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A Geological and Geochemical Reconnaissance of the Alid Volcanic Center, Eritrea, East Africa

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ABSTRACT

Alid volcanic center is a 700-metre tall mountain in Eritrea, northeast Africa. This mountain straddles the axis of an active crustal spreading center called Danakil Depression. Though volcanism associated with this crustal spreading is predominantly basaltic, centers of silicic volcanism, including Alid, are locally present. Young silicic centers imply the recent intrusion of silicic magma to a relatively shallow depth in the crust and thus a possible shallow potent heat source for a hydrothermal convection system. Boiling temperature fumaroles are common on Alid, and their gas compositions indicate a reservoir temperature of at least 250 degree centigrade.

Alid is a 7-km x 5-km structural dome. The domed rocks, in decreasing age are Precambrian schist, a sequence of intercalated sedimentary rocks and basaltic lavas, and a sequence of basaltic and rhyolite lava flows.

Doming was likely caused by intrusion of relatively low-density silicic magma into the upper crust. Subsequent to dome formation, a substantial volume of pyroxene rhyolite magma erupted from a vent near the west end of the summit area of the dome. This eruption produced a blanket of rhyolite pumice over most, if not all, of the dome and fed pyroclastic flows that covered part of the Danakil Depression around the base of the dome. The pumice deposits contain abundant inclusions of granophyric, miarolitic pyroxene granite, chemically indistinguishable from the host pumice. This granite likely represents the uppermost part of the magma reservoir, which crystallized just prior to the pumice eruption. The most recent volcanism near Alid was eruption of basalt lava flows from vents on the floor of the Depression, just north and south of the Dome.

The history of volcanism and high reservoir temperature indicated by fumarole gases on Alid suggest that a geothermal resource of electrical grade lies beneath the mountain. Though drilling is needed to determine subsurface condition, the process of dome formation and the ongoing crustal spreading probably create and maintain fracture permeability on the hydrothermal system that feeds the Alid fumaroles.

INTRODUCTION

Alid volcanic center, Eritrea, lies along the axis of the Danakil Depression, the graben trace of a crustal spreading center that radiates north-northwest from a plate-tectonic triple junction within a complexly rifted and faulted basaltic lowland called the Afar Triangle (Figure 1). Alid has long been recognized as 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).

The Danakil Depression is a subaerial segment of the spreading system that is opening to form the Red Sea. Crustal spreading along the axis of the Red Sea is transferred to spreading along the Danakil segment in a right-stepping en echelon pattern (Barberi and Varet, 1977). The Danakil segment shows increased opening southeastward to the Afar triple junction. Kinematically, this configuration is consistent with spreading about a pivot point near Gulf of Zula, about 40 kilometers north-northwest of Alid, and can account for the triangular shape of the Afar lowland and anti-clockwise rotation of a horst of basement rock (the Danakil Alps) within the zone of en echelon overlap between the Red Sea and Danakil spreading centers (Souriot and Brun, 1992).

A once-continuous basement terrain of Precambrian granitic and metamorphic crust was rifted apart when the Arabian Plate separated from Africa to form the Red Sea. 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 Eritrea and Ethiopian highlands southwest of and adjacent to the Danakil Depression (Figure 1). Precambrian rocks also crop out in the Danakil Alps.

The broad distribution of Precambrian exposures provides a framework for structural reconstruction of the region. Of more local interest, 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).

Crustal spreading along the Danakil Depression began in early Miocene time, and soon thereafter a sequence of complexly interfingering volcanic, alluvial, shallow marine and evaporitic deposits began to accumulate along an axial downwarp that eventually evolved into a graben. Quaternary volcanic deposits exposed in the Depression today are mostly basaltic lava flows erupted from north-northwest-trending fissures oriented perpendicular to the direction of crustal spreading. Locally, basaltic shield volcanoes grew along the axis of the depression. An example is the Erta Ale shield with its active summit lava lake, about 125 kilometers south-southeast of Alid. Elsewhere within the Danakil Depression, centers of silicic volcanism, such as Alid, formed within a regional background of pervasively basaltic volcanism(C.N.R.-C.N.R.S., 1973).

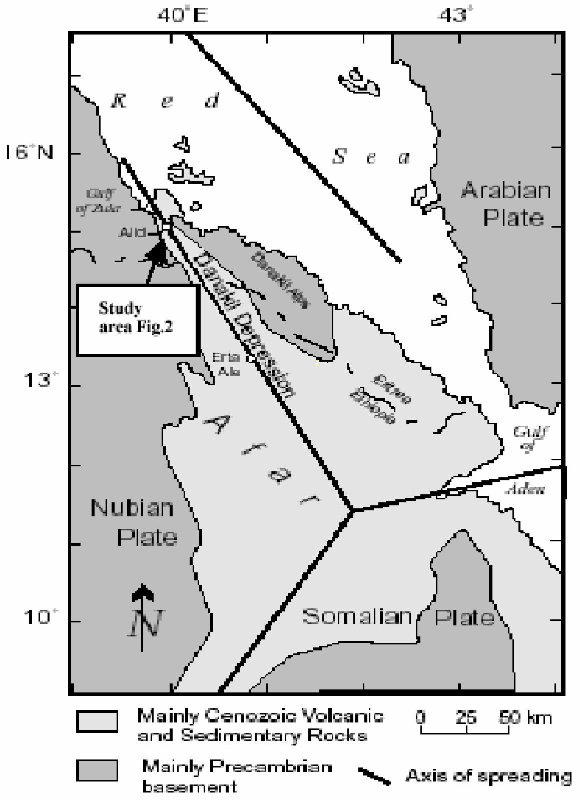

Figure 1. Simplified plate tectonic map of Afar Triangle region Modified from figures in Barberi and Varet (1977)

Where volcanism and accumulation of clastic and evaporitic sedimentary deposits have not kept pace with crustal extension and attendant subsidence, the floor of the depression has continued to drop, locally to elevation of a down-warped and faulted area called the Salt Plain, about half way between Alid and Erta Ale, is 120 meters below sea level, and Giuletti Lake, just southeast of Erta Ale, is about 70 meters below sea level (Barberi and others, 1970).

2.BACKGROUND

Most of the Danakil Depression was uncharted scientifically until as recently as the 1960s, due to the combination of a hostile, hot-and-arid climate and local inhabitants who have sometimes been unreceptive to outside visitors. In summarizing the pre-1942 scientific studies in this region, Danielli (1943) wrote, "taking into account the general conditions of the area, it is quite improbable that the geology will ever by systematically studied." This forecast was overly pessimistic, and by the end of the 1960s, teams of researchers from several countries had completed much reconnaissance work within the Afar Triangle and its Danakil Depression offshoot (C.N.R.-C.N.R.S.,1973).

Ironically, from our perspective, 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 and others, 1970; C.N.R-C.N.R.S., 1973).

However, the results of our field examination indicate that Alid is a structural dome upon which a volcanic vent is superposed and that Alid's caldera-like depressed summit area is 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, we conclude that the geothermal potential of Alid and adjacent area is high, for reasons explained in following sections.

Our field party consisted of 4 Eritrean and 4 American geologists. A total of 18 days was spent in the field. During that time, we crisscrossed Alid and its immediate surroundings with many tens of kilometers of traverses. Hand-held, global-positioning-system (GPS) receivers were used to determine the Universal Transverse Mercator (UTM) coordinates of sample sites and other important field locations. Four GPS receivers were used, each programmed to use WGS-84 as its mapping datum.

The primary base for geologic mapping was 1:60,000-scale aerial photographs, supplemented by 1: 30,000-scale photographs. A 1:100,000-scale, 40-meter-interval contour map made by the USSR military in 1977 also was available.

We collected 60 rock, 6 thermal-water, and 6 fumarolic-gas samples at Alid, and 20 samples of ground and surface waters from highland and lowland regions around Alid and was analyzed in the laboratories of the USGS.

3.GEOLOGIC SETTING AND STRUCTURE OF ALID

The northernmost part of the Danakil Depression is informally known as the Alid Graben, after the volcanic center that is the focus of this report. Alid Graben is about 15-km-wide and asymmetrical in cross section. The western structural and topographic boundary of the graben is marked by a eroded and stepped escarpment. Precambrian basement rocks of the adjacent horst rise from 300 meters to 2,500 meters elevation across a several-kilometers-wide zone of east-dipping normal faults.

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. The top of the Precambrian section just east of the graben is at least 2,000 meters lower than west of the graben. Alid is a slightly elliptical mountain astride the structural axis of the graben. The major axis of this mountain is about 7 kilometers in an ENE-WSW direction, 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 Quarternary basaltic lava that laps 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 (Figures 2 and 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 flanks of the dome are discontinuously veneered by as much as several tens of meters of relatively thin lava flows (the lava shell). At the base of the dome, the flows dip as steeply as 70 degrees, decreasing to about 20 degrees high up on the dome. All dips are radially outward. These structural relations indicate that the dips are not primary. The low viscosity of basaltic magma precludes the possibility that the lava flows 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 epiclastic deposits typical of a shallow intertidal environment, at least one silty bed loaded with micromollusc shells suggestive of an intertidal environment, and beds of evaporitic conditions. The volcanic component of the sedimentary sequence includes thin tabular basaltic lava flows and basaltic 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 summit region of the dome, an area measuring about 3 km by 2 km, is depressed about 200 meters below a discontinuous topographic rim formed in rocks of the lava shell and sedimentary sequence. Outcrops within this depression are mostly rotated landside 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 to form something akin to a chaotic keystone graben at the apex of the dome.

Erosion that accompanied and followed uplift breached the east end of the depressed summit region of the dome. Intermittent streams drain the eastern third of the summit region and have locally eroded through the relatively soft sedimentary sequence to expose Precambrian basement, an inlier of crystalline rocks first recognized by Danielli and Marinelli (1912). The rest of the relatively flat-floored, depressed summit region has internal drainage, and this closed basin presumably is the landform that influenced Barberi and others (1970) and Beyth (1994) to describe Alid as being crowned by a caldera.

How does a structural dome form in an environment of crustal extensions? 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 fact that the Precambrian rocks exposed at the core of Alid include high-density schists may have facilitated such gravity-driven dome formation.

We tentatively interpret rhyolite that is part of the lava-shell veneer on the dome as evidence that a reservoir of silicic magma was present beneath the domed area before, or perhaps just as, doming began. Moreover, the youngest volcanic rocks that we recognize as having been erupted from within the area of the dome are erosional remnants of a rhyolitic pyroclastic blanket that once covered much, or perhaps all, of the structural dome and extended outward kilometers from the dome's base. The vent for these pyroclastic deposits is within the closed-drainage western part of the depressed summit region. The rhyolite pumice unconformably overlies all dome-forming rock units. Moreover, canyons eroded into the flanks of the dome, down through the lava shell and into the sedimentary sequence, are partly occupied by the pumice. These relations indicate that the structural dome existed as an eroded landform at the time of the pumice eruption.

4.PETROGRAPHY AND GEOCHEMISTRY

Major-element chemical analyses were made of 44 rock samples from the Alid volcanic center in the surrounding area. Seven representative analyses are represented in Table 1.

These lavas form bimodal suites that are accordingly discussed as mafic and silicic groups.

The mafic group lavas range from nearly aphyric through sparsely phyric to porphyritic. Mineral assemblages are combination of olivine, clinopyroxene, and plagioclase. These lavas range from 48.5 to 55 wt % SiO_2, most samples between 50 and 52 wt% SiO_2. They are subalkaline, quartz normative, and display a tholeiitic differentiation trend. Thus they are transitional basalts and basaltic andesites. There are no systematic chemical differences among basalt of the lava shell (ls), basalt at the north and south base of Alid (yb), and basalt within the sedimentary sequence (ss). At 50 wt% SiO_2, the incompatible major elements TiO_2 and K_2O vary by approximately a factor of 2, which suggests that the mafic lavas originated from more than one parental magma. The silicic group of rocks ranges from 72 to 74 wt% SiO2. These rocks are quartz- and feldspar-normative and are sub-aluminous. They vary little in major-element composition. The silicic-group rocks include amphibole-bearing ryholite of the lava shell, rhyolite lavas and co-eruptive pyroclastic deposits that flank Alid, rhyolite-pumice fallout and flow erupted from the top of Alid, and abundant lithic blocks of pyroxene granite within these pumice deposits. Amphibole-bearing rhyolites erupted contemporaneous with some basalts of the lava shell and are confined to the medial depressed summit area of Alid. These rhyolites are sparsely phyric with amphibole, anorthoclase, Fe-Ti oxide and, rarely, biotite phenocrysts. The other silicic rocks range from aphyric to porphyritic, but most are sparsely phyric and contain clinopyroxene, anorhtoclase, Fe-Ti oxide and, rarely, quartz and fayalite phenocrysts. Zircon and apatite are sparse accessories.

Until additional chemical data are available, statements about the origin and evolution of the magmatic system at Alid must be considered preliminary. Nonetheless, it seems appropriate to speculate about the magmatic system as it relates to the geothermal system. Although the silicic magmatic system of the Alid volcanic center appears compositionally simple, the absence of intermediate-composition rocks suggest 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 and others, 1975).

Preliminary Sr and Pb isotopic analyses of Alid volcanic rocks (T.D. Bullen, written communication 1996) confirm that the origin of silicic melt must be complex. Isotop variations 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. However it was produced, the subsequent evolution of Alid silicic magma probably was dominated by equilibrium crystallization perhaps accompanied by assimilation of a minor amount of upper crust.

The lithic blocks of pyroxene granite in the pumiceous pyroclastic deposits range from a centimeter to 1 meter in diameter. This pyroxene granite contains a few miarolitic cavities, and its texture is dominated by the granophyric intergrowth of quartz and alkali feldspar. The major-element (Table 1) and isotopic (T.D. Bullen, written communication 1996) compositions of the pyroxene granite and host rhyolite pumice are essentially identical. These features suggest that the pyroxene granite represent the uppermost part of the silicic dome-forming magma body, which had crystallized by the time of the pumice eruption.

5.THERMAL MANIFESTATIONS

We know of 11 sites (named on Figure 2) on Alid with geothermal manifestations. Several of these were located with the help of the local nomadic tribesmen. There may be other manifestations that were not mentioned by these guides. Given their geographically and geologically wide distribution on the dome (Figure 2) and their broadly consistent compositions (Table 2), we believe that the geothermal fluids collected at these sites are representative of the total population, whatever the total number of sites may be.

All manifestation sites have fumaroles. Some also have 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 most fumarolic vents are at boiling for their elevations. None is superheated nor at notably high pressure.

The geothermal manifestations are distributed over the northern two-third of Alid (Figure 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.

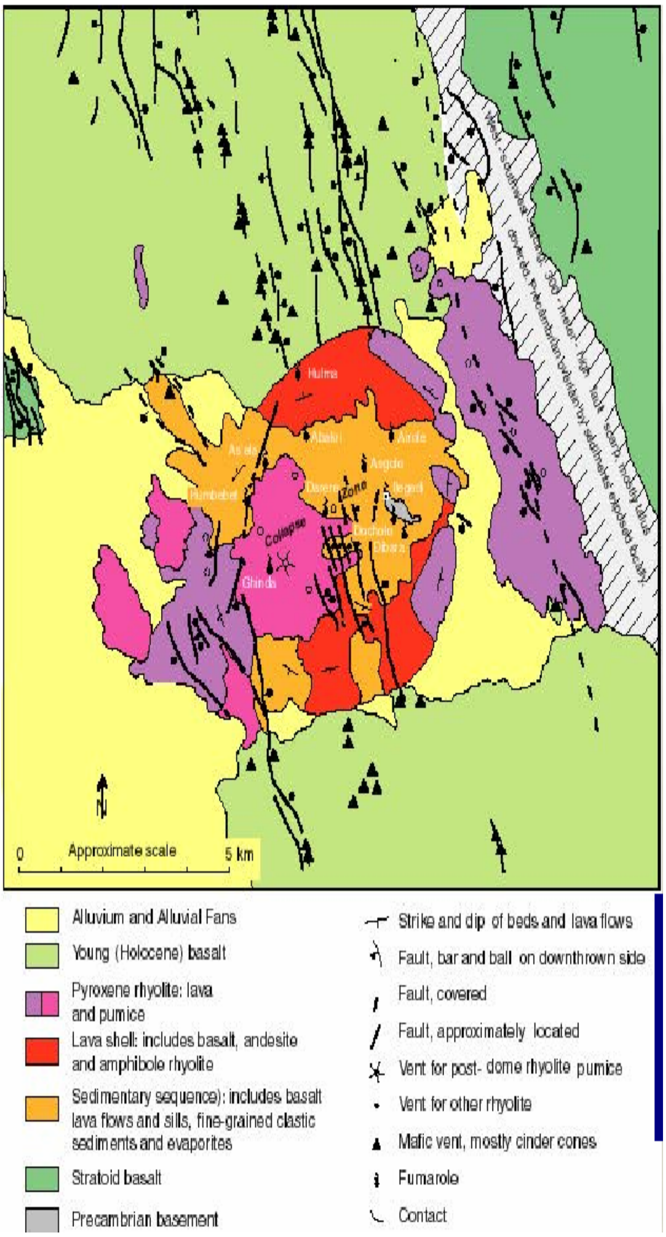

Figure 2: Generalized geologic map of Alid volcanic center (after Clynne et al. 1997)

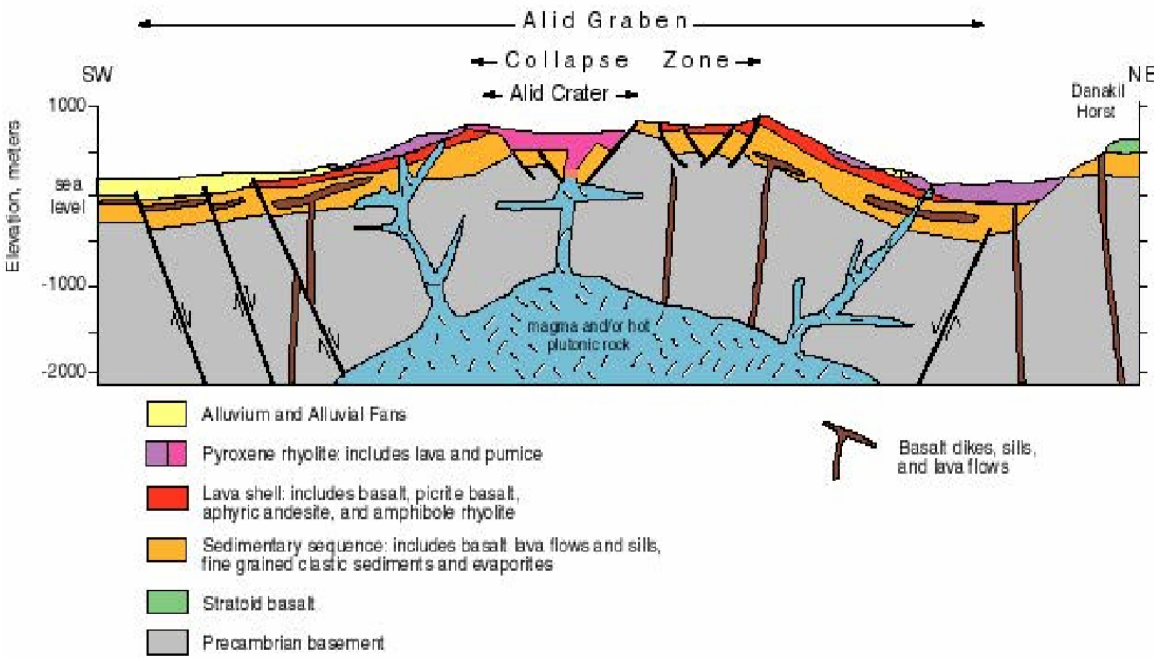

Figure 3: Schematic cross section of Alid volcanic center (after Clynne et al. 1997).

Some fumaroles form weak N45E alignments, which is parallel with some regional basement structures. Alignment parallel to the regionally dominant north-northwest, graben-fault direction is not evident. 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 noncondensable gas compositions of all samples range from 95.5 to 99 mol% CO_2 (Table 2). H_2 is generally the next most abundant component (0.5 to 2.6 mole %). We employed nine gas geothermometers. In our past experience, we have found that the D'Amore and Panichi(1980) method, which utilizes the relative abundance of CH_4, CO_2, H_2S and H_2, generally gives the most reliable results, and this method indicates a reservoir temperature of 266^0C (Table 2) for Ilegedi, the largest and most active of the Alid geothermal manifestations. Other geothermometers (H_2/Ar, CH_4/CO_2, and CO_2/Ar; Giggenbach and Goguel, 1989) yield higher temperatures, up to 340^0C for Ilegedi. Gases from Darere, As'ela and Abakri also yielded consistent and high temperatures of at least 210^0C, and generally much higher. Of the nine gas geothermometers used, only one yielded temperatures less than 200^0C (not reported in Table 2) for the Alid samples.

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 41-48) 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. The 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 from marine carbonate.

6. PROVISIONAL MODEL OF THE ALID MAGMA/HYDOTHERMAL SYSTEM

Basaltic magma erupts along the Danakil Depression in response to ENE-WSW- oriented crustal spreading. This plate-tectonic regime has been active since Miocene time. During part of this late Cenozoic history, the Danakil Depression was below sea level and connected with the Red Sea. Thus, the rocks that accumulated within the Depression include marine deposits (some fossiliferous), clastic sedimentary deposits shed from adjacent horsts, and basaltic flows, sills and pyroclastic materials.

For reasons yet unknown, a reservoir of rhyolitic magma accumulated in the upper curst beneath the part of the Danakil Depression that would later become Alid. Perhaps magma accumulated in a "structural trap" formed by a zone of intersections between the system of north-northwest-trending, curstal-spreading fissures and NE-trending structures evident on satellite images of Precambrian terrain. By whatever processes it formed, this relatively low density body of silicic magma rose upward into, and partly through, the curstal and domed overlying rocks to form Alid. The sharp felxuring 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 lava shell veneer on the dome. 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.

Though the isotopic ages of the rhyolite lavas and pumice are not known at the time of this writing, field observations alone 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.

Although basalt vents that postdate the eruption of the rhyolite pumice are absent on Alid, they are common both north and south of the dome. Several of these vents are within a few hundred meters of the dome's base (Figure 2). Presumably, post-doming basalt was able to reach the surface 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. The continued nearby eruptions of basalt indicate that crustal spreading and associated magmatism remain active in Alid graben.

7. CONCLUSION

In conclusion, evidence to date offers multiple reasons to entertain an increasingly favorable outlook for the geothermal potential of Alid. An upper-crustal magmatic and/or hot plutonic heat source seems likely. Certainly some crustal heat source is present to power the field of fumaroles distributed over the northern part of Alid. The compositions of fumarole gases suggest that the temprature of the underlying hydrothermal reservoir is at least 250^0C. 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.

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REFERENCES

Barberi, F., Borsi, S., Ferrara, G., Marinelli, G., and Varet, J., 1970, Relations between tectonics and magmatology in the northern Danakil Depression (Ethiopia): Phil. Transactions of the Royal Society of London, A, 267, p. 293-311.

Barberi, F., Ferrara, G., Santacroce, R., Treuil, M., and Varet, J., 1975, A transitional basalt-pantellerite sequence of fractional crystallization, the Bonia Center (Afar Rift, Ethiopia): Journal of Petrology, v. 16, p. 22-56.

Barberi, F., and Varet, J., 1970, The Erta Ale volcanic range (Danakil Depression), Northern Afar, Ethiopia: Bulletin Volcanlologique, v. 34, p. 848-917.

Barberi, Franco, and Varet, Jacques, 1977, Volcanism of Afar: Small-scale plate tectonic implications: Geological Society of America Bulletin, v.88, p.1251-1266.

Beyth, M., 1994, A brief assessment of the Alid geothermal field: Report ES-10-94 of the Israel Ministry of Energy and Infrastructure, 11p.

C.N.R.-C.N.R.S., 1973, Geology of northern Afar (Ethiopia): Revue de Geographie physique et de Geologie Dynamique, v.15, Fasc.4, p.443-490.

Dainelli, G., 1943, Geologia dell'Africa orientale: Rend. Accad. d'Italia, Roma.

Dainelli, G., and Marinelli, O., 1912, Resulti scientifici di un viaggio nella Colonia Eritrea: Pubbl. del R. Ist di St. Super e di Perfez. di Firenze.

D'Amore, F., and Panchi, C., 1980, Evaluation of deep temperatures of hydrothermal systems by a new gas geothermometer: Geochemica et Cosmochimica Acta, v.44, p.549-556.

Fahlquist, L., and Janik, C.J., 1992, Procedures for collecting and analyzing gas samples from geothermal systems: U.S. Geological Survey Open-File Report 92-211, 19p.

Giggenbach, W.F., and Goguel, R.L., 1989, Collection and analysis of geothermal and volcanic water and gas discharges: Report CD2401, New Zealand Department of Scientific and Industrial Research, 81p.

LeBas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v.27, p.745-750.

Marinelli, G., Quaia, R., and Santacroce, R., 1980, Volcanism and spreading in the northernmost segment of the Afar Rift (Gulf of Zula): Accademia Nazionale dei Lincei 47.

Souriot, T., and Brun, J., 1992, Faulting and block rotation in the Afar triangle, East Africa: The Danakil "crank-arm" model: Geology, v.20, p.911-914.

United **N**ations **D**evelopment **P**rogram, 1973, Investigations of the geothermal resources for power development, Ethiopia: Imperial Ethiopian Government, 275p.

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

Sample Map Unit	ES96-10 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	9.88	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	1	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. FeO_3 = 0.2 total Fe as Fe_2O_3.

Table 2. Gas Geochemistry and calculated reservoir temperatures of representative of Alid

Sample No.	ELG96-2	ELG96-3	ELG96-4	ELG96-5	ELG95-6
Location	Darere	Ilegedi #1	As'ela	Ilegedi #3	Abakri
Temp. (°C)*	95	95	95	**84	
CO_2 (mol %) #	97.93	95.53	98.20	95.89	98.86
H_2S (mol %)	0.219	0.876	0.749	0.662	0.143
H_2 (mol %)	1.093	2.498	0.503	2.624	0.605
CH_4 (mol %)	0.225	0.132	0.061	0.144	0.85
NH_3 (mol %)	0.128	0.389	0.004	0.005	0.095
N_2 (mol %)	0.412	0.598	0.473	0.653	0.209
O_2 (mol %)	0.0023 nd		nd	nd	0.0005
Ar (mol %)	0.0054	0.126	0.0116	0.0140	0.0047
He (mol %)	0.00151	0.00047	0.00046	0.00073	0.00018
N_2/Ar	76.3	47.5	40.8	46.6	44.5
Gas/Steam (mol/mol)	0.0448	0.0199	0.0259	1.701	0.0565
C ($^0/_{00}$ VPDB)	-3.4	-3.4	-4.9	-3.3	-3.3

Gases collected in Giggenbach bottles according to methods of Fahlquist & Janik (1992).
*ELG96-2, 3,4,6 were boiling-temperature fumaroles with no superheat.
Temperature readings may be ~2°C lower than actual conditions;
@Gas from bubbling pool. # Concentrations in mol% of dry gas; nd: not detected or determined;
D & P=Gas geothermometer of D'Amore and Panchi (1980).
H2/ Ar= Gas geothemometer of Giggenbach and Goguel (1989)