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Remote Sensing: Structural- and InSAR Analyses for a Geothermal Exploration Programme in Northern Tanzania

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ABSTRACT

Available data supporting a geothermal exploration programme in Northern Tanzania in a large scale is extremely limited. In addition, field surveys are complicated by inaccessibility, steep terrain and dense vegetation cover, particularly at Mount Meru volcano.

A combination of remote sensing methods was employed to overcome this problem and figure out an area for further investigations:

A structural analysis based on multispectral satellite data as well as on high and medium resolution digital elevation models (DEMs) was conducted to identify geological units and tectonic features.

Spaceborne Radar Interferometry (InSAR) supplies an excellent method for the detection of vertical ground movements in the range of a few millimetres per year. InSAR was employed to identify hotspots of ground movements, which can indicate enhanced permeability for (hydrothermal) fluids and hydrothermal and magmatic activities.

The structural analysis is the basis for the interpretation of the InSAR-processing results. The mapped lineaments represent faults, strongly connected to the youngest movements of the ongoing rifting of the Neogene rifts. Faults of WNW orientations dominate the Mt. Meru volcanic complex. Along these orientations, young hydrothermal alterations occur in the crater of the central ash cone as the youngest eruption centre.

The InSAR analysis shows linear zones of subsidence up to 13 cm per year at Mt. Meru, which follow the trends of existing faults and seem to be lineament-controlled. Considering

the combined results of these remote sensing studies, an area for further investigations can be suggested ESE of Mt. Meru.

1. Introduction

Within the bilateral project “Geothermal Energy Development Tanzania” between BGR and Tanzanian Partners, the scope of the work lies upon the identification of a reservoir for geothermal energy at Mount Meru. By this time, available data, supporting a geothermal exploration programme in Northern Tanzania at a large scale is extremely limited. A first step should be the localisation of an appropriate area for in-depth investigations.

Besides a proper heat source, sufficient permeability for hydrothermal fluids is indispensable for a geothermal prospect. In areas dominated by non-porous crystalline rocks, the main pathways for those fluids are deep fractures like faults. These structures can be detected as lineaments at the earth´s surface and reflect underground dynamics. An area where lineaments of different orientations intersect offers strongly increased permeability and should be most promising for further prospection

As vast parts of the working area are vegetated, steep and difficult to access, remote sensing in combination with focused ground truth is an excellent approach to meet the requirements for structural mapping.

The structural analysis is based on high- and medium resolution digital elevation models (DEM) and multispectral data. It improves the tectonic/geological understanding of the working area. Faults of different orientations, which can act as pathways for hydrothermal fluids can be detected as lineaments at the earth´s surface.

Spaceborne radar data routinely cover huge areas, and Radar Interferometry (InSAR) processing constitutes an excellent method for the detection of ground movements at a scale of millimetres per year. In combination with structural analyses, InSAR data can help to find locations of enhanced permeability for (hydrothermal) fluids and can also give hints for hydrothermal- and magmatic activities.

2. Previous work

2.1 InSAR

Advanced interferometric SAR (Synthetic Aperture Radar) processing techniques are able to detect and monitor various surface displacements with mm accuracy.

A radar echo contains both amplitude and phase information. Most imaging radar applications use algorithms that utilize only the amplitude to extract physical surface characteristics. SAR interferometry (InSAR) exploits the phase difference between two radar echoes, associated with the same surface object, but measured by two different systems (or different times, respectively) along different directions. Measurement of such a phase difference is known as interferometry (Fig. 1). Radar Interferometry allows to measure surface elevation of individual image pixel, which leads to the generation of DEMs. The Radar phase of different images is sensitive to motion, (Fig. 1), which makes it possible to detect ground motion with an accuracy within millimetres per year via the radar´s phase shift.

Therefore, Radar interferometry is also used to measure surface motion. InSAR techniques either use a pair of images to generate short interval motion (e.g. earthquakes) or a set of data is collected to process motion in time (e.g. volcanic activities, mining, ground water exploitation) Ulaby, F.T. & Long, D.G., (2014).

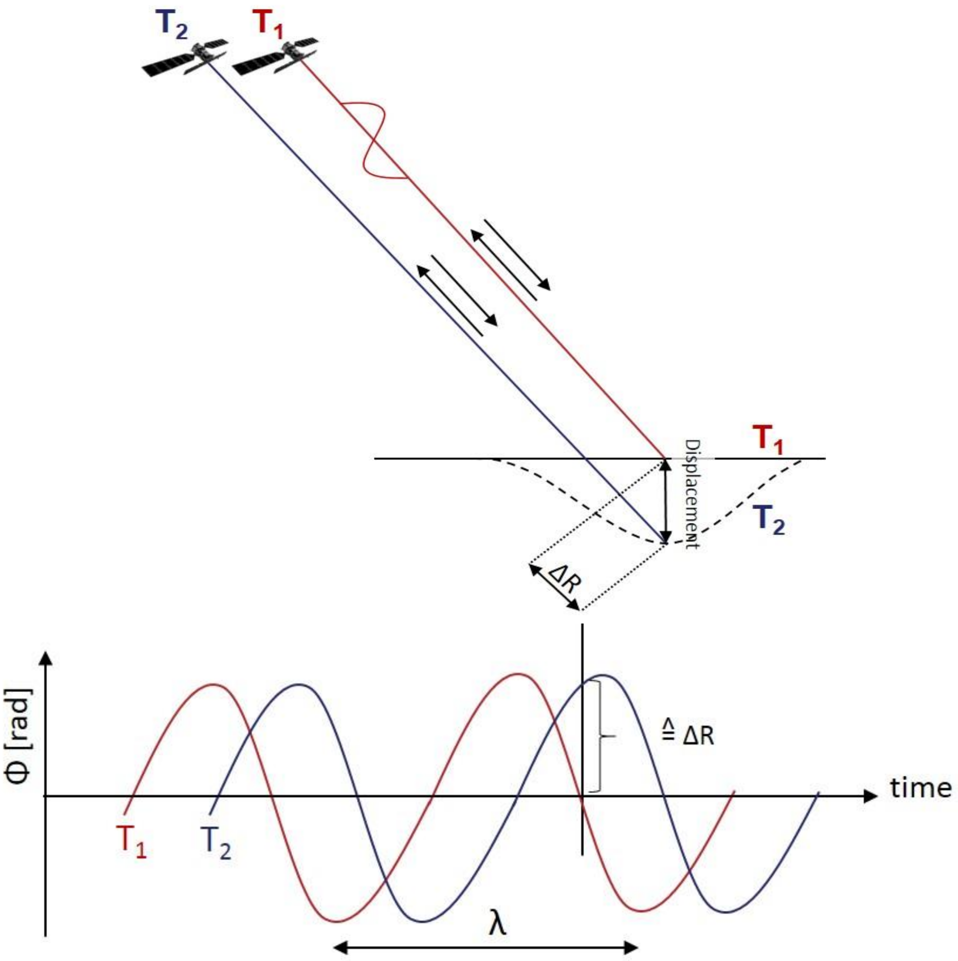

Figure 1: InSAR exploits the phase difference of at least two SAR images to detect vertical ground movement. T1 = time of acquisition for the first image, T2 = acquisition time for the second image, λ = wavelength, ΔR = range difference distance.

3. Methods

3.1 Structural analyses

For structural analyses, shaded relief DEMs (SRTM 30 m ground resolution, TerraSAR-X WorldDEM 12 m resolution) as well as geocoded multispectral satellite images (Landsat TM and Landsat OLI both 30 m resolution) were used. After appropriate image enhancements for lineament detection (e.g. high pass filtering and histogram stretching), the images were transferred into a GIS. The combination of these datasets yields best conditions for further lineament mapping.

3.2 InSAR analyses

For our study at Mount Meru, the most suitable algorithm for InSAR processing was the Small Baseline Subset (SBAS, Beradino et al., 2002), as this method delivers also reliable results in vegetated areas, where others would fail due to lacking scatterers (e.g. persistent scatterer interferometry, PSI).

The method is based on the combination of differential interferograms and allows the computation of a time series of the deformation and is especially suitable for vegetated areas. The SBAS method allows a time series analysis to detect non-linear surface deformations.

We used 24 RADARSAT-2 scenes of the ascending path in “wide fine” beam mode and horizontal-horizontal (HH) polarisation (RADARSAT-2, 2016). The resulting ground resolution is 10 metres. The maximum small baseline is 96 days and the entire scene size of 176 km x 176 km is processed to get sufficient stable reference points. Stable areas are characterised by relatively high coherence (in our case better than 0.25) and are mainly located in topographically flat parts of the scenes. In those areas, assumed to be stable, ground control points are set manually. All observed ground motions are relative to these stable points. The resulting velocity maps are described and interpreted in section “results”.

The relatively short period of Radar-measurement (2013/07/28 to 2015/04/13) as well as surface conditions like vegetated areas and soft structures is a challenge for the detection of ground movements using Radar interferometric methods. The SBAS-algorithm however reveals good results for the further interpretation of subsidence features.

The quality of the data processing can be validated, as Lake Manyara (outside the working area) is also covered by the used Radar scenes. The subsidence observed for this area is well known and documented by authors using different remote-sensing and in-situ methods (Deus, D. et al., 2013).

4. Working Area

The core working area for the geothermal exploration programme comprises Mt. Meru and its closest vicinity (Fig. 2, yellow frame; Fig. 3). Mount Meru is an active volcano with an extensive eruptive history into the first half of 20^{th} century. InSAR analyses are focused on this core area (Fig. 3), whereas the structural analysis, which supports the interpretation of InSAR results, incorporates the wider area with its variety of tectonic features (Fig. 2).

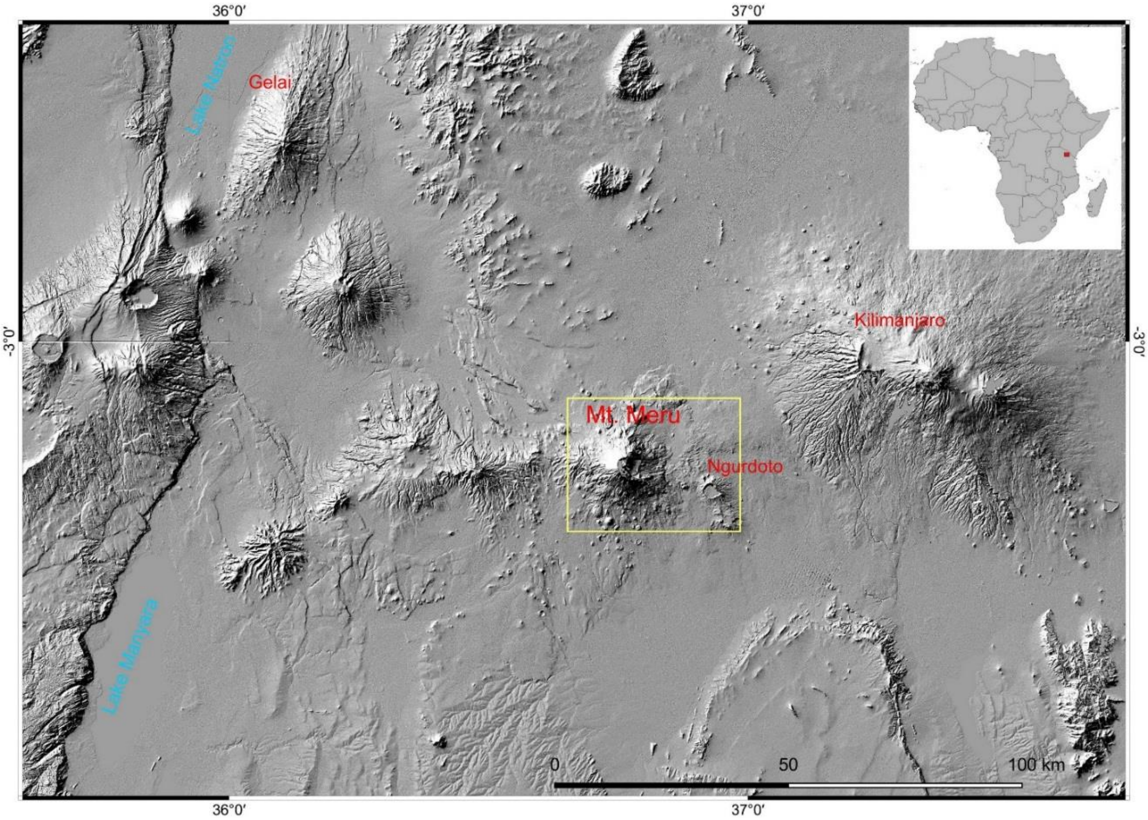

Figure 2: The wider working area and location of Mt. Meru core working area (yellow frame) in Tanzania. 30 m SRTM elevation model shaded relief.

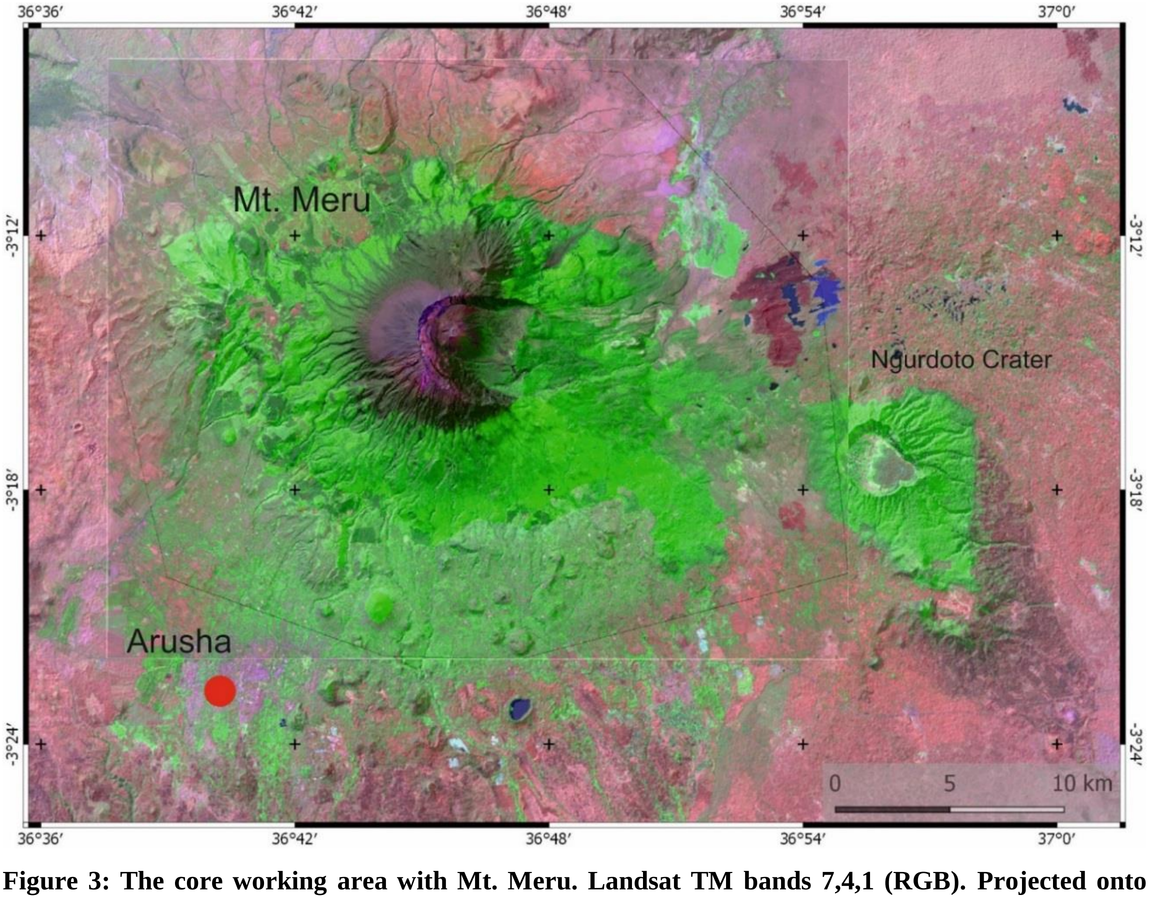

Figure 3: The core working area with Mt. Meru. Landsat TM bands 7,4,1 (RGB). Projected onto high resolution 12m TerraSAR-X WorldDEM (Mt. Meru area only) and 30m SRTM DEM shaded relief.

5. Tectonic setting

The core working area around Mount Meru is situated in the Northern Tanzanian Divergence Zone and is built up on Precambrian rocks of the Tanzania Craton (Archaean) and the north-south trending Mozambique orogenic fold belt (Archean/Proterozoic) Beeckmans, B. (2014), Dawson, J. B. (2008). Three distinct rifts with different orientations dominate the working area in the Northern Tanzanian Divergence Zone (Foster et al., 1997):

1. The Natron-Manyara-Balangida Rift (N-S-trending),
2. the Eyasi-Wembere Rift (NE-trending) and
3. the Pangani Rift (NW-trending).

The rifts are named after the lakes, which have developed on the rift bottoms. They transect the lithospheric boundary between the Archean (Tanzania Craton) and the Proterozoic (Mozambique orogenic fold belt), (Fig. 4). An example of tectonics of Archean rocks is shown in figure 4, where multiphase folding is observed (orange lines). The NW trending Pangani Graben is built up by rocks of the Proterozoic Mozambique orogenic fold belt.

The orientations of the major rifts and of volcano chains (Fig. 4, yellow stripes) are variable and display the changing tectono-magmatic conditions, resulting from an interplay between:

- The regional stress field,
- the local magma-induced stress field and
- stress rotations by mechanical interaction of rift segments (Muirhead et. al., 2015).

The intrusion of aligned volcanic-chains (Fig. 4) widely follows Precambrian basement structures and (reactivated) faults.

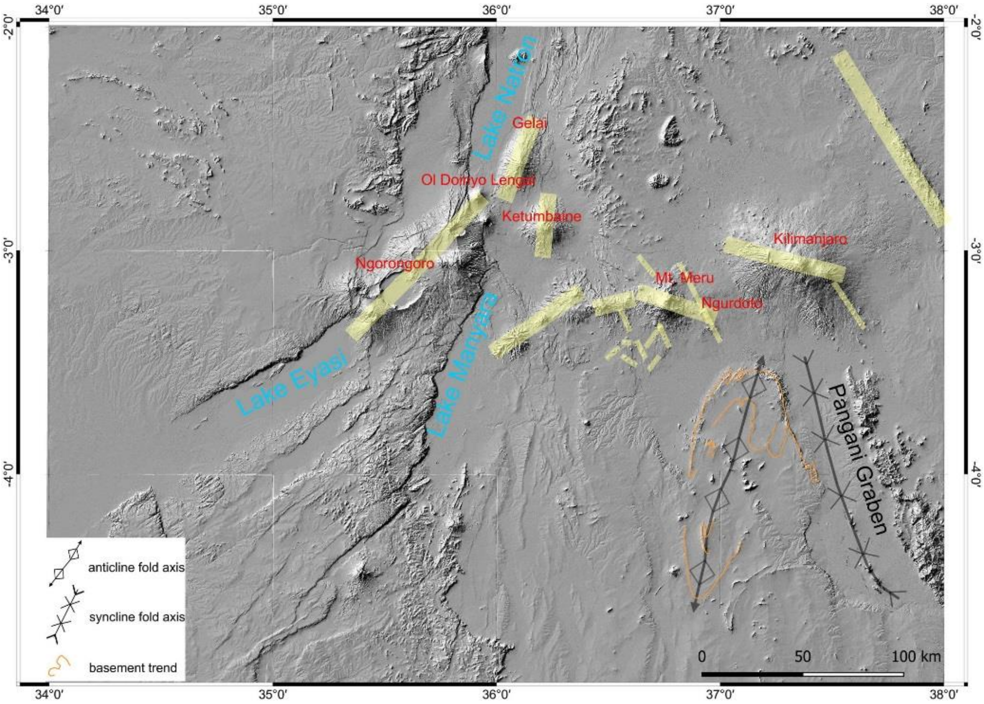

Figure 4: Variable orientations of aligned volcanoes (yellow stripes showing examples). Their intrusion widely follows Precambrian basement structures and (reactivated) faults. One example for Archean basement structures, which shows multiphase folding is highlighted by orange lines. The NW trending Pangani Graben is built up by rocks of the Proterozoic Mozambique orogenic fold belt. Shaded relief SRTM DEM mosaic.

6. Results

6.1 Lineaments

The majority of the mapped lineaments represent faults (Fig. 5). Wherever possible, "normal faults" were distinguished from other "lineaments". They are strongly connected to the ongoing rifting of the Neogene rifts. Normal faults impressively offset older shield volcanoes e.g. Gelai and Ketumbaine (Fig. 6). This faulting follows a NE direction at Gelai and turns to a NW direction slightly farther south at Ketumbaine, displaying the change of the structural trends of the Precambrian basement.

Some lineaments form X-shaped conjugated faults, displaying the regional stress field and the present opening direction of the Natron-Manyara-Rift. This direction most likely displays the recent dominant rifting (Fig. 5).

Lineament mapping was focused to the core area of Mt. Meru and to a certain extent also to the surrounding area outside Mt. Meru (extended area) to examine and exemplify fault- and lineament directions in a larger framework (Fig. 7). All directions of the dominant rifts (Pangani Graben, Natron-Manyara and Lake Eyasi) are reflected also inside the working area. The orientations of the assumed normal faults were not considered in the rose diagrams. The rose diagrams are not weighted by lineament lengths.

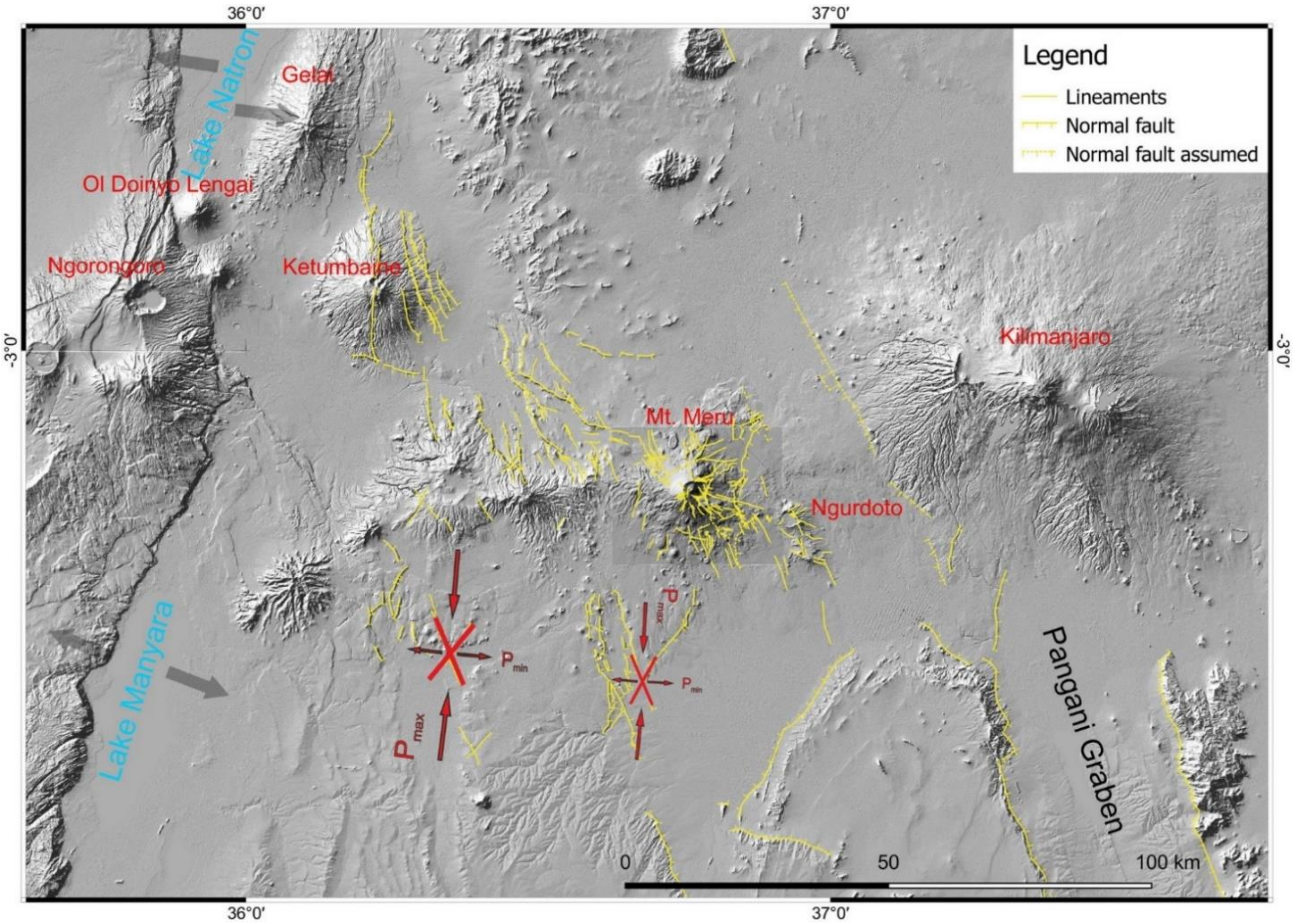

Figure 5: Examples of lineaments and normal faults in the wider area of Mount Meru. Shaded relief SRTM DEM mosaic. The directions of maximum principal stress are displayed as X-shaped stress indicators (red lines). The acute angle between conjugated faults (red lines, two examples) is bisected by the maximum principal stress direction (Pmax). Effective minimal principal stress direction (Pmin) corresponds approximately to the opening direction of the Natron-Manyara-Rift (grey arrows).

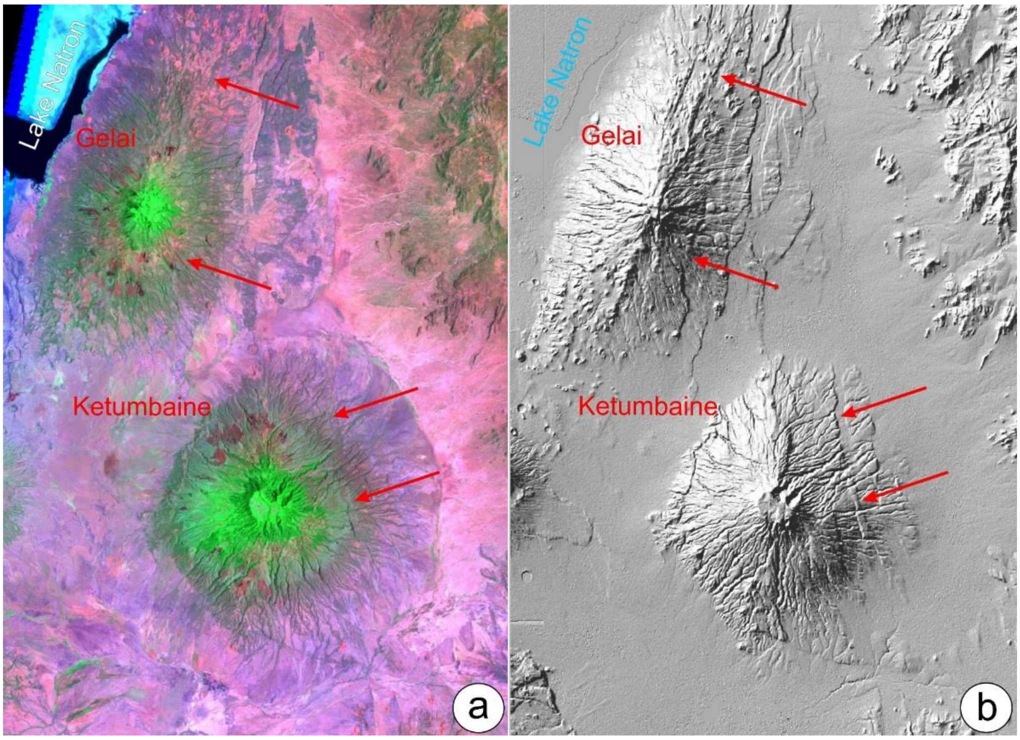

Figure 6: The shield volcanoes Gelai and Ketumbaine are offset by normal faulting (red arrows showing examples), which turns from a NE- at Gelai to a NW direction at Ketumbaine (red arrows). This can be attributed to a change of the structural trend of the Precambrian basement. a): Landsat TM bands 7,4,1 (RGB) supply spectral information about the surface´s character: "false colours" e.g. cyan: salt crust of Lake Natron, black: clear water, pink: bare rock/soil. green: vegetation. b): shaded relief 30m SRTM DEM enhances structures like faults (red arrows, examples).

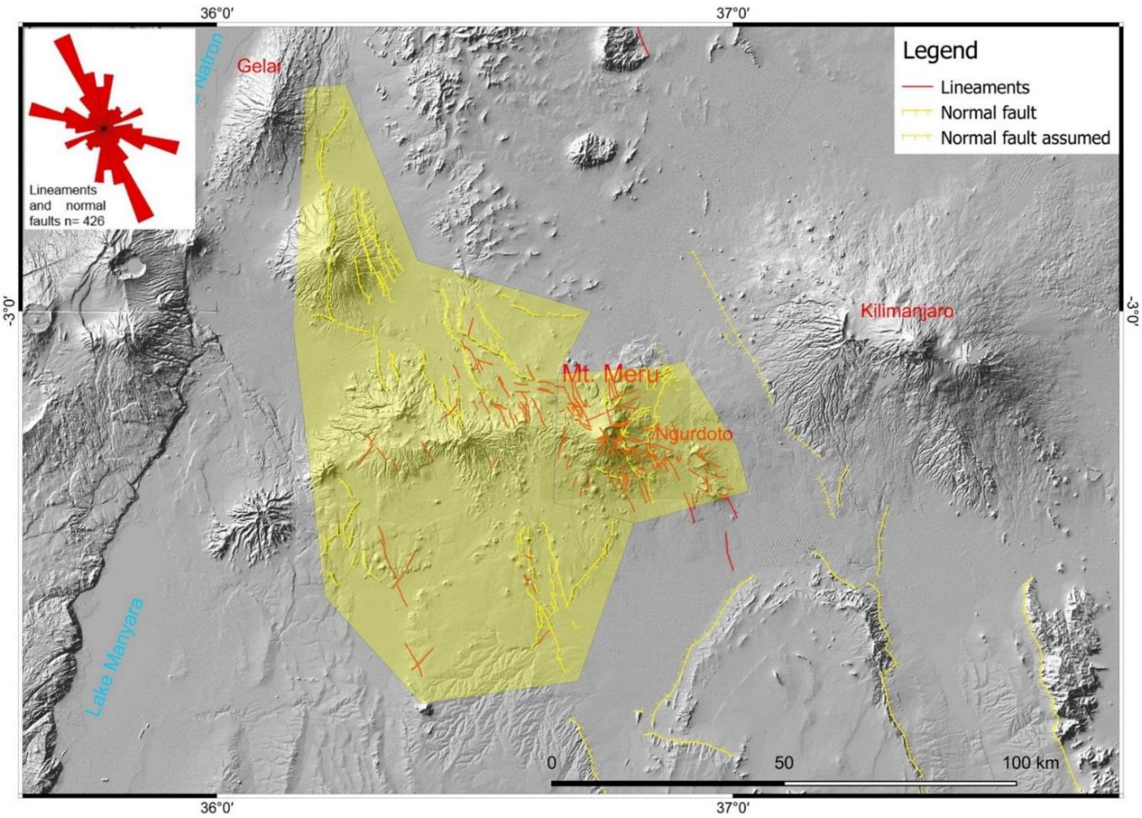

Figure 7: Lineaments and normal faults (n = 426) with rose diagram of the extended and core working areas (yellow polygon).

The Mt. Meru core area is affected by all orientations of reactivated faults, which can also be found in the surrounding area. WNW-ESE orientations are dominant. This orientation shows hydrothermal alterations in the inner central ash cone (Fig. 8).

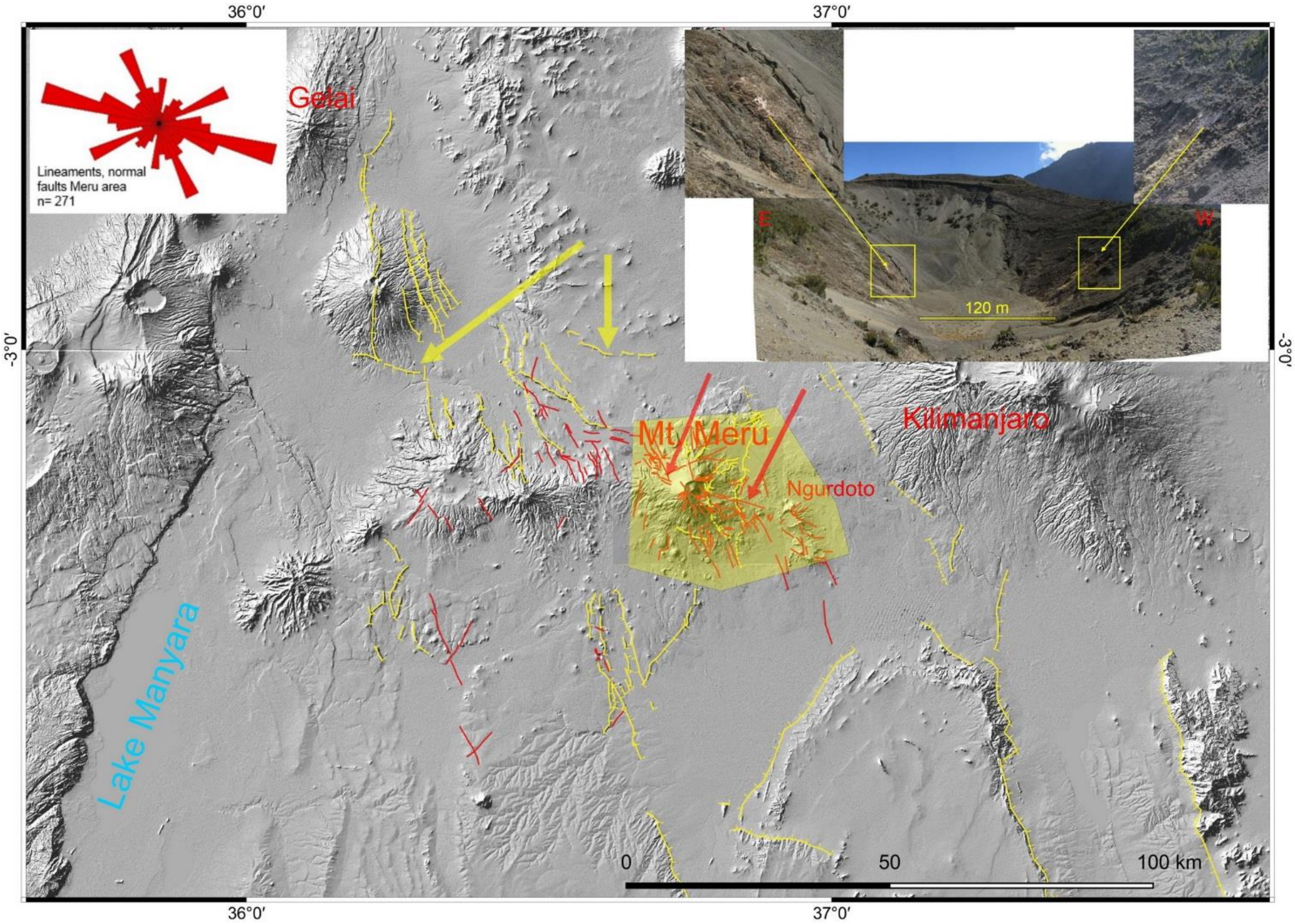

Figure 8: Lineaments and normal faults (n = 271) with rose diagram of the Mt. Meru "core area" (yellow polygon). WNW-ESE orientations dominate this area (arrows). The inset shows hydrothermal alterations in the central ash cone corresponding to this direction.

6.2 Ground Movements

InSAR analysis showed pronounced subsidence of up to 136 millimetres per year at the south-eastern part of Mount Meru, a phenomenon that was not observed in other parts of the wider area. The areas of subsidence occur as clusters, which form elongated zones (Figures 9 and 10a). Most of these zones are not directly associated with individual mapped lineaments, although they follow the overall orientations indicated by lineaments (e.g. normal faults, graben structures) and volcanic chains at other locations of the wider Mt. Meru area (Figure 10b).

It is most likely, that neotectonics (i.e. the ongoing rifting) are the main factor for the development of these linear zones of subsidence. However, it is possible, that changes of the surface hydrology also contribute to the observed ground motions to a certain degree and interfere with tectonically induced subsidence.

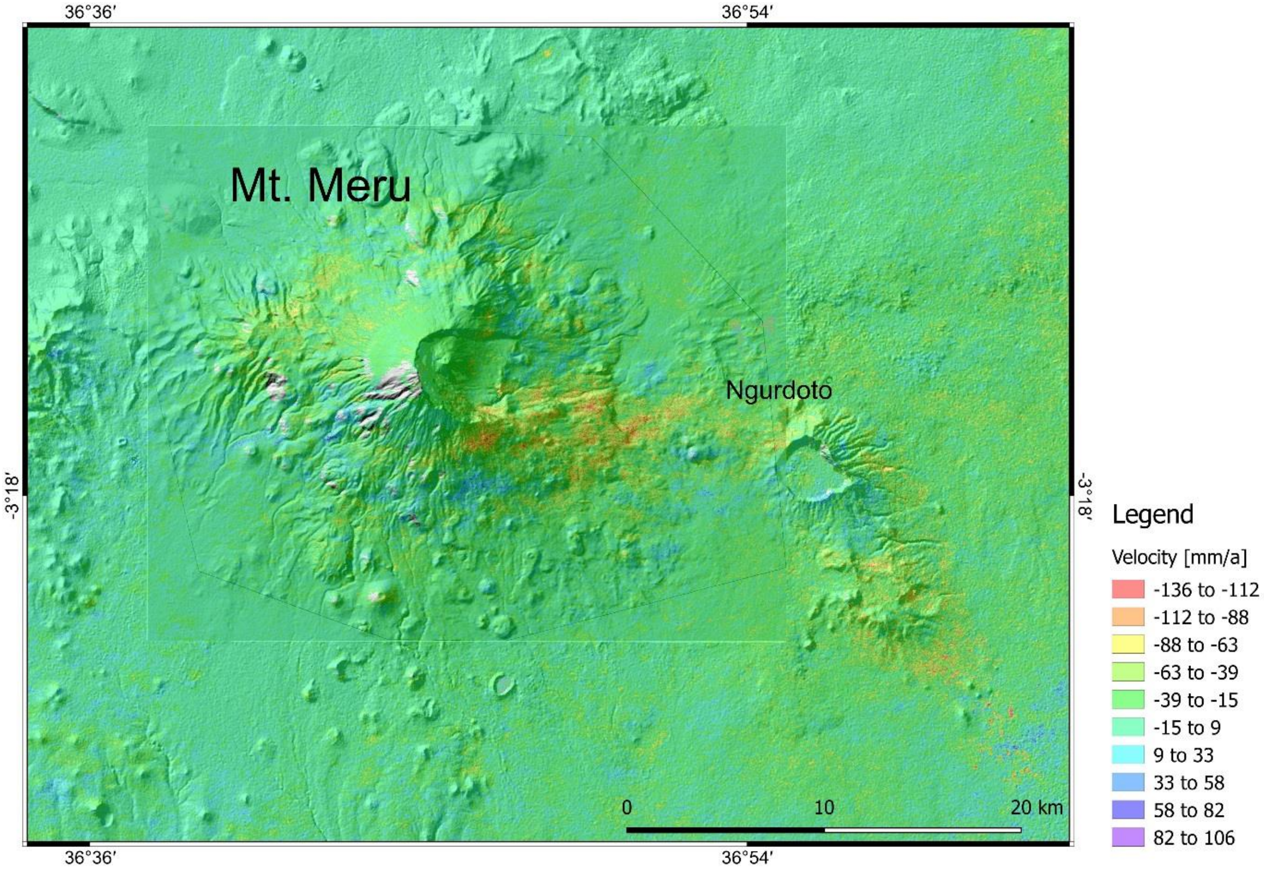

Figure 9: Displacement map projected onto shaded relief DEMs for better orientation. Elongated clusters of subsidence (red, orange) mainly occur SE of Mt. Meru.

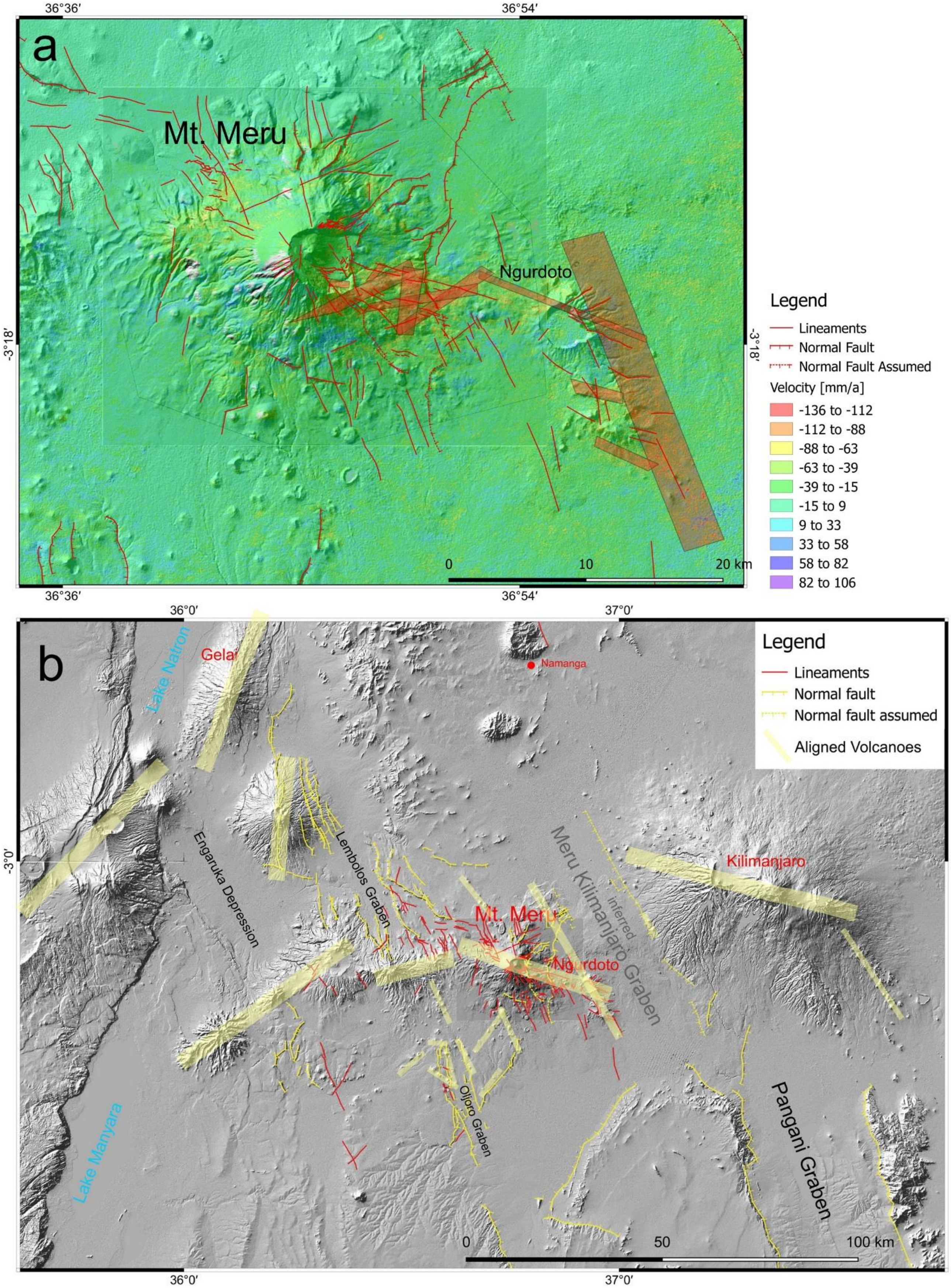

Figure 10: a) Clusters of subsidence and lineaments. The transparent red stripes highlight the zones of subsidence and their orientations, which display the same orientations as b) lineaments and volcanic chains of the surrounding area.

7. Discussion

The combination of multispectral data, high- and medium resolution digital elevation models as well as spaceborne radar interferometry (InSAR) gave consistent evidence on geological and tectonic setting and dynamics of the working area and for fault detection and -mapping.

The mapped lineaments represent faults, strongly connected to the youngest movements of the ongoing rifting of the Neogene rifts. They follow- as the different rifts do - preferably deep reactivated basement structures. Their high density at the Mt. Meru edifice point towards high recent tectonic activity. These faults can be considered as potential pathways for hydrothermal fluids.

Along the dominant WNW orientation of faults of Mt. Meru complex, young hydrothermal alterations occur in the crater of the central ash cone as the youngest eruption centre.

The InSAR analysis shows linear zones of high rates of subsidence at Mt. Meru. The trend of these subsidence zone is aligned with existing faults and can most likely be attributed to neotectonics. They display the most recent movements along faults.

8. Conclusions and Recommendation

The objective to overcome the limited availability of large-scale data could be solved by the application of different remote sensing methods.

The results from remotely sensed structural analyses, InSAR processing and partial ground truthing (alterations in the central ash cone) as well as ground movements point towards one distinct area ESE of Mt. Meru to be promising for further focused investigations (e.g. geophysics, Figure 11):

East-Southeast of Mt. Meru, lineaments of different orientations including the prominent WNW-orientation (see Figure 8) with young hydrothermal alterations in the central ash cone can be found.

These orientation could be a preferred target for further exploration. They are additionally intersected by zones of high subsidence, indicating most recent ground movements, most likely connected to active faulting.

Altogether, these are hints towards increased permeability and a location for sufficient pathways for hydrothermal fluids.

In the recommended area, the topography of the land surface is relatively flat to moderate (Figure 11b). Furthermore, access is good, as an existing road crosses the area (Figure 11a).

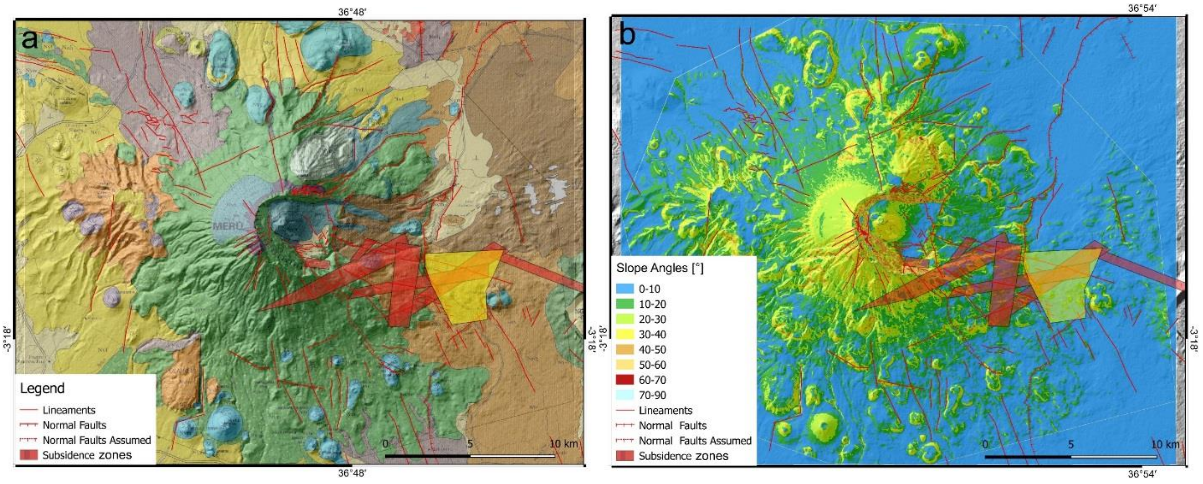

Figure 11: Recommended area (yellow polygon) for further investigations based on the results from remote sensing structural analyses and InSAR ground movement detection. a) Geological map (Wilkinson, P. et al., 1983) over TSX-DEM. b) Slope angle map over TerraSAR-X WorldDEM.

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My colleague Ilona Grünberg conducted the InSAR processing, which is the basis for the ground movement interpretation.

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