate topographic map exists, the shape of the profile is approximate. No vertical exaggeration is implied.*

partly occupied by primary deposits of the pumice. These relations indicate that the structural dome existed as an eroded landform at the time of the pumice eruption.

Lithic inclusions, up to 1 meter diameter, of miarolitic granite characterized by graphic intergrowths of quartz and alkali feldspar are ubiquitous within the pumice deposits. These textures are strong evidence for an upper-crustal magma environment. Our preliminary chemical and isotopic data indicate that the granite is indistinguishable from the host pumice, but is clearly different from Precambrian granites of the area. Thus, we tentatively interpret the granite inclusions as pieces of a solidified rind along the top of the upper crustal magma body that uplifted Alid dome. Pieces of this rind were subsequently carried upward with magma that produced the pumice deposits.

4. PETROGRAPHY AND GEOCHEMISTRY

Representative major-element chemical analyses of volcanic rocks are reported in Table 1. These rocks form a basalt and rhyolite bimodal suite. The mafic rocks range from nearly aphyric through sparsely phyric to porphyritic, with phenocrysts of olivine, clinopyroxene, and plagioclase. These lavas range from **48.5** to 55 wt% SiO_2. They are subalkaline, quartz normative, and display a tholeiitic differentiation trend.

The silicic group of rocks ranges from **72** to **74** wt% SiO_2. These rocks are quartz- and feldspar-normative and are subaluminous. They include amphibole-bearing rhyolite of the lava shell, rhyolite lavas and co-eruptive pyroclastic deposits that flank Alid to the east and west, rhyolite-pumice fallout and flows erupted from the west end of the summit area of Alid, and the lithic inclusions of granite within the pumice deposits. The rhyolites range from aphyric to sparsely porphyritic. Early erupted rhyolite contains sparse amphibole and biotite, but most phenocrysts are clinopyroxene, anorthoclase, Fe-Ti oxide and, rarely, quartz and fayalite.

***Table 1.** Representative major-element chemical analysis of Alid volcanic rocks.*

Sample Map Unit	S96-10 ls$	ES96-8 frhy@	EC96-43 pf	EC96-25 pf*	ED96-6 ss#	EC96-31 ls#	ED96-11 yb#
SiO_2	73.37	71.93	73.14	73.63	51.81	51.53	50.8
Al_2O_3	13.95	13.8	13.33	13.2	15.81	16.78	15.09
Fe_2O_3	0.41	0.71	0.56	0.54	2.41	2.34	2.4
FeO	1.47	2.54	2.01	1.93	8.66	8.41	8.63
MgO	0.19	0.14	0.18	0.16	5.76	4.75	6.88
CaO	0.7	1.21	0.95	0.98	Y.88	10.15	10.05
Na_2O	4.68	4.83	4.77	4.54	2.87	2.95	2.82
K_2O	4.71	4.4	4.73	4.69	0.75	0.96	1.04
TiO_2	0.41	0.28	0.23	0.23	1.53	1.6	1.71
P_2O_5	0.06	0.05	0.04	0.04	0.34	0.35	0.37
MnO	0.05	0.12	0.07	0.06	0.18	0.18	0.19
LOI	0.65	I	2.41	0.6	2.26	0.11	-0.14

$ Rhyolite lava @ Obsidian. *pyroxene granite inclusion in pumiceous pyroclastic flow. # Subaerial basalt lava flow. Analyses by x-ray fluorescence. Dave Siems. analyst, U.S. Geological Survey, Denver, Colorado. All analyses recalculated to 100% on an LOI-free basis. Fe_2O_3=0.2 total Fe as Fe_2O_3.

The absence of intermediate-composition rocks suggests that the silicic melt was not derived from mafic melts by simple crystal fractionation, as has been proposed for some other Danakil silicic systems (e.g. Barberi and Varet, **1970;** Barberi *et al.*, **1975).** Moreover, variations in Sr- and Pb-isotope compositions are inconsistent with simple fractional crystallization and with any model that would produce silicic magma by partial melting of Precambrian basement rocks of the upper crust.

5. THERMAL MANIFESTATIONS

We know of 11 sites (Fig. 2) with fumaroles on Alid. Several of the fumaroles were located with the help of the local nomadic tribesmen, and there may be others that were not mentioned by these guides. 'Given their geographically and geologically wide distribution on the dome (Fig. 2) and their broadly similar compositions, we believe that the geothermal fluids collected at these sites are representative of all fumaroles, whatever the total number of sites may be.

Some fumarole sites include pools of low-chloride thermal water, but no flowing thermal springs are known. The lack of high-chloride thermal springs probably reflects the depth to water table in such an arid climate, or perhaps effective subsurface sealing of an upwelling hot-water hydrothermal-convection system that we infer to exist beneath Alid. Temperatures of fumaroles are at boiling for their elevations.

The geothermal manifestations are distributed over the northern two-thirds of Alid (Fig. 2), both at the summit and at low-flank elevations. This distribution suggests that a heat source creating the steam underlies an equally large part of Alid. The lack of fumaroles on the southern part of Alid is somewhat puzzling in light of our "magma-push" model for dome formation, which implies a magmatic heat source beneath the entire mountain. Perhaps fumarole distribution is a function of as-yet-undefined hydrologic factors and/or structural controls in Precambrian basement rocks.

Some fumaroles form weak N45E alignments, which is parallel with some regional basement structures, but not with the regionally dominant north-northwest, graben-fault direction. Fumarole vents occur in rocks of the lava shell, rocks of the sedimentary sequence, and Precambrian basement. Therefore, location of these thermal features does not appear to be controlled by lithologic contacts.

The non-condensable gas compositions of all samples range fiom 95.5 to 99 mol% CO_2. H_2 is generally the next most abundant component (0.5 to 2.6 mol%). We employed nine gas geothermometers. Only one yielded temperatures less than 200°C. Within a probable uncertainty of 25 to 50 degrees for any single temperature determination, a histogram of all calculated temperatures (Fig. 4) defines a single mode at about 260°C. Variations in calculated temperatures appear to be more a function of geothermometer than of fumarole site. In our past experience, we have found that the D'Amore and Panichi (1980) method, which utilizes the relative abundances of CH_4, CO_2, H_2S and H_2, generally gives the most reliable results, and this method indicates a reservoir temperature of 266°C beneath Ilegedi, the largest and most active of the Alid fumaroles.

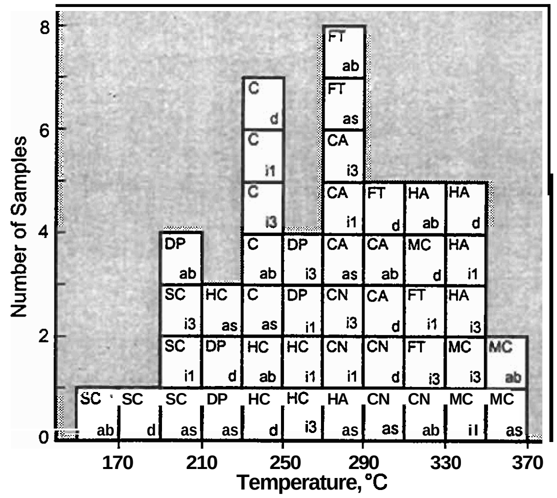

Figure 4. Histogram of calculated gas-geothermometer temperatures for Alid fumaroles. Geothermometers: DP = D'Amore and Panichi (1980); HA = hydrogen-argon, MC = methane-carbon dioxide and CA = carbon dioxide-argon of Giggenbach and Goguel (1989); FT = Fischer-Tropsch and C = carbon dioxide of Arndrsson and Gunnlaugsson (1985); HC = hydrogen-carbon dioxide and SC = hydrogen sulfide-carbon dioxide of Nehring and D'Amore (1984); CN = carbon dioxide-nitrogen of Amdrsson (1987). Fumaroles: D = Darere; i1 and i3 = Ilegedi; as = As'ela; ab = Abakri. See Fig. 2 for locations.

Stable isotopes and N_2/Ar/He relations indicate that the parent geothermal reservoir fluid is air-saturated water (N_2/Ar generally ranges from 41 to 48) that has lost O_2 by reaction with rock at high temperature and that has gained other gases of crustal or magmatic origin. This reservoir water may be old Red Sea water, local meteoric water, or a mixture of the two. Delta ^{13}C varies from -3.3 to -4.9 per mil PDB, consistent with a magmatic source of CO_2, possibly mixed with carbon fiom marine carbonate.

6. PROVISIONAL MODEL OF THE ALID MAGMA/HYDROTHERMAL SYSTEM

Basaltic magma erupts along the Danakil Depression in response to ENE-WSW-oriented crustal spreading, which began in early Miocene time. During part of the time, the Danakil Depression was below sea level and connected with the Red Sea. Thus, the rocks that accumulated within the depression include marine deposits, clastic sedimentary deposits shed fiom adjacent horsts, and basaltic flows, sills and pyroclastic materials.

Rhyolitic magma accumulated in the upper crust beneath the part of the Danakil Depression that would later become Alid. This relatively low density body of silicic magma rose upward into the crust and domed overlying rocks to form Alid. The sharp flexuring recorded in steep dips on the flanks of the dome indicates that the depth to the magmatic source of doming is relatively shallow.

Some of the rhyolitic magma made its way to the surface to feed domes and flows that are part of the dome's lava shell. Later, a substantial pyroclastic eruption from the reservoir of rhyolitic magma produced a blanket of pumice that partly, or perhaps completely, buried the dome and spread outward several kilometers over the adjacent landscape. The granophyric and miarolitic textures in juvenile inclusions of granite in the pumice deposits indicate that the top of the magma body is shallow.

Though the isotopic age(s?) of the rhyolite lavas and pumice are not yet known at the time of this writing, field observations suggest that these rocks were erupted from a reservoir recently enough for any magma left behind in the crust to still be near or above solidification temperature. The absence of post-pumice basalt vents on Alid supports this suggestion, because basaltic melt is not likely to penetrate upward through silicic melt that has a lower density and higher viscosity.

Post-dome basalt vents are common both north and south of Alid. Several of these vents are within a few hundred meters of the dome's base (Fig. 2) and presumably are there because conduits bringing basaltic magma to the surface were beyond any "shadow effect" caused by a body of still-molten silicic melt directly under the structural dome. This continued nearby eruption of basalt indicates that crustal spreading and associated magmatism remain active in Alid graben.

An upper-crustal magmatic and/or hot plutonic heat source beneath Alid seems likely. The compositions of fumarole gases suggest that the temperature of an underlying hydrothermal reservoir is about 250°C or more. Formation of the structural dome must have produced many permeable fractures for the reservoir in the deformed crustal rocks, and ongoing crustal spreading helps create additional fracture permeability within this reservoir.

7. ACKNOWLEDGEMENTS

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