Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Relation between Regional Lineament Systems and Geological Structures: Implications for Understanding Structural Controls of Geothermal System in the Volcanic Area of Itasy, Madagascar

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Keywords: Volcanic area, geothermal site, strike-slip faults, structural controls, Itasy, Madagascar.

ABSTRACT

No detailed investigations have been conducted on the specific structural controls of geothermal individual fields in Madagascar. Knowledge of such structures would facilitate exploration models.

In this study, we utilize satellite imagery, field investigations and compilation of existing data, to characterize the age and the role of faults in the geothermal system of the volcanic area of Itasy. The correspondence between the remote sensing-derived aligned features (lineaments) and the geological structures of the area was verified by means of our own geological field surveys.

The lithology of Quaternary section consists of volcanic rocks including Pleistocene trachyte, limburgite, basanite, basalt and ordanchite lavas overlain by sequences of intercalated ash-flow tuffs. The Precambrian basement is mainly composed of migmatitic gneiss and shows high fracture density. This section is fragmented into multiple north to north-northeast-trending fault blocks. Most of the major geothermal sites occur along or near the north to north-northeast-striking faults that roughly parallel the volcanic area. This belt is called to as the Itasy structural zone. Major fractures and faults arranged broadly in north-south structures suggest east-west thinning and extension direction. These faults, distributed across the ancient crystalline basement exhibit a pre-Pleistocene rupture history.

We speculate that the geothermal system may have experienced transtensional strain fields in association with left-lateral slip along a major strike-slip fault zone. The strike-slip basins recognized in this releasing bend may be a negative flower structure or a classical pull-apart basin caused by dilational left-stepover of the master fault.

The structural settings favoring geothermal activity all involve subvertical conduits of highly fractured rock along fault zones oriented approximately perpendicular to the foliation of Precambrian migmatitic gneiss and increase dilation, thereby allowing geothermal fluids to approach the surface.

1. INTRODUCTION

Diversified researches about geothermal resources have been carried out in Madagascar. But the association of magmatic or non-magmatic geothermal resources and geologic structure in this country is not yet well known, and there is no exploration effort directed toward targeting the controlling fault structure. The temporal and spatial relationships between various structural features within the zone and how individual faults or sets of structures control fluid pathways and geothermal resources are not generally understood.

Previous studies have noted the possible linkage between the east striking faults and the Pleistocene volcanism of Itasy (Laplaine, 1951). A spatial study comparison of high-temperature geothermal sites with known north-northeast striking faults in this area (Figure 1) shows that many of the sites are located along these faults, in particular, and many are located along range-bounding faults (Laplaine, 1951; Bussiere, 1960; Joo', 1968). These researches have noted this relation, but they have largely focused on localized fault stress-strain relations that would account for the dilation of fault apertures permitting upward movement of magma and geothermal water.

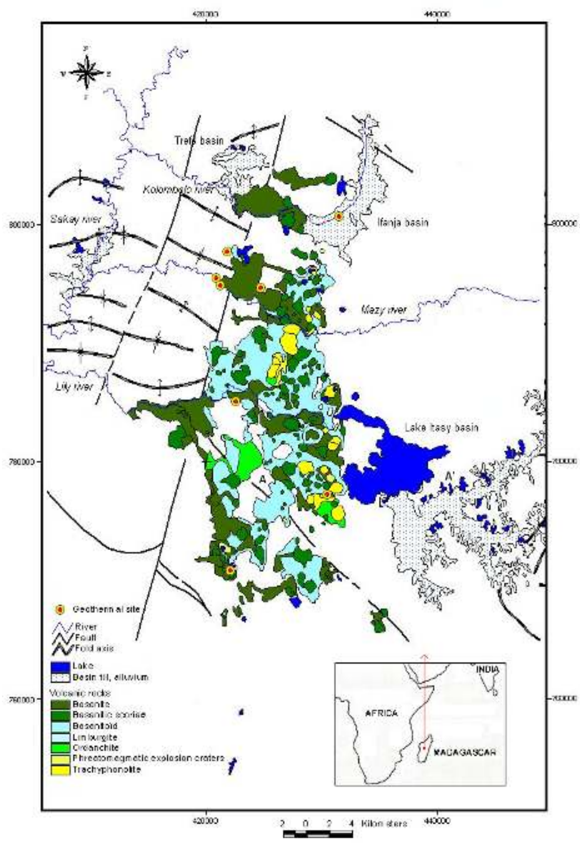

Figure 1: Simplified geological map of the study area showing the tectonic and geothermal sites (after Joo', 1968).

In the world, more recent studies have begun to focus on the role that regional crustal strain plays in controlling geothermal sites. The temporal and spatial relationships between various structural features within the Itasy zone and how individual faults or sets of structures control fluid pathways and geothermal resources are poorly understood. We have been examining spatial and temporal characteristics of faults at the geothermal sites and investigating the tectonic behavior in order to better understand how this relation may be a potential exploration tool.

This paper provides an overview of some of our research, emphasizing remote sensing and geological exploration in particular tectonic and structural studies. The main goals of this project are to (a) characterize the links between thermal aquifers and structural features and (b) better define the boundaries of the geothermal reservoirs.

2. METHODS

In this work we used a combination of techniques including use of software for GIS geological data published in the literature and our own field investigations such as geological exploration, regional lineament studies and structural analysis. Satellite imagery of Landsat 7 ETM+ and Geographical Survey of Madagascar toposheets MN-47 (1:100,000 scale) have been studied to demarcate lineaments, drainage segments, and geomorphic features.

Statistical analysis of the map using directional indicators (aligned rectilinear valleys, valley walls, ridges, crests, passes or a combination of these features), as well as a spatial analysis, helped detect morphological differences in the lineament patterns. In this paper the word "lineament" will be used only when aligned features have been proved to correspond to the intersection between the surface and the main fault and fracture systems.

The results extracted from processed satellite images, were compared to geoscientific data of our own geological field surveys in a geographic information system (GIS). From the available to us digital data, we digitized the structural lineaments (faults and fractures), the fractures and faults as mapped by the Geological Survey of Madagascar (Laplaine, 1951; Bussiere, 1960; Joo', 1968) and by our own field work.

The present study is based on deductive interpretations and summaries of existing evidence about the geological structure, the hydrogeology and geothermal conditions.

3. GEOLOGIC SETTING

The Itasy volcanic field is situated at about 110 km west of Antananarivo, at the western lakeside of Lake Itasy (Figure 1). It covers approximately 700 km^2 and exhibits a striking density and variety of volcanic structures, from effusive ultramafic "oceanite" flows over peléean type trachyte extrusion needles to different types of phreatomagmatic explosions. The volcanic activity is thought to cover the age range from pre-Pleistocene to about 10,000-8,000 years (Brenon and Bussiere, 1959).

The main volcanic features are trachyte and trachyphonolites domes, which often form the initial stages of volcanic construction, basanitic to tephritic scoriae cones, small domes and flows, ordanchite flows and tephra deposits as well as numerous phreatomagmatic explosion craters. Also abundant are tuffs of trachytic/phonolitic and basanitic compositions. Few low temperature thermal springs (geysers) are indicative for persisting geothermal resources. In ascending order, the exposed Quaternary section along the transect consists of six phases distinguishable: (1) Trachyte subcircular domes of presumed pre-Pleistocene age, (2) middle to late Pleistocene predominant basanites with lesser limburgites as observed in domes, cones and flows, (3) a large trachyte flow, (4) local late Pleistocene to early Holocene flows and scoriae of phonotephrite and trachyandesite with haüyne (a blue foide), (5) recent basanites, and (6) a large explosive crater-forming event. Individual lithologic units such as intercalated ash-flow tuffs, locally separated by thin sequences of volcaniclastic sandstone, exposed within these sequences (Laplaine, 1951; Bussiere, 1960; Joo', 1968).

Neogene to Quaternary volcanic rocks and active hot springs are found in several locations on the high central plateau of Madagascar. Itasy geothermal driving force is magmatism associated with thinning crust. Several thermal springs and a human-induced geyser occur in this area of Itasy. The hot springs and geyser lie along the western shore of Lake Itasy (Figure 1). Shallow temperature surveys of both thermal springs in the area show temperature variations of 18 to 58°C (Gunnlaugsson et al., 1981; Besairie, 1959a). However, geothermometers suggest temperatures between 129-152°C that suggest a possible economically viable geothermal system (Gunnlaugsson et al, 1981).

Xenoliths of basement rocks (migmatites, granulites, gneisses) are common and the volcanic edifices all lie directly on this Precambrian basement (Figure 1); and there is – contrary to the Antsirabe volcanic area (Figure 2) – no Miocene to Pliocene basalt underlying the Quaternary volcanic deposits.

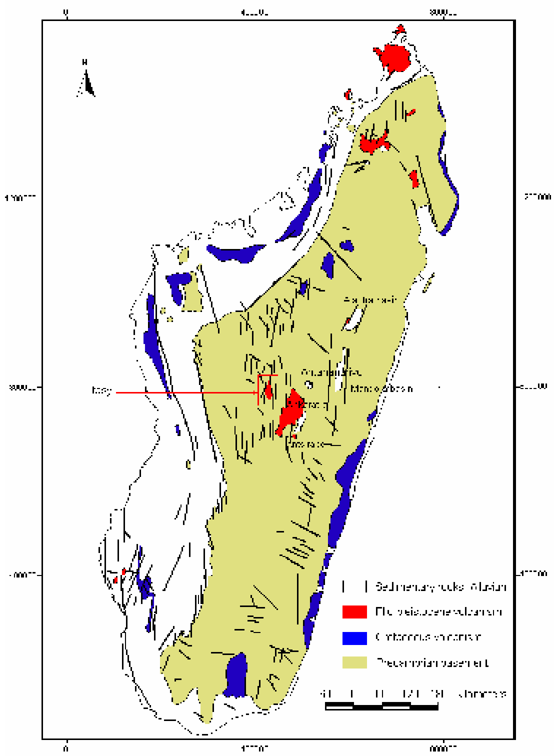

Figure 2: Map of Madagascar showing major fractures, volcanism and location of study area.

In addition, the Precambrian rocks are deformed into closely spaced east-west (E-W) to northwest-southeast (NW-SE) trending folds respectively in the eastern and in the western part of Itasy zone (Laplaine, 1951; Joo', 1968). This E-W of the branch of the Ankazobe-Antananarivo-Fianarantsoa Virgation (AAFV) was first affected by a sinistral transpression. Only a horizontal lineation marked by sillimanite develops here. The foliation of the gneiss dips north suggesting also a thrusting motion induced by the sinistral motion of Angavo-Anjafy shear zone (Rambeloson et al, 2002; Ramasiarinoro, 2008).

4. ACTIVE TECTONIC AND EARTHQUAKES

The main tectonic features and faults of Madagascar are shown on (Figure 2). Several general trends can be observed: (a) The N20°W trend may be related to the separation of Madagascar from Africa with the subsequent opening of the Mozambique Channel and the development of the Mahajunga and Morondava basin. (b) The N20°E trend on the east coast corresponds to the northward motion of separation of India from Madagascar during the Late Cretaceous, which resulted in a very straight and steep coast on the eastern margin of the island. (c) The N10°E trend observed in the center of the island is associated with the Late Tertiary Neogene grabens such as the Alaotra graben north-east of Antananarivo. (d) Finally, a The N8°W trend is related to magmatic reactivation, which could suggest the presence of a deep fracture zone or a zone of crustal weakness.

The Moho depth beneath Madagascar through the inversion of gravity data have been imaged (Fourno and Roussel, 1994). They made a contour map of the Moho topography, which covers the area of exposed Precambrian basement in the eastern and central parts of the island. This revealed a N20°E trending zone of thinned crust along the axis of the island, paralleling the east coast margin. This feature is interpreted as the relic of continental lithosphere extension and thinning (Fourno and Roussel, 1994). North-south throughs (e.g. the Alaotra Basin) are compatible with an east-west recent and present extension (Piqué et al, 1999), confirmed by seismic activity (Fourno and Roussel, 1991; Bertil, 1996).

The majority of the volcanic vents in the Lac Itasy area lie roughly within a rectangle of 45 km north-south and 15 km east-west extension. This could correspond to a graben structure in the basement; through there is no direct evidence for that besides a generally higher basement elevation both to the east and west. There are however numerous indications for vent alignment along structural trends running in a scatter of direction around a generally north-south trend (Brenon and Bussiere, 1959), suggesting a zone of crustal weakness thus aligned (Mottet, 1982).

In the west and north-west sides of the Itasy zone, closely-spaced, north-northeast-striking faults dissect the range (Joo', 1968). Recent study signaled the presence of active faults and the presence of north and north-northeast strike-slip faults has been signaled in the Antananarivo region (Ramasiarinoro, 2008).

A tectonic survey would assign the explanation of the tendency to the reactivation of faults that would influence the western part of this region (Rambolamanana and Ratsimbazafy, 1991) and of which the most important are the N20°E trend, the N15°W trend, the N40°W trend and the N8°W trend.These last two directions are signalled by a seismic survey.

It is of interest to note that Madagascar is a site of substantial seismic activity, with earthquakes of magnitudes exceeding 5.0. About twenty events of substantial seismic activity with magnitudes exceeding 4.0 are observed every year between the periods of 1983-2007 (Figure 3).

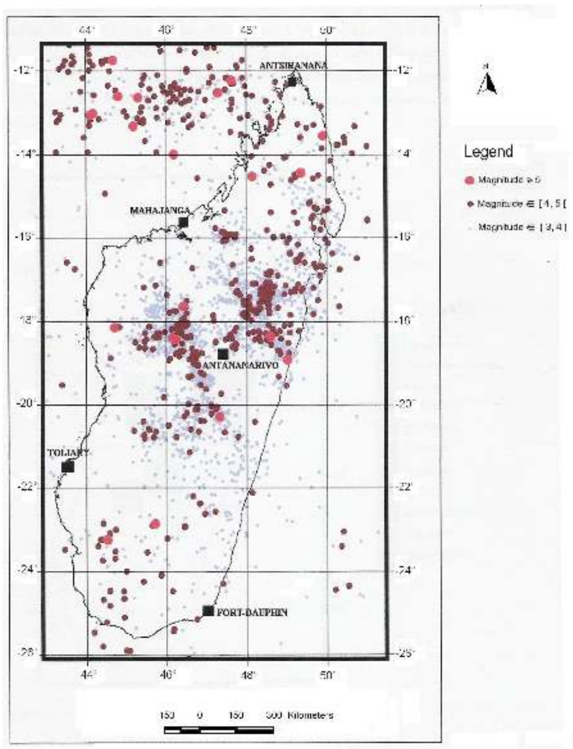

Figure 3: Instrumental seismic activity for the period 1975-2007 for magnitude ≥ 3 (after Rindraharisaona, 2008).

In the coastal basins, earthquakes are associated with volcanic events, with horsts and grabens, and with basement complex/basin contacts. A study of all seismic activities with significant magnitude has been carried out (Bertil and Regnoult, 1998). In the Precambrian basement these earthquakes are associated with volcanism and recent alluvial basins (Figures 2 and 3), often appearing near ancient Precambrian structures such as large ductile shear zones, palaeo-sutures and crustal megafolds. An association of hot springs and seismic activity is also noticed (Bertil and Regnoult, 1998). The most active area is beneath the Ankaratra plateau (north side of Antsirabe volcanic field), where numerous minor earthquakes occur annually at depths of 15–28 km, including magnitude 5.2 and 5.5 events in 1985 and 1991 (Rakotondraompiana et al, 1999). The Ankay–Alaotra rift valley graben (located towards the east coast) is also seismically active, and shows Tertiary and Quaternary evidence of this tectonic activity (Figures 2 and 3). The earthquakes show both a concentration parallel to the north-south strike of the rift (Bertil and Regnoult, 1998), and a secondary north-west trend parallel to the swarm extending from the Ankaratra volcanic field and its extensional counterparts, the magmatic area of Itasy.

We conclude that there are obvious relations between active tectonic, volcanism, hot springs and earthquakes. The seismic activity and hot springs observed at the centre of the island indicate that the phase of volcanic and tectonic reactivation, which started during the Neogene is not yet completed. According to rumors in the area, in 1998 minor volcanic eruptions ("fire geysers") were observed at Kassigie cone, together with some earthquakes. The concentration of earthquakes at the centre of the island can be explained by the presence of a bulge of thermal origin.

5. REGIONAL LINEAMENT SYSTEMS

The region is characterized by short and steep fault scarp bounded valleys and moderately to deeply incised topography related to intense tropical weathering (Bertil and Regnault, 1998). The origin and evolution of this structure and its morphological expressions, however, are not clearly documented.

The structural lineament maps (Figures 4 and 5) have been prepared from the Satellite Imagery (Landsat 7 ETM+, detail of S-38-15-2000, Laborde coordinates), most of which were subsequently checked in the field where ever possible.

The azimuth frequencies for all lineaments (Figure 6) on the basis of cumulative length show the structural trends. They are oriented north-south (N-S or N05°E), north-northwest-south-southeast (NNW-SSE or N160°E), north-northeast–south-southwest (NNE-SSW or N20°E), east-west E-W (N85E), northwest-southeast (NW-SE or N140°E), west-northwest-east-southeast (WNW-ESE or N110°E) and east-northeast-west-southwest (ENE-WSW or N70°E); of which the N-S, NNE-SSW and NNW-SSE trends are prominent in the study area.

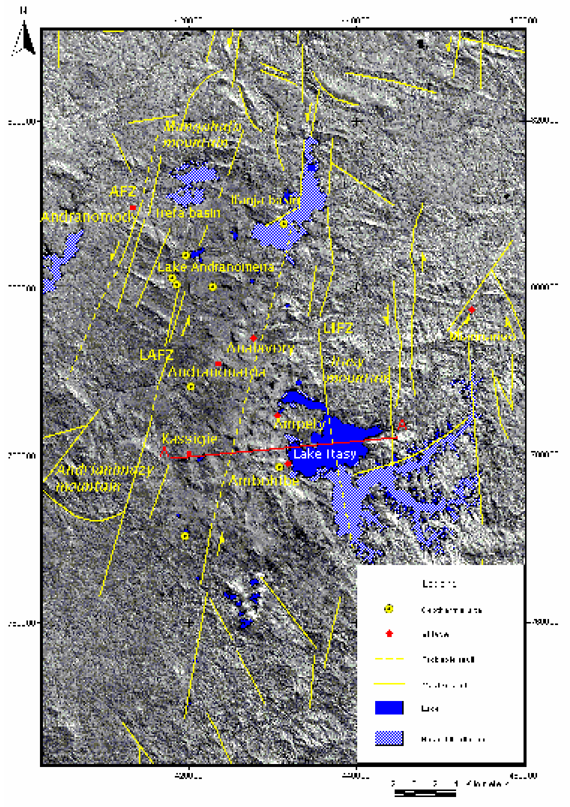

Figure 4: Generalized map showing inferred major fractures and geothermal occurrences along Itasy structural zone.

Inspection of the map of fractures reveals that major discontinuities appear to be arranged broadly in N-S structures. Two main regional fracture sets dip steeply and trend N to NNE, locally deviating towards NW and NNW in the southwest sector and in the east sector respectively.

The clarity and visibility of the fractures vary from one to another and often positively coincide with the length of the feature being mapped. The longest, continuous fractures are usually those which are best expressed on the image, which in turn reflect the fact that these fractures guide evident geomorphic features such as valley axes, gorges, ravines, ridge-top trenches, or slope breaks. Some of these fractures retain their direction over many kilometers or are only slightly curved, cross divides and intermountain basins.

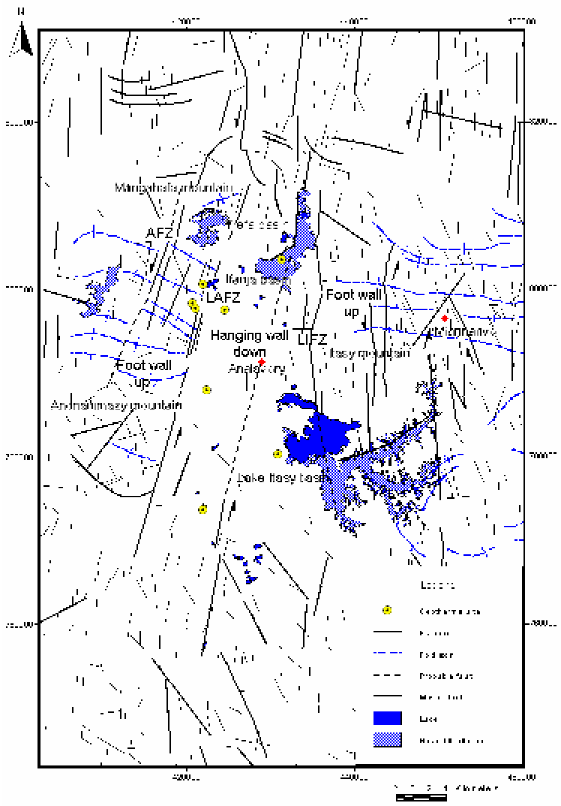

Figure 5: Map of the lineament analysis of the Itasy structural zone.

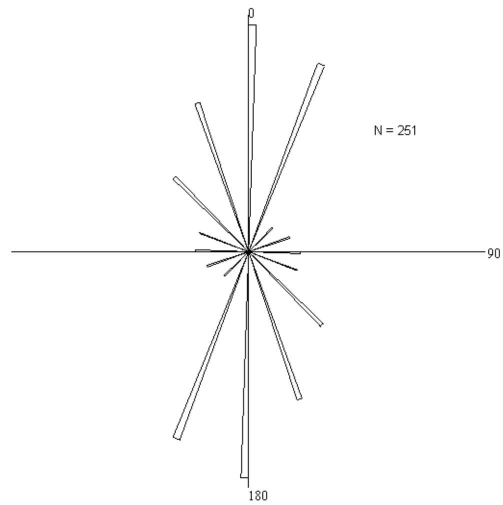

Figure 6: Rose diagram of fracture orientations: numbers and lengths.

Our geological field surveys have shown that aligned valleys, scarps, saddles and crests largely correspond to narrow zones of more or less intensely faulted and fractured rocks. Fault and fracture strikes are broadly consistent with the directions of the feature alignments that, from now on, will be referred to as lineaments.

Preparatory deep weathering in these structural and lithological circumstances favours weathering and erosion, which become focused on the fault zones. This is why today's pattern of drainage lines has utilized these "master fractures", which are probably strike-slip fault zones (Segall et al., 1990). Main streams occupy moderately incised troughs coincident with "master fractures" enclosing shattered and therefore highly erodible rock. The fracture zones have been exploited by fluvial erosion. Some "master fractures" (prominent structures) are not followed by streams along all their mapped lengths (e g faulted NNE-SSW). Instead, streams leave them and take another course, often towards an adjacent fracture zone, whereas many abandoned master fractures run across slopes or divides and into catchments where they guide drainage lines again. Other abandoned fracture zones fade away or terminate.

Several major fractures show a component of lateral movement, hence, they are strictly speaking faults rather than joints. Some of these major fractures show the spatial criteria for the recognition of strike-slip normal faults that are (a) the alignment of scarps along the base of mountain fronts, (b) the development of a component of lateral movement, (c) the development of axial drainage in the hanging wall area and (d) the development of trellis-type drainage in the footwall area.

6. STRUCTURAL FRAMEWORK

Major questions remain concerning the kinematic evolution of the Itasy structural zone and the relations between the geometry and kinematics of the various fault zones and geothermal activity. Structural offsets or topographic features clearly indicate the fault trend. The location of the master fault is strongly expressed by a linear trend of domes, cones, flows and explosion craters that extend a distance of approximately 45 km (Figure 4). Quaternary fault scarps, faceted spurs, and steep mountain fronts, with ~1,300 m of topographic relief, mark also these master faults.

The Itasy zone is fragmented into multiple N to NNE-trending fault blocks, overlapping N to NNE-striking faults most of which dip steeply (Figures 4 and 5). The geothermal sites are commonly associated with this N to NNE-striking fault zones (Figures 1, 4 and 5). Slip data obtained from fault surfaces show that these striking faults generally accommodated dip-slip normal displacement. Field studies indicate that most of them are extension fractures, formed perpendicular to the minimum compressive principal stress, and are steeply dipping to vertical.

There are numerous indications for vent alignment along structural trends running in a scatter of direction around a generally N-S trend (Brenon and Bussiere, 1959). From west to east, major N-S trend in the Itasy zone include - (a) the NNE-striking, WNW-dipping Andranomody fault zone (AFZ) in the western part of the geothermal site area (Figure 4), (b) the NNE-striking, ESE-dipping Lake-Andranomena fault zone (LAFZ), which appears to terminate northward, (c) the N-striking, Ifanja fault zone (IFZ), along the northern margin of the Itasy volcanic area, (d) the N to NNE striking faults, W to WNW-dipping, faults bounding the Lake Itasy (LIFZ) to terminate northward, (e) the N to NNW-striking Miarinarivo fault zone (MFZ), which bounds much of the eastern and northern sides.

Major NNE and NW-striking, range-front faults bound the west and the southwest sides, respectively. The western branch is morphologically more distinct in the field and is limited by NNE-striking, ESE-dipping Lake-Andranomena fault (Figures 4 and 5). This west side is bounded by a complex NNE-striking, strongly steeply dipping normal-sinistral fault zone. In this sector it seems that a NNE-trending horst blocks lies between the oppositely dipping Andranomody fault and Lake-Andranomena fault. Several left steps in the mountain front along this block and the presence of en-echelon folds suggest a left-lateral component of slip (Figures 4 and 5).

Directly north-east of the Itasy volcanic field, however, a well exposed fault surface, which strikes N20°E and dips 35-45° west, contains striae indicative of normal slip (i.e. dip slip). In the vicinity of the geothermal field, many strands of this fault zone are marked by Quaternary scarps. The eastern side of the Itasy geothermal basin field is limited by NNE-striking, WNW-dipping and by N to NNW-normal sub-parallel fault zones (Figures 4 and 5) with pronounced morphological signature. It is important to note, however, that a WNW joint set was observed in the northern sector.

A spatial study of high-temperature geothermal sites of pre-Quaternary-age faults shows that many of the sites are broadly located in along the N to NNE-strike-slip normal faults, located along range-bounding faults or reside on major range-front faults that roughly parallel the volcanic area. This belt of N to NNE-striking faulting and high heat flow is referred to as the "Itasy structural zone" (Figures 1, 4 and 5).

Analyzing the structural and volcano-stratigraphic relations of the Andranonatoa volcanic complex located at 3.5 km SW of Analavory (Figure 4), two main phases become apparent. (a) Multiple trachytic extrusions which form an oval shape, with the long axis over 1km in length along a N20°E direction; a tectonic influence can be therefore be assumed to be likely. (b) Fracturing of the dome along N20°E fault results in a wide trenchlike fracture of 300 m length and roughly 50-100 m width along the summit. The western edge of the fracture is still recognizable by a subvertical trachyte wall of up to 10m height. This is a nice example of strong neotectonics of presumably late Neogene to Pleistocene age in the Lake Itasy area.

Previous and our preliminary studies have noted that many of these geothermal sites have largely focused on localized fault stress-strain relations that would account for the dilation of fault apertures permitting upward movement of geothermal water.

7. DISCUSSION

The compilation of a near-surface thermal aquifer study, a generalized geologic map and the preliminary structural analysis of the area allows us to conclude that the geothermal reservoir resides in Precambrian rocks. However, the boundaries of the geothermal reservoirs in this area remain poorly defined, which poses exploration challenges for further development of the field.

The Itasy zone is composed of Pleistocene volcanic that rest directly on Precambrian magmatitic basement. These Precambrian rocks are deformed into closely spaced E-W-trending folds (Figures 1 and 5). In addition, Closely-spaced, N to NNE-striking faults dissect the range. These faults are a fundamental part of the pre-Pleistocene geologic framework in Itasy region (Figures 4 and 5). In this report, we speculate that the central (volcanic area) and the western (Precambrian basement rocks) sectors consist of a series of fault bounded, relatively low, NNE-trending discontinuous ridges and hills. The ridges and hills generally follow the strike of the faults. No detailed data exist to determine the slip rate of the faults. Well-exposed fault surfaces containing kinematic indicators, such as fault striae and Riedel shears, are sparse. However, fault surfaces exposed in rare outcrop have striae and Riedel shears indicative of sinistral normal oblique-slip movement.

The Andranomody fault zone (AFZ) consists of a series of en echelon faults (Figure 5), some of which contain kinematic data. Total offset along the fault is uncertain. However, Kinematic data from one of these faults indicates subequal components of sinistral and normal slip. It has accommodated ~1000 m of left lateral offset. Normal movement is down-to-the northwest. It is important to note that this western part of the Itasy region does not contain geothermal fields.

The southern Lake Andranomena sector consists of a series of fault bounded (LAFZ), relatively low, NNE-trending discontinuous ridges (Figure 4). The ridges generally follow the strike of the faults. Based on limited kinematic data, morphology of fault scarps, and offset of metamorphic and volcanic units, the NNE-striking fault accommodated sinistral-normal oblique-slip, with possibly a greater sinistral component than normal movement. Indeed, a NNE striking fault, ~10 km north of the Lake Andranomena, did accommodate ~2000 m of sinistral offset. Normal movement is down-to-the southeast (~200 m of vertical slip rate).

Well-preserved fault surfaces have not been observed in the Lake Itasy fault zone (LIFZ). However, two west-facing Quaternary fault scarps were found in this sector (Figure 4). Faults strike from NNE to NNW (with an average strike of north) and generally dip to the west. Faulting style is probably sinistral oblique-slip, with possibly more of a normal movement. The reasons for left-lateral motion on such faults are not yet clear.

The relationships described above indicate that the volcanic area (Figure 1) occupies a transtensional zone or structural depression (Figure 5). This structural zone is limited by the East Itasy mountain Range (Miarinarivo sector), and the Mangahafa mountains range (in North sector) and Andrianimazy mountains range (in SW sector) (Figures 4 and 5). Precambrian basement rocks are tectonically juxtaposed with the Quaternary basin fill along its length and it also cuts across basin fill, in places. Structural analysis of the growth faults measured in the field formed in tectonically controlled basin fill reveals a localized extension in a E-W direction. Fluids can simply flow more readily along moderately to steeply dipping faults oriented perpendicular to the least compressive stress. Why such structures are particularly favorable for localizing geothermal reservoirs within the Itasy structural zone is therefore an important question. A possible explanation is that left-lateral shear along the N to NNE-striking fault zones within the Itasy structural zone may accentuate broadly E-W directed regional extension. A small component of sinistral shear, combined with both regional E-W-directed extension and greater fault and fracture density associated with the transfer of strain between the many en echelon overlapping normal faults, may promote the deep circulation of fluids along N to NNE Itasy structural zone.

8. PRELIMINARY STRUCTURAL MODEL

The geological complexity is shaped by en echelon folds, en echelon overlapping normal faults, strike-slip faults and related basin formations. A general association of high-temperature geothermal sites and the structural controls provided by faults is evident in the spatial patterns of the Volcanic Area of Itasy.

The structural settings favoring geothermal activity all involve subvertical conduits of fractured rock along fault zones oriented approximately perpendicular to the least principal stress (Zoback, 1989; Hickman et al., 1998, 2000). Fluids can simply flow more readily along steeply dipping faults oriented perpendicular to the least compressive stress.

Major discontinuities (fractures and faults) appear to be arranged broadly in N-S structures suggesting E-W thinning. NNE-striking faults play a role in controlling the geothermal reservoir. Kinematic data indicate essentially dip-slip normal displacement on these NNE-striking faults. These NNE-striking faults (principal displacement zone) are orthogonal to the regional WNW extension direction and are thus favorably oriented for fluid flow.

8.1 Strike-Slip Basins

The Itasy structural zone is referred to as a releasing bend which is a bend that accommodate extension (Cunningham and Mann, 2007). Indeed, in releasing bend settings, high extensional strains in pull-apart basins may lead to increased heat flow (that can be exploited as sources of geothermal energy) and possibly volcanism (Aydin and Nur, 1982; Mann et al., 1983; Hempton and Dunne, 1984; Dooley and McClay, 1997); extrusive rocks may then constitute volumetrically significant basin fill (Dhont et al., 1998). Within the bend, oblique deformation may be accommodated by oblique-slip faulting or partitioned into variable components of strike-slip and dip-slip fault displacements (Jones and Tanner, 1995; Dewey et al., 1998; Cowgill et al., 2004b).

Three small strike-slip basins caused by a range of movement complexities along strike-slip fault zones are recognized in the Itasy geothermal field: Trefa basin, Ifanja basin and Lake Itasy basin (Figures 1, 4 and 5). The origin and evolutionary history of strike-slip basins have been studied during the last 30 years (e.g., Ballance and Reading, 1980; Rodgers, 1980; Schubert, 1980; Mann et al., 1983; Biddle and Christie-Blick, 1985; Harding, 1985; Manspeizer, 1985, 1989; Ingersoll and Busby, 1995; McClay and Dooley, 1995; Nilsen and Sylvester, 1995; Rahe et al., 1998). Two hypothesis are possible to explain the origin of these strike-slipe basins: the first one concerns a classical pull-apart basin or rhomb-graben basin caused by left-stepover of the master fault; the second one may be a negative flower structure rather than a classic pull-apart basin based on the strike-slip pattern of margin-boundary faults, and strike-slip complexities developed in and around the basins. In this latter case, upward migration of thermal water may be facilitated by a subsurface dip-slip master fault (probably by a NNE-SSW master strike slip fault) which may connect observed normal faulting (mainly west dipping) on the eastern side of the Itasy geothermal field with observed strike slip normal faults (east dipping) on the western side, (Figures 4 and 5). Because of the lack of reliable structural data, we are not yet enable to present which of these hypothesis gives the probable best response.

8.2 Fluid Movement

Concerning the fluid movement, a generalized picture of the Itasy geothermal system emerges from the combined hydrologic, regional lineaments and geological structures. Recharge to the system probably occurs at a variety of elevations in the surrounding mountain ranges (Figures 4 and 5) fluid pathways appear to be diverse (classical pull-apart basin model and or negative flower structure model). Because in extensional geothermal systems the geothermal fluids are typically traveling up a basin-ward-dipping fault, the geothermal fluids are more likely to migrate through pathways in the hanging wall side of the fault. Extension of the basin also tends to create additional faults (secondary fault) and fractures on the hanging wall that would favor fluid movement (Figure 7).

Although exact recharge areas for the thermal waters cannot be pinpointed, recharge is presumably from the East Itasy mountain Range (Miarinarivo sector), and Mangahafa-Morarano-Andranomody hills and Andrianimazy mountains range in the NW and SW sectors respectively.

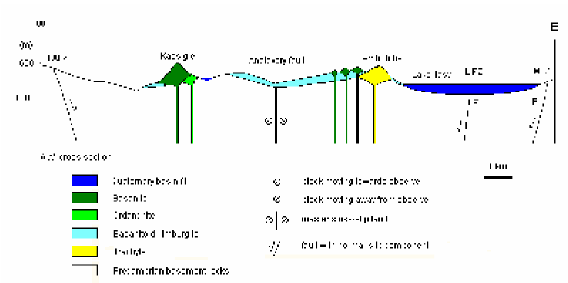

Figure 7: Hypothetical cross section of the Itasy structural zone.

9. CONCLUSIONS

Based on the regional lineament studies, geological exploration, structural analysis, remote sensing and a geothermal GIS, the data acquired in this study have significant implications for understanding the structural controls on the Itasy geothermal field. The Itasy belt occurs in tectonically active regions, where volcanism generally ceased ~10,000 years, suggesting these geothermal sites are not only related to magmatism but are also controlled by fault zones.

Regional structural lineaments (fault and fracture strikes) are consistent with the directions of the feature alignments. Prominent structures are the longest (many kilometers) continuous fractures and best expressed on the image. Master fractures are often marked by Quaternary fault scarps, faceted spurs, and steep mountain fronts with ~1,400 m of topographic relief. They appear to be arranged broadly in N-S structures and most of them show a component of lateral movement. These master strike-slip faults, distributed across the Precambrian crystalline basement exhibit a pre-Pleistocene rupture history.

A preliminary analysis of structural controls on high temperature hydrothermal sites using remote sensing coupled with field investigations indicates that most of the sites are spatially associated with seismically active pre-Pleistocene-age faults. Sites are located directly on or relative close proximity to pre-Pleistocene faults. The sites are associated with faults structures that have ruptured during large magnitude earthquakes during the last 40 years.

Most of the major geothermal sites occur along or near the N to NNE-striking faults that roughly parallel the volcanic area. From now this belt is called to as the Itasy structural zone. Field studies indicate that most of them are extension fractures, formed perpendicular to the minimum compressive principal stress, and are steeply dipping to vertical.

Major discontinuities (fractures and faults) arranged broadly in N-S structures suggest E-W thinning and extension direction. We speculate that the Itasy geothermal field may have experienced transtensional strain fields in association with left-lateral slip along a major strike-slip fault zone. The N and NNE strike-slip normal faults that are perpendicular to the least compressive stress play a role in controlling the geothermal reservoir.

The strike-slip basins recognized in the Itasy releasing bend may be a negative flower structure or a classical pull-apart basin caused by dilational left-stepover of the master fault. In this transtensional deformation, the geothermal fluids are typically traveling up a basin-ward-dipping fault; hence, in this case the geothermal fluids are more likely to migrate through pathways in the hanging wall side of the normal fault. Upward migration of thermal water may be facilitated by master NNE strike slip normal faults steeply dipping. Recharge for the thermal waters occurs at a variety of elevations in the surrounding mountain ranges both in the east and the west sides of Lake Itasy.

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