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## Present-day motion of the Arabian plate

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14 **Abstract**

15       The present-day motions in and around the Arabian plate involve a broad spectrum  
16 of tectonic processes including plate subduction, continental collision, seafloor spreading,  
17 intraplate magmatism, and continental transform faulting. Therefore, good constraints on  
18 the relative plate rates and directions, and on possible intraplate deformation, are crucial to  
19 assess the seismic hazard at the boundaries of the Arabian plate and areas within it. Here  
20 we combine GNSS-derived velocities from 168 stations located on the Arabian plate with a  
21 regional kinematic block model to provide updated estimates of the present-day motion and  
22 internal deformation of the plate. A single Euler pole at  $50.93 \pm 0.15^\circ \text{N}$ ,  $353.91 \pm 0.25^\circ \text{E}$  with  
23 a rotation rate of  $0.524 \pm 0.001^\circ/\text{Ma}$  explains well almost all the GNSS station velocities  
24 relative to the ITRF14 reference frame, confirming the large-scale rigidity of the plate.  
25 Internal strain rates at the plate-wide scale ( $\sim 0.4$  nanostrain/yr) fall within the limits for  
26 stable plate interiors, indicating that differential motions are compensated for internally,  
27 which further supports the coherent rigid motion of the Arabian plate at present. At a  
28 smaller scale, however, we identified several areas within the plate that accommodate strain  
29 rates of up to  $\sim 8$  nanostrain/yr. Anthropogenic activity and possible subsurface magmatic  
30 activity near the western margin of the Arabian plate are likely responsible for the observed  
31 local internal deformation. Put together, our results show a remarkable level of stability  
32 for the Arabian lithosphere, which can withstand the long-term load forces associated with  
33 active continental collision in the northeast and breakup to the southwest with minimal  
34 internal deformation.

35 **Plain Language Summary**

36       Good knowledge of relative motions between tectonic plates is crucial for  
37 earthquake hazard assessments. In this study, we use new geodetic GNSS (also  
38 known as GPS) measurements from many stations on the Arabian Peninsula  
39 to provide updated information about the motion of the Arabian plate relative  
40 to its neighboring tectonic plates. The new GNSS velocities indicate that as a  
41 whole, the Arabian plate moves like a single block, resisting well the push and  
42 pull forces associated with plate boundary processes at its margins. However,  
43 when looking at smaller scales, several areas within the plate are deforming, with  
44 aquifer pressure changes due to groundwater pumping being the main cause of  
45 the deformation in most cases.

## 1 Introduction

The Arabian plate began its independent motion in the late Oligocene, likely facilitated by extensional forces associated with plume-related volcanism beneath the African lithosphere and northward subduction of the Neo-Tethys ocean in response to the Indian-Eurasian continental collision (McClusky et al., 2003; Bellahsen et al., 2003; Bosworth et al., 2005; Fournier et al., 2010). The location of the plate boundaries, as we know them today, resulted from several phases of structural reorganization taking place since the early Miocene including: 1) simultaneous rifting along the Red Sea and Gulf of Aden at ~25 Ma, 2) seafloor spreading in the Gulf of Aden and the Red Sea since ~17.6 Ma and ~13 Ma, respectively, 3) continental collision along the Bitlis suture and the Bitlis-Zagros fold and thrust belt since ~14 Ma, 4) connection of the northern Red Sea with the East-Anatolian fault through the Dead Sea transform fault at ~14 Ma, 5) formation and isolation of microplates including the Danakil and Sinai (~13 Ma) blocks, 6) stabilization of the southernmost Red Sea and full transfer of the Nubian-Arabian extension west of the Danakil block ~8-5 Ma, and 7) formation of the ~800 km long Owen Fracture Zone (OFZ) connecting the Aden-Owen-Carlsberg triple junction to the Makran subduction zone at ~2.4-6 Ma (Vernant et al., 2004; Bosworth et al., 2005; Garfunkel & Beyth, 2006; Fournier et al., 2008; McClusky et al., 2010; Fournier et al., 2010; Reilinger & McClusky, 2011; Leroy et al., 2012; Robinet et al., 2013; Reilinger et al., 2015; Varet, 2018b; Bosworth et al., 2019; Rodriguez et al., 2019; Gomez et al., 2020; Augustin et al., 2021, and references therein, Fig. 1).

Subduction of Nubian and Arabian oceanic lithosphere beneath Eurasia continues at present and is the main driver of the observed oblique opening along the Red Sea and Gulf of Aden rifts, right-lateral strike-slip motion along the OFZ, frontal shortening along the Makran subduction zone, transpression along the Bitlis-Zagros fold and thrust belt, and predominantly left-lateral strike-slip motion along the Dead Sea and East Anatolian faults (Vernant et al., 2004; Reilinger et al., 2006; ArRajehi et al., 2010; Rodriguez et al., 2019; Hamiel & Piatibratova, 2019; Gomez et al., 2020, Fig. 1). Earlier studies combining GNSS measurements, magnetic anomaly profiles, earthquake slip vectors and plate paleo-positions indicate that the relative motions involving the Arabian-Nubian, Arabian-Somalian, and Arabian-Eurasian plate pairs have been unchanged since at least 11, 15, and 24 Ma, respectively (Chu & Gordon, 1998; McQuarrie et al., 2003; ArRajehi et al., 2010; Fournier et al., 2010; Iaffaldano et al., 2014; Schettino et al., 2016). Nevertheless, temporal variations in the Arabian-Nubian-Eurasian relative motion has been suggested based on GNSS-derived angular velocities from stations in Yemen, Bahrain, Oman, and Iran, finite rotations of the ocean-floor along the Eurasia-Nubia-North America plate circuit, as well as global dynamic models (e.g., Calais et al., 2003; Austermaann & Iaffaldano, 2013). This change in the con-

82 vergence rate is interpreted to have initiated since ~5-3.2 Ma, coeval with the most recent  
83 phase of orogenic uplift within the Zagros and adjacent regions (Austermann & Iaffaldano,  
84 2013).

85 The Arabian plate interior is composed of two main crustal domains of  
86 continental lithosphere, likely resulting from mantle processes and marginal  
87 uplift within the Red Sea and the Gulf of Aden (Stern & Johnson, 2010). The  
88 eastern part of the plate is dominated by Mesozoic to Cenozoic sedimentary  
89 rocks, while the Arabian shield in the west is primarily composed of Precambrian  
90 rocks and hosts several Cenozoic alkalic volcanic fields that remain volcanically  
91 active (Hancock et al., 1984; Bosworth et al., 2005; Stern & Johnson, 2010,  
92 Fig. 1). Intraplate magmatism accounts for several volcanic eruptions over the  
93 last few kiloyears and a recent rifting event affecting the western margin of the  
94 plate in 2009 (Camp & Roobol, 1989; Pallister et al., 2010; Jónsson, 2012; Xu et  
95 al., 2016). The orientation of dyke intrusions, the roughly N-S arrangement of  
96 the major volcanic fields (Harrat Rahat, Harrat Khaybar, and Harrat Ithnayn)  
97 as well as the linear vent systems marking their central axes all suggests a  
98 stress field dominated by E-W to ENE-WSW directed extension on the western  
99 margin of the plate (Camp et al., 1992b; Pallister et al., 2010; Trippanera et al.,  
100 2019). This present-day state of stress appears to be governed by northward  
101 asthenospheric flow starting beneath Afar and running through the southern  
102 Red Sea towards the western margins of the plate rather than by Precambrian  
103 basement intraplate tectonic structures (Camp & Roobol, 1989; Pallister et al.,  
104 2010; Lim et al., 2020).

105 The main tectonic structures within the plate interior are marked by the  
106 Najd fault system, the Central Arabian graben system, the Al-Batin arch, and  
107 the Azraq graben (Hancock et al., 1984; Konert et al., 2001; Faqira et al., 2009;  
108 Stern & Johnson, 2010, Fig. 1). The Najd fault system strikes NW-SE across  
109 the Precambrian shield and is predominantly composed of sinistral strike-slip  
110 faults and brittle to brittle-ductile shears zones (Stern & Johnson, 2010). The  
111 Central Arabian graben system runs for ~560 km on the central part of the plate  
112 and is formed by a series of grabens and troughs trending east towards Qatar  
113 in the south, and NW-SE (i.e., subparallel to the terrane boundaries of the  
114 Precambrian shield) in the north (Hancock et al., 1984). The NE-trending Al-  
115 Batin arch runs across the eastern part of the plate from near the Precambrian  
116 shield towards Iran with limited observations suggesting tectonic control by  
117 lineaments of NE-trending normal faults (Hancock et al., 1984; Faqira et al.,

118 2009). The Azraq graben strikes NW and has been interpreted to represent  
119 a mechanically weak trend on the northern part of the plate (Konert et al.,  
120 2001). Despite the presence of these internal structures, seismic activity is  
121 primarily focused along the plate boundaries (ISC, 2022). In addition, intraplate  
122 earthquakes, albeit infrequent (i.e., Tabuk 2004, Lunayyir 2009) show relation  
123 with tensional stresses associated with the opening of the Red Sea extending  
124 several tens of kilometers into the western margin of the plate (Pallister et al.,  
125 2010; Aldamegh et al., 2012; Xu et al., 2015b). Furthermore, significant ground  
126 subsidence, shallow seismicity, opening cracks, and sinkholes documented in the  
127 recent years towards the center of the plate indicate response to groundwater  
128 over-exploitation and rapid urbanization (e.g., Othman et al., 2018).

129 Estimates of the relative motion at the plate boundaries surrounding the Arabian plate,  
130 which provide important inputs for regional earthquake hazard assessments, mostly rely on  
131 GNSS observations and kinematic block modeling (e.g., Vigny et al., 2006; ArRajehi  
132 et al., 2010; Reilinger & McClusky, 2011; Kreemer et al., 2014; Altamimi et al., 2017). How-  
133 ever, despite an overall consistency between kinematic models, differences in GNSS site  
134 numbers, geographic distribution, and observation time spans have resulted in some dis-  
135 crepancies between the predicted relative motions. Adding to that, the present-day motion  
136 and boundary configuration of several microplates surrounding the Arabian plate are still  
137 not fully resolved (e.g., Sinai, Carmel, Mt. Lebanon, Syrian Coast, Helmand, Lut, Central  
138 Iran, Reilinger et al., 2006; ArRajehi et al., 2010; Gomez et al., 2020, Fig. 1). Furthermore,  
139 GNSS-derived differential motions have indicated that the Arabian plate is coherently mov-  
140 ing as a single block, although localized strains consistent with shortening in the Palmyride  
141 Mountains and extension within the western Arabian margins have been observed (e.g.,  
142 ArRajehi et al., 2010; Aldaajani et al., 2021). All the studies above, however, relied on a  
143 limited number of GNSS stations from within the plate interior or included sites spanning  
144 only up to 18 months of measurements, yielding results with limited resolution.

145 Here we report on the analysis of measurements from 189 GNSS stations spanning up  
146 to 17 years of continuous and survey mode observations and provide updated constraints on  
147 the present-day motions of the Arabian plate. We re-estimated the angular velocity describ-  
148 ing the current Arabian-International Terrestrial Reference Frame 2014 (ITRF14)  
149 relative motion using our new GNSS-derived velocities for stations free from plate-boundary  
150 effects. Then, we combined our results with similar estimates for the neighboring tectonic  
151 plates into a kinematic block model to address the present-day relative motions at the plate  
152 boundaries surrounding the Arabian plate. From the same set of GNSS stations, we present  
153 a horizontal strain-rate field for the interior of the Arabian plate on a calculation grid of

154 0.5° in latitude and longitude. Finally, we discuss the implications of our new results for  
155 the plate's motion during recent geological times, as well as for the possible relation of the  
156 estimated internal strains with anthropogenic activity, and subsurface magmatic activity.

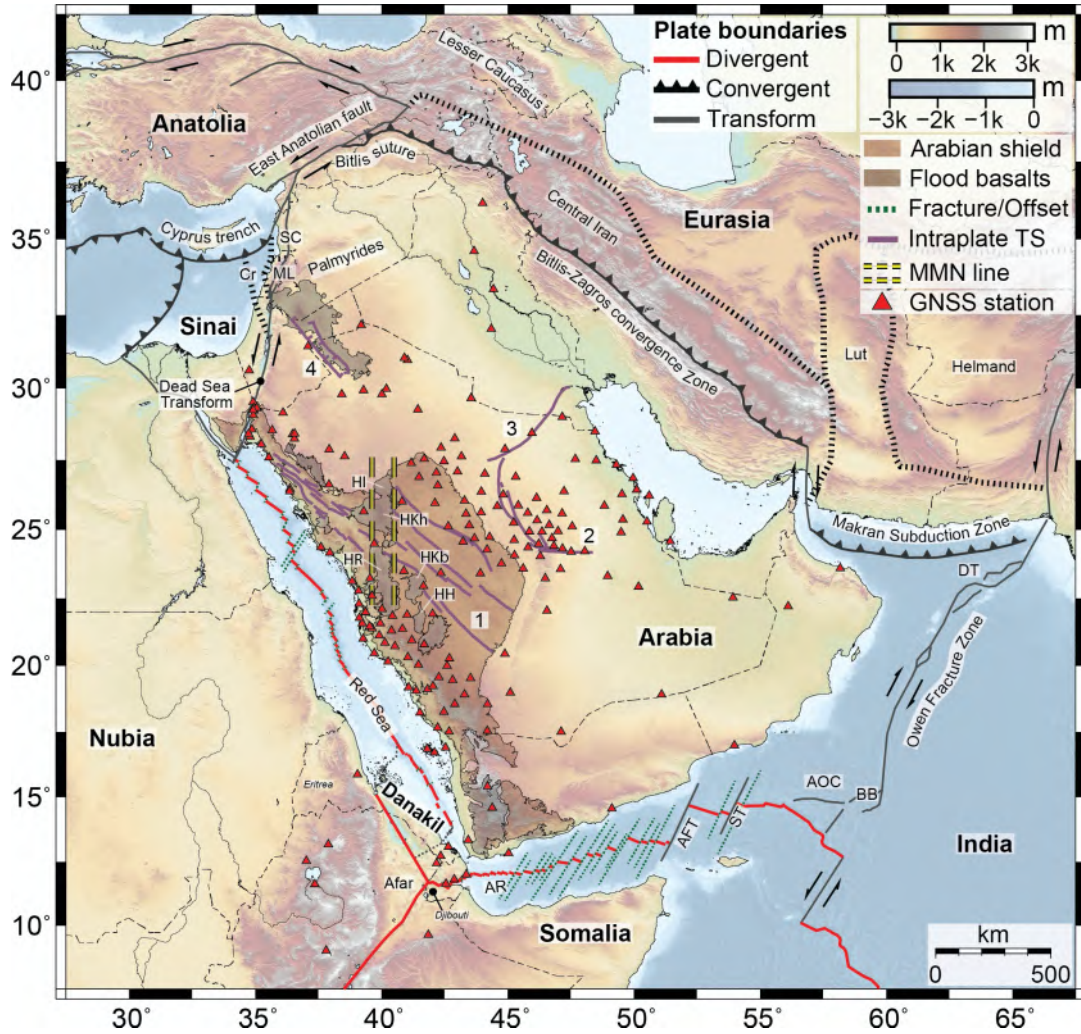


Figure 1. Main plate boundaries around the Arabian plate defined after Bosworth et al. (2005); Schettino et al. (2016); Doubre et al. (2017); Rodriguez et al. (2019); Viltres et al. (2020); Ribot et al. (2021) and A. Afifi (pers. comm.). Background hillshaded topography and bathymetry from <http://topex.ucsd.edu/>. The Carmel (Cr), Mt. Lebanon (ML), Syrian Coast (SC), Central Iran, Lut, and Helmand blocks were drawn after Gomez et al. (2020), Reilinger et al. (2006) and Vernant et al. (2004). Other abbreviations: Tectonic structure (TS), Harrat Rahat (HR), Khaybar (HKh), Ithnayn (HI), Kishb (HKb), Hadan (HH); Alula-Fartak (AFT), Socotra-Hadbeen (ST) transform fault; Aden ridge (AR), Aden-Owen-Carlsberg triple junction (AOC), Dalrymple Trough (DT), Beautemps-Beaupré pull-apart basin (BB), Makkah-Madinah-Nafud (MMN) line. Solid purple lines mark the major intraplate tectonic structures with numbers being 1) Najd fault system, 2) Central Arabian graben system, 3) Al-Batin arch and 4) Azraq graben modified after Hancock et al. (1984), Konert et al. (2001) and Stern and Johnson (2010).



## 2 Data and Methods

### 2.1 GNSS datasets and processing

The geodetic data we used for both the Euler pole and the strain-rate tensor estimations are from 189 GNSS stations spanning up to ~17 years of continuous or survey-mode observations (Fig. 1). The longest time-series (>5 years) belong to continuous GNSS stations installed in the area by MIT (data available at <https://www.unavco.org>), King Abdulaziz City for Science and Technology (KACST), and the IGS (data available at <https://cddis.nasa.gov/archive/gnss/data/daily>). Most of the station data (126 stations), however, only span up to 2.5 years, and were provided by the Saudi Arabia General Authority for Survey and Geospatial Information (data available at <https://ksacors.gcs.gov.sa>, see Table S1 of the supplementary material for details). Additional datasets include GNSS observations from East Africa acquired by MIT, King Abdullah University of Science and Technology (KAUST), and the French mobile network (data available at King et al., 2019; Jónsson, 2020, and <https://gpsmob.resif.fr/donnees>, respectively), and three GNSS stations installed in Yemen and Oman during the YOCCAL project (e.g., Leroy, 2013). Observations from a total of 19 IGS fiducial GNSS stations complemented the geodetic dataset and were used for reference frame stabilization.

The GNSS observations were analyzed with the GAMIT/GLOBK GNSS analysis package (Herring et al., 2018), following the processing steps described by Floyd et al. (2010) and Kogan et al. (2012). In the first step, daily loosely constrained station coordinates and their associated covariance matrices (quasi-observations) were obtained from the double-difference GNSS phase observations. In the next step, we used the GLOBK Kalman filter (Herring et al., 2018) to combine daily quasi-observations into position time-series aligned to the ITRF14 reference frame (defined after Altamimi et al., 2017). The daily solution alignment was achieved by estimating a six-parameter Helmert transformation constraining the positions of the 19 fiducial IGS stations to their ITRF14 values. At this step, outliers were removed from the daily position time-series and appropriate weights to the observations were determined. In the final step, the cleaned daily solutions from the survey-mode and continuous observations were combined into a single survey or 7-day position time-series, respectively, to minimize short-term noise effects.

To better constrain the GNSS station's secular motion given that most of the time-series only extend up to 2.5 years, and to take the station-specific noise structure into consideration, we used the HECTOR-v1.7.2 software package (Bos et al., 2013) instead of the GLOBK Kalman filter for the velocities estimation. It allows for automatic offset detection and outlier removal while estimating trajectory model parameters with realistic uncertainties

192 in time-series with temporally correlated noise (Bos et al., 2008, 2013; Williams, 2003, 2008,  
193 and references therein). For each component, we described the temporal variations in the  
194 position time-series by a trajectory model composed of a linear trend, annual and semiannual  
195 oscillations, and step-function terms to account for earthquakes and/or hardware change.  
196 Likewise, the noise within each position time-series was assumed to derive from a linear  
197 combination of white and power-law components. For the limited number of survey-mode  
198 observations, the trajectory model only included the parameters defining a linear trend to  
199 describe the time-series. In addition, we added random walk process noise components that  
200 predict the same uncertainties as the median values of the noise structure derived from the  
201 continuous GNSS stations prior to the velocity estimation. Finally, angular velocities from  
202 the Altamimi et al. (2017) plate motion model were used to rotate the estimated absolute  
203 station velocities relative to the Nubian plate (Fig. 2).

## 204 2.2 Angular velocity and strain-rate tensor estimation

205 For the estimation of the Arabian-ITRF14 angular velocity, we constructed a simplified  
206 block model based on the plate boundaries shown in Fig. 1 using the TDEFNODE software  
207 (McCaffrey, 1995, 2002, 2009, Fig. 2). Then, we used similar estimates for the neighboring  
208 tectonic plates to estimate the rates and azimuths of present-day motions at the major plate  
209 boundaries in the region (e.g. Red Sea-Afar, Dead Sea Transform Fault, Zagros-Makran col-  
210 lision zone, Owen Fracture Zone, etc., Fig. 1). Since the GNSS observations are mostly  
211 from the Arabian plate (Fig. 2), the angular velocities for the major neighboring tectonic  
212 plates (Nubian, Eurasian, Indian) were taken from Altamimi et al. (2017) and DeMets et  
213 al. (2019), and the microplates (Danakil, Sinai, Anatolian) angular velocities were taken  
214 from Viltres et al. (2020), Hamiel and Piatibratova (2019), and Gomez et al. (2020), re-  
215 spectively (see paragraph below for details). Our regional-scale kinematic model considered  
216 free-slip along the fault segments defining the block's boundaries, while the Euler vectors  
217 (angular velocities) were estimated assuming both (1) rigid block motion, and (2) internal  
218 deformation, by including the parameters defining a uniform horizontal strain-rate tensor  
219 in the optimization. In both cases, the model parameters were estimated by minimizing the  
220 residual horizontal velocities at GNSS sites located at least 50 km away from the prescribed  
221 block boundaries by means of the weighted least squares method.

222 The motion of the Arabian plate was constrained by 168 sites after removing 11 GNSS  
223 stations from within 50 km of the plate boundaries and three GNSS sites (HL04, TB06,  
224 MK94) with time-series affected by transient signals, and therefore, not representing the  
225 steady-state motion of the plate (Table S1). The angular velocities for the Nubian and  
226 Eurasian plates were defined after the Altamimi et al. (2017) plate motion model and con-

227 strained by 24 and 97 sites, respectively. For the Indian and Somalian plates, we used the  
228 angular velocities from DeMets et al. (2019). Their estimates include 29 and 11 GNSS sites,  
229 respectively, and are better constrained than the estimates in Altamimi et al. (2017), which  
230 include only 3 stations on each plate. The motion of the Danakil, Sinai, and Anatolian  
231 microplates were constrained by 8 (Viltres et al., 2020), 7 (Hamiel & Piatibratova, 2019),  
232 and 11 (Gomez et al., 2020) GNSS stations, respectively.

233 We estimated the strain-rate tensor and rotation rates for the entire Arabian plate at a  
234 spatial resolution of  $0.5^\circ$  using the “strain tensor from inversion of baselines”, STIB method  
235 (Masson et al., 2014). The STIB method derives from the “inversion of baseline variations”  
236 method, developed by Spakman and Nyst (2002), and has been successfully used in regions  
237 like Iran, Afar, and the French Alps (e.g., Doubre et al., 2017; Masson et al., 2014; Henrion  
238 et al., 2020). It uses relative baseline changes between all possible pairs of GNSS stations  
239 within a network to derive the velocity gradient at each computation node, independently  
240 of any reference frame (Dobre et al., 2017; Masson et al., 2014). This approach makes  
241 the method less dependent on the network geometry and the quality of the velocity field,  
242 compared to similar methods like the triangle and the gridded approaches (Wu et al., 2011;  
243 Masson et al., 2014; Doubre et al., 2017). Similar to the angular velocity estimation, only  
244 GNSS stations at least 50 km away from the prescribed block boundaries were used in the  
245 inversion. The inversion was performed without regularization (spatial smoothing), and the  
246 covariance matrix for the a priori model was set to be diagonal with a constant value of  
247  $10^{-9}\text{yr}^{-1}$ , i.e., of the order of magnitude of the expected internal deformation within the  
248 plate (e.g., Vigny et al., 2006).

## 249 3 Results

### 250 3.1 GNSS velocity field

251 The GNSS station velocities show a consistent northeast motion and rotation of the  
252 Arabian plate, relative to the Nubian plate (Fig. 2). The motion is  $\sim 19$  mm/yr towards  
253  $\sim \text{N}51^\circ\text{E}$  in the southernmost Red Sea,  $\sim 12$  mm/yr towards  $\sim \text{N}40^\circ\text{E}$  at  $\sim 21.5^\circ\text{N}$ , and  $\sim 7$   
254 mm/yr towards  $\sim \text{N}23^\circ\text{E}$  in the Gulf of Aqaba area (Fig. 2). The horizontal velocity uncer-  
255 tainties for GNSS stations within the Arabian plate interior ( $>50$  km from plate boundary)  
256 average to 0.42 mm/yr, and reach up to 1.13 and 1.35 mm/yr for the north and east com-  
257 ponent, respectively.

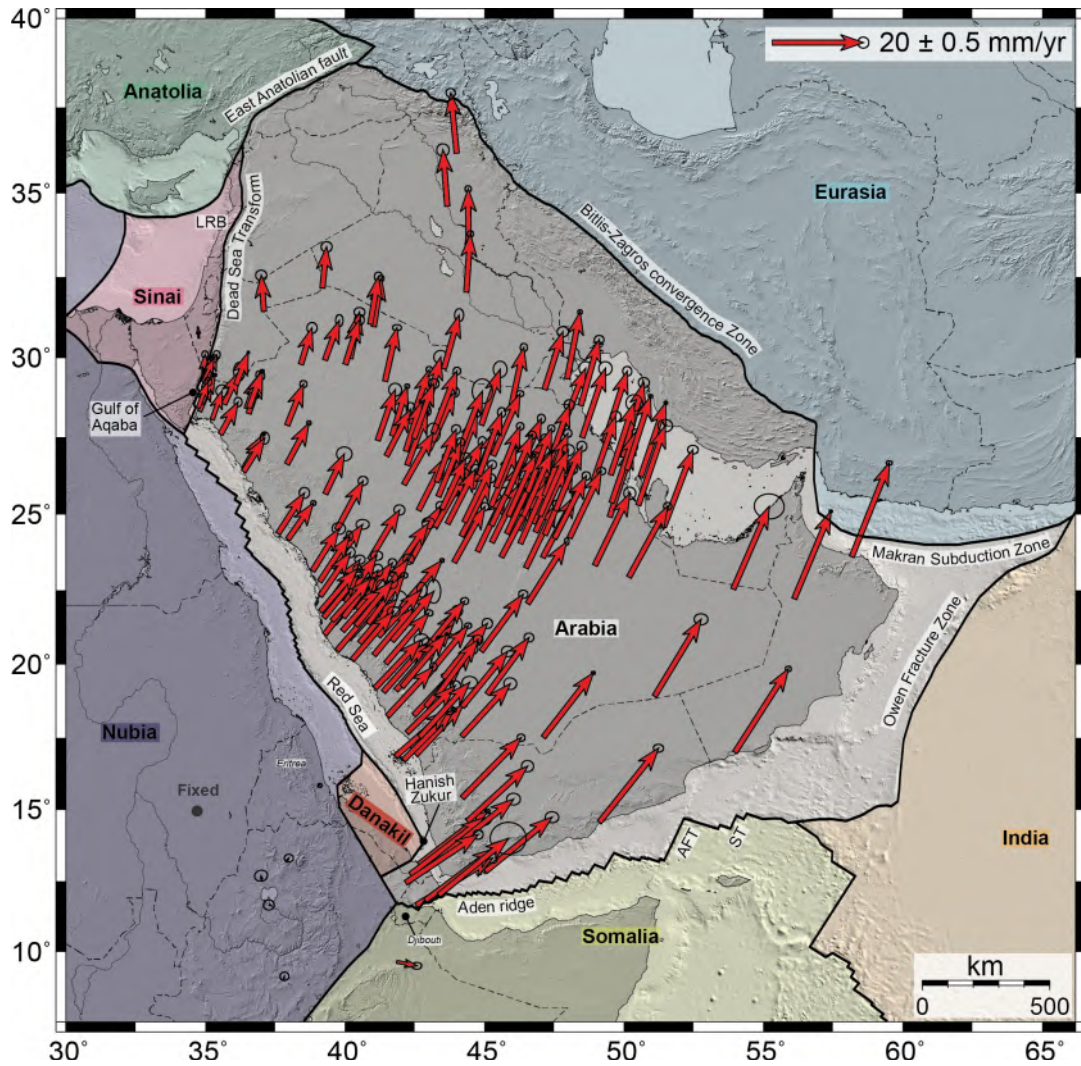


Figure 2. Horizontal GNSS velocities with 95% confidence ellipses rotated into a Nubian-fixed reference frame defined after the Altamimi et al. (2017) plate motion model. Black solid lines mark the simplified kinematic block model derived from the plate boundaries in Figure 1. Abbreviations: Lebanon restraining bend (LRB); Alula-Fartak (AFT), Socotra-Hadbeen (ST) transform fault. Background hillshaded topography and bathymetry are as in Figure 1.

258 GNSS velocities in the southernmost Red Sea, i.e., north of the western part of the  
 259 Aden ridge along the Arabia-Somalia plate boundary confirm the full transfer of the Nubian-  
 260 Arabian relative extension into Afar (Vigny et al., 2006; Doubre et al., 2017, Fig. 2). Their  
 261 present-day motions are well described by the Nubian-Arabian angular velocities, indicating  
 262 that the area in southern Eritrea and northern Djibouti currently represents a part of the  
 263 Arabian plate (Barberi & Varet, 1977; Courtillot, 1982; Viltres et al., 2020, Fig. 1).

### 3.2 Kinematic model

The estimated angular velocity for the Arabian plate relative to the ITRF14 reference frame is consistent with counterclockwise rotation around an Euler pole located at  $50.93 \pm 0.15^\circ \text{N}$ ,  $353.91 \pm 0.25^\circ \text{E}$  at a rate of  $0.524 \pm 0.001^\circ / \text{Ma}$  (Table 1). Our new estimate is within the 2-sigma uncertainties of the Altamimi et al. (2017) angular velocity, but significantly different from the Kreemer et al. (2014) results. The difference likely derives from the low number and distribution of GNSS stations used in the latter study, i.e., only 5 stations in the ESE part of the plate, including two redundant locations (See Table S1 in Kreemer et al., 2014, for details). The WRMS for the 168 sites used in the Arabian plate realization is 0.48 mm/yr, marginally better than the 0.60 mm/yr for 21, and 0.56 mm/yr for 5 GNSS sites used by ArRajehi et al. (2010) and Altamimi et al. (2017), respectively.

Our angular velocity estimates predict counterclockwise rotation of Arabia relative to the Nubian plate around an Euler pole located at  $31.61 \pm 0.24^\circ \text{N}$ ,  $24.22 \pm 0.31^\circ \text{E}$  at a rate of  $0.387 \pm 0.002^\circ / \text{Ma}$ . The resulting Euler pole locates within  $\sim 0.4$  angular degrees, but rotates  $\sim 5\%$  faster compared with the Euler poles in ArRajehi et al. (2010), Reilinger and McClusky (2011), and Altamimi et al. (2017). However, at the 2-sigma uncertainty level, the angular velocities are indistinguishable. As expected from the previous results, we find significant discrepancies with Kreemer et al. (2014), which estimated Euler pole locates  $\sim 7$  decimal degrees eastward and requires  $\sim 29\%$  faster rotation rate.

The agreement between our results and the estimates from ArRajehi et al. (2010), Reilinger and McClusky (2011), and Altamimi et al. (2017) stands for the Arabian-Eurasian and Arabian-Somalian angular velocities of relative motion. However, our resulting Arabian-Indian angular velocity is significantly different from all the previous studies. The associated Euler pole locates up to  $\sim 43$  and  $\sim 47$  angular degrees southward and eastward, respectively, and requires a rotation rate up to  $\sim 3$  times smaller relative to the former studies. Our predicted relative motions along this plate boundary are at the lower limit of the earlier estimates, but represent better the almost pure strike-slip tectonics of the Owen Fracture Zone (e.g., Rodriguez et al., 2019, Fig. 3).

Similar to the Arabian-Indian estimates, the Arabian-Sinai, and Arabian-Anatolian angular velocities reflect clear differences between recent studies addressing the present-day plate kinematics (e.g., ArRajehi et al., 2010; Reilinger & McClusky, 2011; Kreemer et al., 2014; Hamiel & Piatibratova, 2019; Gomez et al., 2020). In these cases, internal deformation (e.g., western Anatolian, Reilinger et al., 2006) combined with a limited number of GNSS stations, and the small size of the microplates (e.g., Sinai, ArRajehi et al., 2010) result in the variety of estimated angular velocities in the studies above. These elements may also

299 contribute in the  $\sim 2/4$  and  $\sim 6/12$  angular degree north and west shifts of the Danakil/Sinai  
 300 microplate instantaneous Euler pole relative to the long-term estimates for the last  $\sim 4.62$   
 301 Ma by Schettino et al. (2016).

Table 1: GNSS-derived angular velocities and uncertainties.

Plate pair	( $^{\circ}$ )		( $^{\circ}/\text{Ma}$ )				Covariance matrix <sup>a</sup> ( $\times 10^{-6}$ )					
	Lat.	Lon.	$\dot{\omega}$	$\dot{\omega}_x$	$\dot{\omega}_y$	$\dot{\omega}_z$	$\sigma_{xx}$	$\sigma_{yy}$	$\sigma_{zz}$	$\sigma_{xy}$	$\sigma_{xz}$	$\sigma_{yz}$
AR-ITRF14	50.93	353.91	0.524	0.3284	-0.0350	0.4068	1.76	1.59	0.72	1.63	1.07	1.02
AR-NU	31.61	24.22	0.387	0.3010	0.1354	0.2031	3.12	2.24	1.56	1.71	1.11	0.93
AR-EU	27.56	17.74	0.417	0.3519	0.1126	0.1928	3.18	1.87	2.50	1.68	2.29	1.10
AR-IN	25.49	313.77	0.020	0.0124	-0.0129	0.0085	10.56	143.29	17.82	32.13	10.77	5.52
AR-SO	23.91	26.53	0.420	0.3440	0.1717	0.1704	23.75	29.40	4.89	24.02	-4.58	5.19
AR-DA	13.83	42.19	-2.474	-1.7797	-1.6130	-0.5915	2671	1992	321	230	924	798
AR-SI*	36.34	14.97	0.135	0.1055	0.0282	0.0803	15.13	1.21	32.49	-	-	-
AR-AN*	27.79	42.45	-0.824	-0.5279	-0.4828	-0.4096	-	-	-	-	-	-

Notes: The angular velocities above describe the rotation of the Arabian plate (AR) relative to the second listed plate and the ITRF14 (defined after Altamimi et al., 2017). The Arabian-ITRF14 angular velocities are constrained by 168 GNSS stations. The present-day motions relative to the neighboring tectonic plates are constrained by recent estimates of their angular velocities relative to the ITRF14 (Altamimi et al., 2017; DeMets et al., 2019; Hamiel & Piatibratova, 2019), except for the Danakil and Sinai microplates, which Euler vectors were reported relative to the ITRF08 (Viltres et al., 2020; Gomez et al., 2020).<sup>a</sup>

Elements of the angular velocity covariance matrix have units of  $(^{\circ}/\text{Ma})^2$ . \* Full covariance matrices were not possible to estimate from the provided information in the respective studies (see Section 2.2). Abbreviations: Nubian (NU), Eurasian (EU), Indian (IN), Somalian (SM) plate, and Danakil (DA), Sinai (SI), Anatolian (AN) microplate.

302 The updated velocity field rotated into an Arabian-fixed reference frame defined after  
 303 the angular velocities estimated in this study (Table 1) is shown in Figure 3. The residual  
 304 GNSS velocities within the Arabian plate interior fall within the 95% confidence interval  
 305 for most of the stations, confirming the coherent rotation of the plate at present. Some  
 306 exceptions to this are observed across the plate and will be described in Section 3.4. As  
 307 previously mentioned, the WRMS for the 168 sites used in the Arabian plate realization is  
 308 0.48 mm/yr, indicating that our single Euler vector explains well almost all the observed  
 309 station motions.

### 310 3.3 Relative motion at plate boundaries

311 In addition to GNSS residual velocities, Figure 3 shows the rate and direction of the  
 312 predicted current motions along the Arabian plate boundary (blue arrows). Following the  
 313 strategy described in McClusky et al. (2010), we estimated the relative motion (strike-  
 314 slip and normal components) along the Arabian plate boundary associated with our set of  
 315 Euler vectors. As from our kinematic model, free-slip and vertical faults are assumed, and

316 therefore, the effects of the dip angles and elastic strain accumulation are not accounted  
317 for. Besides, our block configuration provides a simplified description of the plate boundary  
318 zones, particularly for the Levant and Iran regions, where present-day motions suggest the  
319 interaction of additional microplates (e.g., Carmel, Mt. Lebanon, Syrian Coast, Helmand,  
320 Lut, and Central Iran blocks, Vernant et al., 2004; Gomez et al., 2020, Fig. 1) not considered  
321 in this study.

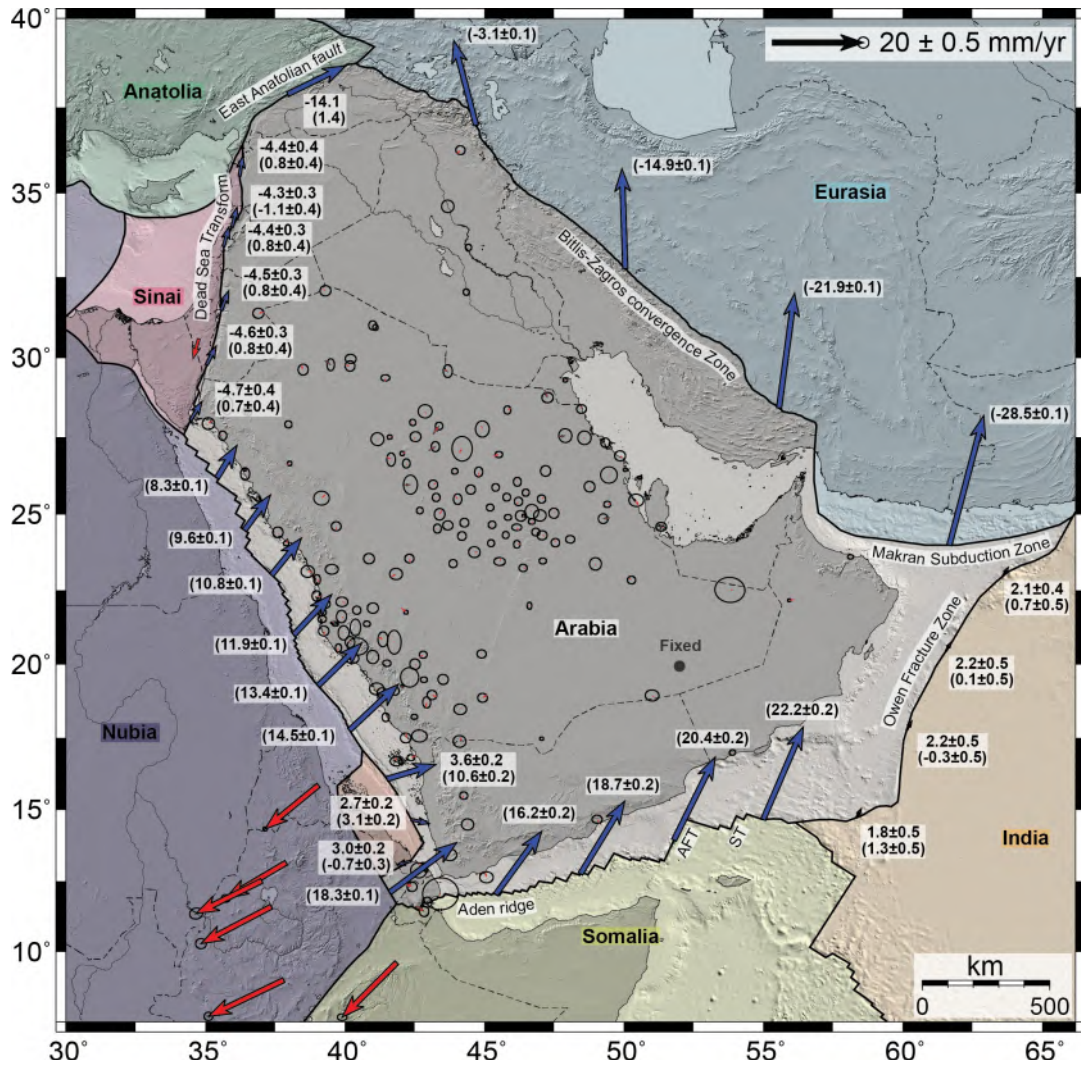


Figure 3. Observed GNSS velocities (red arrows), with 95% confidence ellipses, rotated into the Arabian-fixed reference from the kinematic block modeling results (Table 1). Blue arrows show predicted motions (east side with respect to the west side, or north with respect to south) at selected locations along the plate boundaries with the deduced normal and parallel components (mm/yr) being highlighted by white boxes. The numbers without parentheses (top) show the strike-slip component, with positive values being left-lateral sense of motion and the numbers in parentheses (bottom) show the normal component, with positive values being opening. Black solid lines mark the simplified kinematic block model derived from the plate boundaries in Figure 1. Background hillshaded topography and bathymetry are as in Figure 1.



322 The predicted velocities along the Arabian-Sinai plate boundary indicate primarily  
 323 transtensional motions along the Dead Sea transform fault, consistent with  $4.4\text{-}4.7 \pm 0.3$   
 324 mm/yr of left-lateral strike-slip, and  $\sim 0.8 \pm 0.4$  mm/yr of extension, except for the Lebanon  
 325 restraining bend area (Fig. 1 and 3). Our estimates are in good agreement with recent  
 326 studies in the region constrained by GNSS (e.g., Mahmoud et al., 2005; Reilinger et al.,  
 327 2006; ArRajehi et al., 2010; Al Tarazi et al., 2011; Sadeh et al., 2012; Masson et al., 2015;  
 328 Hamiel & Piatibratova, 2019; Gomez et al., 2020; Castro-Perdomo et al., 2021), InSAR  
 329 (e.g., Li et al., 2021) and geological data (e.g., Klinger et al., 2000; Niemi et al., 2001;  
 330 Ferry et al., 2007), particularly south of the Lebanon restraining bend (Fig. 1). At the  
 331 center latitude of the Lebanon restraining bend ( $\sim 34^\circ\text{N}$ ) where the block boundary turns  
 332 eastward, our angular velocities predict average compressional motions of  $\sim 1.1 \pm 0.4$  mm/yr,  
 333 consistent with the suggested shortening of the bend and in the Palmyride Mountains area  
 334 (e.g., Kazmin, 2001; Alchalbi et al., 2010; ArRajehi et al., 2010, Fig. 3).

335 For the Arabian-Nubian and Arabian-Danakil plate pairs, the kinematic modeling in-  
 336 dicates a gradual transfer of the Nubian-Arabian relative extension from the Red Sea into  
 337 Afar (Fig. 1 and 3). From north to south, the extensional motions increase from  $\sim 7.2 \pm$   
 338  $0.1$  mm/yr at the latitude of the Nubian-Arabian-Sinai triple junction ( $\sim 27.5^\circ\text{N}$ ) to  $\sim 15.0$   
 339  $\pm 0.1$  mm/yr at the Nubian-Arabian-Danakil triple junction ( $\sim 17.0^\circ\text{N}$ ). From  $\sim 17.0^\circ\text{N}$  to  
 340 the Hanish-Zukur Islands group ( $\sim 13.8^\circ\text{N}$ ) the Arabian-Nubian relative extension gradually  
 341 dies out along the main axis of the southern Red Sea rift, simultaneously with a southward  
 342 increase in differential motions on the western Danakil margin (Fig. 3). Going inland  
 343 from the Hanish-Zukur Islands group, the predicted relative motions indicate primarily left-  
 344 lateral strike-slip tectonics, with a fading extensional component as the block boundary  
 345 cuts through Central Afar towards the inland axis of the southern Red Sea rift (Fig. 1 and  
 346 3). Here, the Arabian-Nubian predicted motions match the GNSS-derived velocities ( $0.8$   
 347 mm/yr of WRMS for the 6 GNSS stations), indicating that the area is coherently moving  
 348 with the Arabian plate at present (Fig. 3).

349 From west to east the Arabian-Somalian predicted opening motions range from  $\sim 15.2$   
 350  $\pm 0.2$  mm/yr in the Gulf of Tadjoura to  $\sim 22.9 \pm 0.2$  mm/yr near the Aden-Owen-Carlsberg  
 351 triple junction (Fig. 1 and 3). The predicted extension rates are consistent with geodetic  
 352 estimates of the relative plate motion by ArRajehi et al. (2010) and Altamimi et al. (2017).  
 353 Likewise, the azimuth of the relative motion predicts the expected oblique extension along  
 354 the Aden ridge, and pure strike-slip along the Alula-Fartak, and Socotra-Hadbeen transform  
 355 faults (e.g., Leroy et al., 2004; D'Acremont et al., 2010; Ahmed et al., 2016, Fig. 1 and 3).

356 The azimuths of the predicted relative motion along the Arabian-Indian plates boundary

357 are in agreement with the right-lateral strike-slip motions prevailing over the last millions of

358 years along the OFZ (Fournier et al., 2008; Rodriguez et al., 2019). The model predictions  
359 indicate opening motions of  $\sim 0.7 \pm 0.5$  mm/yr and  $\sim 1.3 \pm 0.5$  mm/yr for the northern  
360 and southernmost extremities of the OFZ, respectively, consistent with the active normal  
361 faults associated with the Dalrymple Trough and the Beautemps-Beaupré pull-apart basin  
362 (Fournier et al., 2008; Rodriguez et al., 2014, Fig. 1 and 3). The kinematic modeling results  
363 predict mild compression at  $\sim 17.8^\circ$  N, in contrast with former estimates (e.g., ArRajehi et al.,  
364 2010), but in line with the presence of restraining bends between  $\sim 16.5$ - $20.3^\circ$  N (Fournier et  
365 al., 2011). The average right-lateral strike-slip component for the OFZ ( $\sim 2.2 \pm 0.5$  mm/yr)  
366 is at the lower limit of the MORVEL plate motion model (DeMets et al., 2010), and falls  
367 below former estimates constrained by GNSS (e.g.,  $\sim 2.5$ - $3.2 \pm 0.5$  mm/yr, ArRajehi et al.,  
368 2010) and multibeam and seismic data (e.g.,  $\sim 4.2$ - $5$  mm/yr, Rodriguez et al., 2019).

369 For the northeastern Arabian plate boundary, our kinematic model shows a first-order  
370 description of the current regional-scale relative motions. A full description of the patterns  
371 of strain accumulation along this boundary requires updated constraints on the present-day  
372 motions of the Helmand, Lut, and central Iran blocks (e.g., Vernant et al., 2004; Reilinger et  
373 al., 2006; Khorrami et al., 2019). Using the Arabian-Eurasian plate boundary configuration  
374 and their associated angular velocity we estimate  $\sim 29.0 \pm 0.1$  mm/yr of roughly frontal  
375 shortening along the Makran subduction zone, and shortening motions decreasing towards  
376 northwest from  $\sim 22.0 \pm 0.1$  mm/yr to only  $\sim 3.0 \pm 0.1$  mm/yr along the Zagros collision  
377 zone (Fig. 1 and 3). Despite the omission of the central Iran block, the relative motion  
378 in the Zagros collision zone indicates the expected oblique convergence characterizing the  
379 complex stress regime of the area (Reilinger et al., 2006; Vernant & Chéry, 2006).

380 Our kinematic model predicts predominantly left-lateral strike-slip ( $\sim 14$  mm/yr) with  
381 a small opening component ( $< 1.5$  mm/yr) between the Arabian and the Anatolian plates  
382 (Fig. 3), similar to Reilinger et al. (2006) and Gomez et al. (2020). Compared with the  
383 former studies, our estimates result in a larger strike-slip, but a smaller normal component  
384 at this location. This suggests that a trade-off resulting from differences in the directions of  
385 relative block motion with respect to the local fault strikes is the main driver of the observed  
386 discrepancies.

### 387 3.4 Internal deformation

388 As discussed in Section 3.2, a single Euler pole can explain almost all the observed  
389 station motions within the Arabian plate interior (Fig. 3). Exceptions to this include  
390 16 GNSS sites (9.5% of the stations) with residual velocities larger than 1.0 mm/yr. To  
391 test whether or not plate-wide internal motions could explain these residual velocities, we

392 included the parameters defining a uniform strain-rate tensor in our kinematic modeling.

393 The resulting uniform strain-rate tensor predicts 0.4 nanostrain/yr of  $\sim$ N94°E oriented  
394 shortening, consistent with the magnitude of internal motions proposed by Vigny et al.  
395 (2006). The predicted internal motions fall, however, below the upper bound for stable plate  
396 interiors (e.g., Argus & Gordon, 1996; Gordon, 1998), confirming the broad-scale rigidity of  
397 the Arabian plate. Therefore, the major contributions to the observed differential motions  
398 are related either with locally straining areas that balance each other out within the plate  
399 (e.g., ArRajehi et al., 2010) or noise within our updated velocity field.

400 The results from our second analysis using the STIB method (Section 2.2) are shown in  
401 Figure 4. For visualization, the 0.5° grid estimates for the areal strain-rate (first invariant)  
402 were oversampled to 0.1° by means of the adjustable tension continuous curvature splines  
403 method (GMT5, Wessel et al., 2013). The resulting map shows effects from single isolated  
404 GNSS stations in the northern, and south-southeastern parts of the computational domain  
405 (Fig. 4). Thus, we focus our discussion mostly on the central part of the plate where the  
406 station coverage yields the highest baselines density.

407 At the plate-wide scale, the areal strain-rate map shows areas under extension neigh-  
408 bored by regions undertaking compressional motions. This is consistent with our previous  
409 result, as these competing differential motions almost entirely compensate within the plate,  
410 resulting in insignificant plate-wide strain rates. Still, several locally straining areas can be  
411 identified within the region of good spatial coverage of GNSS stations (numbered 1-9 in Fig.  
412 4). Their distribution and strain orientation show no evidence of relation with  
413 intraplate tectonic structures, however, three of the extensional areas locate  
414 close to the Harrat Rahat volcanic field (4), the southern part of the Central  
415 Arabian graben system (6), and the Azraq graben (1), respectively. Instead,  
416 most of the areas are either located near agricultural fields (1-3, 5, 7, 9) or cities  
417 (6, 8). What is more, their spatial distribution correlates well with areas of known ground-  
418 water over-exploitation in Saudi Arabia, where 83-90% of the total water demand comes  
419 from agriculture (Abderrahman, 2001, Fig. 5). Besides, areas 6 and 8 locate near the cities  
420 of Riyadh and Al Hofuf, respectively, where significant ground subsidence resulting from  
421 rapid urbanization over units characterized by karst geomorphology have been identified  
422 (Amin & Bankher, 1997; Aljammaz et al., 2021).

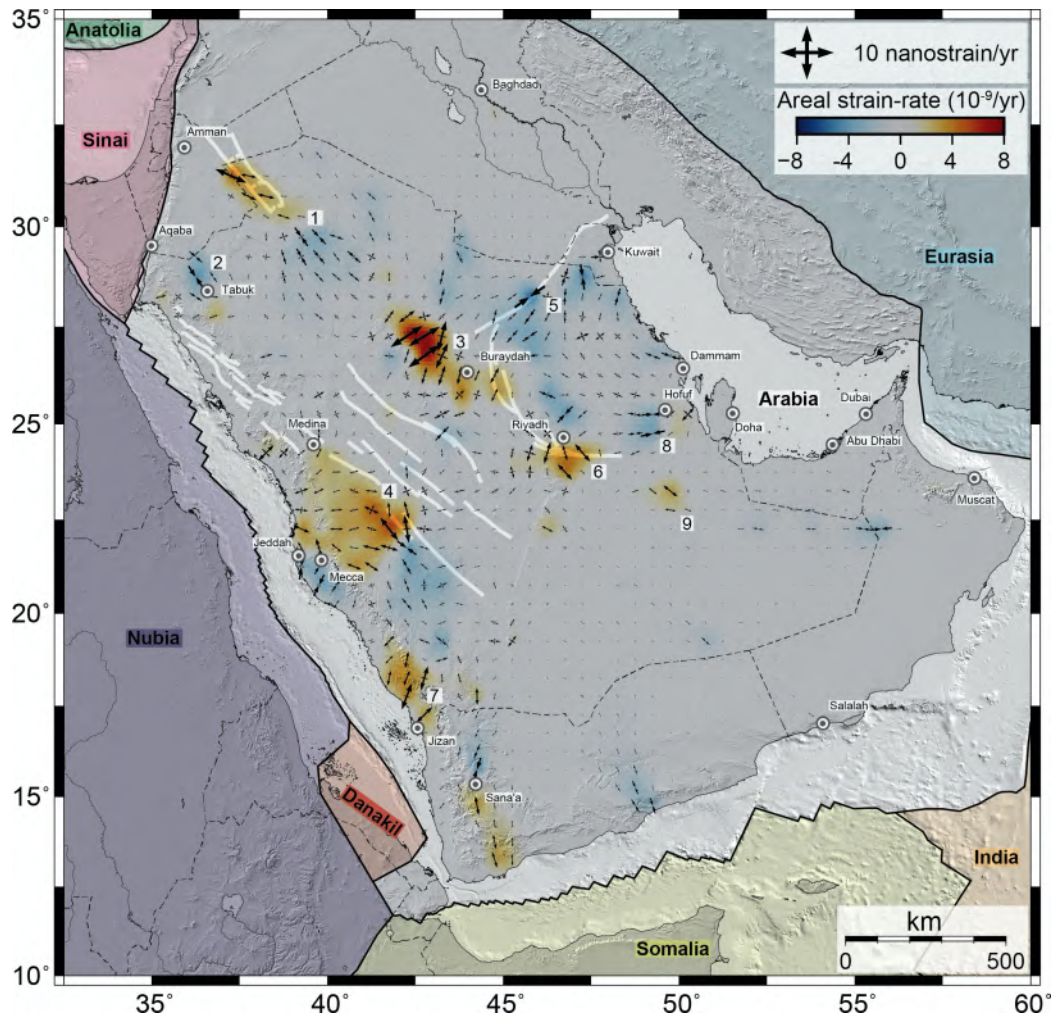


Figure 4. Principal horizontal strain rates and directions (black arrows) and areal strain-rate (first invariant, extension positive) estimated from the spatially-variable horizontal strain-rate tensor in Arabia. Black solid lines mark the simplified kinematic block model derived from the plate boundaries in Figure 1. Faint solid white lines and circled dots mark major intraplate tectonic structures shown in Fig. 1 and cities, respectively. Background hillshaded topography and bathymetry as in Figure 1.

423

#### 4 Discussion

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Our estimated Arabian-ITRF14 angular velocity implies consistency between recent derivations of the Arabian-Nubian-Eurasian relative plate motions (e.g., ArRajehi et al., 2010; Reilinger & McClusky, 2011; Altamimi et al., 2017), confirming the steady motion of the Arabian plate at present. The Arabian-Nubian Euler vector is also consistent within the 95% confidence interval with former estimates derived from combination of magnetic

429 anomaly profiles and earthquake slip vectors (e.g., Chu & Gordon, 1998; Schettino et al.,  
430 2016). This indicates that the present-day motions between the plates have remained un-  
431 changed since at least the time of the oldest magnetic lineation identified in the Red Sea  
432 ( $\sim 4.62$  Ma, Schettino et al., 2016). This time more than doubles when considering the  
433 agreement with the ArRajehi et al. (2010) and Reilinger and McClusky (2011) estimates,  
434 setting the time for steady motion of the Arabian relative to the Nubian and the Eurasian  
435 plates back to  $\sim 11 \pm 2$  and  $\sim 24 \pm 4$  Ma, respectively. We support this interpretation of  
436 steady motion between the plate triplet for the last  $\sim 11 \pm 2$  Ma, as the suggested 30 degrees  
437 northward shift of the Nubian-Eurasian Euler vector during recent geological times (e.g.,  
438 Calais et al., 2003) would have become evident for at least one of the plate pairs, given  
439 the differences in number, geographic distribution, and observation time spans of the GNSS  
440 sites constraining the relative plate motion.

441 In addition to the Arabian-Somalian angular velocities reported by ArRajehi et al.  
442 (2010) and Reilinger and McClusky (2011), the updated estimates are consistent with the  
443 noise-reduced Euler vector obtained by Iaffaldano et al. (2014). Based on the plate paleo-  
444 positions during the last  $\sim 20$  Ma (defined after Fournier et al., 2010) their study indicates  
445 that the plate pair relative motion remained stable since at least  $\sim 15$  Ma. Likewise, the  
446 analysis of high-resolution sequences of finite rotations between the Indian-Somalian and  
447 Indian-Eurasian plates during the same time period indicates stationary poles of rotations  
448 for the two plate pairs since  $\sim 12.5$  Ma (e.g., Iaffaldano et al., 2018; DeMets et al., 2019).  
449 Together, the results above imply the steady-state motion of the Arabian plate relative to  
450 the Nubian, Somalian, Indian, and Eurasian plates since at least the beginning of seafloor  
451 spreading along the full extent of the Red Sea  $\sim 13$  Ma (Augustin et al., 2021).

452 The major discrepancies between our estimated angular velocities and recent estimates  
453 from ArRajehi et al. (2010) and Reilinger and McClusky (2011) are associated with the  
454 Arabian-Indian plate pair. Our new estimate predicts better the almost pure strike-slip  
455 tectonics of the OFZ, but seems to underestimate the magnitude of relative motion. At the  
456 predicted present-day slip rate ( $\sim 2.2$  mm/yr), our kinematic model yields an age for the  
457 formation of the OFZ of 4.5-5.4 Ma, consistent with the age range estimated by Fournier et  
458 al. (2008). However, recent analysis combining structural and stratigraphic studies indicate  
459 that the 10-12 km morphological offsets observed along the present location of the OFZ  
460 date only  $\sim 2.4$  Ma, requiring dextral motions of 4.2-5 mm/yr along its entire length during  
461 this time (Rodriguez et al., 2019). A literal interpretation of the differences between the  
462 instantaneous and long-term predicted relative motion for the Arabian-Indian plate pair  
463 involves either increase in the Arabian-Eurasian and/or slowdown of the Indian-Eurasian  
464 convergence rate. We consider these scenarios rather unlikely taking into account the ap-

465 parent steady motion between the plate triplet during the last  $\sim 13$  Ma (e.g., McQuarrie et  
466 al., 2003; ArRajehi et al., 2010; Reilinger & McClusky, 2011; Iaffaldano et al., 2014, 2018;  
467 DeMets et al., 2019). As stressed by DeMets et al. (2019), the angular velocity  
468 used to define the motion of the Indian plate in their study fails to reconcile the  
469 long-standing discrepancies between the predicted long-term and instantaneous  
470 India-Eurasia relative motion, despite being constrained by a larger number of  
471 GNSS stations compared with former estimates. Therefore, another direct inter-  
472 pretation of our results that needs to be tested is whether or not more than one Euler  
473 vector (additional blocks) are needed to fully explain the present-day motion of the Indian  
474 plate.

475 The predicted fault slip vectors for the Arabian-Anatolian and Arabian-Sinai plate  
476 boundaries are well represented by the focal mechanisms associated with the largest in-  
477 strumental earthquakes nucleating along these boundaries, i.e., the 2020 Mw 6.7 Elazig,  
478 and the 1995 Mw 7.2 Nuweiba earthquake, respectively (U.S.G.S, 2021). The predomi-  
479 nantly left-lateral strike-slip relative motions between the Arabian-Anatolian plate pair has  
480 been interpreted by Reilinger et al. (2006) as a result of lateral lithospheric transport out of  
481 the Arabia-Eurasian convergence zone associated with slab rollback forces along the Hellenic  
482 and Cyprus trenches (Fig. 1). As previously mentioned in Section 3.2, the updated Arabian-  
483 Sinai angular velocity simultaneously predicts well the predominant left-lateral strike-slip of  
484 the Dead Sea transform fault, while supporting the shortening motions around the Palmyride  
485 fold-thrust belt suggested by Alchalbi et al. (2010) and ArRajehi et al. (2010).

486 The Arabian-Danakil angular velocity predicts reducing opening motions to the south-  
487 east that vanish at the latitude of the Hanish Zukur Island group, consistent with the lack  
488 of seismic activity and oceanic crust beneath the Red Sea south of  $\sim 13.8^\circ$  N (e.g., Schettino  
489 et al., 2016; Augustin et al., 2021, Fig. 3), and the full transfer of the Nubia-Arabia relative  
490 extension into Afar (Vigny et al., 2006; McClusky et al., 2010; Doubre et al., 2017; Viltres  
491 et al., 2020). This result is further supported by the small WRMS for the 6 GNSS stations  
492 in central Afar (0.8 mm/yr, Section 3.2) that include 3 sites not considered in the angular  
493 velocity estimation because of their proximity to the plate boundary (Fig. 3). Along the same  
494 line, our kinematic model results provide support for the addition of the southernmost part  
495 of Eritrea and northern Djibouti to the Arabian plate at present (Varet, 2018a; Viltres et  
496 al., 2020, Fig. 3).

497 The stable motion of the Arabian-Nubian plates since  $\sim 11 \pm 2$  Ma and the north-  
498 ward migration of the Danakil-Nubian Euler pole at  $\sim 5$  Ma (e.g., McClusky et al., 2010;  
499 Reilinger & McClusky, 2011) implies a change of the Arabian-Danakil Euler pole at that  
500 time. Reilinger and McClusky (2011) associated this shift with the initiation of seafloor



501 spreading in the southern Red Sea based on oceanic crustal ages derived from magnetic  
502 anomalies (e.g., Cochran, 1983; Garfunkel & Beyth, 2006). However, recent results indi-  
503 cate that seafloor spreading along the entire length of the Red Sea dates back to ~13 Ma  
504 (Augustin et al., 2021), meaning that the Euler pole shift responds to a distinct geodynamic  
505 process in the area. We speculate that the Danakil-Nubia, and therefore, the Arabia-Danakil  
506 Euler pole shifts at ~5 Ma are related not to seafloor spreading in the southern Red Sea,  
507 but to the addition of the southernmost part of Eritrea and northern Djibouti as stabilized  
508 margins of the Arabian plate (Varet, 2018b, Fig. 3).

509 The horizontal strain-rate results suggest that the internal strains building up within  
510 the Arabian plate at present have mostly anthropogenic origins. Eight of about nine areas  
511 showing measurable strain rates are located either near areas known for groundwater over-  
512 exploitation or rapid urbanization, characterized by karst geomorphology (Amin & Bankher,  
513 1997; López Valencia et al., 2020; Aljammaz et al., 2021; Müller Schmied et al., 2021, Figs.  
514 4 - 6). Despite the spatial correlation between the deforming areas (1) and  
515 (6) with suggested structures belonging to the Azraq graben and the Central  
516 Arabian graben system we find the re-activation of these internal structures  
517 to be an unlikely driver of the observed strains. First, evidence of surface  
518 expression from the re-activation of these long-lived structures at present are  
519 missing (e.g., Konert et al., 2001; Faqira et al., 2009). In addition, the extensional  
520 strains estimated for some of these areas (i.e., 3, 6, 7, 9) are consistent with reports of  
521 shallow seismicity, opening cracks, and sinkholes in response to land subsidence mostly  
522 induced by water pumping (e.g., Youssef et al., 2014; Othman et al., 2018; Othman &  
523 Abotalib, 2019). Field observations show that extensional strains can develop in subsiding  
524 areas as a consequence of both vertical differential compaction and horizontal fluid flow in  
525 the subsurface (e.g., Sheng et al., 2003; Holzer & Galloway, 2005; Pacheco et al., 2006).  
526 Looking at the vertical velocity field (see Table S2 in the supplementary material for  
527 details), systematic upward motions are found in the Buraydah area, which may indicate  
528 some degree of aquifer recovery in the 2017-2019 period (Figs. 5 and 6). For the rest of  
529 the extensional straining zones (i.e., Riyadh, Jizan), the vertical velocities show downward  
530 motions. Thus, we suggest that differential compaction enhanced by well depths below 1000  
531 meters (e.g., Othman & Abotalib, 2019) may provide the driving forces for the observed  
532 deformation.

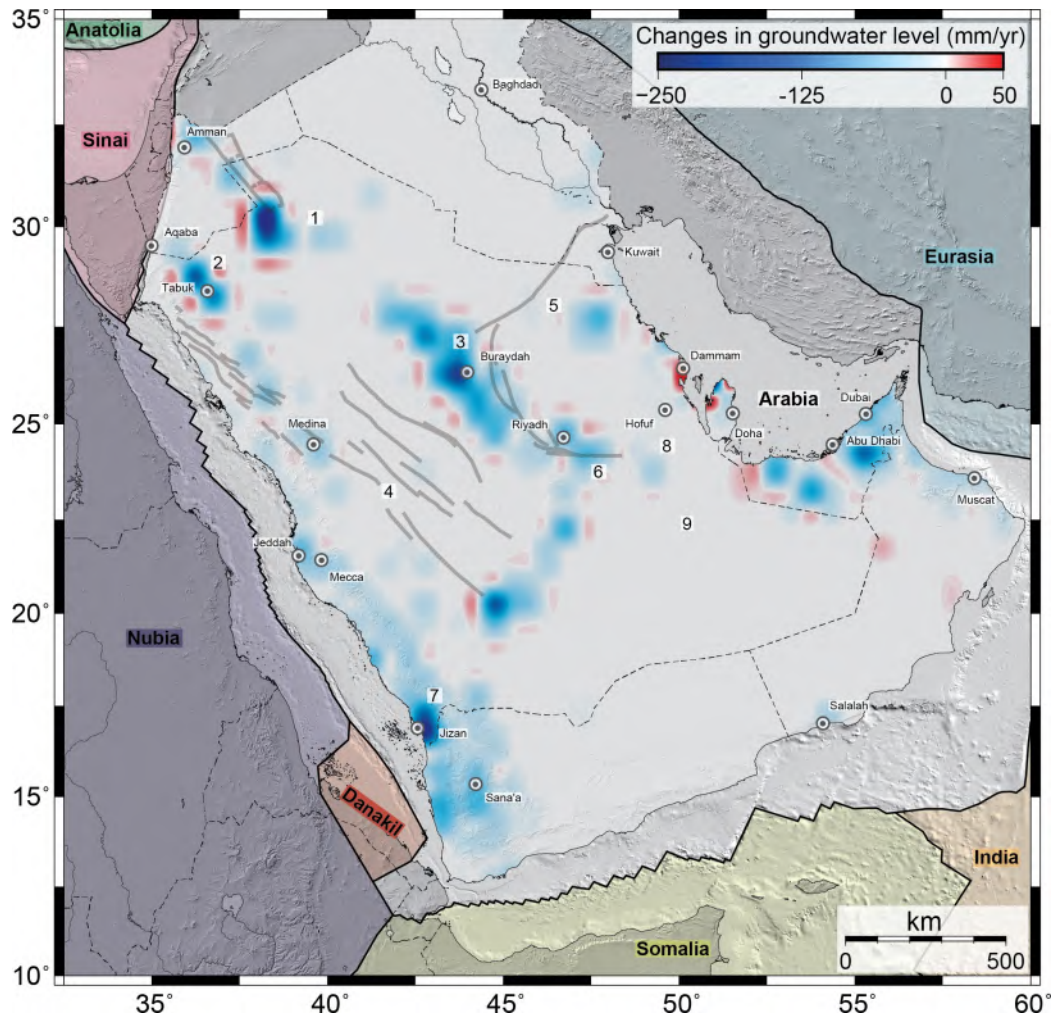


Figure 5. Changes in groundwater level for the time period 2000-2016 derived after the Water-GAP v2.2d model (Müller Schmied et al., 2021). Numbers 1-9 refer to areas showing significant local strain rates (see main text). Black solid lines mark the simplified kinematic block model derived from the plate boundaries in Figure 1. Faint solid grey lines and circled dots mark major intraplate tectonic structures shown in Fig. 1 and cities, respectively.

533 Even the straining area in central-west Saudi Arabia (4) is flanked by zones suggesting  
 534 groundwater depletion, and therefore, the observed strains may include contributions from  
 535 anthropogenic activity (Figs. 4 and 5). The horizontal strain-rate tensors for this area  
 536 suggest roughly E-W oriented extension at the center and NW-SE extension at the sides. For  
 537 the central part, the observed E-W oriented extension is consistent with the N-S direction of  
 538 the proposed asthenospheric flow beneath the so-called MMN (Mecca-Madina-Nafud) line,  
 539 well expressed by volcanic vent lineations in Harrat Rahat, Harrat Khaybar, and Harrat

540 Ithnayn, respectively (Camp & Roobol, 1992a; Pallister et al., 2010, Fig. 1). On the  
 541 eastern side, where the strains are larger, the areal strain-rate map indicates  
 542 clockwise rotation of the direction of extension, in line with the overall orientation of volcanic  
 543 vents in Harrat Kishb, and Harrat Hadan volcanic fields, relative to the MMN line (Figs. 1  
 544 and 4). The maximum horizontal strains for this area reach ~5-6 nanostrain/yr within the  
 545 Harrat Kishb and the northernmost Harrat Hadan volcanic fields, respectively (Fig. 1 and  
 546 4). This may indicate subsurface magmatic activity at present in an area that accounts  
 547 for several volcanic eruptions during the last kiloyears, including at least one  
 548 historical eruption in 1256 AD (Camp & Roobol, 1989; Downs et al., 2018).

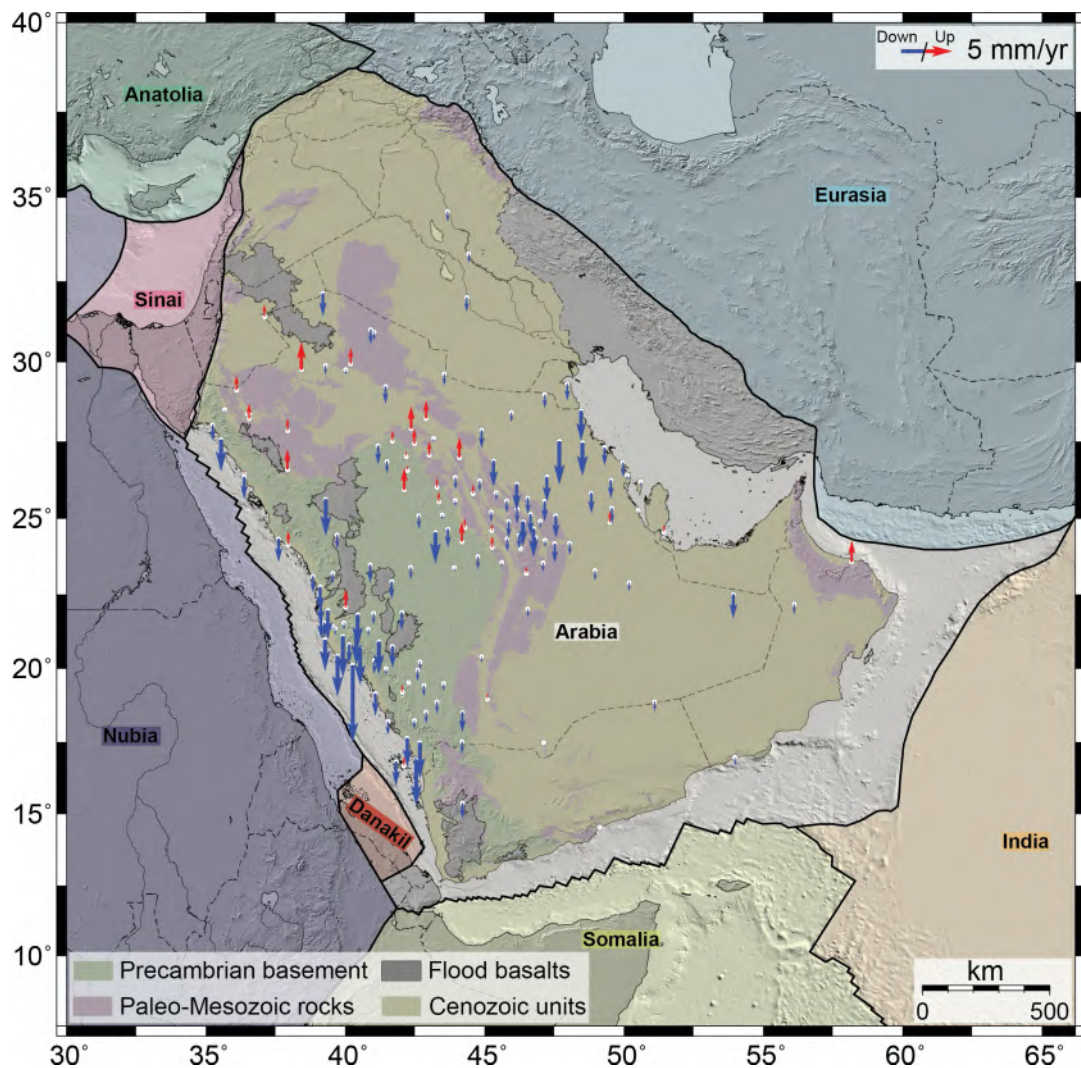


Figure 6. Vertical velocities for the continuous GNSS stations used in the block modeling presented in Section 3.2 and generalized age and rock type domains where the stations are located defined after Pollastro (1998).

549 Taken together, the results above show that the Arabian lithosphere is sufficiently  
 550 strong to withstand large-scale forces associated with plate boundary processes (i.e., active  
 551 continental collision and seafloor spreading on the northeastern and southwestern margins,  
 552 respectively), gravitational potential energy differences, and basal drag (McClusky et al.,  
 553 2000). This long-term stability of the plate likely results from a crust and lithosphere  
 554 thickness combination that strengthens the plate interior and concentrates most of the  
 555 deformation along its weaker margins (e.g., Jackson et al., 2021). Although very small, the  
 556 estimated  $\sim$ N94°E plate-wide shortening does not support for extensional forces associated  
 557 with the Afar mantle plume and rifting along the Red Sea and the Gulf of Aden to be  
 558 driving the Arabian plate into Eurasia as they will produce N-E oriented compression (e.g.,  
 559 Reilinger et al., 2006). Thus, we endorse the interpretations that the motion of Arabia is  
 560 driven by far-field slab-pull forces resulting from the subduction of Afro-Arabian oceanic  
 561 crust beneath Eurasia (Bellahsen et al., 2003).

## 562 5 Conclusions

563 In this study we analyzed GNSS measurements for 189 stations spanning between  $\sim$ 2.5  
 564 to  $\sim$ 17 years of continuous and survey mode observations to constrain the present-day mo-  
 565 tion and deformation of the Arabian plate. Our tightly constrained angular velocity for the  
 566 Arabian-ITRF14 relative motion ( $\dot{\omega}_x = 0.3284 \pm 0.0013$ ,  $\dot{\omega}_y = -0.0350 \pm 0.0013$ , and  $\dot{\omega}_z =$   
 567  $0.4068 \pm 0.0010$  °/Ma) confirms that only one Euler vector is needed to explain the current  
 568 station velocities. The kinematic modeling resulted in fault slip rates that are generally  
 569 consistent with earlier estimates (e.g., ArRajehi et al., 2010; Reilinger & McClusky, 2011),  
 570 except for the Arabian-Indian plate pair, for which slower right-lateral strike-slip motions  
 571 are predicted. The small plate-wide internal strains ( $\sim$ 0.4 nanostrains/yr) corroborate the  
 572 large-scale rigidity of the Arabian plate, however, at a smaller scale, several areas of lo-  
 573 calized internal deformation can be identified. We postulate that differential compaction  
 574 resulting from fossil groundwater over-exploitation and subsurface magmatic activity are  
 575 the main drivers of the observed internal deformation. The Arabian lithosphere shows a  
 576 remarkably long-term level of stability despite being affected by load forces associated with  
 577 active continental collision in the northeast and breakup to the southwest.

## 578 6 Open Research

579 Global Navigation Satellite System (GNSS) daily files acquired within the  
 580 Arabian plate and eastern Africa were accessed through the IGS ([https://cddis](https://cddis.nasa.gov/archive/gnss/data/daily)  
 581 [.nasa.gov/archive/gnss/data/daily](https://cddis.nasa.gov/archive/gnss/data/daily)), Unavco (<https://www.unavco.org>, see King  
 582 et al., 2019, for details), the King Abdullah University of Science and Technology

583 (see Jónsson, 2020, for details), the Saudi Arabia General Authority for Survey  
584 and Geospatial Information (<https://ksacors.gcs.gov.sa>), the French mobile  
585 network (<https://gpsmob.resif.fr/donnees>), the YOCMAL project (see Leroy,  
586 2013, for details) and the King Abdulaziz City for Science and Technology (data  
587 available by request to the Geodesy and Navigation Center). The GNSS mea-  
588 surements were analyzed with the GAMIT/GLOBK (<http://geoweb.mit.edu/gg/>)  
589 software packages. Earthquake locations and focal mechanisms were down-  
590 loaded from the International Seismological Centre (ISC, <http://www.isc.ac.uk/iscbulletin/search/catalogue/>,  
591 last accessed February 2022). Digital elevation  
592 model (DEM) and bathymetry data were downloaded from <https://topex.ucsd.edu/>  
593 (last accessed July 2021). All plots in this article were produced using the  
594 Generic Mapping Tools version 5.4.5 (<https://www.generic-mapping-tools.org>)  
595 and the Python plotting library Matplotlib (<https://matplotlib.org>). The sup-  
596 plemental material for this article includes two tables with the horizontal and  
597 vertical components of the GNSS-derived velocity field, respectively.

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