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ORIGINAL PAPER

ANALYSIS OF RECENT AFRICAN TECTONIC PLATE SYSTEM KINEMATICS BASED ON GNSS DATA

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ABSTRACT

The African tectonic plate system consists of the Africa Plate, Somali Plate, Arabia Plate, and a few microplates. These plates have complex kinematics and involve both convergent and divergent motion, resulting in various fault systems and geological features, therefore require constant analysis. This paper presents an analysis of the recent kinematics of the African tectonic plate system based on the coordinates and time series of daily solutions of continuous GNSS stations obtained from the Nevada State Geological Survey, which are freely available. A total of 217 continuous GNSS stations were selected for the study, including 126 for the Africa Plate, 49 for the Somali Plate, and 36 for the Arabia Plate. This study involved three stages: horizontal velocity determination, strain rates determination, and rotation pole determination. The horizontal velocities of continuous GNSS stations in the ITRF2014/IGS14 reference frame on the African tectonic plate system during 1996–2022 were obtained. Deformation processes were analysed, particularly at plate boundaries such as the East African Rift System. The horizontal velocities of GNSS stations were used to determine the rotation poles of the African tectonic plate system main plates. The velocities, deformations, and rotation poles of the plates were found to be consistent with previous studies. The results confirmed the presence of different geodynamic processes within the African tectonic plate system.

INTRODUCTION

The African tectonic plate system is a complex network of tectonic plates and boundaries that make up the Earth's crust beneath the African continent and the surrounding regions. This system consists of the major Africa Plate (named Nubia Plate in some sources), two minor plates Somali and Arabia and a few microplates (Fig. 1.).

The Africa Plate is the fourth largest plate in the world, with an area of about 61,334,000 km^2 (Brown and Wohletz, 2007). It contains much of the continent of Africa (except for its easternmost part) and the adjacent oceanic crust to the west and south. The Africa Plate borders North America Plate and South America Plate to the west; the Eurasia Plate, Aegean Sea Plate, and Anatolia Plate to the north; the Arabia Plate and Somali Plate to the east and the Antarctic Plate to the south.

The Somali Plate is a minor tectonic plate with an area of about 16,667,000 km^2 (Brown and Wohletz, 2007). The plate is centered around Madagascar Island, covering roughly half of the east coast of Africa, spanning from the north in the Gulf of Aden to the East African Rift Valley in the south. The Somali Plate is bounded by the Africa Plate to the west; the Arabia Plate to the north; the India Plate and Australia Plate to the east and the Antarctic Plate to the south.

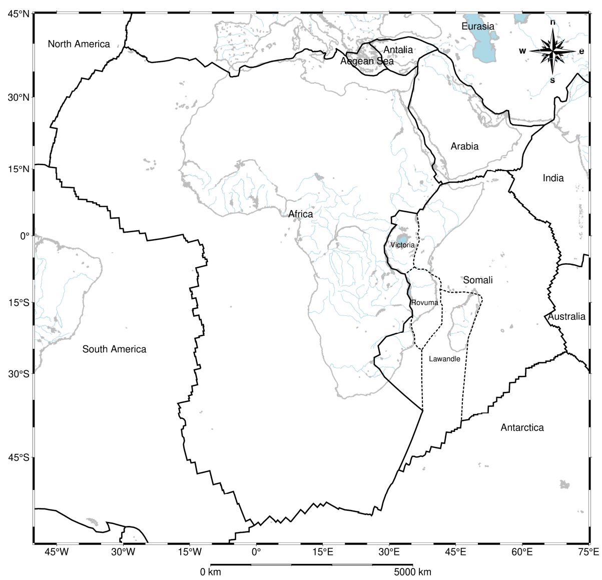

Fig. 1 African tectonic plate system with surrounding plates (The map was compiled using plate boundaries of Bird in 2003).

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The Somali Plate is currently in the process of separating from the Africa Plate along the East African Rift Valley (Fernandes et al., 2004; Chorowicz, 2005; Gaina et al., 2013; Saria et al., 2014).

The Arabia Plate is a minor tectonic plate with an area of about 5,010,900 km^2 (Brown and Wohletz, 2007). It comprises mainly the Arabian Peninsula, with its territory stretching towards the west to encompass the Sinai Peninsula and the Red Sea, and towards the north to cover the Levant region. The Arabia Plate is bounded by the Africa Plate to the west; the Anatolia Plate and Eurasia Plate to the north; the India Plate to the south and the Somali Plate Plate to the east.

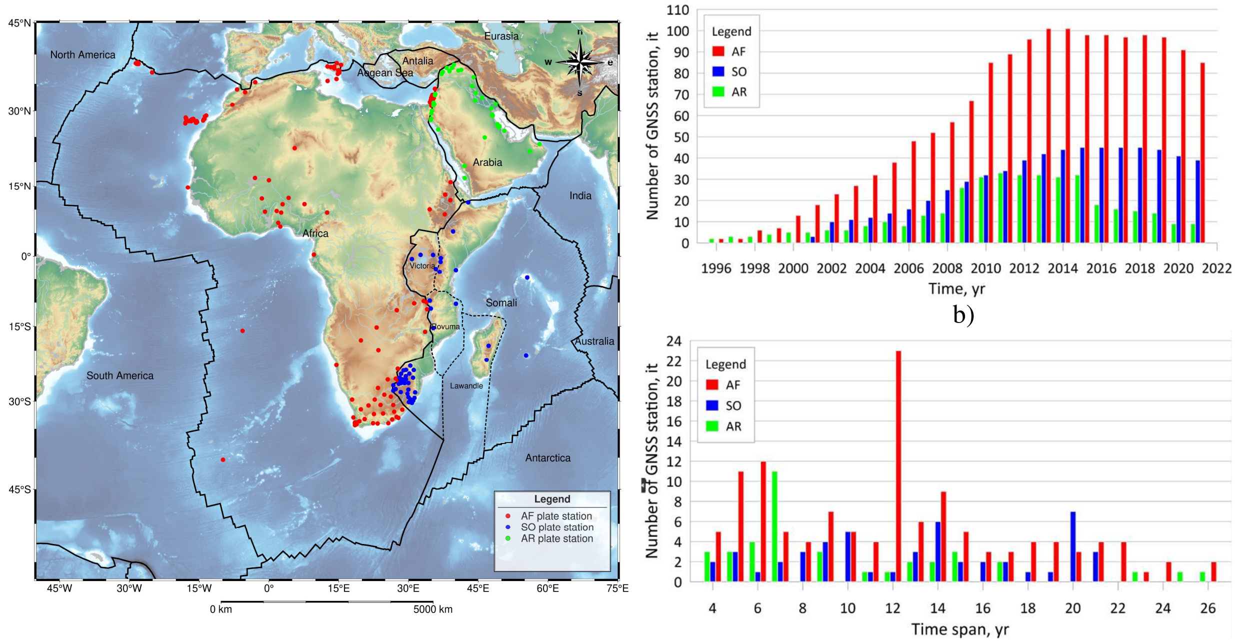
The kinematics of these plates are complex and involve both convergent and divergent motion and various fault systems. The boundary between the South America Plate and the Africa Plate is a divergent boundary, where a new oceanic crust is formed as the plates move apart. This boundary runs through the middle of the South Atlantic Ocean and is marked by the Mid-Atlantic Ridge, a long underwater mountain range that runs from the Arctic Ocean to the Southern Ocean (NOAA, n.d., para. 1). The boundary between the Africa Plate and the Eurasia Plate, which is located along the eastern edge of the Mediterranean Sea, is a complex zone of tectonic activity where the Africa Plate is being subducted, or forced beneath the Eurasia Plate (Cavazza and Stampfli, 2004). This subduction zone results in the formation of mountain ranges, such as the Atlas Mountains in North Africa and the Alps in southern Europe. The collision of the Arabia Plate with the Eurasia Plate has created the Zagros and Alborz Mountains in Iran (Mehdipour Ghazi and Moazzen, 2015). The movement of the Somali Plate and the India Plate has resulted in the formation of the Chagos-Laccadive Ridge, a long underwater mountain range that runs from the central Indian Ocean to the northern tip of Madagascar (Sreejith et al., 2019). The Chagos-Laccadive Ridge is thought to have formed due to the movement of the Indian Plate over a mantle plume, which caused massive volcanic eruptions that formed the Deccan Traps, a large volcanic plateau in western India (Sreejith et al., 2019).

The significant feature of the African Plate's movement is the East African Rift System, which is a series of deep valleys or rifts that extend from the Red Sea down to southern Africa (Fernandes et al., 2004; Chorowicz, 2005; Gaina et al., 2013; Saria et al., 2014). The rift system is a divergent plate boundary, where the Africa Plate is pulling apart and gradually separating into two parts. This process has led to the formation of the Rift Valley lakes, such as Lake Victoria and Lake Tanganyika, and volcanic activity in the region (Ebinger et al., 2010). The Arabia Plate and the Africa Plate meet along the Red Sea, which is a divergent boundary where the two plates are moving away from each other. This movement has led to the formation of a rift valley known as the Red Sea Rift, which continues to widen and deepen over time (Mitchell and Stewart, 2018). The Arabia Plate and the Somali Plate meet along the Gulf of Aden, which is a divergent boundary where the two plates are moving away from each other and lead to the formation of Aden Ridge (D' Acremont et al., 2005; Fournier et al., 2010; Fernandes et al., 2012).

The African tectonic plate system is responsible for many of the geological features and phenomena that are found in Africa and the surrounding regions, including the formation of rift valleys, mountain ranges, basins, and plateaus, as well as contributing to seismic activity, such as earthquakes and volcanic eruptions. The movement of these plates also affects the Earth's climate and weather patterns, as well as the distribution of plant and animal species across the continent. Geodynamic research in this region is of great scientific interest, which will further provide a more detailed understanding of the processes occurring between African tectonic plate system. Recently, GNSS methods are of particular interest as they can study spatial displacements and ensure a relatively high accuracy of the definition. There are examples of applying these methods to geodynamic studies of the separate parts of African tectonic plate system (Fernandes et al., 2004; Saria et al., 2013; Gomo et al., 2017; Deville et al., 2018; Viltres et al., 2022). All authors confirm the north-eastern direction of movement of this tectonic structures. The determined movements are within 20-60 mm/yr and differ for different parts of the African tectonic plate system. Therefore, there is a need to conduct a comprehensive geodynamics study of the entire African tectonic plate system. Therefore, this study aimed to investigate the recent horizontal deformation processes of the African tectonic plate system (including the Africa Plate, Somali Plate and Arabia Plate) based on GNSS data.

DATA

The freely available coordinates and time series of daily solutions (IGS14 time series data of 24-h final solutions in tenv3 format) of continuous GNSS stations were obtained from the website of the Nevada Geodetic Laboratory in 2022 (Blewitt et al., 2018), as the primary data for this research. Precise Point Positioning (PPP) with GIPSY-OASIS-II software was used by the Nevada Geodetic Laboratory to calculate the coordinates and time series of continuous GNSS stations. While the transformation parameters between ITRF2014 and IGS14 are not published since their global values are assumed to be zero (Figurski and Nykiel, 2017), we will use the ITRF2014/IGS14 abbreviation for this study since the frames are practically identical. The selection of continuous GNSS stations in this study followed the enhanced criteria proposed by Altamimi et al. (2017). It should be noted that all available data were analyzed, from 1996 for the Africa Plate and Arabia Plate and from 2001 for the Somali Plate plate. In total, 217 stations were selected for the study (126 for the Africa plate, 49 for the Somali plate and 36 for the Arabia plate).



a) c)

Fig. 2 a) Continuous GNSS station network of African tectonic plate system and characteristics of b) station availability and c) station time span. (The map was compiled using plate boundaries of Bird in 2003).

The distribution of selected continuous GNSS stations and the time series statistics are shown in Figure 2.

Continuous GNSS station network of African tectonic plate system (see Fig. 2a) is heterogeneous and not dense. This is directly related to the uneven settlement of people in these regions, as well as the development of these regions. Only the southern part of the African continent within South Africa can be considered sufficiently dense and homogeneous. Continuous GNSS stations are practically absent in the north-central part of the African continent in the Sahara desert as well as in other desert regions. Figure 2b provides evidence of the increase in the quantity of GNSS stations within the continuous GNSS station network of the African tectonic plate system over time, and obviously, this trend is closely associated with the advancement and wider usage of GNSS technologies.

Time series of daily solutions of continuous GNSS stations are heterogeneous in time (see Fig. 2c). The longest selected time series of daily solutions have a duration of 26 years, and the shortest - 4 years. Also, starting from 2010, the time series of almost all GNSS stations are homogeneous and continuous

METHOD

The methodology of this study involved three main stages: horizontal velocity determination, strain rates determination, and rotation pole determination. All numerical calculations, data analysis, and results visualization were performed with the use of MathCad v15 and Generic Mapping Tools v6.4 (Wessel et al., 2013; Wessel et al., 2019).

HORIZONTAL VELOCITY DETERMINATION

To identify and rejected any outliers in the loaded time series of daily solutions from continuous GNSS stations, a threshold of three-sigma normalized residuals was applied. Time series that contained offsets were excluded from the processing. The time series of daily solutions of each selected continuous GNSS stations was analyzed to determine the horizontal velocity. To fit the time series the following model, which took into account the annual and semi-annual signals with periods of 365.25 and 182.63 days (Blewitt et al., 2001, Collilieux et al., 2007) was used:

$$y(t_i) = y_0 + b(t_i) + \\ + \sum_{f=1}^{2}\left[c_f \cdot \sin(2\pi f t_i) + d_f \cdot \cos(2\pi f t_i)\right] + \varepsilon_y(t_i), \quad (1)$$

where $y(t_i)$ is the initial position at the reference epoch $t = t_i$ (unit of year), y_0 and b are the position and velocity parameters, $\varepsilon_y(t_i)$ is the noise, c_f and d_f are the periodic motion parameters ($f = 1, 2$ represent the annual and semi-annual seasonal terms, respectively).

STRAIN RATES DETERMINATION

According to strain rates analysis, the deformation is assumed to be homogeneous across some areas. Since the analysed network (see Fig. 2a) is not dense or homogeneous, we use irregular grid in the form of triangle net based on Delaunay algorithm (Delaunay, 1934), where continuous GNSS stations are triangle vertices. For detailed analysis of geodynamic processes, the two-dimensional (Lagrangian) strain rate tensor has been determined for each triangle:

$$e = \begin{bmatrix} e_{xx} & e_{xy} \\ e_{yx} & e_{yy} \end{bmatrix} \quad (2)$$

The components of the strain rate tensor are defined as follows (Shen et al., 1996; Sagiya et al., 2000):

$$e_{xx} = \frac{1}{\Delta t} \cdot \frac{\partial u}{\partial x}$$
$$e_{yy} = \frac{1}{\Delta t} \cdot \frac{\partial v}{\partial y} \quad (3)$$
$$e_{xy} = e_{yx} = \frac{1}{2\Delta t} \cdot \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

where (u, v) are the movements at the epoch of GNSS stations during the time interval Δt in the directions of (x, y).

The two-dimensional strain rate tensor parameters were used to calculate the required strain rates parameters (strain rate crosses, area strain rate, maximum shear strain rate and strain rate rotational wedges).

ROTATION POLES DETERMINATION

To determine the rotation poles was used methods proposed in Savchyn (2022b) which uses, generalizes and modernizes the approaches given in Marchenko et al. (2012), Tretyak et al. (2018) and Savchyn (2022a). This methods based on the correlation between the components of horizontal velocities and the rotation pole of the plate:

$$v_{B_i} = \omega \cdot \cos(\phi) \cdot \sin(L_i - \lambda)$$
$$v_{L_i} = \omega \cdot [\sin(\phi) - \cos(L_i - \lambda) \cdot tg(B_i) \cdot \cos(\phi)] \quad (4)$$

where ω represents angular velocities of the tectonic plate; ϕ and λ indicate the coordinates of the pole of rotation; B and L represent coordinates of continuous GNSS station with the determined components of horizontal velocities v_B and v_L.

RESULTS

HORIZONTAL VELOCITY DETERMINATION

As a result of time series analysis and time series fitting using dependence (1), the horizontal velocity components in ITRF2014/IGS14 reference frame for continuous GNSS station located on the African tectonic plate system were determined, and the accuracy of determining these values was evaluated. These data were used to illustrate the spatial distribution of the horizontal velocity field of the African tectonic plate system (Fig. 3).

The obtained values (see Fig. 3) indicate a northeast direction of movement at a rate of 18.8–47.8 mm/yr with an accuracy of 2.4-16.7% of the vector length, or 0.5-9.5 mm/yr. But obtained values are slightly different for different plates.

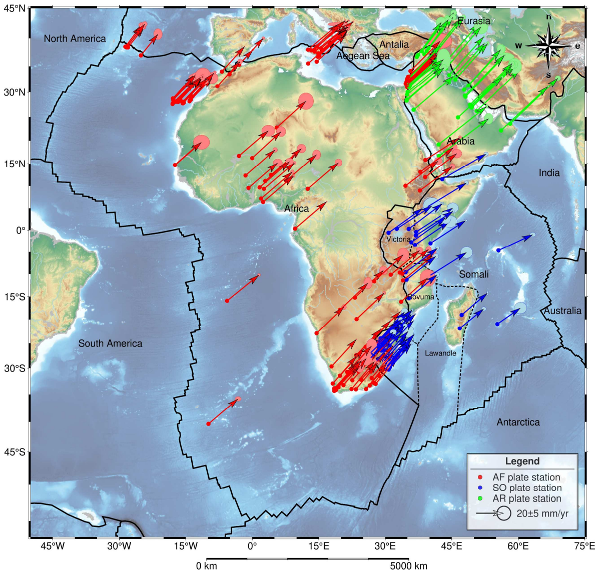


Fig. 3 Spatial distribution of the horizontal velocity field of the African tectonic plate system in ITRF2014/IGS14 reference frame.

For the Africa Plate, the northeast direction varies in the range of 37.2°–57.2°, and the horizontal velocity is in the range of 18.8-30.9 mm/yr. This plate is characterized by the lowest velocities rate among the studied ones. Continuous GNSS stations PIED, HOR1, PTRP, AZS2, and QEMD (all in Azores) are characterized by the lowest horizontal velocities, instead, continuous GNSS stations MRAV, YRCM, LAUG, JSLM, AREL, GILB, NZRT, BSHM, TELA, MSRU, SALP and KLHV (all in the Sinai Peninsula) have the highest velocities.

For the Somali Plate, the northeast direction varies in the range of 38.5°–64.8° and the horizontal velocity is in the range of 20.4-36.6 mm/yr. Continuous GNSS stations LEPO and VOIM (Reunion Islands and Madagascar) are characterized by the lowest horizontal velocities, instead, continuous GNSS stations DJIG (Gulf of Tajura) have the highest velocities.

For the Arabia Plate, the northeast direction varies in the range of 34.8°–53.0° and the horizontal velocity is in the range of 30.3-47.8 mm/yr. This plate is characterized by the highest velocities rate among the studied ones. Continuous GNSS stations ADIY, SURF KLIS, and ANTP (all in South-Eastern Taurus) are characterized by the lowest horizontal velocities, instead, continuous GNSS stations YIBL and SQUO (all in the south-eastern Arabian Peninsula) have the highest velocities.

The data obtained correlate well with the previous results presented in Fernandes et al. (2004), Saria et al. (2013), Saria et al. (2014), Reilinger et al. (2015), Gomo et al. (2017), Viltres et al. (2022).

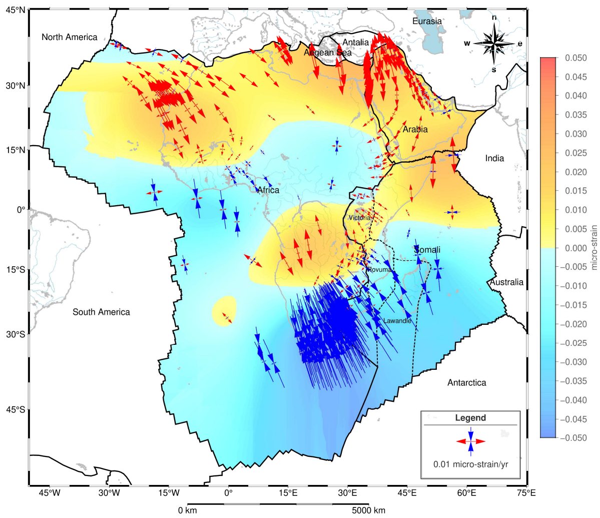


Fig. 4 Spatial distribution of the velocity field of area strain rate with strain rate crosses in the African tectonic plate system.

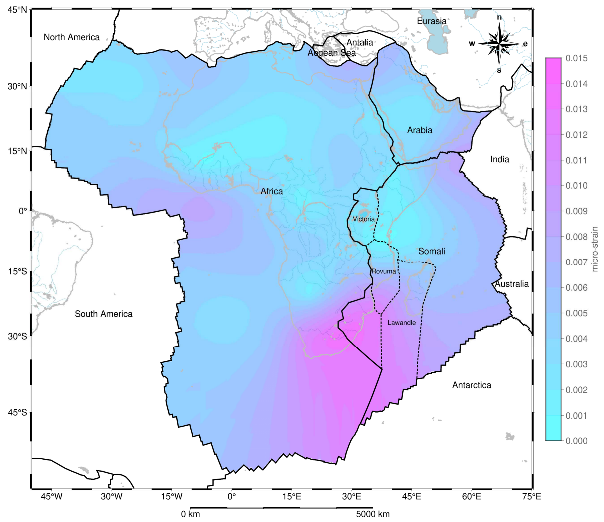


Fig. 5 Spatial distribution of the velocity field of maximum shear strain rate in the African tectonic plate system.

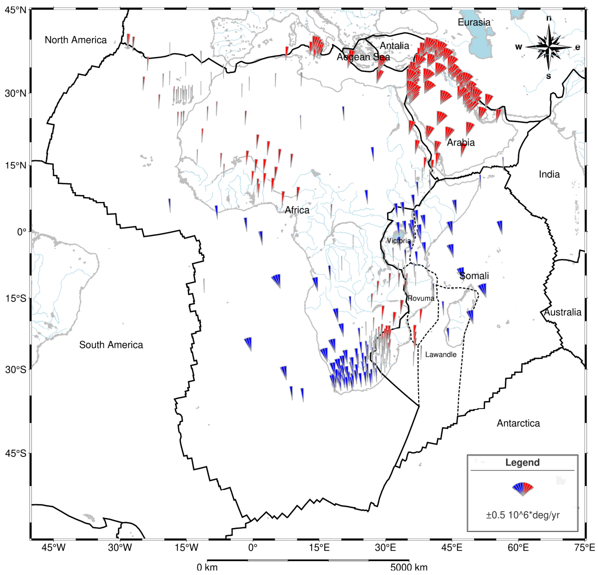


Fig. 6 Spatial distribution of the velocity field of strain rate rotational wedges in the African tectonic plate system.

STRAIN RATES DETERMINATION

The horizontal velocities of continuous GNSS stations (see Fig. 3) were used to determine strain rates parameters (strain rate crosses, area strain rate, maximum shear strain rate and strain rate rotational wedges). The spatial distribution of these values in the African tectonic plate system are presented in Figures 4–6.

The presented figures confirm the existence of quite different geodynamic processes within the African tectonic plate system. Area strain rate values (see Fig. 4) vary from -0.048 micro-strain/yr (compression) to +0.028 micro-strain/yr (extension). Maximum compressions are identified in the southern part of the African tectonic plate system at the boundary of the Africa Plate and Somali Plate. In contrast, maximum extensions are identified in the northern part of the African tectonic plate system at the boundary of the Africa Plate and Arabia Plate. The maximum shear strain rate values (see Fig. 5) vary from 0 to +0.014 micro-strain/yr. However, in comparison with area strain rate, the spatial distribution of these values is more homogeneous for the African tectonic plate system. Maximum values of maximum shear strain rate are identified in the southern part of the African tectonic plate system at the boundary of the Africa Plate and Somali Plate, as well as for area strain rate. The strain rate rotational wedges (see Fig. 6) vary from -0.40·106 °/yr (counter clockwise) to +0.56·106 °/yr (clockwise). The maximum clockwise values are identified for the Arabia Plate, and it is interesting that such maximal values are almost homogeneous for the entire Arabia Plate. The maximum counter clockwise values are not homogeneous and occur rarely in the Somali Plate's central part and the Africa Plate's southern part.

The obtained results confirm the presence of divergent processes at the Africa Plate–Arabia Plate, Arabia Plate–Somali Plate and Africa Plate–Somali Plate boundaries which known as the East African Rift System and extends from the Red Sea in the north to Mozambique in the south (Fernandes et al., 2004; Chorowicz, 2005; Gaina et al., 2013; Saria et al., 2014; Mitchell and Stewart, 2018). For a more detailed visualization and analysis of these processes, the strain rate crosses were separately defined for the characteristic points of these three plate boundaries (Fig. 7).

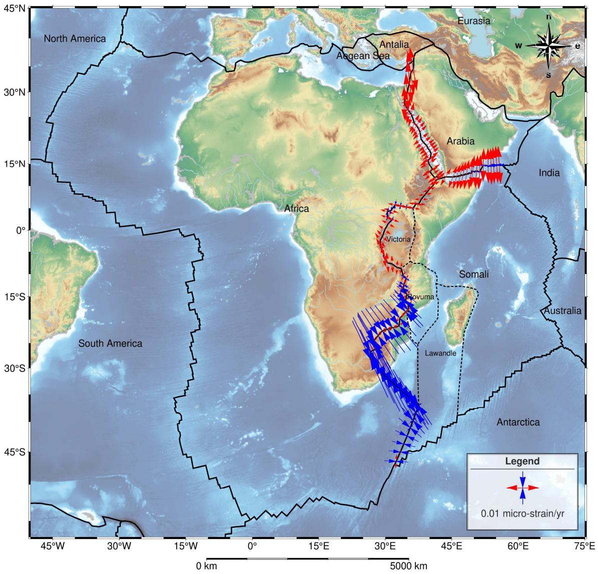


Fig. 7 Spatial distribution of the velocity field of strain rate crosses of Africa Plate–Arabia Plate, Arabia Plate–Somali Plate and Africa Plate–Somali Plate boundaries.

According to these results (see Fig. 6), the Africa Plate-Arabia Plate boundary is divergent, but this divergence is different. Along the Red Sea, the two plates move in different directions, which leads to further expansion and deepening of the Red Sea Rift (Mitchell and Stewart, 2018). However, the northern part of this boundary along the Sinai Peninsula and the Mediterranean Sea is characterized by a slightly different direction of divergent processes.

According to the above results, the Arabia Plate-Somali Plate divergence increases from east to west along the Gulf of Aden, which leads to further expansion and deepening of the Aden Ridge (D'Acremont et al., 2005; Fournier et al., 2010; Fernandes et al., 2012). The northern part of the Africa Plate-Somali Plate boundary is also characterized by divergent processes and they are much smaller in comparison with the above-described zones. However, they also led to the formation of rift known Rift Valley lakes (including Lake Victoria, Lake Tanganyika, Lake Malawi and others) (Ebinger et al., 2010). Instead, the southern part of the Africa Plate-Somali Plate boundary is characterized by convergent processes.

ROTATION POLES DETERMINATION

The horizontal velocities of continuous GNSS stations (see Fig. 3) were used to determine the rotation poles of the African tectonic plate system main plates in the ITRF2014/IGS14 reference frame (Table 1). It should be pointed out that the rotation poles were determined relative to the NNR (no-net-rotation) reference frame. To ensure the NNR condition the approach proposed by Altamimi et. al. in 2002 and Altamimi et. al. in 2003 was used.

Table 1 Recent rotation poles of the African tectonic plate system main plates in the ITRF2014/IGS14 reference frame.

Name	ω, °/m.y.	φ, °N	λ, °E
Africa Plate	0.274±0.001	48.805±0.222	79.744±0.539
Somali Plate	0.302±0.003	48.839±0.153	93.755±1.102
Arabia Plate	0.573±0.010	49.993±0.282	3.818±0.900

Analysing the results (see Table 1), it can be noted that rather different angular velocity and different pole coordinates of these three plates further confirm the presence of complex geodynamic processes within the African tectonic plate system.

The Africa Plate has the highest accuracy of rotation poles determination, while the Arabia Plate has the lowest. A rather large difference in accuracy is obviously related to the amount of available high-quality data from continuous GNSS stations.

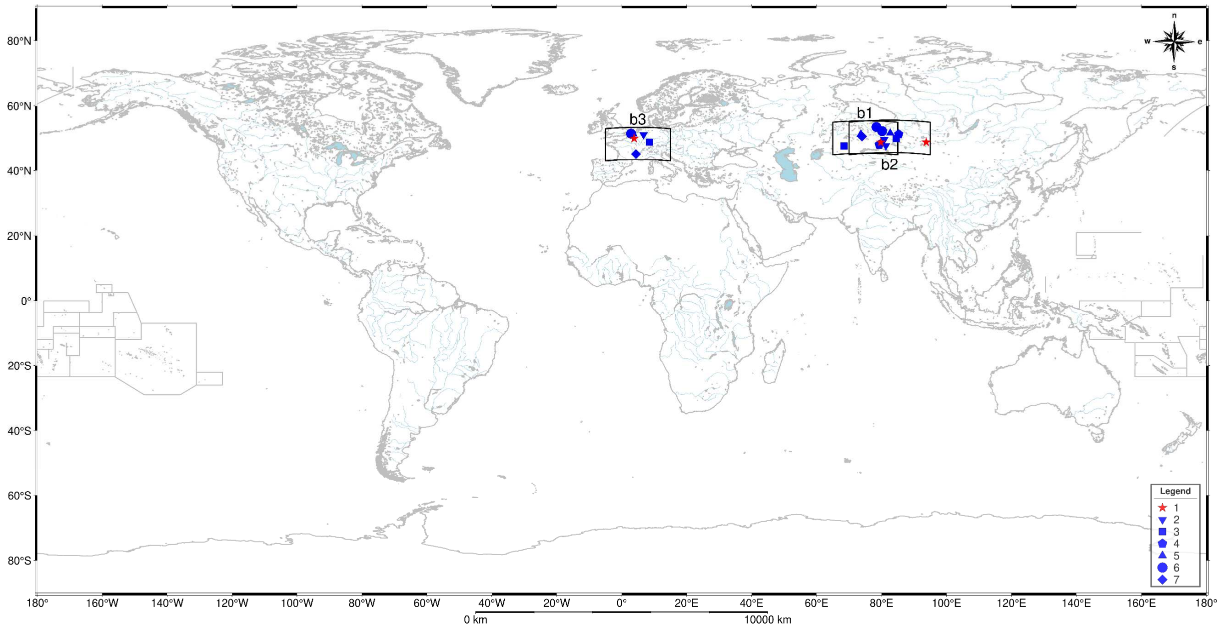
The rotation poles of the Africa and Somali Plates are quite similar. This similarity is due to the fact that in the past Africa and Somali Plates were part of the same plate, but it is obvious that in the future this similarity of rotation poles will decrease due to the recent divergent and convergent processes on their border.

DISCUSSION

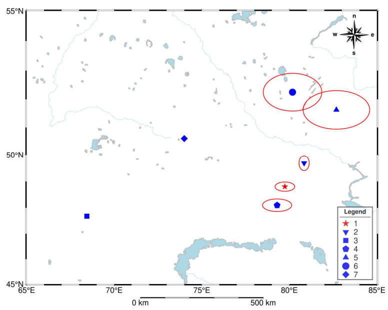
The Africa, Somali and Arabia Plates are the subject of many studies, but they are mostly studied this plates separately or in pairs (Fernandes et al., 2004; Saria et al., 2013; Gomo et al., 2017; Deville et al., 2018; Viltres et al., 2022). In this study, we consider them as a complex system – African tectonic plate system. Obviously, this provided an opportunity to obtain new valuable information about recent geodynamic processes.

To make this research reproducible, we used free available data of the Nevada Geodetic Laboratory in 2022 (Blewitt et al., 2018), as well as well-known enhanced criteria proposed by Altamimi et al. (2017) for continuous GNSS stations selection.

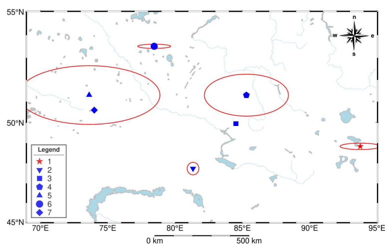
The issue of determining rotation poles solely on the basis of GNSS is quite discussional. Nowadays, different space measurement techniques, including VLBI (Very Long Baseline Interferometry), SLR (Satellite Laser Ranging) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) are actively used for rotation poles determination. Some examples of the use of VLBI, SLR and DORIS for rotation poles determination can be found in Kraszewska et al. (2016, 2018), Jagoda et al. (2019) and Jagoda and Rutkowska (2020). Altamimi et al. (2017) note that recent solution ITRF2014 is based on the homogeneous reprocessing of the four space techniques SLR, DORIS, VLBI, and GNSS, where the maximum time series available for each geodetic technique were used.



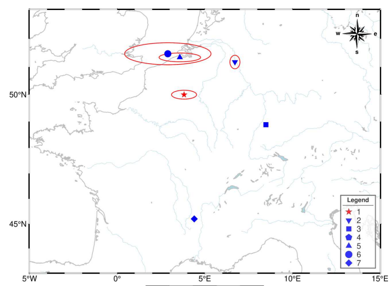
a)



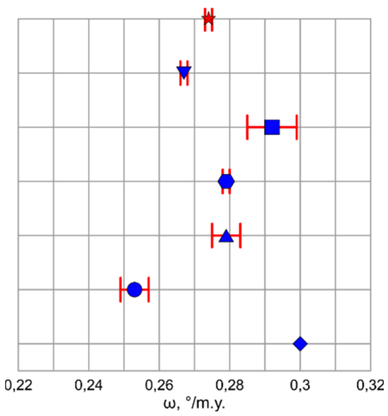
b1) Africa Plate



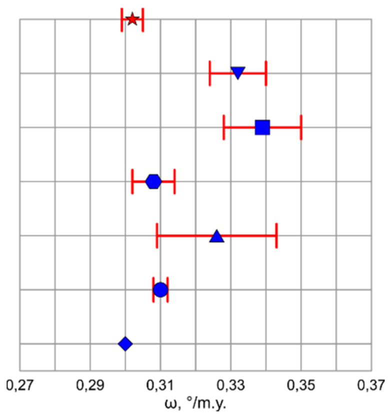
b2) Somali Plate



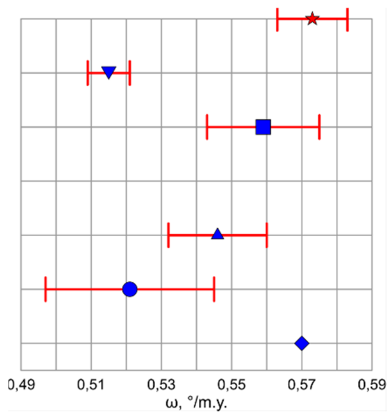
b3) Arabia Plate



c1) Africa Plate



c2) Somali Plate



c3) Arabia Plate

Fig. 8 Assessment of recent rotation poles of the African tectonic plate system main plates in term of location of the rotation poles (a, b1, b2 and b3) and their angular velocities (c1, c2 and c3). The figures were compiled using known models of tectonic plate movements 1 – This work; 2 – ITRF2014 (Altamimi et. al., 2017); 3 – NNR-MORVEL56 (Argus et al., 2011; Sella et al., 2002); 7 – NNR-NUVEL1 (Argus and Gordon, 1991).

However, due to the absence or small number of SLR, DORIS and VLBI stations on Africa, Somali and Arabia Plates, we consider it inappropriate to use such data for this plates rotation poles determination.

To assest the level of reliability and accuracy of the obtained values of the rotation poles, we compared them with the known models of tectonic plate movements: NNR-NUVEL1 (Argus and Gordon, 1991), REVEL2000 (Sella et al., 2002), CGPS2004 (Prawirodirdjo and Bock, 2004), APKIM2005 (Drewes, 2009), NNR-MORVEL56 (Argus et al., 2011) and ITRF2014 (Altamimi et al., 2017). The results of the assessment are shown in Figure 8. The choice of models for comparison was based on the popularity of the models, also models with at least two of the three studied tectonic plates were selected.

It was found that the obtained values (see Fig. 8) are quite close to the known models and are characterized by a fairly high accuracy of determination. The obtained rotational poles are closest to the ITRF2014 (Altamimi et al, 2017) and only this model values are determined at a similar level of accuracy.

CONCLUSIONS

An analysis of the recent kinematics of the African tectonic plate system based on freely available from the Nevada State Geological Survey the coordinates and time series of daily solutions of continuous GNSS stations were presented. A total of 217 stations were selected for the study, including 126 for the African Plate, 49 for the Somali Plate, and 36 for the Arabian Plate.

The horizontal velocities of continuous GNSS stations in ITRF2014/IGS14 reference frame on the African tectonic plate system during 1996–2022 were obtained. The obtained values showed a northeast direction of movement with velocity rates 18.8-47.8 mm/yr and accuracies of 2.4-16.7% of the vector length. The Africa Plate had the lowest velocities, while the Arabia Plate had the highest velocities. The results were consistent with previous studies.

The analysis of deformation processes in the Antarctic plate was carried out. The results confirm the existence of different geodynamic processes within the African tectonic plate system, particularly at plate boundaries such as the East African Rift System. The Africa Plate-Arabia Plate boundary is divergent, and the Arabia Plate-Somali Plate divergence increases from east to west along the Gulf of Aden. The northern part of the Africa Plate-Somali Plate boundary is characterized by divergent processes leading to the formation of Rift Valley lakes, while the southern part is characterized by convergent processes.

The horizontal velocities of GNSS stations were used to determine the rotation poles of the African tectonic plate system main plates. The obtained values are similar with known models of tectonic plate movements. The different angular velocity and pole coordinates of the plates confirm the presence of complex geodynamic processes within the African tectonic plate system.

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The author used open-access data and open-source software to perform this work. The software that required a license was provided by Lviv Polytechnic National University. The author is ready to provide all intermediate data of the results of calculations and analysis upon request for comparison and further research.

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