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Original article

Crustal Movement at Ol Doinyo Lengai based on GPS Measurements

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Abstract

Continuously monitoring of Horizontal and Vertical movements in vulnerable areas due to earthquakes and volcanic activities is vital. These geohazard activities are the result of a slow deformation rate at the tectonic plate boundaries. The recent development of GPS (Global Positioning System) technology has made it possible to attain a millimeter level changes in the Earth's crust. This study used continuously observed GPS data at the flank of Ol Doinyo Lengai volcanic Mountain to determine crustal motion caused by impinging volcano from mantle convention. We analyzed 8 GPS observed from June 2016 to Dec 2019 using a well-documented Global Kalman Filter GAMIT/GLOBK software. The resulting velocity from GAMIT/GLOBK analysis was then used to compute the relative motion of our study area with respect to Nubia plate. Our analysis discovered a minor motion of less than 5mm/year in both horizontal and vertical components.

Keywords : Horizontal and Vertical Crustal Movement, Global Positioning System, Geodetic Velocity, Ol Doinyo Lengai, East African Rift

1. Introduction

The eastern branch of the great EAR (East African Rift) is well known for its richness in magma which makes it an ideal place to study crustal motion associated with magmatic activities (Corti, 2012; Ring *et al*., 2018). Ol Doinyo Lengai Mountain studied here is an active volcanic mountain located on the eastern branch of EAR, Tanzania. It is bordered by Lake Natron and Natron border fault. Its summit elevation is 2,890metres (Dawson, 1962). The records of periodic eruptions of ash and lava at Ol Doinyo Lengai is dated back to early 1880s with the increase in precision in the 20th Century. Recent explosive activities of Ol Doinyo Lengai occurred in September 2007 and continued to 2008 (Keller *et al*., 2010).

Lately, space geodetic techniques have been used in determining crustal motions. Among the many space geodesy systems; GPS has recently advanced in determining horizontal and vertical velocity fields in a well-defined reference frame (Altamimi *et al*., 2011). These derived GPS velocity patterns serve many applications ranging from various normal surveying to geophysical applications such as tectonic studies, seismic studies, deformation studies and plate kinematics studies (Segall and Davis, 1997).

The determination of accurate horizontal and vertical velocity field in areas characterized by volcanic eruptions is crucial for understanding and interpreting geophysical processes occurring at volcanoes. Our study provides the first horizontal and vertical crustal motion analysis at Ol Doinyo

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Lengai based on continuous GPS measurements from stations located around the mountain. The results presented in this paper are tied to the latest release ITRF2014 (International Reference Frame 2014). Compared to this study, the analysis of previous velocity fields on earlier studies, for example (Stamps *et al*., 2008; Saria *et al*., 2014) were mainly focused on the whole part of the EAR and some were tied on the older version of ITRF.

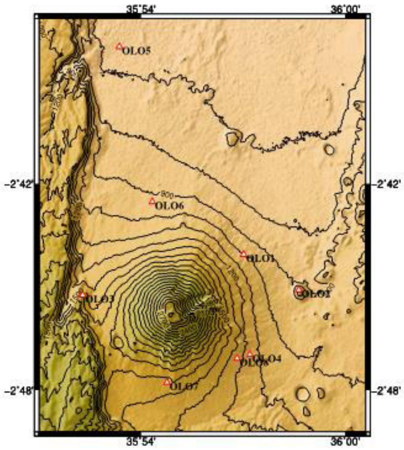


Fig. 1. GPS stations installed at Ol Doinyo Lengai

Fig. 1. shows how GPS equipment's are distributed around our study area. Stations OLO1-OLO5 were established in 2016 while the remaining 3 stations were deployed in the area in the following years. Station OLO3 is strategically positioned on the Natron fault flank so that it can detect both rift motion as well as volcano deformation.

1.1 Previous works

Due to the fact that the study area is located within a divergent tectonic boundary, where the African tectonic plate is in a process of breaking into two major plates namely Nubia plate to the north and Somalia plate to the south. This fact has given the region a spotlight on many geophysical studies. In 2007-2008 occurrence of magma-seismic events in the area has created opportunities to study the interaction between faulting and volcanic deformation. The magma-seismic events caused deformation and faulting in the area which was observed by InSAR (Interferometric Synthetic Aperture Radar) measurements, Envisat as well as campaign-style GPS measurements of 2006 and 2008 (Baer *et al*., 2008; Calais *et al*., 2008). The findings gave evidence of strain accumulation which is caused by the initial stages of continental rifting and thinning of the crust. InSAR observations show that the July 17th, 2007 deformation resulted from a dyke intrusion of about 7kms. Another work was done in the region to determine the rate of extension of the East African Rift by using GPS data, earthquake slip vectors, as well as spreading rate data. The finding resulted from this work shows that there is an extension rate of 5.2 mm/year across the EAR basin with an east-west extension on the northern and central parts of the EAR (Saria *et al*., 2014).

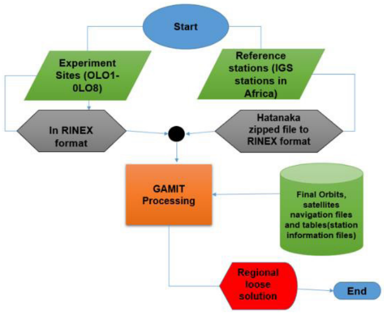
2. Methodology

2.1 Data processing

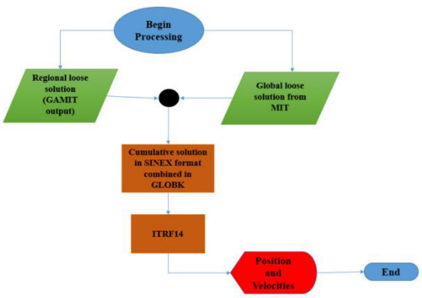
The GPS data sets processed here include 3.5 years of continuous observations (June 2016 –Dec 2019) of 8 stations (OLO1-OLO8) (Stamps *et al*., 2016; Stamps *et al*., 2017) located at Ol Doinyo Lengai which are shared freely and can be downloaded from UNAVCO (University NAVSTAR Consortium) archives (www.unavco.org). We processed our GPS data by using GAMIT/GLOBK software version 10.70 (Herring *et al*., 2010) following processing strategies explained in (Nocquet *et al*., 2006). Our processing involves two main phases; GAMIT phase and GLOB phase. In the first phase, GAMIT (Fig. 2(a)) was used to process double-differences GPS data of both our study area and regional reference stations. Other data which were included in this initial phase are IGS (International GNSS Service) final orbits, satellite vectors, tropospheric delay parameters, earth orientation parameters as well as antenna phase center models from IGS (Schimid *et al*., 2007), solid Earth and polar tide corrections (McCarthy and Petit, 2004), and ocean loading corrections using FES2004 model (Lyard *et al*., 2006). The resulted output of the initial phase was loose constrained daily least-squares adjustment estimates for the station coordinates, orbital parameters, carrier phase ambiguities, and their corresponding variance-covariance matrix. The second phase involves the combination of results obtained from initial phase with the global solution for the IGS stations used which were downloaded at MIT

(Massachusetts Institute of Technology) in SINEX (Solution Independent Exchange) format. The combination was done in a two-way approach. The first approach is by using GLRED (Global Parameter REDucing) program to obtain positional time series and the second approach was done by using GLOBK software (Fig. 2(b)) to obtain position and velocities (Table 1 and 2).

The global combination allows us to optimally tie our solution to the latest ITRF2014 (Altamimi *et al*., 2016).



(a) GAMIT processing to obtain regional loose solution in SINEX format

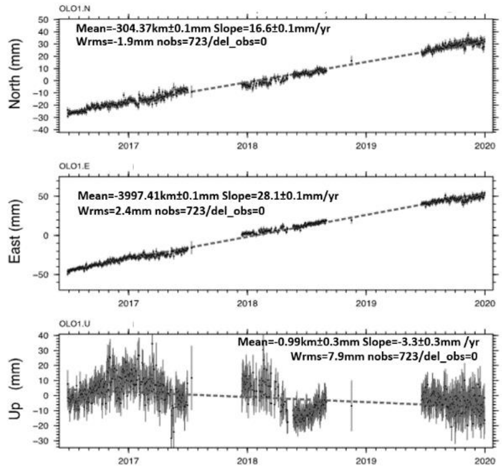


(b) GLOBK combination of regional loose solution and global loose solution

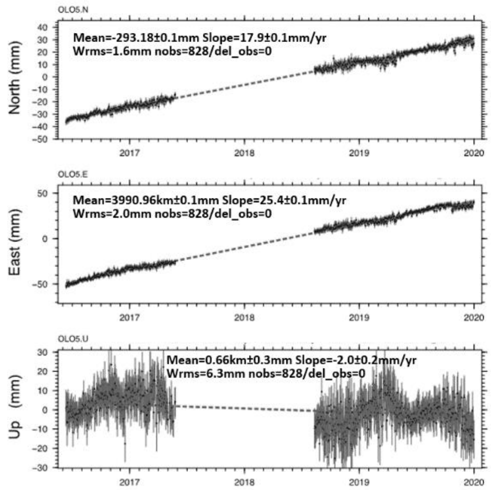
Fig. 2. Flow charts showing GAMIT/GLOBK processing

3. Results and Analysis

Fig. 3(a) and 3(b) show the selected position time series for station OLO1 and station OLO5 respectively. The two sites are among the sites which have data of more than 3 years of continuous observations. The jumps were removed using time series analysis program embedded in GLOBK software that corrects for gaps, outliers, and estimates correlated noise in relation to time by using realistic sigma algorithm.



(a) Time series for station OLO1



(b) Time series station OLO5

Fig. 3. GPS position time series of some selected sites from the study area

Position and their accuracies (Table 1) presented in ECEF (Earth-Centered, Earth-Fixed) system obtained in our second step of processing.

We analyze the velocity field of our experiment sites (Table 2) and plot absolute velocities (Fig. 3(a)) which show that they follow a north east pattern which agrees with the theory that African plate tectonically moves in northeast direction. Other stations like OLO7 was found to have unreliable data for analysis.

We then computed the relative motion of our study area (Fig.

Table 1. Position and Accuracies of experiment sites

STN	X(m)	Y(m)	Z (m)	σ_X	σ_Y	σ_Z
OLO1	5158236.95848	3740835.11137	-302267.47194	0.0003	0.0002	0.0001
OLO2	5156504.96535	3743283.13216	-304172.81255	0.0004	0.0003	0.0001
OLO3	5163694.13395	3733963.68067	-304476.00985	0.0003	0.0002	0.0001
OLO4	5157946.10236	3741039.35310	-307639.00588	0.0006	0.0005	0.0002
OLO5	5162364.39618	3735464.44229	-291147.36526	0.0003	0.0002	0.0001
OLO6	5161197.90388	3736841.28678	-299447.26297	0.0003	0.0002	0.0001
OLO8	5158431.88229	3740532.71973	-307849.20619	0.0006	0.0004	0.0002

Table 2. Position and Velocities of our experiment sites

STN	Latitude (˚)	Longitude (˚)	$V_{e\ (mm/year)}$	$V_{n\ (mm/year)}$	$\sigma_{e\ (mm/year)}$	$\sigma_{n\ (mm/year)}$	correlation
OLO1	35.95022	-2.73421	28.07	17.15	0.07	0.06	0.046
OLO2	35.97718	-2.75140	27.90	15.57	0.56	0.47	-0.022
OLO3	35.87139	-2.75398	25.47	19.07	0.08	0.07	0.097
OLO4	35.95324	-2.78277	27.72	17.63	0.27	0.23	-0.039
OLO5	35.88934	-2.63368	24.95	18.33	0.06	0.05	-0.019
OLO6	35.90551	-2.70871	21.68	18.25	0.16	0.14	-0.016
OLO8	35.94699	-2.78462	27.72	17.63	0.27	0.23	-0.039

4(b)) based on Nubia tectonic plate. Nubia tectonic plate covers the largest part out of five quantified plate from the African deformed plate, which began on early Miocene (Njoroge *et al*., 2015). Given the size of Nubia plate compared to other plates, and its low level of tectonic activities in its interior, it has been suggested to be the base for the AFREF (African Geodetic Reference Frame) (Saria *et al*., 2013).

In order to obtain the relative motion of Ol Doinyo Lengai, we first compute the angular velocity of Nubia and determines how other plates are deforming with respect to Nubia. With that respect, we started by inverting Nubia's angular velocity with respect to no net rotation frame (ITRF14) based on previous studies developed method. We analyzed the IGS stations and among 42 stations used in this study, 13 stations were found to be located on Nubian plate. The stations include ADIS, MAS1, ZAMB, RBAY, SUTH, SUTM, ULDI, HARB, BJCO, YKRO, HRAO, WIND and NKLG.

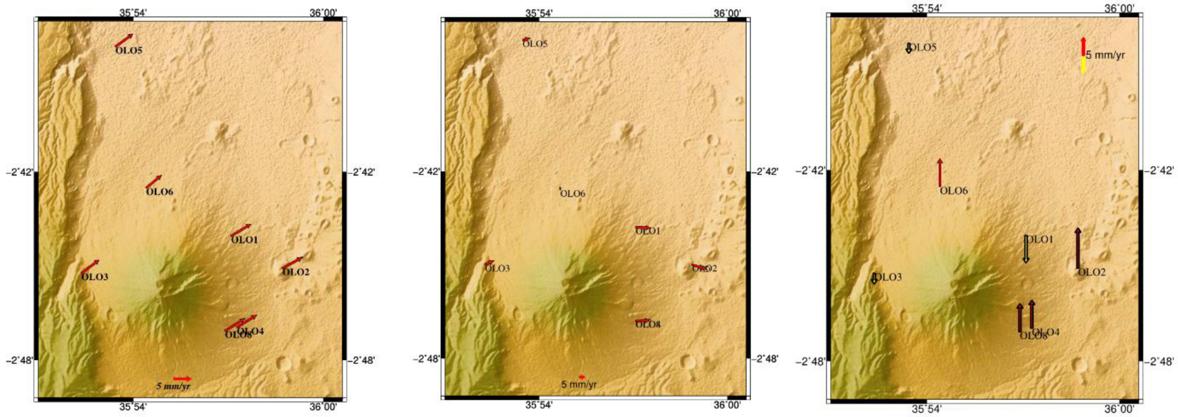
In order to determine the best GPS stations clearly defines stable Nubia plate from a set of 13 stations, we repeatedly removed one station at a time and examined whether each site velocity statistically fits well to the rigid plate model without certain site using Chi-squares statistic and F-ratio test (Stein and Gordon, 1984; Saria *et al*., 2013). Eq. (1) below illustrates the F- ratio defining the standard statistical test used to compare variances of distribution (degree of freedom estimates).

$$F = \frac{(X_{P_1}^2 - X_{P_2}^2)/(P_1 - P_2)}{X_{P_2}^2 / P_2}, \quad (1)$$

Where X^2 is Chi –square and P_1 and P_2 are degree of freedom for the estimates

Since the subset of stations that best fit a rigid plate rotation must achieve a Chi-square close to a unit, a set of three sites among thirteen sites meets the requirement. The sites which were found to have a Chi square closer to a unit are BJCO, SUTM and SUTH.

Relative motion (Fig. 4(b)) shows that most of the stations have a counter-clockwise direction. Relative movement indicates a motion of less than 5mm/year. Although this study



(a) Absolute velocity (b) Relative velocity (c) Vertical velocity

Fig. 4. Observed crustal motion from the selected sites

used only GPS data, the result obtained are consistent with the previously published results of the kinematics of EAR 5.4mm/year (Saria *et al*., 2013), 5.2mm/year (Saria *et al*., 2014) at Afar Triple Junction, 7.0mm/year (Stamps *et al*., 2008) which used a combination of GPS data and earthquake slip vector data. However, the 5mm/year crustal motion found in this study is based on the smaller part of the EAR and serves as a base for studying the impending volcano at Ol Doinyo Lengai. The relative motion increases on the eastern side of the mountain compared to west side as shown by stations OLO1, OLO2, OLO4 and OLO8 in which we speculate the motion to be caused by Natron Fault as the study area is located in the nearby Natron fault and within the divergent boundary formed by the EAR. Vertical velocities (Fig. 4(c)) show both subsidence and uplifting with most of the stations having a motion of less than 5mm/year which might suggest swelling of the mountain due to magma activities.

4. Conclusion

We used GPS derived velocities from available stations installed at Ol Doinyo Lengai mountain to analyze present-day horizontal and vertical crustal motion. Based on our analysis we found out that the mountain is subjected to crustal motion of less than 5mm/year for both horizontal and vertical component. The counter clockwise direction showed by the relative motion is possibly caused by the Natron border fault motion. The vertical movement shows minor subsidence and minor uplifting on different parts of the mountain. This might have been caused by volcanic deformation but more work needs to be done to prove this hypothesis by including different data type in the analysis like earthquake slip vector data and satellite data as well as volcanic deformation models like Mogi model. Improved geodetic coverage on the mountain is however essential for further analysis and for monitoring of volcanic activities.

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