ANALYSIS OF THE RELATIONSHIP OF AUTOMATICALLY AND MANUALLY EXTRACTED LINEAMENTS FROM DEM AND GEOLOGICALLY MAPPED TECTONIC FAULTS AROUND THE MAIN ETHIOPIAN RIFT AND THE ETHIOPIAN HIGHLANDS, ETHIOPIA

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ABSTRACT

The paper deals with the functions that automatically extract lineaments from the 90 m Shuttle Radar Topographic Mission (SRTM) of Digital Elevation Model (DEM) (Consortium for Spatial Information 2014) in the software ArcGIS 10.1 and PCI Geomatica. They were performed for the Main Ethiopian Rift and the Ethiopian Highlands (transregional scale 1,060,000 km^2), which are one of the tectonically most active areas in the world. The values of input parameters – the RADI (filter radius) value, GTHR (edge gradient threshold), LTHR (curve length), FTHR (line fitting error), ATHR (angular difference), and the DTHR (linked distance threshold) – and their influence on the final shape and number of lineaments are discussed. A map of automated extracted lineaments was created and compared with 1) the tectonic faults on the geological map by Geological Survey of Ethiopia (Mangesha et al. 1996) and 2) the lineaments based on visual interpretation by the author from the same data set. The predominant azimuth of lineaments is similar to the azimuth of the faults on the geological map. The comparison of lineaments by automated visualization in GIS and visual interpretation of lineaments carried out by the authors around the Jemma River Basin (regional scale 16,000 km^2) proved that both sets of lineaments are of the same NE–SW azimuth, which is the orientation of the rift. However, lineaments mapping by automated visualization in GIS identifies a larger number of shorter lineaments than lineaments created by visual interpretation.

Keywords: lineaments, faults, azimuth, morphometry, Main Ethiopian Rift

Received 27 May 2016; Accepted 12 October 2016

1. Introduction

1.1 Morphostructural analysis and goals of the paper

Morphostructural analysis includes a set of several methodologies aimed at clarifying the direct and indirect linkage between landforms and the structure of the Earth's crust, whose development and character are currently dependent on the development of the mantle and core (Fairbridge 1968; Demek 1987). On the basis of observed manifestations of active tectonics and the geological structure (as faults and folds) it is then possible to define basic elementary structural units that form a morphologically compact unit. The various methods of morphostructural analysis are based either on field research or they present a set of morphometric techniques and methods of remote sensing. These analysing reference charts, aerial or satellite images and digital elevation models, most commonly in the environment of geographic information systems (GIS) (Casas et al. 2000; Novak & Soulakellis 2000; Kim et al. 2004; Jordan et al. 2005; Jordan & Scott 2005; Ekneligoda & Henkel 2006, 2010; Huggett 200; Arrowsmith & Zielke 2009; Abdullah et al. 2010; Özkaymak & Solzbilir 2012). In order to diversify the knowledge of the tectonic structure of the area, a branch of the morphostructural analysis called morphotectonic analysis, i.e. analysis of fracture systems, fault analysis and analysis of linearly arranged elements of topographic relief – lineaments, is used.

In this paper we aim at understanding the methods of lineaments extraction using automated extensions in ArcGIS 10.1 and in PCI Geomatica (*sensu* Sarp 2005; Kocal et al. 2007; Abdullah et al. 2010; Hubbard et al. 2012; Muhammad & Awdal 2012). We analysed relief and lineament networks at the transregional scale (1,060,000 km^2) using the SRTM DEM – in a much larger area than has been reported in the literature (Hung et al. 2005; Abdullah et al. 2010 and references therein). Automated lineament extraction over such a large area allows quick generation of many lineaments. The development of the DEM usage cause an increase of the number of articles focusing on automated visualization of lineaments. Those authors argue that this is a fully objective method. However, changes in the input parameters directly affect the final shape and number of lineaments. In this paper we discuss the input parameters – the RADI (filter radius) value, GTHR (edge gradient threshold), LTHR (curve length), FTHR (line fitting error), ATHR (angular difference), and the DTHR (linked distance threshold) – and compare the automated extracted lineaments with confirmed faults from the geological map and visual interpretation of lineaments carried out by the authors.

The main objectives of this work are:

https://doi.org/10.14712/23361980.2017.1
Kusák, M. – Krbcová, K. (2017): Analysis of the relationship of automatically and manually extracted lineaments from DEM and geologically mapped tectonic faults around the Main Ethiopian Rift and the Ethiopian Highlands, Ethiopia
AUC Geographica, 52, No. 1, pp. 5–17

(1) to perform automated lineament extraction within the Main Ethiopian Rift and the Ethiopian Highlands;
(2) to define stratigraphic and structural homogenous units using geological maps of Ethiopia (Geology Survey of Ethiopia 1996), extract the layer of geologically proven faults and compare the morphometric characteristics of the faults and lineaments;
(3) to compare the clipped layer of lineaments, which were extracted for the Main Ethiopian Rift and the Ethiopian Highlands using automated visualization in GIS and visual interpretation of lineaments carried out by the author, where the lineaments were drawn on the territory regional scale.

1.2 Lineaments

Linearly arranged elements of relief (lineaments) – for example linear sections of a valley or straight sections of slopes – should be considered as a potential zone of brittle fracture of bedrock with an influence on the geomorphological evolution of the area (Hobbs 1904 in Abdullah et al. 2010). According to Minár & Sládek (2009), lineaments are surface discontinuities probably tectonic in origin and are named as follows according to the method of their construction on the map: 1) photolineaments are linear boundaries identified from aerial or satellite images; 2) topolineaments are linear boundaries identified from topographic maps; 3) morpholineaments are linear boundaries determined solely from the properties of the relief (now mostly using a digital elevation model). Therefore, an analysis of lineaments can give an insight into landscape evolution and the study of lineaments thus allows to obtain information on tectonic activity over large areas, which is useful mainly for areas with limited field access (Ehlen 2004).

Currently, the most common method of extracting lineaments is the use of shaded digital elevation models and topographic maps. The lineaments may be drawn by:

(1) A modern method using automated programs called *automated visualization of lineaments*. According to Abarca (2006), the automated visualization of lineaments involves: A) processing of digital terrain models, i.e. creating shaded relief images; B) setting thresholds, according to which lineaments are automatically plotted; C) automated extraction of lineaments; D) post-processing procedures for lineament conversion from raster to vector and fixing or removing erroneous lineaments. In this paper we present a map of lineaments for the Main Ethiopian Rift and the Ethiopian Highland (a total study area of 1,060,000 km^2; Figure 1) compiled using automated extensions in ArcGIS 10.1 and in PCI Geomatica. The size and remoteness of the study area together with limited availability of detailed topographic information makes this area an ideal location for the utilization of approaches based on a global DEM. For the analysis we used the Shuttle Radar Topography Mission (SRTM), which has dramatically improved the availability of consistent high quality relief information in remote areas of the world. The potential of the SRTM dataset for lineament analysis has been successfully explored by several authors (Sarp 2005; Kocal et al. 2007; Abdullah et al. 2010; Hubbard et al. 2012; Muhammad & Awdal 2012).

(2) An older manual method called *visual interpretation of lineaments by the author*. Lineaments are drawn from different parts of base maps, and then the layers are overlapped (Ehlen 2004). Each author, however, uses individual identification criteria, which are usually based on sensory perception and cannot be quantified, or lineament maps are somewhat subjective and cannot be exactly reproduced by other authors (Wladis 1999). For

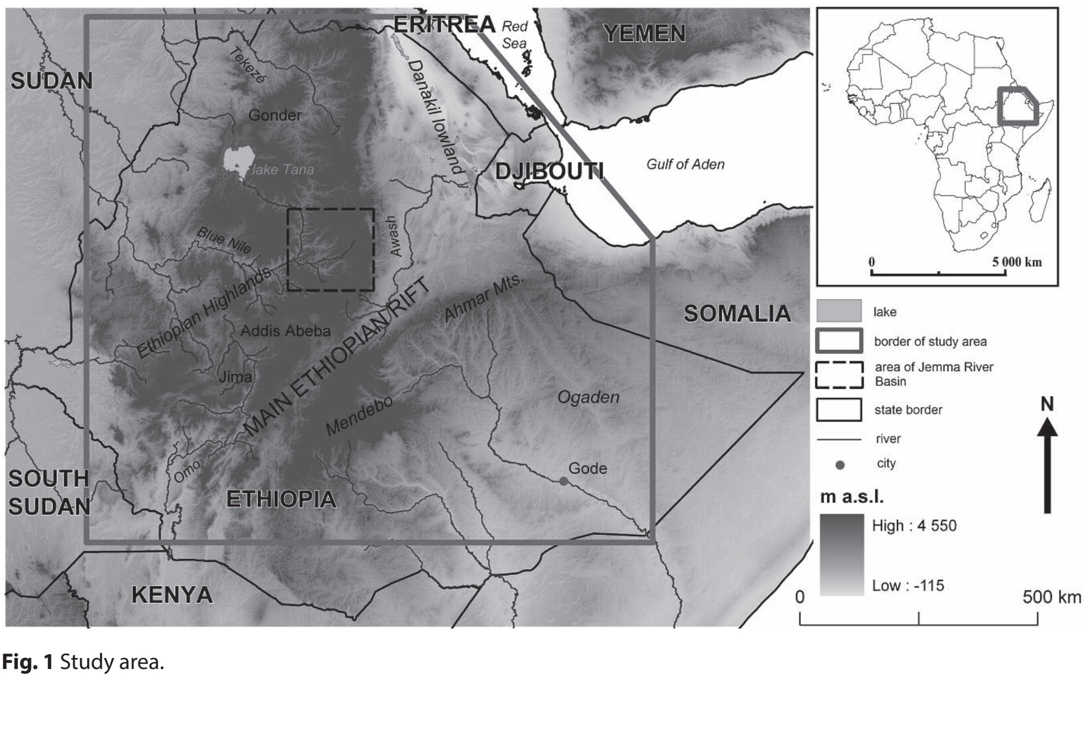

Fig. 1 Study area.

a comparison in this paper we compiled a map of lineaments for the Jemma River Basin using the classic manual method. The Jemma River, the left tributary of the Abay – Blue Nile, cut its valley in the Ethiopian Highlands to the west of the Rift Valley, approximately between 8°–14° north latitude and 36°–40° east latitude, covering the area of 16,000 km^2 (Figure 1).

2. Geological evolution of the study area

The study area is located on the African continent and is composed of the Main Ethiopian Rift and the Ethiopian Highlands. The Ethiopian Highlands are one of the most tectonically active areas in the world and lie in the border zone of three lithospheric plates, i.e. the Eurasian, African and Arabian Plate (Beyene, Abdelsalm 2005). This area has been influenced by sea transgressions (250–65 m.y. ago), episodic volcanism (65 m.y. ago), and the tectonic uplift (in the last 30 m.y.) (Kazmin 1975; Pik et al. 2003; Beyne, Abdelsalam 2005; Gani, Abdelsalam 2006; Gani et al. 2007, 2009; Wolela 2010). The Ethiopian Highlands are a rather complex structural block divided by the Rift Valley (Yunnur, Chorowicz 1998). They are characterized by volcanoes and high altitude plateaux (up to 3,000 m a.s.l.) cut by deep canyons. The flat surface of the structural blocks is the result of tectonic uplift and piling up of lava flows (Pik et al. 2003). The active uplift of the highlands activated fluvial erosion. Three uplift phases with increasing incision rates have been identified for the past 31 m.y.. Furthermore, a significant relationship was found between the uplift rates and the incision rates, which provides evidence of tectonically controlled incision (Gani et al. 2009).

The study area – the Ethiopian highlands experienced distinct geological events, e.g. repeated sea transgression and regression, Tertiary and Quaternary volcanism, uplift of Ethiopian Highlands (in the last 30 m.y.) and opening of Main Ethiopian Rift (in the last 18 m.y.), which caused the formation of faults and fractures (Kazmin 1975; Pik et al. 2003; Beyne, Abdelsalam 2005, 2006; Gani et al. 2007, 2009; Wolela 2010). The geology of the Ethiopian Highlands has been described by many authors who distinguish several differing phases of evolution: for instance Mangesha et al. (1996) recognized 7 phases; Assefa (1980, 1981) 5 phases and Russo et al. (1994) 8 phases of geological evolution. Gani et al. (2007, 2009) and Wolela (2010) distinguished 3 main periods: 1) presedimentation, 2) sedimentation and 3) post-sedimentation. The presedimentation phase (600–250 m.y. ago) is characterized by denudation processes of a Paleozoic crystalline basement, whose rocks dominate in the area. The later phase of sedimentation is dated between 250 and 65 m.y. ago (spans the entire Mesozoic) and recorded repeated sea transgression and regression. The record of this sedimentation time span can be found in the lower parts of the Jemma River network (e.g. sandstones). The third Tertiary post-sedimentation phase began 65 m.y. ago and is responsible for strong volcanic activity. A more in-depth view reveals one volcanic period in the Tertiary (Hofmann et al. 1997) and another in the Quaternary (Gani, Abdelsalam 2006). In general, lava flows dramatically influenced the river network because they covered the paleolandscape with ancient drainage and created a new surface over large areas.

As a result of tectonic activity, the Ethiopian plateau was uplifted (29 m.y.) (Beyene, Abdelsalam 2005; Pik et al. 2003) and the Afar depression emerged (24 m.y. ago) (Gani, Abdelsalam 2006). The southern and central parts of the Main Ethiopian Rift opened 20 m.y. ago (Gani et al. 2007). This opening was associated with the separation of the Danakil blocks (Somalian Plate) from the Nubian Plate, when Kieffer (2004) and Gani, Abdelsalam (2006) dated the emergence of shield volcanoes in the Ethiopian Highlands (10.7 m.y. old). The tectonic uplift rate was fluctuated and the erosion processes also has been changing. Sengor (2001) established the uplift rate of approximately 0.1 mm/year since the Eocene. The rate increased from the Pliocene to the Pleistocene (Wolela 2010). McDougal et al. (1975) assume an average rate between 0.5 and 1 mm/year. Gani et al. (2007) calculated the total uplift for the last 30 m.y. as being 2.2 km minus 300 m for denudation and 150 m for sediment consolidation, which means a total of 1,750 m. As mentioned above, the southern and central openings of the Main Ethiopian Rift are estimated to start 20 m.y. ago (Gani et al. 2009), whereas the northern part of the Rift in the Ethiopian Highlands is 11 m.y. old (Wolfenden et al. 2004). The Afar depression and the Main Ethiopian Rift divided the Ethiopian Highlands into their north-western and south-eastern parts (Kazmin 1975; Coulié et al. 2003).

Uplift of the Ethiopian Highlands, emergence of the Afar depression, separation of the Danakil blocks (Somalian Plate) from the Nubian plate and the opening of the Main Ethiopian Rift (18 m.y. to the Present) caused the formation of faults and fractures in the rock succession of the Ethiopian Highlands: from crystalline rocks (Paleozoic pre-sedimentation stage) to the younger volcanic rocks (Quaternary volcanism) (Gani et al. 2009). The prevailing orientations of the faults and fractures is NE–SW and NW–SE. Uplift of the Ethiopian Highlands caused streams to cut into bedrock and the formation of deep canyons linked to tectonic disturbances (Gani, Abdelsalam 2006; Gani et al. 2007, 2009).

3. Methods and results

The lineaments were automatically extract from the 90 m SRTM in the software ArcGIS 10.1 and PCI Geomatica. They were performed for the Main Ethiopian Rift and the Ethiopian Highlands (transregional scale 1,060,000 km^2). The values of input parameters – the RADI (filter radius) value, GTHR (edge gradient threshold), LTHR (curve length), FTHR (line fitting error), ATHR (angular difference), and the DTHR (linked distance threshold) – and their influence on the final shape and number of lineaments are discussed. Lineaments by automated visualization in GIS were compared with visual interpretation of lineaments carried out by the authors around the Jemma River Basin (regional scale 16,000 km^2).

3.1 Extraction of lineaments

3.1.1 Shuttle Radar Topographic Mission DEM

The *Shuttle Radar Topographic Mission* (SRTM) is an almost globally available digital elevation model (from 60°N to 56°S), which resulted from a single pass interferometric processing of C-band Synthetic Aperture Radar (SAR) data acquired by the Endeavour Shuttle mission in February 2000 (Rabus et al. 2003; Farr et al. 2007). During the mission 95% of the target area was covered by at least two acquisitions corresponding to the ascending and descending paths to avoid data gaps in radar shadow areas in rough terrain. The globally available version of the SRTM in public domain features horizontal resolution 3 arc seconds, which corresponds approximately to 90 m. Its mission specification required a vertical accuracy of below 16 m, which has been achieved (Gorokhovich, Voustianiouk 2006). The original dataset contains a certain amount of gaps mainly due to radar shadows in areas of rugged terrain. Since then several approaches were proposed in order to fill these gaps (Reuter et al. 2007). Tiles of the digital models are available in a mosaic of 5° longitude × 5° latitude. To capture the area of interest, i.e. the Main Ethiopian Rift and the Ethiopian Highlands, four tiles were used, i.e. 44-10, 44-11, 45-10 and 45-11, which were then combined in ArcMap 10.1 (ESRI 2011) into one digital elevation model. Since this is an area around the 10th parallel, the Z-factor value was 0.00000912 m.

Topographic surfaces described as discrete elevation function f (x, y, z) are of high interest for geoscientists. Variables such as slope inclination or slope aspect derived from the elevation data are particularly suitable for investigation of surface shapes and structures since they reflect processes that lead to their formation (Kennelly 2008). The image layer derived from DEM which is highly relevant for morphologic interpretation is hill shading. Variations in brightness in the hill shading image are a function of the illumination direction and the orientation of the surface. The brightness value is calculated as the cosine of the incidence angle of the illumination vector. Subtle changes in shades of grey render the terrain with a three-dimensional appearance. Hill shading conveys much stronger three dimensional impressions than a mere visualization of the elevation model in grey tones. Furthermore, it enhances interpretability of detailed surface structures often completely imperceptible in the DEM visualization.

3.1.2 Data processing

To generate the lineaments from a digital elevation model (DEM) using PCI Geomatica (PCI Geomatics 2010), it is paramount to create shaded relief images, in which a light source is directed from four different directions. Shaded relief images were created in ArcMap 10.1 (ESRI 2011) using the hillshade tool (Spatial Analyst Toolbox → Surface toolset). The first shaded relief image was illuminated from the north, i.e. the solar azimuth (sun angle) was 0° and solar elevation was 30° (Abdullah et al. 2010). Other shaded relief images were created with identical solar elevations and were illuminated from

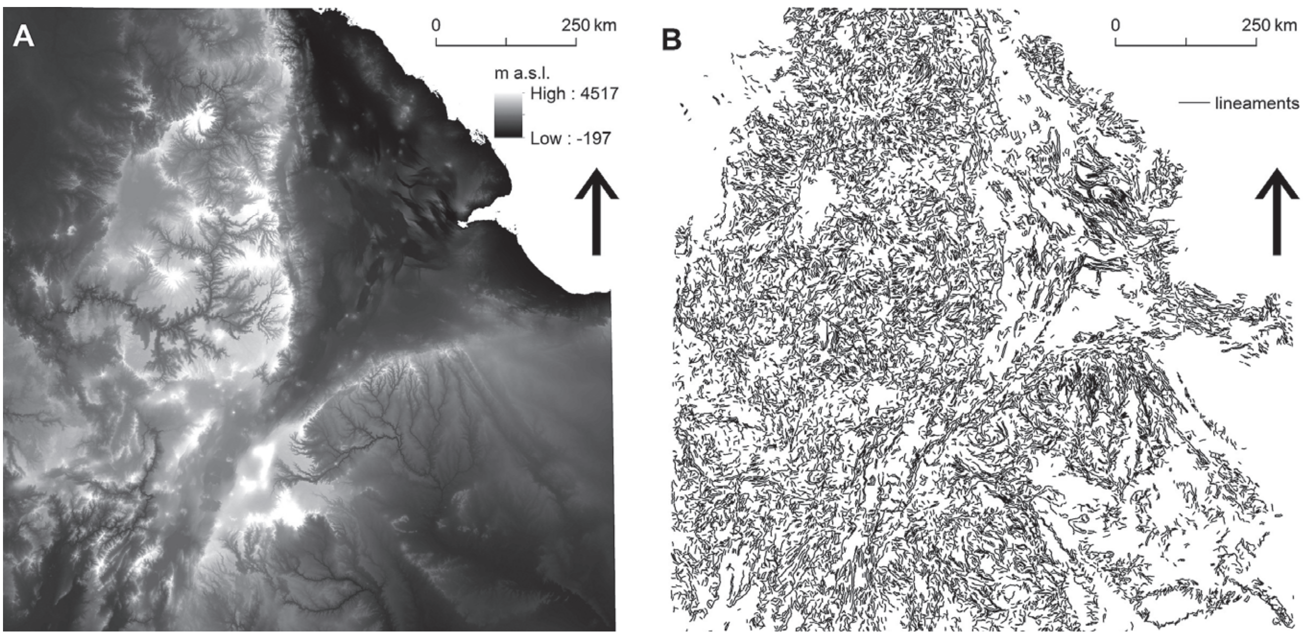

Fig. 2 (*a*) digital elevation model; (*b*) automated lineament extraction.

various directions: 1) from the north-east (solar azimuth of 45°); 2) from the east (solar azimuth of 90°); 3) from the south-east (solar azimuth of 135°).

The next step was to generate a shaded relief image from the previous four shaded relief images (in ArcMap Spatial Analyst toolbox → Local toolset → Combine tool). The combined shaded relief image was created by combining shaded relief images with a solar azimuth of 0°, 45°, 95° and 135°, respectively (*sensu* Abdullah et al. 2010; Muhammad, Awdal 2012). These combined shaded relief images were used for automatic extraction of lineaments in PCI Geomatica (PCI Geomatics 2010) (Figure 2).

3.1.3 Lineament extraction

The tool for automatic lineament extraction in the PCI Geomatica program (PCI Geomatics 2010) is called LINE. The LINE tool consists of six parameters: the RADI (filter radius) value, GTHR (edge gradient threshold), LTHR (curve length), FTHR (line fitting error), ATHR (angular difference), and the DTHR (linked distance threshold) (*sensu* Sarp 2005). The values used in the analysis depend on the data and the size of the study area (*sensu* Kocal et al. 2007; Hubbard et al. 2012). RADI parameter the radius of the edge detection filter in pixels (PCI Geomatics 2010). The larger the RADI (filter radius) value, the less noise and detail appear in the edge detection result. Based on the area, the value of the RADI parameter was 24. GTHR (edge gradient threshold) specifies the threshold for the minimum gradient level for an edge pixel (PCI Geomatics 2010). The suitable output binary image was achieved using GTHR = 94. LTHR (curve length) specifies the minimum length of the curve, which is considered as the lineament (PCI Geomatics 2010). We used a value of 50, which means that the smallest lineament is 50 pixels (4.5 km) long. If the lower value of curved length was chosen, the resulting lineaments would be too short taking into consideration the large study area. On the other hand, if the curved length was chosen higher, the resulting lineaments would link together. FTHR (line fitting error) defines the tolerance for fitting line segments to a curved lineament (PCI Geomatics 2010). A larger value provides less noise and straighter lineaments; for our analysis we used FTHR = 7. ATHR (angular difference) defines the maximum angle between two vectors for them to be linked (PCI Geomatics 2010). The ATHR value used in this analysis was 40, which means that the maximum angle between two linked vectors was 40°. DTHR (linked distance threshold) specifies the maximum distance between two vectors to be linked (PCI Geomatics 2010). The distance between two vectors in our study was 30 pixels (2.7 km).

3.2 Morphometric characteristics of lineaments

The following morphometric characteristics (*sensu* Křížek, Kusák 2014) were used to characterize the lineaments near the Main Ethiopian Rift and the Ethiopian Highlands:

a) the number of lineaments N is determined as the number of all lineaments in the study area;

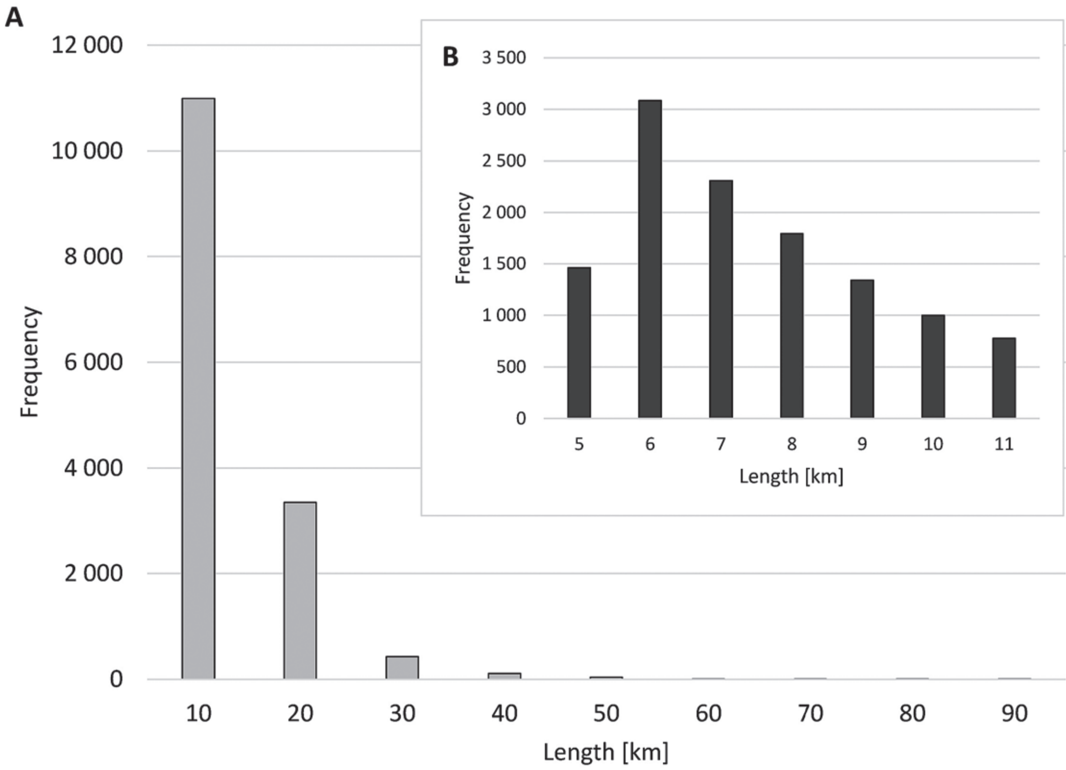

Fig. 3 Frequency of the total lengths of lineaments: (*a*) 10 km frequency; (*b*) 1 km frequency.

b) the total length of lineaments L_t is defined as the sum of lengths of all lineaments in the study area;
c) the morphotectonic network density D is defined by the relation:
$D = L_t / P$ (1),
where P is the study area;
d) the azimuth of lineaments A is determined as the lineament orientation to the geographic coordinate system. The azimuth of lineaments is illustrated by rose diagrams, which are divided into 72 intervals of 5° (in total 360°) moving clockwise. The numbers of lineaments in the rose diagrams are multiplied by their length.

The total length of lineaments L_t and the azimuth of lineaments A were calculated in ArcMap (ESRI 2011) using of the extension Easy Calculate 10 (Ian-ko 2014).

The morphotectonic network of lineaments near the Main Ethiopian Rift and the Ethiopian Highlands consist of 14,940 lineaments. The shortest lineament in the morphotectonic network reach a length of 4.5 km and the longest lineament reach a length of 85 km. In total, 73.6% of the lineaments reach a length of 10 km (Figure 3a), while the number of lineaments in the study area increases with increasing length of lineaments to the length of 6 km, then the number of lineaments decreased with increasing length (Figure 3b). Taking into that the total length of lineaments is 134,151 km and the study area is 1,060,000 km^2, then the morphotectonic network density of lineaments is 0.13 km/km^2. Azimuths of lineaments near the Main Ethiopian Rift and the Ethiopian Highlands were distributed evenly in all directions. On such a surface area, where the different parts of landscape have different geneses and ages, i.e. in history they developed by different tectonic processes, the morphometric characteristic azimuth of the lineaments does not give accurate information. Therefore, the azimuth of lineaments proved to be the most important morphometric characteristic of the morphostructural analysis (Minár, Sládek 2009; Abdullah et al. 2010). Due to this fact and because we considered the azimuth of lineaments to have no dominant direction, the study area need to be divided into seven *subregions*.

3.3 Comparison of extracted lineaments and faults from the geological map of Ethiopia

A detailed analysis of azimuths of faults and lineaments by automated visualization in GIS was performed for the individual *subregions*. The geological map at the scale 1 : 250,000 (Mangesha et al. 1996) was used to divide the area of The Main Ethiopian Rift and the Ethiopian Highlands into 7 geologically homogenous units (Table 1; Figure 4), in order to compare them with the diagrams of the faults and lineaments (see Figure 5; 6). The units are as follows from the youngest one:

a) Afar depression – *subregion 2* is formed by Holocene sediments. Most tectonic faults and lineaments are of the NW–SE azimuth, the same direction as the expansion direction of the Afar depression;
b) Main Ethiopian Rift – *subregion 4* is formed by Pleistocene sediments, the main faults and lineaments are in the same direction as the Main Ethiopian Rift, the NE–SW azimuth;
c) Western part of the Ethiopian Highlands *subregion 1* and *3* and the eastern *subregion 7* consist of Eocene rocks. While the tectonic predisposition of the Main Ethiopian Rift (*subregion 4*) and Afar depression (*subregion 2*) is clear, the strong tectonic uplift in the westernmost part of the Ethiopian Highlands (*subregions 1* and *3*) demonstrates slightly more variability i.e. the tectonic faults and lineaments are predominantly in the N–S azimuth, but there are also many lineaments in a wide range of azimuths. The area of *subregion 7* is too small to perform an analysis of the faults (i.e. on the geological map there are only a few tectonic faults), so this *subregion* was not considered in further analysis;
d) In the south-eastern part of the study area there is a small *subregion 6* which is composed of Cretaceous sediments. There are tectonic faults and lineaments with no dominant azimuth;
e) Eastern part of the Ethiopian Highlands – *subregion 5* is the oldest part of the area and is formed by Late Jurassic rocks. *Subregion 5* was uplifted and inclined to the southeast during the uplift of the Ethiopian Highlands. The tectonic faults and lineaments are predominantly in the NW–SE azimuth, and are supplemented by several faults (NE–SW azimuth) perpendicular to the main direction of the tectonic faults.

The main reason for including the lineament analysis in the determination of the influence of tectonics in the morphostructural analysis is that the lineaments are lithologicallly and/or tectonically controlled. The lineaments are considered as a potential zone of brittle bedrock fracture influencing the geomorphological evolution of the area. (Hobbs 1904 in Abdullah et al. 2010), or more specifically that the lineaments are surface discontinuities of a probable tectonic origin (Minár & Sládek 2009). The predominant azimuth of the lineaments determined by automated visualization in GIS (Figure 6) is similar to the azimuth of the faults on the geological maps of the Geology Survey of Ethiopia (Figure 5; 1996). Because the total number of lineaments (14,940) is much higher than total number of faults (3,004), the lineaments demonstrate slightly more variability of azimuths. However, not every lineament determined by automated visualization in GIS represents a tectonic fault on the landscape and the number of faults on the geological map of the Geological Survey of Ethiopia (Mangesha et al. 1996) is considerably generalized. For a more accurate understanding of the relationship between the lineaments and the landscape, the lineaments determined by automated visualization in GIS were compared with the visual interpretation of

Tab. 1 Seven geologically homogenous units.

Subregions	Area [km²]	Type of rock	Azimuth of faults	Azimuth of lineaments	Azimuths explanation
subregion 1	280,000	Eocene rocks	N–S	N–S	tectonic uplift caused the formation of the lineaments with a N–S direction
subregion 2	183,500	Holocene sediments	NW–SE	NW–SE	the same direction as the expansion of the Afar depression
subregion 3	194,000	Eocene rocks	N–S	N–S	tectonic uplift caused the formation of the lineaments with a N–S direction
subregion 4	100,000	Pleistocene sediments	NE–SW	NE–SW	the same direction as the Main Ethiopian Rift
subregion 5	192,000	Late Jurassic rocks	NW–SE	NW–SE	the same direction as the inclination of its geological unit
subregion 6	65,500	Cretaceous sediments	none dominant	none dominant	more generations of faults were formed at different geological times
subregion 7	45,000	Eocene rocks	–	–	the area is too small to perform an analysis of the faults

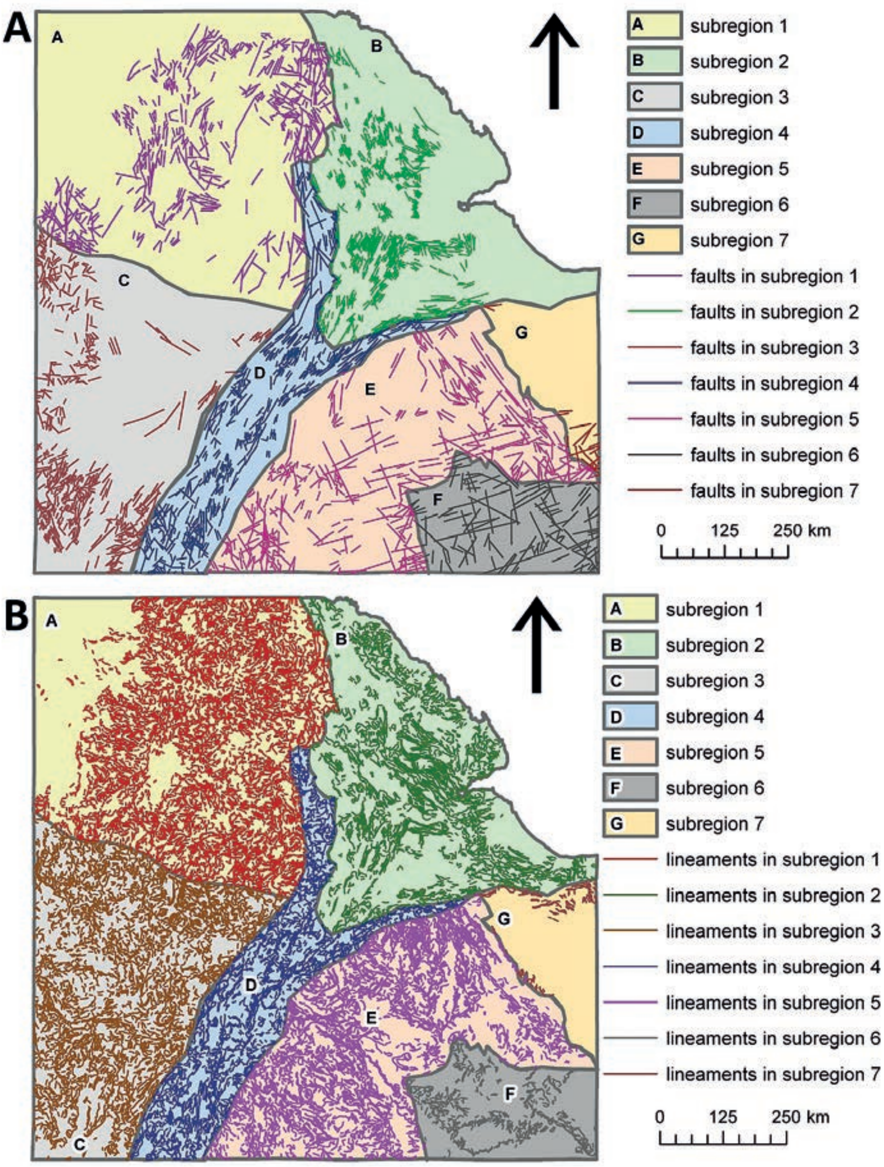

Fig. 4 Geologically homogenous units (Geology Survey of Ethiopia 1996), (*A*) tectonic faults and (*B*) lineaments. Note: (*a*) and (*c*) western part of the Ethiopian Highlands – *subregion 1* and *3* and (*g*) eastern part – *subregion 7* consists of Eocene rocks; (*b*) Afar depression – *subregion 2* is formed by Holocene sediments; (*d*) the Main Ethiopian Rift – *subregion 4* is formed by Pleistocene sediments; (*e*) eastern part of the Ethiopian Highlands – *subregion 5* is formed by Late Jurassic rocks; (*f*) *subregion 6* is formed by Cretaceous sediments.

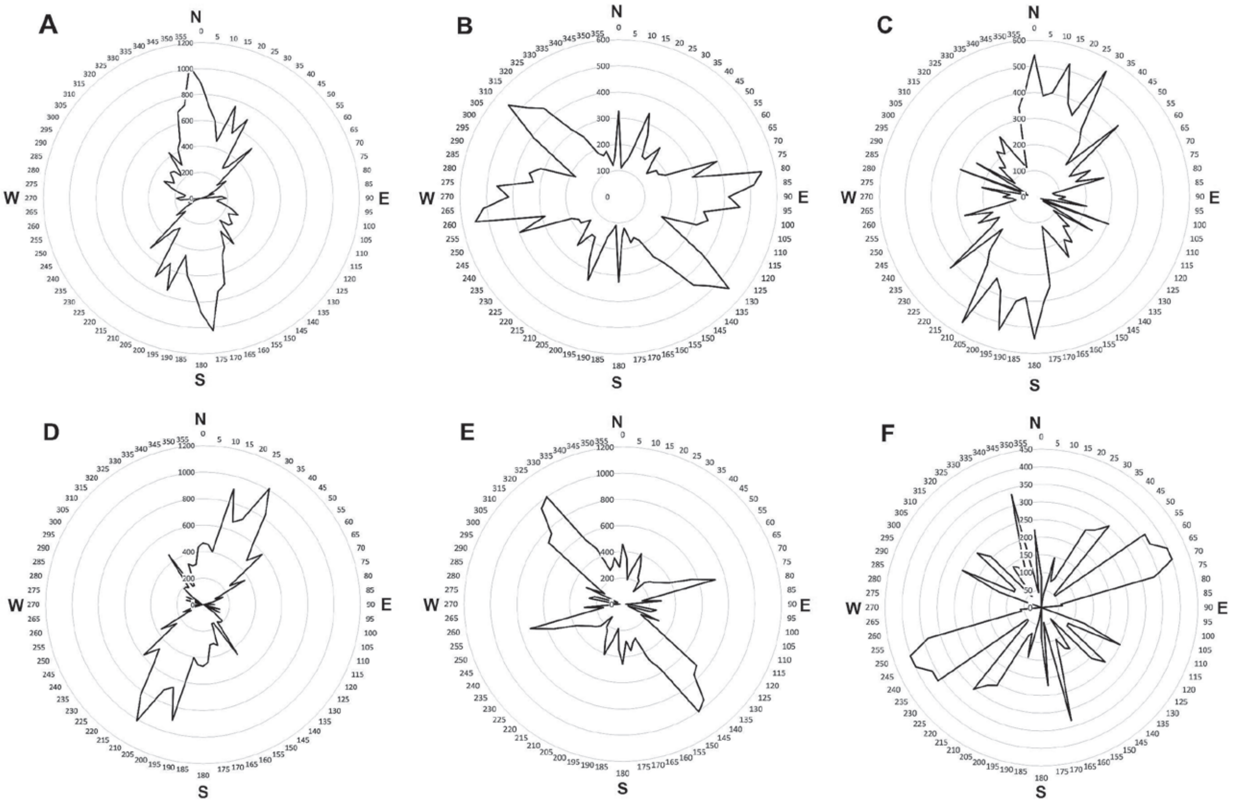

Fig. 5 Azimuth of the faults on the geological map (Geology Survey of Ethiopia 1996). Note: (*a*) N–S azimuth (orientation 175°–355°) of faults in *subregion 1*; (*b*) NW–SE azimuth (orientations 80°–260°; 130°–310°) of faults in *subregion 2*; (*c*) N–S azimuth (oriantations 0°–180°; 25°–205°) of faults in *subregion 3*; (*d*) NE–SW azimuth (orientation 25°–205°) of faults in *subregion 4*; (*e*) NW–SE azimuth (orientations 75°–255°; 145°–325°) of faults in *subregion 5*; (*f*) the faults in *subregion 6* have no dominant azimuth.

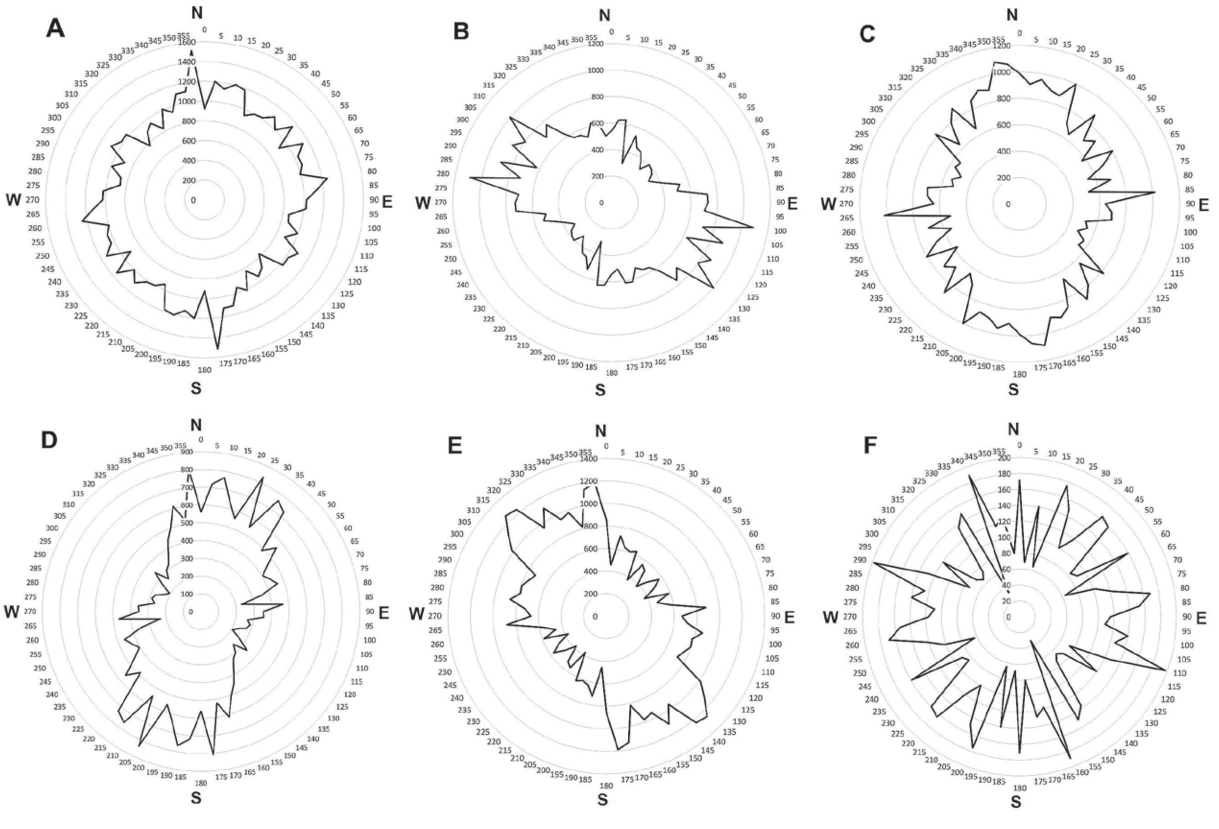

Fig. 6 Azimuth of the lineaments. Note: (*a*) N–S azimuth (orientation 175°–355°) of lineaments in *subregion 1*; (*b*) NW–SE azimuth (orientations 100°–280°; 130°–310°) of lineaments in *subregion 2*; (*c*) N–S azimuth (orientations 0°–180°) of lineaments in *subregion 3*; (*d*) NE–SW azimuth (orientations 0°–180°; 135°–215°) of lineaments in *subregion 4*; (*e*) NW–SE azimuth (orientations 140°–320°; 175°–355°) of lineaments in *subregion 5*; (*f*) the lineaments in the *subregion 6* have no dominant azimuth.

lineaments by the author performed around the Jemma River Basin.

3.4 Comparison of lineaments performed manually and extracted automatically

A total of 408 lineaments were mapped by visual interpretation by the author around the Jemma River Basin and its close surroundings (an area covering 16,000 km^2; Figure 7a). The total length of lineament was 5,248 km. This part of the Ethiopian Highlands was influenced by tectonic processes associated with the formation of the Rift Valley. The lineaments have a main NE–SW azimuth (Figure 7b) – the main direction of the azimuth is N25°E and the second direction is N60°E. The NE–SW azimuth of lineaments is consistent with the orientation of the rift.

Lineaments were mapped in the same area by automated visualization in GIS 833 with a total length of 7,553 km (Figure 7c). The main azimuth of these lineaments is also in a NE–SW direction (Figure 7d), with the difference that the main direction of the azimuth is N60°E–N65°E and the second direction is N25°E.

This difference is caused by the different methods of lineaments mapping. During the visual interpretation of the lineaments, the authors identified mainly linear units of thalwegs and ridges in the landscape (Figure 7a). This results in a smaller number of longer lineaments (the most frequently determined total length of lineaments interpreted by the author was between 10 and 15 km). The mapping of lineaments by automated visualization in GIS identifies the lineaments by differences of grayscale of the pixels in the hill shading image – the lineaments

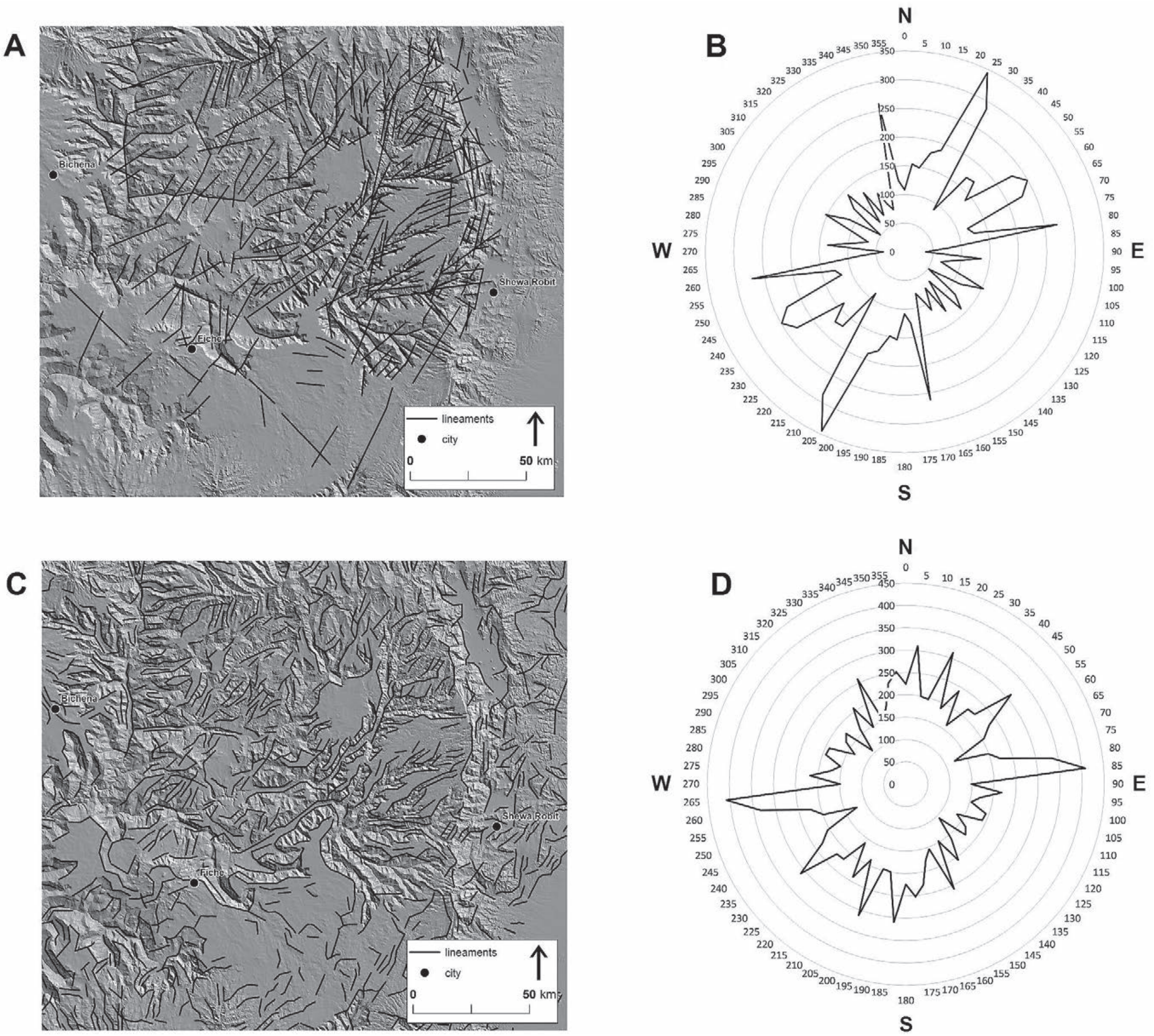

Fig. 7 Lineaments around the Jemma River Basin and its close surroundings. Note: (*a*) visual interpretation of lineaments by the author; (*b*) rose diagram of frequency of lineaments. The dominant NE–SW azimuth (orientations 25°–205°; 180°–260°) of lineaments visually interpretated by the author; (c) lineaments by automated visualization in GIS; (d) rose diagram of frequency of lineaments. The dominant NE–SW azimuth (orientations 45°–225°; 180°–260°) of lineaments by automated visualization.

mainly copied the borders of valleys as opposed to the valley thalwegs (Figure 7c). The result is a larger number of shorter lineaments (the most frequently determined total length of lineaments by automated visualization in GIS was 5 km).

4. Discussion

Automated lineament extraction has been performed by various authors (Kocal et al. 2007; Hung et al. 2005; Abdullah et al. 2010). The authors have also used various different study areas and various input DEM resolutions. Compared with other authors, we used the largest study area (Table 2). Therefore, we needed to use different parameters and thresholds. The resolution also plays the dominant role in the quality of the extracted lineaments. In comparison, we used a lower quality DEM because our input DEM resolution was only 90 m.

The parameters also differ from other authors' parameters (see Table 2). We used larger RADI parameters because the larger the RADI value, the less noise in the result, to the detriment of the amount of detail (Kocal et al. 2007). According to these authors, the value between 5 and 7 gives good results, whereas higher values result in a loss of data. We experimented with the GTHR parameter because its value is difficult to determine at first. We used the highest LTHR value because our study area was very large, so we needed to have long rectilinear lineaments, which were considered to be the lineaments. An interesting difference is also in the FTHR value. The lower the value, the shorter the line segments approximate to the lineaments. The default value is 3 in PCI Geomatica, which corresponds to Kocal et al. (2007), who published, that to obtain shorter line segments the recommended FTHR parameter is between 2 and 3. However, if we considered the size of study area, lower FTHR value produced a shorter segments in the polyline and thus higher amount of noise. The smaller the ATHR parameter, the more disconnected the lineaments appear. We tried several ATHR parameters but the value of 20, which is recommended, showed very short discontinuous lineaments and a value higher than 40 showed polygon shaped lineaments. In comparison with Hung et al. (2005) and Abdullah et al. (2010), we used the highest DTHR parameter value. We wanted to have a higher maximum distance between two vectors. Kocal et al. (2007) and Hung et al. (2005) used very small DTHR values because they had a very small study area. Abdullah et al. (2010) used a DTHR value of 20. Due to the fact that we had a very large study area and we wanted to detect lineaments separately, according to the resolution of the input DEM, a DTHR value of 30 was considered to be the best choice.

This paper demonstrates that the number of lineaments extracted by automatic methods is higher than the number of manually created lineaments. The automatically extracted lineaments are also shorter than man-made lineaments and not every extracted lineament represents a geological feature. This is the main problem of the automated method. Furthermore, the results depend on the previous data resolution. It is assumed that if the resolution of the previous DEM in this large study area would be higher, then the number of extracted lineaments would also be higher. Another error is caused by the border of the input DEM, because the pixel size there can be distorted.

5. Conclusion

The presented study demonstrates that the SRTM DEM with 90 m resolution has enough quality for lineament extraction. For automated lineament extraction from the SRTM DEM, the suitable parameters are necessary. We determined that the size of the study area can be larger than presented by several authors so far (e.g. Hung et al. 2005; Kocal et al. 2007 and Abdullah et al. 2010), i.e. 1,060,000 km^2.

The morphotectonic network consisted of 14,940 lineaments; the most common length of the lineaments was 10 km (73.6%). The predominant azimuth of the lineaments is similar to the azimuth of the faults on the geological map of the scape 1 : 250,000; however, because the total number of lineaments is much higher than the total number of faults (in total 3,004 faults) the lineaments demonstrate slightly more variability of azimuths.

Tab. 2 Parameters used in the automatic extraction of lineament by different authors in comparison with this paper.

Authors	Abdullah et al. (2010)	Hung et al. (2005)	Kocal et al. (2007)	Our work
Study area [km^2]	2,340	284	15	1,060,000
Resolution [m]	30	30	1	90
RADI	12	5	12	24
GTHR	90	10	26–60	94
LTHR	30	7	20–30	50
FTHR	10	3	3	7
ATHR	30	7	20	40
DTHR	20	3	1	30

A detailed analysis of the faults and lineaments azimuths in geologically homogenous units showed a high degree of parallelism. The visual interpretation of lineaments by the author around the Jemma River Basin and the lineaments by automated visualization in GIS at the regional scale have the same NE–SW direction – and in the same orientation like the Rift. Lineaments visually interpreted by the author consist of linear units of thalwegs and ridges in the landscape. This resulted in a smaller number of longer lineaments. In contrast, the mapping of lineaments by automated visualization in GIS identifies the lineaments by differences in the grayscale of the pixels in the hill shading image and the lineaments copied mainly rather border valleys than valley thalwegs, which results in a larger number of shorter lineaments.

In conclusion, the automated lineament extraction is recommanded for larger area (transregional scale). In our opinion, the speed of rendering lineaments leads to a decrease of the accuracy morphostructural analysis results. The method should be still complemented by the author's manual control of lineaments.

Acknowledgements

This study was supported by the Grant Agency of the Czech Republic (P209/12/J068) and the Grant Agency of Charles University in Prague (1436314).

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RESUMÉ

Analýza vztahu automaticky a ručně vykreslených lineamentů z DEM a tektonických poruch kolem Etiopského riftu a Etiopské vysočiny, Etiopie

Článek se zabývá metodami automatického vykreslení lineamentů pomocí programů ArcGIS 10.1 a PCI Geomatica s použitím dat SRTM DEM s velikostí pixelu 90 m (CGIAR-CSI 2014). V článku jsou diskutovány hodnoty vstupních parametrů a jejich vliv na konečný tvar a počet vykreslených lineamentů v okolí Etiopského riftu a Etiopské vysočiny (nadregionální měřítko), které patří mezi tektonicky nejvíce ovlivněné části světa. Na základě automatických metod GIS programů byla vytvořena mapa lineamentů, která byla následně porovnána 1) s reálnými tektonickými poruchami zaznamenanými v geologické mapě v měřítku 1 : 250 000 (Mangesha et al. 1996) a 2) s lineamenty vykreslenými na základě autorské vizuální interpretace digitálních modelu reliéfu v okolí povodí řeky Jemmy (regionální měřítko).

Převládající azimuty lineamentů se ukázaly být shodné s azimuty tektonických poruch na geologických mapách. Z porovnání automaticky vykreslených lineamentů v prostředí GIS a lineamentů vzniklých autorským vykreslením vyplývá, že u obou skupin lineamentů převažuje SV–JZ orientace, tedy stejný směr jakým je orientovaný i Etiopský rift. Z tohoto srovnání dále vyplývá, že mapování lineamentů pomocí automatizovaných metod v prostředí GIS identifikuje větší počet lineamentů, ale jejich délka je – oproti ručnímu vykreslení – kratší.

Závěrem lze říci, že automatizované metody vykreslení lineamentů jsou vhodné pro analýzy rozsáhlých území (transregionální měřítko). Podle našeho názoru, rychlost vykreslení lineamentů vede k poklesu přesnosti výsledků morfostrukturní analýzy a metody by stále měla být doplněna o autorovu manuální kontrolu vykreslených lineamentů.

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