The Geology of Northern Danakil Depression and its Geothermal Significance

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ABSTRACT

The Danakil Depression is part of the Afro-Arabian Rift System that connects the Red Sea with the Afar Triple Junction. The Danakil Depression is separated from the highland part of Eritrea by a N-S trending fault escarp whereas the western margin was formed by the rotation of the Danakil Alps resulting in down-warping of the Depression.

The Danakil depression is floored principally by Pliocene and younger volcanic rocks, most importantly by the Afar Stratoid series. They are by far the most important geological units in terms of coverage and preservation of igneous features and tectonic activities. The Depression between the Alps and the highlands, is covered by Tertiary-Quaternary rocks. Basaltic flows, scoria cones, and alkaline to peralkaline silicic rocks were erupted locally in the Danakil Depression during Quaternary in particular over the past 1 My. In this zone widespread fields of fissure lavas are covered by products from spatter cones and explosive phreatic craters. The Continual opening of the Danakil Depression enabled the plate to subside allowing ingress of sea to inland. This results in deposition of thick salt plain in the south.

Geothermal surface manifestations are commonly associated with the peralkaline silicic rocks in the Danakil Depression. Alid volcanic crater in the central part of the area and the Jalua volcano close to the Gulf of Zula are the prominent examples which show extensive fumarolic activities.

1. INTRODUCTION

The Danakil Depression is the terminus of an embryonic spreading axis – the northern part of the Afar triangle, a key position of the African Rift System that connects the Red Sea with the Afar Triple Junction (Fig. 1). It separates the African plate from the Danakil microplate. The Danakil Depression is located on the eastern lowland its northern tip is the gulf of Zula, and is 180km far from Asmara, to the south is open towards Ethiopia. Most of the region is covered by a thick succession of flood basalts.

The area is a low lying plain that shows a marked difference in elevation with its surrounding regions. It is flanked to the west by the Eritrean-Ethiopian Plateau and on the east by the Danakil Block with an elevation reaches 3000m in Embasoira and 2100 m in Nabro, respectively. This is a striking contrast to the depression, where elevations range from about 800 m to more than 100 m below sea level in Dallol. This range of low elevation is marked by a number of topographically high volcanic centers.

After introducing the rift system and the regional geology, the detail geology of the Danakil Depression will be summarized in this paper. Discussion on the geology in relation to geothermal resource will follow.

2. REGIONAL GEOLOGIC SETTING

The Neoproterozoic basement, which represents part of the Arabian–Nubian Shield, is prevalent on the periphery of the Danakil Depression (Fig. 2). The Arabian–Nubian Shield covers vast terrain to the north and northwest of the Afar Depression in eastern Eritrea and northern Ethiopia, respectively (Vail, 1985; Berhe, 1990; Stern, 1994). These rocks were assembled and metamorphosed from 800 to 650Ma during closure of the Mozambique Ocean, suturing the components of East and West Gondwana along the East African Orogen (Stern, 1994). The Neoproterozoic rocks of the Arabian–Nubian Shield also occupy parts of the Danakil Alps.

The pre-rift stratigraphic sequence of the Afar region is best exposed in the Danakil Block, where the Jurassic section reaches over 4000 m (Bunter et al., 1998; Sagri et al., 1998). The Mesozoic sedimentary rocks that get progressively younger, but its thickness consistently becomes thinner towards the south and southwestern Ethiopia (Bosworth et al, 2005)

The oldest strata are generally Early Jurassic or possibly Triassic overlying crystalline basement, with higher units extending into the Early Cretaceous. This Mesozoic section represents a major transgressive-regressive cycle, which has been assigned to the Adalo series (Bunter et al., 1998). The base of the section is comprised of fluvial, deltaic, and marginal marine sandstones and conglomerates of the Adigrat Sandstone that attain a thickness of 1600m.

These siliciclastic rocks are over lain conformably by over 2400m of the Middle to Upper Jurassic Antalo Limestone. The carbonates were deposited in a low-angle ramp environment, with several flooding surfaces and numerous cycles of relative sea-level change (Sagri et al., 1998).
A return to continental conditions occurred in the latest Jurassic to Early Cretaceous; with deposition of the fluvial Amba Aradom Sandstone (Merla et al., 1979). These upper siliciclastic rocks reach a thickness of about 500 m (Bunter et al., 1998). The pre-rift strata of the Danakil area are cut by numerous extensional faults. Fields of fault blocks are rotated by as much as 45° has been observed in the Danakil Block. This long pre-Tertiary history of tectonism created pre-existing heterogeneities with variable orientation that have represented a mould for the development of the East African Rift System. After long denudation, a volcanic event of trap series flood basalts erupted during Oligocene to Miocene. In the central plateau, volcanism started about 30 Ma ago (Aiba/Oligocene Alaji transitional basalt and Asmara alkaline basalt) and ended about 20 Ma ago (Adi Ugri alkaline basalt and Serae rhyolite) (Zanettin et al., 2006). This volcanism represents the initial phase of eruption from a mantle plume. The pre-rift lithospheric structure controlled the initial rift evolution, with lithospheric-scale pre-existing weaknesses, Neo-Proterozoic shear zones, controlling rift location and propagation in roughly NNW-SSE structures in the Danakil Depression (Ghebreab, 1998).

Two parallel NNW-trending rifts, the broad subaerial Afar depression and the southern Red-Sea, had formed by Early Miocene times as Arabia separated from Africa. Since then Danakil micro-plate has been moved counterclockwise during the last 11 million years (Eagles et al., 2002). The Syn Rift volcanism in the area is represented by the Dalha Series or Lower Afar Stratoid basalt, which is exposed in the eastern shoulder of the Depression. Its age is assigned to be (<8 Ma) and is essentially undeformed. It covers a wide belt at the eastern shoulder of the depression. The Dalha-Afar Stratoid break in volcanism at about 5 Ma, if it really exists, corresponds regionally with the onset of Red Sea oceanic spreading (Bosworth, 2005). Barberi et al. (1975) put the age to represent the transition from continental rifting to oceanic spreading from the eruptive style and structuring of the Afar Stratoid series. The Quaternary axial range volcanic, especially in the northern Afar are characterized by shield volcanoes and fissural eruptions (Beyene and Abdelselam, 2008).

**3. GEOLOGIC SETTING OF THE NORTHERN DANAKIL DEPRESSION**

The northernmost part of the Danakil Depression is informally known as the Alid graben, is about 15-km-wide and asymmetrical in cross section (Duffield, 1997). 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. Precambrian basement rocks of the adjacent horst rise from 300 meters to 2,500 meters elevation across this fault zone. 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 region has been subjected to rapid crustal spreading, as evidenced by numerous NNW-SSE fissures with related active volcanism and normal faults. This crustal spreading is coupled with the counterclockwise rotation of the Danakil micro-plate the Danakil block being pinned to Africa near the Gulf of Zula in the Red Sea.

During rift initiation in the Danakil Depression, detrital sedimentary formation known as Red Series were deposited (CNR-CNRS team, 1973). This is the oldest sediment found within the depression, which is well exposed in the Alid dome shoulder. The Lower Afar stratoid basalt emplaced in the period of less than 8 My were the first eruption in this part of the depression. Stratoid basalt collected from atop the horst immediately east of Alid yielded an age of 1.1 million years (Duffield, 1997), which is in agreement with the 1.2-million year age inferred earlier by Barberi and others (1972). Therefore the age for this is quite young than Dalha Series. Some of these lavas cap the horst along the east side of the graben and fault blocks within the horst-bounding fault zone.
Faulting within the young axial rifts of the Danakil Depression, as with Afar in general, displays predominantly dip-slip movement. Indeed a component of active rift-parallel strike-slip movement as inferred from field relationships and seismic focal plane analyses.

The subsidence resulted in down-warping with below sea-level in parts of the Danakil Depression, which pave a way for the ingresson of the Red-Sea. However the corridor was subsequently closed to form a wide and thick evaporates.

Active rifting accompanying volcanism continued through the Quaternary in the Danakil Depression. Basaltic flows, scoria cones, and alkaline to peralkaline silicic rocks were erupted locally in the Afar Depression over the past 1 My (Varet, 1978; Tefera et al., 1996). However, only younger ones are localized in the northern part of the Danakil Depression. The silicic differentiates in the form of pyroclastics and rhyolitic flows (Fig. 2).

The northern limit of the area is covered by a big silicic stratovolcano. It is affected by a large central volcanotectonic depression, open to the sea (CNR-CNRS team, 1973). This volcano called Jalua is mainly built by lava flows of peralkaline silica nature. It shows fumarolic activity on its western flank.

The Irafaile volcanic center, situated at the northern limit of this silicic strato-volcano, is a rhyolite dome with a caldera rim at its top. Hot springs issues from its eastern flank of the dome and flows to the Red-Sea at the Gulf of Zula.

At the center of the northern part of the depression an Alid dome standing on the rift floor with a slightly elliptical mountain astride the structural axis of the graben. The dome is mainly built by the emplacement of the rhyolite magma issuing both as a flow and pumice. All the rhyolite ages from the K-Ar age are within 33.5kyr (Lowenstern, 1997) and the Doming was mature, and maybe complete, by the time that the last pyroxene rhyolite was emplaced, perhaps as recently as 15,000 years ago (Duffield, 1997).

Active rifting accompanied by young fissure basalts eruption along the the rift floor. These axial ranges basaltic flows are younger than Alid dome and lap unconformably against the north and south lower flanks of the mountain (Duffield, 1997). Vents of these basalts are marked by cinder cones commonly aligned on north northwest-trending fissures. Age of this is assigned to be of probable Holocene (Duffield, 1997).

Alluvium includes both fluvial and aeolian deposits. Younger alluvial fans are those that are actively growing. Alluvium fans surrounding the volcanic areas have lithologies similar to the domes and cinder cones, whereas those in adjacent areas to western escarpment have mostly basement lithologies.
4. THE GEOLOGIC SETTING AND ITS GEOTHERMAL IMPLICATION

The Danakil Depression is governed by a NNW-SSE tectonics and by a less alkaline volcanism, its dominant rock series ranging from transitional mildly alkaline basalts to peralkaline silicic differentiates (Barbieri et al., 1970). These peralkaline differentiates mainly in the form pyroclastics and flows are indispensable rock suites in dealing with the geothermal resource exploration. Alid volcanic center, Jalua and Irafaile are notable examples where geothermal manifestations occur.

The field geologic data and digital image interpretation show that a shallow less than 4 km body of rhyolitic magma intruded beneath Alid, caused structural doming, and erupted as pyroclastic material (Lowenstern, 1999). The lack of basaltic vents on Alid that are younger than the pyroclastic deposits, as observed on both north and south of the dome as fissural basalt, may signify that silicic magma still resides beneath Alid and impedes the ascent of basaltic magma (Bailey et al., 1976; Clynne et al., 1996). Even though the sites of the acidic dome occurring in the north portion of the Danakil Depression are a bit to the west from the axial center, the same hypothesis applies, where it is not affected by the younger fissural basaltic eruptions.

These silicic differentiates are in all forms domal uplift, which exerted fracturing and pave a way to have sufficient permeability to make viable geothermal reservoir. The study in Alid shows that the subsurface beneath Alid is highly fractured and has sufficient permeability (Lowenstern, 1999). Clearly, the deformation associated with 1 km of late Pleistocene structural uplift would result in intense fracturing of the Precambrian wallrock and the overlying sedimentary and volcanic units.

Both Alid and Jalua have similar ages as Beyth (1994) reported that both acted as dams that blocked the Red Sea from the Danakil Depression. And both shows fumarolic surface manifestations. Therefore it is concluded that geothermal exploration strategy should focus on young silicic differentiates within the north Danakil Depression. This idea may also apply to areas on the Danakil block, as Nabro is a notable example. Detail geologic and geothermal studies are necessary to further confirm the above idea.
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