Adama Science and Technology University

Mapping faults around Adama Town: Implication for future earthquake triggering potential

By

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ABSTRACT

The northern Main Ethiopian Rift (MER) manifests a complete finger print evolution characteristics of continental rifting from rift initiation to incipient sea floor spreading. Adama is located in the southern extreme of the active volcano-tectonic segment of the northern Main Ethiopian rift. We did a structural and geomorphological mapping of faults to investigate their future earthquake triggering potential. We have collected about 129 structural (faults and fractures) measurements. All measurement data were collected from inside Adama town and its surroundings. We calculated palestress direction of the area which generated all the faults using kinematic analysis techniques. Our data shows the exerted force which is responsible for deformation in the area is oriented about N 112^0 E to N 68^0 W. The results of our kinematic analysis is statistically similar with the current regional stress direction which is inferred from continues geophysical monitoring. Our data shows minor deflection stretching direction with respect to the regional to the south. We suggest that the minor deflection could be resulted due to crustal strength heterogeneity. We have evaluated faults also through morphological investigations using stream profile index. We identified a sharp jump of elevation (Knick point) along stream profile across fault planes. We checked each of knick points in the field and suggested that it is an indication of past earthquake occurrence evidence. From the integration of structural data and geomorphological evidences, we recognized that faults around the town mainly the western side faults are active. Like historical earthquake of the 1996 could reoccur in this area due to slip along one of the nearby faults. Pilot study on ground cracks around the town shows a significant relationship with faults of the area. We suggest that the weathered rock fragments accumulation along the slope of the fault planes especially in the east of the town can result landslide even by a smaller magnitude of earthquake occurrence.

Acknowledgement

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1. Introduction

1.1, Background

Surface manifestations of faults in the tectonically active regions are common morphological expressions. Morphological expression of these active faults could be varied, mostly based on the activity of the fault itself, the lithology affected by faulting and climatic condition of the area Douglas and Robert (2013). Our study area located in the Main Ethiopia Rift which is part of the (EARs) containing a series of active rift zones with associated effusive to explosive volcanic products concentrated along the general trend of the rift. MER system traditionally classified into three segments based on the relative intensity of the Volcano-Tectonic activities and faults architecture. These are southern MER segment, central MER segment, and northern MER segment. But the boundary which divides each of them is in a debate.

Petrologists and structural geologists classified the boundary based on the intensity and petrographic characteristics of volcanic products and structural features characteristics Corti (2009) while geophysicsts use geophysical criteria to divide each of the sections Keir *et al*. (2015).

Adama is located almost at the southern boundary of the most active volcano-Tectonic region of the northern MER. This rift connects the EARS with the Afar triple junction where the three rifts interact. The section is characterized by complex extensional tectonics features manifested with associated quaternary volcanic outpourings. The area is situated along one of the active right stepping en echelon arranged magmatic segment of Gedemissa-Boset. Considering the areas location within the Great Rift Valley of East Africa specifically in the northern Main Ethiopian rift, it is believed that the region is both seismically and volcanically active. One of the most commonly known structural effects of earthquake is formation of factures which will progress to faults with significant vertical displacements. It is suggested that larger fault scarps such as the Adama fault scarp form through a continuous earthquake generations. Therefore a fault scarp formation is the result of a series of earthquakes. The nature of fault propagation can be identified from the field and satellite images using geomorphological signatures. We aimed to identify active faults and their propagation characteristics around Adama town. We used both field and high resolution satellite image data analysis to identify faults. Geomorphological investigations are also integrated with structural data to evaluate the activity of faults. We aimed also to compare the area's structural data with recent geophysical study results. Furthermore, we aimed also to map ground cracks of the area around to check their relation with the current tectonic activity of the region. We used the current available geological software's to analyze the generated primary data of this project.

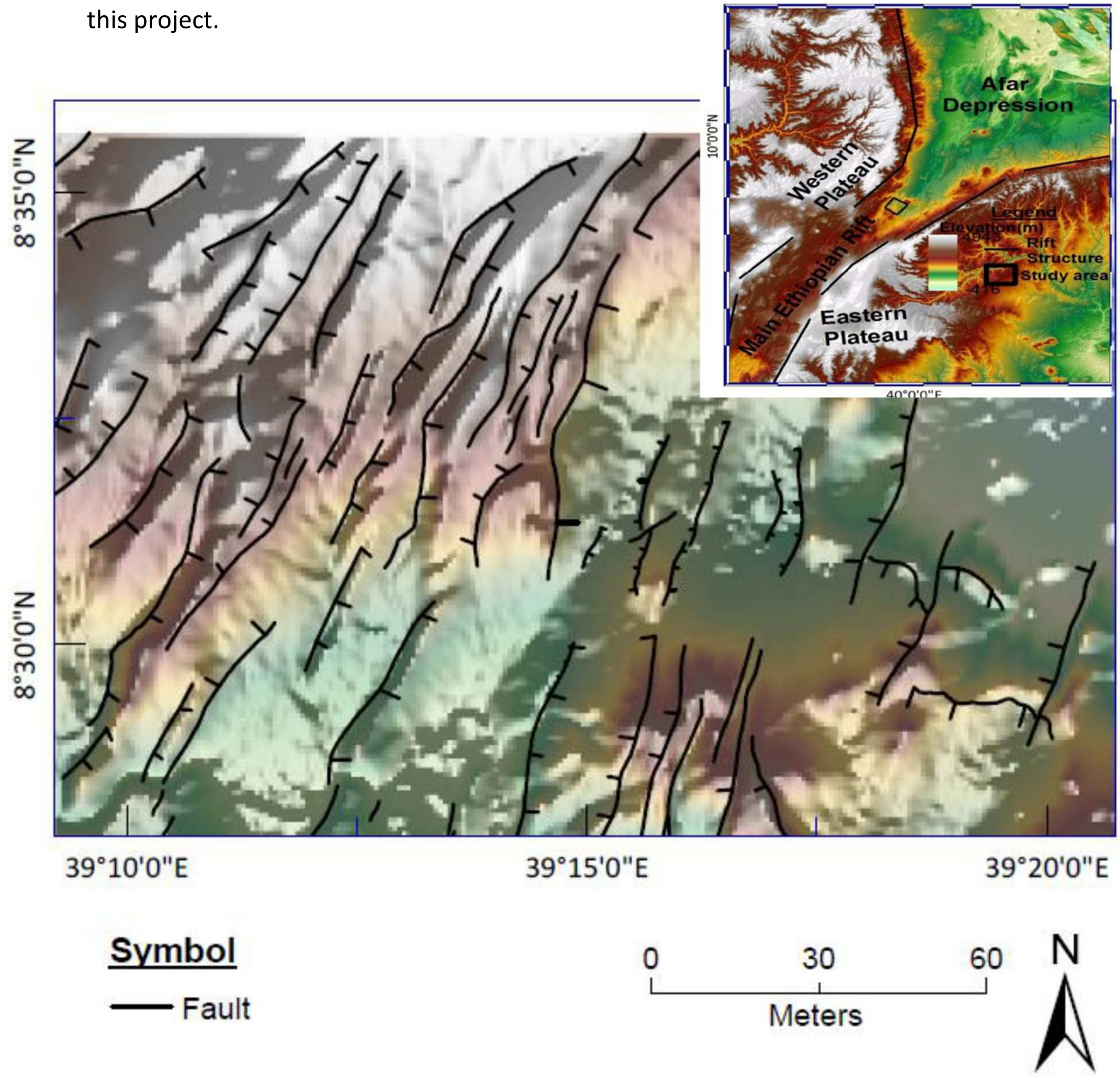

Figure 1 : Location map of the study area.

2. Volcano-Tectonic setting of the Northern Main Ethiopian Rift

EARs are a Miocene-Quaternary intercontinental extensional system composed of several interacting rift segments, from Mozambique to Afar. At Afar, the EARs join with the Gulf of Aden and Red Sea Rifts. Both are characterized by matured continental rift settings. Continental flood volcanism in Afro-Arabia extends over an area of at least 600 0 km^2, stretching from south-western Ethiopia through Eritrea and Djibouti to Yemen. Volcanism was associated with rifting of the Afro-Arabian continent in late Oligocene-early Miocene times and initiation of sea floor spreading in the Gulf of Aden 16 Ma and the Red Sea 4 Ma d'Acremont et al. (2005). The Red Sea–Gulf of Aden–Main Ethiopian rift–rift–rift triple junction lies on the broad Ethiopian plateau, believed to have developed above a Palaeogene mantle plume. Compilations of $^{40}Ar/^{39}Ar$ data from the Red Sea and Gulf of Aden regions show that flood basalts and associated felsic rocks were erupted across a ~1000 km diameter region between 30Ma and 29 Ma Chernet *et al. (*1998), roughly coeval with the initiation of NE-directed extension in the southern Red Sea, and the Gulf of Aden. According to Pik *et al. (*2008) these afar plume related flood volcanism eruption occur in a relatively short period of a geological time (~1Ma) in an approximate time range from 29Ma to 28Ma. Continental flood volcanism in Ethiopia-Yemen is presumed to be associated with the Afar plume and comprises voluminous sub-aerial basaltic lavas and silicic pyroclastic rocks. This flood volcanism assumed to produce about a 4 km thick volcanic pile, but erosional remnants (2 km) of which are well-preserved on the Ethiopian and Yemeni plateaus. However, Ebinger and Sleep (1998) and Sengor (2001) suggested that any volcanism prior to ~30Ma as being related to rifting in the Rudolf area in southern Ethiopia rather than being related to the Afar Dome.

This volcanism initiated prior to 30.9 Ma in Ethiopia and may predate initiation of similar magmatic activity in Yemen. Rhyolitic volcanism in Ethiopia commenced at 30.2 Ma, contemporaneous with the first rhyolitic ignimbrite unit in Yemen at ~30 Ma. Ethiopian volcanism shows a progressive and systematic younging from north to south along the escarpment and parallel to the rifted margin, from pre-rift volcanic products in the south to syn-rift northern volcanism in the north. A dramatic decrease in volcanic activity in Ethiopia between 25 and 20 Ma and 25-19 in Yemen marks the transition from pre- to syn-rift volcanism (~25-26 Ma) triggered by the separation of Africa and Arabia. A second magmatic hiatus and angular unconformity in the northern Main Ethiopian Rift is evident at 10.6-3.2 Ma, and is also observed throughout the Arabian plate in Jordanian, Saudi Arabian and Yemeni. Most of the Cenozoic faults in the Horn of Africa have been interpreted as reactivated structures of the Pan-African Mozambique belt and the Arabian-Nubian shield. Furthermore, from these all compiled age data, recent thermochronologic study Balestriale *et al. (*2015) suggests that volcanism and rifting in Ethiopia is not as such in a systematic order to explain as younging to the north or to the south.

The EARs is one of the geological wonders of the world, a place where the earth`s geodynamic processes actively occurring to create a new crustal plate by splitting apart the older ones. In simple terms a rift can be thought as a fracture in the earth`s surface that widen over time or as technically as, an elongated basin bounded by opposed steeply dipping normal faults. This great African rift valley starts from Syria and extends up to Madagascar. Since these Great Rift Valley was formed by divergent plate boundary, which result a progressive crustal thinning. That is essential for the outpouring of mantle originated magmatic products. This east African rift valley cuts Ethiopia in to Northwest and Southeast passing through mega cities of the country. The great rift valley of Ethiopia is part of EAR that runs through Ethiopia in a Southwest direction from Afar triple junction. It separated the countries high stand plateaus to the northeastern plateau and the Somalia plateau to the south. The rift developed as these two plates began to move apart during the Miocene period along the EARs. It resulted about 80km wide subsided low land by large discontinuous normal faults. These large displacement faults give rise to major tectonic escapements separating the rift floor from surrounding plateaus. These marginal faults are assumed to be inactive in a relatively matured northern section of the Main Ethiopian rift and active to the southern part.

This tectonically and volcanically active region of the northern main Ethiopian rift where Adama is found contains two systematic structural features. These are marginal faults which bounded the rift from the west and east and rift floor concentrated younger faults called Woniji Fault Belts (WFB). Kinematics of the Main Ethiopian rift is still in a debate. According to Boccaletti (1998) & Bonini (2005) the rift had undergone two stages of rifting since the Miocene time. Before 3Ma the kinematics of the Ethiopia plate and the Somalian plate oriented NW-SE direction. Afterwards, the kinematics shifted to an approximate East-West direction. Muluneh (2015) suggested strike slip related northeast-southwest directed extension throughout the history of rifting in the region. From an integration of field and analogue modeling laboratory experiments Corti (2008) and Earbello *et al. (*2016) explained kinematics of the main Ethiopian rift east west directed continuous extension since the Miocene time.

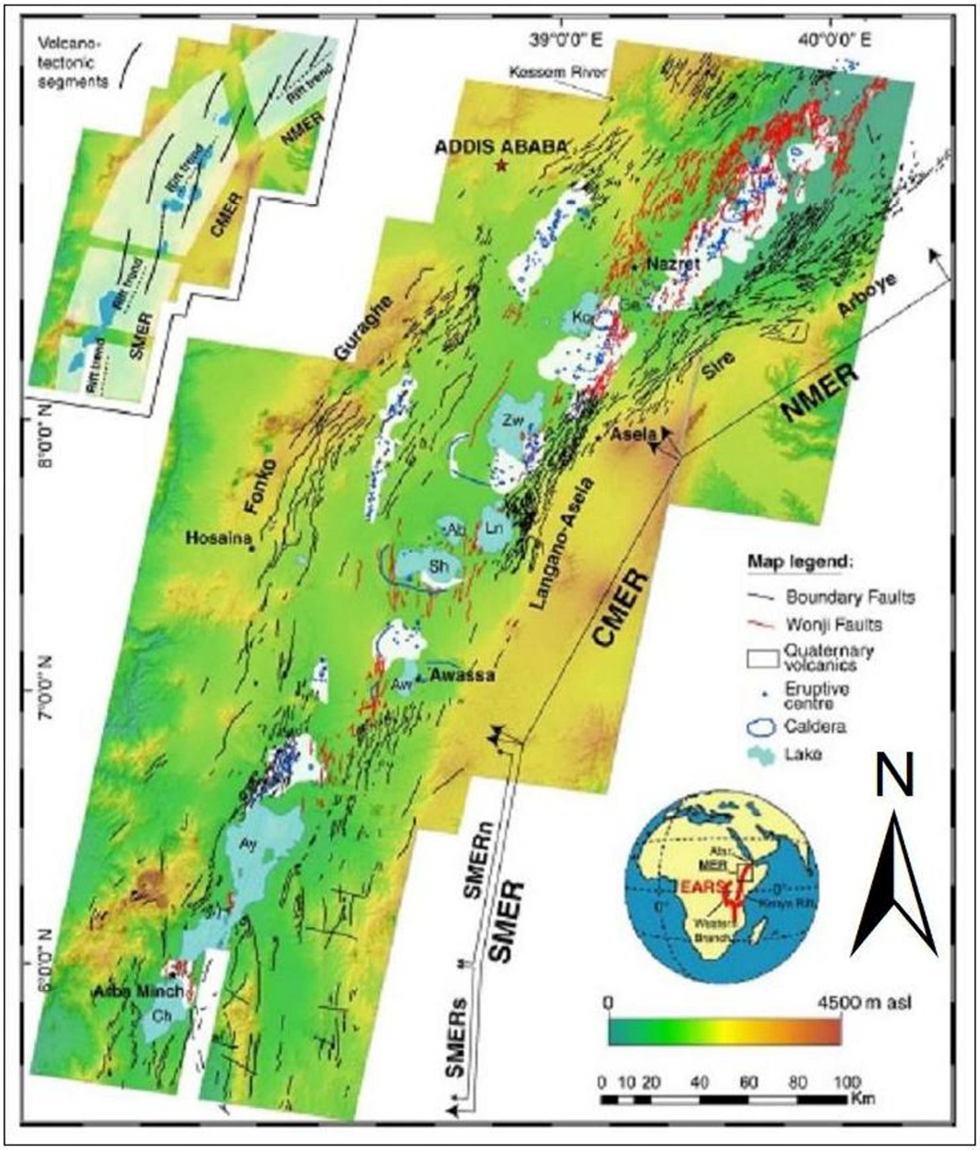

Figure 2: Tectonic map of the Main Ethiopian rift showing the three main sectors. Namely Southern Main Ethiopian Rift (SMER), Central Main Ethiopian Rift (CMER), and Northern Main Ethiopian Rift (NMER)(modified from Agostini *et al*., 2011).

3. Geological setting of Adama area

The MER which started to develop in Miocene time is part of the East African Rift System (EARS) and comprises a series of rift zones extending over a distance of about 1000 kilometers from the Afar Triple Junction Boccaletti *et al*. (2000). The Main Ethiopian rift is associated with bimodal quaternary magmatism which shows an overall bimodal composition, change in volume and composition along MER. The northern most part is mainly characterized by widespread basaltic lava flows, associated with shield volcanoes or erupted fissures. Conversely, felsic central volcanoes usually characterized by calderas are responsible for the emission of rhyolite, ignimbrite and predominate in central southern part of the rift Abebe *et al. (*2007). Rift margins of the main Ethiopian rift are bounded by a succession of fault scraps that are about 500m high whereas the rift floor is characterized by segmented shorter displacement and length faults. One of these areas is the Nazret-Dera area, which is situated between two main en echelon rights stepping north to north eastern trending Wonji fault belt (WFB) segment within the floor. One of the belts is situated along the western side. The other fault belt originates in the eastern sector and extends northward to the Kessem river valley area. The volcanic succession outcropping in the Nazret-Dera area subdivided into eight main units Boccaletti *et al. (*1999). But in specific to our study area the volcanic stratigraphic units are classified into six.

3.1. Nazret Unit

The Nazreth unit is made up of a sequence of ignimbrite sheet interbedded with paleosol layers, indicating frequent breaks in the volcanic activity and aphyric flood basalts. The ignimbrite units are frequently strongly welded at the base and unwelded at the top. They are mainly characterized by stretched glassy 'fiamme', showing a pantelleritic composition (Figure 3) and by abundant basaltic lithic fragments. They are mainly transitional and subordinate alkaline. This rock unit expose as an elongated outcrop mainly concentrated along fault scarps and dominates the western side of the town. The age of this unit ranges from 1.7 Ma to 1.5 Ma.

Figure 3: Showing highly stretched welded ignimbrite exposure from the western scarp of Adama town (this study).

3.2. Boku-Tade Unit

The Boku-Tade unit is represented by ignimbrite sheets, pyroclastic fall and surge deposits, and highly fractured lava domes with associated obsidian layers. The surge deposit covers the central and western part of the area and their maximum thickness is about 2 m. This thickness decreases toward the east of the area. According to Morton *et al.,* (1979) the Boku caldera cone diameter ratio was probably close to one, so that caldera collapse led to the distraction of the greater part of the remnant cone. This unit mainly exposed to the south of Adama town, namely around Boku. It is a remnant of a caldera where today the remnant is archy type escarpment. It is not only limited to this area rather it exposed also to east, west and to the northeast along the scarp near to the University. It is highly weathered and fractured (Figure 4). This product therefore is roughly coeval with the following Bofa basalts, which are essentially developed in the central part of the rift area. Age determination from radiometric dating technique shows an average age ranging from 0.83 Ma up to 0.51 Ma Morton *et al. (*1979).

Figure 4: showing highly fractured sheeted ignimbrite outcrop from the west of the Adama Science and Technology University (this study).

3.3. Bofa Unit

This rock unit is mainly of fissure origin which crop out in the central area of the rift and overlies the ignimbrite sequence of the Keleta unit. These rocks are mainly transitional basalt, with subordinate alkaline basalt and mugearites. The rock unit uniquely exposed only in minor places mainly in the central and southwest of the study area. The unit commonly contains plagioclase porphyry olivine basaltic lava flows with a maximum thickness of about 5 meters. Thickness of this unit sequence decreases from northeast to southwest in the central part of the rift. The radiometric age ranges from 0.61 to 0.4 Ma Morton *et al. (*1979).

3.4. Dera-Sodere Unit

This unit is the most widespread ignimbrite unit which is characterized by thin layers of unwelded or poorly welded ash containing brown-pink matrix, scattered, rounded pumice clasts and lithic fragments within thin paleosol. Even though it is widespread, it mainly exposed in the southeast and north of the town. It also exposed along a stream cut in the southwest of the town to the side of the main road to Woniji (Figure 5). Its composition is pantelleritic and it contains a few crystal fragments of sanidine. The thickness of the layer varied from place to place. But on average it is about 5 meters.

Figure 5: Showing Dera-Sodere unit exposure to the west of the main road Adama-Woniji (this study).

3.5. Gedemsa Unit

The product of this unit is related to the collapse of a caldera approximately 8 km in diameter out cropping southwest of Boku caldera. The pre-caldera activity gave rise to pantellerite rhyolite ignimbrites associated with ash flows, pumice falls and surge deposits. The post-caldera product is composed of resurgent pantelleritic lava domes and basaltic spatter cones scattered within the caldera depression and outside the rime of the caldera. Therefore, this unit is an integration of many other sub-units. The total thickness of the layers is about 95 meters. Information about the timing all the volcanic products associated the Gedemsa unit is controversial. According to Morton *et al.,* (1979), building up of Gedemsa cone started 0.85-0.07 Ma but K/Ar age on the whole rock of a green welded tuff is 0.21 Ma.

3.6. Wonji Unit

Spatter cones and cinder cones with associated alkali basaltic lava flow spatially distributed mainly dominating the southeastern part of the study area closer to the main road to Asela. These cones are also exposed in the southwestern part of the study are near to Wonji sugar plantation farm. Petrographically, it is characterized by having porphyritic to subaphyric lavas with phenocrysts of plagioclase. The nature of exposure of cones varied from place to where it is mainly vesicular red in color. But in some places it exposed as gray in color. This variation in exposure color could be related with oxidation reaction intensity of the rock with the available atmospheric oxygen. Under this unit lacustrine deposits are also categorized. This lacustrine deposit is mainly exposed along the flood plain of Awash River.

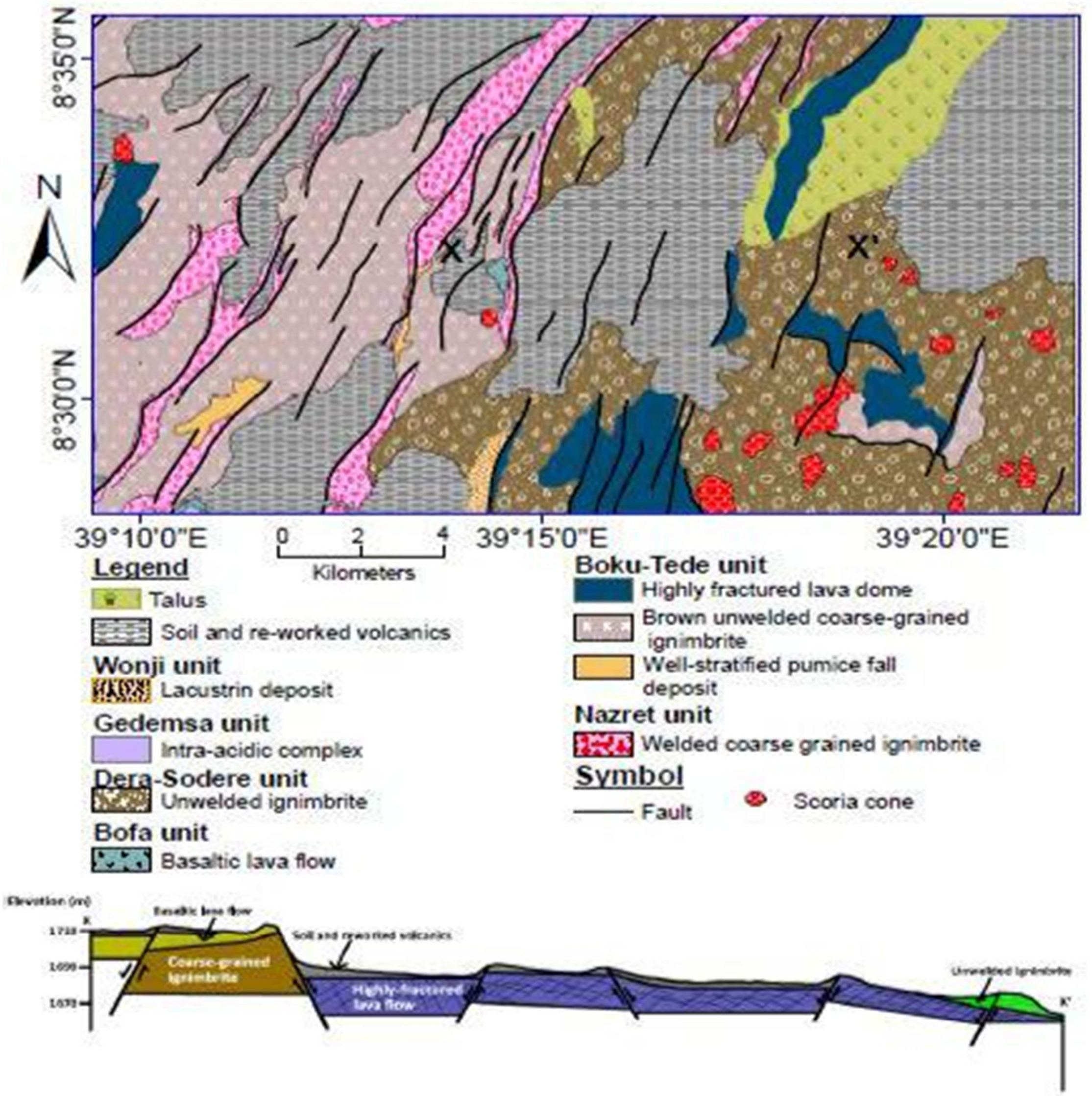

Figure 6: Geological map of the study area (modified from Morton *et al.,* 1979)

4. Methods and Materials

The methods adopted for this study includes a morphological investigation of the area using high resolution Google earth images. This high resolution images were downloaded from freely available websites and geo-referenced using the current available updated ArcGIS 10.3.1 software. Using ArcGIS techniques we digitized faults which were not mapped in the previous published maps of the region. In addition to this, we mapped ground cracks within the town and around it including measuring the strike of them using ArcGIS techniques. Orientation of faults, ground cracks and joints measured using Brunton Compass. Systematic techniques followed to encounter good exposure of fault planes. Stream network map of the area generated from the Shuttle Radar Topographic Mission Digital Elevation Model (SRTM DEM, 30m resolution) using Arc-GIS. Majority of faults are mapped from previously unpublished maps of the area, but some structures are mapped using high resolution satellite image and Google earth images. Based on the characteristics of stream networks extracted from DEM, we choose stream networks flowing across the strike of faults to investigate their slope gradient variation. For this approach we used Hacker profile and SL index analysis of streams. The longitudinal river profile is a curve, which represents the variation of elevation with the downstream distance of a river Hack (1957). The y-axis represents elevation at each point along the profile line where as the x-axis represents horizontal distance.

$SL= (\Delta H/\Delta L)\ L$

Where DH/DL is the channel gradient for a particular segment (DH ¼ difference in elevation, DL ¼ length of segment); L is the total length of the channel from its source to the midpoint of the particular segment. Knick points are mostly associated with high values of SL index in comparison to the adjacent segments. In general, the segments with high SL index Correspond either to change in lithology or an active fault Hack (1973), Keller and Pinter (2012). In a profile, a graded river is approximated by a straight, inclined line Hack and Young (1959). However, ungraded river profiles are mostly marked by a concave or convex upwards segments, depending on the degree of erosion and rate of uplift. The SL index is calculated. From this slope gradient along the stream, we evaluated the activities of some selected faults. In addition to these all, fault attitude measurement was done to compare with the current tectonic force of the region. We used a pilot geophysical investigation specifically Vertical Electrical Sounding (VES) in two different stations to estimate the unconsolidated soil burden

5. Result and Discussion

5.1 Structural features of Adama area

The main easterly inclined an archy type segment of the Main Ethiopian rift is the northern extreme of the great East African rift which is seismically and volcanically active region. Adama area is located within most active region of the Main Ethiopian Rift. Structures exposed in this area varied in length and orientation to some extent, but on average faults and fractures have the same orientation. The general orientation of structures is ranges from N 10^0 W to N 25^0 E Strike and Dips with the range of 65^0-80^0

to the west or east. Not only this common range of structural orientations, but also there are some exceptional east-west oriented structures that probably link two nearby propagating faults. We collected about 104 fault plane and fracture plane measurements from five sites geographically distributed to all directions of the city. These are the western, southern, southwestern, eastern and northern. The least number of faults exposed and measured are from the north and east of the town Adama. High displacement longer faults are the characteristics of the western faults of the town (Figure 10.). In this part of the area, faults created narrow horest and graben features. Mostly, the width of the subsided blocks becomes narrow either to the north or to the south. This narrow feature is mostly associated with dyeing out of faults. Faulted blocks are relatively greatly uplifted in this side of the area. There are very less number of systematical distributing scoria cones or cinder cones in this side of the town compared with the other parts. Orientation data of the faults from this side plotted on a stereographic projection (Figure 7). The overall orientation of all the faults plotted show N 22^0 E.

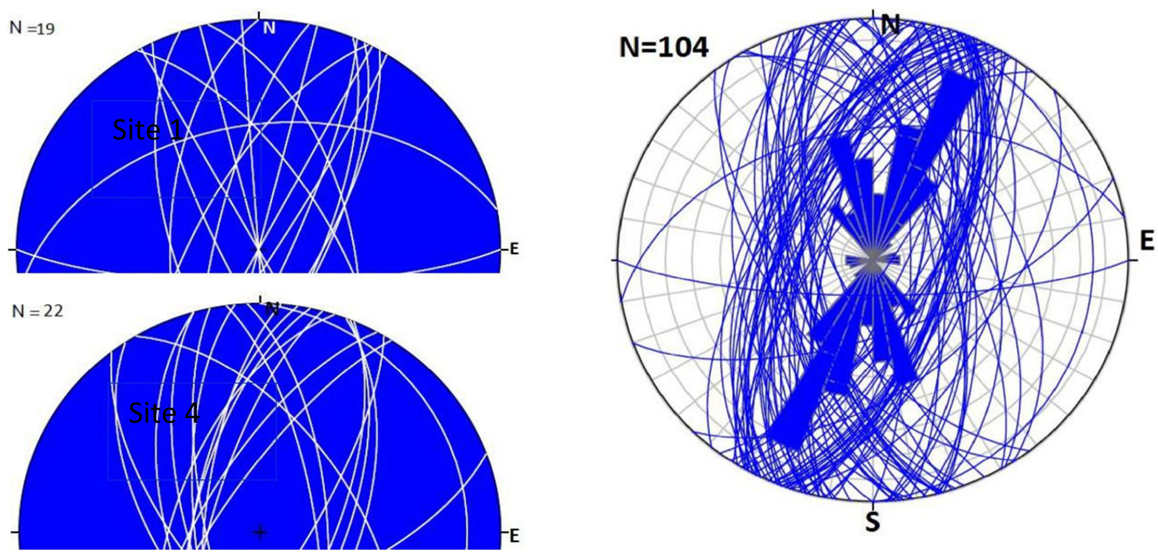

Figure 7: Representative stereographic plotting of data from fault planes and fractures and all strike plot data to average the general orientation of faults in the area.

The eastern side of the town is characterized by an elongated volcanic ridge. This elongated volcanic ridge expressed collapsing features mainly by shorter faults. The shorter faults are linked by some east-west oriented much shorter faults. The collapse of the ridge follows the general orientation of faults of the area. Following this structures historical landslide evidences can be seen very clearly (Figure 8). We recognized that the thickness of the weathered rock fragment in this part of the town is higher. Due to thicker weathered regolith, structural influence of the region and human activity (Quarrying at the base of the ridge) trigger the occurrence of landslide.

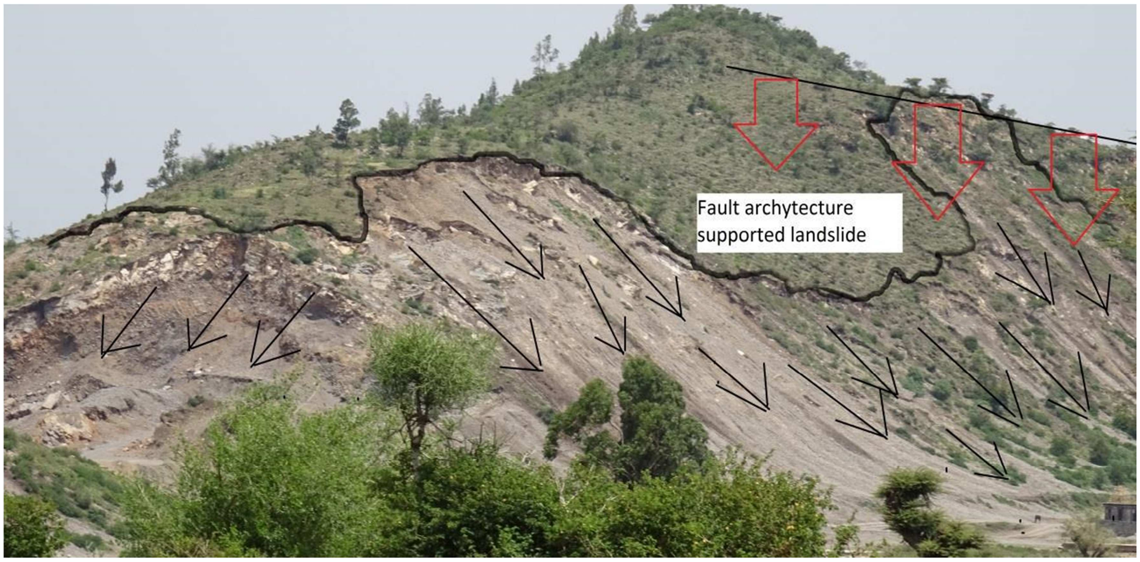

Figure 8: Landslide feature in the east of the town near to Adama science and Technology University (this study).

The southern part of the town and its surroundings are characterized by closely spaced parallel faults associated with systematically distributed scoria cones and volcanic ridges. In addition to faults in this area, there are also ground cracks which are parallel to faults. As like the faults in the west of the town, the faults in this part forms narrow horest and graben structures. Uniquely in this part of the study area, faults are the main path way for the outflow of shallow magma chamber induced hot-springs in the area known as Boku thermal spring. Not only this but also other hot-spring is also found in this area specifically to the southeast of Adama town called “Gergedi” hot spring. Both of the hot springs outflow along the fault plane probably connecting to the deep source. Compared with the western side faults geometry, faults in this area are shorter both in length and vertical displacement. Some of the faults in the south and north propagating towards to each other and closer to link within the town. Even though it is difficult to identify the tip of faults within the town due to urbanization, but morphological signatures indicate that faults are also active within the town where people already constructed their buildings. (Figure 11).

Faults in the north of the town are few in number, but longer in length. Some of the faults in this section are identified propagating towards to the north of the town. As like the other faults, human activities hide the faults morphology. This human activity significantly influenced the faults activity identification and investigation. In line with measurement of structures of the area, we have also collected joints data. The joints in the area are mostly classified into two systems of joints. The first system of joint strike N 90^{0} E and the second is perpendicular to the first and parallel to the strike of faults in the area. The overall faults data plotting on the stereographic projects are N 22^{0} E strike and 65^{0} .dip from which pole of each data calculated.

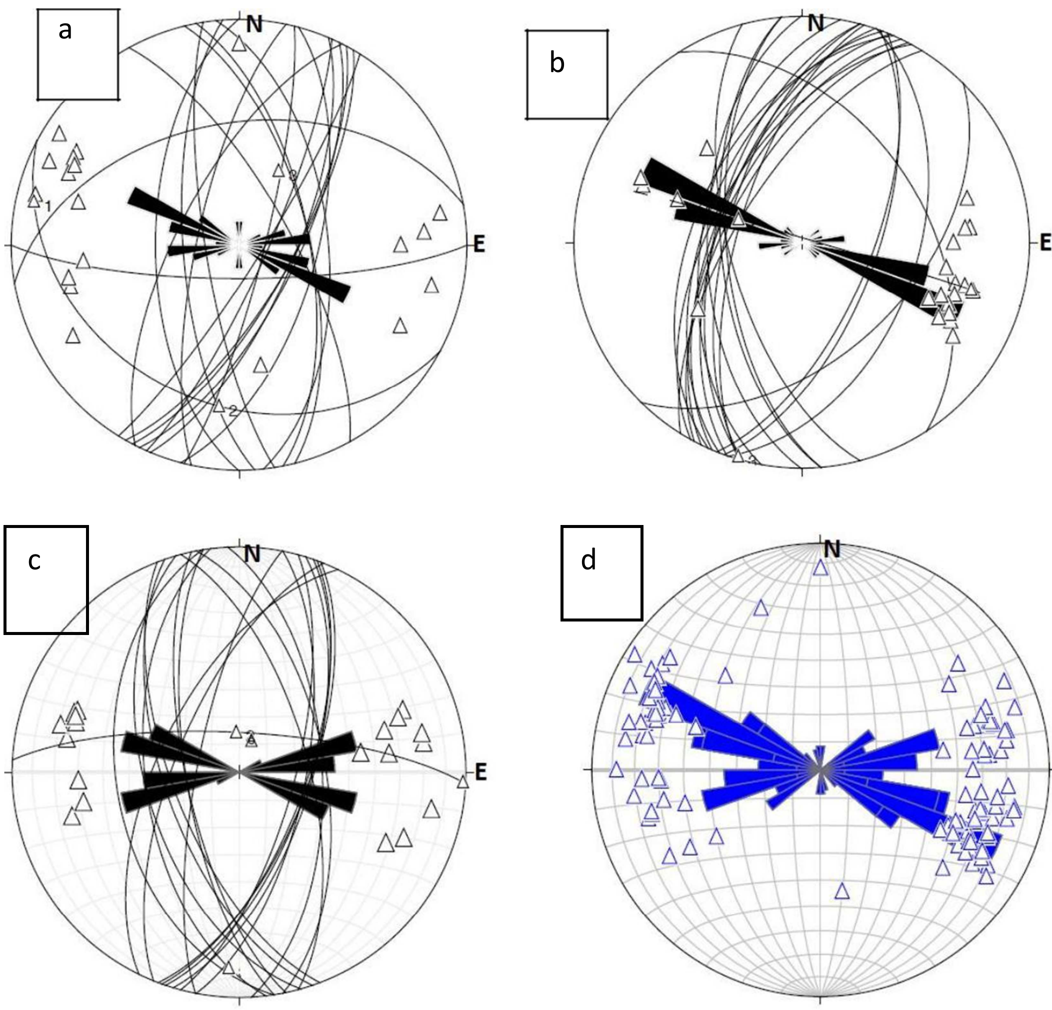

Figure 9: Calculated poles plotting from strike and dip measurement from representative sites 1, 3 and 5 (a, b and c respectively). The last plot (d) shows all the calculated poles from all sites.

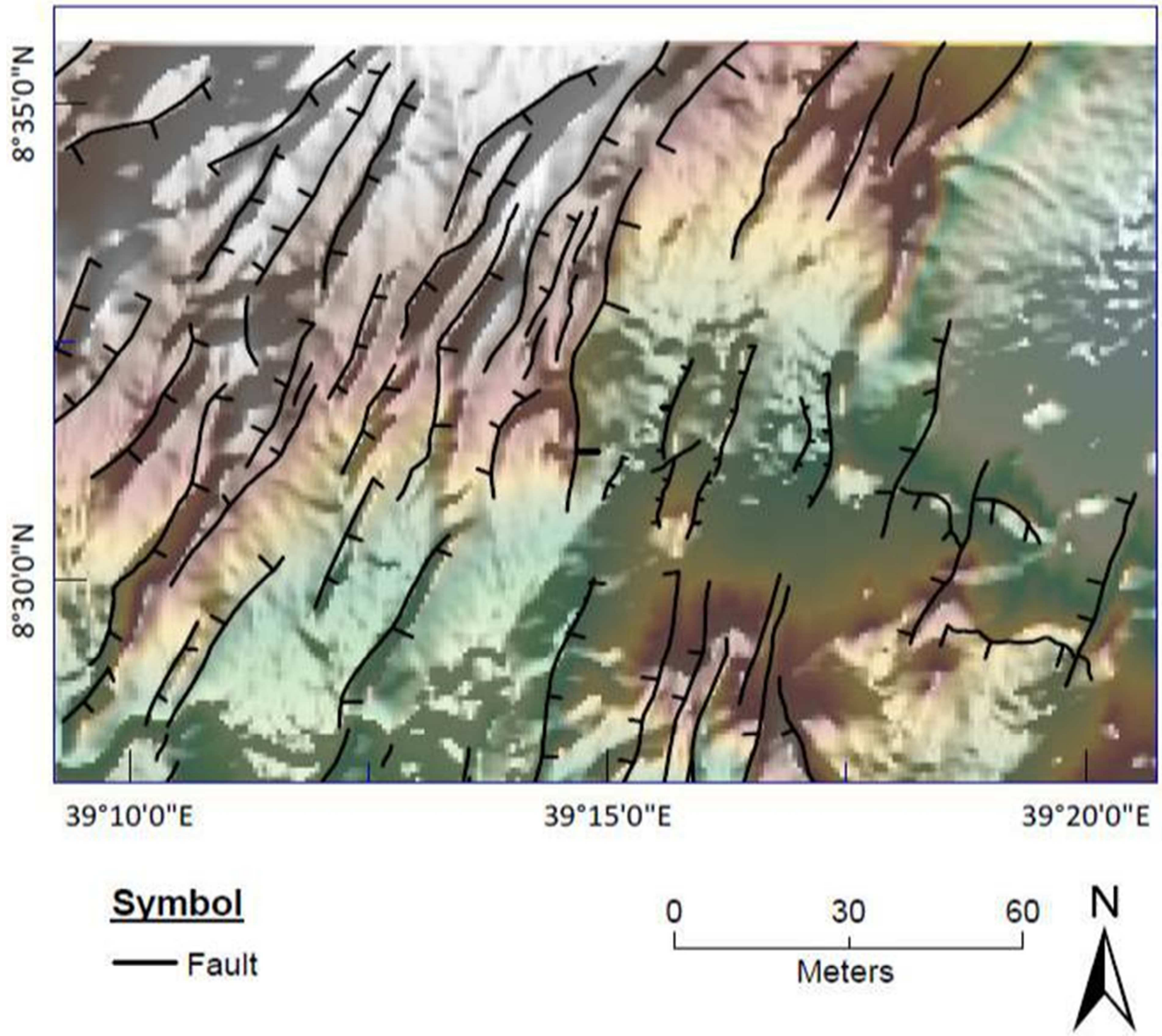

Figure 10: Structural map of the study area (Adama and its surroundings) overlay on a 30 m resolution DEM. We produced this map from previous map (Alula *et al.,* 1979), high resolution satellite image and field check.

5.2 Morphological features of the study area

Geomorphological features of Adama area are the result of different geological structural finger prints and volcanic products pileups. Faults form elongated blocks of uplifted mountain regions and a depression induced from downthrown blocks. The uplifted block is usually rocky whereas the downthrown block is mainly soil and reworked colluvium to alluvial deposits. Stream network characteristics are significally influenced by quaternary faulting activities of the area. In neotectonics studies stream flow characteristics gives valuable information about the activities of faults in an area. We used the principle of Stream profile index (SL) to identify effect of lithologic or structural control on the Hacker profile. The principle states that the higher value of SL could result from either lithological changes or structural control (active fault). In the Adama area we identified that most of stream flows are parallel to the faults strike. There is only little number of streams flowing across the strike of faults. We have selected three stream segments (Figure locations a, b and c) preferentially from the west of the town because of majority of faults are found in the west of the town. The higher values (SL) identified from each of across fault flowing streams and each of the points were also checked and we conducted field visit to verify that is either due to lithological changes or the presence of active fault. We confirmed that each of the point lie on the same lithology of the adjacent points. When faults form, they are going to expose previously fresh lithological units due to the relative movement of blocks. The exposed surface will be subjected to weathering and erosion based on the blocks relative positions and local climate. Older faults scarps will be much more morphologically evolved than the younger ones. Therefore, younger fault scarps will have little or no soil on the fault plane and exposed fresh rock outcrop with steep slope stream profile while the older scarps are the opposite. Majority of fault scarps fresh fault plane outcrop nature and immature stream profile signature. Therefore, we suggest that this morphological signature and fault plane exposure feature indicates that most faults found within and around the town are active.

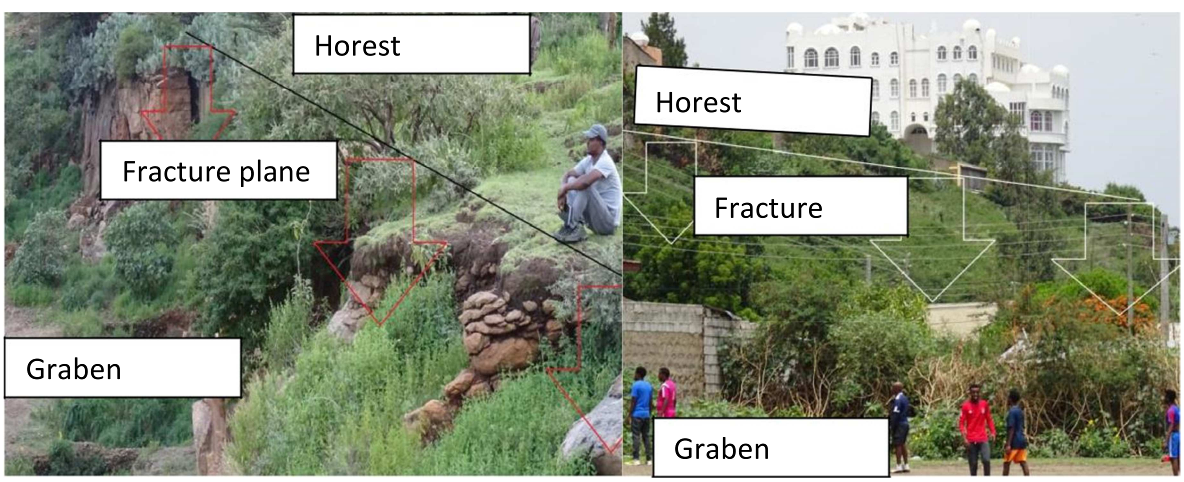

Figure 11: Showing fresh fault outcrop inside the town.

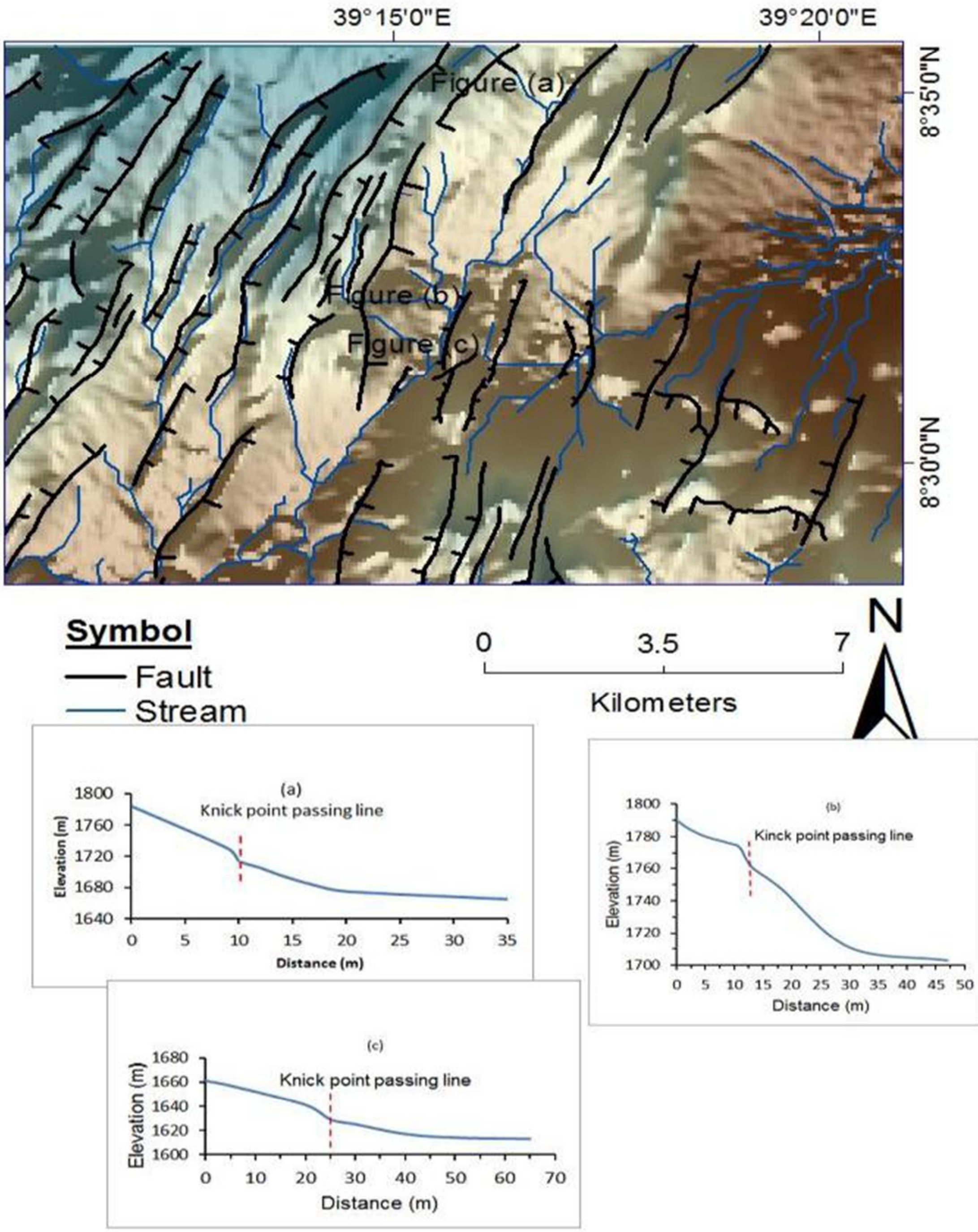

Figure 12: Showing fracture control stream flows and morphology of the area. Stream flow profile sections are plotted using hacker profile. The red dotted line indicate knick points on each profile (a, b and c) indicating active fault signature.

5.3. Ground Cracks

Ground crack feature is a common ground failure characteristic in the rift valley of Ethiopia. To list the most huge and recent ground crack occurrence is in Ziway 2012 and Shashemen 2014.This the 2014 ground crack got full attention in the country due to its greater width and length. Even though the cause of these ground cracks not yet identified in scientific reasoning, it is becoming a critical problem in the rift valley regions of Ethiopia. Likewise the other rift section of Ethiopia, ground crack is a frequent phenomenon in Adama area. We have investigated these ground cracks in Adama and its surroundings to check their relationship with the structures of the area. We have measured also the orientation of ground cracks identified in the field and using high resolution Google Earth image. These ground cracks most commonly form in the rainy season. Their spatial distribution in different parts of the town is significantly different (Figure 13). There are very less ground cracks in the north east and north west extreme of the town. A relatively much higher number of ground cracks in the southern part of the town. Likewise, the intensity of their spatial distribution, their geometrical parameters such as crack width and crack length are also variable. These mainly seasonal dependent ground cracks are more frequent and intense phenomenon in the southern part of the town. Our geophysical and field survey investigation identified the reworked volcanic and soil material thickness variations at least in the two extreme (north and south) directions of the town. The thickness is significantly more in the south than in the north (Figure 14). We believe that this could be one of the reasons for the spatial distribution and geometrical and variability of ground cracks around Adama town. In addition to these, we have also collected and analyzed ground crack orientation data from the different parts of the town. The average orientation of ground crack measurement data obtained from stereo net plotting is N 13^0 E (Figure 15). We compared our field structural data and the ground cracks orientations. The result indicates that they are statistically similar. Even though we believe that a number of factors could cause ground cracks, statistical analysis of the structural data indicates that the regional tectonic stress of MER area has an input on ground crack occurrences in the area.

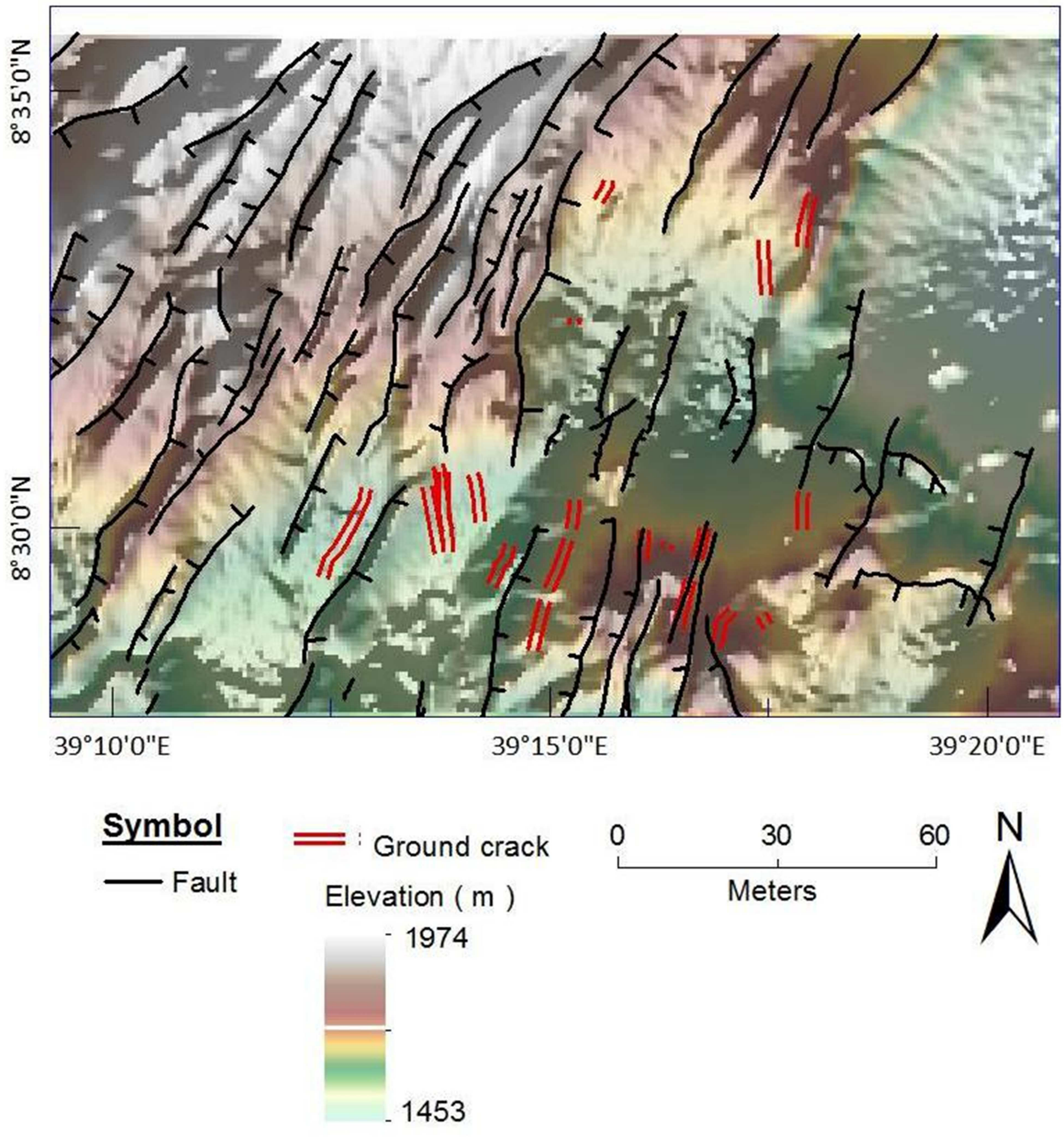

Figure 13: Ground crack map of our study area overlay on a 30 m resolution DEM and structural map of the area.

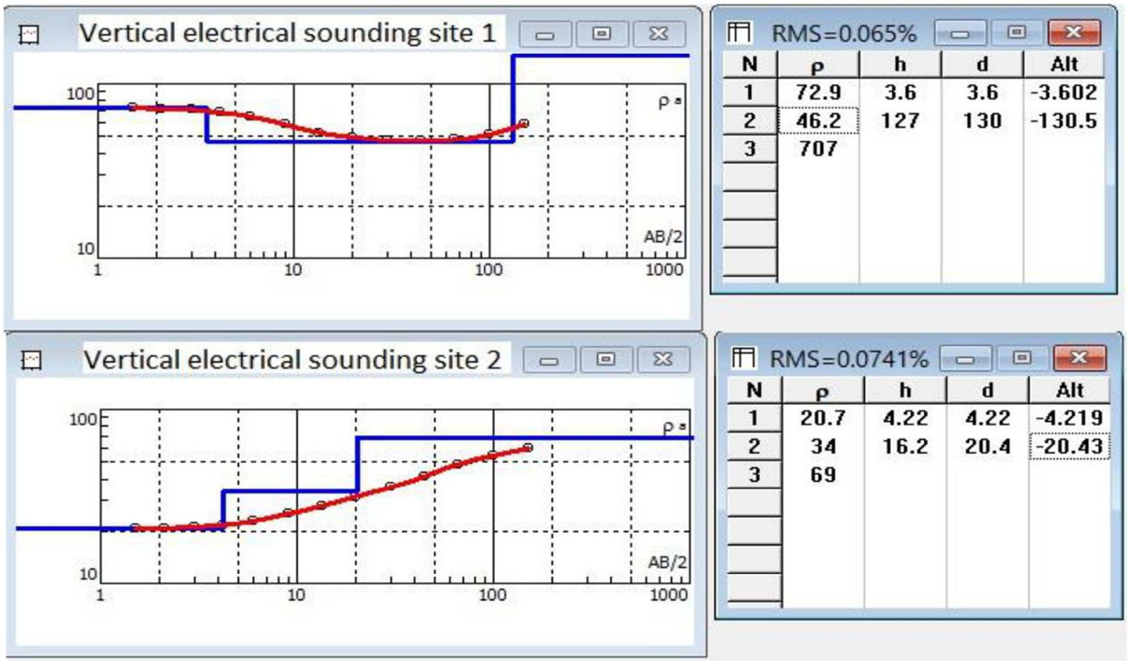

Figure 14: Showing geophysical investigation of selected areas to investigate ground crack relationship with structure and rock behavior. In site 1 (south of Adama town) it three layers identified where the week layer is about 135 meters including the thinner top dry soil. Where as in site 2 the thickness of mechanically week layer is about 25 meters.

Figure 15: Showing ground crack orientation relationship with faults attitude.

6 . Conclusion

Along the strike of the East African rift system, it has been recognized that seismic and volcanic activities are significantly variable. From the two main branches of this rift the eastern branch is characterized as much more active with respect to both volcanic and seismic activities. Further detail, from the three sections of the Main Ethiopian rift, the northern segment is the most active volcano-tectonic region. We investigated the activities of faults in Adama by integrating structural, geomorphological and geophysical data. From these multidisciplinary approach and integrated data, we summarized our conclusion as follows:

1. Paleostress analyses of faults show N 112^{0} E to N 68^{0} W stretching direction. This indicates, the stress is statistically similar with the current stress of the region obtained from geophysical study. However, we observed minor deviation of our result from the average of the regional stress that could be resulted due to local variation in mechanical strength of the lithospheric crust. Faults overlap zones are future expected deformation concentration areas (Figure 17).
2. Geomorphic signatures of streams confirmed active fault characteristic. From these integrated data, we believe that faults especially in the West of the towns are active which can result sliding along the faults planes even with smaller magnitude of Earthquake.
3. From the statistical similarity of structural attitude of faults and ground cracks, the tectonic stress of the MER has a considerable impact on the occurrences of ground crack formation in the area. The cracks density variation in the different parts of the study area could be resulted from the weak soil overburden thickness variation in each section.

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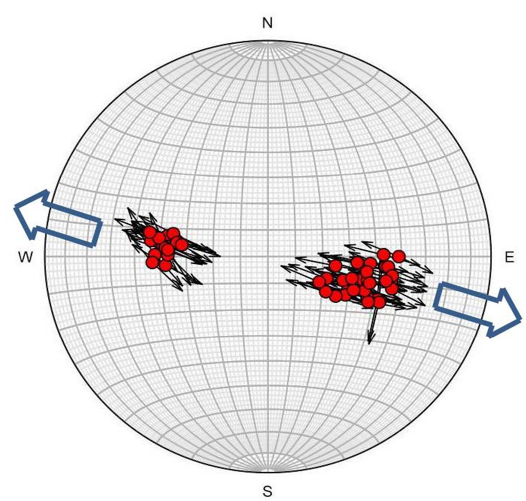

Figure 16: Kinematic analysis result of all the structural data collected from the study area.

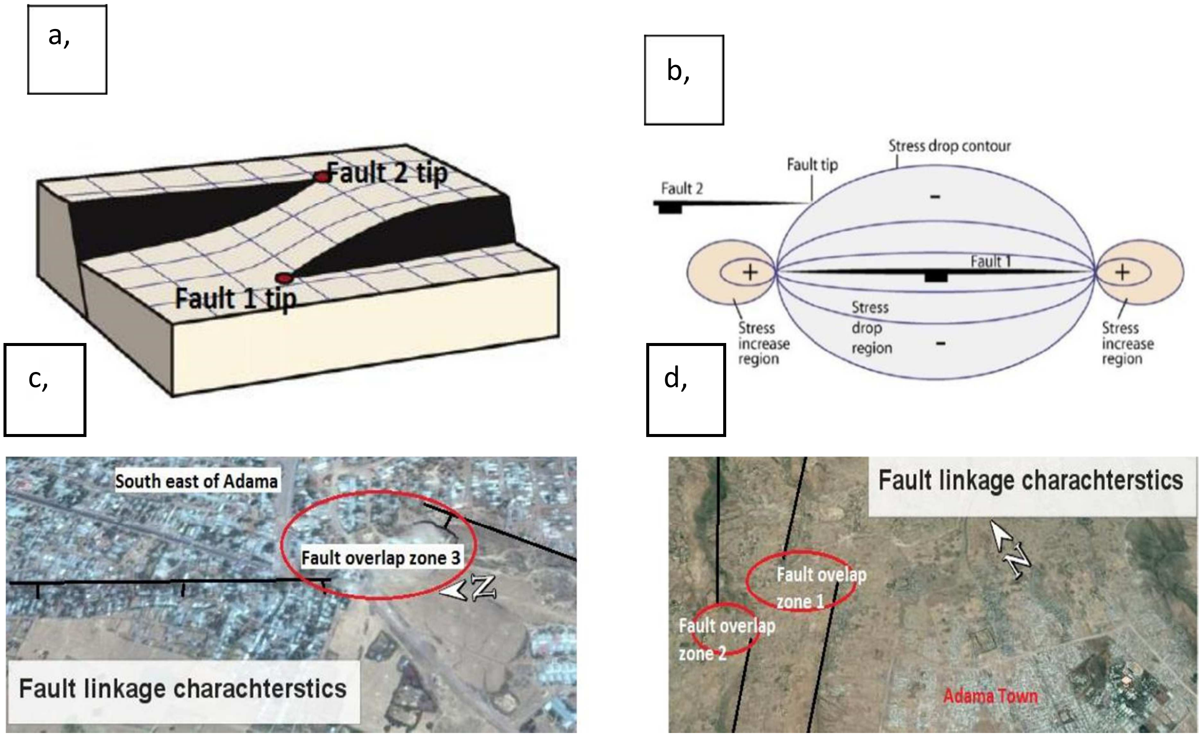

Figure 17: Showing model of fault propagation and stress accumulation zones A and B respectively (modified from Fossen & Rotevatn, 2016) and C and D locations of fault overlap zone identified in this study.

7 . Recommendations

Our study integrated mainly structural and geomorphological data. Even though the coverage is limited, we tried to integrate with one geophysical method. Faults activities investigation will give better result when a multiple geophysical methods are carried out. To better evaluate future earthquake potential and their expected geologic hazard assessment, we recommend the following:

1. Continuous monitoring of the area using geophysical monitoring.
2. Detailed investigation of landslide potential around the area to minimized future expected occurrence. We recommend this because of we have seen strongly weathered regolites accumulation along the slope of fault scarps in the area.
3. Because of the geodynamic complexity of the region, the recommended geophysical method has to be multi-approach.
4. Ground crack occurrence in the area could be linked with different factors. We recommend a multi-disciplinary approach to investigate the real cause of ground cracks in the area.

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