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Structural Model of the Itasy Geothermal Prospect in Central Madagascar: Preliminary Review

Lala Andrianaivo and Voahanginirina J. Ramasiarinoro

andrianaivol@gmail.com , andrianaivo@univ-antananarivo.mg, ramasiarinoro@yahoo.fr

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ABSTRACT

The Itasy geothermal prospect, situated at about 110 km west of Antananarivo capital, exhibits a striking density and variety of volcanic structures on the western side of Lake Itasy. The volcanic edifices all lie directly on the Precambrian basement mainly composed of migmatite and gneiss. The majority of the volcanic vents lie roughly within a rectangle of 45 km north-south (N-S) and 15 km east-west (E-W) extension suggesting a graben structure in the basement. Deformation has been analyzed from tension fractures – which are perpendicular to the direction of extension – and from field structural analysis. The Precambrian basement shows high fracture density and is fragmented into multiple north (N) to north-northeast (NNE)-trending fault blocks. Most of the major geothermal sites occur along or near the N to NNE-striking faults that roughly parallel the volcanic area. Kinematic data indicate essentially dip-slip normal displacement on the NNE-striking faults (principal displacement zone). Stress data indicate that the principal stress axe (σ_1 = N25W) is orthogonal to the regional east-northeast (ENE) thinning direction. Thus, on a regional scale, the tectonic regime responsible for the distribution of volcanic vents and geothermal sites is extension. Left-lateral shear along NNE-striking fault zones within the Itasy structural zone may accentuate ENE-directed regional extension. This mechanism, combined with a greater density of faults and fractures induced by the transfer of strain between the en echelon overlapping normal faults, may promote deep circulation of geothermal fluids along the N-striking fault zones. We speculate that the geological structures of the Itasy prospect are mainly composed of strike-slip faults and related basins. Two hypotheses are possible to explain the origin of these strike-slip basins: the first one concerns a classical pull-apart basin or rhomb-shaped graben and the second one may be a negative flower structure. Few low temperature thermal springs are indicative for persisting geothermal resources. The geothermal system is volcano-tectonic type. It has been termed magmatic geothermal and is associated with recent faulting in areas of thinned and extending crust.

1. INTRODUCTION

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

Although faults clearly control most of the geothermal activity in this area, relatively few detailed investigations have been conducted on the specific structural controls of individual systems. Because knowledge of such structures would facilitate exploration models, we have focused on the specific structural controls of individual systems.

Faults are known to be the primary control on geothermal activity in transtensional regions, but questions remain concerning the favorable types and parts of faults for geothermal activity. Better characterization of the structural controls in such regions is needed to develop and enhance exploration strategies, particularly the selection of drilling sites in fields without surficial expressions.

Ages of deformation in the study area may vary from structure to structure and from place to place on structures. Styles of deformation in individual structures may vary through time as a natural consequence of the nature and distribution of rock types. Interpretations of age, therefore, may require arduous field work and significant supporting data even for single structures. In general sense, the latest age of faulting in the study area is poorly defined, although rocks as young as the Itasy volcanic rocks are cut by mapped faults.

The main objectives of this work are to delineate the Quaternary three-dimensional strain field, to elucidate relations between faults and thermal aquifers, and constrain stress orientations, to provide a progress report of our multi-disciplinary investigations and to discuss potential implications of our findings on understanding the structural controls of geothermal reservoirs in the Itasy prospect where geothermal fields are commonly associated with north to north-northeast-striking fault zones.

More details on structural controls for the Itasy geothermal area has been studied in previous work (Andrianaivo and Ramasiarinoro, 2010).

2. TECTONIC AND GEOLOGIC SETTING

The youngest plate reorganization in the Indian Ocean started ~34 Ma ago with the opening of the Red Sea and the formation of the East African Rift, and since the mid Miocene, Madagascar has come under an extensional tectonic regime (Bertil & Regnoult, 1998).

Multiple indications for this east-west extension can be observed on the central highlands of the island:

- 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),

- image of the Moho depth beneath Madagascar through the inversion of gravity data suggesting the presence of N20°E trending zone of thinned crust along the axis of the island, paralleling the east coast margin (Fourno and Roussel, 1994),

- a high seismic activity with normal fault focal mechanisms and distribution preferentially along pre-existing tectonic trends (Bertil & Regnoult, 1998),

- gravimetric and seismic data indicating a thinned crust and lithosphere, related to asthenospheric upwelling (Rakotondraompiana et al. 1999),

- extensional structures such as grabens and basins (Piqué et al. 1999), as well as extensive Tertiary to Quaternary volcanism.

Such young volcanic fields can be found in the central highlands (Lac Itasy and Ankaratra) (Figure 1).

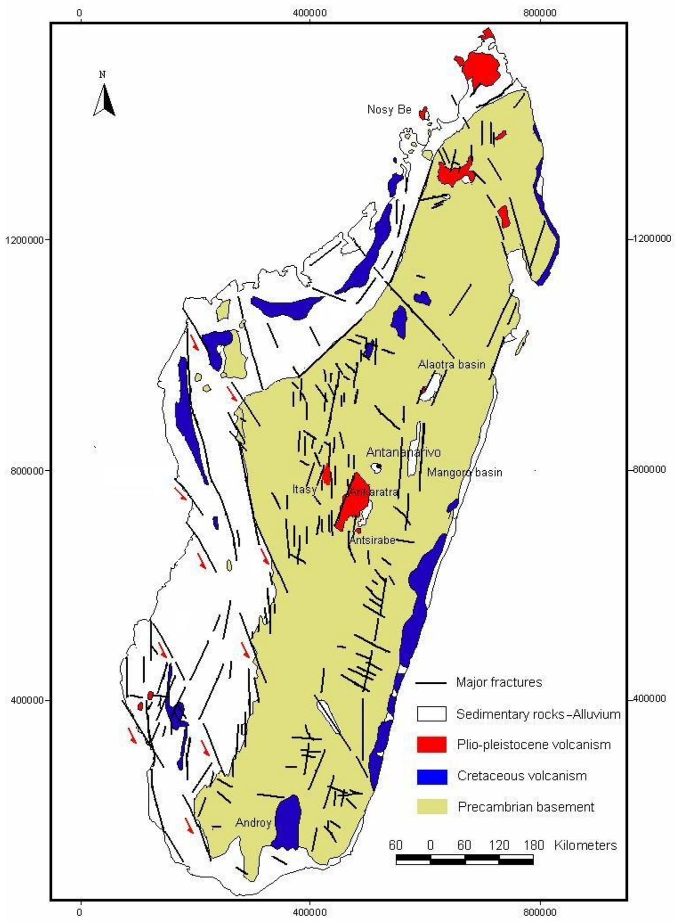

Figure 1: Map of Madagascar showing major fractures, volcanism and location of study area

The Lac Itasy field is dominated by basanitic to tephritic material that forms small flows and tuff cones, larger phonolitic flows and trachytic domes. The volcanic centers in Itasy area are inactive but are considered relatively young. Existing age data suggest that this field is not older than Quaternary; the age record is probably Upper Pleistocene based on radiometric dating and morphology (Ratsimbazafy & Rakoto, 1996).

The volcanic edifices all lie directly on the Precambrian basement mainly composed of migmatite and gneiss. The majority of the volcanic vents lie roughly within a rectangle of 45 km north-south (N-S**)** and 15 km east-west (E-W) extension suggesting a" graben" structure in the basement composed of migmatites and gneisses. Late tectonic movements associated with the basaltic eruptions induced a fault system oriented NNE-SSW (Joo', 1968; Fourno and Roussel, 1994; Andrianaivo and Ramasiarinoro, 2010) or a generally N-S trend (Brenon and Bussiere, 1959; Mottet, 1982).

3. METHODS

In this study, we utilize satellite imagery (Landsat 7 ETM+ No.159073 of 2000), 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.

Deformation has been analyzed from tension fractures (Ramsay, 1967), from morphotectonic method and from field structural analysis.

4. EARTHQUAKES AND ACTIVE TECTONIC

The main tectonic features and faults of Madagascar (Figure 1) are as follow:

- The N15°- 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.

- 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.

- The N05°-N10°E trend observed in the center of the island is associated with the Late Tertiary Neogene grabens such as the Antsirabe graben, the Alaotra graben north-east of Antananarivo.

- Finally, 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.

- Recent study signaled the presence of active faults (Andrianaivo and Ramasiarinoro, 2010) in the Itasy area. A tectonic survey would assign the explanation of the tendency to the reactivation of faults that would influence the western part of the Itasy area (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.

In the Precambrian basement earthquakes are associated with volcanic events (Figures 1 and 2) and recent alluvial basins, often appearing near ancient Precambrian structures such as large ductile shear zones, palaeo-sutures and crustal megafolds.

The Ankaratra plateau including Itasy volcano field is the most seismically region active (Figure 2). The earthquakes show secondary north-west trend parallel to the swarm extending from the Ankaratra volcanic field and its extensional counterparts, the magmatic area of Itasy.

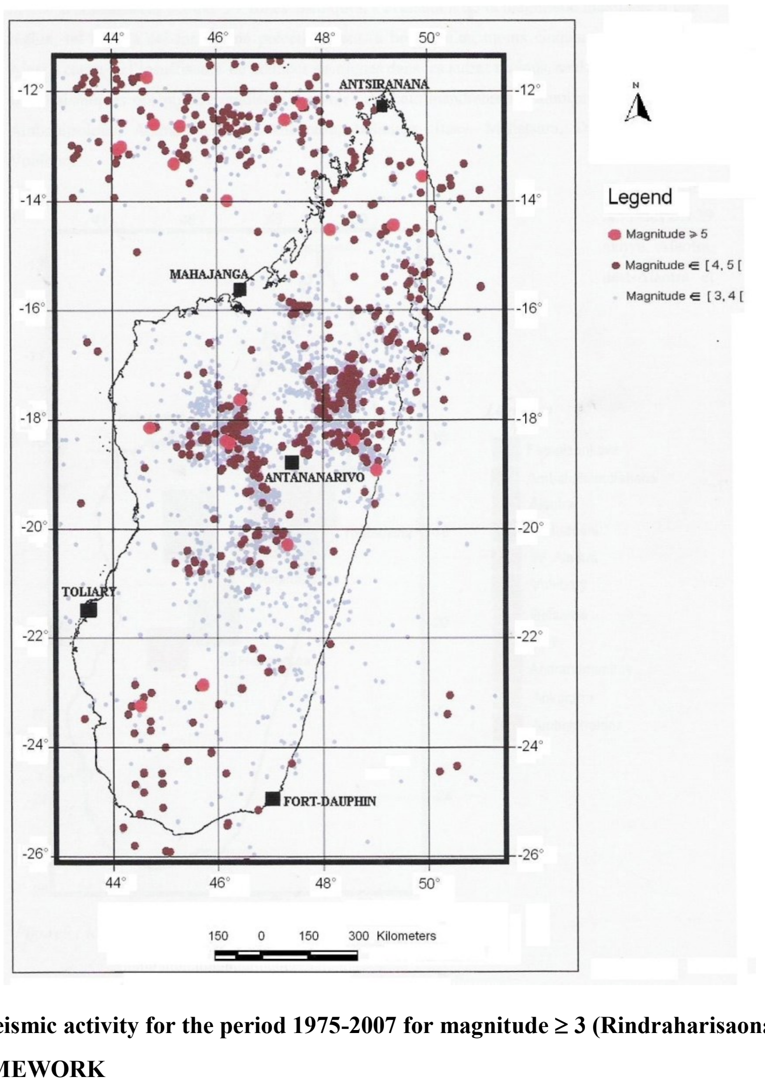

Figure 2: Instrumental seismic activity for the period 1975-2007 for magnitude ≥ 3 (Rindraharisaona, 2008)

5. STRUCTURAL FRAMEWORK

Several general trends can be observed (Figures 3 and 4): north-south (N-S) or N05°E-N10°E, north-northwest-south-southeast (NNW-SSE) or N160°E, north-northeast–south-southwest (NNE-SSW) or N20°E, east-west (E-W) or N85°E), northwest-southeast (NW-SE) or N140°E, west-northwest-east-southeast (WNW-ESE) or N110°E) and east-northeast-west-southwest (ENE-WSW) or N65°E-N70°E, of which the N-S, NNE-SSW and NNW-SSE trends are prominent in the study area (Figures 7 and 8). The main tectonic features and faults have been studied in previous work (Andrianaivo and Ramasiarinoro, 2010).

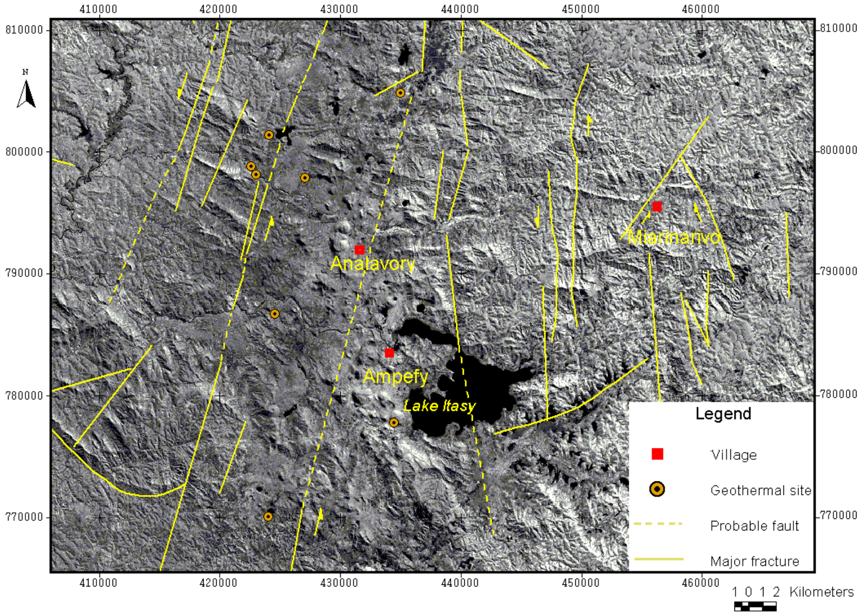

Figure 3: Generalized map showing inferred major fractures along Itasy structural zone on Landsat image

- The eastern branch of the Itasy rift basin is morphologically more distinct in the field and remotely sensed images (Figure 3), with several segments striking N-N20E with west-dipping fault planes creating a series of escarpments up to 400 m high with well developed triangular facets and short and steep fault scarp bounded valleys (Andrianaivo and Ramasiarinoro, 2010).
- The western side is limited by NNE striking, east-dipping sub-parallel fault zones with less pronounced morphological signature.
- The Precambrian basement shows high fracture density and is fragmented into multiple north (N) to north-northeast (NNE)-trending fault blocks.
- Most of the major geothermal sites occur along or near the N to NNE-striking faults that roughly parallel the volcanic area (Figure 4).

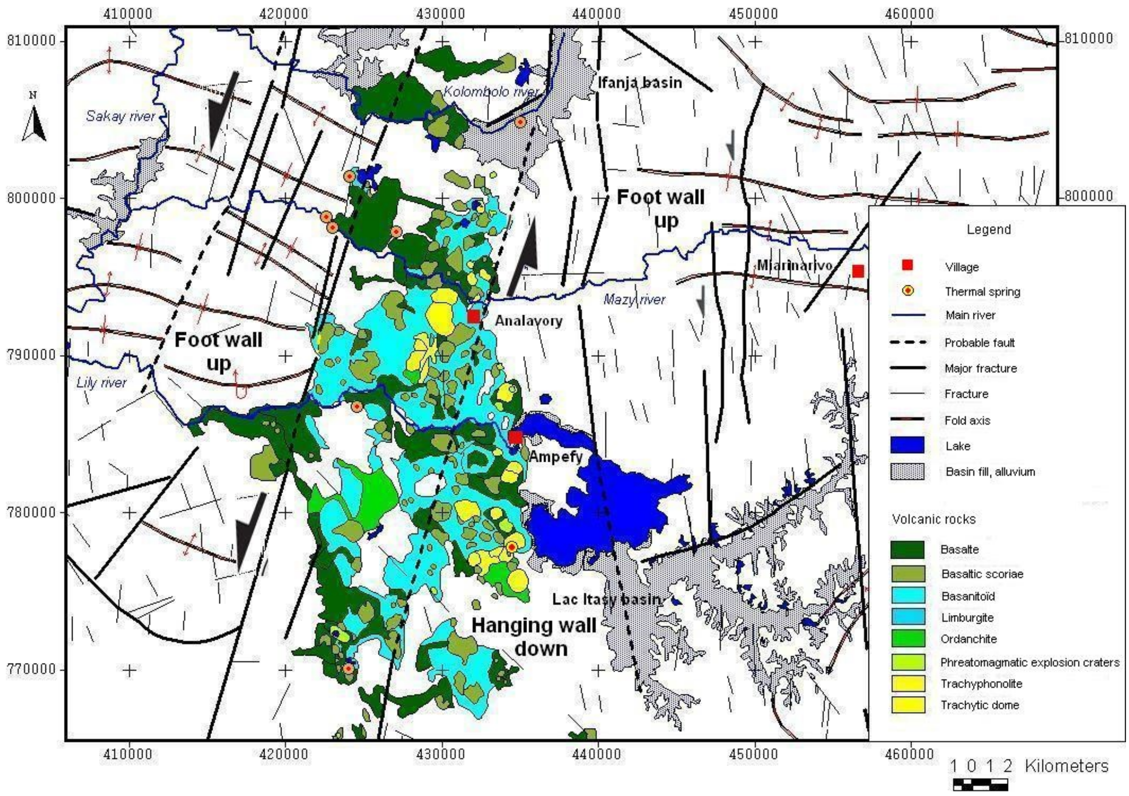

Figure 4: Map of the study area showing the tectonic, the volcanism and the geothermal sites

Kinematic data indicate essentially dip-slip normal displacement (Figures 4 and 5) on the NNE-striking faults (principal displacement zone).

Stress data indicate that the principal stress axe (σ_1 = N25W) is orthogonal to the regional east-northeast (ENE) thinning direction (Figure 9).

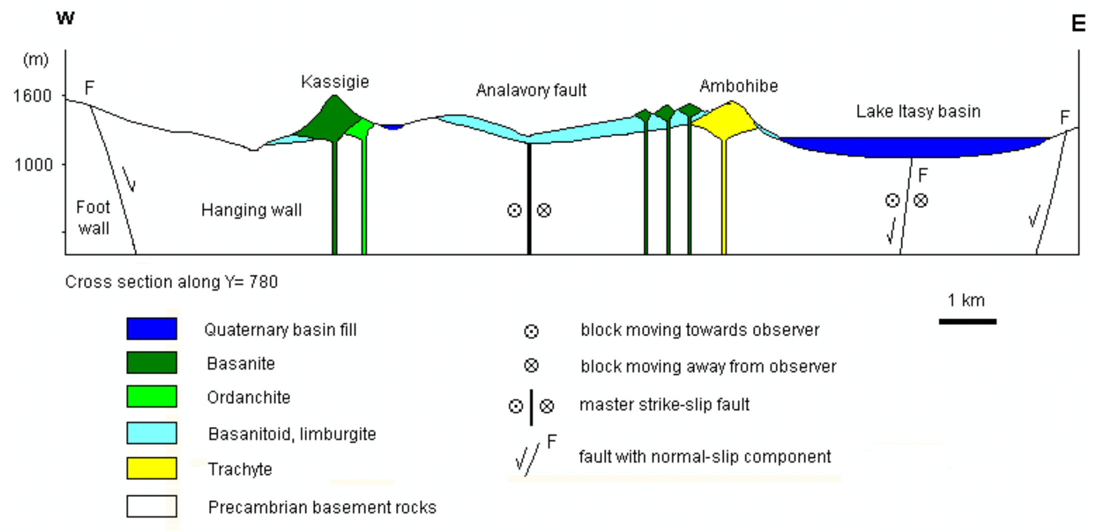

Figure 5: Hypothetical cross section of the Itasy structural zone

6. DISCUSSION

No detailed data exist to determine the slip rate of the faults. Well-exposed fault surfaces containing kinematic indicators, such as fault striae (Figure 6) and Riedel shears, are sparse. However, fault surfaces exposed in rare outcrop have striae and Riedel shears indicative of sinistral normal oblique-slip movement (Andrianaivo and Ramasiarinoro, 2010). These faults are a fundamental part of the Pleistocene geologic framework in Itasy area.

Focal mechanism of the studies with seismic survey, morphotectonic method and field structural analysis in the central highland indicate predominantly strike-slip and normal faulting, with a global north-south orientation.

Based on limited kinematic data, morphology of fault scarps, and offset of metamorphic and volcanic units, the N to NNE-striking faults accommodated sinistral-normal oblique-slip (Figure 7, 8 and 9). The reasons for left-lateral motion on such faults are not yet clear.

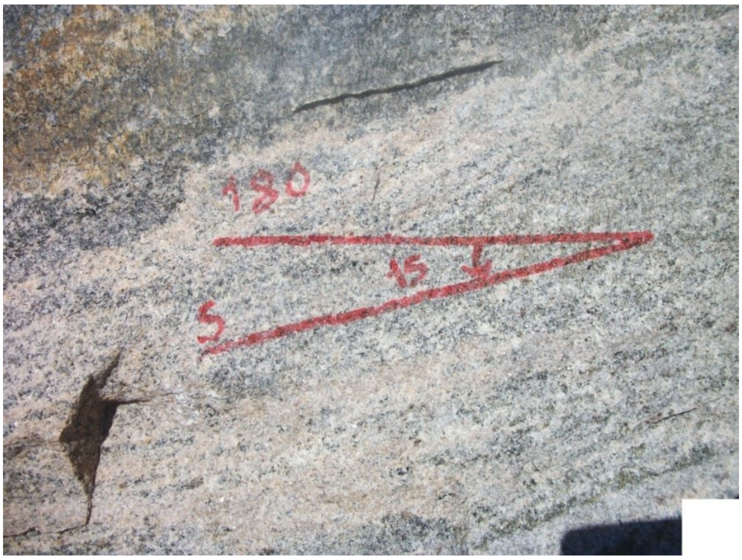

Figure 6: Field photograph showing close-up view of slickenside with a rake of up to 15° on the fault segment comprising the Lac Andranomena fault set

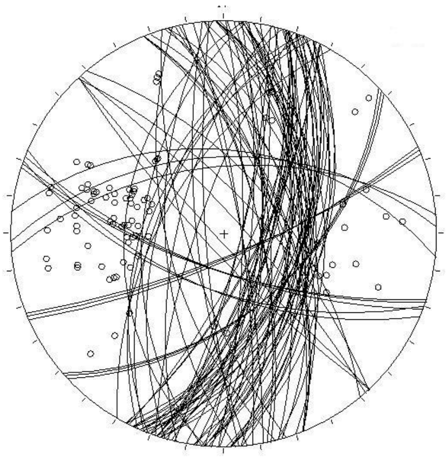

Figure 7: Great circles of fractures/faults - Lower hemisphere - Equal angle projection

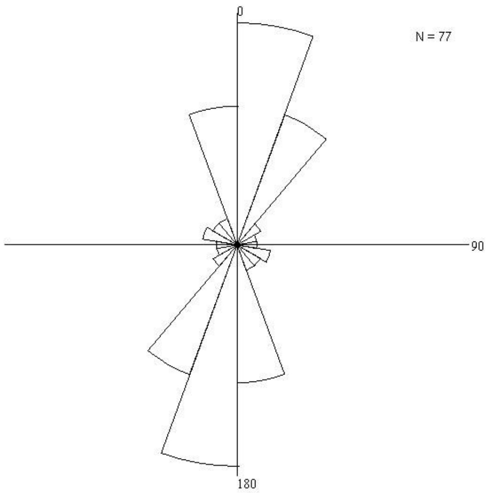

Figure 8: Rose diagram of major fracture orientations: numbers and lengths

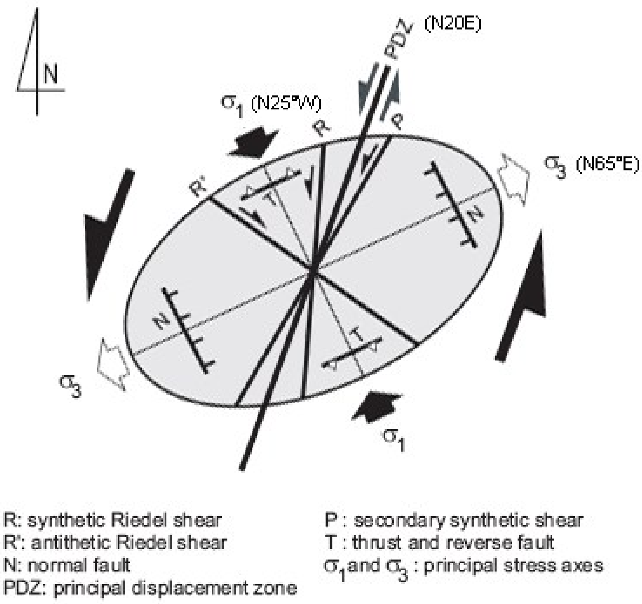

Figure 9: Plan view geometric relations between structures formed during a simple shear deformation history - schematic portrayal of accentuation of ENE-directed extension in an NNE trending zone of left-lateral shear

This general tectonic observation is consistent with the stress direction derived from neotectonic structures such as east-west folds (Figure 4) and northerly strike-slip faults seen at the surface. The implication also is that rock deformation continues in the subsurface, even though mapped evidence of continued faulting at the surface is relatively sparse.

The ENE trend of the minimum horizontal principal stress within the area (Figure 9) can account for the association of geothermal fields with the NNE striking faults.

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 moderately to steeply dipping faults oriented perpendicular to the least compressive stress.

The transfer of strain between the en echelon overlapping normal faults may also promote deep circulation of geothermal fluids along a greater density of N-striking fault zones.

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 NNE-striking fault zones within the Itasy structural zone may accentuate ENE-directed regional extension.

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; Dooley and McClay, 1997); extrusive rocks may then constitute volumetrically significant basin fill (Dhont et al., 1998). Within the releasing 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; Cunningham and Mann, 2007).

Two small strike-slip basins caused by a range of movement complexities along strike-slip fault zones are recognized in the Itasy geothermal field: Ifanja basin and Lake Itasy basin (Figure 4 and 5). Two hypothesis are possible to explain the origin of these strike-slip basins (Mann et al., 1983; McClay and Dooley, 1995; Nilsen and Sylvester, 1995; Rahe et al., 1998): 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. Because of the lack of reliable structural data, we are not yet able to present which of these hypothesis gives the probable best response

Based on the association of geological setting, resources and geothermal system is volcano-tectonic type. It has been termed magmatic geothermal and is associated with recent faulting in areas of thinned and extending crust (Andrianaivo and Ramasiarinoro, 2010).

7. CONCLUSION

The geological structures of the Itasy area are mainly composed of strike-slip faults and related basins in transtensional tectonic regime. These faults, distributed across the ancient crystalline basement exhibit a pre-Pleistocene rupture history.

On a regional scale, the tectonic regime responsible for the distribution of volcanic vents and geothermal sites is extension. Thus, the geothermal system is volcano-tectonic type.

Left-lateral shear along NNE-striking fault zones within the Itasy structural zone may accentuate ENE-directed regional extension.

This, combined with a greater density of faults and fractures induced by the transfer of strain between the en echelon overlapping normal faults, may promote deep circulation of geothermal fluids along the N-striking fault zones.

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 Plio-Pleistocene period, is not yet completed

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