Relations between drainage pattern and fracture trend in the Itasy geothermal prospect, central Madagascar

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Abstract - The study region, including the geothermal site and the Quaternary volcanic field of Itasy, is located in the western part of Antananarivo capital in central Madagascar. Bedrock is Precambrian migmatite gneiss and cut by numerous lineaments of various orientation, length and geomorphic expression.

We have mapped fractures, drainage network and drainage lines from satellite imagery and toposheets. The structural lineaments and the channel (drainage) segments of the region have been studied. Azimuths are shown on rose diagrams for fractures and drainage lines and then visually and statistically compared.

It is clear that the drainage of the Precambrian basement surrounding the Lake Itasy shows a subdendritic to subparallel pattern. The coincidence of drainage and fracture patterns is strong, which implies causal relationships. Of these, abrupt deflection in the course of the streams, development of trellis-type drainage in the footwall area and development of axial drainage in the hanging wall area indicate structural control of the drainage. It is concluded that most of the streams are structurally controlled and others are carving out their own path.

The north-south direction of channel segment is the range of directions broadly accordant with the dominant fracture direction. Two fracture directions, north-south and east-west, control the location of fluvial valleys and rates of incision.

Some of the major fractures are strictly speaking strike-slip normal faults which show a component of lateral and vertical and oblique movement. Most of the major thermal springs and geyser occur along or near the north to north-northeast-striking faults that roughly parallel the volcanic area. For that, we speculate that there are obvious relations between faulting, volcanism and geothermal sites.

Abrupt deflection in the course of the streams, presence of faults and subvertical faults, triangular facets and fault scarps confirm neotectonism and indicate that the region has remained tectonically unstable.

Keywords: Lineament, fracture, drainage, structural control, thermal springs, Itasy.

Résumé – La région étudiée, comprenant le site géothermique et le champ volcanique Quaternaire d'Itasy, est localisée dans la partie ouest d'Antananarivo, centre de Madagascar. Le socle précambrien, migmatitique à gneissique, est coupé par de nombreux linéaments de directions, de longueurs et d'expressions géomorphologiques variées.

Nous avons dressé des cartes de fractures, du réseau hydrographique et de drainage ou d'écoulement à partir d'images satellites et de cartes topographiques. Les linéaments structuraux et les lignes de drainage des rivières de la région ont été étudiés. Leurs directions azimutales sont montrées sur des diagrammes en rosette pour les fractures et les lignes d'écoulement des rivières et sont ensuite comparées visuellement et statistiquement.

Il est clair que le réseau hydrographique du socle Précambrien qui entoure le Lac Itasy montre un modèle subdendritique à subparallèle. La coïncidence entre les modèles de drainage et de fracture est frappante et implique ainsi des rapports causaux. De ceux-ci, la déviation abrupte du cours des ruisseaux, le développement de drainage de type en treillis dans le compartiment

surélevé (mur) et le développement de drainage axial dans le compartiment abaissé (toit) d’une faille normale suppose un contrôle structural de l'écoulement.
On en conclut que la plupart des ruisseaux sont sous contrôle structural tandis que d’autres taillent leur propre chemin. La direction nord-sud des segments des ruisseaux concordent grossièrement avec celle de la fracture dominante. Les deux directions de fracture, nord-sud et est-ouest, contrôlent l'emplacement des vallées fluviales et le taux d'incision.
Quelques-unes des fractures majeures sont strictement des failles obliques qui montrent un composant de mouvement latéral (décrochement), vertical et/ou oblique. La plupart des sources thermales majeures et des geysers se trouvent tout près ou le long des failles de décrochement de direction nord-sud à nord-nord-est qui sont approximativement parallèles à la région volcanique. Pour cela, nous spéculons qu'il y a des relations évidentes entre failles de décrochement, volcanisme et sites géothermiques.
La présence de déviation abrupte des cours des ruisseaux, de failles subverticaux, de facettes triangulaires et d’escarpements de failles confirment le néotectonisme et indiquent que la région est restée tectoniquement instable.

Mots clés: Linéaments, fracture, drainage, structural contrôle, sources thermales, Itasy.

1. INTRODUCTION

Pleistocene to Quaternary volcanic rocks, active hot springs, human-induced geyser and possibility of geothermal resource characterize the Itasy region. But major questions remain concerning the role of faults in hydrothermal system. In the literature, previous studies have noted the role of faulting in the controls of geothermal system and the possible linkage between the presence of faults and the Pleistocene to Holocene volcanism of Itasy **[9]**. A spatial study comparison of high temperature geothermal sites with known north-northeast striking faults in this region shows that many of the sites are located along these faults, in particular, and many are located along range-bounding faults (**[9], [4]**, **[7], [1]**).

Another question concerns the role of these fractures (faults and joints) in controlling the location of fluvial valleys and rates of incision. For this purpose it is of interest to study the relationships between fractures and drainage.

The Itasy prospect is located nearly 110 km in the western part of Antananarivo capital in central Madagascar, and lies between E 397300 - 470600 longitudes and S 831200 - 735000 latitudes (Laborde projection).

The study area including the volcanic field of Itasy and the Miarinarivo sector, presents a variety of landforms of different size and origin. The morphology is diversified. The regional relief is mainly dominated by elongate east-west (E-W) residual resistant ridges, with altitudes reaching more than 1400m, particularly in the Antananarivo ductile shear zone. Below the granitic, the volcanic and the quartzite ridge crests, the fundamental planation surface is developed at an altitude of about 900 to 1100m in the areas made of gneiss.

The morphotectonic analysis helps to identify tectonic processes at the surface **[8]**. Fractures belong to the key factors influencing geomorphic evolution of rock landscapes. In many areas, they show geometrically coherent and visually striking patterns, often coincident with outlines and shapes of individual landforms of various origins.

At larger scales, causal relationships between fractures and drainage lines have long been suspected (**[11], [10]**), following the assumption that any discontinuities within the host rock offer lines or zones of decreased resistance and therefore are more easily exploited by weathering and erosion than adjacent, more massive rock compartments.

Satellite imagery and aerial photographs are usually employed to map drainage lines, but mapping fractures is more difficult as their traces are often obscured by regolith cover and vegetation.

The construction of a series of digital maps showing the spatial distribution of the main morphotectonic indices has been made.

The aims of this work are
(a) to evaluate the relationship between the remote sensing-derived aligned features (lineaments) and the regional fractures (faults and joints),
(b) to better understand the control of the structural lineaments on the drainage network,
(c) to discuss details of fractures (faults and joints) control on the drainage network and
(d) to determinate the possible relations between thermal springs and regional fractures.

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 works (such as geological exploration, regional lineament studies and structural analysis).

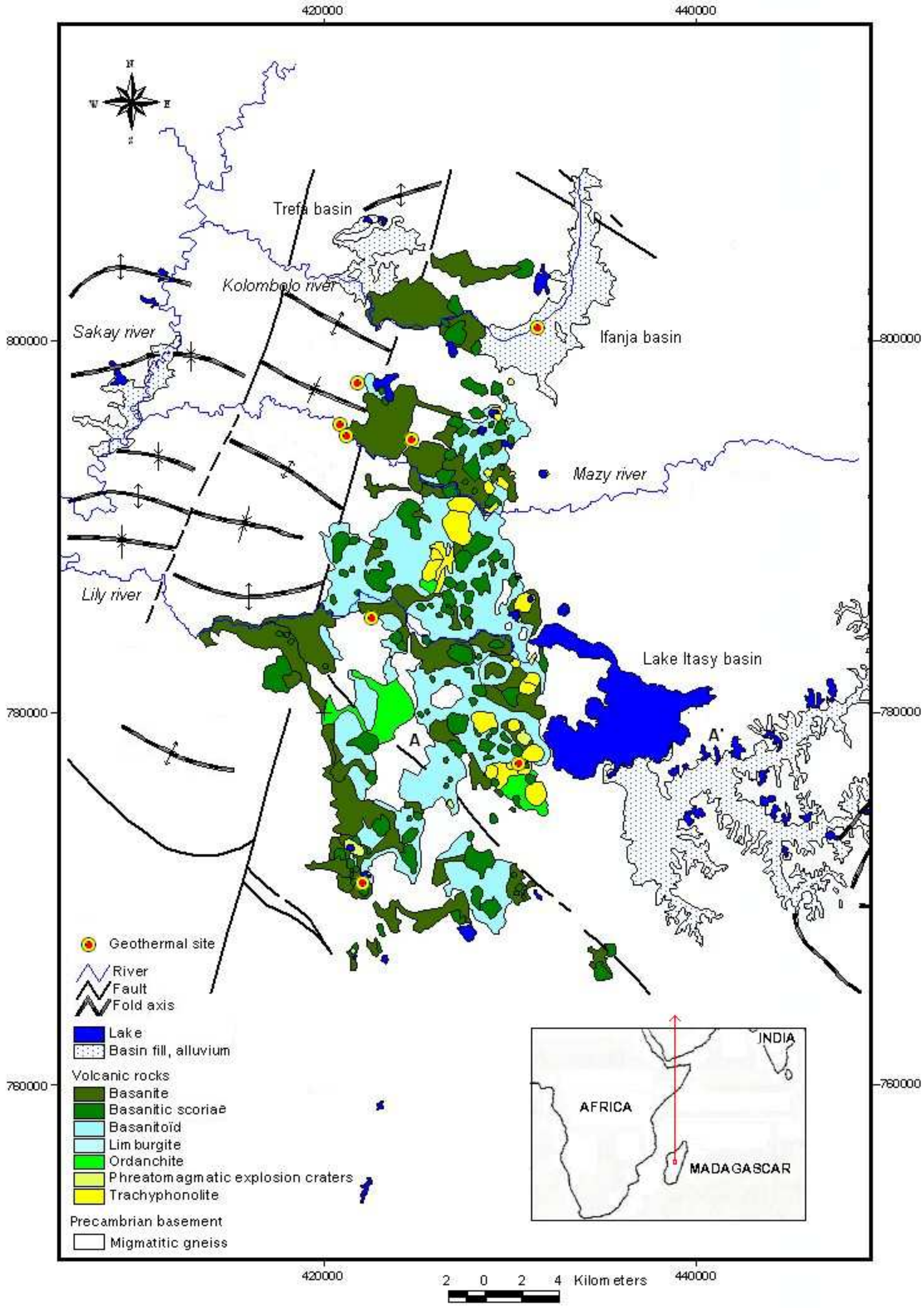
Satellite imagery of Landsat 7 ETM$^+$ detail of S-38-15-2000 (Laborde projection), and Geographical Survey of Madagascar toposheets MN-47 (1:100,000 scale) have been studied to demarcate lineaments, drainage segments, and geomorphic features. The drainage map has been prepared from the toposheets (Geographical Survey of Madagascar, 1958-1969), and the stream order has been determined following Strahler **[19]**.
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.

Rose diagrams for the lineaments and drainage segments are drawn, and correlation of the histograms has been made to understand the control of the structural lineaments on the drainage pattern.

From the available to us digital data, we digitized
- the drainage network
- the channel (stream) segment
- the structural lineaments (fractures)
- the fractures and normal faults as mapped by Joo’ **[7]** and by our own field works.
- the fold axis, the fractures and faults as mapped by the Geological Survey of Madagascar (**[9], [4], [7]**) and by our own investigations.

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 Holocene age (about 10,000-8,000 years)



[3].

Figure 1: Simplified geological map showing the tectonic, thermal spring occurrences and location of Itasy region [7]

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.

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 foïde), (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 (**[9], [4], [7]**).

These volcanic rocks rest directly on Precambrian migmatitic gneiss basement (**[9], [4]**, **[7]**). 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 prospect (**[9]**, **[7]**). 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 (**[15]**, **[13]**).

In the west and north-west sides of the Itasy prospect, closely spaced, north-northeast-striking faults dissect the range (**[7]**). Recent study signaled the presence of active faults and the presence of north (N) and north-northeast (NNE) strike slip faults has been signaled in the Antananarivo region **[13]**.

It is worth noting that thermal springs in the volcanic area of Itasy offer the possibility of geothermal energy (**[6]**, **[14]**). Many of the geothermal sites are related to volcanism and also controlled by fault zones (**[5], [1]**). Most of these sites are not so located and require evaluation before the geothermal potential of the area can be assessed.

Major questions remain concerning the relations between the geometry and kinematics of the various fault zones and geothermal activity. And insufficient information is publicly available to evaluate the individual resources and to characterize the age and the role of faults and fractures in the geothermal system of the volcanic area of Itasy. Such information could characterize the links between thermal aquifers and structural features.

4. RESULTS

4.1. Geomorphological framework

For the purpose of this study, we have selected two test sectors - Ampefy sector (including the volcanic area of Itasy) and Miarinarivo sector - ranging in size from 31.5*44.5 km (size of Soavinandriana toposheet M-47 at 1:100,000 scale) to 22*44.5 km (size of western part of Miarinarivo toposheet N-47 at 1:100,000 scale) respectively.

The region is characterized by short and steep fault scarp bounded valleys, moderately to deeply incised topography (Figure 2) related to intense tropical weathering **[2]** and triangular facets along the mountain front. The origin and evolution of this structure and its morphological expressions, however, are not clearly documented.

4.1.1. Ampefy sector

The study sector sometimes has rugged relief, several major rivers flowing in the general E-W direction (Mazy, Matiandrano, Kolombolo, Lily) (Figures 1 and 3), many narrow valleys and a lot of other interesting landforms.

In the north side, a feature to note is the alignment of scarps along the base of some mountain fronts and some of the fractures show the development of a component of lateral movement characterizing the presence of fault **[1]**.

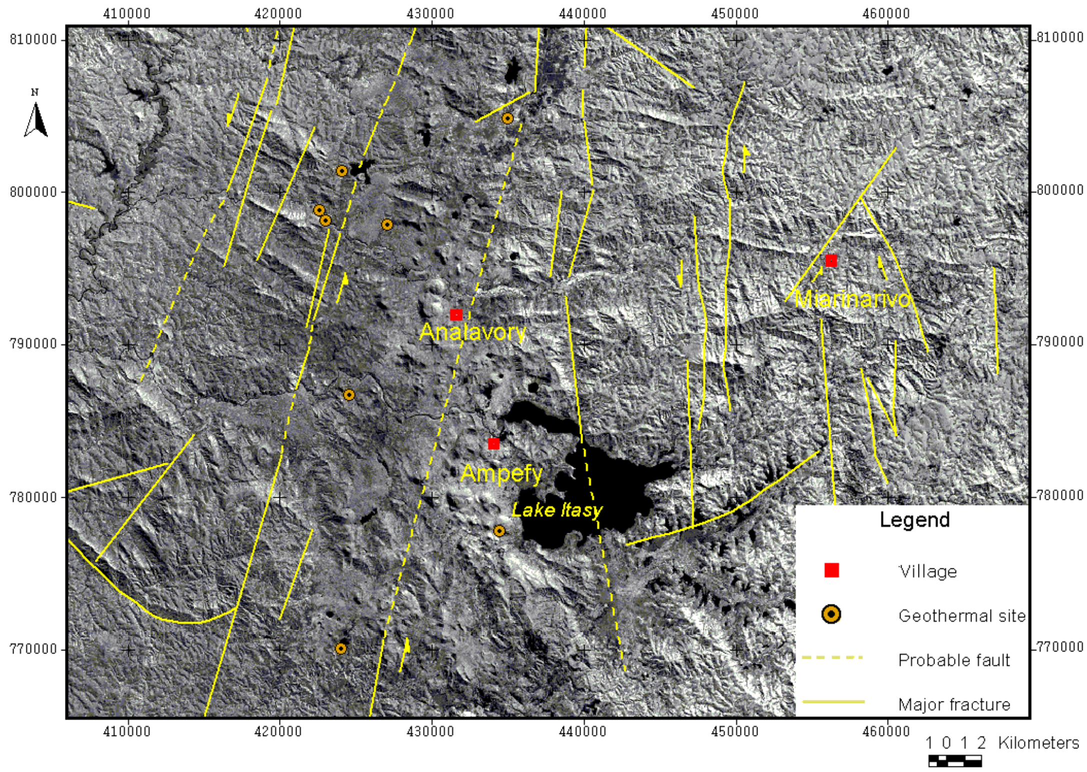


Figure 2: Generalized map (satellite imagery) showing inferred major fractures, and thermal springs (geothermal sites).

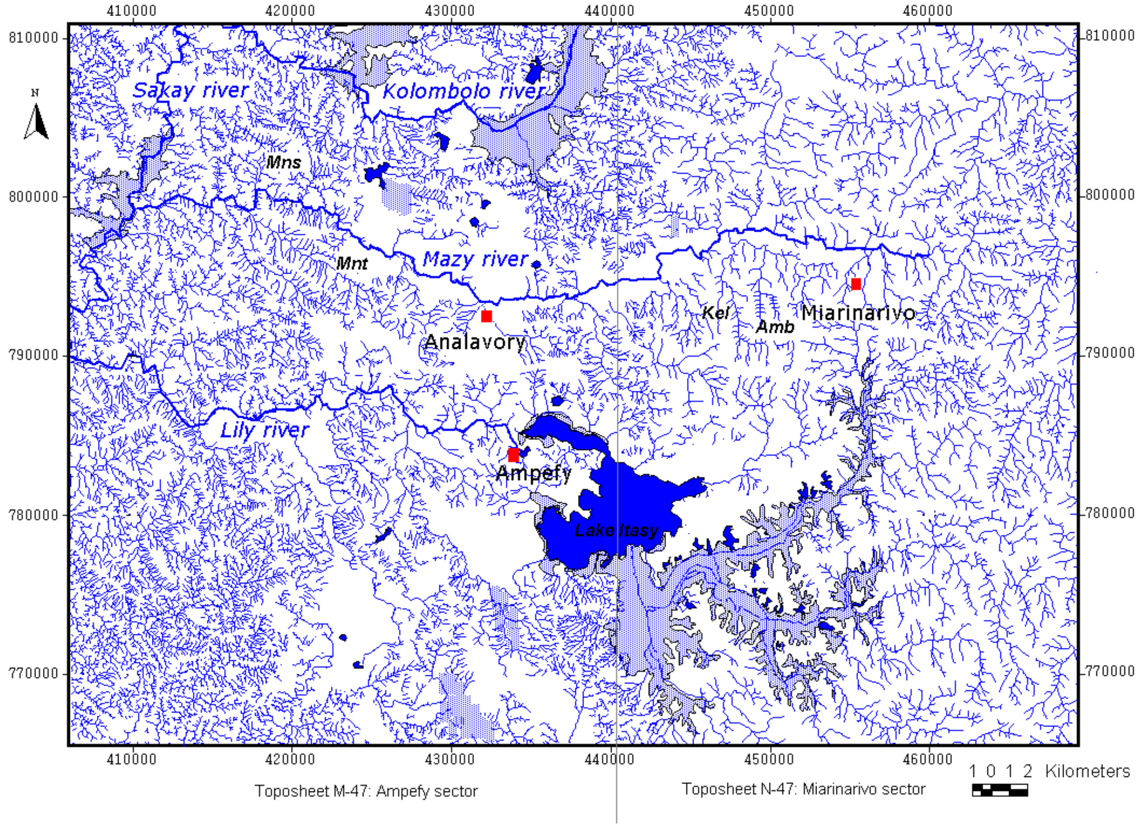


Figure 3: Map of the entire drainage network of the study area (Mnt: Mantalaha creek, Mns: Manasibe creek, Amb: Ambavarano creek, Kel: Kelitiana creek)

A predominant part of the terrain is an undulating upland at 1200-1400 m with numerous topographic basins occupied by lakes. In contrast to the other sector (Miarinarivo sector) considered in this study, many valleys have wide floors (Ifanja basin) and are only moderately incised.

Watershed areas include sharp-crested divides, extensive high-altitude surfaces of moderate relief (900 m) and ridges radiating from a central point.

Below the ridge crests of mountain ranges; the morphology is characterized by a fundamental planation surface developed at an altitude of about 900 to 1100m in the NW and the SW sides of the volcanic area.

Alluvial sediments of volcanic origin such as volcaniclastic sandstones are locally present within the valley floors and valley sides and assigned to Holocene age.

4.1.2. Miarinarivo sector

The Miarinarivo sector is located in the east (E) side of the volcanic area of Itasy. In this western part of the Antananarivo ductile shear zone, the relief is mainly dominated by elongate east-west (E-W) residual resistant ridges. Fold axis mapped by the Geological Survey of Madagascar (**[9]**, **[4]**, **[7]**) are broadly in accordance with this morphological feature. It is clear that the coincidence of landform and foliation patterns is strong, which implies causal relationships, and may indicates structural control.

The morphology is predominantly one of an undulating plateau at 1300-1600 m, although a lower level at 1230-1260 occurs around the Lake Itasy.

This sector sometimes has many narrow valleys. Major valleys are moderately incised. Alluvial sediments occupy floors of major valleys and some of the basins, their presence often being indicated by stream meandering.

Stream downcutting has developed a series of characteristic erosional landforms along the mountain front, the triangular facets (Figure 4). These triangular facets are developed along the mountain front, on the footwall area of the normal faults or subvertical faults. In the east of Miarinarivo Village, the footwall area of the fault is dissected by streams with W-E flow.

4.2. Drainage pattern

The map (Figure 3) shows a subdendritic to subparallel drainage pattern, in general, and the higher order streams, in particular, show a more or less trellis drainage pattern. Most of the higher and medium order streams follow a general structural trend that indicates that these drainages may be structurally controlled.

Examining only the higher order channels (4th and 5th orders) **[19]** the sector is characterized by abrupt deflection in the course of the rivers and the drainage network shows a preferred E-W and N-S orientation.

4.2.1. Ampefy sector

The west (W) side of the volcanic area of Itasy is drained by one main river: the Sakay River (5th order) which shows a dominant NNE–SSW direction.

The Kolombolo, Mazy and Lily rivers (4th order) flow longitudinally to the mountain ranges (E-W direction).These three rivers cross the volcanic field of Itasy and consist of more or less perpendicular tributaries to the Sakay River (5th order).

Figure 4: Triangular facets along mountain front south-east of Miarinarivo Village

The Mazy and Kolombolo rivers are both characterized by a similar trellis pattern geometry and a similar direction of the main trunks. The drainage networks within this sector NW show a dominant NNW–SSE direction (N150). In particular, they both flow from southeast (SE) to northwest NW (N135) or locally from east (E) to west (W) direction, running parallel to the direction of the mountain ranges and to that of the main geological structures of the northwest (NW) to west (W) sector (Figure 3).

The map shows also a development of axial drainage in the area and a subparallel drainage pattern for the rivers and the streams (Kolombolo, Mazy, Mantalaha and unnamed rivers). The drainage network follows a general structural trend (sub parallel to the foliation) and shows a more or less trellis drainage pattern.

The SW sector is characterized by a subdendritic drainage pattern.

4.2.2. Miarinarivo sector

Within the Antananarivo ductile shear zone, particularly in the northeast (NE) and the east (E) sectors of the volcanic area of Itasy, the drainage network shows a preferred east-west E-W orientation and with several subperpendicular tributaries (N-S direction).

For example, the course of Mazy River follows a preferred E-W orientation, flows longitudinally to the mountain ranges and often shows abrupt deflection; most of its tributaries show subperpendicular direction.

A similar organization can be found in the north (N) side of the Lake Itasy and, with tributaries more or less perpendicular to each main river.

Small unnamed rivers (2th and 3th order channel) show sometimes a similar trellis pattern geometry and a similar direction of the main trunks.

Besides these similarities, the drainage system in the south-east (SE) sector is characterized by little tributary basins draining the mountain ranges while the tributaries are all relatively short, flowing at less than 5 km from the main divide.

In the Miarinarivo sector most of river systems present a subdendritic pattern and they flow approximately perpendicular to the main divide (Figure 3).

4.3. Lineaments and channels segment analysis

4.3.1. Distribution of lineaments

Rectilinear valleys, valley walls, narrow linear hill ranges and ridges, crests, passes or a combination of these features, when aligned, were drawn as lines.

Although these lines correspond to “lineaments” sensu **[20]**, this term is not used here to avoid possible misinterpretation with structural lineaments (aligned features corresponding to the intersection between the surface and the main fault and fracture systems). Most of them were subsequently checked in the field where ever possible.

The structural lineament map (Figure 5) has been prepared from the Satellite Imagery (Landsat ETM+).

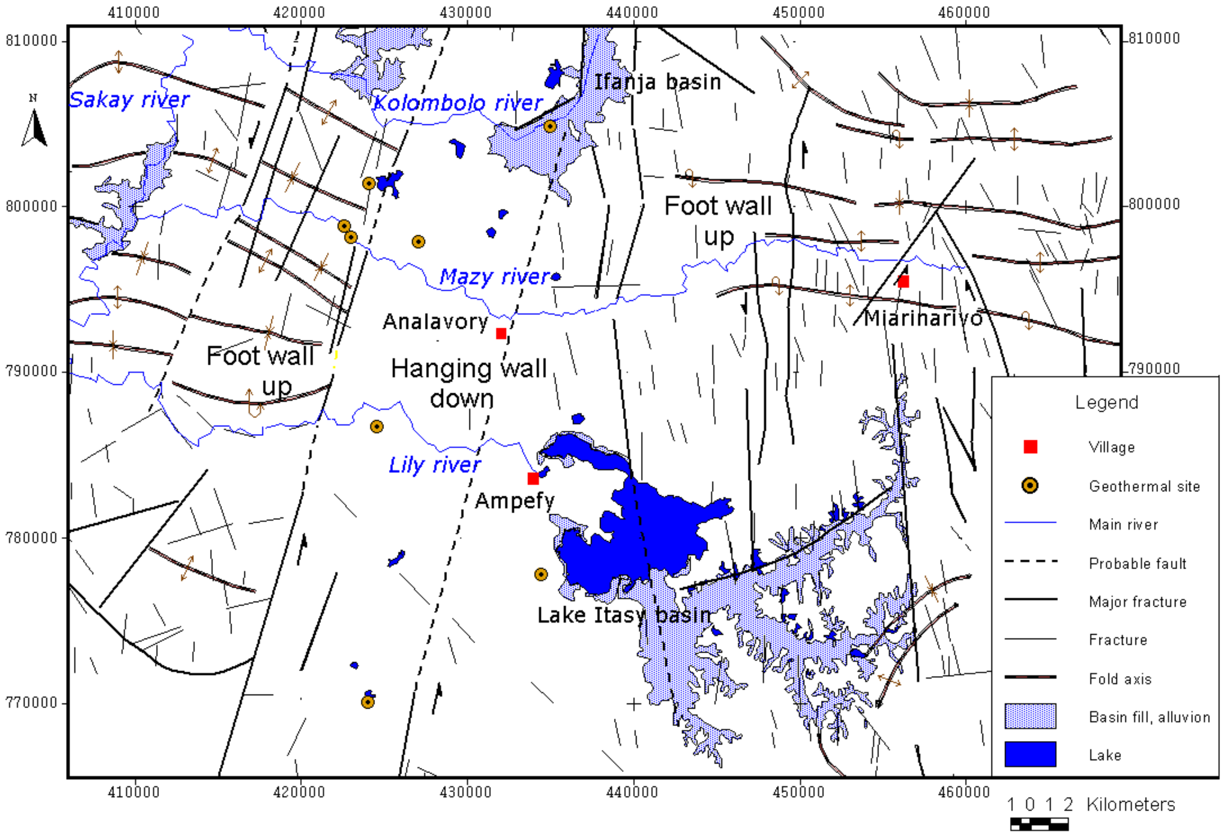


Figure 5: Map of the lineament analysis of the Itasy structural zone [1]

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 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 to N05°W), north-northwest–south-southeast (NNW-SSE or N160°E), north-northeast–south-southwest (NNE-SSW or N20°E), east-west (E-W or N85E), northwest-southeast (NW-SE or N140°E), west-northwest–east-southeast (WNW-ESE or N110E) 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 region.

Most of the hot springs and geyser occur along or near the N to NNE-striking faults that roughly parallel the volcanic area; suggesting possible relations and links between major geothermal sites and these major fractures **[1]**.

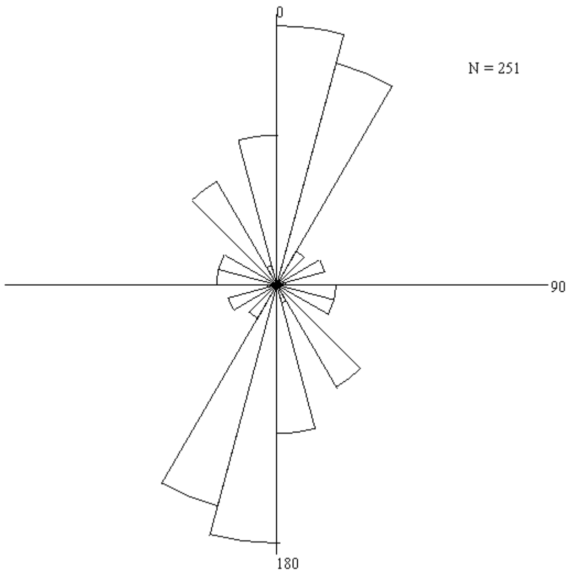


Figure 6: Rose diagram of fracture orientations: numbers and lengths.

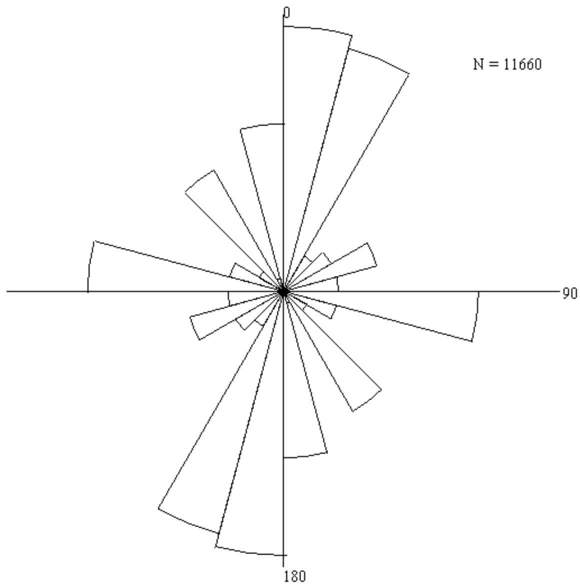


Figure 7: Rose diagram of the channel segment analysis

4.3.2. Channel segments analysis

The channel (drainage) segments map have been drawn from the drainage map and analyzed in terms of their trend and length. The data so obtained are represented in the form of a rose diagram. Channel segment analysis shows five prominent trends, N-S, E-W, NNE-SSW, NNW-SSE, ENE-WSW and NW-SE trends (Figure 8). Amongst these, **E-W**, **N-S**, **NW-SE** and **NNE-SSW** trends are found to be more predominant mainly in the Ampefy sector (Figure 7).

A histogram showing the comparison of the orientation of lineaments and channel segments is shown in Figure 9. It shows that the distribution of lineaments and channel segments gives a common area of superimposition of 65%. Of these, the higher order channel segments follow an E-W major lineament trend, whereas the lower order channel segments yielding the higher values of cumulative lengths are dominantly oriented along the N.

However, most of the channels follow the structural lineament trend, and deflection in the channels may be also structurally controlled.

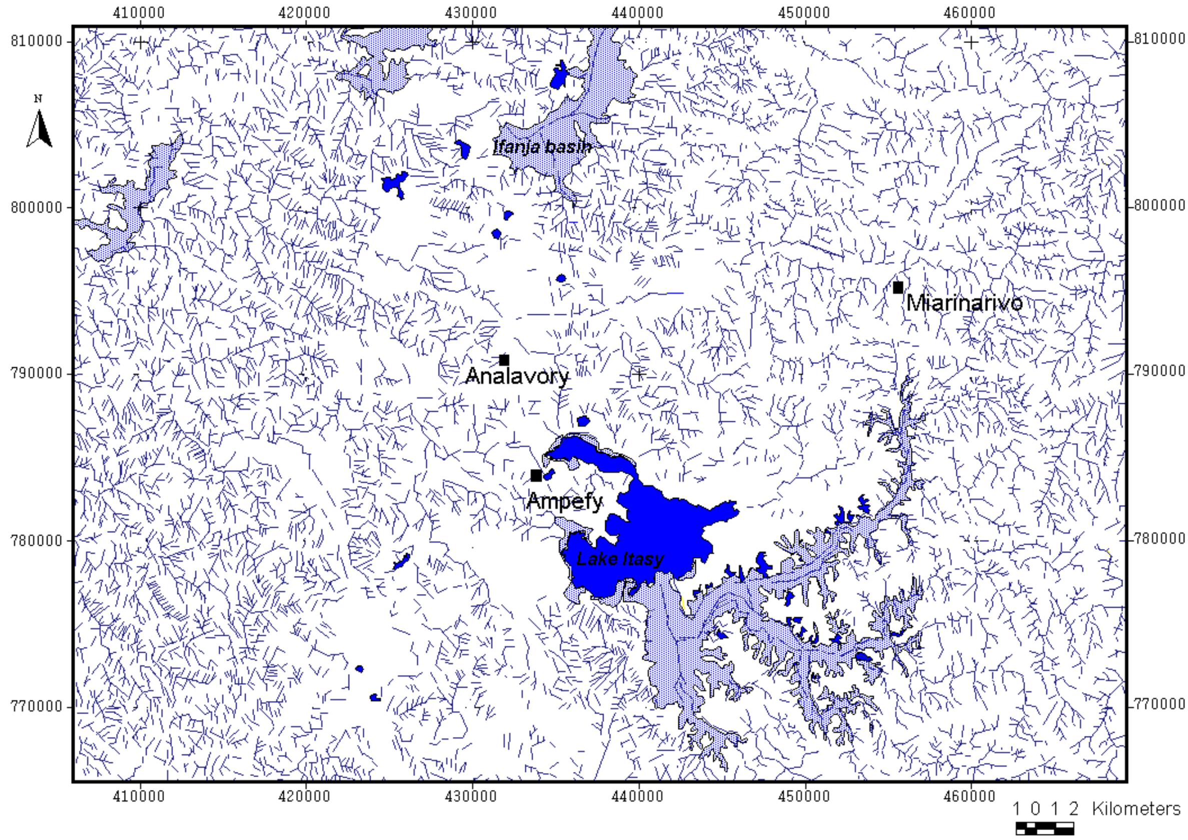


Figure 8: Channel (stream) segment map of the study region

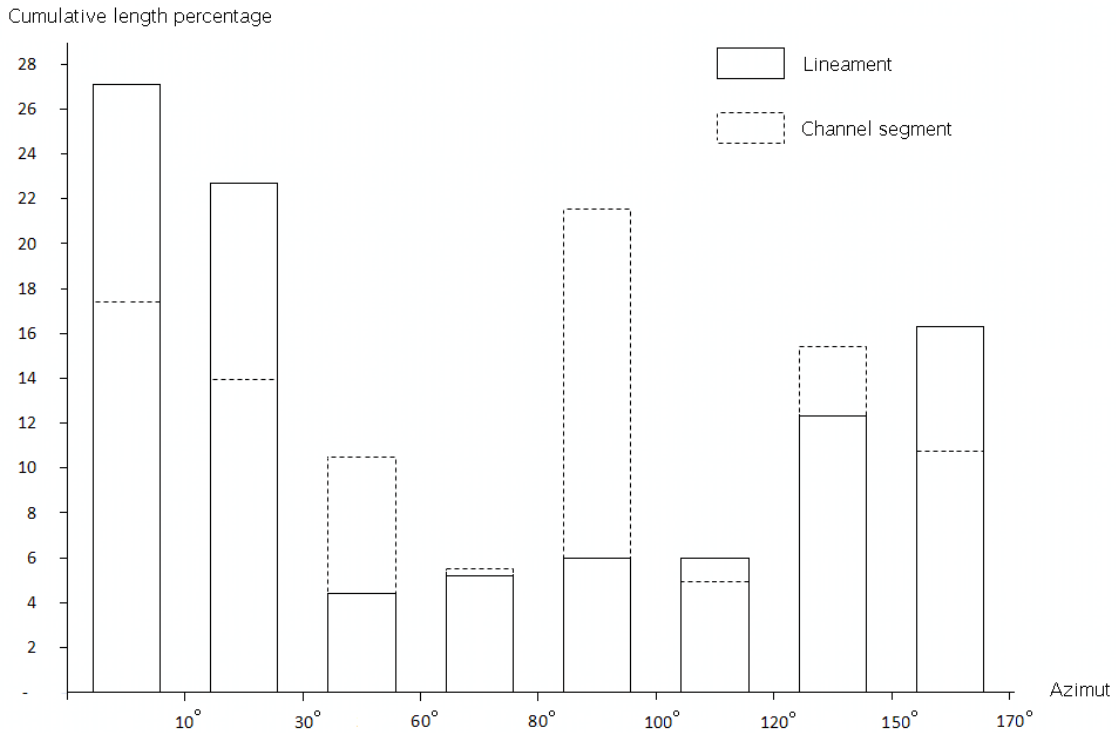


Figure 9: Histograms comparing the directional trends of lineaments and channel segment.

These directions of every river channel segment and the direction of the aligned morphological features will be compared and contrasted with the strike of tectonic structures measured in the field.

4.3.3. Lineaments and channel segments relationships

The structural lineaments in the area around the volcanic terrain (Ampefy sector) are oriented N and NNE. Although the channel segments of the drainage net broadly follow the general structural lineament, they have also carved out their path independent of the structure, as is evident from the trellis drainage pattern. The prominent lineament trends are N and NNE, while the prominent channel segment trends are E, N, NW and to some extent NNE. Of these the E and N trends are prominent in the channel segment, and of which E trend otherwise absent or insignificant in the lineaments.

Histograms of Figure 9, showing the correlation of lineament and channel segment distributions, clearly show attainment of separate peaks. The histograms show that the E trend is almost negligible in the lineaments, but this trend is significant in the channel segments. This unexpected phenomenon may be accredited to neotectonism, as the streams are one of the indicators of the present-day manifestation of structural orientation in their eagerness to find slopes. On the other hand, the ENE trend is almost equally distributed in the lineament and channel segments.

It is concluded that many of the streams are structurally controlled, but some streams have carved out an independent course. The channels around Ifanja basin (ancient lake) follow an N trend, coinciding with the general structural trends (N and NNE). Present-day drainage (Figure 3), including Lake Itasy and Ifanja basin seems to be the result of the interaction of the structural lineaments and channels over the poorly consolidated sediments.

Changes in stream sinuosity or gradient indicate the area of surface deformation **[17]**. In the present case, faults and particularly the subvertical faults around these lakes appear to be responsible for changes in the landforms and surface deformation **[1]**.

4.4. Fractures–drainage pattern relationships

Inspection of the map of fractures reveals a more or less different picture (Figure 5). Major discontinuities appear broadly to be arranged in N-S structures.

Abrupt deflections in the course of the main streams, such as Kolombolo, Mazy and Lily rivers, have been observed. This geomorphic feature seems indicate the role of the tectonism.

Unfortunately, the sedimentary cover (alluvium) on the high plateau surfaces and on the volcanic area obscures the fracture pattern in west-central portions of the study region.

4.4.1. Ampefy sector

The drainage pattern is dominated by the E-W trend (Figure 3), which is followed by the main rivers draining the area (Kolombolo, Mazy and Lily rivers), the upper section of the Mantalaha Creek and some of their tributaries.

These rivers and unnamed streams in the north–west are those apparently disregarding the available structure, flowing obliquely to local fracture directions.

In the west side, streams such as Mantalaha Creek, Manisabe Creek show a development of axial drainage in the hanging wall area, although Sakay River shows a development of trellis-type drainage in the footwall area.

Kolombolo, Mazy and Lily Rivers follow E-W direction over long distances which may indicate the existence of concealed fractures.

In the west, the main river: Sakay River follows NNE-SSW trend. In the south, a few unnamed streams follow E-W to NE-SW trend and flow obliquely to local fracture directions. But in each case, the adjustment to locally SW-NE and NNE-SSW fracture lines, respectively, can be demonstrated.

The argument for the explanation of this behavior is that: in the absence of prominent vertical joints, it is easier for a stream to erode its bed if the existing joints are oblique to the valley direction **[12]**.

On the fracture map, NNE–SSW trending fractures have evidently not been exploited by any significant streams.

4.4.2. Miarinarivo sector

In the eastern and the northern part of the Itasy region, N-S fractures are evident, while towards the SE they give way to NNW-SSE. More latitudinal E-W trend reappears in the NE.

Drainage lines in the Miarinarivo sector follow moderately incised valleys. Smaller tributaries in headwater sector follow various directions dictated by the local slope and join trunk streams at acute or right angles. In a few examples, they initially flow in the opposite direction to the trunk stream (tributaries of Ambavarano Creek). Further downstream fractures appear to take principal control as indicated by the scarcity of tributary streams flowing from N or E even if this is the direction of maximum slope.

Most of major tributaries of the Mazy River follow the predominant direction of fractures and indeed, streams such as Ambavarano Creek, Kelitiana Creek seem to directly exploit major fractures (N-S trend). Besides, comparable agreement occurs for ENE-WSW trending streams.

4.4.3. Comments

In the Itasy region, there is a considerable agreement between fracture patterns and drainage patterns as far as the E and NE sectors are concerned.

Inspection of the map of fractures (Figure 5) reveals that major discontinuities appear to be arranged broadly in N-S structures. This map confirms the dominant position of N-S to NNE-SSW trend and reveals that the other directions are represented by isolated discontinuities of rather short length. These two main regional fracture sets dip steeply and trend N to NNE, locally deviating towards NNW and NW in the east sector and in southwest the sector respectively.

In the SW sector, several NW-SE fractures are superimposed, which again is the direction not very prominent on rose diagrams. In the northern part of the Itasy region E-W fractures are evident. Two regional fracture directions E-W and N-S control the location of fluvial valleys and rates of incision.

Most of rivers draining the region flow within moderately incised valleys oriented mainly E-W to N-S. The N-S drainage direction is the range of directions broadly accordant with the dominant fracture direction. The E-W drainage direction corresponds mainly to the dominant direction of foliations and those of fold axis within the western part of Antananarivo ductile shear zone.

Some of the fractures show a component of lateral movement or oblique movement

(Figure 10), they are strictly speaking faults rather than joints.

5. DISCUSSION

It has been observed that the clarity and visibility of the fractures vary from one to another and often coincide with the length of the feature being mapped. The longest, continuous fractures are usually well expressed on the image (Figures 2 and 5).

These fractures broadly 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.

Our geological field surveys have shown that aligned valleys, scarps, triangular facets, 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 structural lineaments.

Such major or master fractures, with 0.5 m to 10 m wide and bounded by two boundary faults enclosing a zone of highly fractured and shattered rock are probably strike-slip fault zones **[18]**.

In these prominent structures, development of cataclastic zones and significant alteration of primary minerals are observed. Chlorite, epidote, and sericite may replace hornblende, biotite, and feldspars. Because our study was based on the examination of satellite imagery and field investigations, we are unable to present microscopic petrography evidence (analysis of thin sections) in support of this last hypothesis.

The pattern of drainage lines has utilized these major fractures. Main streams occupy moderately incised troughs coincident with major fractures enclosing shattered and therefore highly erodible rock. The fracture zones have been exploited by fluvial erosion.

Some master fractures are not followed by streams along all their mapped lengths (e g faulted NNE-SSW). Instead, streams leave them (Kolombolo River in ancient Lake Ifanja) 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.

The majority of the fractures show no component of lateral movement, hence, they are strictly speaking joints rather than faults. Some of these 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 a component of vertical or oblique movement
d) the development of axial drainage in the hanging wall area and
e) the development of trellis-type drainage in the footwall area.
f) the development of triangular facets along the mountain front on the footwall area.

Some of these fractures have actually been identified as faults, active in the pre-Pleistocene and probably even in the Present day. Recent study signaled the presence of this active tectonic **[1]**; and the explanation of the tendency to the reactivation of faults that would influence the western part of this region is signaled by a seismic survey **[16]**.

Various geomorphic features indicating neotectonism in the area have been observed. These are triangular facets; fault scarp; faults and subvertical faults; and abrupt deflection in the course of the streams. It further suggests that the region has remained tectonically unstable.

Concerning the hydrothermal system, 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.

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

It is important to note that the Precambrian basement shows high fracture density. This section is fragmented into multiple north to north-northeast-trending fault blocks **[1]**. Most of the major thermal springs and geyser (geothermal sites) occur along or near the N to NNE-striking faults that roughly parallel the volcanic area. The probable linkage between the N to NNE striking faults and the Pleistocene to Holocene volcanism of Itasy has been noted in previous studies (**[1], [9]**). For that, we speculate that there are obvious relations between faulting, volcanism and hot springs occurrences.

6. CONCLUSIONS

In this study, we have demonstrated strong adjustment of drainage pattern to fracture pattern that exists in the Itasy prospect. It is shown through qualitative and quantitative correlation between valley and fracture directions and assumes various forms.

In plan, most of valleys follow fractures even if this locally means orientation very much different in respect to the regional slope arising from tectonic tilt of the range. Main streams occupy moderately incised troughs coincident with major fractures enclosing shattered and therefore highly erodible rock. The fracture zones have been exploited by fluvial erosion.

Acting as narrow central zones of structural weakness, the high fracturing may also be responsible for the presence of some valleys with wide floors. Two fracture directions, N-S and E-W control the drainage lines, the location of fluvial valleys and rates of incision.

It is concluded that most of the streams are structurally controlled and others are carving out their own path.

There is also a possible linkage between known N to NNE fractures and the presence of thermal springs and geyser. These regional fractures may be responsible for the structural controls of geothermal resource in the prospect.

Regional structural lineaments such as 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. Major 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 and/or vertical movement. These major strike-slip faults and normal faults are broadly distributed across the Precambrian crystalline basement and may exhibit a pre-Pleistocene rupture history.

Further, various morphological features, such as abrupt deflection in drainage courses, faults and subvertical faults, triangular facets and fault scarps confirm neotectonism and indicate that the region has remained geodynamically active.

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