Assessing the effect of volcano-tectonic activity on the spatial distribution of surface temperature in the Main Ethiopian Rift, using integrated approach of remote sensing data

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ABSTRACT
Heat energy continuously flows from the interior of the earth’s layers to the surface, usually associated with rifiting and faulting the earth’s crust. So, the spatial distribution of heat energy in the earth’s crust differs laterally and vertically depending on several factors, such as radioactive isotopes in the area’s rock, volcano-tectonic, and hydrological nature. The study was conducted in the Northern segment of the Main Ethiopian Rift. Geological and volcanic structures have been considered to determine the effect of volcano-tectonic activity on the spatial variability of surface temperature. The surface kinetic temperature was retrieved from Landsat 8 imagery using the Emissivity Modulation method, resulting in minimum and maximum values of 21 and 45.9°C. The higher surface temperature anomalies (>45°C) have been found in the region of densely concentrated geological and volcanic structures. Based on this present study’s analysis, the effect of volcano-tectonic activity has been observed on the spatial distribution of surface temperature over the study area. Most of these areas have been found in Dofan to Fantale volcanic fields. Moreover, it is observed along the Main Ethiopian rift axis in which recent volcano-tectonic activity was found.

Introduction
Several factors affect the spatial distribution of surface temperature. Among these, land use/land cover classes, solar reflectance, thermal emissivity and heat energy budget affected by active thermal sources, heat transfer at the earth’s atmosphere and thermal properties of objects (Feizizadeh et al., 2013; Hofierka et al., 2020; Lai et al., 2020; Moran, 1995; Prakash, 2000; Sholihah & Shibata, 2019). Thermal properties include thermal conductivity, specific heat, density, heat capacity, thermal diffusivities and thermal inertia of the objects (Moran, 1995; Prakash, 2000). As per these studies, active thermal sources and thermal properties of the objects’ can play a considerable role in the spatial distribution of surface temperature in the rift area. This is due to the movement of heat from the interior part to the surface that is usually associated with rifiting and faulting of the earth’s crust (Eliyasi, 2016). This allows heat energy to continuously flow from the deeper part of the earth’s layers to the surface of the earth’s crust through permeable rocks, faults, fractures, joints and volcanic intrusions. On the other hand, the spatial distribution of heat in the earth’s crust differs laterally and vertically depending on several factors, such as the content of radioactive isotopes in the rock, volcano-tectonic and hydrological nature of the area.

The Main Ethiopian Rift is a major volcanically and tectonically active region in the East African countries (Abebe et al., 2005; Ayalew et al., 2016; Bonini et al., 2005). The rift has been established inside an extremely differentiated lithospheric layer with many tectonic and volcanic activities in the last one billion years ago (Corti, 2009; Corti et al., 2018; Wadge et al., 2016). The extensional drift in the Main Ethiopian Rift is measured as 6–7 mm/year, while less than 2 mm/year in Kenya Rift and southwards (Agostini et al., 2011a; Bertani et al., 2018; Bonini et al., 2005; Corti et al., 2018). This extensional drift between the major Nubian and Somalian plates is higher in the Northern sector of the Main Ethiopian rift (Bonini et al., 2005; Chu & And, 1999; Fernandes et al., 2004) because the volcano-tectonic activities in the Northern sector of the Main Ethiopian rift are closely associated with Quaternary to recent magmatism (Agostini et al., 2011b; Bonini et al., 2005; Chernen et al., 1998; Pizzi et al., 2006).
Two regular fault systems primarily influence the Main Ethiopian Rift: border faults and a set of faults affecting the rift floor known as Wonji Fault Belt (Agostini et al., 2011a; Hayward & Ebinger, 1996; Keir et al., 2011). However, the border faults are inactive in the Northern sector. Still, they accommodate considerable extension in the Main Ethiopian Rift’s central and southern sectors (Agostini et al., 2011a). The Wonji Fault Belt is significantly active in the Northern sector. It is in an initial stage of development in the central and essentially insignificant in the Southern sector of the Main Ethiopian Rift (Bonini et al., 2005; Corti et al., 2018).

Consequently, the Northern Main Ethiopian Rift is mainly influenced by Wonji Fault Belt. The Wonji Fault Belt faults are primarily categorized by moderately short, closely spaced, and active faults that display slight vertical throw with related extension fractures and grabens (Agostini et al., 2011a; Bonini et al., 2005; Cernhet et al., 1998; Pizzi et al., 2006; Woldegabriel et al., 1990). These faults are faithfully associated with Quaternary to recent volcano-tectonic activity over the Main Ethiopian Rift. Previous geophysical studies have shown that the extensional drift is reserved with a mixture of magma intrusion and normal faulting. The magmatic intrusion has modified the composition and thermal structure of the crust and lithospheric layer under the Wonji Fault Belts (Bonini et al., 2005; Chu & And, 1999; Fernandes et al., 2004).

Along the axis, variations in faulting and magmatism throughout the Main Ethiopian Rift have governed the spatial distribution of surface temperature over the area (Beutel et al., 2010; Siegburg et al., 2018). Because the movements of heat from the internal source of the earth’s crust to the surface are closely related to the existence of faulting and rift (Eliyasi, 2016) and these tectonic movements and volcanisms have been considerable impacts on the spatial variability of surface temperature (Beutel et al., 2010; Chan et al., 2018; Haselwimmer & Prakash, 2013; Siegburg et al., 2018). It influenced human evolution in the past at the vast topographical and chronological scales, essentially relating to long-term topographic and climatic variation at the continental scale (Bailey et al., 2000; Yirgu et al., 2006).

The volcano-tectonic activities are mainly associated with material movements and energy transfer from the inner part of the earth’s layers to the surface of the earth’s crust. Such geological processes change the state of thermal radiation at the surface of the earth’s crust (Ma et al., 2010). Because of this, it is possible to investigate the effect of recent volcano-tectonic activities on the spatial distribution of surface kinetic temperature anomalies derived from satellite imagery. The satellite imagery is used to monitor the spatial distribution of surface temperature (Eneva, 2010; Feizizadeh et al., 2013; Haselwimmer & Prakash, 2013; Hui et al., 2015; Pastor, 2010), concentration of geological structures (Hung et al., 2005), active volcanic and active thermal areas (Urai et al., 2002; Velador et al., 2003); due to this reason, the satellite data have a great advantage to investigate the relationship between thermal information and volcano-tectonic activities. Hence, this study aims to assess and understand the impact of the volcano-tectonic activity on the spatial distribution of surface kinetic temperature over the Northern sector of the Main Ethiopian Rift. The study was mainly focused on the area of Boseti-Kone and Dofan-Fantale volcanic fields where a recent continental rift extension was found. The study area was studied by different researchers using ground-based geological survey. However, the detailed analysis and assessment of volcano-tectonic influences on the spatial distribution of surface temperature over the study area was limited. However, in the present study, the effect of volcano-tectonic activities on the spatial distribution of surface kinetic temperature were clearly investigated using integrated approaches of remote sensing data.

The study area

The study area is part of the Northern Segments of the Main Ethiopian Rift, bounded within the limits of 550,000 to 610,000 East longitude and 950,000 to 1,010,000 North latitude, and covers a total area of 2447 Km² as shown in Figure (1). The study area’s elevation ranged from 851 to 2120 meters, and the slope angle ranged from 0 to 84.4 degrees. The area has an average distance of 126 km east of Addis Ababa, and its administrative location is at the boundary of the Amhara and Oromia regional states. In addition, the study area contains well-known volcanic fields Boseti-Kone and Dofan-Fantale volcanic segments, which are believed to have been created by the recent volcano-tectonic activity.

The area is mainly characterized by dry and rainy seasons. The long rainy season passes in the summer, from June to September. Based on the available meteorological data obtained from the National Meteorology Agency of Ethiopia, the mean annual rainfall ranges between 800 and 1000 mm. The dry period extends from October to February. The minor rain season occasionally occurs from February to April. The study area is mainly covered by barren land and lava flows. The vegetation cover is typical of arid and semi-arid climate zones, with scattered acacia, especially thorn bushes and shrubs.
Materials and methods

Data

In this study, integrated different data sources were used for our analysis. The Landsat 8 imagery of January 16/2019 has been downloaded from the United States Geological Survey (USGS) satellite imagery website: [https://earthexplorer.usgs.gov/](https://earthexplorer.usgs.gov/) with a path and row of 168 and 054, respectively. The AlosPalsar digital elevation model at 12.5 m spatial resolution has been downloaded from the Alaska Satellite Facility satellite imagery website. The lithological and geological structure maps were collected from the Geological Survey of Ethiopia (GSE). Moreover, the location of geological structures, volcanic landforms, hydrothermally altered areas, hot springs, fumaroles, and other important data was collected during our field works. The present study methodology flow chat is shown in Figure (2).

Data preprocessing for Landsat 8 imagery

Due to many influential factors, the radiometric and atmospheric correction was applied on Landsat 8 OLI and TIRS bands according to Landsat 8 user guidelines (USGS, 2019). In the first step, the radiometric correction was conducted on Red (band 4) and NIR (band 5) of OLI and TIR1 (band 10) of TIR sensors. They can be converted to spectral radiance using the following equation, with the radiance scaling factors provided in the metadata file (USGS, 2019). The calculation of sensor spectral radiance is fundamental in converting image data from multiple sensors and platforms into a meaningful standard radiometric scale. The radiometric correction of Red (band 4), NIR (band 5) of OLI sensors, and TIR1 (band 10) sensors involves rescaling the raw digital numbers transmitted from the satellite to calibrated digital numbers with the same radiometric scaling for all scenes processed on the ground for a specific period (Chander et al., 2009).

In the second step, the atmospheric correction was conducted on Landsat 8 OLI sensors Red (band 4) and NIR (band 5). It is a critical preprocessing step for the quantitative analysis of surface reflectance. It is mainly used to remove the influence of the atmospheric particle since remotely sensed images have information about the atmosphere and the earth’s surface. This study performed the atmospheric correction using the Fast Line of sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) atmospheric
correction model in ENVI software. During atmospheric correction processes, a scene average visibility of the image (aerosol, haze amount, and clouds) was computed.

Moreover, it also adjusts spectral polishing for artifact suppression, correct pixel mixing for scattering of surface-reflected radiance, and accurate images collected in vertical (nadir) and slant-viewing geometries (ENVI, 2009). To minimize the effect of noise on spectral images, the minimum noise fraction (MNF) rotation techniques would be applied using ENVI software followed by an inverse transform method. The Minimum noise Fraction (MNF) transformation is mainly utilized to get absolute surface reflectance by eliminating atmospheric particle (residual) noise from the reflectance image (Ourchif et al., 2019). Table (1) shows the OLI and TIRS bands constant values used to estimate radiance from DN values.

\[ L_\lambda = M L_\lambda x Q_{Cal} + A_L \]  \hspace{1cm} (1)

where \(L_\lambda\) is the Spectral radiance (W/(m² * sr * μm)), \(ML_\lambda\) is the multiplicative radiance value, \(A_L\) is the additive radiance value, and \(Q_{Cal}\) is the pixel values in DN.

**Data processing**

Geological structures such as large fractures, joints, and faults are surface expressions of a zone of structural weakness or structural displacement of the earth’s crust (Abdullah et al., 2013a, 2013b). So those areas are an indicator for the occurrence of tectonic activity (Salui, 2018). Therefore, geological structural settings such as fault displacement, concentration zone of faults, fault terminations, step over, and pull apart contribute to the flow of heat energy to the structural target area (Hinz et al., 2015). In this study, geological structures (faults, fractures or fissures, and joints) were extracted automatically using the LINE module of PCI Geomatics software from higher resolution AlosPalsar digital elevation model (12.5) after integration of slope and aspect thematic layers using fuzzy overlay analysis in ArcGIS software.
(Abdullah et al., 2013a, 2013b; Hung et al., 2005; Salui, 2018; Sukumar et al.). However, automatic extraction of geological structure using the LINE module of PCI Geomatics software has its disadvantages. A non-geological structure such as agricultural boundary and canal may be added during the automatic extraction of geological structure from satellite imagery. According to Salui (2018), these artificial lineaments are removed by comparing the results obtained from the high-resolution digital elevation model (12.5 m), existing structural map, and Landsat 8 OLI sensors panchromatic band at 15 m spatial resolution that should be suitable for structural mapping.

The extracted structural map generated geological structures (faults, fractures, and joints) density maps. A structural density map was used to identify the spatial distribution of faults, fractures, and joints. Geological structure density analysis is a system used to calculate the number of faults, fractures, and joints per unit area (Wibowo, 2010). This study calculates the structural density using the line density option under the spatial analyst toolbox in ArcGIS software. This software counts the number of geological structures per unit area. To determine the effect of tectonic activity on the spatial distribution of geological structures over the study area, this geological structure density map was classified as very high, high, moderate, low, and very-low-density zones. This classified geological structures density map was correlated with the spatial distribution of surface temperature retrieved from Landsat 8 imagery to assess the overall effect of tectonic activity over the study area.

Volcanic landforms such as composite cones, cinder cones, silicic volcanic domes, calderas, and craters can constitute evidence for volcanic activity and underground heat sources (Kubai & Kandie, 2014; Yousefi et al., 2007). These active volcanic landforms are important factors to control the movement of heat from the interior of the earth’s layers to the surface and provide significant considerations into the generation and assessment of a large volume of silicic magma bodies (Cole et al., 2005; Lipman, 1984). Satellite imagery has been used to monitor these active volcanic landforms (Urai et al., 2002). In this study, the data layer of these features is extracted from the digital elevation model at 12.5 spatial resolution using ArcGIS software. In the first step, the slope and aspect map of the study area was generated using a spatial analysis toolbox. Secondly, these two datasets were integrated using a fuzzy overlay analysis tool to enhance the visibility of these volcanic features. Then, volcanic landforms such as composite cones, cinder cones, caldera, crater, and silicic domes are observed. Finally, these features are digitized in polyline format using ArcGIS software. The digitizing as polyline format is mainly used to generate the density of volcanic landforms since density cannot be analyzed for polygon shapefile format. A density map was generated and classified as very high, high, moderate, low, and very low to find out the effect of volcanic activity on the spatial distribution of volcanic landforms. A volcanic landforms density map was correlated with the spatial distribution of surface temperature retrieved from Landsat 8 imagery to detect the overall effect of volcanic activity over the study area.

This study investigates the spatial distribution of surface kinetic temperature using Landsat 8 OLI/TIRS imagery. The image has a minimum percentage of land cloud cover and high image quality over the study area. In addition, the dry season has been selected to minimize the effect of vegetation phenology and crops on the spatial distribution of surface kinetic temperature. In the study area, the dry period extends from October to February. Therefore, the Landsat imagery of January 16/2019 has been used to retrieve the surface kinetic temperature distributed over the study area. Landsat 8 imagery of OLI sensor band 4(red) and band 5(NIR) and TIRS sensor band 10 (TIR-1) have been used to retrieve the surface kinetic temperature of the study area. This study did not use Landsat 8 thermal infrared imagery of band 11 (TIR-2) due to the high stray light effect (USGS, 2019). Conversion of spectral radiance to radiant temperature is critical for retrieving surface kinetic temperature from satellite imagery.

The Normalized Difference Vegetation Index (NDVI), Fractional Vegetation Cover (FVC), and Land Surface Emissivity estimate surface kinetic temperature from satellite imagery. NDVI is a vegetation tool usually used to know the vegetation states of the study area depending on the spectral variability of satellite imagery (Bhandari & Singh, 2012). For this study, atmospheric-corrected surface reflectance band 4(red) was subtracted from band 5 (NIR) and divided by the sum of that band (Huang et al., 2013).

\[
NDVI = \frac{NIR - Red}{NIR + Red}
\]  

(2)

where NDVI is Normalized Difference Vegetation Index, NIR is Near Infrared Band

Fractional vegetation cover (vegetation proportion) was calculated based on an NDVI histogram (Carlson & Ripley, 1997; Sobrino et al., 2008; Sobrino & Raissouni, 2000). In a particular area, fractional vegetation cover can be calculated by considering the variability of NDVI (Sholihah & Shibata, 2019).

\[
P_V = \left( \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^2
\]  

(3)
Where NDVI is the Normalized Difference Vegetation Index, NDVI_{min} is the soil’s NDVI value, NDVI_{max} is vegetation’s NDVI value.

In this study, the land surface emissivity value of the study area was calculated using the NDVI thresholds method (Sobrino & Raissouni, 2000). It is a suitable method for the calculation of surface emissivity from Landsat imagery. Land surface emissivity was commonly calculated from NDVI threshold values by considering three different land cover classes, such as NDVI < 0.2, 0.2 ≤ NDVI ≤ 0.5, and NDVI > 0.5 (Sobrino et al., 2008; Yu et al., 2014). The NDVI < 0.2, the pixel is considered bare soil. In the second case, 0.2 ≤ NDVI ≤ 0.5, the pixel is composed of a mixture of bare soil and vegetation, and in the third case, NDVI > 0.5, the pixel is reflected in a fully vegetated area (Sekertekin & Bonafoni, 2020).

Since the study area is a mixture of soil and vegetation, the second case was applied for this study as equation (4).

\[
\varepsilon_\lambda = \varepsilon_{\lambda A}P_V + \varepsilon_{\lambda S}(1 - P_V) + C_\lambda \tag{4}
\]

where \(\varepsilon_{\lambda A}, \varepsilon_{\lambda S}\) are vegetation and soil emissivity, respectively, and \(C_\lambda\) is cavity effect.

Due to surface roughness (\(C_\lambda = 0\) for a homogenous and flat surface). The cavity effect for the rough surface (heterogeneous surface) area is calculated as follows:

\[
C_\lambda = (1 - \varepsilon_{\lambda S})(1 - P_V)\varepsilon_{\lambda A}F' \tag{5}
\]

\(C_\lambda\) is the term that depends on the surface characteristics and considers the internal reflections (cavity effect); \(F'\) is a shape factor whose mean value ranges between zero and one, depending on the geometrical distribution of the surface. The geometrical factor cannot be estimated from a satellite image, whose mean value, assuming different geometrical distributions, is 0.55 (Sobrino & Raissouni, 2000).

The land surface emissivity values of soil and vegetation must be known to calculate land surface emissivity using a mixed pixel equation. The emissivity values of soil and vegetation for Landsat 8 thermal infrared band 10 are given as 0.9668 and 0.9863, respectively (Jiménez-Muñoz et al., 2014; Yu et al., 2014). So, the land surface emissivity value of mixed pixel was obtained as the following equation (12).

\[
\varepsilon_\lambda = 0.9863P_V + 0.9668(1 - P_V) + C_\lambda, 0.2 \leq NDVI \leq 0.5 \tag{6}
\]

where 0.9863 is the emissivity values of vegetation and 0.9668 is the emissivity values of soils for Landsat 8 thermal band 10.

In this study, thermal infrared (TIR1 bands) of Landsat 8 imagery has been converted from spectral radiance to radiant temperature, an adequate temperature viewed by the satellite sensor under consideration as a unit of emissivity (USGS, 2019).

\[
T_R = \frac{K_2}{ln\left(\frac{K_1}{\varepsilon_\lambda} + 1\right)} \tag{7}
\]

\(T_R\) is the radiant temperature in kelvin, \(\lambda\) is the cell value as radiance, and \(K_1\) and \(K_2\) are constant. Thus, the radiant temperature in the unit of kelvin is converted to degree Celsius as follows:

\[
T_K(C^o) = T_R(K) - 273.15 \tag{8}
\]

\(T_R(C^o)\) is the radiant temperature in degree Celsius, and \(T_K\) is the radiant temperature in kelvin. Thermal constant values for Landsat 8 TIR1 (band 10) are \(K_1 = 774.8853\) and \(K_2 = 1321.0789\) (USGS, 2019).

The thermal infrared remote sensing exploits everything above absolute zero Kelvin emits radiation in the thermal infrared electromagnetic spectrum region with wavelength ranging from 3 to 5 µm and 8–14 µm. The amount of energy radiated from the objects depends on the objects’ land surface emissivity and kinetic temperature. The radiant temperature for the black body is the same as that for the kinetic temperature, but it varies for non-black bodies. So, the surface kinetic temperature of the non-black body is estimated using the relation between radiant and kinetic temperature (Moran, 1995; Pastor, 2010; Prakash, 2000).

\[
T_K = \frac{T_R}{\varepsilon_\lambda} \tag{9}
\]

\(T_K\) is the surface kinetic temperature, \(T_R\) is the radiant temperature in degree Celsius, and \(\varepsilon_\lambda\) is land surface emissivity.

The resulting surface kinetic temperature map was classified into five subclasses to investigate the spatial variability of surface kinetic temperature over the study area (very low, low, moderate, high, and very high).

**Results and discussions**

**Results**

**Geological structures**

The results of the analyzed geological structure indicate that most of the study area has abundant short and closely spaced faults, fractures, and joints whose structural trends are mainly in the northeastern and southwestern directions. This may be the effect of Wanji Fault Belt. The most closely spaced faults, fractures and joints were found in the western escarpment.
and northern parts of the study area towards the Afar Depression. Significant amounts of faults, fractures, and joints were found in the middle portion of the study area following the Main Ethiopian Rift axis and the northeastern and southwestern directions. Less apparent faults, fractures, and joints were found in the southern and southeastern parts of the study area.

Geological structure density map was analyzed from the structural map of the study area. The purpose of the structural density analysis was to calculate the frequency of faults, fractures, and joints per unit area shown in Figure (5). The produced density map shows the concentrations of these geological structures over the study area. The geological structure density map result shows that very high density was found in the western escarpment, northern and northeastern portion of the study area compared to the southern and southwestern parts of the study area. This indicates the occurrence of highly concentrated faults, fractures, and joints in the area, which are used as a pass for thermal fluids from the interior of the Earth layer to the surface of the earth’s crust. Table (2) shows the geological structures density as qualitative and quantitative expression.

**Volcanic landforms**

The results of digitized volcanic landform as polyline format show that a series of composite cones, cinder cones, silicic volcanic domes, calderas, and craters were found in the middle portion of the study area along the northeastern and southwestern direction following the rift axis of the Main Ethiopian Rift as shown in Figure (7). Those active volcanic landforms also clearly observed the digital elevation model of the study area after integrating slope and aspect thematic layers using fuzzy overlay analysis in ArcGIS software, as shown in Figure (6). These volcanic landforms indicate that the study area is the center of the volcanic eruption. As shown in Figure (7), Boseti volcano was found in the southwestern portion of the study area. Kone volcanic complex has been found in the central part of the study area. Moreover, the Quaternary-recent Fantale volcano has been located in the northern portion of the study area. Table (3) shows the volcanic landforms density map qualitative and quantitative expression.

**Surface kinetic temperature**

As shown in Figure (9), the results for the surface kinetic temperature range from 21 to 45.9°C. The classified surface kinetic temperature map shows that Lake Beseka, Kessem dam, Kessem River, and Awash River have a temperature ranging from 21 to 26°C. In the region of Metehara agro-industrial zone and some irrigation sites following Kessem and Awash River have a temperature ranging from 27 to 32°C. The Boset-Bercha, Kone, and Fantale volcanic complex has a temperature ranged from 33 to 45.9°C. The lava flows and caldera areas have a temperature ranged from 33 to 38°C. However, the composite cones, ash, pumice fall deposit and most volcanic fields have a temperature above 39°C. The silicic volcanic domes have a temperature ranged from 45 to 45.9°C. Table (4) shows the qualitative and quantitative expression of NDVI, FVC, LSE, Radiant and Surface kinetic temperature.

**Validation**

The consistency of the surface kinetic temperature resulting from Landsat 8 thermal infrared sensor was validated using daytime average 8 days per pixel land surface temperature products of MODIS (MOD11A2) and ground-based thermal manifestation parameters. Hence, MODIS land surface temperature products with a 1-kilometer spatial resolution were acquired on a period of 11/01/2019 to 18/01/2019 from the United States Geological Survey (USGS) portal with path and row of 168 and 054, respectively. The surface kinetic temperature resulted from Landsat 8 TIRS sensor with 30 meter spatial resolution was resampled using bilinear interpolation technique to 1000 meter spatial resolution to correlate with MOD11A2 land

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**Table 2.** Geological structures density map qualitative and quantitative expression.

| Structural density (Km/Km²) | Rank | Qualitative expression | Area (Km²) |
|-----------------------------|------|------------------------|------------|
| 0–0.2                       | 1    | Very Low               | 419.84     |
| 0.201–0.692                 | 2    | Low                    | 507.83     |
| 0.693–1.9                   | 3    | Moderate               | 608.02     |
| 1.91–4.87                   | 4    | High                   | 596.29     |
| 4.88–12.2                   | 5    | Very High              | 314.74     |

**Table 3.** Volcanic landforms density map qualitative and quantitative expression.

| Volcanic landforms density (Km/Km²) | Rank | Qualitative expression | Area (Km²) |
|-------------------------------------|------|------------------------|------------|
| 0–0.0277                            | 1    | Very Low               | 1315.04    |
| 0.0278–0.0928                       | 2    | Low                    | 131.45     |
| 0.0929–0.246                        | 3    | Moderate               | 365.88     |
| 0.247–0.605                         | 4    | High                   | 516.49     |
| 0.605–1.45                          | 5    | Very High              | 118.24     |

**Table 4.** Qualitative and Quantitative expression of NDVI, FVC, LSE, Radiant and Surface kinetic temperature.

| Qualitative Expression of T° | Approximated NDVI value | Approximated FVC value | Approximated LSE value | Radiant T°(C) | Surface Kinetic T°(C) |
|------------------------------|-------------------------|------------------------|------------------------|---------------|-----------------------|
| Very High                    | –0.896 – 0.543          | 0.2                    | 0.985                  | 41 – 45.7     | 45 – 45.9             |
| High                         | –0.542 – 0.189          | 0.201–0.4              | 0.985–0.986            | 36.1 – 40.9   | 39 – 44               |
| Moderate                     | –0.188–0.164           | 0.401–0.6              | 0.986                  | 31.2 – 36     | 33 – 38               |
| Low                          | 0.165–0.517            | 0.601–0.88             | 0.986–0.987            | 26.3 – 31.1   | 27 – 32               |
| Very Low                     | 0.518–0.871            | 0.801–1                | 0.987                  | 21.3 – 26.2   | 21 – 26               |
surface products. The statistical correlation were done by taking 9 sampling sites during our field works, resampled Landsat 8 and MODIS surface temperature products. Hence, the sampling sites was selected at hydrothermally active areas which have concentrated thermal manifestations in the form of hot springs, fumaroles, hydrothermally altered, mud pools and steaming grounds.

The statistical comparison of the surface kinetic temperature between Landsat 8 TIRS and MODIS LST products has a Root Mean Square Error of 1.71°C. The maximum difference between Landsat 8 and MODIS LST products are 2°C (Qin et al., 2011). Hence, the value was found to be below an acceptable range as shown as Table (5). Moreover, those sampling sites have concentrated thermal manifestations in the form of hot springs, fumaroles, mud pools, hydrothermally altered ground and steaming as mentioned in Table (5).

**Discussions**

As per the previous study, tectonic activity increases from the south and central segments towards the northern segment of the Main Ethiopian Rift and Afar Depression (Bonini et al., 2005; Chu & And, 1999; Fernandes et al., 2004). The analyzed geological structure map results also show that more concentrated faults, fractures, and joints were found in the northern portion of the study area towards the Afar Depression, as shown in Figure (4). Those geological

| Sampling sites       | MODIS LST(M) in °C | Landsat 8 SKT (L) in °C | M-L in °C | (M-L)² in °C |
|----------------------|--------------------|-------------------------|-----------|-------------|
| Habilo areas         | 34.7               | 32.2                    | 2.5       | 6.25        |
| Tedicha-Melka areas  | 40.3               | 36.8                    | 3.5       | 12.25       |
| Hubicha 1            | 34.4               | 32.1                    | 2.3       | 5.29        |
| Hubicha 2            | 26.7               | 24.1                    | 2.6       | 6.76        |
| Kesem river          | 30.1               | 29.8                    | 0.3       | 0.09        |
| Fantale volcano areas| 45.8               | 45.6                    | 0.2       | 0.04        |
| Bulga 1              | 24.1               | 23.2                    | 0.9       | 0.81        |
| Bulga 2              | 38.3               | 37.1                    | 1.2       | 1.44        |
| Debhit              | 44.3               | 44.7                    | -0.4      | 0.16        |
| Sum of (M-L)²        | 26.33              |                         |           |             |
| Sum of (M-L)²/total sample | 2.92          |                         |           |             |
| Square root of sum/total samples | 1.71       |                         |           |             |

Table 5. Comparison of Landsat 8 and MODIS LST products.
Figure 4. Geological structures map of the study area.

Figure 5. Geological structure density map of the study area.
structures also clearly observed the digital elevation model of the study area after integrating slope and aspect thematic layers using fuzzy overlay analysis in ArcGIS software, as shown in Figure (3). Moreover, the results of composite cones, cinder cones, silicic volcanic domes, calderas, and craters density analysis show that highly concentrated volcanic features were observed in the middle portion of the study area northeastern and southwestern direction, as shown in Figure (8). In addition, the higher density surface offers highly concentrated volcanic features.

Boset-Bericha volcanic complex (BBVC) located at the southern portion of the study area oriented Boset-Kone magmatic segment. It is one of the largest stratovolcanoes in the Main Ethiopian Rift. These volcanic fields have calderas, basaltic lava flows and spatter and cinder cones, silicic volcanic domes, composite cones, and ash and pumice fall deposits. In addition, these areas have dyke intrusion and induced faulting (Bendick et al., 2006). In those areas, heat flow is higher than at another volcano in the rift (Mazzarini et al., 2013). The results of our analysis also show that
Figure 7. Volcanic landforms map of the study area.

Figure 8. Volcanic landforms density map of the study area.
Figure 9. Surface kinetic temperature map of the study area.

Figure 10. Spatial association of surface kinetic temperature with geological factors.
higher surface temperature anomalies are detected in those areas. The temperature ranged from 33 to 38°C in the lava flows and calderas areas. However, above 39°C, the surface temperature was found in composite cones, ash, pumice fall deposits, and most volcanic fields. The silicic volcanic domes have a temperature ranging from 45 to 45.9°C.

Kone volcanic complex is located in the middle portion of the study area or south-west of Fantale volcano. A complex symmetric tectonic graben trend south-west from the Afar Depression (Rampey et al., 2010, 2014). The area has two fault lines that have caused the volcanic activity within Kone volcanic complex, and those are normal faults (Wanji Fault Belt) and ring fractures (Agostini et al., 2011a). The normal faults cause magma to rise to induce volcanic activity, while ring fractures have caused the calderas to collapse. Kone volcanic complex is made up of a number of calderas, lava flow, basaltic cinder cone and silicic volcanic domes. As shown in Figure (9), these calderas and lava flow areas have a temperature ranging from 33 to 38°C. The basaltic cinder cone and silicic volcanic domes have a temperature ranging from 45 to 45.9°C. This may be related to the internal source of heat energy. Thus, both volcanic and tectonic activities affect the spatial distribution of surface temperature over the Kone volcanic complex.

Most of the higher surface temperature anomalies were found in the northern portion of the study area towards the Afar Depression. Those areas have a higher surface temperature ranging from 39 to 45.9°C. In some parts of these areas, higher surface temperature ranging from 45 to 45.9°C was observed. This is related to volcanic, tectonic activity over the study area (Agostini et al., 2011b). Because those areas have concentrated hydrothermal manifestation in hot springs, fumaroles, hydrothermally altered ground, and mud pools, moreover, these areas have concentrated geological structures (faults, fractures, and joints) and silicic volcanic domes.

Fantale volcano area is a hydrothermally active area with a higher surface temperature ranging from 39 to 45.9°C. The area has concentrated thermal manifestations in hot springs, mud pools, fumaroles, steaming grounds, and the site also characterized by hydrothermally altered ground. Habilo-Tedecha area is also one of the hydrothermally active areas located northwest of Fantale volcano, close to the western escarpment. The area has many hot springs, mud pools, fumaroles, and steaming or altered grounds. Hubicha areas are also another hydrothermally active located south of Fantale volcano on the southwestern shore of Lake Beseka. The areas have many hot springs and discharge into the lake. They originate at the base of recently faulted basalt running north-northeast direction. There is also a running deep fissure close to the hot springs. The hydrothermal activity was also observed near Kessem River, located in the northern portion of the study area. However, in most of the study areas, a temperature ranging from 39 to 44°C. This included town, barren areas, and a mixture of rock/soil, and less vegetated areas.

Higher surface temperature anomalies (>44°C) were spatially distributed over concentrated geological structures (faults, fractures, and joints) and active volcanic landforms (silicic volcanic domes, cinder cones, and composite cones), as shown in figure (10 and 11 (a-g)). The effect of this volcano-tectonic on the spatial distribution of surface temperature was observed over the study areas, as shown in Figure 11 (a-g). Most of the higher surface temperature anomalies were detected near and northwest of Fantale volcano, in which highly concentrated geological structures and active volcanic features were found. Higher surface temperature anomalies were also located near active volcanic landforms along the northeastern and southwestern directions following the rift axis of the Main Ethiopian Rift. Recent volcanic activity on the spatial distribution of surface temperature in those areas has been observed in Figure 11(a-g).

**Conclusion**

Surface kinetic temperature retrieved from Landsat 8 imagery of January 16/2019 resulted in minimum and maximum temperatures of 21 and 45.9°C, respectively. As per our analysis, the spatial distribution of surface temperature was affected by volcanic-tectonic activity over the study area. Higher surface temperature anomalies (>44°C) were found in the densely concentrated faults, fractures, joints, silicic volcanic domes, cones, and hydrothermally altered grounds. Moreover, higher surface temperature anomalies’ distribution was spatially correlated with active thermal areas like fumaroles, hot springs, mud pools, and steaming grounds. Based on our analysis, the location of higher surface temperature anomalies was associated with internal heat flows and used as an indicator for geothermal energy. This study showed the importance of remote sensing technology for an effective investigation method to assess the effect of volcanic-tectonic activities on the spatial distribution of surface temperature anomalies. Recently, remote sensing has been enormous for spatial and temporal analysis of land surface temperature. Moreover, remote sensing techniques have a considerable role in identifying the
impact of geological factors like volcanism, tectonic activity, and active thermal source on the spatial distribution of surface temperature of the rifting area. Hence, remote sensing satellite data are useful for qualitatively and quantitatively analyzing surface temperature anomalies associated with volcano-tectonic activity and active thermal sources. Additionally, this study locates potential geothermal sites over the study

Figure 11. Spatial association of surface kinetic temperature with geological structures and volcanic landforms viewing on digital elevation model (12.5 m).
area since the higher surface temperature is related to active thermal sources, volcanism, and tectonic movement.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported that there is no funding associated with the work featured in this article.

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