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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 (~ 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 ~ 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; Austermann & 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.

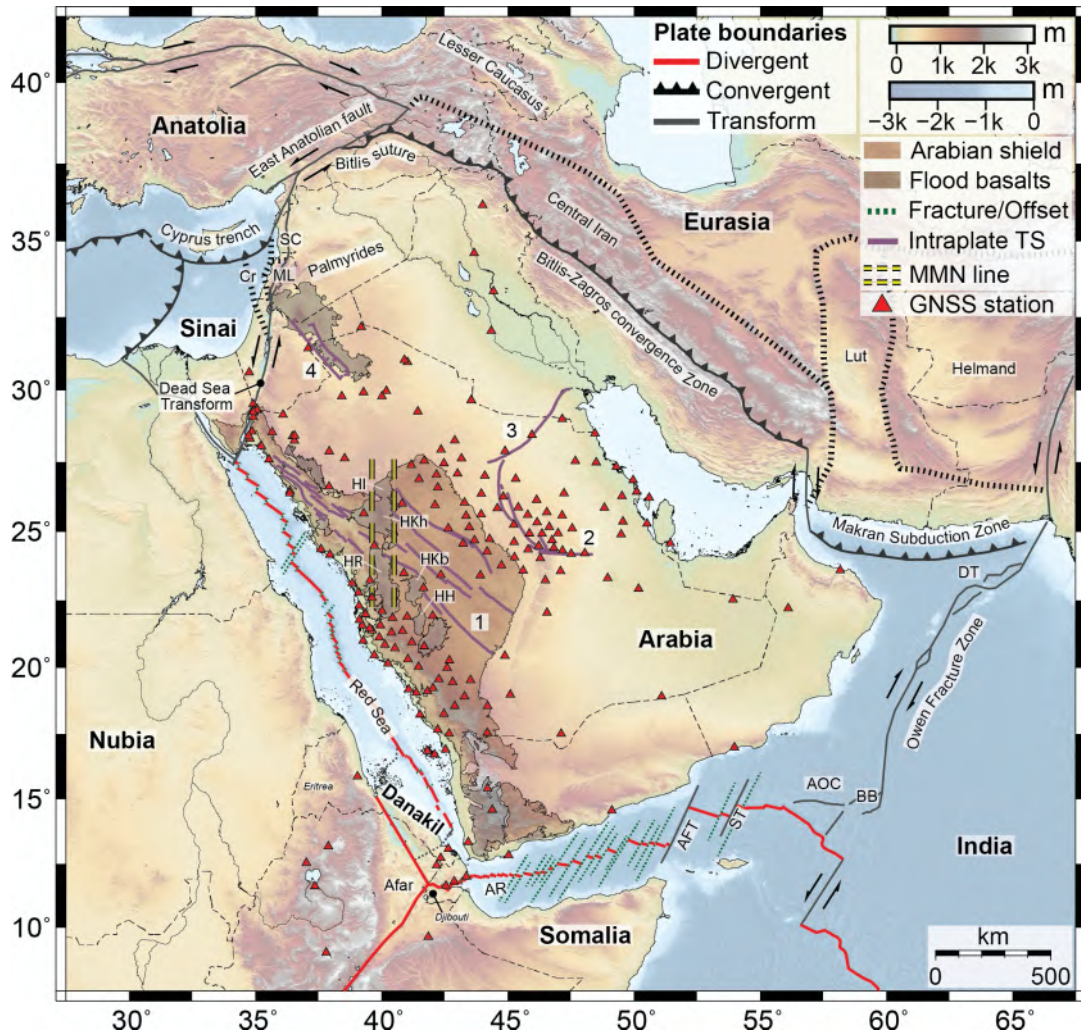


Figure 1. Main plate boundaries around the Arabian plate defined after Bosworth et al. (2005); Schettino et al. (2016); Doubre et al. (2017); Rodriguez et al. (2019); Viltres et al. (2020); Ribot et al. (2021) and A. Afifi (pers. comm.). Background hillshaded topography and bathymetry from <http://topex.ucsd.edu/>. 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 YOCMAL 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° 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}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 ~ 19 mm/yr towards
253 $\sim \text{N}51^\circ\text{E}$ in the southernmost Red Sea, ~ 12 mm/yr towards $\sim \text{N}40^\circ\text{E}$ at $\sim 21.5^\circ\text{N}$, and ~ 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.

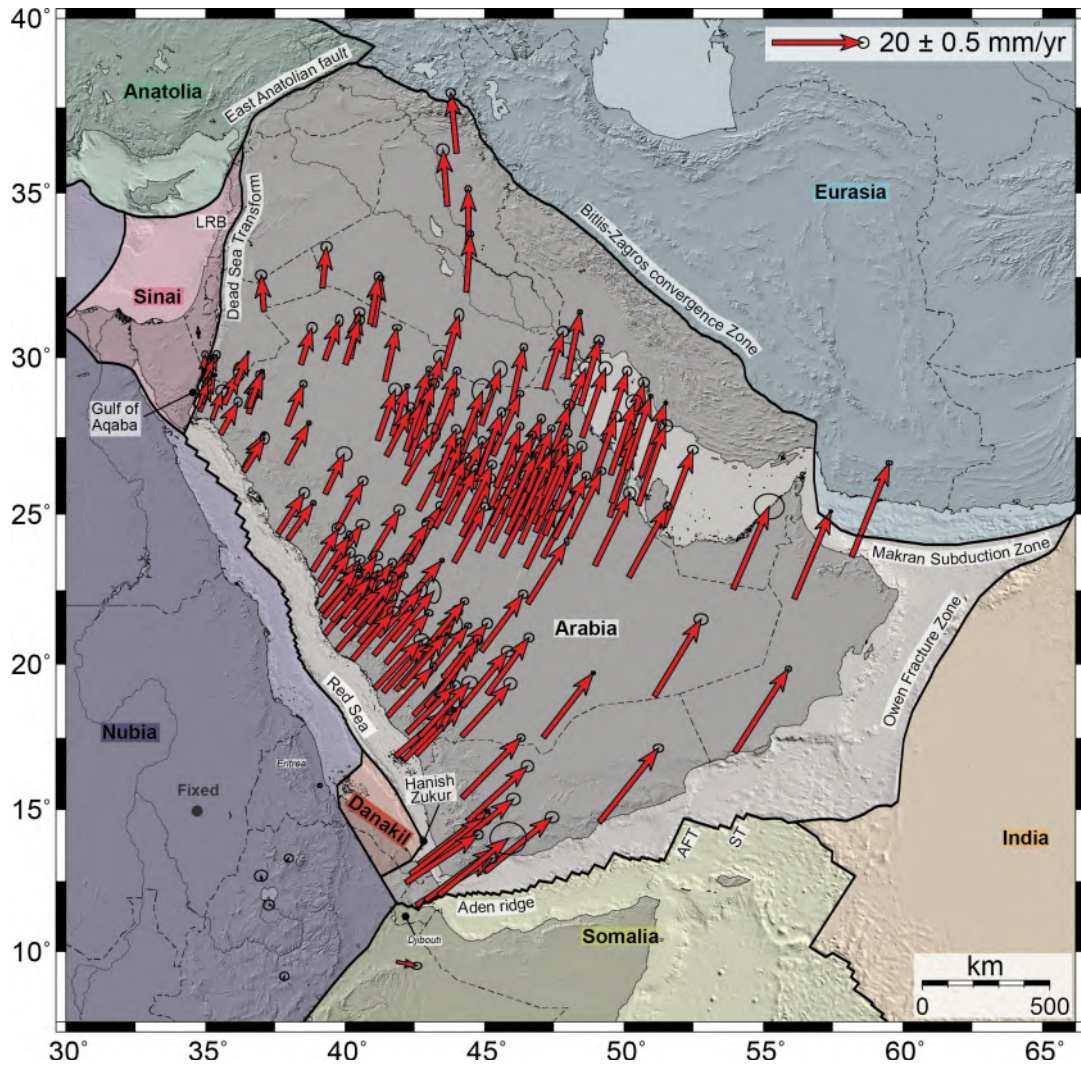


Figure 2. Horizontal GNSS velocities with 95% confidence ellipses rotated into a Nubian-fixed reference frame defined after the Altamimi et al. (2017) plate motion model. Black solid lines mark the simplified kinematic block model derived from the plate boundaries in Figure 1. Abbreviations: Lebanon 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 ~ 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 ~ 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 ~ 43 and ~ 47 angular degrees southward and eastward, respectively, and requires a rotation rate up to ~ 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 ~ 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 ^a ($\times 10^{-6}$)					
	Lat.	Lon.	$\dot{\omega}$	$\dot{\omega}_x$	$\dot{\omega}_y$	$\dot{\omega}_z$	σ_{xx}	σ_{yy}	σ_{zz}	σ_{xy}	σ_{xz}	σ_{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).^a 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.

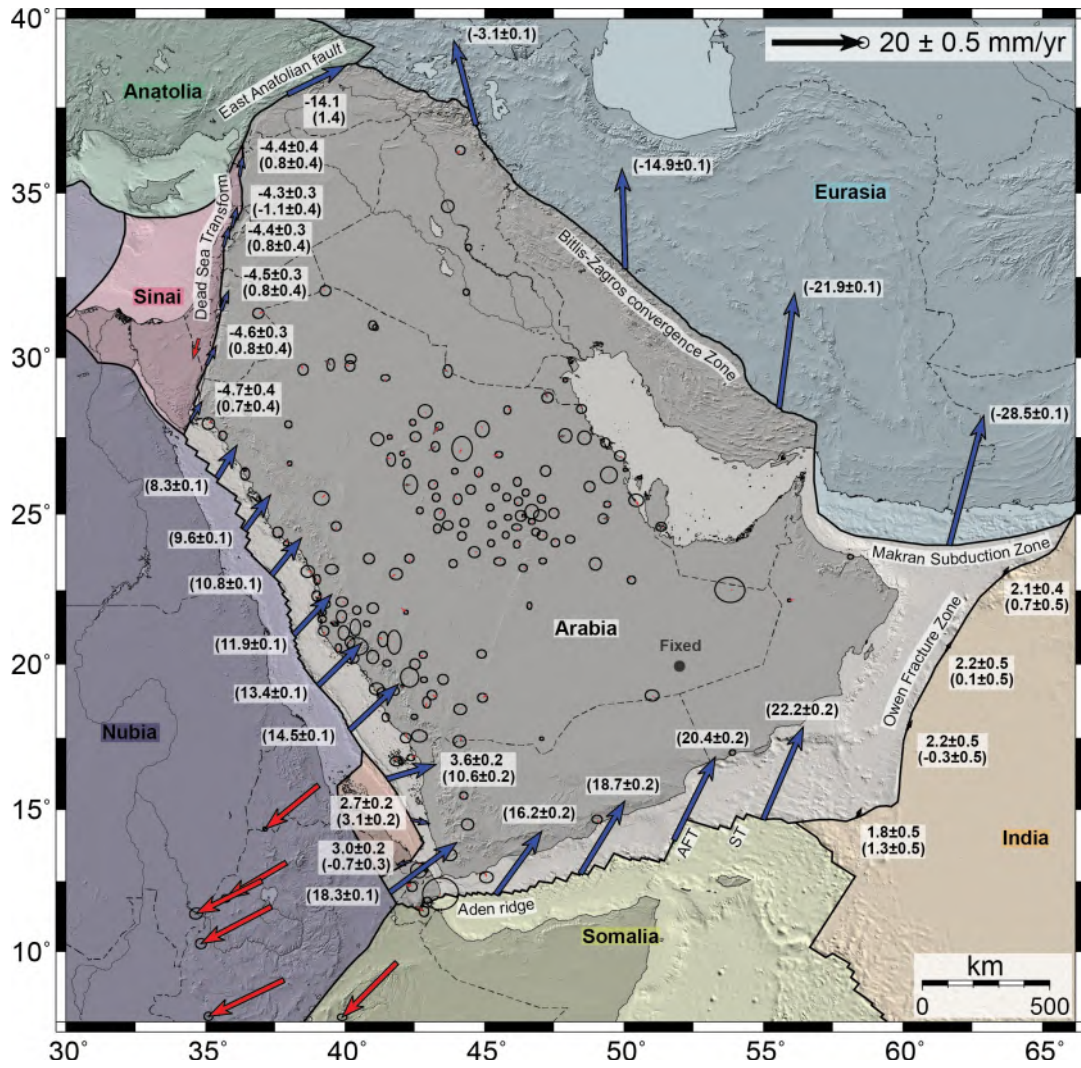


Figure 3. Observed GNSS velocities (red arrows), with 95% confidence ellipses, rotated into the Arabian-fixed reference from the kinematic block modeling results (Table 1). Blue arrows show predicted motions (east side with respect to the west side, or north with respect to south) at selected locations 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 ~ 15.0
339 ± 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 ~ 15.2
350 ± 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'Acromont 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 ~ 16.5 - 20.3° 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., ~ 2.5 - 3.2 ± 0.5 mm/yr, ArRajehi et al.,
368 2010) and multibeam and seismic data (e.g., ~ 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 (~ 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).

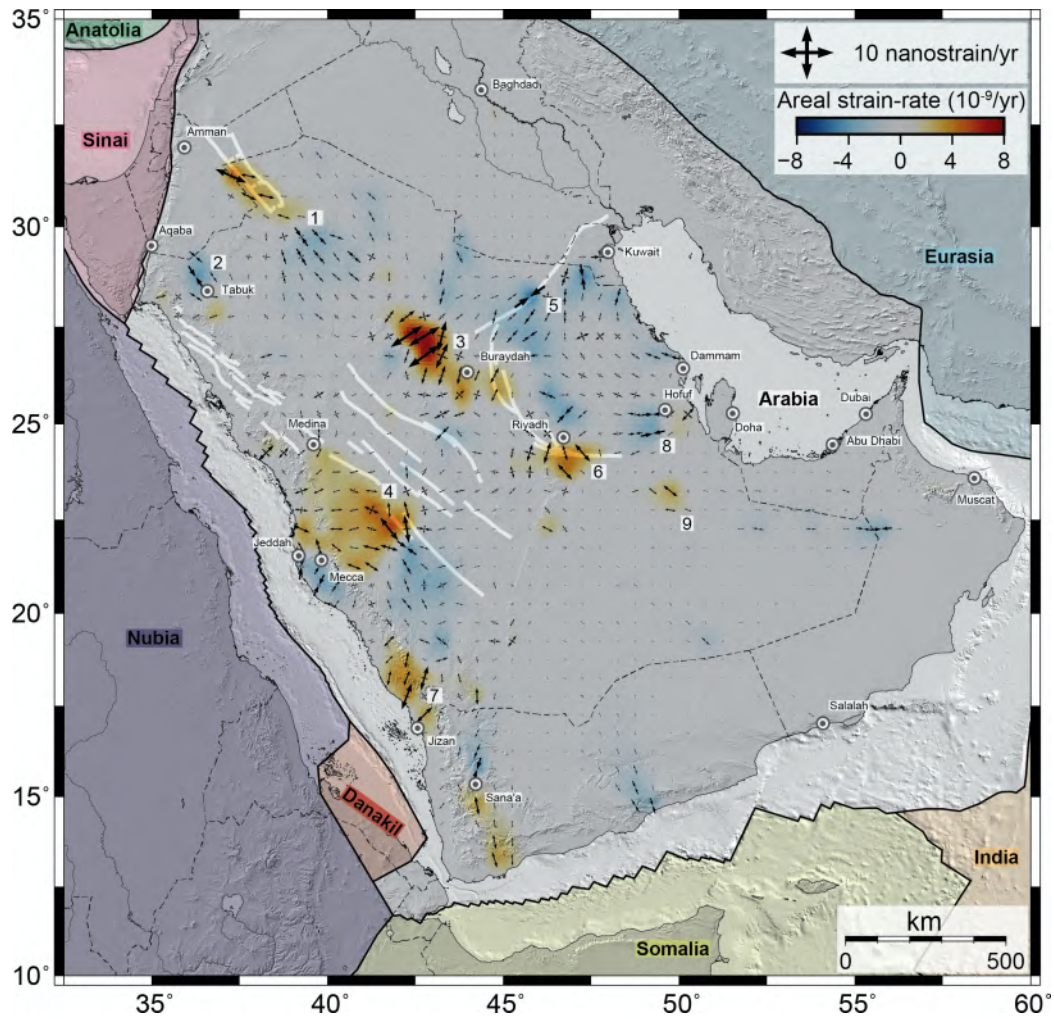


Figure 4. Principal horizontal strain rates and directions (black arrows) and areal strain-rate (first invariant, extension positive) estimated from the spatially-variable horizontal strain-rate tensor in Arabia. Black solid lines mark the simplified kinematic block model derived from the plate boundaries 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 (~ 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 ~ 20 Ma (defined after Fournier et al., 2010) their study indicates
445 that the plate pair relative motion remained stable since at least ~ 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 ~ 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 ~ 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 (~ 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 ~ 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-

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

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

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

The stable motion of the Arabian-Nubian plates since $\sim 11 \pm 2$ Ma and the northward migration of the Danakil-Nubian Euler pole at ~ 5 Ma (e.g., McClusky et al., 2010; Reilinger & McClusky, 2011) implies a change of the Arabian-Danakil Euler pole at that 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.

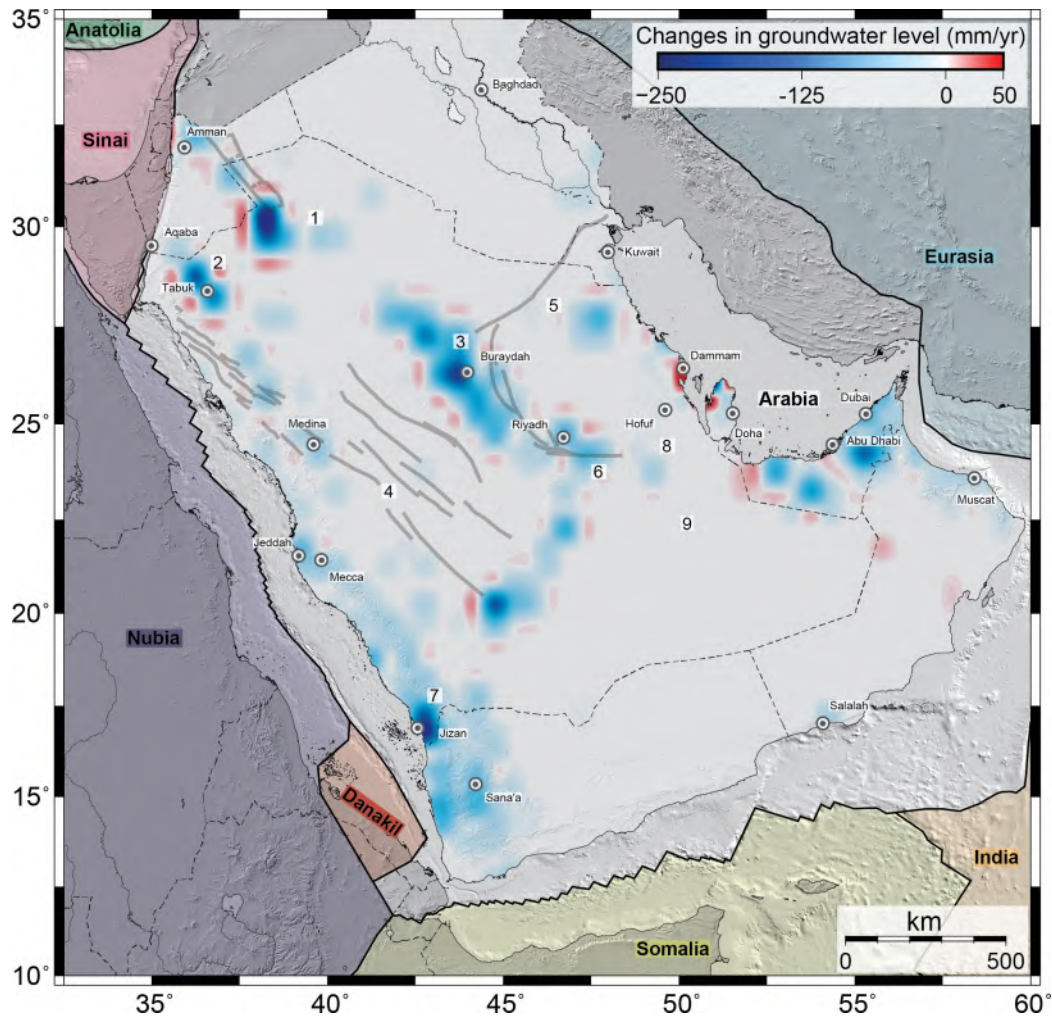


Figure 5. Changes in groundwater level for the time period 2000-2016 derived after the Water-GAP v2.2d model (Müller Schmied et al., 2021). Numbers 1-9 refer to areas showing significant local strain rates (see main text). Black solid lines mark the simplified kinematic block model derived from the plate 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 $\sim 5\text{-}6$ 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).

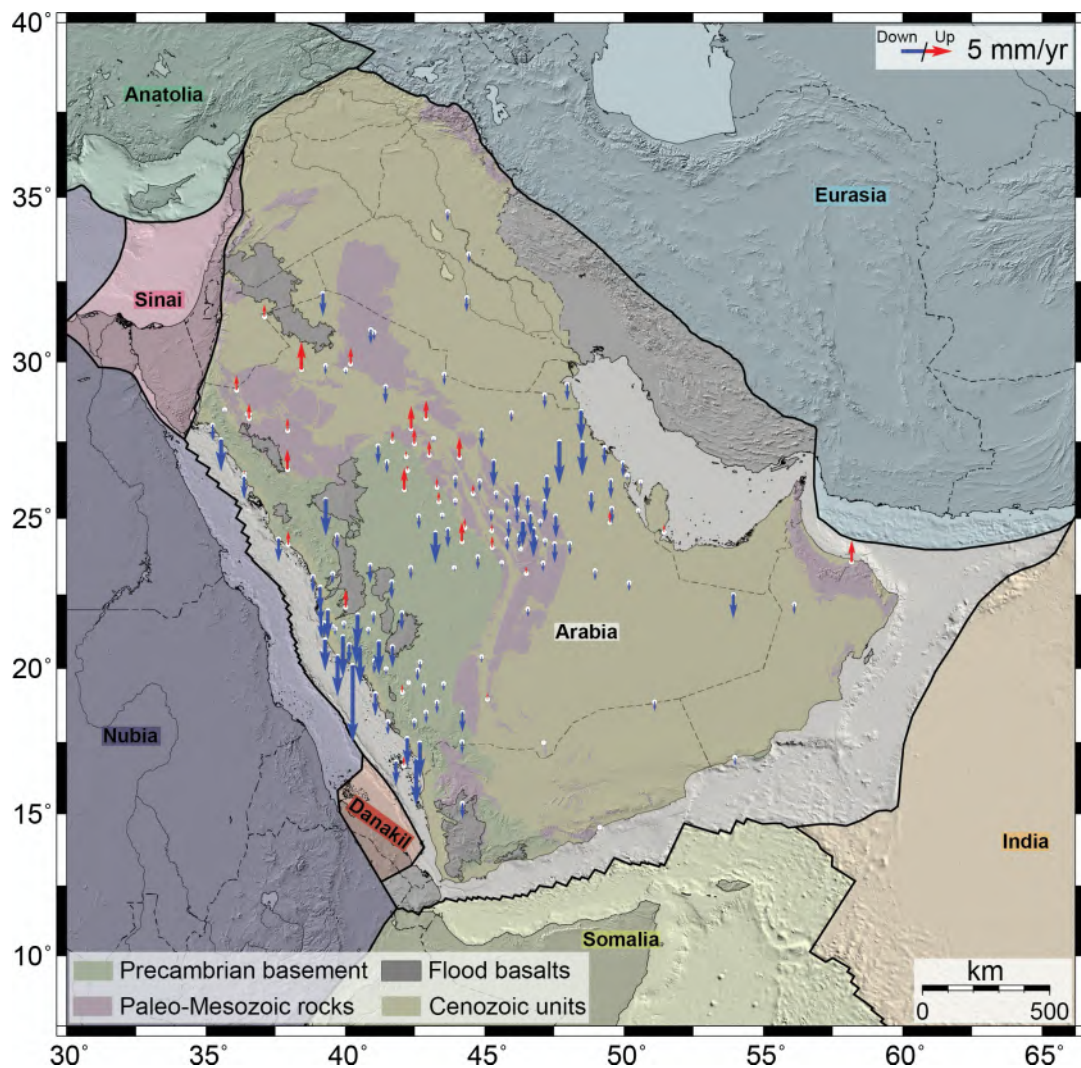


Figure 6. Vertical velocities for the continuous GNSS stations used in the block modeling presented in Section 3.2 and generalized age and rock type domains where the stations are located defined after Pollastro (1998).

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 ± 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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612 References

- 613 Abderrahman, W. A. (2001). Energy and water in arid developing countries: Saudi arabia,
614 a case-study. *International Journal of Water Resources Development*, 17(2), 247-255.
615 doi: 10.1080/07900620120031306
- 616 Ahmed, A., Doubre, C., Leroy, S., Kassim, M., Keir, D., Abayazid, A., ... Al-Ganad, I.

- 617 (2016). Seafloor spreading event in western Gulf of Aden during the November 2010-
618 March 2011 period captured by regional seismic networks: evidence for diking events
619 and interactions with a nascent transform zone. *Geophysical Journal International* ,
620 205 (2), 1244-1266. doi: 10.1093/gji/ggw068
- 621 Alchalbi, A., Daoud, M., Gomez, F., McClusky, S., Reilinger, R., Romeyeh, M. A., ...
622 Barazangi, M. (2010). Crustal deformation in northwestern Arabia from GPS mea-
623 surements in Syria: Slow slip rate along the northern Dead Sea Fault. *Geophysical*
624 *Journal International* , 180 (1), 125-135. doi: 10.1111/j.1365-246X.2009.04431.x
- 625 Aldajani, T., Furlong, K., & Malservisi, R. (2021). The rigidity of the wety/tern Ara-
626 bian margin: extensional strain rate field from GPS networks. *Arabian Journal of*
627 *Geosciences* , 14 (5), 393. doi: 10.1007/s12517-021-06751-x
- 628 Aldamegh, K. S., Hussein Moussa, H., Al-Arifi, S. N., Moustafa, S. S. R., & Moustafa,
629 M. H. (2012). Focal mechanism of badr earthquake, saudia arabia of august 27, 2009.
630 *Arabian Journal of Geosciences* , 5 (4), 599-606. doi: 10.1007/s12517-010-0200-8
- 631 Aljammaz, A., Sultan, M., Izadi, M., Abotalib, A. Z., Elhebiry, M. S., Emil, M. K.,
632 ... Becker, R. (2021). Land subsidence induced by rapid urbanization in arid en-
633 vironments: A remote sensing-based investigation. *Remote Sensing* , 13 (6). doi:
634 10.3390/rs13061109
- 635 Altamimi, Z., Métivier, L., Rebischung, P., Rouby, H., & Collilieux, X. (2017). ITRF2014
636 plate motion model. *Geophysical Journal International* , 209 (3), 1906-1912. doi: 10
637 .1093/gji/ggx136
- 638 Al Tarazi, E., Abu Rajab, J., Gomez, F., Cochran, W., Jaafar, R., & Ferry, M. (2011). Gps
639 measurements of near-field deformation along the southern dead sea fault system.
640 *Geochemistry, Geophysics, Geosystems* , 12 (12). doi: 10.1029/2011GC003736
- 641 Amin, A. A., & Bankher, K. A. (1997). Karst hazard assessment of eastern saudi arabia.
642 *Natural Hazards* , 15 (1), 21-30. doi: 10.1023/A:1007918623324
- 643 Argus, D. F., & Gordon, R. G. (1996). Tests of the rigid-plate hypothesis and bounds
644 on intraplate deformation using geodetic data from very long baseline interferometry.
645 *Journal of Geophysical Research: Solid Earth* , 101 (B6), 13555-13572.
- 646 ArRajehi, A., McClusky, S., Reilinger, R., & et al. (2010). Geodetic constraints on present-
647 day motion of the Arabian Plate: Implications for Red Sea and Gulf of Aden rifting.
648 *Tectonics* , 29 (3). doi: 10.1029/2009TC002482
- 649 Augustin, N., van der Zwan, F. M., Devey, C. W., & Brandsdóttir, B. (2021). 13 million
650 years of seafloor spreading throughout the red sea basin. *Nature Communications* ,
651 12 (1), 2427. doi: 10.1038/s41467-021-22586-2
- 652 Austermann, J., & Iaffaldano, G. (2013). The role of the zagros orogeny in slowing down
653 arabia-eurasia convergence since 5 ma. *Tectonics* , 32 (3), 351-363.

- 654 Barberi, F., & Varet, J. (1977). Volcanism of afar: Small-scale plate tectonics implications.
 655 *GSA Bulletin*, 88, 1251-1266. doi: 10.1130/0016-7606(1977)88 <1251:VOASPT> 2.0
 656 .CO;2
- 657 Bellahsen, N., Faccenna, C., Funiciello, F., Daniel, J., & Jolivet, L. (2003). Why did arabia
 658 separate from africa? insights from 3-d laboratory experiments. *Earth and Planetary
 659 Science Letters*, 216 (3), 365-381. doi: 10.1016/S0012-821X(03)00516-8
- 660 Bos, M. S., Fernandes, R. M. S., Williams, S. D. P., & Bastos, L. (2008). Fast error
 661 analysis of continuous gps observations. *Journal of Geodesy*, 82 (3), 157-166. doi:
 662 10.1007/s00190-007-0165-x
- 663 Bos, M. S., Fernandes, R. M. S., Williams, S. D. P., & Bastos, L. (2013). Fast error
 664 analysis of continuous GNSS observations with missing data. *Journal of Geodesy*,
 665 87 (4), 351-360. doi: 10.1007/s00190-012-0605-0
- 666 Bosworth, W., Huchon, P., & McClay, K. (2005). The red sea and gulf of aden basins.
 667 *Journal of African Earth Sciences*, 43 (1), 334-378. doi: 10.1016/j.jafrearsci.2005.07
 668 .020
- 669 Bosworth, W., Taviani, M., & Rasul, N. M. A. (2019). Neotectonics of the red sea, gulf
 670 of sues and gulf of aqaba. In I. C. Rasul Najeeb M.A.and Stewart (Ed.), *Geological
 671 setting, palaeoenvironment and archaeology of the red sea* (p. 11-35). Cham: Springer
 672 International Publishing. doi: 10.1007/978-3-319-99408-6 2
- 673 Calais, E., DeMets, C., & Nocquet, J.-M. (2003). Evidence for a post-3.16-ma change in
 674 nubia-urasia-north america plate motions? *Earth and Planetary Science Letters*,
 675 216 (1), 81-92. doi: 10.1016/S0012-821X(03)00482-5
- 676 Camp, V. E., & Roobol, M. J. (1989). The Arabian continental alkali basalt province: Part
 677 I. Evolution of Harrat Rahat, Kingdom of Saudi Arabia. *GSA Bulletin*, 101 (1), 71-95.
 678 doi: 10.1130/0016-7606(1989)101 <0071:TACABP> 2.3.CO;2
- 679 Camp, V. E., & Roobol, M. J. (1992a). Upwelling asthenosphere beneath western arabia
 680 and its regional implications. *Journal of Geophysical Research: Solid Earth*, 97 (B11),
 681 15255-15271. doi: 10.1029/92JB00943
- 682 Camp, V. E., Roobol, M. J., & Hooper, P. R. (1992b). The Arabian continental alkali
 683 basalt province: Part III. Evolution of Harrat Kishb, Kingdom of Saudi Arabia. *GSA
 684 Bulletin*, 104 (4), 379-396. doi: 10.1130/0016-7606(1992)104 <0379:TACABP> 2.3.CO;
 685 2
- 686 Castro-Perdomo, N., Viltres, R., Masson, F., Klinger, Y., Liu, S., Dhahry, M., . . . Jónsson,
 687 S. (2021). Interseismic deformation in the Gulf of Aqaba from GPS measurements.
 688 *Geophysical Journal International*, 228 (1), 477-492. doi: 10.1093/gji/ggab353
- 689 Chu, D., & Gordon, R. G. (1998). Current plate motions across the Red Sea. *Geophysical
 690 Journal International*, 135 (2), 313-328. doi: 10.1046/j.1365-246X.1998.00658.x

- 691 Cochran, J. R. (1983). A model for development of red sea. *Am. Assoc. Pet. Geol. Bull.*,
692 67, 41-69. doi: 10.1144/GSL.SP.2006.259.01.04
- 693 Courtillot, V. (1982). Propagating rifts and continental breakup. *Tectonics*, 1 (3), 239-250.
694 doi: 10.1029/TC001i003p00239
- 695 D'Acromont, E., Leroy, S., Maia, M., Gente, P., & Autin, J. (2010). Volcanism, jump
696 and propagation on the Sheba ridge, eastern Gulf of Aden: segmentation evolution
697 and implications for oceanic accretion processes. *Geophysical Journal International* ,
698 180(2), 535-551. doi: 10.1111/j.1365-246X.2009.04448.x
- 699 DeMets, C., Gordon, R. G., & Argus, D. F. (2010). Geologically current plate motions.
700 *Geophysical Journal International*, 181(1), 1-80. doi: 10.1111/j.1365-246X.2009.04491
701 .x
- 702 DeMets, C., Merkouriev, S., & Jade, S. (2019, 11). High-resolution reconstructions and GPS
703 estimates of India-Eurasia and India-Somalia plate motions: 20 Ma to the present.
704 *Geophysical Journal International*, 220(2), 1149-1171. doi: 10.1093/gji/ggz508
- 705 Doubre, C., Déprez, A., Masson, F., Socquet, A., Lewi, E., Grandin, R., ... Wright, T.
706 (2017). Current deformation in Central Afar and triple junction kinematics deduced
707 from GPS and InSAR measurements. *Geophysical Journal International*, 208(2), 936-
708 953. doi: 10.1093/gji/ggw434
- 709 Downs, D. T., Stelten, M. E., Champion, D. E., Dietterich, H. R., Nawab, Z., Zahran, H.,
710 ... Shawali, J. (2018). Volcanic history of the northernmost part of the Harrat Rahat
711 volcanic field, Saudi Arabia. *Geosphere*, 14(3), 1253-1282. doi: 10.1130/GES01625.1
- 712 Faqira, M., Rademakers, M., & Afifi, A. M. (2009). New insights into the Hercynian
713 Orogeny, and their implications for the Paleozoic Hydrocarbon System in the Arabian
714 Plate. *GeoArabia*, 14(3), 199-228. doi: 10.2113/geoarabia1403199
- 715 Ferry, M., Meghraoui, M., Karaki, N. A., Al-Taj, M., Amoush, H., Al-Dhaisat, S., & Barjous,
716 M. (2007). A 48-kyr-long slip rate history for the Jordan valley segment of the Dead
717 Sea fault. *Earth and Planetary Science Letters*, 260(3), 394-406. doi: 10.1016/j.epsl
718 .2007.05.049
- 719 Floyd, M. A., Billiris, H., Paradissis, D., Veis, G., Avallone, A., Briole, P., ... England,
720 P. C. (2010). A new velocity field for Greece: Implications for the kinematics and
721 dynamics of the Aegean. *Journal of Geophysical Research: Solid Earth*, 115 (B10).
722 doi: 10.1029/2009JB007040
- 723 Fournier, M., Chamot-Rooke, N., Petit, C., Fabbri, O., Huchon, P., Maillot, B., & Lep-
724 vrier, C. (2008). In situ evidence for dextral active motion at the Arabia-India plate
725 boundary. *Nature Geoscience*, 1(1), 54-58.
- 726 Fournier, M., Chamot-Rooke, N., Petit, C., Huchon, P., Al-Kathiri, A., Audin, L., ...
727 Merkouriev, S. (2010). Arabia-Somalia plate kinematics, evolution of the Aden-Owen-

- 728 carlsberg triple junction, and opening of the gulf of aden. *Journal of Geophysical*
729 *Research: Solid Earth*, 115 (B4).
- 730 Fournier, M., Chamot-Rooke, N., Rodriguez, M., Huchon, P., Petit, C., Beslier, M., &
731 Zaragosi, S. (2011). Owen fracture zone: The arabia-india plate boundary unveiled.
732 *Earth and Planetary Science Letters*, 302 (1), 247-252. doi: [https://doi.org/10.1016/](https://doi.org/10.1016/j.epsl.2010.12.027)
733 [j.epsl.2010.12.027](https://doi.org/10.1016/j.epsl.2010.12.027)
- 734 Garfunkel, Z., & Beyth, M. (2006). Constraints on the structural development of afar im-
735 posed by the kinematics of the major surrounding plates. *Geological Society, London,*
736 *Special Publications*, 259 (1), 23-42. doi: 10.1144/GSL.SP.2006.259.01.04
- 737 Gomez, F., Cochran, W. J., Yassminh, R., Jaafar, R., Reilinger, R., Floyd, M., ...
738 Barazangi, M. (2020). Fragmentation of the Sinai Plate indicated by spatial vari-
739 ation in present-day slip rate along the Dead Sea Fault System. *Geophysical Journal*
740 *International*, 221 (3), 1913-1940. doi: 10.1093/gji/ggaa095
- 741 Gordon, R. G. (1998). THE PLATE TECTONIC APPROXIMATION: Plate Nonrigidity,
742 Diffuse Plate Boundaries, and Global Plate Reconstructions. *Annual Review of Earth*
743 *and Planetary Sciences*, 26 (1), 615-642. doi: 10.1146/annurev.earth.26.1.615
- 744 Hamiel, Y., & Piatibratova, O. (2019). Style and distribution of slip at the margin of a pull-
745 apart structure: Geodetic investigation of the southern dead sea basin. *Journal of Geo-*
746 *physical Research: Solid Earth*, 124 (11), 12023-12033. doi: 10.1029/2019JB018456
- 747 Hancock, P. L., Kadhi, A. A., & Sha'at, N. A. (1984). Regional joint sets in the arabian
748 platform as indicators of intraplate processes. *Tectonics*, 3, 27-43.
- 749 Henrion, E., Masson, F., Doubre, C., Ulrich, P., & Meghraoui, M. (2020). Present-day
750 deformation in the Upper Rhine Graben from GNSS data. *Geophysical Journal Inter-*
751 *national*, 223 (1), 599-611. doi: 10.1093/gji/ggaa320
- 752 Herring, T. A., King, R. W., Floyd, M. A., & McClusky, S. C. (2018). Documentation for the
753 gamit/globk gps analysis software, release 10.7. *Department of Earth, Atmospheric,*
754 *and Planetary Sciences, Massachusetts Institute of Technology, Cambridge.*
- 755 Holzer, T. L., & Galloway, D. L. (2005). Impacts of land subsidence caused by withdrawal of
756 underground fluids in the United States. In J. Ehlen, W. C. Haneberg, & R. A. Larson
757 (Eds.), *Humans as geologic agents* (Vol. 16, p. 87-99). Geological Society of America.
758 doi: 10.1130/2005.4016(08)
- 759 Iaffaldano, G., Davies, D. R., & DeMets, C. (2018). Indian ocean floor deformation induced
760 by the reunion plume rather than the tibetan plateau. *Nature Geoscience*, 11 (5),
761 362-366. doi: 10.1038/s41561-018-0110-z
- 762 Iaffaldano, G., Hawkins, R., & Sambridge, M. (2014). Bayesian noise-reduction in Ara-
763 bia/Somalia and Nubia/Arabia finite rotations since 20 Ma: Implications for Nu-
764 bia/Somalia relative motion. *Geochemistry, Geophysics, Geosystems*, 15 (4), 845-854.

- 765 ISC. (2022). *International Seismological Centre (2022), On-line Bulletin (last accessed*
766 *February 2022)*. doi: 10.31905/D808B830
- 767 Jackson, J., McKenzie, D., & Priestley, K. (2021). Relations between earthquake distri-
768 butions, geological history, tectonics and rheology on the continents. *Philosophical*
769 *Transactions of the Royal Society A: Mathematical, Physical and Engineering Sci-*
770 *ences*, 379(2193), 20190412. doi: 10.1098/rsta.2019.0412
- 771 Jónsson, S. (2012). Tensile rock mass strength estimated using insar. *Geophysical Research*
772 *Letters*, 39(21). doi: 10.1029/2012GL053309
- 773 Jónsson, S. (2020). *Southern saudi arabia and eritrea 2016-gps/gnss observations dataset*.
774 doi: 10.7283/DR9Z-PV96
- 775 Kazmin, V. G. (2001). The late paleozoic to cainozoic intraplate deformation in north arabia:
776 a responce to plate boundary-forces. *Stephan Mueller Special Publication Series*, 2,
777 123-138.
- 778 Khorrami, F., VERNANT, P., Masson, F., Nilfouroushan, F., Mousavi, Z., Nankali, H., ...
779 Alijanzade, M. (2019). An up-to-date crustal deformation map of Iran using integrated
780 campaign-mode and permanent GPS velocities. *Geophysical Journal International*,
781 217(2), 832-843. doi: 10.1093/gji/ggz045
- 782 King, R., Floyd, M., Reilinger, R., & Bendick, R. (2019). *Gps velocity field (mit 2019.0)*
783 *for the east african rift system generated by king et al*. doi: 10.1594/IEDA/324785
- 784 Klinger, Y., Avouac, J. P., Abou Karaki, N., Dorbath, L., Bourles, D., & Reyss, J. L.
785 (2000). Slip rate on the Dead Sea transform fault in northern Araba valley (Jordan).
786 *Geophysical Journal International*, 142(3), 755-768. doi: 10.1046/j.1365-246x.2000
787 .00165.x
- 788 Kogan, L., Fisseha, S., Bendick, R., Reilinger, R., McClusky, S., King, R., & Solomon, T.
789 (2012). Lithospheric strength and strain localization in continental extension from
790 observations of the east african rift. *Journal of Geophysical Research: Solid Earth*,
791 117(B3). doi: 10.1029/2011JB008516
- 792 Konert, G., Afifi, A. M., Al-Hajri, S. A., & Droste, H. J. (2001, 07). Paleozoic Stratigraphy
793 and Hydrocarbon Habitat of the Arabian Plate. *GeoArabia*, 6(3), 407-442. doi:
794 10.2113/geoarabia0603407
- 795 Kreemer, C., Blewitt, G., & Klein, E. C. (2014). A geodetic plate motion and global
796 strain rate model. *Geochemistry, Geophysics, Geosystems*, 15(10), 3849-3889. doi:
797 10.1002/2014GC005407
- 798 Leroy, S. (2013). *Young conjugate margins laboratory in the gulf of aden (yocmal) project,*
799 *anr 07-blanc-135-02*.
- 800 Leroy, S., Gente, P., Fournier, M., D'Acremont, E., Patriat, P., Beslier, M.-O., Huchon,
801 P. (2004). From rifting to spreading in the eastern gulf of aden: a geophysical survey

- 802 of a young oceanic basin from margin to margin. *Terra Nova*, 16(4), 185-192. doi:
803 10.1111/j.1365-3121.2004.00550.x
- 804 Leroy, S., Razin, P., Autin, J., Bache, F., d'Acremont, E., Watremez, L., ... Al Lazki, A.
805 (2012). From rifting to oceanic spreading in the gulf of aden: a synthesis. *Arabian*
806 *Journal of Geosciences*, 5(5), 859-901. doi: 10.1007/s12517-011-0475-4
- 807 Li, X., Jansson, S., & Cao, Y. (2021). Interseismic deformation from sentinel-1 burst-overlap
808 interferometry: Application to the southern dead sea fault. *Geophysical Research*
809 *Letters*, n/a(n/a), e2021GL093481. doi: 10.1029/2021GL093481
- 810 Lim, J.-A., Chang, S.-J., Mai, P. M., & Zahran, H. (2020). Asthenospheric Flow
811 of Plume Material Beneath Arabia Inferred From S Wave Traveltime Tomogra-
812 phy. *Journal of Geophysical Research: Solid Earth*, 125 (8), e2020JB019668. doi:
813 10.1029/2020JB019668
- 814 López Valencia, O. M., Johansen, K., Aragón Solorio, B. J. L., Li, T., Houborg, R.,
815 Malbeteau, Y., ... McCabe, M. F. (2020). Mapping groundwater abstractions
816 from irrigated agriculture: big data, inverse modeling, and a satellite-model fu-
817 sion approach. *Hydrology and Earth System Sciences*, 24(11), 5251-5277. doi:
818 10.5194/hess-24-5251-2020
- 819 Mahmoud, S., Reilinger, R., McClusky, S., Vernant, P., & Tealeb, A. (2005). Gps evidence
820 for northward motion of the sinai block: Implications for e. mediterranean tectonics.
821 *Earth and Planetary Science Letters*, 238(1), 217-224. doi: 10.1016/j.epsl.2005.06.063
- 822 Masson, F., Hamiel, Y., Agnon, A., Klinger, Y., & Deprez, A. (2015). Variable behavior of
823 the dead sea fault along the southern arava segment from gps measurements. *Comptes*
824 *Rendus Geoscience*, 347(4), 161-169. doi: 10.1016/j.crte.2014.11.001
- 825 Masson, F., Lehujeur, M., Ziegler, Y., & Doubre, C. (2014). Strain rate tensor in Iran
826 from a new GPS velocity field. *Geophysical Journal International*, 197(1), 10-21. doi:
827 10.1093/gji/ggt509
- 828 McCaffrey, R. (1995). Defnode users' guide. *Rensselaer Polytech. Inst.*.
- 829 McCaffrey, R. (2002). Crustal block rotations and plate coupling. In *Plate boundary zones*
830 (p. 101-122). American Geophysical Union (AGU). doi: 10.1029/GD030p0101
- 831 McCaffrey, R. (2009). Time-dependent inversion of three-component continuous gps for
832 steady and transient sources in northern cascadia. *Geophysical Research Letters*, 36(7).
833 doi: 10.1029/2008GL036784
- 834 McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., ... Veis,
835 G. (2000). Global positioning system constraints on plate kinematics and dynamics
836 in the eastern mediterranean and caucasus. *Journal of Geophysical Research: Solid*
837 *Earth*, 105(B3), 5695-5719. doi: 10.1029/1999JB900351
- 838 McClusky, S., Reilinger, R., Mahmoud, S., Ben Sari, D., & Tealeb, A. (2003). GPS con-

- 839 strains on Africa (Nubia) and Arabia plate motions. *Geophysical Journal Interna-*
840 *tional*, 155 (1), 126-138. doi: 10.1046/j.1365-246X.2003.02023.x
- 841 McClusky, S., Reilinger, R., Ogubazghi, G., Amleson, A., Healeb, B., Vernant, P., ... Ko-
842 gan, L. (2010). Kinematics of the southern red sea-afar triple junction and implications
843 for plate dynamics. *Geophysical Research Letters*, 37 (5). doi: 10.1029/2009GL041127
- 844 McQuarrie, N., Stock, J. M., Verdel, C., & Wernicke, B. P. (2003). Cenozoic evolution
845 of neotethys and implications for the causes of plate motions. *Geophysical Research*
846 *Letters*, 30 (20).
- 847 Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., ...
848 Döll, P. (2021). The global water resources and use model watergap v2.2d: model
849 description and evaluation. *Geoscientific Model Development*, 14 (2), 1037-1079. doi:
850 10.5194/gmd-14-1037-2021
- 851 Niemi, T. M., Zhang, H., Atallah, M., & Harrison, J. B. J. (2001). Late Pleistocene and
852 Holocene slip rate of the Northern Wadi Araba fault, Dead Sea Transform, Jordan.
853 *Journal of Seismology*, 5 (3), 449-474. doi: 10.1023/A:1011487912054
- 854 Othman, A., & Abotalib, A. Z. (2019). Land subsidence triggered by groundwater with-
855 drawal under hyper-arid conditions: case study from central saudi arabia. *Environ-*
856 *mental Earth Sciences*, 78 (7), 243. doi: 10.1007/s12665-019-8254-8
- 857 Othman, A., Sultan, M., Becker, R., Alsefry, S., Alharbi, T., Gebremichael, E., ... Ab-
858 delmohsen, K. (2018). Use of geophysical and remote sensing data for assessment of
859 aquifer depletion and related land deformation. *Surveys in Geophysics*, 39 (3), 543-566.
860 doi: 10.1007/s10712-017-9458-7
- 861 Pacheco, J., Arzate, J., Rojas, E., Arroyo, M., Yutsis, V., & Ochoa, G. (2006). Delimitation
862 of ground failure zones due to land subsidence using gravity data and finite element
863 modeling in the querétaro valley, méxico. *Engineering Geology*, 84, 143-160.
- 864 Pallister, J. S., McCausland, W. A., Jónsson, S., Lu, Z., Zahran, H. M., Hadidy, S. E., ...
865 Moufti, M. R. H. (2010). Broad accommodation of rift-related extension recorded
866 by dyke intrusion in saudi arabia. *Nature Geoscience*, 3 (10), 705-712. doi: 10.1038/
867 ngeo966
- 868 Pollastro, R. M. (1998). *Bedrock geology of the arabian peninsula and selected adjacent areas*
869 *(geo2bg)*. [https://catalog.data.gov/dataset/bedrock-geology-of-the-arabian-](https://catalog.data.gov/dataset/bedrock-geology-of-the-arabian-peninsula-and-selected-adjacent-areas-geo2bg)
870 *-peninsula-and-selected-adjacent-areas-geo2bg*.
- 871 Reilinger, R., & McClusky, S. (2011). Nubia-Arabia-Eurasia plate motions and the dynam-
872 ics of Mediterranean and Middle East tectonics. *Geophysical Journal International* ,
873 186 (3), 971-979. doi: 10.1111/j.1365-246X.2011.05133.x
- 874 Reilinger, R., McClusky, S., & ArRajehi, A. (2015). Geodetic constraints on the geodynamic
875 evolution of the red sea. In N. M. Rasul & I. C. Stewart (Eds.), *The red sea: The*

- 876 *formation, morphology, oceanography and environment of a young ocean basin* (p. 135-
877 149). Berlin, Heidelberg: Springer Berlin Heidelberg. doi: 10.1007/978-3-662-45201-1
878 _7
- 879 Reilinger, R., McClusky, S., Vernant, P., Lawrence, S., Ergintav, S., Cakmak, R., Karam,
880 G. (2006). Gps constraints on continental deformation in the africa-arabia-eurasia con-
881 tinental collision zone and implications for the dynamics of plate interactions. *Journal*
882 *of Geophysical Research: Solid Earth*, 111 (B5). doi: 10.1029/2005JB004051
- 883 Ribot, M., Klinger, Y., Jónsson, S., Avsar, U., Pons-Branchu, E., Matrau, R., & Mallon,
884 F. L. (2021). Active faults' geometry in the gulf of aqaba, southern dead sea fault,
885 illuminated by multibeam bathymetric data. *Tectonics*, 40 (4), e2020TC006443. doi:
886 10.1029/2020TC006443
- 887 Robinet, J., Razin, P., Serra-Kiel, J., Gallardo-Garcia, A., Leroy, S., Roger, J., & Grelaud, C.
888 (2013). The paleogene pre-rift to syn-rift succession in the dhofar margin (northeastern
889 gulf of aden): Stratigraphy and depositional environments. *Tectonophysics*, 607 , 1-16.
890 doi: 10.1016/j.tecto.2013.04.017
- 891 Rodriguez, M., Chamot-Rooke, N., Huchon, P., Fournier, M., Lallemand, S., Delescluse, M.,
892 Mouchot, N. (2014). Tectonics of the Dalrymple Trough and uplift of the Murray
893 Ridge (NW Indian Ocean). *Tectonophysics*, 636 , 1-17. doi: 10.1016/j.tecto.2014.08
894 .001
- 895 Rodriguez, M., Huchon, P., Chamot-Rooke, N., Fournier, M., & Delescluse, M. (2019).
896 Structural reorganization of the India-Arabia strike-slip plate boundary (Owen Frac-
897 ture Zone; NW Indian Ocean) 2.4 million years ago. In J. C. Duarte (Ed.), *Trans-*
898 *form Plate Boundaries and Fracture Zones* (p. 146-155). Elsevier. doi: 10.1016/
899 B978-0-12-812064-4.00007-4
- 900 Sadeh, M., Hamiel, Y., Ziv, A., Bock, Y., Fang, P., & Wdowinski, S. (2012). Crustal
901 deformation along the dead sea transform and the carmel fault inferred from 12 years
902 of gps measurements. *Journal of Geophysical Research: Solid Earth*, 117 (B8). doi:
903 10.1029/2012JB009241
- 904 Schettino, A., Macchiavelli, C., Pierantoni, P. P., Zannoni, D., & Rasul, N. (2016). Re-
905 cent kinematics of the tectonic plates surrounding the Red Sea and Gulf of Aden.
906 *Geophysical Journal International*, 207(1), 457-480. doi: 10.1093/gji/ggw280
- 907 Sheng, Z., Helm, D. C., & Li, J. (2003). Mechanisms of Earth Fissuring Caused by Ground-
908 water Withdrawal. *Environmental and Engineering Geoscience*, 9(4), 351-362.
- 909 Spakman, W., & Nyst, M. (2002). Inversion of relative motion data for estimates of the
910 velocity gradient field and fault slip. *Earth and Planetary Science Letters*, 203 (1),
911 577-591. doi: 10.1016/S0012-821X(02)00844-0
- 912 Stern, R. J., & Johnson, P. (2010). Continental lithosphere of the arabian plate: A geologic,

- 913 petrologic, and geophysical synthesis. *Earth-Science Reviews*, 101 (1), 29-67. doi:
914 10.1016/j.earscirev.2010.01.002
- 915 Trippanera, D., Ruch, J., Passone, L., & Jónsson, S. (2019). Structural Mapping of Dike-
916 Induced Faulting in Harrat Lunayyir (Saudi Arabia) by Using High Resolution Drone
917 Imagery. *Frontiers in Earth Science*, 7. doi: 10.3389/feart.2019.00168
- 918 U.S.G.S. (2021). *Earthquake Catalogue*. <https://earthquake.usgs.gov/earthquakes/search/>.
- 919 Varet, J. (2018a). Transverse volcanic alignments along afar margins. In *Geology of Afar*
920 *(East Africa)* (p. 241-251). Cham: Springer International Publishing. doi: 10.1007/
921 978-3-319-60865-5_9
- 922 Varet, J. (2018b). Afar, a hot-spot for earth's geodynamics studies. In *Geology of afar*
923 *(east africa)* (p. 285-293). Cham: Springer International Publishing. doi: 10.1007/
924 978-3-319-60865-5_11
- 925 Vernant, P., & Chéry, J. (2006). Mechanical modelling of oblique convergence in the
926 zagros, iran. *Geophysical Journal International*, 165 (3), 991-1002. doi: 10.1111/
927 j.1365-246X.2006.02900.x
- 928 Vernant, P., Nilforoushan, F., Hatzfeld, D., Abbassi, M. R., Vigny, C., Masson, F., Chry,
929 J. (2004, 04). Present-day crustal deformation and plate kinematics in the Middle East
930 constrained by GPS measurements in Iran and northern Oman. *Geophysical Journal*
931 *International*, 157 (1), 381-398. doi: 10.1111/j.1365-246X.2004.02222.x
- 932 Vigny, C., Huchon, P., Ruegg, J.-C., Khanbari, K., & Asfaw, L. M. (2006). Confirmation of
933 arabia plate slow motion by new gps data in yemen. *Journal of Geophysical Research:*
934 *Solid Earth*, 111 (B2). doi: 10.1029/2004JB003229
- 935 Viltres, R., Jónsson, S., Ruch, J., Doubre, C., Reilinger, R., Floyd, M., & Ogubazghi,
936 G. (2020). Kinematics and deformation of the southern Red Sea region from GPS
937 observations. *Geophysical Journal International*, 221 (3), 2143-2154. doi: 10.1093/
938 gji/ggaa109
- 939 Wessel, P., W. H. F., S., R., S., J., L., & Wobbe, F. (2013). Generic mapping tools:
940 Improved version released. *EOS Trans. AGU*, 94 (45), 409-410.
- 941 Williams, S. D. P. (2003). The effect of coloured noise on the uncertainties of rates estimated
942 from geodetic time series. *Journal of Geodesy*, 76 (9), 483-494. doi: 10.1007/s00190
943 -002-0283-4
- 944 Williams, S. D. P. (2008). CATS: GPS coordinate time series analysis software. *GPS*
945 *Solutions*, 12 (2), 147-153. doi: 10.1007/s10291-007-0086-4
- 946 Wu, Y., Jiang, Z., Yang, G., Wei, W., & Liu, X. (2011). Comparison of GPS strain rate
947 computing methods and their reliability. *Geophysical Journal International*, 185 (2),
948 703-717. doi: 10.1111/j.1365-246X.2011.04976.x
- 949 Xu, W., Dutta, R., & Jónsson, S. (2015b). Identifying Active Faults by Improving Earth-

950 quake Locations with InSAR Data and Bayesian Estimation: The 2004 Tabuk (Saudi
951 Arabia) Earthquake Sequence. *Bulletin of the Seismological Society of America*,
952 *105*(2A), 765-775. doi: 10.1785/0120140289

953 Xu, W., Jónsson, S., Corbi, F., & Rivalta, E. (2016). Graben formation and dike arrest
954 during the 2009 harrat lunayyir dike intrusion in Saudi Arabia: Insights from InSAR,
955 stress calculations and analog experiments. *Journal of Geophysical Research: Solid
956 Earth*, *121*(4), 2837-2851. doi: 10.1002/2015JB012505

957 Youssef, A. M., Sabtan, A. A., Maerz, N. H., & Zabramawi, Y. A. (2014). Earth fissures
958 in Wadi Najran, Kingdom of Saudi Arabia. *Natural Hazards*, *71*(3), 2013-2027. doi:
959 10.1007/s11069-013-0991-5