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RECONSTRUCTION OF THE MENENGAI STRUCTURAL SETTING THROUGH EXISTING LITERATURE, INTEGRATED INTERPRETATION OF AERIAL PHOTOS AND SATELLITE IMAGES (LANDSAT ETM+7 AND ASTER) - KENYAN RIFT VALLEY

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ABSTRACT

The Menengai geothermal prospect is located in the middle of the East African Rift System (*Kenyan Rift Valley*). This prospect covers an area of about 90 km^2 in correspondence of the "*triple junction*" of such rift, at the intersection of the ENE-WSW trending Kavirondo Rift with the Gregory Rift.

The reconstruction of the structural setting of the Menengai area was based on the existing literature, integrated with the interpretation of Aerial Photos and Satellite Images (Landsat ETM+7 and Aster). Available information indicated that the structural setting of the area is dominated by the presence of tensional-type N-S systems related to the regional stress. The main tectono-volcanic axes (TVA) identified in the area correspond to the Molo and Solai systems.

As refers to the classification and recognition of *volcanic forms,* mention was made of the likely presence of another calderic structure, in addition to the Menengai one. This caldera, named "Olbanita caldera", located NW of Menengai and visible only along its western rim, has an estimated diameter of about 12 km. Moreover, evidence was found that the so-called "*Menengai shield volcano*" is actually constituted by two separate edifices, one of them encompassing the whole Menengai caldera and the other corresponding to the N-S oriented Ol Rongai chain.

The main findings of the *linear features orientation and density* analysis, illustrated by means of maps and azimuth distribution diagrams, are the following:

- The structure at regional level is controlled by a family of tensional-type N-S faults extending along the Rift and constituting the main TVA recognized in the area, i.e. the Molo and Solai systems allegedly forming a complex graben-horst system. However, other fault systems become predominant within the Menengai caldera, in particular the NNW-SSE ones, which are highlighted by the occurrence of well aligned eruption centres and fumarolic activity. Another important system corresponds to the E-W direction expressed by a long-linear extending between MW-01 and MW-03 exploration wells and by other parallel faults, which seem to partly control the areal extent of the geothermal reservoir.

- Two structures of the NNW-SSE system (trending N.7W and N.30W) appear to be of major importance, as indicated by their pronounced surface expression, their control over the volcanic emission centres and the association with high density linear features. These structures, also clearly expressed by the distribution of the micro-seismic events, define a block 4 to 6 km wide, extending throughout the caldera, which is deemed to correspond to the sector where the magmatic chamber is shallowest and the thermal anomaly most pronounced.

OBJECTIVE OF THE STUDY

The remote sensing techniques were applied to the Menengai Prospect, under development by the Geothermal Development Company Ltd. and located in the middle of the East African Rift System (*Kenyan Rift Valley*), a divergent tectonic plate boundary 40 to 80 km wide, in south-western Kenya. The prospect occurs in correspondence of the "*triple junction*" of such rift, which is at the intersection of the ENE-WSW trending Kavirondo (also called Nyanza) Rift with the Gregory Rift in the point where the latter one changes its direction from NNE-SSW to NW-SE (see Figure 1). Such junction is considered to be the site of a mantle plume and corresponds to a concentration of large calderas associated with huge explosive eruptions, contrasting with the predominantly lavic and fissural activity of the northern and southern sectors of the rift.

The main objective of the present study was the reconstruction of the Structural Setting of the Menengai area. The study was based on the existing literature, integrated with the results of the specifically commissioned investigation for the interpretation of aerial photos and satellite images (Landsat ETM+7 and Aster).

This investigation has been carried out at distinct levels of detail in the following areas:

- The *Whole Study Area* (~640 km^2, at scale 1:30.000), which includes the caldera sector and extends beyond it, especially towards the north (see Figure 2).

- The *Caldera Sector* (~140 km^2, at scale 1:15.000), which includes the whole caldera and a limited area around it (see Figure 3).

STRATIGRAPHIC SETTING OF THE MENENGAI PROSPECT

The reconstruction of the stratigraphic setting of the Menengai Prospect, and specifically of the geological nature and thickness of the formations underlying the Menengai caldera, is hindered by the morphological configuration of the zone, inasmuch as the recent units (syn-calderic pyroclastic flows and post-caldera volcanics) cover most of the area, while the pre-caldera units (Menengai shield volcano and Tertiary products of the rift floor) outcrop only in a few isolated spots, especially along the caldera walls and fault scarps.

In principle, on the base of the nature of the outcrops along the flanks of the Rift, it is expected that volcanic rocks of predominantly trachytic composition underlie the caldera floor over a thickness of thousands of meters. Below the few hundred meters thick cover of post-caldera products, trachytic lava of the Menengai shield volcano with minor pyroclastic intercalations and an estimated thickness of 500-1000 m should be found, being on its turn underlain by Pliocene volcanics.

In consideration of the limitations imposed by the surface geology, the exploratory wells drilled to-date were expected to provide the basic information required for clarifying this matter. Actually, the achievement of this objective has been largely hindered by the combination of different factors, and in particular by the lack of obvious marker horizons within the monotonous sequence mainly consisting of trachyitic lavas and by the fact that the identification of the lithological features of the intersected formations (as well as of the secondary mineralogy) has been largely based on the analysis of cuttings by means of binocular microscope, only partly integrated by microscopic mineralogy and X-ray diffractometry.

In spite of these constraints, the analysis of the deep wells lithology allows to draw some useful elements for the reconstruction of the stratigraphic setting. It is observed in fact that intercalations of tuff are rather frequent in the upper 700 m (with possible continuous levels at 300-400 m and 600-700 m), becoming less common downwards. On the other hand, levels of intrusive material, in general classified as syenite, occur usually in the lower portion of the wells and are particularly common in the eastern portion of the investigated area, where the magmatic chamber is expected to become more shallow.

In general, wherever some correlation elements could be recognized, the structure appears to be sub-horizontal, with the possible exception in the western portion, which may be located in an uplifted block, with a downthrow of the eastern block of about 100 m.

In general, looking at the whole sequence, trachyte appears to constitute about 90 % of the total, whereas the remainder consists of pyroclastic and intrusive products. Under this situation, the stratigraphic control over the distribution of the geothermal system is obviously very limited, inasmuch as suitable lithologic conditions, in terms of brittle nature of the rock which may favour pervasive fracturing, can be found almost everywhere. On the other hand, the absence of clear marker horizons which can facilitate the correlation among the wells represents a negative element for the reconstruction of the geological history and of the structural setting of the area.

ORTHOPHOTO

A true colour orthophoto generated by the mosaic of aerial photos acquired specifically for this project has been provided by GDC (see Figure 3). The orthophoto has a ground resolution of 0.4 m (40 cm) and is projected in the UTM Arc 1960 system, so it has not been necessary to do any coordinate conversion.

The orthophoto covers almost of the caldera area, the eastern side being the only portion left out. It has been used both for the geomorphologic and the structural part of this study, mainly to enhance the detail of the analysis in the caldera area due to the very high ground resolution of this imagery, as well as for the reconstruction of drainage pattern.

SATELLITE IMAGERY

Three different types of satellite data were acquired: Landsat ETM+7 (path/row 169/60, dated 2000-01-27, 30 m resolution), Terra Aster (free download from the Aster Volcano Archive ava.jpl.nasa.gov/, including the 3 bands of the *vnir sensor* with 15 m resolution) and Aster GDEM (Global Digital Elevation Model, which is actually a Digital Surface Model, generated by the processing of stereo pair images, tile 1°x1° code 20121002104208_1326339454).

This multiple choice was dictated by the fact that different sensors offer different types of information, increasing the possibilities of interpretation. The study covers the whole concession area as well as the surrounding region.

GEOMORPHOLOGICAL STUDY: ANALYSIS OF LANDFORMS

The analysis of landforms in this study refers essentially to the recognition and classification of the volcanic features, defining the following categories (see Figure 4):

- *Pre-caldera Shield Volcano*, this category reflects an areal landform unit showing the inferred boundary of the Menengai shield volcano that existed before the explosion originating the present caldera. This boundary has been traced using both morphologic criteria (the limits of the Ol Rongai and the caldera relief) and the information contained in the available bibliography and geological maps (Leat, 1984 and 1991; McCall, 1967). The boundary of the shield volcano comprises, in the northern part, the Ol Rongai ridge, oriented NW-SE, with some eruptive centres aligned with a tectonic structure (Molo TVA).

- *Volcanic Apparatuses*, areal landform unit derived from the activity of one volcanic apparatus or of more apparatuses genetically related. In the Study Area it is represented by some volcanoes located essentially at the southern border of the caldera and outcropping from the rift floor near the Nakuru Lake.

- *Lava Terrain*, areal landform unit, representing the lava flows which were erupted within the Menengai Caldera after its collapse.

- *Caldera Rims and Crater Rims,* linear landforms representing the edges, respectively, of a caldera and of a crater. Specifically, in the Study Area two caldera rims have been recognized: 1) the Menengai Caldera rim, running almost continuously along the walls, except for two interruptions, one to the West, where one of the lava flows has partially obliterated the caldera edge, and one to the East, corresponding to the Solai Graben that cuts through the caldera with a N-S trend. 2) Another possible rim is located to the NW of Menengai, related to a caldera centred on the Olbanita area (Leat, 1991), of which only the western portion is clearly visible in the satellite images.

- *Eruption Centres,* landform unit encompassing local-scale monogenic edifices, and extending either where volcano craters have been identified, or where ancillary data (mainly bibliographic or sketch maps: Omondi, 2011; Suwai, 2011) suggested their presence.

- *Lacustrine Basins and Swamps,* areal landform units representing lakes (such as Nakuru) and marshy areas (Olbanita Swamp).

FRACTURE ANALYSIS

Making specific reference to the structural (fracture analysis) aspects, the linear features recognized in the images have been classified into four distinct categories according to their length and conspicuousness, namely:

- *Regional Lineaments*: long features, generally crossing the whole area and extending also outside, that are assumed to represent fracture zones of regional importance.
- *Faults*: discontinuities accompanied by a relative movement of the two blocks involved. In the remotely sensed imagery, these features are usually connected with escarpments present along the Rift borders and over its floor or with evident linear elements visible in the imagery (often affecting drainage) associated with known faults documented in the existing geological maps.
- *Major Fractures*: fairly long features characterized by clear morphological evidences.
- *Lineations*: features of small length and minor evidence.

The statistical elaboration of the data relevant to the fracture analysis provides the following information on the structure for both the areas considered: *Whole Study Area* and *Caldera Sector*.

a. Azimuth Distribution

The azimuth of the linear features, in terms of number and length, can be represented in the form of "rose diagrams", subdivided either by category or by geological unit. The analysis of the azimuth distribution frequencies and of their variability leads to the definition of "Azimuth Sectors", for which it is assumed that the linear features there included are the expression of a discrete structural dynamics. Such structural directions are defined as *trends*.

The diagram of the total field referred to the *Whole Study Area* (Figures 5 and 6a) shows as follows:

- ✓ a clearly predominant N-S direction followed by a NE-SW trend and, subordinately, by a NNW-SSE one.
- ✓ An E-W trend can be also recognized in terms of percentage of length.

The rose diagrams of the four different types of linear features partly confirm these trends, but with some peculiarities:

- ✓ *Lineations* (see Figure 6b) show directions which are generally coherent with the total field;
- ✓ *Major fractures* (see Figure 6c), no specific trend prevails, as the rose diagram exhibits almost equally oriented peaks in all directions, with a slight prevalence of the NE-SW trend;
- ✓ *Faults* (see Figure 6d) show exclusively a N-S trend;
- ✓ *Regional lineaments* (see Figure 6e), two main directions prevail: N-S and ESE-WNW, followed by a less frequent NE-SW.

In the Menengai *Caldera Sector* (see Figure 7), only *lineations* and *major fractures* have been considered, since the number of *faults* and *regional lineaments* was not sufficient for a consistent statistical analysis (see Figures 8a, 8b and 8c). The rose diagram of the total field is very similar to the one of the Whole Study Area, except for a slight increase in the percentage length of linear features along the NE-SW and NNE-SSW directions. Also *lineations* show a diagram almost identical to the total field, confirming the strong influence already seen for the Whole Study Area. The diagram of *major fractures* in the *Caldera Sector* is instead rather different from the global one, since a prevailing trend along the NE-SW/N55E-S55W direction is clearly shown, followed by NW-SE and E-W trends.

b. Density of Linear Features

The distribution of the density of the linear features reflects effects of different origin, mainly the mechanical properties and age of the outcropping formations, as well as the amount and type of structural deformation, which affected these formations. For a correct analysis of the intensity of fracturing, as derived from the density of the linear features, a weight has been attributed to the linear features themselves, in terms of parameters characterizing the suitability of the fractures to allow fluid circulation, namely:

- *Type* of linear feature (lineament, major fracture or lineation), giving a measure of its importance in terms of bedrock involvement.
- *Slope*, intended as a morphological property which affects infiltration and subsurface circulation of the fluids.
- *Stress Nature* (tensional or compressional), which influences the degree of aperture of the fractures and hence its ability to favour fluids circulation.

Whole Study Area - The area showing the highest density of fractures (see Figure 9) appears to be located along a N-S direction in the western part of the Study Area, starting North of the Olbanita Swamps, across the Athinai volcanics, then following the Molo TVA and the eastern part of the Menengai Caldera, to exit West of the Nakuru Lake. Observing the map of total field (see Figure 5) it seems evident that several linear features are aligned along this "belt", mostly regional lineaments and faults, which can probably be related to an important N-S oriented tectonic structure and that explains the high density. Other zones of high density, developed in a N-S direction as well, can be found North and West of the Caldera, corresponding to groups of faults cutting the Rift floor (among these the ones defining the Solai TVA), and in the north-eastern edge of the Study Area on the border hills, mostly related to faults and major fractures.

Caldera Sector - The density map of weighed linear features (see Figure 10) confirms the indications of the other maps, singling out a significant area of high density, located in the western part of the caldera and corresponding to the main N-S tectonic structure discussed above. It stretches from Ol Rongai southwards, inside the caldera, and then crosses the volcanoes of the Makalia Fault Zone. Along this belt, near the southern edge of the caldera, an important zone of fractures concentration is shown, related to the widespread occurrence of faults, major fractures and lineations. Even in this case, the contribute is given mostly by lineations and major fractures.

c. Density of Nodes

The distribution and density of the crossing points of two or more linear features can support the geothermal exploration by giving information on the secondary permeability of the geological formations. For a correct analysis of the intensity of fracturing, as derived from the nodes density, the same criteria used for the linear features density has been adopted, by attributing weights to the parameters related to potential fluid circulation, that is type, slope and stress of the linear features. Through the calculation of the density of the nodal points and the application of weights for the above mentioned parameters, a Density Map of Weighted Nodes has been elaborated for both the Whole Study Area and the Caldera Sector (see Figures 11 and 12).

Whole Study Area **-** The analysis of the map of density of the nodal points for the Whole Study Area (see Figures 12), not considering the Caldera Sector which will be dealt with in the specific map (See Figures 13), shows two main areas with higher density. To the West, several nodes are aligned along a roughly N-S line passing West of the Olbanita Swamp, across the Ol Rongai Ridge and the caldera and ending at the southern border of the caldera itself. The most pronounced nodes concentration occurs around the Olbanita Swamp next to the Athinai Volcanics (bounded by significant faults), at the northern foothills of the Ol Rongai Ridge and south of the Menengai Caldera, in the Makalia Fault Zone. A relatively higher density is also present in the Solai Graben area, to the NE of the Menengai Caldera.

Caldera Sector **-** The map of density of nodal points (see Figure 12) shows local concentrations of nodes near the north-western edge, where an eruption centre is also located, and in the south-western part, along several eruption centres alignment. Both these concentrations seem to represent the continuity in the Caldera Sector of the N-S alignment of nodes previously discussed. Other high density nodes can be found in the northern part of the caldera, but not particularly correlated to eruption centres, and in the eastern part, with a NE-SW trend associated with a major fracture.

MENENGAI STRUCTURAL SETTING

The reconstruction of the structural setting (see Figure 13) of the area has been based on the existing literature, integrated with the results of the interpretation of the aerial photos and satellite images It is reminded that, according to the available information, the structural setting of the area is dominated by the occurrence of N-S systems of tensional type related to the regional stress. The main tectono-volcanic axes (TVA) recognized in the area correspond to the Molo and Solai systems, which are presumed to form a complex graben-horst system.

The Molo system appears to be interrupted in correspondence of the Menengai caldera, while the Solai system cuts the recent pyroclastic deposits, determining the formation of a graben in the eastern extremity of the caldera. At any rate, essentially no tectonic features are reported within the caldera itself.

As mentioned above, the remote sensing study was focused towards the recognition and classification of the *Volcanic Landforms* and the *Analysis of the Linear Features* in terms of orientation and intensity.

As refers to the classification and recognition of the *Volcanic Landforms*, mention should be made of the probable presence of a calderic structure, in addition to the one corresponding to the Menengai caldera. This caldera, located to the NW of Menengai and visible only along its western rim, has an estimated diameter of about 12 km and is interpreted as derived from the emission of ignimbrites from vents centred south of the Olbanita swamp. This inferred caldera has been therefore named “Olbanita caldera” and is deemed to have developed much earlier than the Menengai caldera, that is 0.3-0.5 Ma ago (Geotermica Italiana, 1987). The existence and characteristics of the Olbanita caldera are not due to directly affect the exploration strategy for the Phase I Menengai development, but are obviously of major importance for Phase II.

Moreover, it appears evident that the so called “shield volcano” is actually constituted by two separate edifices, one of them encompassing the whole Menengai caldera and the other corresponding to the N-S oriented Ol Rongai chain.

The main findings of the analysis of the *Linear Features Orientation*, illustrated by the above described azimuth distribution diagrams, are summarized here after:

- As expected, the rose diagram of the total field relevant to the whole investigated area shows a predominant N-S direction, followed by less conspicuous NE-SW, NNW-SSE and E-W trends.
- The N-S trend is especially predominant in the faults category, thus reflecting the structural style of the Kenya Rift Valley, in particular north of the Menengai caldera. On the other hand, the NNW-SSE trend exhibits a pronounced frequency of the regional lineaments, expressed by a series of long-linears, which cross the whole study area with a spacing of about 10 km.
- The rose diagrams referred to the specific caldera sector show some significant differences, especially in the category of major fractures, where there is a clear predominance of the NE-SW/ENE-WSW trend and subordinately of the NNW-SSE and E-W trends. The N-S trend is represented mainly by the Solai TVA, which affects the eastern border of the caldera.
- The NNW-SSE trend seems to be responsible for the alignment of eruption centres both within the caldera and in the Ol Rongai area. Another alignment of eruption centres recognized within the caldera appears to be controlled by the NE-SW trend.
- The E-W trend, expressed by a long-linear extending between wells MW-07 and MW-03, seems to partly control the distribution of the secondary mineralogy and the areal extent of the reservoir.
- It is interesting to observe the high density of linear features in the interior of the Menengai caldera, which in the previous studies seemed to be essentially unaffected by tectonic evidences. These linear features, recognized mostly through aerial photos interpretation, are largely transversal to the regional N-S trend and may be partly correlated with the calderic collapse. They affect the very recent volcanic products, pointing to their young age and to the presence of intense neo-tectonic activity.
- The most conspicuous structure identified through direct observation corresponds to a NNW-SSE fault crossing the whole caldera floor and associated with a downthrow of the eastern block. Possibly another fault, sub-parallel (N.7W-S.7E) and some 4 km to the west of the former structure, passes across the caldera and extends outside of it, controlling the location of the Ol Rongai eruption centres. These two faults seem to delimit a structural unit, characterized by an echelon style, where all the wells drilled up to date except MW-07 are located.
- It is interesting to observe the close correlation between these two major structures and the distribution of the seismic events, as identified through the micro-seismic monitoring. It may be observed in fact that the sector of

strongest concentration of these events is about 5 km wide, being delimited on both sides by the N.7W-S.7E and NNW-SSE faults.

- The NW-SE and NE-SW lineations observed in the caldera have presumably a tensional character and have accordingly a direct bearing on the permeability of the formations.

As refers to the *Intensity of the Linear Features*, as expressed by their density and by the density of the weighted nodes, in the whole study area anomalous intensities are observed, albeit not very clearly, along the Solo and Molai TVA, following a general N-S direction and extending also south of the Menengai caldera. It is worth mentioning that the analysis of the linear features density allows to define also the border of the Olbanita caldera located NW of the Menengai caldera.

For what concerns the specific Menengai caldera sector, the linear features intensity (weighted nodes density does not provide any useful contribution) exhibits anomalous density values in three specific sectors, namely:

1. The above mentioned NNW-SSE fault crossing the eastern sector of the caldera.

2. The above mentioned N.7W-S.7E fault that extends outside of the caldera up to the Ol Rongai eruption centres.

3. The N-S faults cutting the eastern extremity of the caldera and belonging to the Solai TVA.

Such correlation between major structural elements and linear features density provides a form of confirmation of the hypothesized structural setting of the Menengai area.

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FIGURES

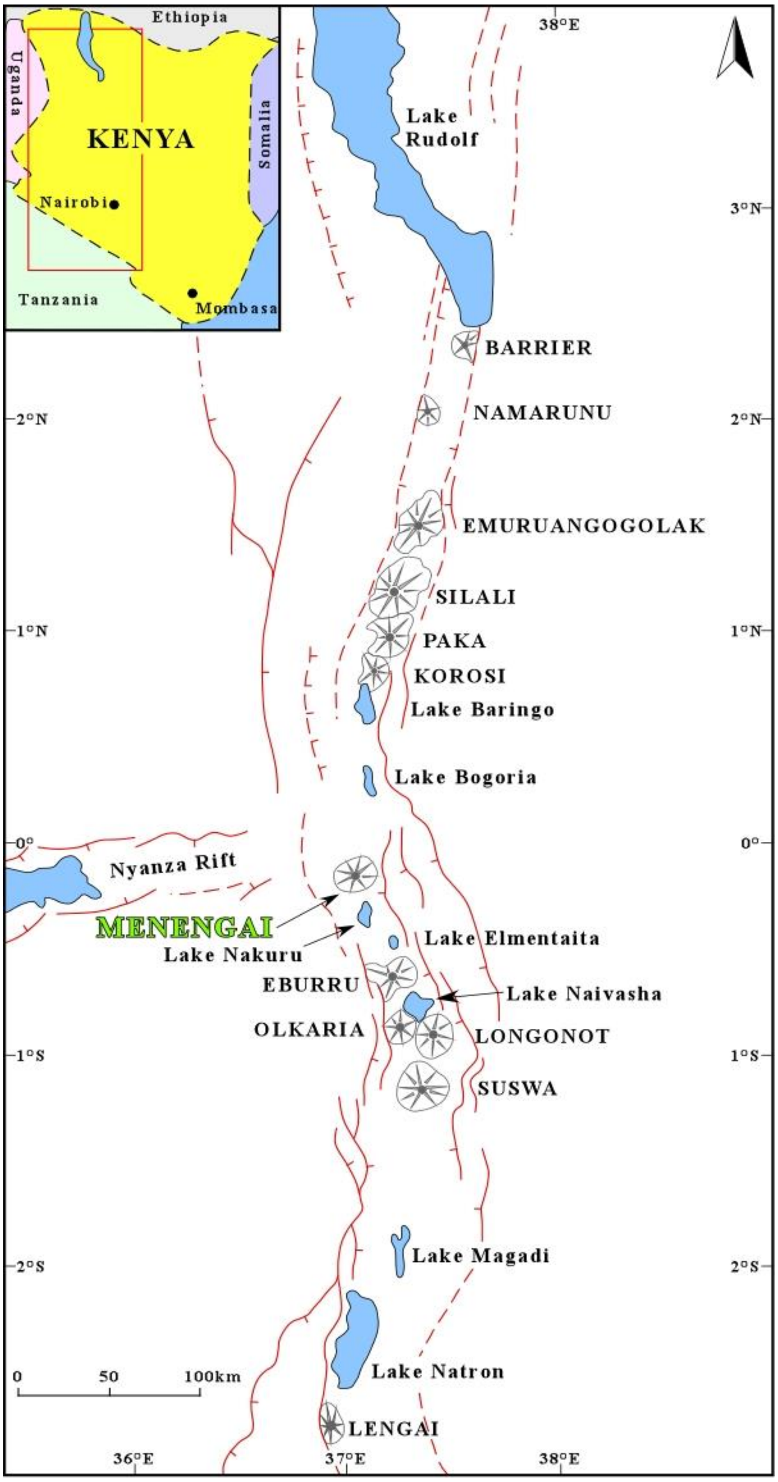

Figure 1 - Kenyan Rift Valley

Figure 2 - Whole Study Area using as Graphical Base a TERRA ASTER VNIR (FCC RGB 1,2,3 - Acquired: 2002-12-18)

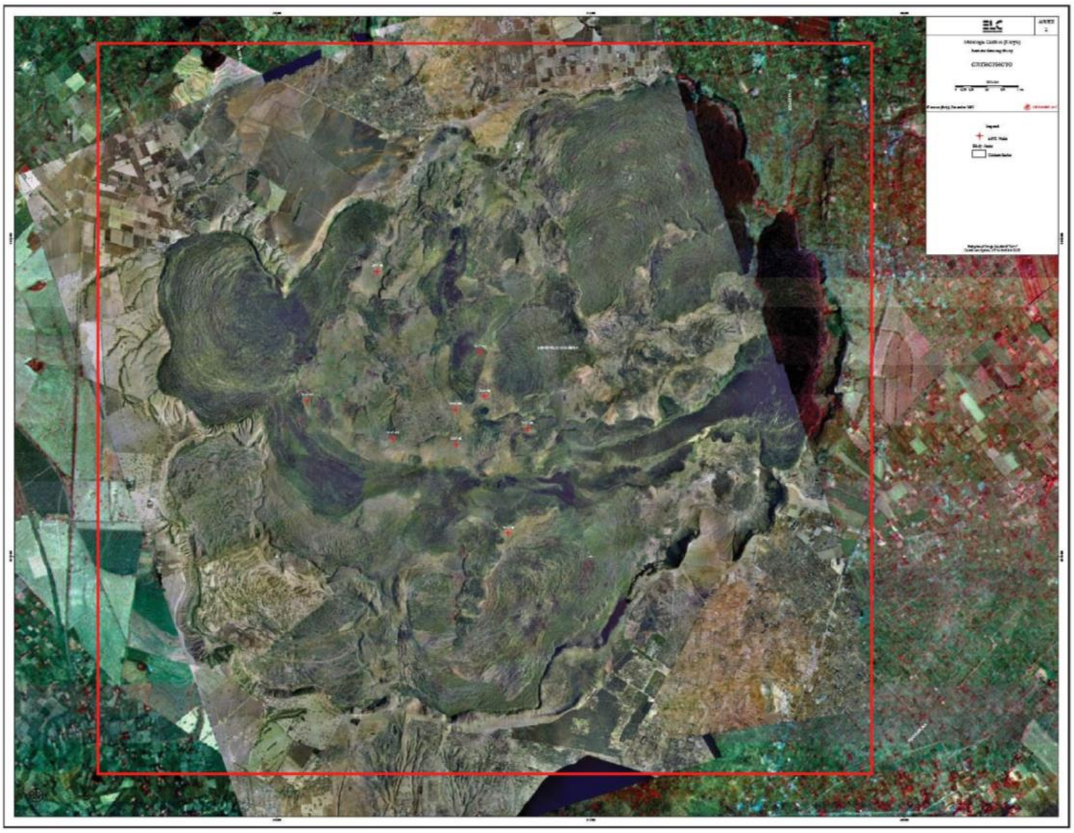

Figure 3 - Caldera Sector Using as Graphical Base a True Colour Orthophoto Generated by the Mosaic of Aerial Photos

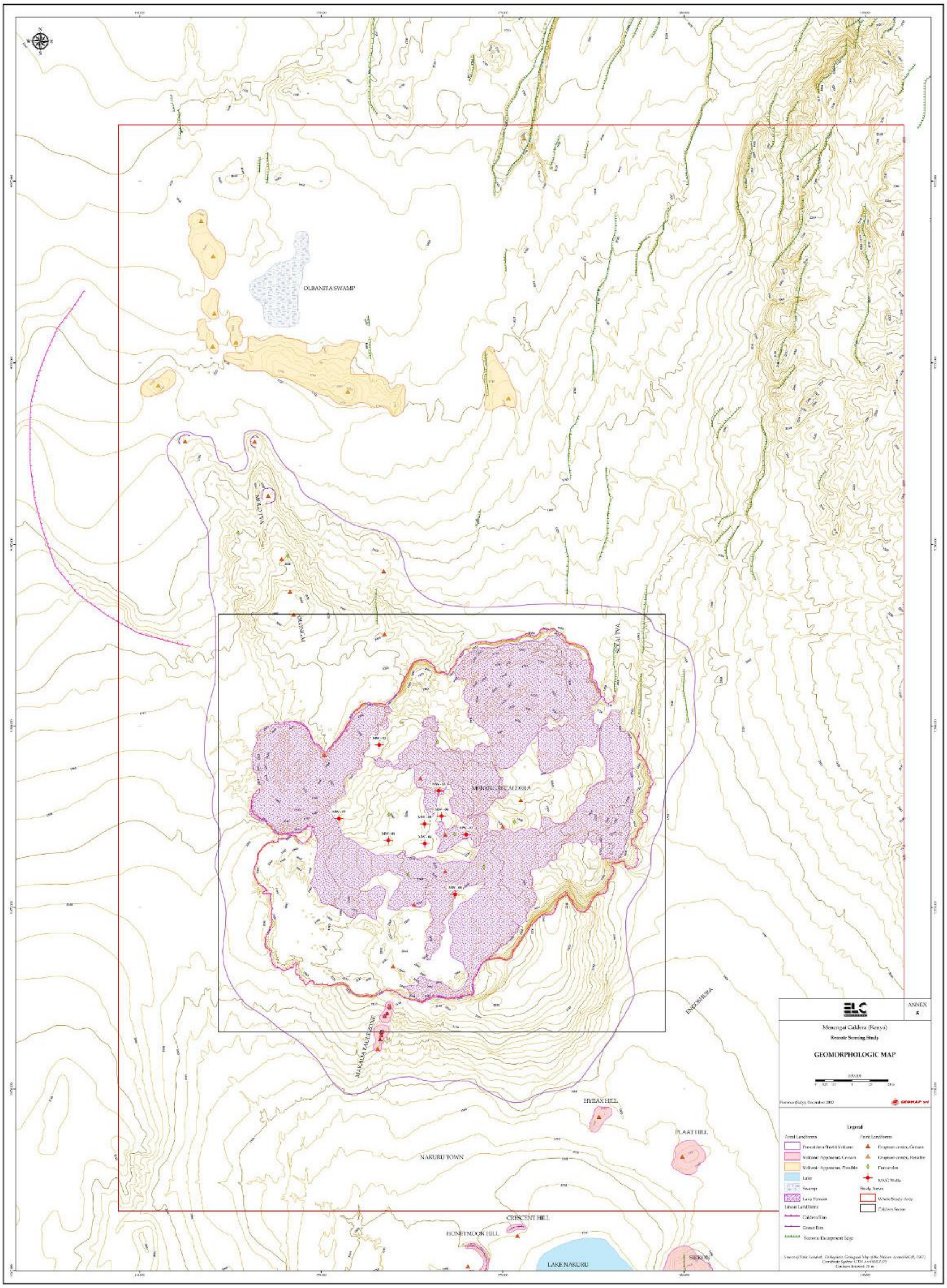

Figure 4 - Geomorphological Map

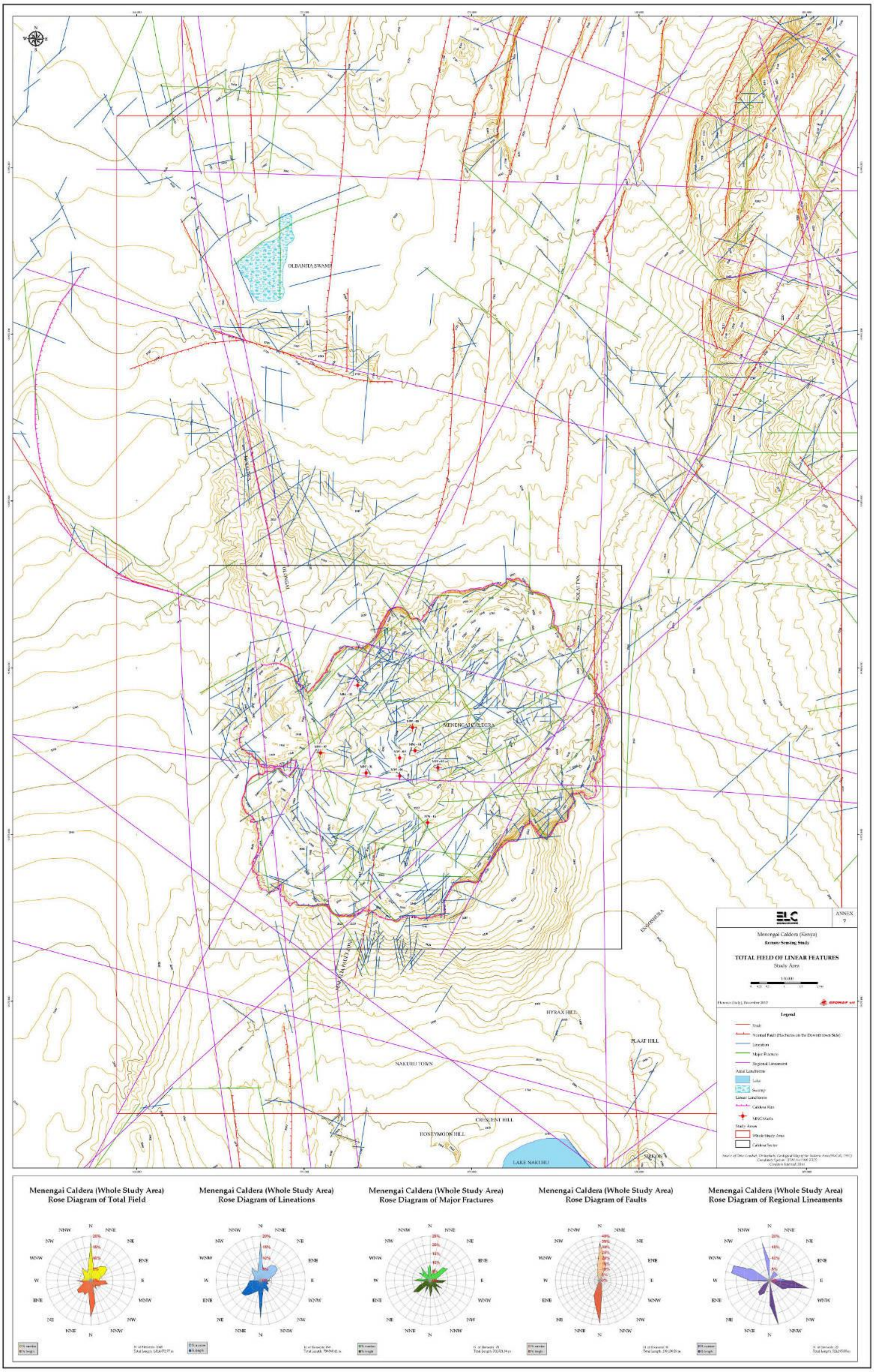

Figure 5 - Total Field of Linear Features for the Whole Study Area

Figure 6a-e - Rose Diagrams of the Total Field of Linear Features for the Whole Study Area

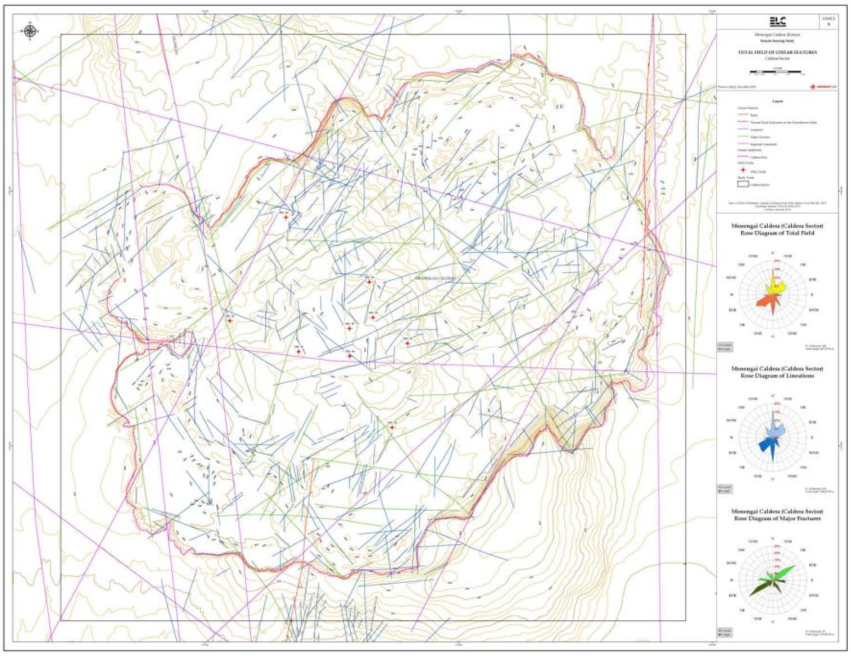

Figure 7 - Total Field of Linear Features for the Caldera Sector

Figure 8a-c - Rose Diagrams of the Total Field of Linear Features for the Whole Study Area

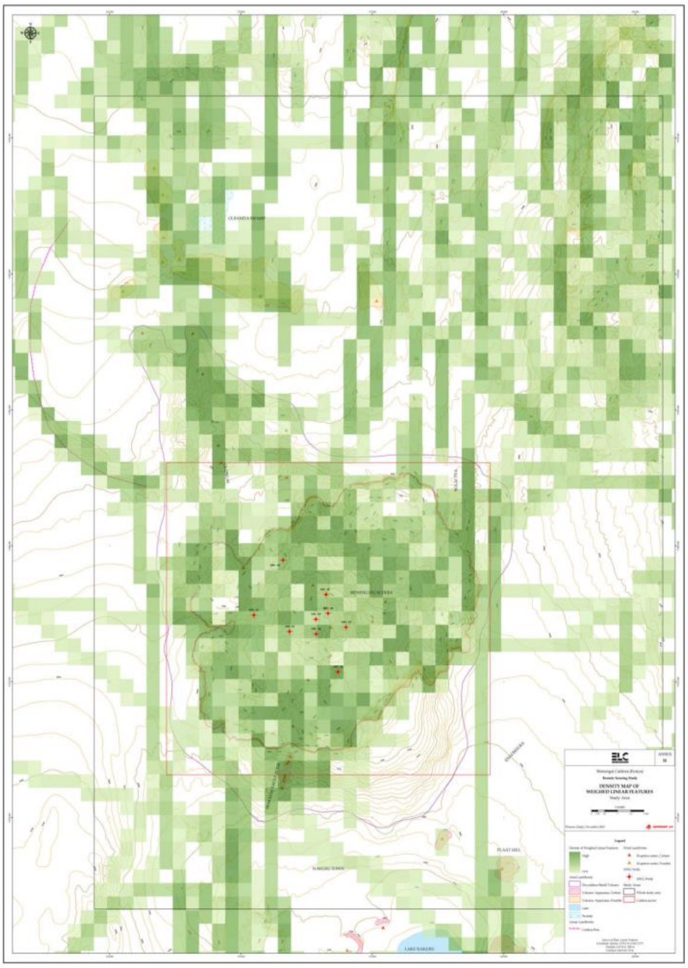

Figure 9 - Map of Density of Weighed Linear Features for the Whole Study Area (size of the pixel 500x500 m)

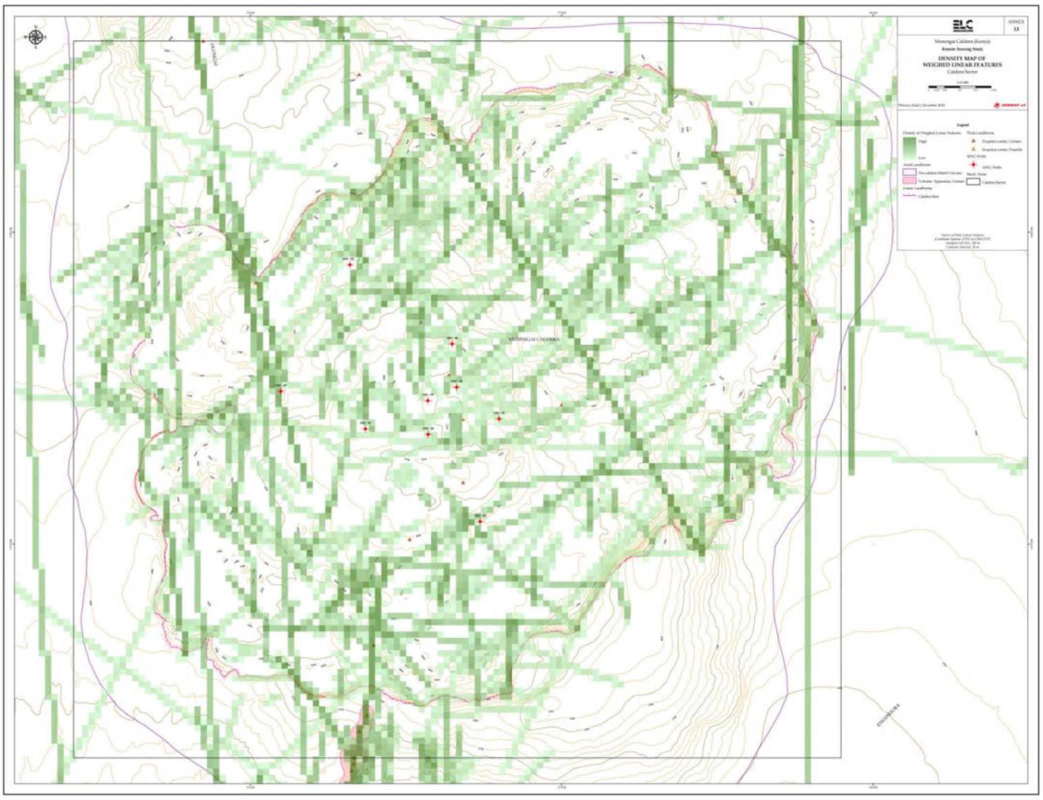

Figure 10 - Map of Density map of Weighed Linear Features for the Caldera Sector (size of the pixel 100x100 m)

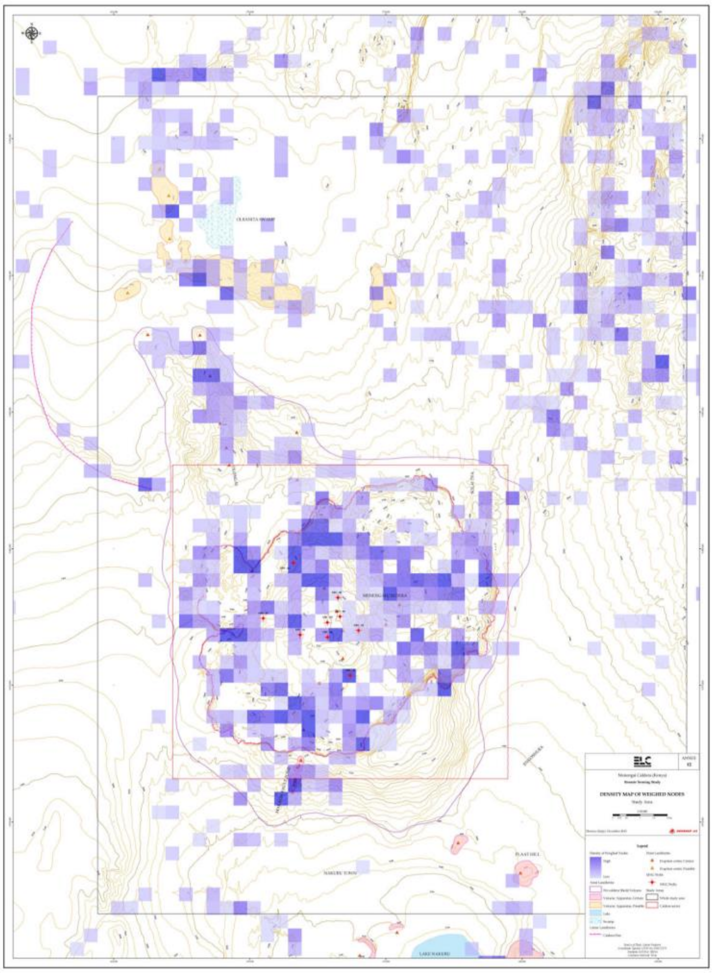

Figure 11 - Map of Density of the Nodal Points for the Whole Study Area (size of the pixel 500x500 m)

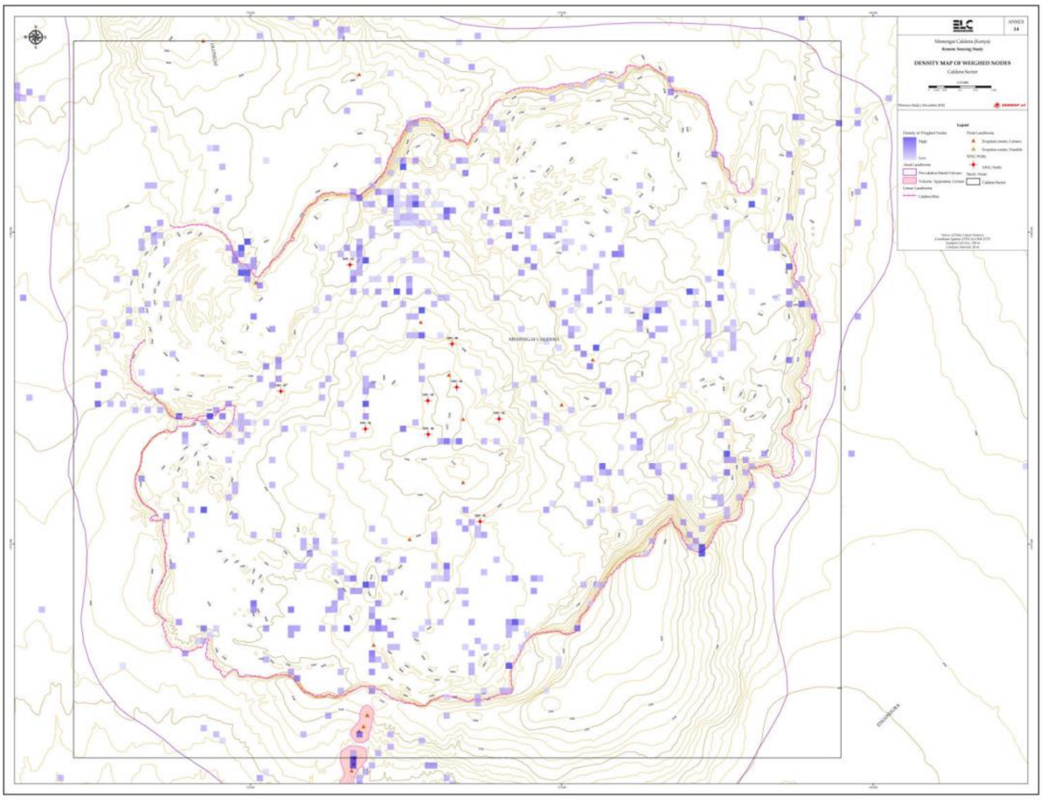

Figure 12 - Map of Density of the Nodal Points for the Caldera Sector (size of the pixel 100x100 m)

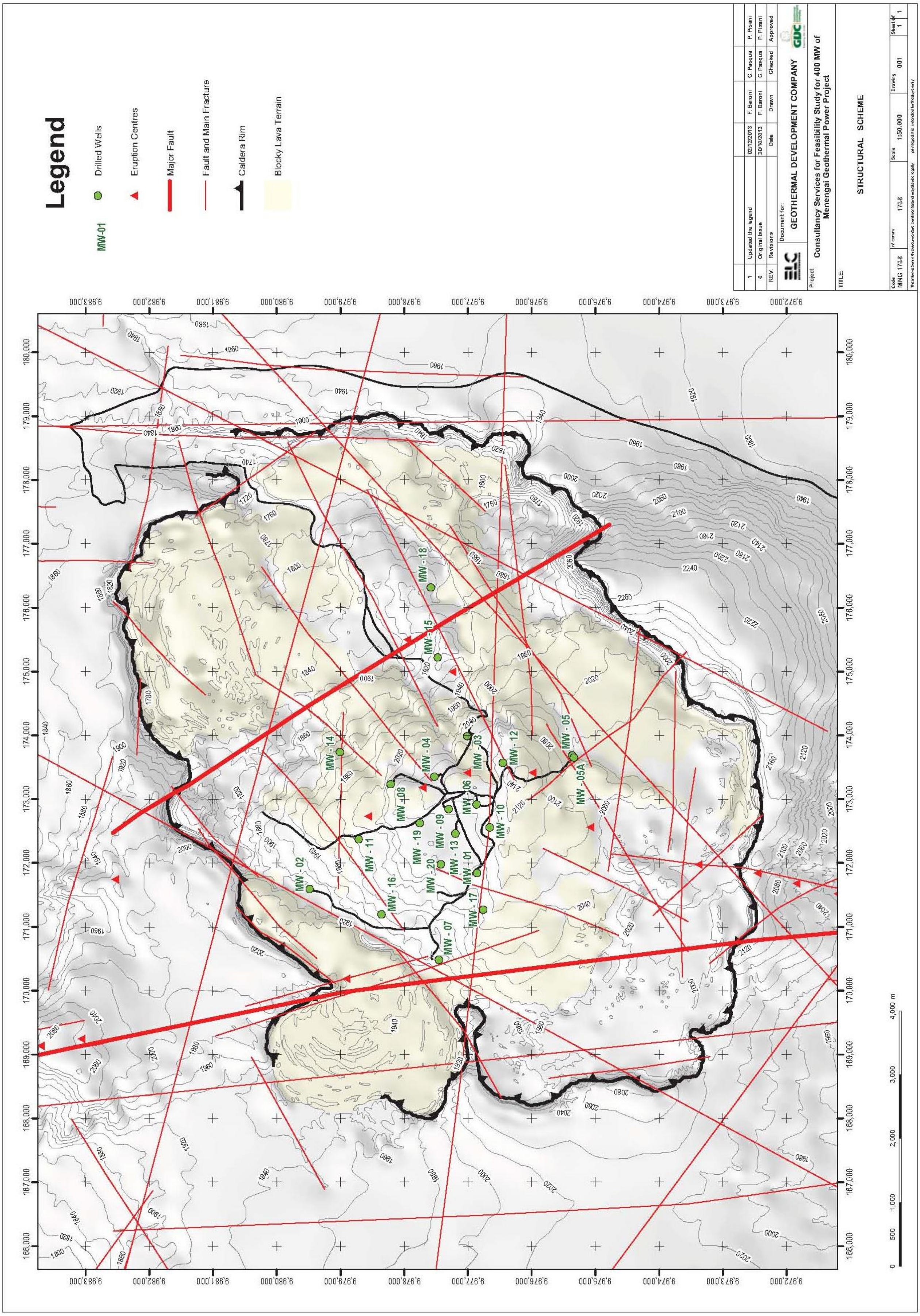

Figure 13 - Structural Scheme of Menengai Geothermal Prospect