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Mapping of the Geological Structures Using Digital Elevation Model (DEM)-Derived Flow Direction: A Case Study of Rungwe Volcanic Province, Southwest Tanzania

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Abstract

This study aimed to assess the potentiality of Digital Elevation Model (DEM)-derived flow direction in mapping geologic structures, specifically in areas with thick overburden of soil or volcanic materials such as in the Rungwe Volcanic Province, SW Tanzania. Clustering of flow directions based on trends of structure sets found in the study area was applied and it successfully revealed a large number of geological structures through demarcated tectonic blocks from patterns created by flow directions. Northwest–southwest (NW-SE) and NE-SW- trending lineaments are the dominant structural sets in the area whereas N-S and E-W-trending lineaments constitute the minor sets. Moreover, the approach has also unveiled the NW-SE-trending faults that control most of the volcanic centers. The extracted lineaments by the method presented in this research are consistent with the known geological structures and structure surface manifestations such as volcanic centers, hot springs and earthquake epicenters. Findings of this study has revealed that the method can be applied as a robust technique to map crustal structures mostly in early phases of exploration, and has shown good results in delineating faults in areas with thick overburden such as soils and volcanic materials.

Keywords: Applied Remote Sensing, Flow Direction, Geological Structures, Rungwe Volcanic Province

Introduction

Geological structural mapping has been the standard activity in the mapping campaigns for many years in the field of geoscience; this is due to the fact that structures make a key component in many geological activities. For example, structures help to delineate lines of weakness and accommodation zones within the crust of which these areas are favorable places where pregnant hydrothermal fluids precipitate metals and form mineral deposits. Structures are also applied in defining highly fractured zones where heated waters from magmatic heat sources can accumulate and form geothermal reservoirs(van der Meer et al. 2014), and they can create trapping mechanisms for hydrocarbons (e.g., Harris and Weber 2006) and other resources in different geologic terrains. Overall, geological structures have enormous contributions during decision making that aim to advance geological investigations of a certain area on interest. However, structure mapping exercise may end up being difficult if proxies of these structures are obscured on the earth's surface by young supracrustal rocks (e.g., Smets et al. 2016). This has been the case in the Rungwe Volcanic Province (RVP), SW Tanzania (Figure 1), where piles of volcanic materials have covered most of the RVP area and resulted into difficulties in understanding the structure setting of the area.

RVP is located to the SW Tanzania along the triple junction and/or accommodation zone between the Rukwa, Nyasa (Malawi) and Usangu rifts (Figure 1). The area has experienced several episodes of volcanism that resulted into piling-up of thick layers of volcanic materials. Indeed, volcanism in the area is believed to have resulted into the concealing of many of the once surface exposed geological structures, and as a result there are very few reported faults. Apart from major faults, which delineate rifts boarder faults within the RVP, minor faults including secondary and tertiary faults, which are also important in defining areas potential different resources such as geothermal systems, have not been mapped by the conventional geological mapping methods. For example, only few faults have been reported in areas surrounding the Ngozi crater, within the Ngozi Geothermal System (NGS), and thus have caused difficulties in assessing its geothermal potentials (Personal communication with Tanzania Geothermal Development Company).

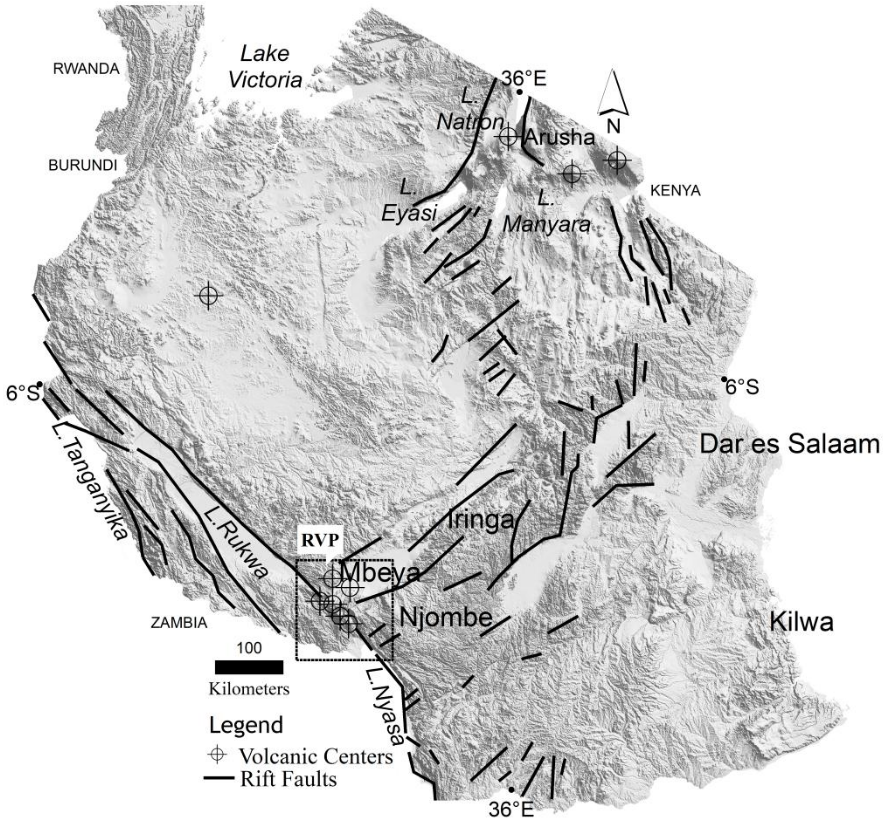

Figure 1: Tanzania DEM Map showing the East African Rift System (EARS) faults, the location of the Rungwe Volcanic Province (RVP) within EARS and the rift basins. RVP, the area under the square box, is also where the three rift basins (Rukwa, Usangu and Nyasa/Malawi) are converging.

From this observation, there is an indication that most of the structures are believed to have been covered by volcanic materials. The logical assumption of this study is that RVP must have been highly fractured and characterized by multiple fault systems contrary to the current reported few structures (e.g., Walker 1969, Fontijn et al. 2012, Garofalo 2013). This is due to the fact that the RVP is located at the triple junction of the East African Rift System (EARS) where the eastern and western branches meet the southern branch (Figure 1). Thus, the complex tectonic movements in the area, which are due to the existing thin crust with the average thickness of 39 km (Borrego et al. 2018), were expected to be manifested on the surface in the RVP by complex structural deformations.

Most of the geological mapping campaigns in the area have applied conventional methods, which to a large extent have failed to uncover the structural complexity of this area. This is a challenge and, to a large extent, hinders effective exploitation of resources in the RVP, for example, geothermal energy. The observed challenge in the RVP as well as recent advancements in geological mapping technology pose the opportunity to test the potential of new mapping methods in addressing the problem of scarce structures in the RVP. In the last three decades, remote sensing has proved to be a robust supplementary tool for geological mapping (van der Meer et al. 2012, van der Meer et al. 2014). Geoscientists are intensively using different remote sensing data sets for geological mapping and in exploration of earth resources (e.g., Hewson et al. 2005, van Ruitenbeek et al. 2005, Macheyeki 2008, Macheyeki et al. 2008, Masoud and Koike 2011, Mshiu 2011, Grohmann and Miliaresis 2013, Mshiu et al. 2015, Smets et al. 2016, Cudahy et al. 2017, Faulds et al. 2017). For example, Mshiu et al. (2015) used the 90 m resolution Shuttle Radar Topographical Mission (SRTM) data and Landsat Enhanced Thematic Mapper (ETM+) data to map crustal pathways of paleo-hydrothermal fluids in the Sukumaland Greenstone Belt in Tanzania. A recent study in the western branch of the EARS has revealed topographic and bathymetric data can offer reliable results to interpret fault systems (Smets et al. 2016). This shows that applying geomorphology characteristics for identification of geological structures, for example, faults and folds is not new. Drainage patterns including those derived from DEM have been used to depict geological structures so as to understand tectonism. The method is widely accepted and has been investigated extensively (e.g. Burnett and Schumm 1983, Ouchi 1985, Mather 1993, Jackson et al. 1998, Zelilidis 2000, Maynard 2006). Drainage patterns are also suggested to be capable of unveiling previously unidentified structures and in some cases relatively young tectonic control on the landscape. For example, drainage patterns in southeast Queensland have been reported as a key in the identification of concealed geological structures (Hodgkinson et al. 2007). However, the limitation of using drainage pattern is that the genesis of other drainage anomalies remains ambiguous, previous investigators have reported that drainages may be caused by active faults or folds or by catastrophic climatic, tectonic or extraterrestrial events and some lack structural control (e.g. Ollier and Haworth 1994, Twidale 2004). Elmahdy et al. (2019) reported on automated detection of lineaments in tropical region, areas with dense vegetation, by using topographic fabric grain algorithm and SRTM data. The above authors have revealed that the method is selective as it works better in mountainous areas than flat areas. Despite the observed correlation of resulted structures with some of the known geological structures, some lineaments from their study were observed to correspond to rivers. This is a challenge since not all rivers follow geologic structures; some rivers may follow weathering and erosion lines depending on the lithologies found in the area under study.

DEM-derived hillshade is another approach commonly used to identify geological structures (e.g. Mshiu et al. 2015). Similar to the weaknesses observed in drainage pattern and other methods, it is difficult to trace the exact locations of lineaments with hillshade method due to the roughness created by shadows that result from differences in surface elevation. Hence, lineaments obtained using hillshade approach has high chance of being erratic. Based on the above challenges which mostly are related to the above-described methods, this study intended to investigate the potential of DEM-derived surface flow directions as an alternative approach to map geological structures including the concealed ones in the study area.

Regional Geology of Rungwe Volcanic Province

Rungwe Volcanic Province (RVP) is located in the southwestern Tanzania bordering Lake Nyasa basin to the south, Rukwa basin to the northwest, and Usangu Basin to the northeastern side (Figure 1 and Figure 2). The RVP is unconformably overlying the Precambrian basement, and in some parts the Karoo age-equivalent strata or Cretaceous sedimentary units. Dominant volcanic rocks in the area are basalt, trachytes, phonolitic lavas and tuff (Fontijn et al. 2012).

According to Harkin (1960), volcanic rocks in RVP have been subdivided into two groups, older and younger volcanic rocks. Older volcanic rocks: The group is represented by major extrusive centers North Poroto, Mbeya Block, Elton Plateau and Kiwira. Sequence of volcanism in these areas occurred between Late Miocene about 9 Ma to around 1.6 Ma. This eruption period of the older volcanic rocks correspond to the first two stages of volcanism (Stage-1: Late Miocene, Stage-2: Late Pliocene-Early Pleistocene), which were grouped based on the field relationship and radiometric ages (Ebinger et al. 1989, Delvaux et al. 1992, Ivanov et al. 1999, Fontijn et al. 2010b). Basalt of the North Poroto extrusive center are reported to be relatively older than trachyandesites, trachytes, phonolitic-trachytes, phonolites and tuff. The reported trachytes from the base of Ngozi crater are dating around 2.2 Ma (Ebinger et al. 1989). For the Ngozi caldera, it might have been formed recently, around 10-12 Ka (Fontijn et al. 2010a, 2010b, Fontijn et al. 2012).The Mbeya block is comprised of phonolites and basalt, the latter being older. The Elton plateau is characterized by agglomerates, the youngest in the area, tuff and phonolite lava breccias. Kiwira is mainly dominated by basaltic rocks. Younger volcanic rocks: In this group, the representative major extrusive centers are Rungwe, Kyejo and Tukuyu. Events of volcanism in these areas are reported to have started from Mid-Pleistocene about 0.6 Ma to recent and have been correlated with Stage-3 of volcanism in RVP (e.g. in Fontijn et al. 2010b). Rungwe volcanic center is characterized by phonolitic-trachyte, tuff, basalt, pumice and ash, which erupted in the late Pleistocene. So far, the oldest dated Rungwe lava is 0.25 Ma (Ebinger et al. 1989). Kyejo volcanic center is characterized by basaltic lavas and phonolitic-trachytes whereas Tukuyu has basalt and phonolites. An important thing to note is that more than 100 volcanic cones and domes have been interpreted to belong to the most recent phase of volcanism in RVP (Harkin 1960).

RVP is fully tectonic controlled; the volcanic province lies between the major EARS faulting systems, i.e., Livingstone, Rukwa and Usangu border faults (Figure 2), these faults have been active since the Miocene time (Delvaux et al. 1998, Fontijn et al. 2012). The area is dominated by a strike-slip fault, which trends NW-SE to N-S. The observed strike-slip faults are expressing a compression stress regime with horizontal principal compression in ENE-WSW direction (Delvaux and Barth 2010). Structural investigations in the area also revealed a strong tectonic control on the locations of volcanic centers. For example, Fontijn et al. (2012) reported that all volcanic centers in the RVP are aligned along a major buried fault trending NW-SE that intersects with NNE-SSW faults.

Materials and Methods

Preprocessing of ASTER DEM data

Thirty meters (30 m) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) data used in this study were downloaded from the USGS earth explorer database under the link https://earthexplorer.usgs.gov/. The preprocessing and analysis of the DEM data were performed using ArcGIS software.

Preprocessing of 30 m resolution ASTER DEM data, which covers the area 526835 to 584165 Eastings and 8984687 to 9022391 Nothings, was performed to reduce geometrical errors as well as replacing the void pixels with the average value from the surrounding pixels. Geometrical errors correction was done by adjusting ASTER DEM data images with reference to locations of non-movable objects in the topographical maps, among the objects are road crosses and rivers triple junctions.

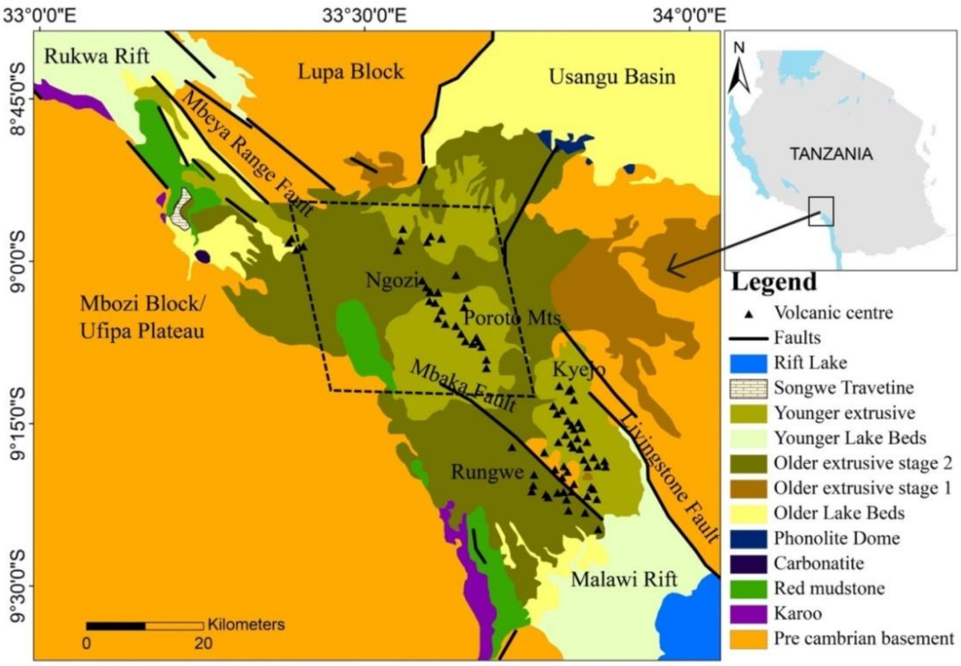

Figure 2: The geological map of RVP, showing different lithologies and structures (including recent lava flows, also volcanic centers, hot springs and crustal structures). The parallelogram shaped polygon is the study area. The map has been modified from Fontijn et al. (2012).

Hillshade

Information from geological maps and results from previous researches (e.g., Lemna et al. 2019, Fontijn et al. 2010a, 2010b, Ebinger et al. 1989) were used to create the hillshade of the study area. Hillshade results were used in assessing the enhancement of lineaments by flow direction image (FDI). Azimuth angles and altitudes were set with respect to the orientation of known structure in the study area to create hillshade image. Based on the geology of the study areas the NW-SE and NE-SW-trending structures were enhanced by illumination at NE (45° azimuth) and NW (315° azimuth), respectively. The altitude applied was 30° for all structure sets since it gave good results based on the topography of the study area.

Flow direction

Before computing the flow direction, depressions and sink pixels in ASTER DEM data were filled using a fill tool in ArGIS software, the software that can easily manage raster and vector data, the spatial data. Theoretically, this is done by converting sink pixels into flat areas so as to allow the computation of flow direction. The process of computing flow direction uses slope to determine the steepest slope (the drop) in each pixel in the digital elevation model data (DEM) (Greenlee 1987). In computing the drop, the algorithm uses Z-value (elevation) and slope differences for 8 neighboring pixels. Overall, the computations of flow direction were done based on the equation (i) below.

Drop = (Z value difference /Distance* 100)… (i)

Results from the computed flow direction are integer numbers 1, 2, 4, 8, 16, 32, 64 and 128 assigned to the pixels. Each number represents the direction of flow in 8 different cardinal directions. For example, 64 and 4 in Figure 3 below correspond to the flow directions towards north and south, respectively.

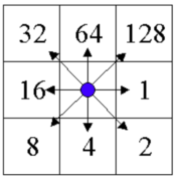

Figure 3: Flow direction codes normally resulting from the calculation of flow direction using Digital Elevation Model (DEM). Each number represents flow in 8 different cardinal directions.

Based on the concept behind this study, intense crustal fracturing due to tectonic processes creates the pattern of tectonic blocks. Large areas of bedrocks in the crust are broken into fragments of different sizes and shapes based on the faults resulted from the tectonic forces exerted on the area. Often the movements of these blocks are accompanied by tilting due to compaction or stretching of the crust (e.g. Herwegh et al. 2017); hence, the resulted tectonic blocks have different slopes and slope direction (azimuth). For the case of this study, it is anticipated that demarcations of tectonic blocks can be observed through flow direction. Regardless of the size, the studied tectonic block will be dominated by pixels of the same flow direction of which their edges are crustal fractures, and in most cases the edges will be faults.

Enhancement of the tectonic blocks from calculated flow direction was done by clustering pixels based on similarity in flow direction to enhance the targets, which are crustal structures. In this study, clustering of flow was done based on the existing information on structures in the RVP of which the area is dominated by NW-SE and NE-SW-trending structures (e.g. Delvaux et al. 1998, Lemna et al. 2019). Clustering of pixels with flow direction values 128 (NE), 1(E) and 64 (N flow) versus cluster 8 (SW), 16 (W) and 4 (S) will enhance NW-SE-trending structures. The two opposite flow direction sets above must be displayed in differentcolors. Cluster 128 (NE), 1(E) and 64 (N flow) versus cluster 32 (NW), 16 (W) and 4 (S) can enhance both sets of structures (NW-SE and NE-SW) depending on the enhanced tectonic blocks.

Manual extraction of lineaments using on screen digitizing was the approach used to extract the edges of the identified tectonic blocks, which in this study they represent lineaments. Only edges of the observed conspicuous tectonic blocks were extracted. False signals from unwanted linear features such as anthropogenic lineaments (e.g., transmission line, railway, roads, etc.), streams from surface processes like erosion, as well as linear volcanic edifices, were identified and managed by overlaying the extracted lineaments on topographical maps of the area.

Validation of lineaments was done by assessing the correlation between the extracted lineaments with known faults in the study area, as well as hot springs, volcanic centers and earthquake epicenters. Statistical analysis of structures using rose diagram was another method applied to validate the resulted structures, which major sets of lineaments in the study area were checked against trends of structures reported in geological maps and reports (Figure 7a).

Results

The resulted flow direction image (FDI) has revealed the existence of tectonic blocks, which their edges are interpreted to be crustal fractures in this study. These fractures are linear with all characteristics related to crustal structures of the study area. Pixels with related flow directions create flow direction blocks, which in this study are interpreted to be tectonic blocks. Edges of these blocks are linear and can be identified easily based on the clustered pixels with related flow directions (Figures 4 and 6).

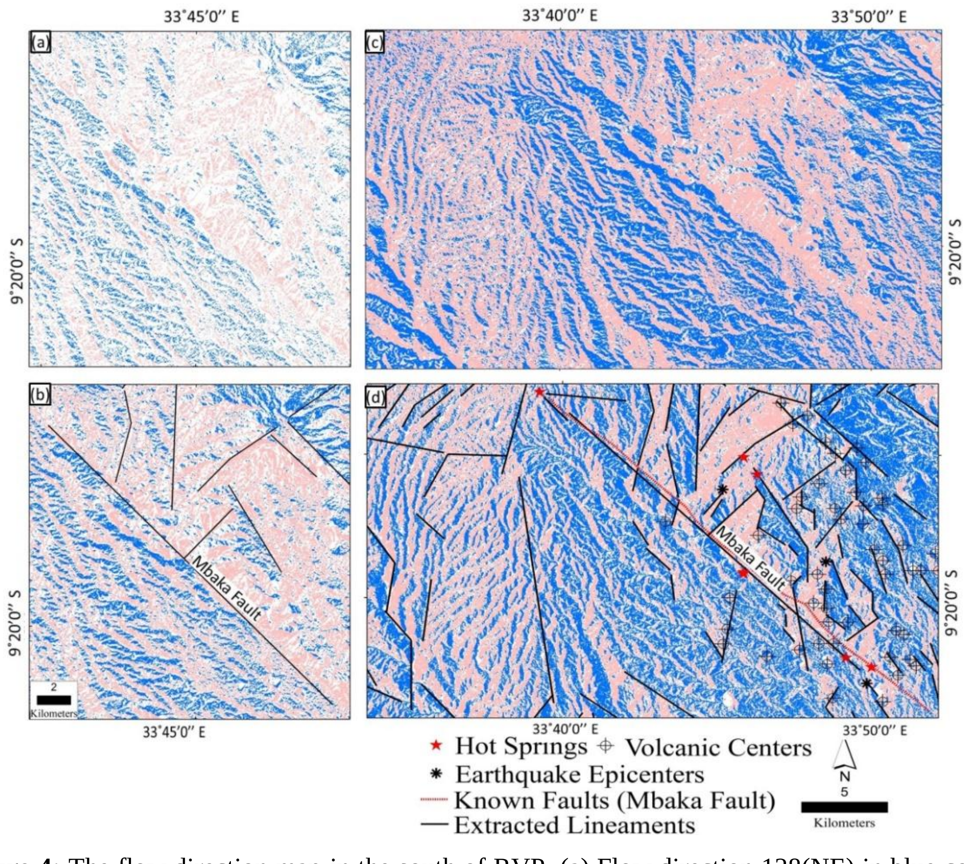

Figure 4: The flow direction map in the south of RVP, (a) Flow direction 128(NE) in blue colour versus 8(SW) in coral colour, (b) Cluster 128(NE):1(E) in blue colour versus 8(SW):16(W) in coral colour, overlaid by major lineaments (c) Cluster 128(NE):64(N):1(E) in blue colour versus 8(SW):16(W):4(S) in coral colour, (d) Cluster 128(NE):2(SE):1(E) in blue colour versus 32(NW):16(W):8(SW) in coral colour, overlaid by the extracted lineaments, Mbaka fault, hot springs, volcanic centers and earthquake epicenters.

Some known major faults in the study area coincide with the edges of the FDI blocks. For example, the Mbaka fault that is located south of the RVP has been clearly mapped (Figure 4). Observations indicate that some of these lineaments are also mapped in the hillshade image. However, FDI seems to be superior over hillshade image as it shows clearly the linear shape of structures as tectonic blocks are delineated through sharp linear edges outlined by differences in flow direction or texture (Figure 5).

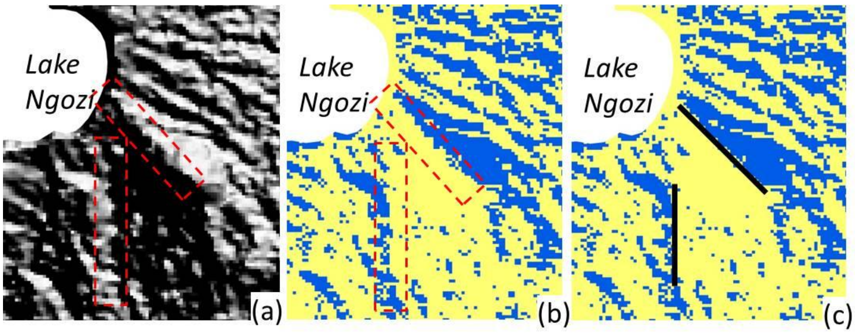

Figure 5: Lineament enhancement by (a) hillshade (45° azimuths, 30° altitude) and (b) flow direction image enhancing the NW-SE- and N-S-trending structures. (c) The Figure 5b flow direction image overlaid by demarcated structures in thick black lines.

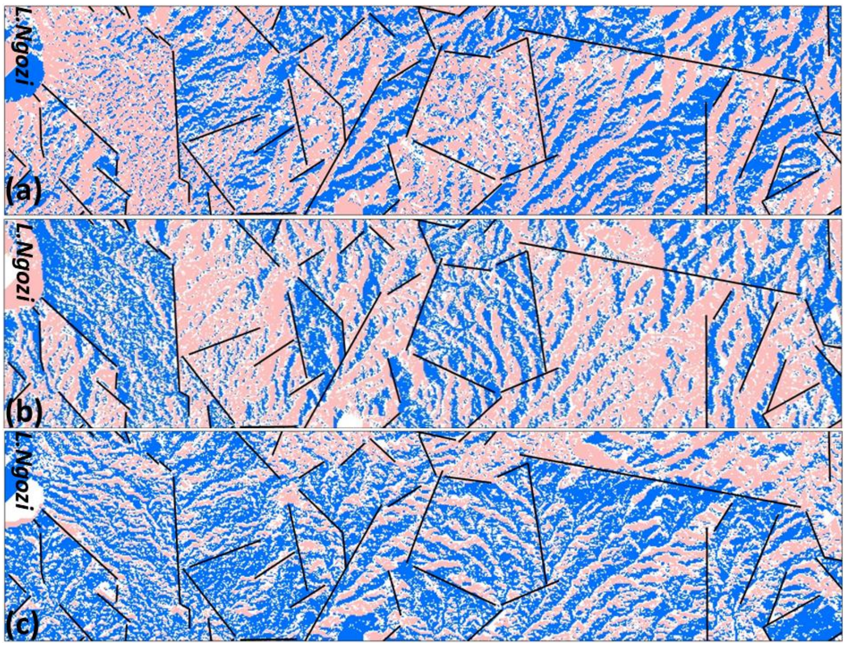

Figure 6: Flow direction image from the study area (a) Cluster 64:32:16 (blue) versus 1:2:4 (coral), (b) Cluster 32:16:8 (blue) versus 128:1:2 (coral), (c) Cluster 8:4:2 (blue) versus 128:64:32 (coral). Dark lines are the edges of the tectonic blocks that represent lineaments in this study.

Based on the edges of flow direction on the demarcated tectonic blocks, a large number of lineaments have been mapped in the study area (Figure 6). Results indicate that the method can map lineaments of up to less than 1 km length. Moreover, the fault reported to control spatial distribution of the volcanic centers in the RVP is also revealed through the interconnected lineaments extracted from the FDI. Overall, the FDI interpretation has revealed the presence of four sets of structures in the study area, these are NW-SE, NE-SW, N-S, and E-W-trending structures where the NW-SE and NE-SW-trending structures constitute dominant sets (Figure 7a).

Discussion

Interpretation of the resulted flow direction image (FDI) has revealed a number of previous known and unknown faults in the study area. The Mbaka Fault in the south of the RVP is the best example of the known faults mapped by this method (Figure 4). The presented method in this paper has mapped tectonic blocks as patterns made by flow directions; these are the areas in FDI defined by clusters of pixels with related flow directions. The latter are values indicating similar trends of flow whose spatial patterns appear as blocks with linear and sharp boundaries (e.g., Figure 7 and Figure 8).

A large number of lineaments, more than 1872, have been mapped as revealed in Figure 7 and Figure 8. The observed success is due to enhancement of tectonic blocks that is done with reference to the set structures that are reported to dominate the studied area. In the RVP, NW-SE and NE-SW are the two dominant structure sets. The two sets of structures were enhanced by clustering flow directions 128(NE):1(E):64(N) versus 8(SW):16(W):4(S) as a set to enhance NW-SE-trending structures, and cluster 32(NW):16(W):64(N) versus cluster 2(SE):1(E):4(S) to enhance NE-SW-trending structures (Table 1). Clustering of the flow directions above showed clear demarcation of the tectonic blocks; however, clarity of tectonic blocks boundaries decreases when the number of flow directions involved in clustering decreases. For example, for a cluster containing two flow directions on one side of a set, e.g., cluster 128(NE):1(E) versus cluster 8(SW):16(W), the delineated tectonic blocks will be shown but the clarity of the demarcated tectonic block is weaker when compared to the cluster made by three flow directions. The clarity of the block boundaries is further decreasing when cluster is made by one flow direction; compare Figure 4a and 4b. Enhancement of both sets of structures is also possible. This is done by creating two clusters of flow directions, each intended to enhance one set of structure in the area; the two clusters will have to be displayed in different colors. For the case of RVP, cluster 64(N):128(NE):1(E) versus cluster 32(NW):16(W):8(SW) in two different colors, have enhanced the two sets of structures in the RVP, the NW-SE and NE-SW-trending structures, respectively (Figure 7). Edges of the resulted tectonic blocks are clear that they make lineaments of the two structure sets in the RVP easily identified. Apart from displaying correlated flow directions, the delineated tectonic blocks also reveal different textures depending on the flow directions used during clustering (Figure 6). All these characteristics contribute to the enhancement of the tectonic blocks, which the edges of these blocks are the targeted lineaments.

Table 1: Flow direction sets and clusters applied to enhance the NW-SE and NE-SW trending structures

Flow direction (FD) set	Cluster	Description	Enhanced crustal structure
Set-1	128:1:64	It combines the flow directions towards northeast (NE), east (E) and north (N).	NW-SE trending structures
	8:16:4	It combines the flow directions towards west (W), southwest (SW) and south (S).	
Set-2	32:16:64	It combines the flow directions towards northwest (NW), west (W) and north (N).	NE-SW trending structures
	1: 2: 4	It combines the flow directions towards east (E), southeast (SE) and south (S).	

The extracted lineaments correlate well with other geological features, i.e., previous mapped faults, hot springs, earthquake epicenters as well as volcanic centers, which all have geologic association with faults. The latter play the role as conduit to thermal fluids and magmas from magma chambers towards the earth's surface; hence their relationship with the mapped lineament from this study is a validation of the approach used to map the lineaments. Earthquake epicenters also show spatial association with some of the mapped lineaments. They are near to some of the lineaments; this might be the indication that some lineaments could be active faults (Figure 7b and Figure 8).

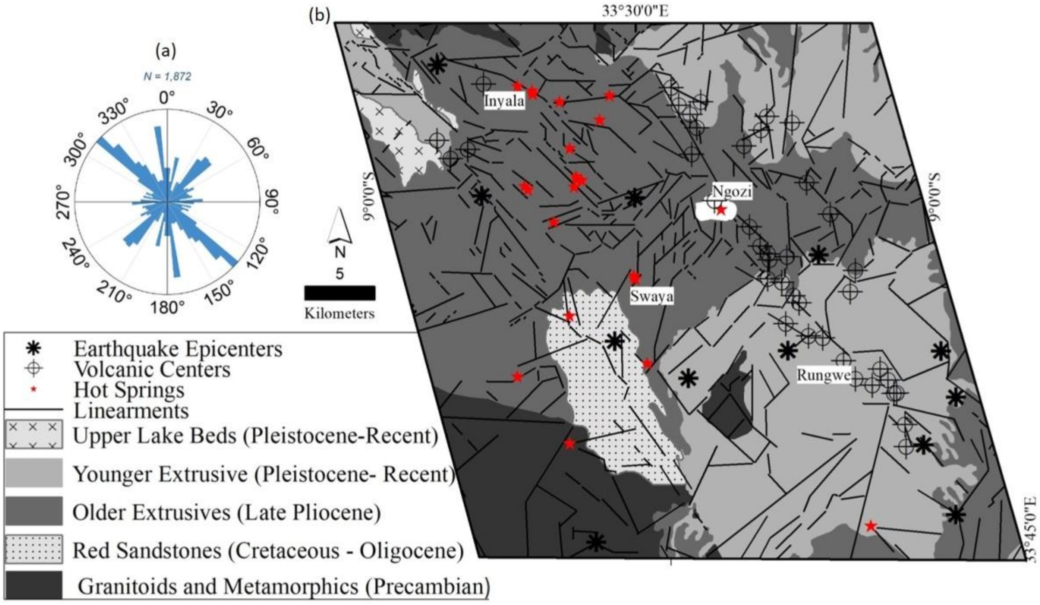

Figure 7: (a) Rose diagram showing different sets of structures found in the RVP, (b) Map showing crustal lineaments from interpretation of FDI overlaid on lithologies of the study area.

Results indicate that the approach has the ability to identify minor lineaments with length less than a kilometer. Apart from the fact that ASTER DEM data have relatively good spatial resolution which might have contributed to the effective identification of lineaments, another factor could be the method used in this study. The approach used in this study can easily trace the precise location of the lineaments than the hillshade method (Figure 5). The precise location of the lineament is difficult to trace when using hillshade method due to the roughness created by shadows resulted from differences in elevation. The applied method in this study uses edge of the delineated tectonic blocks instead of the shadow which is a result of the obstructed imaginary light rays illuminated on the ASTER DEM data.

Interpretation of the FDI, however, needs to be done with caution, mostly in distinguishing tectonic blocks and their edges from other linear features such as volcanic edifices. The latter may sometimes show similar characteristics. Use of other data sets, e.g., topographical maps during interpretation helps to identify such false linear features and reduce errors in the results obtained. Hence, in the process of identifying lineaments in this study, topographical maps were used to validate lineaments during interpretation.

Resulted lineaments revealed that geologic structures might have been involved in the formation of lithological boundaries in some places; this is due to the observed spatial relationship between the lithological boundaries and some of the lineaments. However, there is no observed correlation between textures of the mapped tectonic blocks and rock types found in the study area, compare lithologies in Figure 7 and tectonic blocks in Figure 8. The presence of the above relationship would have indicated that the mapped textures are contributed by the crustal rocks in the area.

The approach has also unveiled the concealed faults that control spatial locations of volcanic centers in the study area (e.g., in Fontijn et al. 2012). These faults are mapped as interconnected segments of lineaments, trending NW-SE starting from Rungwe towards northwest through Ngozi crater. Most of the volcanic centers are aligned along these lineaments (Figure 7b). The rose diagram of the extracted lineaments has revealed the presence of two dominant sets of structures in the study area, these are NW-SE and NE-SW-trending structures, N-S and E-W-trending structures which constitute the minor sets (Figure 7a). The NW-SE-trending set is observed to have a relatively large number of structures when compared to NE-SW set.

Based on the assessments made on geothermal potential of the area (Garofalo 2013), the NW-SE-trending structures are spatially controlling most of the hot springs; the structures are probably connected deeper to the crust, areas where heat sources are likely to be found. There are also few NE-SW lineaments around Lake Ngozi, especially to the SW of the lake whose presence might be indicating that they also play an important role in the hydrology of the Ngozi geothermal system (Figure 8). Further investigation is needed to prove this concept.

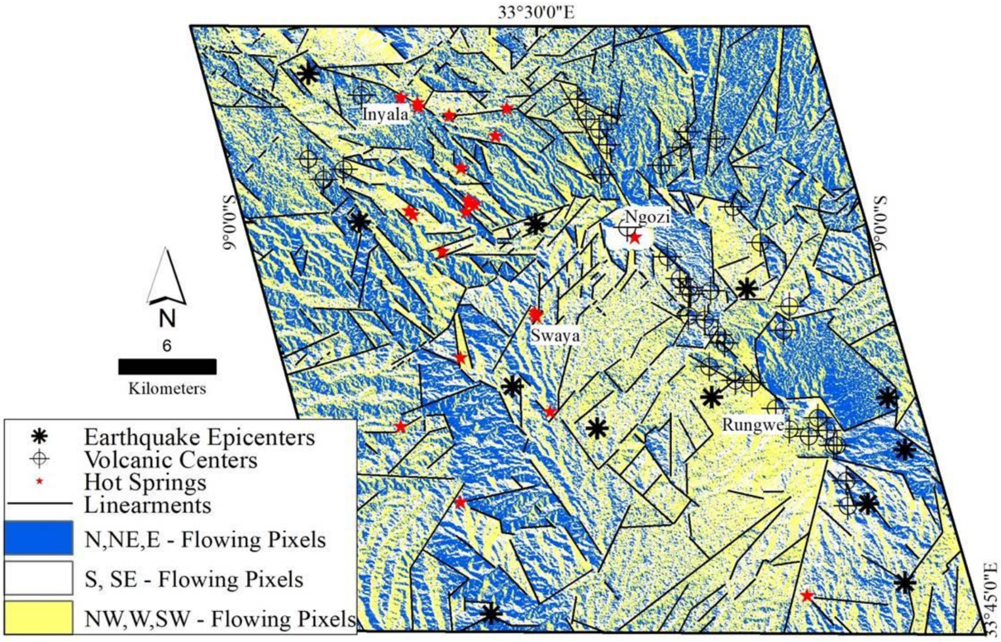

Figure 8: Map showing crustal lineaments from DEM-derived flow direction method coinciding with edges of the tectonic blocks. Hot springs, volcanic centers and earthquake epicenters plot along the edge of the blocks and extracted lineaments.

Conclusion

The method used in this study, which involved clustering of flow directions has managed to enhance signals from the obscured structures through the delineated tectonic blocks, and as a result large numbers of crustal lineaments have been mapped. The method has simplified the process of lineament identification through using the edges of the mapped tectonic blocks, which has managed to map lineaments with the length up to less than a kilometer. The same improvement is revealed in the precision of locating lineaments during extraction as there is less or no displacement that is normally caused by shadow effect when using hillshade method.

Results have revealed no indication of the influence from lithological boundaries in identifying lineaments; this is also true for different textures created from clustering of flow directions that they also do not correlate with lithological boundaries.

NW-SE and NE-SW are the dominant sets of lineaments extracted from the study area, whereby the N-S and E-W-trending structures are the minor lineament sets. Of all the sets of lineaments in the study area, the NW-SE contains a large number of lineaments, this makes NW-SE structures to be a major set in the RVP. Along with the mapped structure sets, the study has unveiled the concealed lineaments that control some volcanic centers in the study area. Moreover, there is a good correlation between mapped structures and known geological structures as well as other surface manifestations such as volcanic centers, hot springs and earthquake epicenters.

This study presents a reliable approach in mapping crustal structures to support the conventional mapping methods in areas with a challenge of thick soil cover or volcanic materials that conceal underneath structures. However, for mapping subsurface structures, the method can be coupled with methods with crust penetrating power such as geophysical data to validate the mapped lineaments.

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