

# 1 **Monitoring aseismic creep trend in Ismetpasa and Destek segments throughout the NAF with a** 2 **large scale GPS network**

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## 7 **Abstract**

8 North Anatolian Fault Zone (NAFZ) is an intersection area between Anatolian and Eurasian  
9 plates. Arabian plate, which squeezes the Anatolian plate from the south between Eurasian plate and  
10 itself is also responsible for this formation. This tectonic motion causes Anatolian plate to move  
11 westwards with almost a 20 mm/year velocity which has caused destructive earthquakes in the history.  
12 Block boundaries that form the faults are generally locked to the bottom of seismogenic layer because  
13 of the friction between blocks, and responsible for these discharges. However, there are also some  
14 unique events observed around the world, which may cause partially or fully free slipping faults. This  
15 phenomenon is called “aseismic creep”, and may occur through the entire seismogenic zone or at least  
16 to some depths. Additionally, it is a rare event in the world located in two reported segments along  
17 the North Anatolian Fault (NAF) which are Ismetpasa and Destek.

18 In this study, we established GPS networks covering those segments and made three  
19 campaigns between 2014-2016. Considering the long term geodetic movements of the blocks  
20 (Anatolian and Eurasian plates), surface velocities and fault parameters are calculated. The results of  
21 the model indicate that aseismic creep still continues to some rates of  $13.2\pm 3.3$  mm/year at Ismetpasa  
22 and  $9.6\pm 3.1$  mm/year at Destek. Additionally, aseismic creep behavior is limited to some depths and  
23 decays linearly to the bottom of the seismogenic layer at both segments. This study suggests that this  
24 aseismic creep behavior will not prevent a medium-large scale earthquake in the long term.

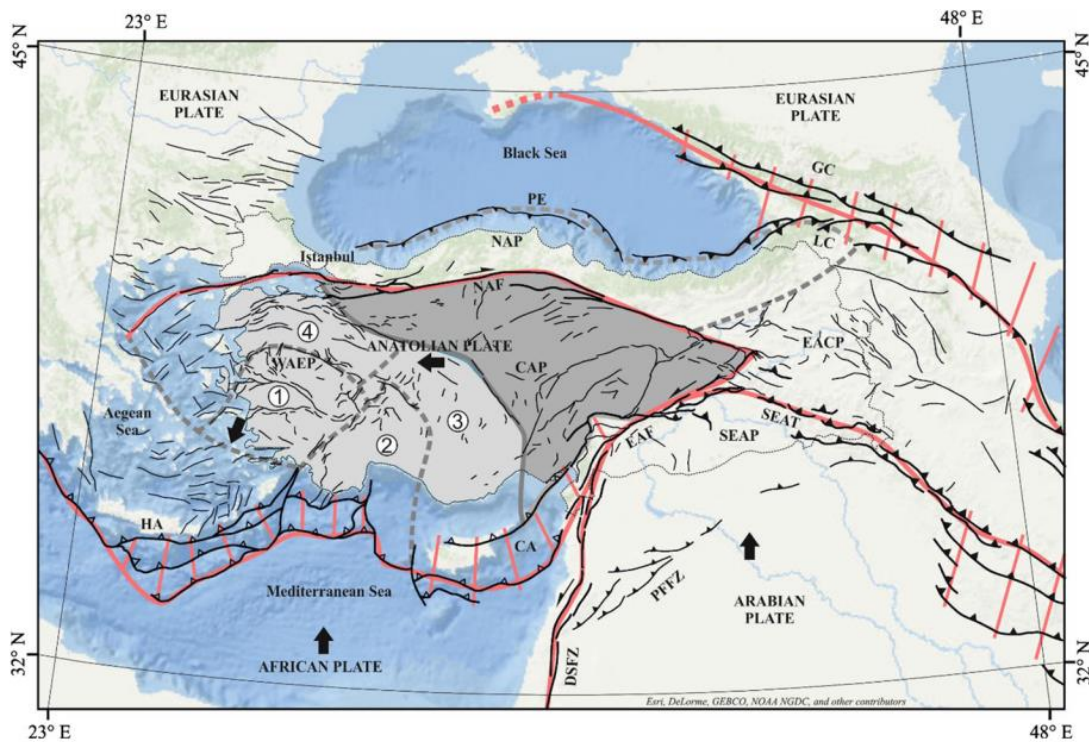
25 **Key words:** NAFZ, aseismic creep, GPS, block modelling

## 26 **Introduction**

27 Fault zones all around the world are formed by the tectonic plate motions and is a natural  
28 boundary between blocks. They are generally locked to the bottom of seismogenic layer and cannot  
29 slip freely compared to the velocities within the blocks because of the friction between rocks.  
30 Therefore, movement in these regions generally minimal and causes earthquakes when the motion of

31 the blocks overrides the friction force. After discharge (earthquake), faults begin to accumulate strain  
32 and this cycle continues until the next earthquake (Reid 1910, Yavaşoğlu 2011).

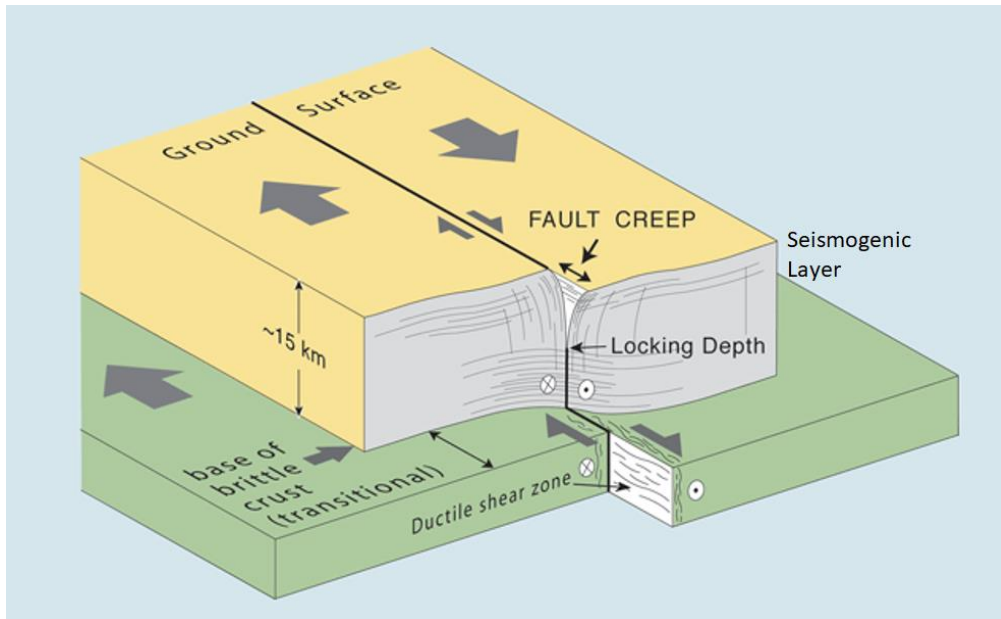
33 NAF(North Anatolian Fault) is a tectonic plate boundary between Anatolian and Eurasian  
34 plates. It slowly moves ~20 mm/year to the west by the overthrusting Arabian plate from the south  
35 and compresses the plate motion with the help of a massive Eurasian plate in the north. Those tectonic  
36 forces constitute North Anatolian Fault, which lies between Karliova triple junction from the east to  
37 the Aegean Sea to the west for almost 1200 km long. The width of the fault trace ranges between 100  
38 m to 10 km. Anatolian plate moves 20-25 mm/year to the west relative to the Eurasian plate. There  
39 are velocity variations along the fault that is, west region moves faster than the eastern part and is a  
40 right-lateral strike slip fault (Fig. 1) (Ketin 1969-1976, McClusky et al. 2000, Cakir et al. 2005, Şengör et  
41 al. 2005, Reilinger et al. 2006, Yavaşoğlu et al. 2011, Bohnhoff et al. 2016).



42  
43 **Figure 1.** Formation of the North Anatolian Fault and interacting tectonic plates (from Emre et al.  
44 2018). Anatolian plate moves westwards due to African and Arabian plates overthrusting. (1) West  
45 Anatolian graben systems, (2) Outer Isparta Angle, (3) Inner Isparta Angle, and (4) Northwest  
46 Anatolia transition zone. The original version of the figure is available in Emre et al. 2018.

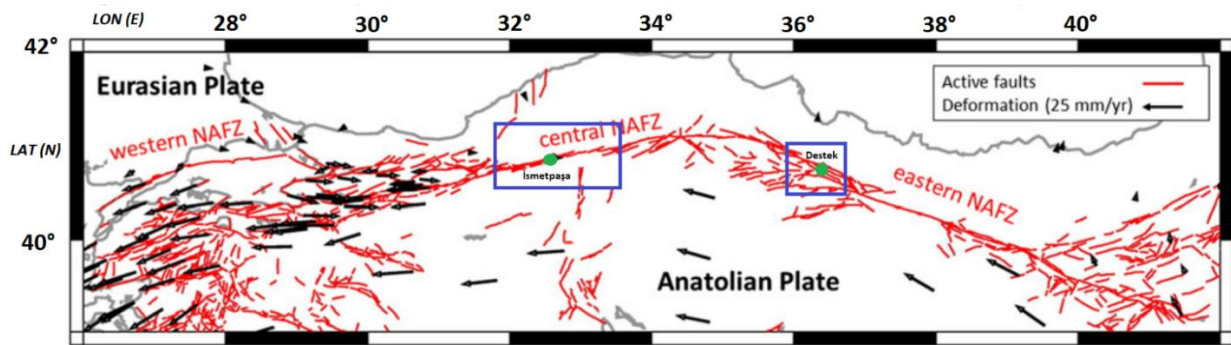
47 Earthquake mechanisms might have different characteristics in some regions. Faults may move  
48 freely without an earthquake and this motion reported at some unique places like Hayward fault  
49 (Schmidt et al. 2005), the Superstition Hills fault(Wei et al. 2011) and Ismetpasa segments (Cakir et al.  
50 2012) which can be observed from the surface(Ambraseys 1970, Yavasoglu et al. 2015). This  
51 phenomenon is called “aseismic creep” and may occur in two different ways. If the creep takes place

52 to the bottom of seismogenic layer and the surface velocities are equal or close to the long-term  
53 tectonic velocities, there will not be enough strain accumulation for a large scale earthquake (Şaroğlu  
54 ve Barka 1995, Cakir et al. 2005). On the other hand, if that free motion is not observed to the bottom  
55 of the seismogenic layer or observed surface velocities are smaller than the tectonic velocities, strain  
56 will accumulate to a final earthquake (Fig. 2) (Karabacak et al. 2011, Ozener et al. 2013, Yavasoglu et  
57 al. 2015). Also, aseismic creep in a region may occur continuously or fade out after some period  
58 (Kutoglu et al. 2010).



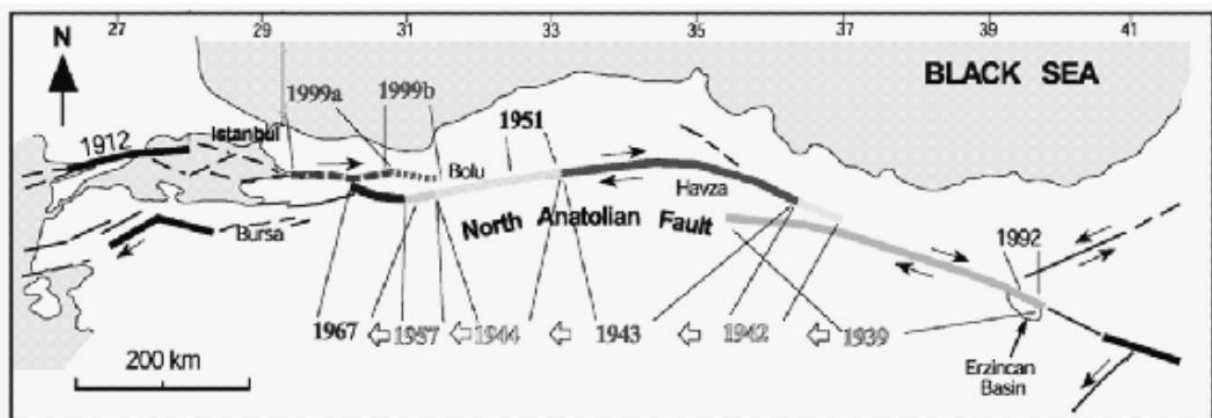
59  
60 **Figure 2.** Aseismic creep structure in a fault zone. Fault may slip freely to some depths and locked  
61 after to the bottom (URL-1).

62 NAF reported to have segments which show aseismic creep since 1970 at Ismetpasa and with  
63 a more recent discovery, Destek (Ambraseys 1970, Karabacak et al. 2011). Aseismic creep at the  
64 Ismetpasa is reported to occur along ~70-80 km, from Bayramoren (east) to the Gerede (west) (Fig. 3).  
65 It was discovered at the wall of the Ismetpasa train station at 1970 and several minor and large scale  
66 studies monitored the area since then (Table 1). That segment hosted three destructive earthquakes  
67 (1943 Tosya  $M_w=7.2$ , 1944 Gerede  $M_w=7.2$ , 1951 Kursunlu  $M_w=6.9$ ) that may have triggered or affected  
68 the creep (Şaroğlu ve Barka 1995, Cakir et al. 2005, Karabacak et al. 2011, Kaneko et al. 2013) (Fig. 4).



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70 **Figure 3.** Active fault segments on the North Anatolian Fault (NAF). Blue rectangles define Ismetpasa  
 71 and Destek segments from west to east, respectively (after Bohnhoff et al. 2016).

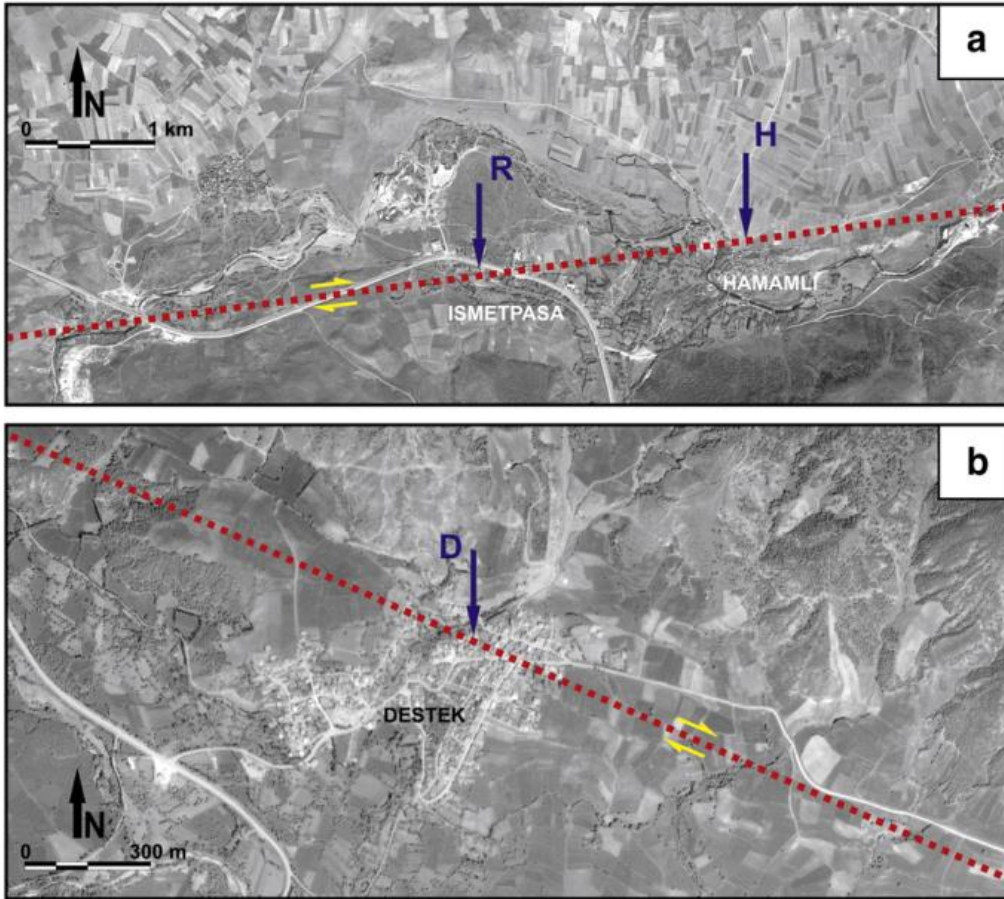


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73 **Figure 4.** Earthquakes on the North Anatolian Fault between 1939-1999. Both 1943 and 1944  
 74 earthquakes suspected to have influence on the creeping phenomena (from Kutoglu et al. 2010).

75 In addition, creep at the Destek segment reported at 2003 on a field trip around the region.  
 76 Unlike the Ismetpasa segment, number of studies at this segment is just a few, and also the length of  
 77 this segment is unclear. 1943 Tosya earthquake, which is reportedly the biggest earthquake in the  
 78 segment, affected this area (Karabacak et al. 2011) (Table 2).

79 All the studies around those segments indicate the continuity of creep but the results are  
 80 inconsistent and cannot clearly refer whether that event has an increasing trend or not. Most of the  
 81 researches (Ambraseys 1970, Aytun 1982, Eren 1984, Altay and Sav 1991, Deniz et al. 1993, Kutoglu et  
 82 al. 2008&2009&2013, Karabacak et al. 2011, Ozener et al. 2013, Bilham et al. 2016) generally are on a  
 83 micro-scale and focused on the Ismetpasa or a network near this village with geodetic methods, while  
 84 others on a macro-scale with InSAR (Deguchi 2011, Fialko et al. 2011, Köksal 2011, Kaneko et al. 2013,  
 85 Cetin et al. 2014, Kutoglu et al. 2013) which needs a ground truth (Fig 5&6).

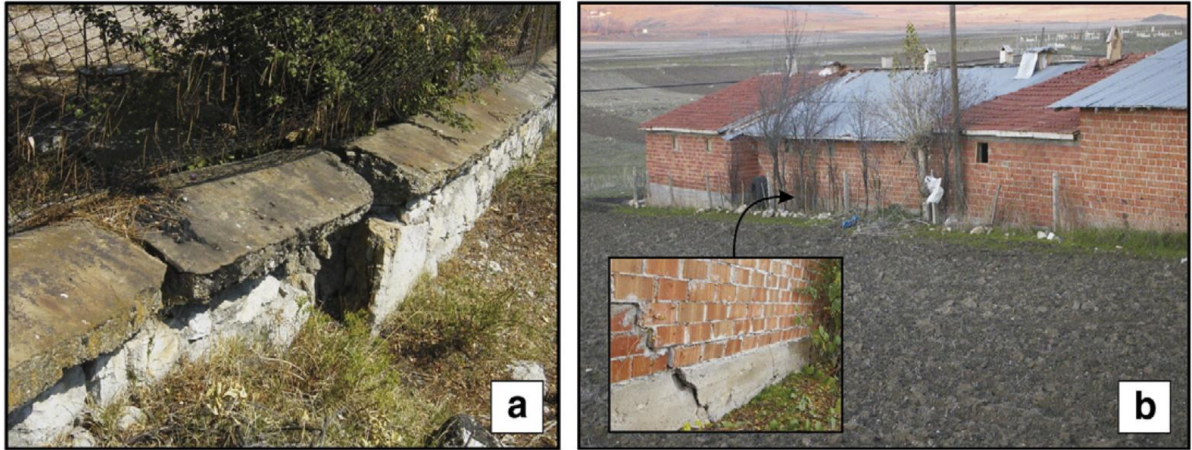


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**Figure 5.** Reported aseismic creep zones at Ismetpasa (a) and Destek (b) segments from a recent study. (a) “R” shows creep observed at the wall at the Ismetpasa train station, and “H” shows the creep at Hamamli village. (b) “D” represents the reported creep at Destek town (from Karabacak et al. 2011).



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100

**Figure 6.** Aseismic creep sites (a)at Ismetpasa railway station, and (b) damaged brick-wall at Hamamlı village close to Ismetpasa. (c) Out-bended wall at Destek village (from Karabacak et al. 2011).

101            Those results cannot reveal the creep trend clearly. In addition, a ground network is required  
102 to exhibit the fault characteristics clearly along the segments. For this reason, we established a ground  
103 network forming profiles around those segments and made three observations annually from 2014 to  
104 2016.

105 **Table 1.** Studies and their results to observe aseismic creep at the Ismetpasa segment between 1970-  
 106 2016.

Study	Creep rate(cm/year)	Years covered	Method
Ambraseys(1970)	2.0 ± 0.6	1957-1969	Wall offset measurements
Aytun(1982)	1.10 ± 0.11	1969-1978	Doppler
Eren(1984)	1.00 ± 0.40	1972-1982	Trilateration
Deniz et al.(1993)	0.93 ± 0.07	1982-1992	Trilateration
Cakir et al.(2005)	0.80 ± 0.30	1992-2000	InSAR
Kutoglu&Akcin(2006)	0.78 ± 0.05	1992-2002	GPS
Kutoglu et al.(2008)	1.20 ± 0.11	2002-2007	GPS
Kutoglu et al.(2010)	1.51 ± 0.41	2007-2008	GPS
Karabacak et al.(2011) [1.region]	0.84 ± 0.40	2007-2009	LIDAR
Karabacak et al.(2011) [2. region]	0.96 ± 0.40	2007-2009	LIDAR
Deguchi(2011)	1.4	2007-2011	PALSAR
Fialko et al.(2011)	1.0	2007-2010	PALSAR
Ozener et al.(2013)	0.76 ± 0.10	2005-2011	GPS
Köksal(2011)	1.57 ± 0.20	2007-2010	DInSAR
Görmüş(2011)	1.30 ± 0.39	2008-2010	GPS
Kaneko et al.(2013)	0.9 ± 0.2	2007-2011	InSAR
Cetin et al.(2014)	0.8 ± 0.2	2003-2010	InSAR(PSI)
Altay and Sav(1991)	0.76 ± 0.1	1982-1991	Kripmetre
Kutoglu et al.(2013)	1.3 ± 0.2	2008-2010	GPS
Kutoglu et al.(2013)	1.25 ± 0.2	2007-2010	InSAR
Ambraseys(1970) - Bilham et al.(2016) revision	1.04 ± 0.04	1957-1969	Revaluation of photographs
Aytun(1982)	1.50	1957-1969	Revaluation of photographs
Aytun(1982) – Bilham et al.(2016) revision	1.045 ± 0.035	1957-1969	Revaluation of photographs
Bilham et al.(2016)	0.61 ± 0.02	2014-2016	Creepmeter

107 **Table 2.** Studies and their results to observe aseismic creep at the Destek segment.

Study	Creep rate (cm/year)	Years covered	Method
Karabacak et al.(2011)	0.66 ± 0.40	2007-2009	LIDAR
Fraser et al.(2009)	0.6	2009	Trench study

108 **Network Design Around the Creeping Segments**

109 Designing a monitoring network around tectonic structures is always related to the geological  
 110 characteristics and fault geometry, which includes the locking depth and earthquake related motions  
 111 (coseismic movements) through the fault. Previous studies indicate that the velocities for the stations  
 112 distant from the fault plane can be used to derive long-term plate velocities, while nearby station  
 113 velocities are suitable to detect the locking depth of a fault (Taskin et al. 2003, Halicioğlu et al. 2009).  
 114 In addition, velocities of the observation stations gradually decrease when their locations approach to  
 115 the fault plane. Another factor is the number of the stations and this is related to the fault length and  
 116 width, but the station locations perpendicular to the fault plane must not exceed the ( $\pm 1/\sqrt{3}$ ) of the

117 locking depth. Also, several research specify this limit to the double of the depth (Taskin et al. 2003,  
118 Kutoglu and Akcin 2006, Kutoğlu et al. 2009, Halicioğlu et al. 2009, Poyraz et al. 2011, Bohnhoff et al.  
119 2016). For this purpose, the following equation is used in general to obtain to proper distances of the  
120 observation stations from the fault plane:

$$V(x) = \frac{V_T}{\pi} \arctan\left(\frac{x}{D}\right) \quad (1)$$

121 where:

- 122 -  $V$  : Fault parallel velocity
- 123 -  $V_T$  : Long term tectonic plate velocity
- 124 -  $x$  : Distance to fault plane
- 125 -  $D$  : Locking depth of the fault (Halicioğlu et al. 2009).

126 Location of the stations may vary according to the geological surface elements, but they are  
127 generally established on the both sides of the fault to form a profile on each block to obtain surface  
128 velocities (Yavasoglu et al. 2015).

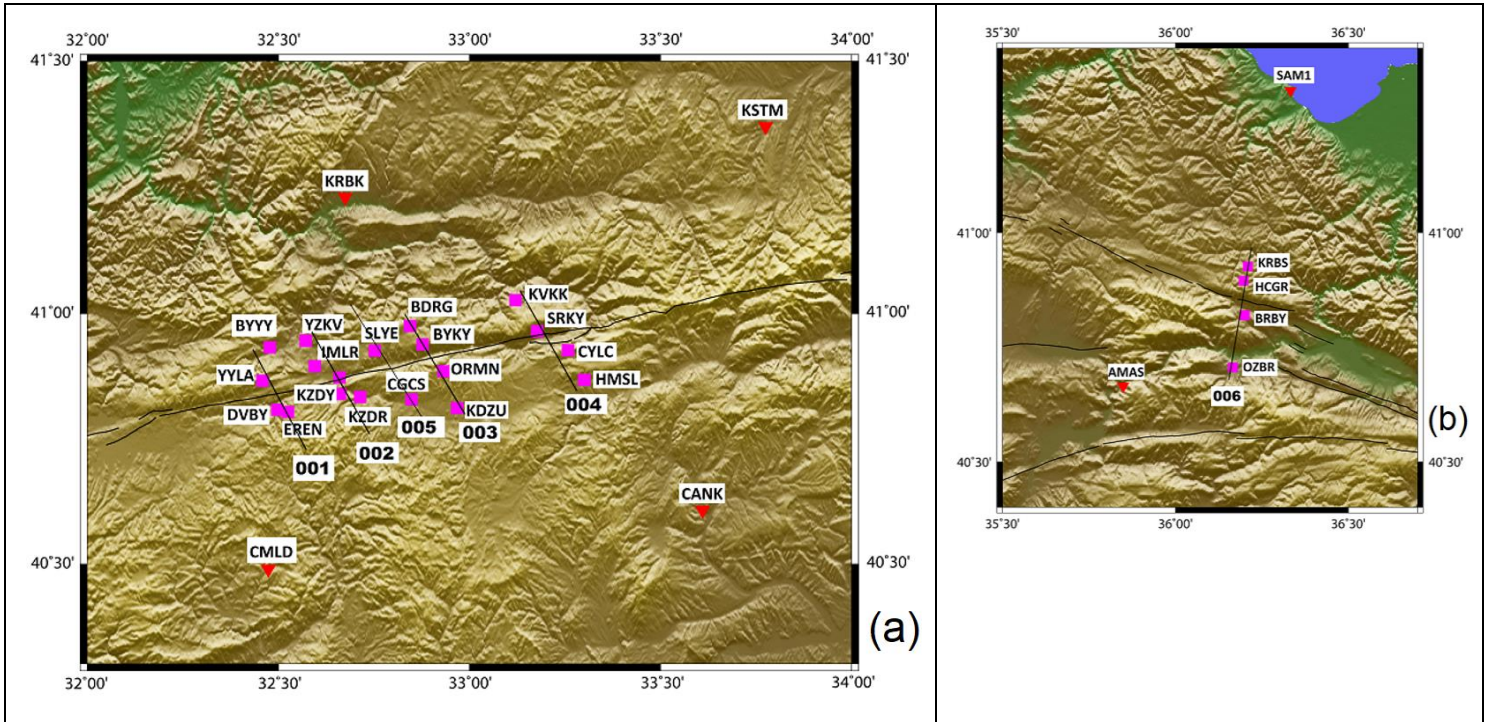
129 Geologic structure at the tectonic block boundaries and fault plane geometry also affects the  
130 tectonic behaviour. To better understand this mechanism, established network around the fault zone  
131 is observed with different techniques periodically or continuously. The variation of the observations  
132 are clues to detect those amplitudes, and GPS is the most common technique for that kind of studies.  
133 This technique is very effective and efficient to collect data from ground stations established around  
134 the faults (Poyraz et al. 2011, Aladoğan et al. 2017).

135 Profiles intersect with fault plane vertically are used to estimate the locking depth. However,  
136 in such regions like Ismetpasa and Destek, there is an additional locking depth deduced from the  
137 previous studies, which indicates that the creeping layer of the seismogenic zone does not reach to  
138 the bottom, but around 5-7 km depth in those areas (Kaneko et al. 2013, Ozener et al. 2013, Cetin et  
139 al. 2014, Bilham et al. 2016, Rousset et al. 2016). For this reason, aseismic layer's attenuation depth is  
140 another crucial element to understand the creeping mechanism (Fig 2). Also considering the 5-7 km  
141 depth value with the *Eq.1*, station locations are chosen as 3 and 10 km on the both sides of the fault  
142 forming profiles, while NAF general locking depth is around 15 km (McClusky et al. 2000, Poyraz et al.  
143 2011, Bohnhoff et al. 2016).

144 Before the 3 epochs of observations, a network was planned forming 4 profiles at the  
145 Ismetpasa, and 1 profile at the Destek segments and including surrounding continuous GPS  
146 stations(Real Time Kinematic Continuously Operating Reference Stations-RTK CORS) (Fig 7). Aim of this  
147 study was to monitor this network periodically to calculate the velocity field with combining the results



148 with CORS station velocities and estimate the creep ratio within the Ismetpasa and Destek segments  
 149 (Yavasoglu et al. 2015).



150 **Figure 7.** Planned profiles and campaign GPS stations(pink) at Ismetpasa(a) on the left and Destek(b)  
 151 on the right. Profiles 001-004 planned and established on the Ismetpasa segment, and profile 005  
 152 added to the network using two suitable stations. Profile 006 is on Destek segment. Fault traces on  
 153 the south of profile 006 are secondary faults. Other continuous GPS sites (RTK CORS) shown in  
 154 red(after Yavasoglu et al. 2015).

155 While establishing the network, first consideration for 3 and 10 km on the both sides of the  
 156 fault generally occurred, but some minor changes took place according to the geological structure of  
 157 the area. In addition, another profile between the 2<sup>nd</sup> and 3<sup>rd</sup> profiles formed with the suitable location  
 158 of two unplanned stations. Finally, there are 5 profiles within ~70 km along the Ismetpasa and 1 profile  
 159 along the Destek.

160 Observations are completed around the July and August for 3 years using relative geolocation  
 161 based on carrier phase observations with GPS technique (Table 3). Force centering equipment and GPS  
 162 masts were used when necessary. First campaign was on the 235-238 and 241 GPS days in 2014,  
 163 second was on 215-221 GPS days in 2015, and the last one was between 210-220 GPS days in 2016.

**Table 3.** Campaign stations, their locations and facility types.

Profile number	Station ID	Site	Latitude (°)	Longitude (°)	Type of facility
<b>001</b>	BYYY	Büyükyayalar	40.49	32.48	Bronze
	YYLA	Yayla Village	41.45	31.78	Bronze
	DVBY	Davutbeyli Village	39.43	32.50	Bronze
	EREN	Elören Village	40.81	32.50	Bronze
<b>002</b>	YZKV	Yazıkavak Village	40.80	32.53	Bronze
	IMLR	İmanlar Village	40.95	32.57	Bronze
	HMMP	Hamamlı Village	40.90	32.60	Pillar
	KZDR	Kuzdere Village	41.23	32.68	Pillar
<b>005 (intermediate)</b>	SLYE	Kapaklı Village	41.85	32.72	Pillar
	CGCS	D100 wayside	39.86	32.85	Pillar
<b>003</b>	BDRG	Boduroğlu Village	39.89	32.76	Bronze
	BYKY	Beyköy Village	40.83	32.85	Pillar
	ORMN	Forest	40.94	32.86	Bronze
	KDZU	Kadiözü Village	40.88	32.93	Pillar
	KVKK	Kavak Village	40.81	32.97	Bronze
<b>004</b>	SRKY	Sarıkaya Village	41.03	33.12	Bronze
	CYLC	Çaylıca Village	40.97	33.18	Bronze
	HMSL	Hacimusla Village	40.93	33.26	Pillar
	KRBS	Korubaşı Village	40.82	36.20	Bronze
<b>006</b>	HCGR	Hacıgeriç Village	40.71	36.17	Bronze
	BRBY	Borabay	40.90	36.20	Pillar
	OZBR	Özbaraklı Village	39.66	35.87	Pillar

165 After the first campaign, KZDY station was damaged and removed from rest of the project. Raw  
166 data collected for a minimum of 8 hours at each station for the rest of the project and evaluated with  
167 GAMIT/GLOBK software (Herring et al. 2015a, 2015b) at first, then the results used as input to block  
168 modelling software TDEFNODE (McCaffrey 2002, 2009). A total of 63 stations (22 campaign, 30  
169 surrounding RTK CORS, 11 IGS) are used in this network to monitor Ismetpasa and Destek segments  
170 and the remaining region between them (Table 4).

**Table 4.** Continuous GPS(RTK CORS) stations and their locations.

Station ID	Province	Station ID	Province	Station ID	Province
<b>AKDG</b>	Yozgat	<b>FASA</b>	Ordu	<b>RDIY</b>	Tokat
<b>AMAS</b>	Amasya	<b>GIRS</b>	Giresun	<b>SAM1</b>	Samsun
<b>ANRK</b>	Ankara	<b>HEND</b>	Sakarya	<b>SIH1</b>	Eskişehir
<b>BILE</b>	Bilecik	<b>HYMN</b>	Ankara	<b>SINP</b>	Sinop
<b>BOLU</b>	Bolu	<b>IZMT</b>	İzmit	<b>SIVS</b>	Sivas
<b>BOYT</b>	Sinop	<b>KKAL</b>	Kırıkkale	<b>SSEH</b>	Sivas
<b>CANK</b>	Çankırı	<b>KRBK</b>	Karabük	<b>SUNL</b>	Çorum
<b>CMLD</b>	Ankara	<b>KSTM</b>	Kastamonu	<b>TOK1</b>	Tokat
<b>CORU</b>	Çorum	<b>KURU</b>	Bartın	<b>VEZI</b>	Samsun
<b>ESKS</b>	Eskişehir	<b>NAHA</b>	Ankara	<b>ZONG</b>	Zonguldak

173 **GPS Data Evaluation**

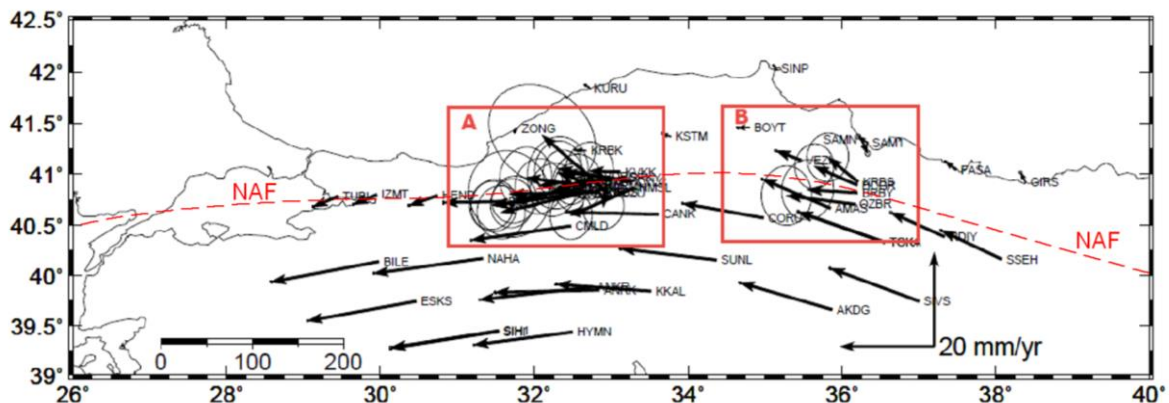
174 GPS data for cGPS and IGS stations' data processed at campaign observation dates. In addition,  
 175 observations for those stations during January (for 7 days) included at the GAMIT/GLOBK step to  
 176 increase the stabilization of the designed networks.

177 The networks linked to the ITRF 2008 global coordinate system by using surrounding IGS sites  
 178 (Table 5) (Yavaşoglu et al. 2011, Herring et al. 2015a, 2015b). After the transformation with GLOBK,  
 179 the root mean square (rms) of the stations was only 0.7 mm/year.

180 **Table 5.** IGS stations defined in the site.defaults file of GAMIT to constitute reference frame (\*  
 181 indicates stations selected for GLOBK stabilization)

Station ID	City/Country
ANKR	Ankara/Turkey
BUCU*	Bucharest/Romania
CRAO*	Simeiz/Ukraine
MATE*	Metara/Italy
ONSA*	Onsala/Switzerland
SOFI*	Sofia/Bulgaria
TEHN*	Tehran/Iran
TELA	Tel Aviv/Israel
TUBI	Kocaeli/Turkey
WZTR*	Koetzting/Germany
ZECK*	Zelenchukskaya/Russia

182 Results show that the velocity of the stations located on the Anatolian plate are ranging from  
 183 15 to 20 mm/year (Fig 8), which is similar with the previous studies (McClusky et al. 2000, Reilinger et  
 184 al. 2006, Yavaşoglu et al. 2011).



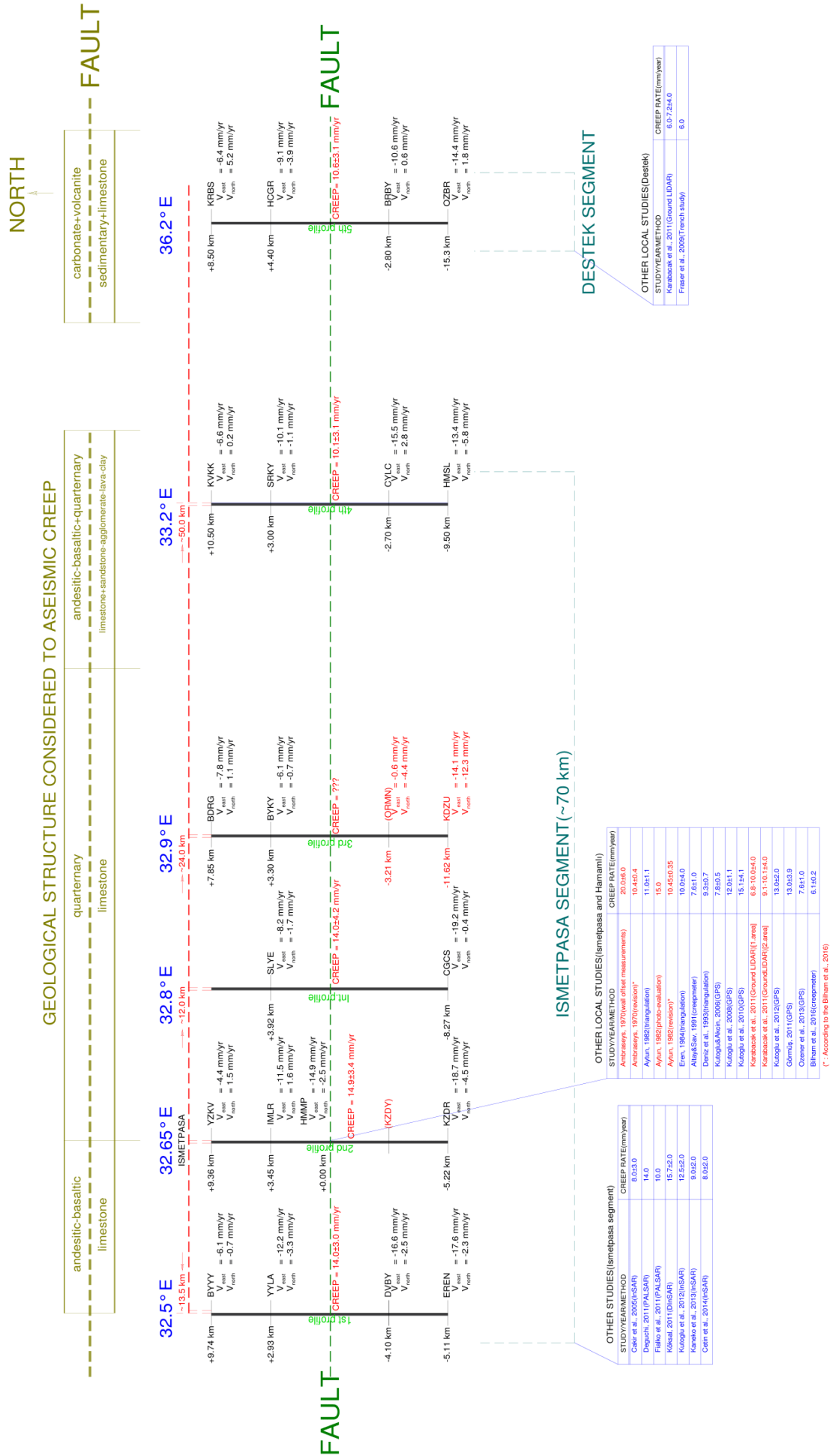
185 **Figure 8.** GLOBK results for station velocities relative to fixed Eurasian plate. (A) includes the  
 186 Ismetpasa segment, and Destek segment is inside (B). Dashed lines represent the fault trace of North  
 187 Anatolian Fault (NAF). Velocities at the north of the NAF are very small as expected, where south  
 188 velocities indicate the westward motion of the Anatolian plate (after Aladoğan 2017).  
 189

190 The GLOBK results for all of the station velocities are used as input for block modelling to  
 191 predict the aseismic creep ratio within fault plane in the predefined segments (Table 6, Fig.9).

192 **Table 6.** All cGPS and campaign point velocities and location errors (uncertainties) when Eurasian  
 193 plate selected as fixed.

Station ID	Velocity(mm/yr)		Error		Station ID	Velocity(mm/yr)		Error	
	V <sub>EAST</sub>	V <sub>NORTH</sub>	V <sub>EAST</sub>	V <sub>NORTH</sub>		V <sub>EAST</sub>	V <sub>NORTH</sub>	V <sub>EAST</sub>	V <sub>NORTH</sub>
AKDG	-19.5	5.7	0.1	0.1	KDZU	-14.1	12.3	4.6	4.4
AMAS	-14.5	6.2	0.1	0.1	KKAL	-20.1	1.5	0.1	0.1
ANRK	-22.1	-0.5	0.1	0.1	KRBK	-2.3	0.1	0.1	0.1
BDRG	-7.8	1.1	1.7	1.9	KRBS	-6.4	5.2	1.8	2.1
BILE	-22.8	-4.3	0.1	0.1	KSTM	-1.9	0.6	0.1	0.1
BOLU	-12.8	-0.2	0.1	0.1	KURU	-0.9	0.5	0.1	0.1
BOYT	-2.5	-0.1	0.1	0.1	KVKK	-6.6	0.2	2.1	2.5
BRBY	-10.6	0.6	2.3	2.6	KZDR	-18.7	-4.5	2.1	2.3
BYKY	-6.1	-0.7	1.5	1.8	NAHA	-23.1	-3.2	0.1	0.1
BYYY	-6.8	-1.0	2.1	2.4	ORMN	-0.6	-4.4	1.8	2.0
CANK	-19.4	0.5	0.1	0.1	OZBR	-14.4	1.8	2.2	2.6
CGCS	-19.2	-0.4	3.5	3.7	RDIY	-11.4	5.1	0.1	0.1
CMLD	-21.1	-3.0	0.1	0.1	SAM1	-1.9	1.3	0.2	0.2
CORU	-17.2	3.1	0.1	0.1	SAMN	1.3	-3.0	0.2	0.2
CYLC	-15.5	2.8	2.0	2.4	SIH1	-22.8	-3.6	0.1	0.2
DVBY	-16.6	-2.5	2.0	2.3	SIHI	-22.8	-3.6	0.1	0.2
EREN	-17.6	-2.3	1.9	2.1	SINP	-0.7	0.5	0.1	0.1
ESKS	-23.1	-4.2	0.1	0.1	SIVS	-18.8	7.0	0.1	0.1
FASA	-2.2	1.8	0.1	0.1	SLYE	-8.2	-1.7	2.0	2.3
GIRS	-1.0	2.1	0.1	0.1	SRKY	-10.1	-1.1	2.1	2.5
HCGR	-9.1	3.9	1.7	1.9	SSEH	-12.8	6.1	0.1	0.1
HEND	-6.0	-2.2	0.1	0.1	SUNL	-20.4	2.4	0.1	0.1
HMMP	-14.9	-2.5	2.0	2.0	TOK1	-18.4	6.4	0.1	0.1
HMSL	-13.4	-5.8	1.8	2.1	VEZI	-5.3	2.1	0.1	0.1
HYMN	-20.9	-2.7	0.1	0.1	YYLA	-12.2	-3.3	1.9	2.1
IMLR	-11.5	1.6	2.3	2.6	YZKV	-4.4	1.5	2.6	3.1
IZMT	-5.0	-2.1	0.1	0.1	ZONG	-0.5	-0.7	0.1	0.1

194



**Figure 9.** Geological structure related to the aseismic creep, station velocities, estimated creep ratio, and earlier studies around the Ismetpasa and Destek regions (Akbaş et al. 2002., Cetin et al. 2014)



196 Aseismic creep ratio estimated by interpolation through the profiles using surface velocities  
197 except the 3<sup>rd</sup> profile at first (Table 7).

198 GAMIT process indicates abnormal deformation for ORMN and KDZU campaign stations, so  
199 their data removed from the block modelling step. Additionally, the creep estimation for that profile  
200 unfeasible. Actually, this is not a drawback for block modelling, because the remaining station  
201 velocities are all used to model the region uneventfully.

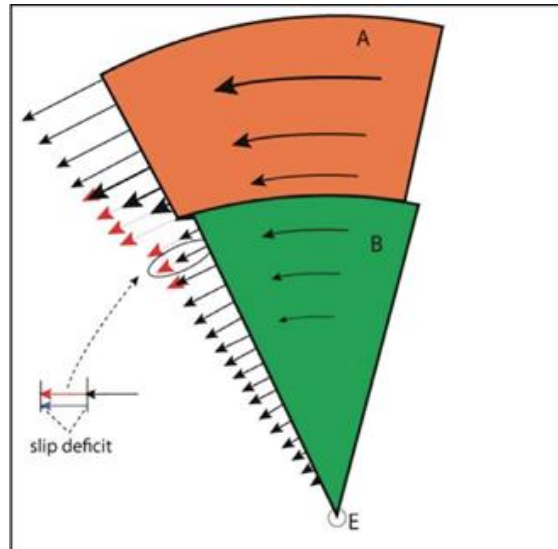
202 **Table 7.** Aseismic creep rate at the Ismetpasa segment.

Profile	Aseismic creep rate(mm/year)
001	14.0±3.0
002	14.9±3.6
005(intermediate)	14.0±4.0
004	10.1±3.0

203 With the calculated surface velocities, Destek segment also have a creep trend through the  
204 campaign period. Estimated creep rate in this study according to GLOBK results is 10.6±3.1 mm/year  
205 in this region, and indicates aseismic creep similar with the recent studies (Fraser et al. 2009, Karabacak  
206 et al. 2011).

## 207 **Block Modelling**

208 Station velocities are suitable to predict surface and block motions around them locally. On  
209 the other hand, observations inside the blocks provide adequate long-term block velocities and  
210 rotations with high precision. Blocks generally demonstrate a regular movement, but their motion  
211 differ at their boundaries from this overall velocity. They cannot move freely around the faults because  
212 of the friction of rocks, generally infer underspeed, may down to none (Fig 10). That difference in the  
213 velocity is called “slip deficit” and causes earthquakes after the friction threshold is surpassed (Kutoglu  
214 and Akcin 2006, McCaffrey 2014, Yavasoglu et al. 2015).

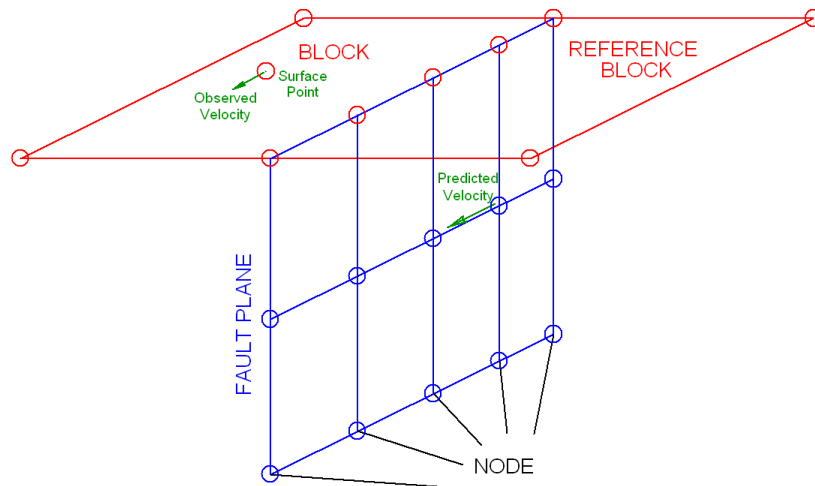


215

216 **Figure 10.** Motions of tectonic blocks around the same Euler pole and slip deficit at their boundaries.  
 217 Long-term block velocities evolve at the fault zones and gap between them is responsible for strain  
 218 accumulation and earthquakes (from Cakmak 2010).

219 Slip deficit represents that expected velocities of the blocks pass through some  
 220 deformations regarding the geological structure when approaching the fault zone and frequently  
 221 decreases. This is based on the geometry of the fault plane, which can only be predicted and based on  
 222 the surface velocities. In that context, TDEFNODE software used in this study to predict the fault plane  
 223 locking interaction regarding the depths, which calculates variations of the block motions, strain  
 224 accumulation within the blocks and rotations through interseismic or coseismic period (Okada 1985,  
 225 McCaffrey 2009, Yavaşoğlu 2011).

226 Basic input for the software includes GPS velocities, blocks with Euler poles, fault geometry  
 227 and locking depth. Interacting blocks are represented as elastic blocks and assumed to have elastic  
 228 deformation because of their rotation around Euler poles. All of the defined system is assumed to float  
 229 inside a half-space where one of the blocks is fixed and have zero strain or movement. Fault geometry  
 230 is defined by the user with nodes, and their locking ratios ( $\phi$ ) can be defined manually or as a function  
 231 of depth (Fig. 11). Then, the software predicts the underground velocities based on the routines of  
 232 Okada (1985) and estimates the surface velocities according the defined values. Fault geometry  
 233 estimation is the key feature to minimize the difference between observed and predicted surface  
 234 velocities with the help of  $\chi^2$  test result, which represents the accuracy of the entire model (McCaffrey  
 235 2002, Aktuğ and Çelik 2008, Yavasoglu et al. 2011).



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**Figure 11.** Fault plane geometry defined to the control file of TDEFNODE. Nodes divides the fault plane into sub-regions to defined depths and their locking ratio may differ from each other.

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TDEFNODE is not only used for interacting blocks for interseismic strain accumulation, but also for faults which are partially or fully free slipping like aseismic creep. Software's model is suitable to define the locking ratios of all nodes independently from (0-1). (0) represents that the fault at that node is freely slipping, and (1) for a fully locked node. That allows user to define the fault plane with layers by using depth contours and to predict the fault plane if those layers are partially or fully locked (Url-2).

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Aseismic creep is an earthquake-free motion along the earth surface, but in some cases it's hard to detect whether this motion is a free slipping event or an interseismic movement. Thus, the observation network around the fault plane should be planned carefully regarding the  $\pm 3-10$  km station locations mentioned before (Fig 12).

249

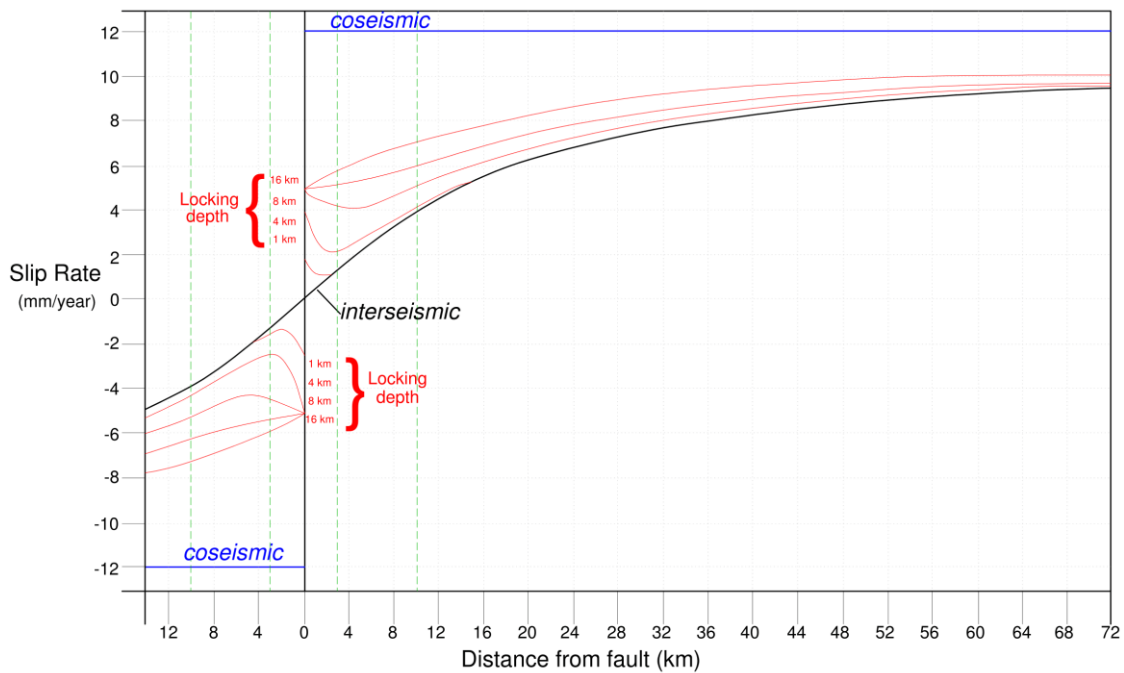
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252

During TDEFNODE process, one of the tectonic blocks should be chosen as fixed to estimate the fault parameters. Therefore, Euler pole is defined as (0, 0, 0) for the Eurasian plate and (30.7, 32.6, 1.2) for the Anatolian plate. Values represent latitude, longitude and angular velocity, respectively (McClusky et al. 2000).

253



254

255 **Figure 12.** Slip rate along a fault plane during interseismic and coseismic events. Blue lines represents  
 256 the coseismic, and black line represents the interseismic behaviour, where red lines demonstrates  
 257 the aseismic creep ratios at two sides of the fault for different locking depths. Green lines indicates 3  
 258 and 10 km on the both side of the fault where the interseismic behavior disintegrates from aseismic  
 259 creep (after Yavasoglu et al. 2015).

260 *Figure 12* demonstrates the suitable distances to detect aseismic creep. If an aseismic creep is  
 261 suspected on a fault plane, then the optimum locations for the observation stations should be around  
 262 3 and 10 km on both sides of the fault and can be resolved from the interseismic movements.  
 263 Therefore, observation stations, which are mentioned before, are established around the fault as  
 264 profiles to detect this discrepancies and to detect the main locking depth of the fault and attenuation  
 265 depths for the creep event. Their locations are suitable to evaluate both creeping ratios and locking  
 266 depths of the faults.

267 **Discussion**

268 Station velocities all around the region indicate the relative motion of the Anatolian plate  
 269 regarding the Eurasian plate. Movements ranges between 15-24 mm/year inside the southern plate  
 270 where the northern motion reaches down to ~1 mm/year. That result is consistent with the previous  
 271 studies (~24±2 mm/year)(McClusky et al. 2000, Reilinger et al. 2006, Yavasoglu et al. 2011). In addition,  
 272 model locking depths and results are similar with a more recent study with InSAR, which indicates that  
 273 the locking depth of the fault at Ismetpasa segment around 13-17 km and long-term tectonic  
 274 movement is about 24-30 mm/year (Hussain et al. 2018).

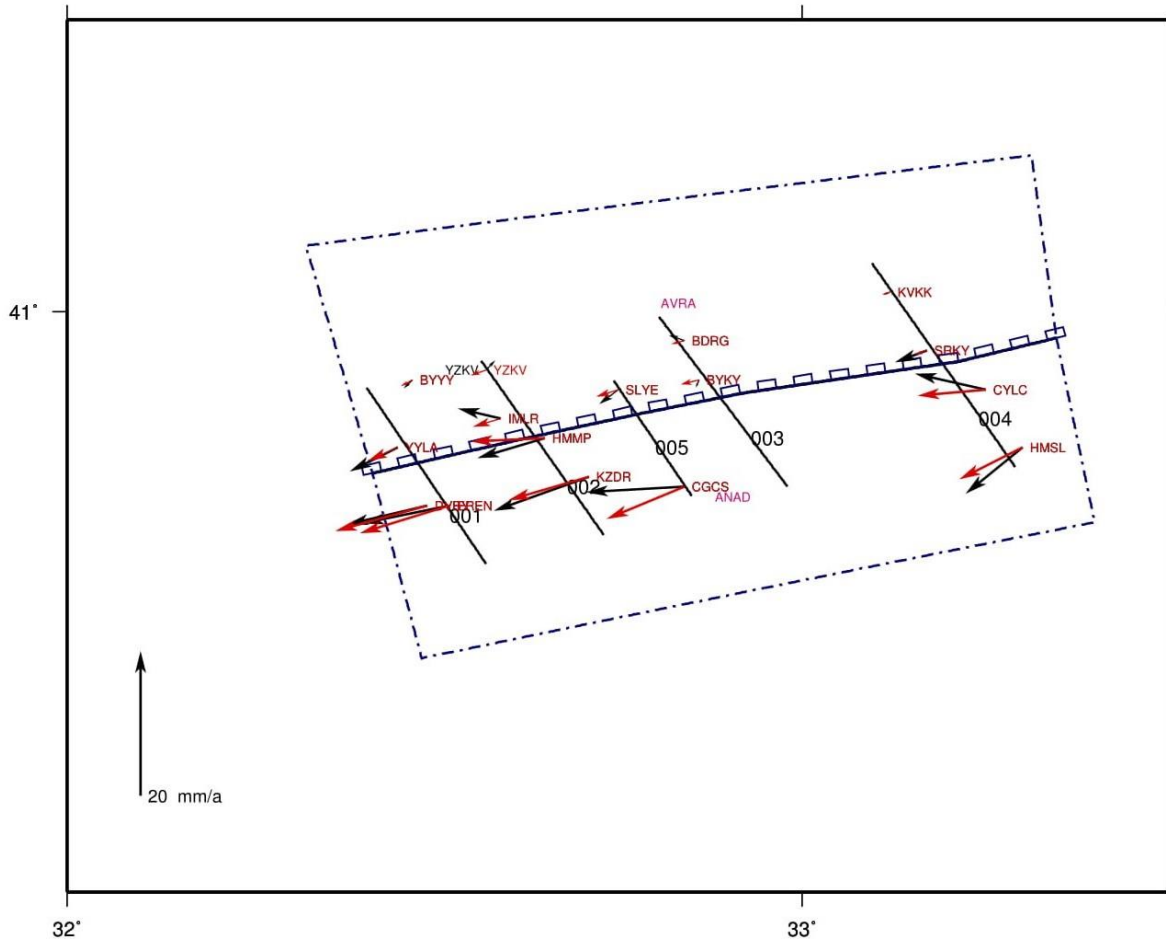
275 Special features of the inspected segments are revealed by the network established near the  
276 fault plane. Regarding the surface velocities of the observation points, profiles on both Ismetpasa and  
277 Destek segments indicate movements. That ranges between 10.1-14.9 mm/year and 10.6 mm/year for  
278 Ismetpasa and Destek segments, respectively.

279 Additionally, modeled fault plane evaluation for observed and calculated station movements  
280 demonstrates similar results with the locking depths of both creeping and seismogenic layers (Fig. 13).  
281 Station velocities on the south of the NAF are faster than the north-end as expected (Fig. 14). Regarding  
282 the long-term geodetic block motions, modeled weighted locking ratios indicate a  $13.0 \pm 3.3$  mm/year  
283 of aseismic creep all over the Ismetpasa segment. That movement does not include the whole fault  
284 plane, thus the creeping layer seems to slip freely to 4.5 km depths from the surface and decays  
285 between 4.5-6.75 km. The seismic data and previous studies (Cakir et al. 2005, Yavaşoğlu et al. 2011,  
286 Hussain et al. 2019) indicate that the locking depth all over the fault as  $\sim 15$  km. This result  
287 demonstrates the fully locked portion of the fault plane is between 6.75-15 km, which supported by  
288 the  $\chi^2$  test result (1.00).

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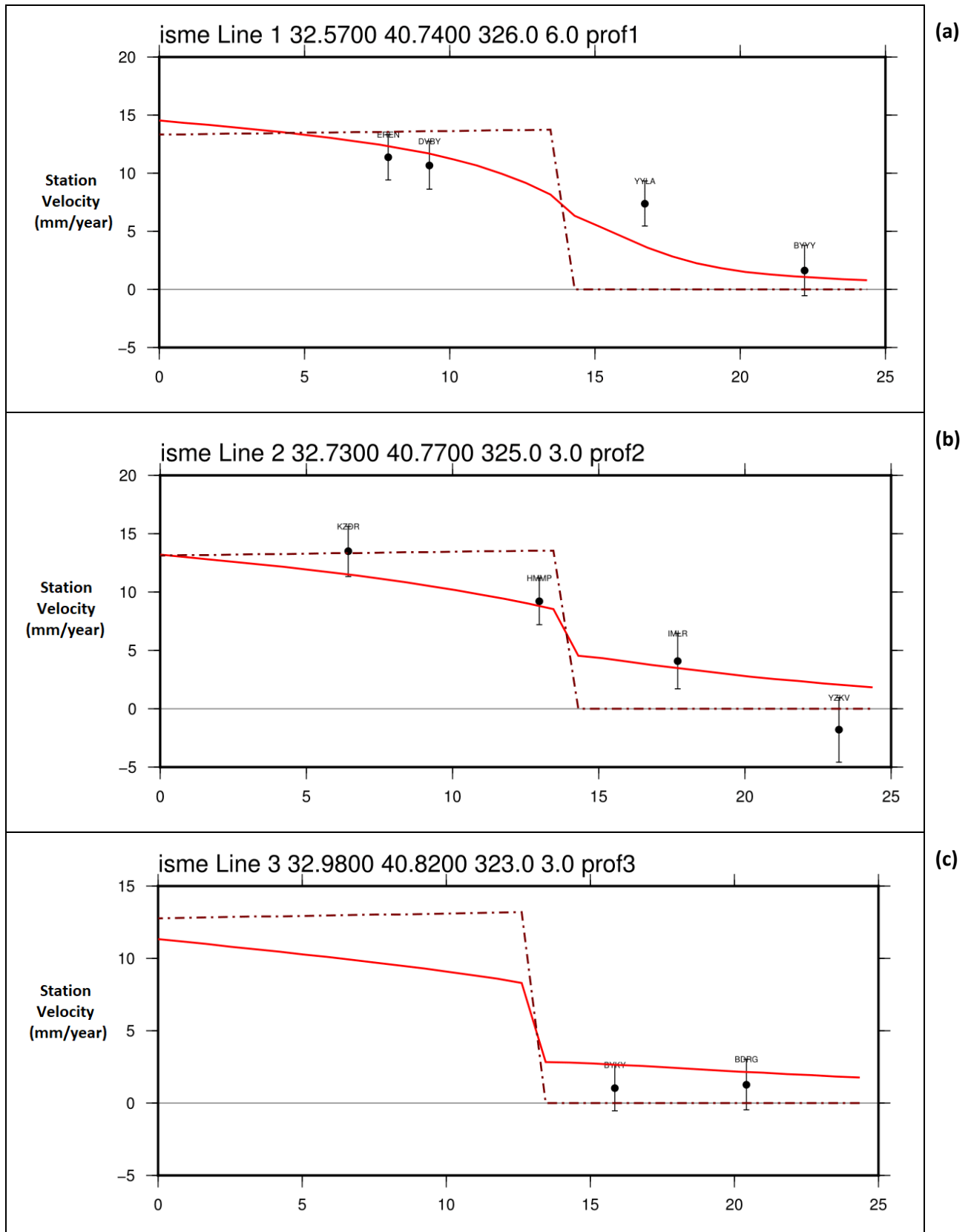


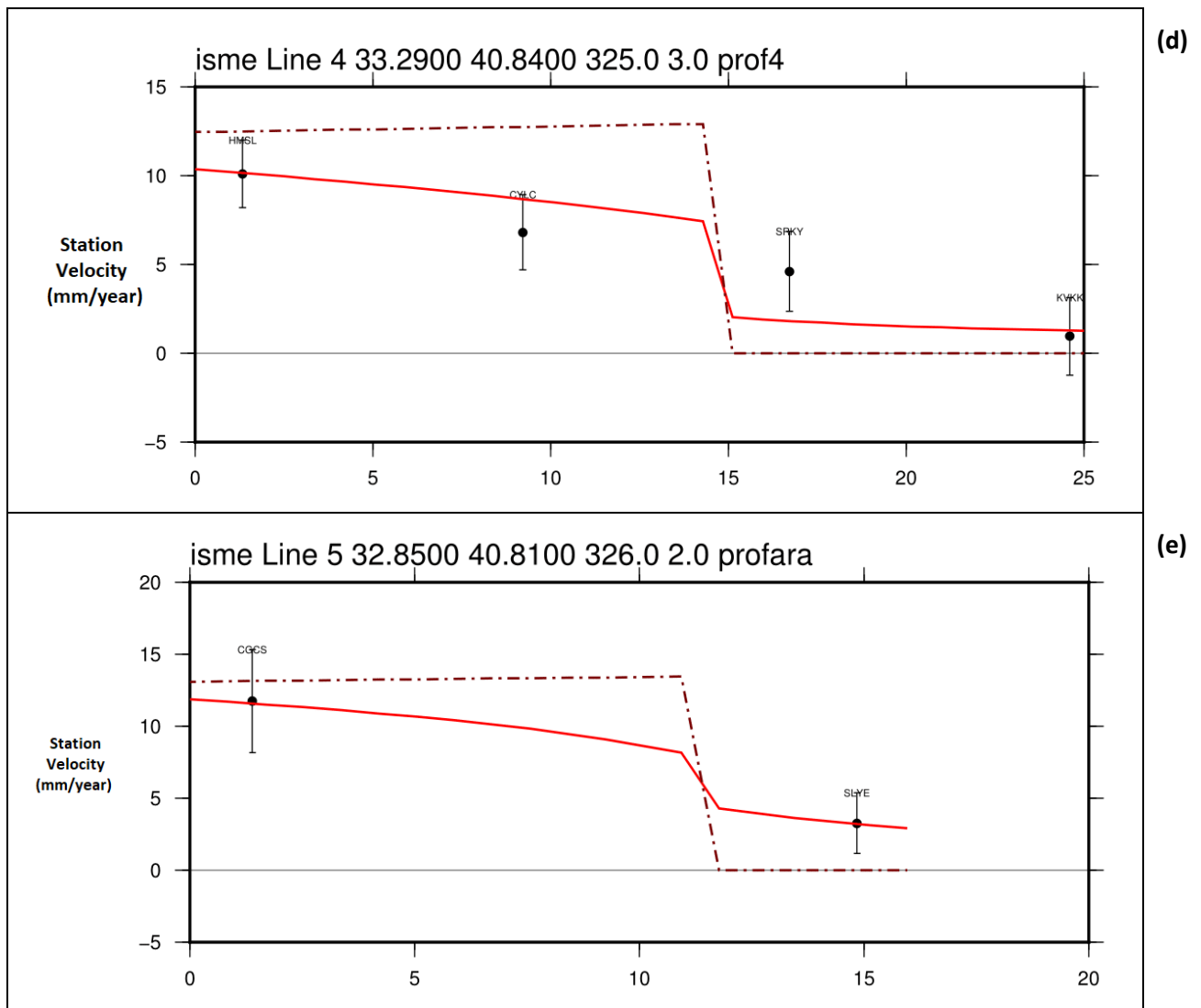
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292 **Figure 13.** Model area for Ismetpasa segment with Eurasian plate (AVRA) on the north and Anatolian  
 293 plate (ANAD) on the south (dashed lines), divided by the creeping segment of the NAF. Black and red  
 294 arrows represent the observed and modeled velocities respectively, obtained from GAMIT/GLOBK  
 295 and TDEFNODE. Five profiles are numbered from west to east with 001 to 004, where 005 represents  
 296 the intermediate profile established during the 1<sup>st</sup> campaign. Two stations (SLYE and CGCS)  
 297 on the south-end of the profile 003 removed from the model due to unexpected velocities. Rectangles imply  
 298 the fault trace.

299

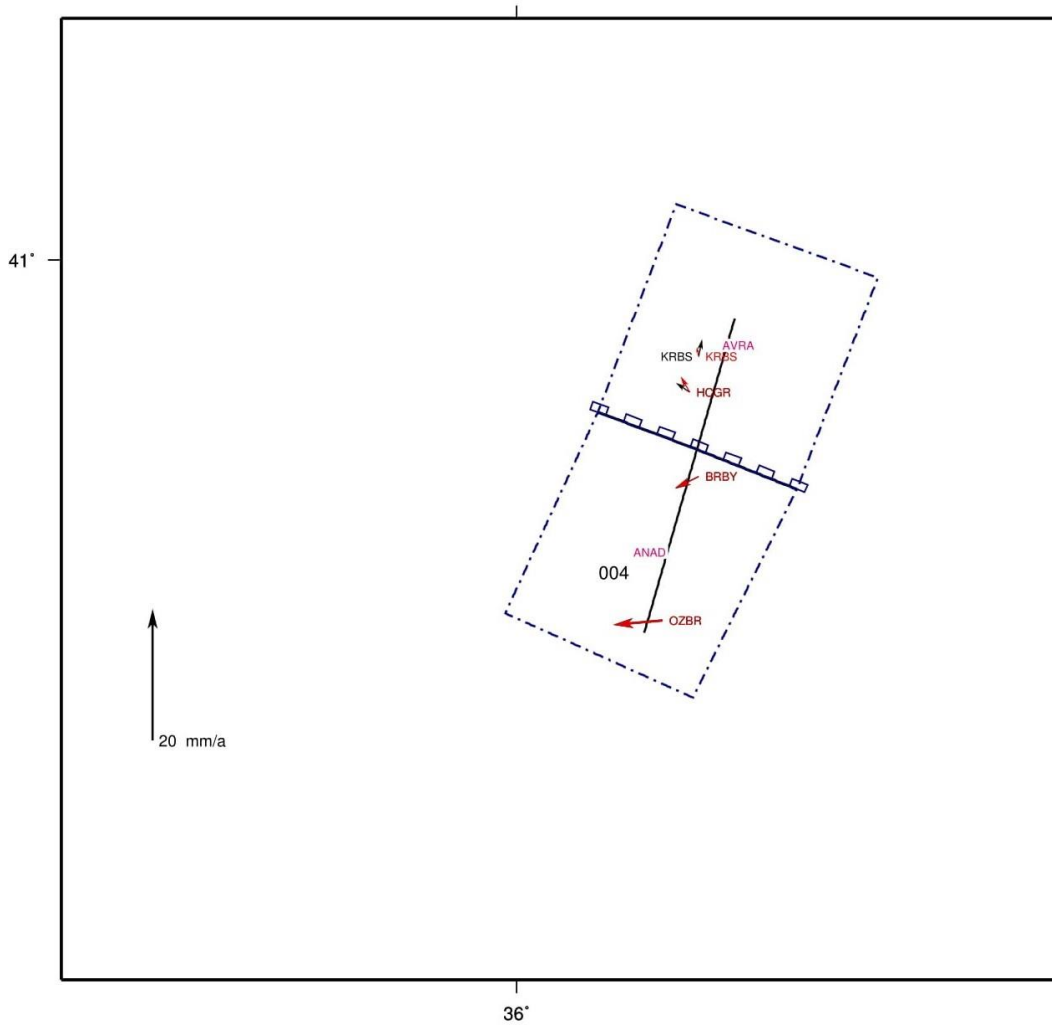
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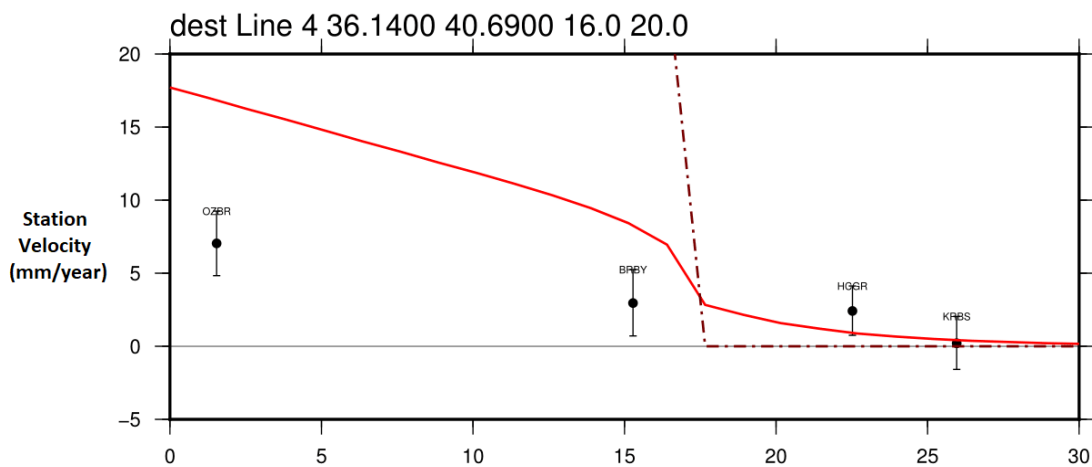
301 **Figure 14.** Station velocities distant 25 km for each side(east-west)through the profiles 001-  
 302 005. Each station represented by a block dot, its code, and error ratio with vertical lines. Dashed lines  
 303 are the block boundaries and red lines for the trend of velocity variations. Profiles 001-004 shown  
 304 with a, b, c, and d, respectively. Intermediate profile(005) shown as (e). All the profiles are dispread  
 305 from south to north.

306 Destek segment also have similar results for the observed and modeled velocities (Fig 15). The  
 307 surface velocities for the profile (006) at this region indicates velocity differences (Fig 16). In addition,  
 308 the modeled fault plane indicates that the creeping segment is limited to 4.3 km depth from the  
 309 surface decays linearly between 4.3-6.0 km. The remaining layer of the fault seems to be fully locked  
 310 down to the seismogenic layer. Free slipping portion have a 9.6 mm/year motion which is similar with  
 311 the estimated surface velocities ( $10.6 \pm 3.1$  mm/year). The  $\chi^2$  test result (1.01) and the seismic data  
 312 confirms the accuracy of the model.



313

314 **Figure 15.** Model area for Destek segment with Eurasian plate(AVRA) on the north and Anatolian  
 315 plate(ANAD) on the south(dashed lines), divided by the creeping segment of the NAF. Black and red  
 316 arrows represent the observed and modeled velocities respectively, obtained from GAMIT/GLOBK  
 317 and TDEFNODE. 004 represents the profile in the area and rectangles imply the fault trace.



318

319 **Figure 16.** Station velocities and profile (006) for the Destek profile. Each station represented by a  
 320 block dot, its code, and error ratio with vertical lines. Dashed lines are the block boundaries, and red  
 321 lines for the trend of velocity variations. Profile dispread from south to the north.

322 Moreover, paleomagnetic data indicates a predominantly clockwise rotation of the blocks  
323 bordered by the faults between Ismetpasa and Destek segments. Examining the results with this study  
324 promotes that behavior with the GPS field of the region, especially on the Anatolian side of the NAF  
325 (Figure 13&15) (İşseven and Tüysüz, 2006).

326 We find no clear evidence for attenuation at both segments. On the contrary, there is a slight  
327 increase at Ismetpasa and almost 50% of an increase at Destek regarding the previous studies. The  
328 frequency of this phenomenon at both segment is unclear, but results at *Hussain et al. (2018)* assists  
329 that argument that the creep event will continue until the next large-scale earthquake.

### 330 **Conclusion**

331 NAF reported to have a creeping phenomena at Ismetpasa since 1970 and observed with  
332 different techniques for a long time period with a recent discovery at Destek. All the previous studies  
333 concentrate on whole segments or at least some regions along those segments. With this study, a GPS  
334 network covering the whole Anatolian region along the NAF is established for the first time and results  
335 for the velocity area used as input for block modeling. Also, the first GPS network covering Destek  
336 segment established during this study.

337 Network design and location of the observation points distinguished according to the main  
338 locking depth of the NAF and attenuation depth for the aseismic creep event. Model results show  
339 similar outcomes for both Ismetpasa and Destek segments, where locking depth for those segments  
340 are ~15 km, and attenuation for the creeping layer depths varies between ~4-6 km.

341 Through all the models, results for this study indicate that the creeping behaviour still  
342 continues at both Ismetpasa and Destek segments, with a ratio of  $13.0 \pm 3.3$  mm/year and  $10.6 \pm 3.1$   
343 mm/year, respectively. Block modeling and seismic data indicate that the creeping segment does not  
344 reach to the bottom of the seismogenic layer (~15 km) and is limited to some depths, which may not  
345 prevent a medium-large scale earthquake in the long term. In addition, we found no evidence for the  
346 attenuation of aseismic creep. Also, the frequency of this movement at Ismetpasa is unclear and it is  
347 not possible to predict the aseismic creep ratio precisely for long-term, but results might indicate a  
348 small increase in the trend regarding the previous studies in the region.

349 Additionally, the creeping ratio seems to increase almost 50% at the Destek segment  
350 considering the previous studies, which might indicate a relief at that segment. However, according to  
351 the model, aseismic creep is limited to some depths (~6.0 km) and creep ratio is smaller than the long  
352 term block movements. The increasing trend is not sufficient to release all the strain in that segment.  
353 This might indicate strain accumulation on the both ends of the segment.



354 The established network by this study should be monitored periodically for the assessment of  
355 the frequency of aseismic creep precisely, which may include possible clues for a clear fault plane  
356 definition and earthquakes. In addition, results indicate that this creep event will be monitored to the  
357 next earthquake, which might reveal valuable information for fault zone layout model.

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