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Research Article

# Determination of Crustal Deformation around Afar (Erta Ale) using Sentinel 1 SAR Interferometry

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## ABSTRACT

This study is conducted to analyze the crustal deformation pattern at a locality in the Afar region which is geographically located in northern part of east African rift valley between 13° 20‘N to 13° 50‘N latitudes and 40°30‘E to 41°00‘E longitudes, within the triple junction that is formed by the Arabian, Nubian and Somalian diverging plates. The region is one of the active volcanic areas in the world, where the episode of plate movement resulted in seafloor spreading that causes the earth's surface to deform in the form of surface cracking, sliding, subsiding and faulting. Presently this dynamic process of earth's deformation in space and time can be accurately detected by satellite space geodetic observations. Using SARPROZ software we applied PSInSAR technique to estimate crustal deformation in the study area based on the analysis of geodetic data. Sentinel-1A SAR image datasets from October 2014 to December 2019 were used to make multi- temporal analysis and we obtained the corresponding subsidence map over the Afar area (Erta Ale). The land deformation analysis showed that the investigation is suffering a severe land movement in most of the area of interest (AOI) which varies approximately from −29.61mm/year (subsidence) to 4.31 mm/year (uplift), and the cumulative displacement from -153.32mm to 24.29mm respectively. The highest value was observed around Erta Ale. This indicates that magma flow and volcano-tectonic activities are still a primary mechanism of deformation.

**Keywords**: PSInSAR; Crustal Deformation; Subsidence; Uplift; Sentinel-lA

## INTRODUCTION

Crustal deformation is now a series problem in volcanically active areas such as Afar. Afar is created by the separation of Arabia, Nubia and Somalia plate (Barberi and Varet, 1977; Courtillot, 1980; Ebinger et al., 2010). Our Knowledge of Earth dynamics related to tectonic, seismic, volcanic activities are developed through measurement of crustal deformation. Using inexpensive techniques for monitoring crustal deformation is highly necessary to take the necessary precaution. Nowadays a lot of measurement techniques are developed to study crustal dynamics. In particular, we are interested in estimating crustal deformation in and around Erta Ale (Ethiopia) area using Persistent Scaterer Interferometric Aperture Radar (PSInSAR). Interferometric Synthetic Aparture Radar (InSAR) has become a widely used method for the detection and measure of small ground movements (Burgmann et al., 2000). So far a number of researches have been done to determine active tectonics and near-surface stress field using different methods. PSInSAR technology were used because it is considerably more precise; it eliminates undesired atmospheric influences, recover the digital elevation model (DEM) and is less sensitive to the geometry of image acquisition and extract the actual deformation map components from multi-temporal SAR images and large spatial coverage (Ferretti, A et al, 2000; Curlander, et al, 1991; Gens R et al, 1996). In addition, it overcame the geometric and temporal

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decorrelation along with the atmospheric phase screen (APS) disturbance. It detects displacement within millimeter to sub-millimeter accuracy. Based on algorithms proposed in literature (Ferretti, A et al, 2000, 2001; Kampes, B.M 2006) PSInSAR applies a single master configuration analysis which is able to monitor the temporal transition of surface deformation. Because of the looking angle, InSAR can better give deformation fields mainly described by a vertical component (Stramondo et al., 2008; Polcari et al., 2014) or volcanos inflation/ deflation (Palano et al., 2008; Malinverni et al., 2014; Fernández et al., 2015; Trasatti et al., 2015).

This study tried to estimate the velocity of crustal deformation of Afar (Erta Ale) area using PSInSAR technique. The study tried to carry out the experiment of generating a ground displacement map and focused on estimating the velocity of crustal deformation in the Afar (Erta Ale) area, Ethiopia.

## STUDY AREA AND DATA USED

The study area is found within the northern part of Afar depression which lies at the triple junction between the Main Ethiopian Rift (MER), the Red Sea rift and the Gulf of Aden (Tesfaye et al., 2003). It divides the Nubian, Arabian and Somalian diverging plates and chronologically dated approximately 29 -31Ma (Wolfeden et al., 2005). It is geographically located in Northern Main Ethiopian Rift between 13° 20‘N to 13° 50‘N latitudes and 40°30‘E to 41°00‘E longitudes as shown in figure 1.

The data source for the InSAR processing was Sentinel-1A missions and accessed through the Copernicus Open Access Hub. The geometric specifications of this satellite constellation (i.e., short spatial and temporal baselines) promise improved data quality (higher coherence) and enhanced performance of PS-InSAR techniques. The satellites provides medium and high resolution SAR image every 12 days in all weather conditions see table 1. A total of 49 images acquired on the descending orbit all from the time interval in between October 2014 to December 2019 were used.

**Figure 1**: Study Area.

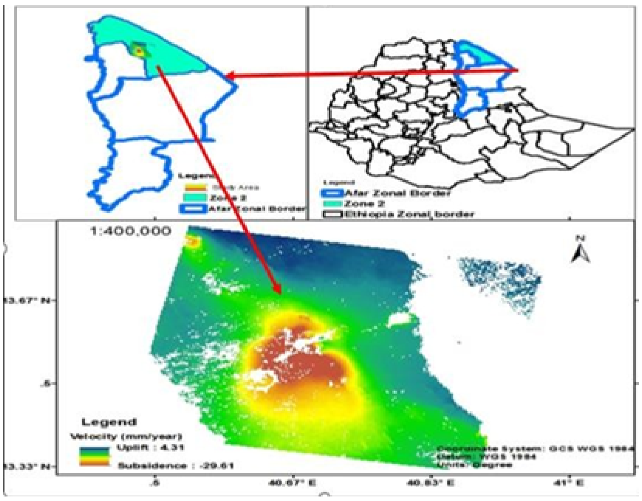



**Table 1**: Satellite information of Sentinel-1A data used in this study.

| Parameters | Description |
|---|---|
| Acquisition Pass | Descending |
| Image Number | 49 |
| Sensor | Sentinel-1A |
| Product type | SLC |
| Acquisition mode | IW |
| Sub-Swath | 2 |
| Acquisition angle | 39.3205 |
| Polarization | VV |
| Wave length | 5.6cm |
| Acquisition time | Nov 2014-Dec 2019 |
| Locality | Afar Zone 2, Ethiopia |

## METHODOLOGY

### Psinsar Technique

To determine the line-of-sight (LOS) mean land subsidence velocity and vertical deformation time series Sentinel-1A SAR image data were used. We apply the procedures implemented in SARPROZ software (Perissin D 2015). PSInSAR needs between 15 and 20 acquisitions for a successful result (Ferretti et al., 2001). A total of 49 images acquired between October 2014 and December 2019 were used. The images were acquired, along a descending orbit with an incidence angle of approximately 39.32◦. The orbit state vector was refined using Sentinel-1A precise orbit ephemerides (POE) to reduce errors due to the satellite orbit inaccuracies. POE are published online by ESA [Precise Orbit Ephemerides, 2019]. The precise orbits were downloaded by the software for each image. Single look complex (SLC) images are coregistered to a single-master acquisition. Spatial and temporal de-correlation effects were roughly reduced by the master image which is selected by the software (Kampes, 2005). Interferograms were generated using orbital data and an external digital elevation model (DEM) were used to remove flat earth with topographic influence. Persistent scatterer candidates (PSCs) were selected and a reference point was chosen. The interferometric phase of the PSCs are obtained by:

$$\Delta\phi_{i,k}(p) = \Delta\phi_{i,k}^{flat}(p) + \Delta\phi_{i,k}^{height}(p) + \Delta\phi_{i,k}^{disp}(p) + \Delta\phi_{i,k}^{atm}(p) + \Delta\eta_{i,k}(p)$$

Where indices k is master image and $i$ slave images of the interferometric pairs. The first term in Equation 1, the flat terrain, can be estimated from orbital data and removed. For the sake of simplicity, we will not consider the possible orbital inaccuracies. The second term corresponds to the topographic phase (DEM) error which is due to the inaccuracy of the external DEM and the third term is the displacement. A common way to model the displacement is that of assuming it linear deformation in time. The fourth term which is the atmospheric delay has been shown in the literature that the atmospheric delay has a decorrelation length of several hundreds of meters (Hanssen, R, 2001). The last term in Equation 1 indicates noise. The noise was estimated from the model residuals. Based on the use of amplitude dispersion index (ADI) on a stack of single-master interferograms stable pixels were selected (Ferretti et al., 2001; Hooper et al., 2007). Pixels are defined as PS if their phases are dominated by stable scatterer. Small values of ADI are good estimates of the phase dispersion (Ferretti et al., 2001). Consequently, a pixel is taken as a PS candidate if it fulfills the amplitude stability index criteria:

$$D_a = \frac{\sigma_a}{m_a} \cong \sigma_v < 0.25$$

Where, $\sigma_a$, $m_a$ and $\sigma_v$ are the standard deviation, mean of amplitude values and the phase standard deviation respectively.

The connection of the selected PS points made by using the Delaunay triangulation (DT) process to form a spatial graph. The phase contribution between two adjacent pixels of the spatially correlated atmosphere is neglected (Hanssen 2001). Through maximization of the periodogram, the height and velocity of each connection, were estimated. (Perissin and Wang 2012) which is mathematically described as:

$$\eta[\Delta v(p_{ij}).\Delta h(p_{ij})] = \frac{1}{N}\sum_{i=1}^{N} e^{j[\Delta\varphi_{i,k}(p_{sj}) = \frac{4\pi}{\lambda}\Delta v(p_{sj})B_{t,i} - \frac{4\pi}{\lambda R sin\theta}\Delta h(p_{s,j})B_{n,i}}$$

Where, N is the number of interferograms, $\lambda$ is the wave length of the radar, $\theta$ *and* $R$ are the looking angle and target distance from the sensor respectively. The term $p_{sj}$ denotes the connection between adjacent persistent scatterer points $p_s$and$p_j$. $\Delta\varphi_{i,k}$ is double difference interferometric phase in the image pairs i and k. The temporal coherence and interferometric normal baselines are denoted by $B_{t,i}$ *and* $B_{n,i}$.

The solution is given by

$$\Delta\tilde{v}(p_{s,j}), \Delta\tilde{h}(p_{s,j}) = argmax\{|\eta[\Delta v(p_{s,j}), \Delta h(p_{s,j})]|\} \quad 4$$

The maximum absolute value of the periodogram is called Temporal Coherence (TC).

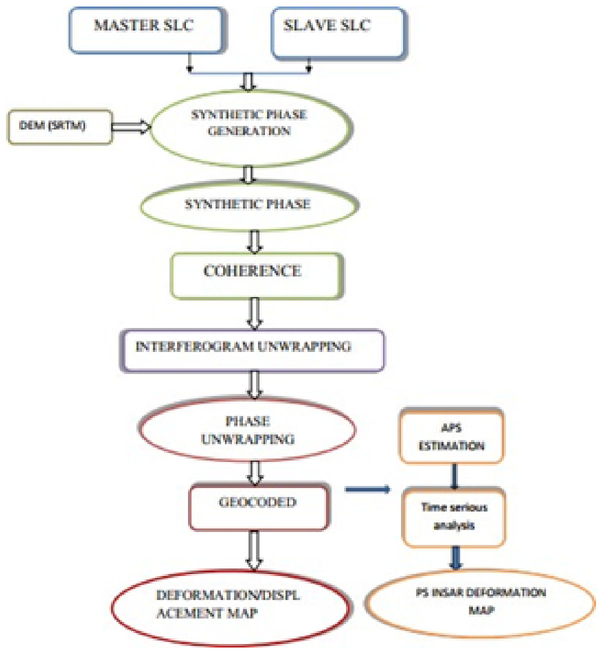
$$\tilde{\eta}(p_{s,j}) = |\eta[\Delta\tilde{v}(p_{s,j}), \Delta\tilde{h}(p_{i,j})]| \quad 5$$

The accuracies of the height and deformation velocity estimates are dependent on the temporal coherence and baseline distribution, but independent of the interferometric combination, thus the expressions are useful for all time-series InSAR analysis techniques. To get the absolute values of each PS candidates the estimated unknowns are integrated using a carefully selected reference point. This reference point is a point with no deformation or zero velocity. Undesirable choice of the reference point may leads to create biased parameters on PSs. After doing this the influence of phase noise as well as the atmospheric phase, are separated based on their temporal and special behavior differences. Using a larger threshold the atmospheric phase are removed and finally PS pixels are selected. For all pixels the unknown parameters are estimated. Finally, the PS points with large temporal coherence values generate the subsidence map.

# THE PSINSAR METHODOLOGY

The applied processing steps were as follows: Importing SLC data, master image extraction, Slave images extraction and co-registration, SAR data focusing and registration, multi-baseline construction, DEM simulation, differential interferogram generation, multi-image sparse grid phase unwrapping, APS estimation and removal (Gens, R et al, 1996), PS point selection, PS point displacement history analysis, and average deformation estimation. DEM from the Shuttle Radar Topography Mission (SRTM), with three arc-sec resolution, was applied for topographic phase removal. The movements of the PS targets are retrieved as a function of time with respect to the master image selected as shown in figure 2. By processing the phase of SAR images with the PSI technique, 3D localization of PS points with millimeter displacement along the satellite LOS can be retrieved and the final outcome was geocoded to and displayed in Google Earth.

**Figure 2**: Conceptual frame work of data processing.



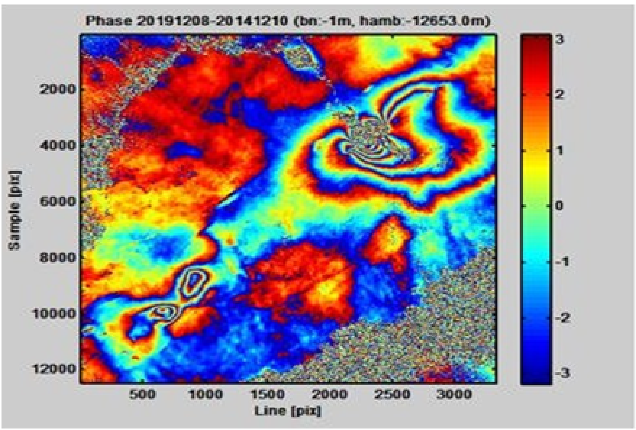

# RESULTS AND DISCUSSION

## Analysis of Ground Displacement

The PSInSAR technology gives the best results in urban areas and in areas with bare rocks, and overall where it is possible to identify objects the reflection of which does not change with time (Ferretti et al., 2001; Bürgmann et al., 2006). The Forest and lakes located around the study area do not contain PS points. Vegetation is responsible for the loss of coherence between the acquisitions and thus the capability to detect PS is low. In figure 3, two images having perpendicular baseline difference 56m were acquired on the date 2014/12/10 and 2019/12/08.

Using these two SAR images flattened and DEM removed, but wrapped interferograms were generated. The fringes which is observed tells us how much deformation and where it took place. The color pattern have to be interpreted, if we get started from the center away where we are having less concentration of fringes then blue red yellow were observed which means this area must have gone subsided. Whereas like we start here blue red yellow blue red yellow, this area must have visit and half wavelength, so half the wavelength of sentinel 1A SAR sensor was counted so as to get total exact deformation (149.32mm).

**Figure 3**: Flattened, DEM removed but wrapped Interferogram around Erta Ale between date 2014/12/10 and 2019/12/08. There are approximately six full cycle of fringes there, which corresponds to 149.32 mm during the six years period.




For example figures 4 – 8 shows the map detected by SARPROZ using PSInSAR techniques during the period of study showing the time series of the subsidence and uplift around the five selected areas. That is the deformation of Erta Ale, Ale Begu, Hayli Gubi, Alu, and Gorroble are

-149.32mm, 70.6, -75.8mm, -61.0mm and -50.1mm respectively. These areas are areas where critical subsidence was observed, the maximum critical subsidence is found at the center of the study area which is Erta Ale. Analysis of the result of the time series shows the study area is characterized by a subsidence with an increasing trend through time. Distinct, local uplift features are observed in some areas characterized by erratic positive velocities.

**Figure 4**: The map detected by Sarproz using PSInSAR, during the period 2014-2019, showing the time series of the subsidence around Erta Ale cumulative displacement -149.3mm.

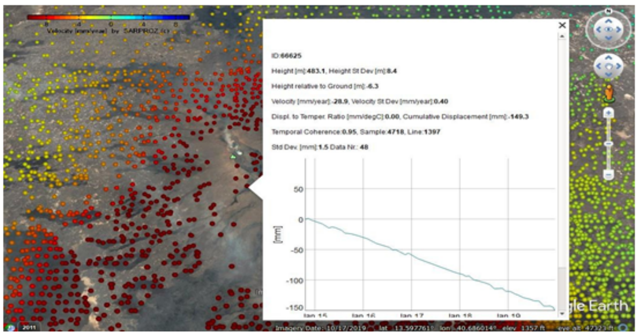


**Figure 5**: The map detected by PSInSAR, during the period 2014-2019, showing time series of the subsidence around Ale Begu cumulative displacement -70.6mm.

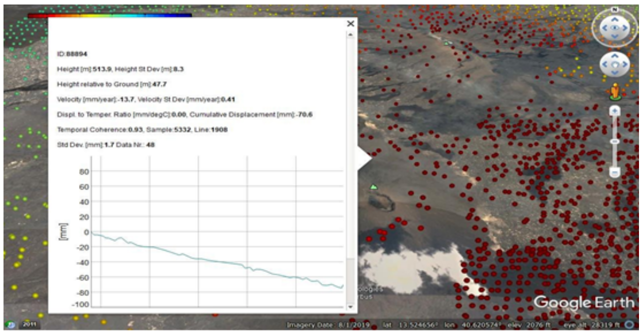


**Figure 6**: The Map detected by PSInSAR, during the period 2014-2019, showing time series of the subsidence around Hayli Gubi cumulative displacement -75.8mm.

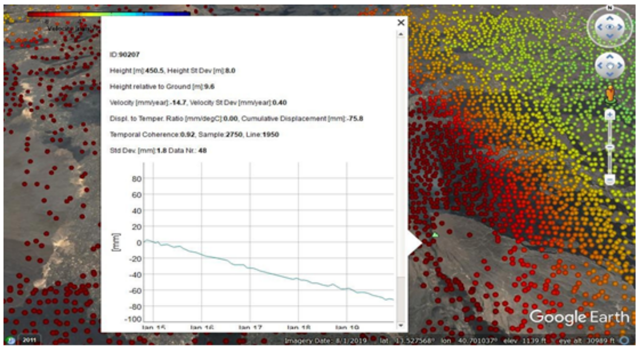


**Figure 7**: The Map detected by PSInSAR, during the period 2014-2019, showing the time series of the subsidence around Alu cumulative displacement -61.0mm.

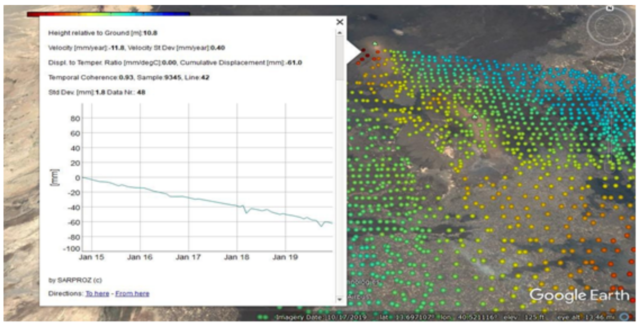
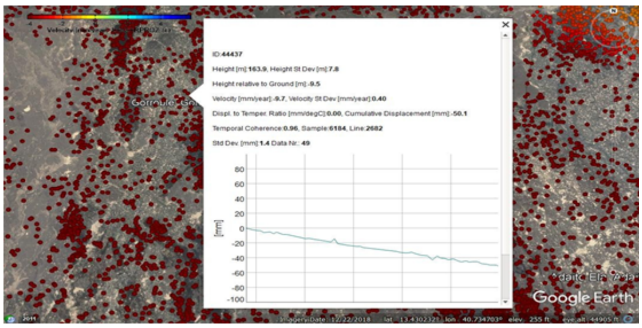


**Figure 8**: Map detected by PSInSAR, during the period 2014-2019, showing the time series of the subsidence around Gorroble with cumulative displacement -50.1mm.



(Figure 10) to the right shows the 3D representations of the PS points' locations geocoded to Google Earth, where the color of the points indicates the heights of the points. Figure 9 shows the cumulative displacement of each pixel of interferograms at each day of acquisition with respect to the first date of acquisition (red/yellow) areas of subsidence and blue areas of uplift. This shows that as the time advances the area continued to subside. The difference arises from the duration of the data sets used. There is a gradual increase in subsidence rate. Figures 11a and 11b clearly reveal that the rates of crustal velocity and cumulative displacement distribution of the AOI. The result indicates the volcanically active areas such as Erta Ale, Ali Begu, Hayli Gubbi, Alu and Gorroble are areas of critical subsidence. We can generalize the PSInSAR approach can give the time series of surface displacements and show various patterns and magnitudes of deformation in the resettlement zone. The applied classical PS-InSAR analysis detect subsidence and uplift areas. In Figures 4 -8 the crustal movement can be observed on the interferogram, the coherence is good since most of the study area is full of desert.

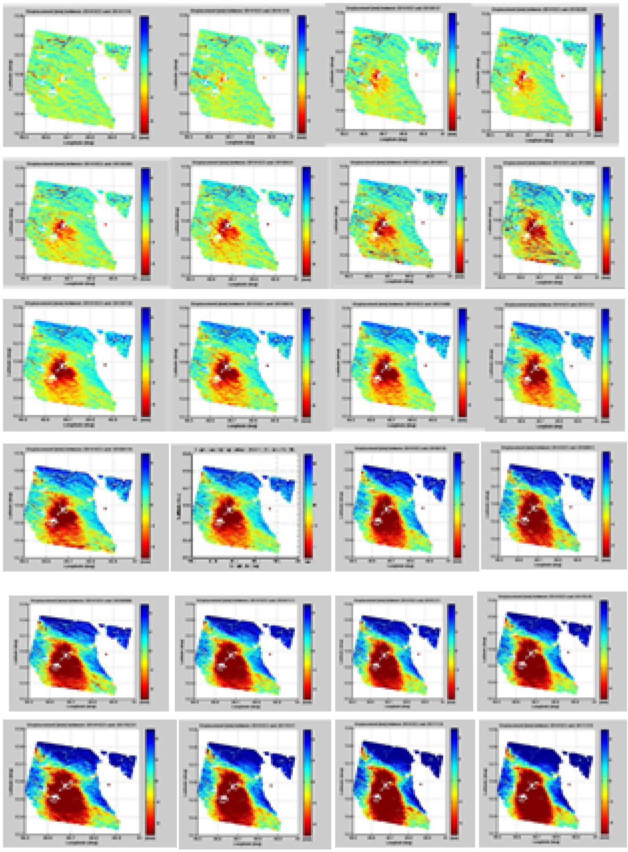


**Figure 9**: Cumulative displacement in mm of each pixel of interferograms at each day of acquisition with respect to the first acquisition date. (red/yellow) areas of subsidence and blue color positive displacement uplift.

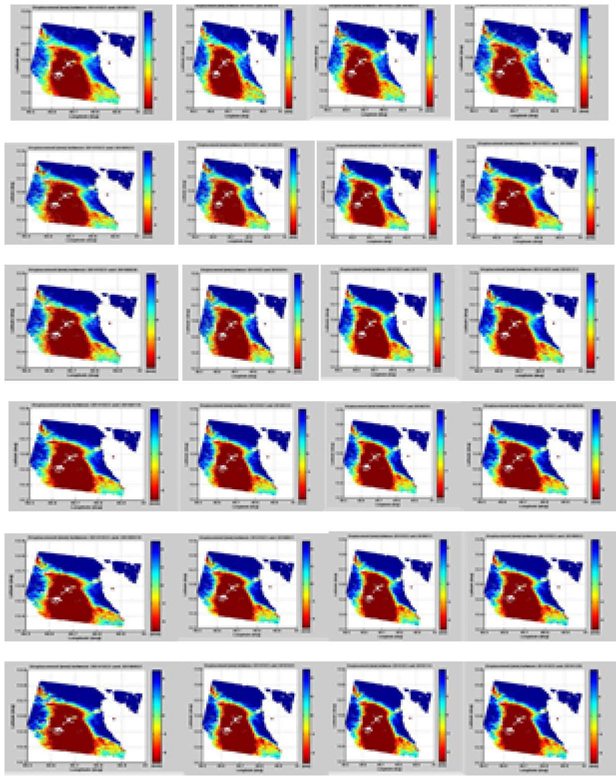


**Figure 10**: To the left the Scatter plot of the AOI, the colors red and blue show subsidence and uplift respectively, to the right deformation velocities of PS points in Erta Ale area identified by PS-InSAR from Sentinel satellite data, geocoded to Google Earth.

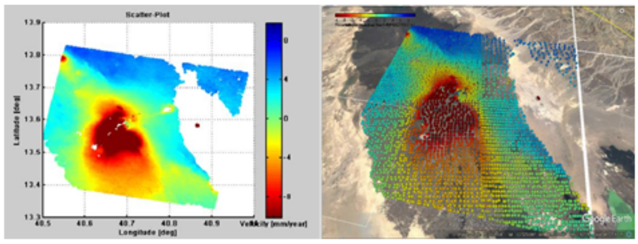



**Figure 11**: A deformation map of AOI identified by PS-InSAR from Sentinel 1A satellite data from October 2014 to December 2019 (a) to left velocity in mm/year; negative velocity values (red/orang) area of subsidence and positive velocity Values (blue) area of uplift. (b) to the right cumulative displacement in mm; (red/yellow) areas of subsidence and blue color positive displacement uplift.

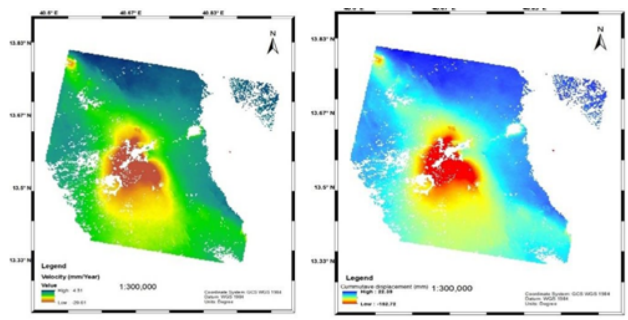
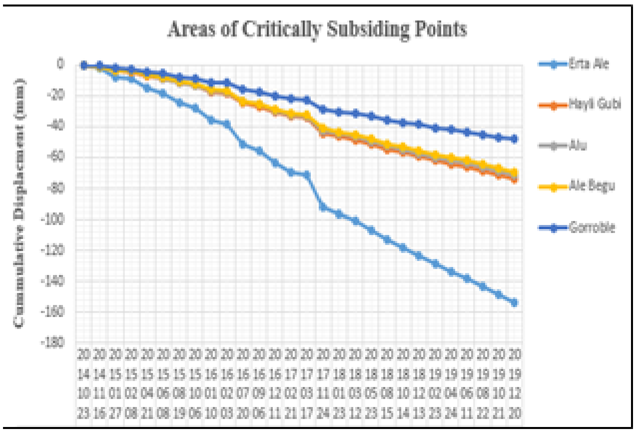


**Figure 12**: Vertical deformation time series for the 2014 - 2019 period showing critical subsidence areas (characterized by 153.32 mm maximum subsidence rate).




As one can see from figure 11 the deformation map obtained from PSInSAR processing the central study area is subsided by -149.3mm and the outer area got uplift by 28.9mm which is almost the same with the result obtained from the interferogram shown in the figure 3. The jump between 2017/03/17 and 2017/11/17 which is shown in the figure 12 above possibly be the spilling of large amount of lava that was observed on January 21, 2017. So PSInSAR is a power full technique to exploit or measure such a deformations.

## INTERPRETATION AND DISCUSSION

In this section, we tried to analyze the cause of displacement in the AOI from the points of geological formations, which is usually the dominant factors of ground displacement.

Identifying the underlying cause of regional displacement patterns can be challenging and different hypotheses should be tested. In Afar, nucleation of deformation was favored by thermal anomalies related to mantle plumes that caused weakening of the lithosphere and strain localization (Bellahsen et al., 2003). Erta Ale (found in Afar triangle) is an area which is highly affected by active extensional tectonics and basaltic magmatism from which the Gulf of Aden, red Sea and Ethiopian rift system radiate (Bonini M, 2015; McClusky et al., 2010; Kogan et al., 2012; Vigny et al., 2007; Saria et al., 2013). The main elements of tectonics in Afar are normal faults and open fissures. The strike slip faults are strike parallel to or at small angle with the rifting axis. (Abbate, et al., 1995). Erta Ale is the most active basaltic shield volcano in the Afar Region of northeastern.Ethiopia. This studies clearly indicated that the area is an active area and it is lying at the center of divergence where symmetric magnetic properties are observed. Rapid uplift or subsidence in response to magmatic intrusions or to tectonic extension are distributed throughout Northern Afar (Amelung et al., 2000; Pagli et al., 2014; McClusky et al., 2010; Kogan et al., 2012; Vigny et al., 2007; Saria et al., 2013). The source of subsidence in the area has possibly been associated with magmatic/tectonic activities (Amelung et al., 2000; Pagli et al., 2014). The result obtained from PSInSAR also agree with the previous studies that indicates the area is active.

## CONCLUSIONS

Recently, PSInSAR becomes a powerful technology solution which helps in the determination and monitoring of surface deformation across small-scale structures at high level of accuracy to mm. The different orbit imaging capabilities and selection of appropriate look angle of the recently available high resolution radar satellites have also increased its suitability for monitoring of land subsidence.

In this study, we monitored and mapped the extent and pattern of land subsidence in volcanically active areas of Afar depression through analysis of Sentinel-1A dataset. The analysis enabled us to map the land subsidence in Afar depression between 2014 and 2019. The study allowed in identifying the areas of Afar that are highly prone to geo-hazard associated with land subsidence. Land subsidence is continued to be among the major challenging geological hazards causing damage to infrastructure and threatening life in many part of the world. The study area, (the Afar Depression) and its surrounding, is located in Northern Main Ethiopian Rift, and known as one of the most frequently volcanically active territory in the region, particularly around Erta Ale. The special trend of land subsidence revealed by Sentinel-1A measurements support that it is a widespread occurrence in the study area. The source of subsidence in the area has possibly been associated with magmatic/tectonic processes. A continues magma flow of the area contribute to the observed subsidence. We believe that the estimations are correct for the center of the study area where the density of detected PSI was very high. The area where the subsidence is inferred includes the regional state of Afar. Within the triple Junction of the diverging plates and a subsidence of this extent is a source of geo-hazard. The nearby towns are homes for large population and capital intensive infrastructures which are under construction. Therefore, attention should be given to what is happening to the area in order to mitigate geo-hazards.

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