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Geoscientific Instrumentation Methods and Data Systems Discussions
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Monitoring aseismic creep trend in Ismetpasa and Destek segments throughout the NAF with a large scale GPS network

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Abstract

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

In this study, we established GPS networks covering these segments and made three campaigns between 2014-2016. Considering the long term geodetic movements of the blocks (Anatolian and Eurasian plates), previous studies for each segment, calculated surface velocities and fault parameters; aseismic creep still continues to some rates, 13.2±3.3 mm/year at Ismetpasa and 9.6±3.1 mm/year at Destek. Results indicates that this aseismic creep behavior will not prevent a medium-large scale earthquake in the long term.

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

Introduction

Fault zones all around the world are formed by the tectonic plate motions and is a natural boundary between blocks. They are generally locked to the bottom of seismogenic layer and cannot slip freely compared to the velocities within the blocks because of the friction between rocks. Therefore, movement in these regions generally minimal and causes earthquakes when the motion of the blocks overrides the friction force. After discharge (earthquake), faults begin to accumulate strain and this cycle continues until the next earthquake (Reid 1910, Yavaşoğlu 2011).

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https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

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

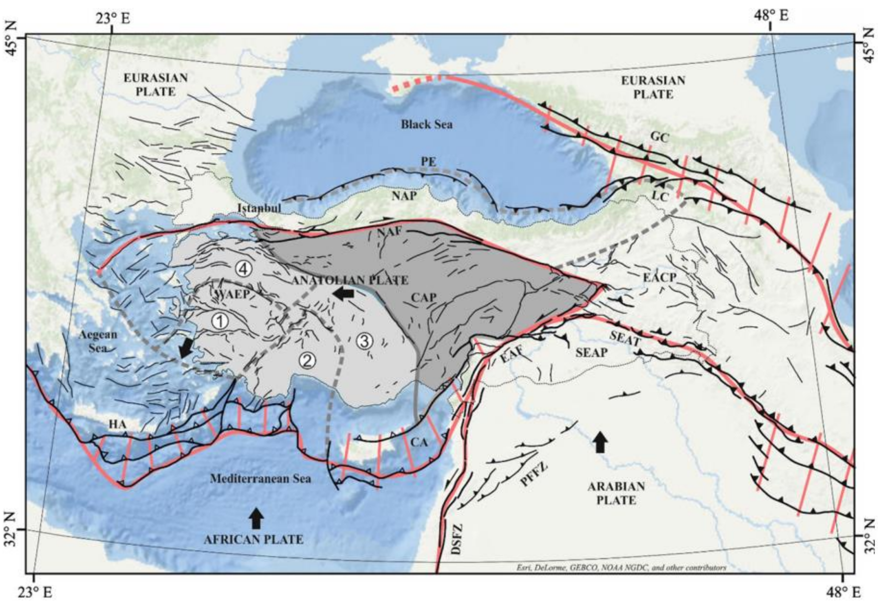

Figure 1. Formation of the North Anatolian Fault and interacting tectonic plates (from Emre et al. 2018). Anatolian plate moves westwards due to African and Arabian plates overthrusting. (1)West Anatolian graben systems, (2) Outer Isparta Angle, (3) Inner Isparta Angle, and (4) Northwest Anatolia transition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

Earthquake mechanism might have different characteristics in some regions. Faults may move freely without an earthquake and this motion reported at some unique places like Hayward fault (Schmidt et al. 2005), the Superstition Hills fault(Wei et al. 2011) and Ismetpasa segments (Cakir et al. 2012), and can be observed from the surface(Ambraseys 1970, Yavasoglu et al. 2015). This phenomenon is called “aseismic creep” and may occur in two different ways: If the creep takes place to the bottom of seismogenic layer and the surface velocities are equal or close to the long-term tectonic velocities, there will not be enough strain accumulation for a large scale earthquake (Şaroğlu ve Barka 1995, Cakir et al. 2005). On the other hand, if this free motion is not observed to the bottom

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

of the seismogenic layer or observed surface velocities are smaller than the tectonic velocities, strain will accumulate to a final earthquake (Fig. 2) (Karabacak et al. 2011, Ozener et al. 2013, Yavasoglu et al. 2015). Also, aseismic creep in a region may occur continuously or fade out after some period (Kutoglu et al. 2010).

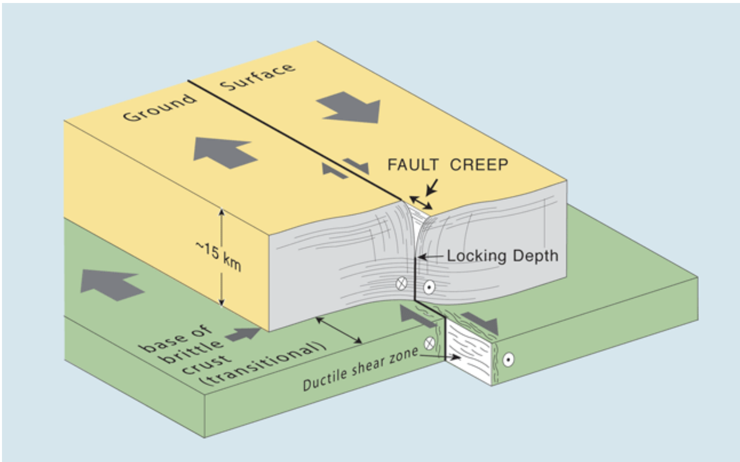

Figure 2. Aseismic creep structure in a fault zone. Fault may slip freely to some depths and locked after to the bottom (URL-1).

NAF reported to have segments which shows aseismic creep until 1970: Ismetpasa and Destek, where the second site is a more recent discovery (Ambraseys 1970, Karabacak et al. 2011). Aseismic creep at the Ismetpasa reported to occur along ~70-80 km from Bayramoren at the east to the Gerede at the west. It was discovered at the wall of the Ismetpasa train station at 1970 and several minor and large scale studies monitored the area until then (Table 1). This segment hosts three destructive earthquakes (1943 Tosya M_w=7.2, 1944 Gerede M_w=7.2, 1951 Kursunlu M_w=6.9) that may have triggered or affect the creep (Şaroğlu ve Barka 1995, Cakir et al. 2005, Karabacak et al. 2011, Kaneko et al. 2013).

On the other side, creep at the Destek segment reported at 2003 on a field trip around the region. Unlike the Ismetpasa segment, number of researches at this segment is just a few, and also the length of this segment is unclear, but 1943 Tosya earthquake affected this area (Karabacak et al. 2011) (Table 2).

All the studies around these segments indicates the continuity of creep but the results are inconsistent and cannot clearly refer whether this event has an increasing trend or not. Most of the researches (Ambraseys 1970, Aytun 1982, Eren 1984, Altay&Sav 1991, Deniz et al. 1993, Kutoglu et al. 2008&2009&2013, Karabacak et al. 2011, Ozener et al. 2013, Bilham et al. 2016) generally are on a micro-scale and focused on the Ismetpasa or a network near this village with geodetic methods, while

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

others on a macro-scale with InSAR (Deguchi 2011, Fialko et al. 2011, Köksal 2011, Kaneko et al. 2013, Cetin et al. 2014, Kutoglu et al. 2013) which needs a ground truth (Fig 3).

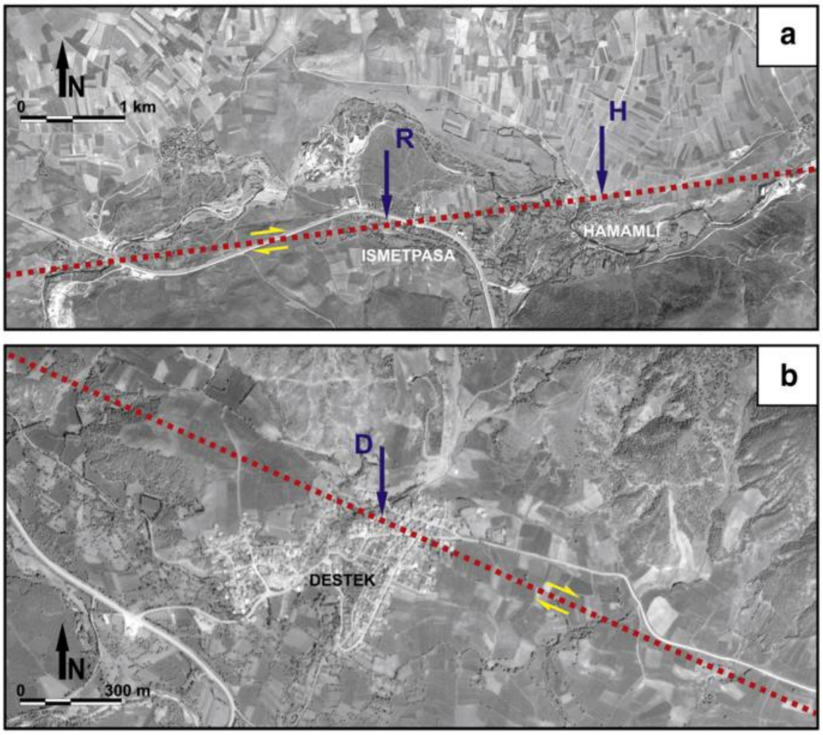

Figure 3. Reported aseismic creep zones at Ismetpasa (a) and Destek (b) segments from a recent study. (a) “R” shows creep observed at the wall at the Ismetpasa train station, and “H” shows the creep at Hamamli village. (b) “D” represents the reported creep at Destek town (from Karabacak et al. 2011).

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

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

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

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&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

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

Network Design Around the Creeping Segments

Designing a monitoring network around tectonic structures always related to the geological characteristics and fault geometry, which includes the locking and earthquake related motions (coseismic movements) through the fault. Previous studies indicate that the velocities for the stations distant from the fault plane can be used to derive long-term plate velocities, while nearby station velocities are suitable to detect the locking depth of a fault (Taskin et al. 2003, Halıcıoğlu vd. 2009). In addition, velocities of the observation stations gradually decrease when their locations approach to the fault plane. Another factor is the number of the stations and this is related to the fault length and wideness, but the station locations perpendicular to the fault plane must not exceed the (±1/√3) of the

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

Geoscientific Instrumentation Methods and Data Systems Discussions

locking depth. Also, some researches specify this limit to the double of the depth (Taskin et al. 2003, Kutoglu&Akcin 2006, Kutoğlu vd. 2009, Halıcıoğlu vd. 2009, Poyraz vd. 2011, Bohnhoff et al. 2016). For this purpose, the following equation is used in general to obtain to proper distances of the observation stations from the fault plane:

$$V(x) = \frac{V_T}{\pi}\arctan(\frac{x}{D}) \tag{1}$$

where:

- V : Fault parallel velocity
- V_T : Long term tectonic plate velocity
- x : Distance to fault plane
- D : Locking depth of the fault(Halıcıoğlu vd 2009).

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

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

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

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

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

Geoscientific Instrumentation Methods and Data Systems
Discussions

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

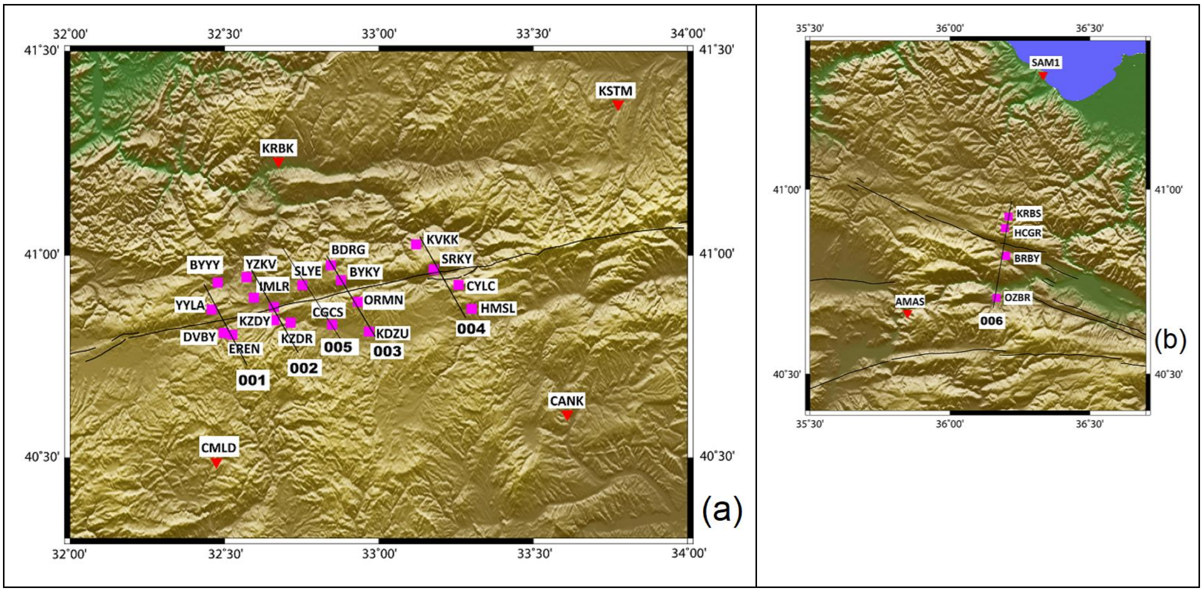

Figure 4. Planned profiles and campaign GPS stations(pink) at Ismetpasa(a) on the left and Destek(b) on the right. Profiles 001-004 planned and established on the Ismetpasa segment, and profile 005 added to the network using two suitable stations. Profile 006 is on Destek segment. Other continuous GPS sites (RTK CORS) shown in red(after Yavasoglu et al. 2015).

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

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

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

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

Profile number	Station ID	Site	Latitude (°)	Longitude (°)	Type of facility
001	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
002	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
005 (intermediate)	SLYE	Kapaklı Village	41.85	32.72	Pillar
	CGCS	D100 wayside	39.86	32.85	Pillar
003	BDRG	Boduroğlu Village	39.89	32.76	Bronze
	BYKY	Beyköy Village	40.83	32.85	Pillar
	ORMN	Forest	40.94	32.86	Bronze
	KDZU	Kadıözü Village	40.88	32.93	Pillar
004	KVKK	Kavak Village	40.81	32.97	Bronze
	SRKY	Sarıkaya Village	41.03	33.12	Bronze
	CYLC	Çaylıca Village	40.97	33.18	Bronze
	HMSL	Hacımusla Village	40.93	33.26	Pillar
006	KRBS	Korubaşı Village	40.82	36.20	Bronze
	HCGR	Hacıgeriç Village	40.71	36.17	Bronze
	BRBY	Borabay	40.90	36.20	Pillar
	OZBR	Özbaraklı Village	39.66	35.87	Pillar

After the first campaign, KZDY station was damaged and removed from rest of the project. Raw data collected for a minimum of 8 hours at each station for the rest of the project and evaluated with GAMIT/GLOBK software (Herring et al. 2015a, 2015b) at first, then the results used as input to block modelling software TDEFNODE (McCaffrey 2002, 2009). A total of 63 stations (22 campaign, 30 surrounding RTK CORS, 11 IGS) are used in this network to monitor Ismetpasa and Destek segments 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
AKDG	Yozgat	**FASA**	Ordu	**RDIY**	Tokat
AMAS	Amasya	**GIRS**	Giresun	**SAM1**	Samsun
ANRK	Ankara	**HEND**	Sakarya	**SIH1**	Eskişehir
BILE	Bilecik	**HYMN**	Ankara	**SINP**	Sinop
BOLU	Bolu	**IZMT**	İzmit	**SIVS**	Sivas
BOYT	Sinop	**KKAL**	Kırıkkale	**SSEH**	Sivas
CANK	Çankırı	**KRBK**	Karabük	**SUNL**	Çorum
CMLD	Ankara	**KSTM**	Kastamonu	**TOK1**	Tokat
CORU	Çorum	**KURU**	Bartın	**VEZI**	Samsun
ESKS	Eskişehir	**NAHA**	Ankara	**ZONG**	Zonguldak

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

GPS Data Evaluation

In this study, all campaign station observed between 2014-2016 for 3 campaigns and data were evaluated with GAMIT/GLOBK software. Also, GPS data for cGPS and IGS stations downloaded to cover every six month between August 2009-2016 to increase the stabilization at the GLOBK step. The networks linked to the ITRF 2008 global coordinate system by using surrounding IGS sites (Table 5) (Yavaşoglu et al. 2011, Herring et al. 2015a, 2015b). After the transformation with GLOBK, the root mean square (rms) of the stations was only 0.7 mm/year.

Table 5. IGS stations defined in the site.defaults file of GAMIT to constitute reference frame.

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

Results show that the velocity of the stations inside the Anatolian plate are gathering up to 15-20 mm/year (Fig 5), which is similar with the previous studies (McClusky et al. 2000, Reilinger et al. 2006, Yavaşoglu et al. 2011).

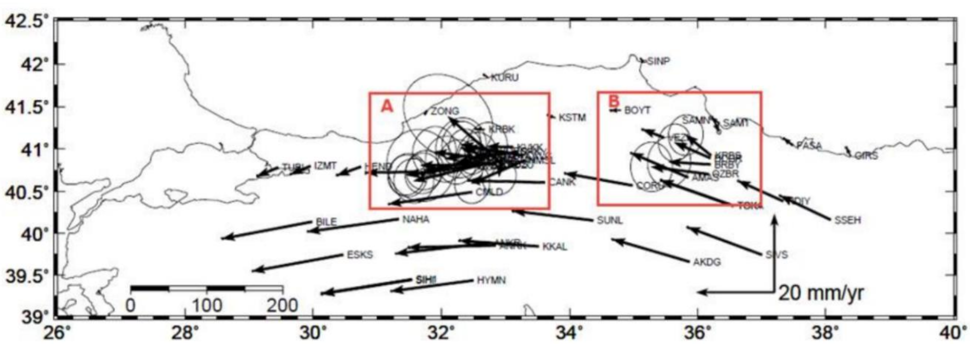

Figure 5. GLOBK results for station velocities when Eurasian plate selected as fixed. (A) includes the Ismetpasa segment, and Destek segment is inside (B). Velocities at the north of the NAF are very small as expected, where south velocities indicates the Anatolian plate's motion to the west (from Aladoğan 2017).

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

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

Table 6. All cGPS and campaign point velocities and location errors (uncertainties).

Station ID	Velocity(mm/yr)		Error		Station ID	Velocity(mm/yr)		Error	
	V_{EAST}	V_{NORTH}	V_{EAST}	V_{NORTH}		V_{EAST}	V_{NORTH}	V_{EAST}	V_{NORTH}
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

https://doi.org/10.5194/gi-2019-24
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Geoscientific Instrumentation Methods and Data Systems Discussions
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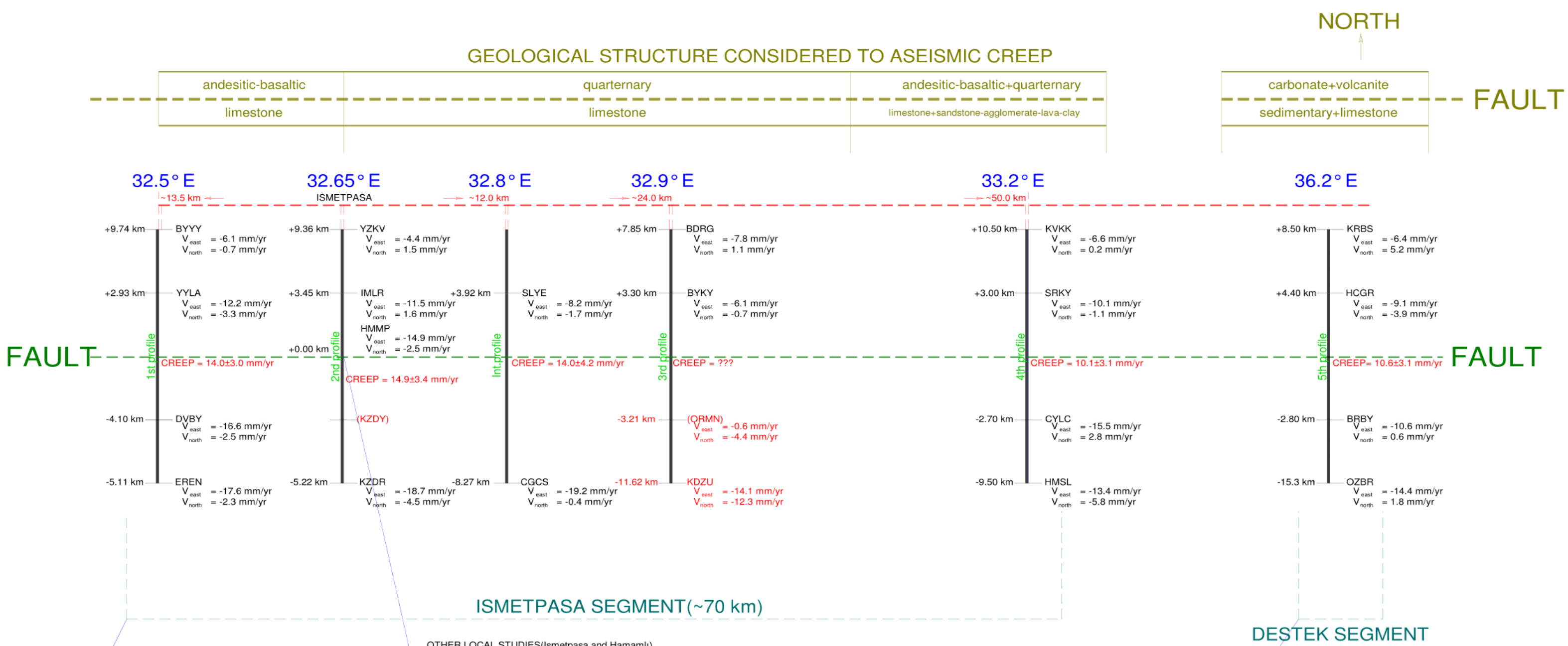

OTHER STUDIES(Ismetpasa segment)

STUDY/YEAR/METHOD	CREEP RATE(mm/year)
Cakir et al., 2005(InSAR)	8.0±3.0
Deguchi, 2011(PALSAR)	14.0
Fialko et al., 2011(PALSAR)	10.0
Köksal, 2011(DInSAR)	15.7±2.0
Kutoglu et al., 2012(InSAR)	12.5±2.0
Kaneko et al., 2013(InSAR)	9.0±2.0
Cetin et al., 2014(InSAR)	8.0±2.0

OTHER LOCAL STUDIES(Ismetpasa and Hamamlı)

STUDY/YEAR/METHOD	CREEP RATE(mm/year)
Ambraseys, 1970(wall offset measurements)	20.0±6.0
Ambraseys, 1970(revision)*	10.4±0.4
Aytun, 1982(triangulation)	11.0±1.1
Aytun, 1982(photo-evaluation)	15.0
Aytun, 1982(revision)*	10.45±0.35
Eren, 1984(triangulation)	10.0±4.0
Altay&Sav, 1991(creepmeter)	7.6±1.0
Deniz et al., 1993(triangulation)	9.3±0.7
Kutoglu&Akcin, 2006(GPS)	7.8±0.5
Kutoglu et al., 2008(GPS)	12.0±1.1
Kutoglu et al., 2010(GPS)	15.1±4.1
Karabacak et al., 2011(Ground LIDAR)[1.area]	6.8-10.0±4.0
Karabacak et al., 2011(GroundLIDAR)[2.area]	9.1-10.1±4.0
Kutoglu et al., 2012(GPS)	13.0±2.0
Görmüş, 2011(GPS)	13.0±3.9
Ozener et al., 2013(GPS)	7.6±1.0
Bilham et al., 2016(creepmeter)	6.1±0.2

(* : According to the Bilham et al., 2016)

OTHER LOCAL STUDIES(Destek)

STUDY/YEAR/METHOD	CREEP RATE(mm/year)
Karabacak et al., 2011(Ground LIDAR)	6.0-7.2±4.0
Fraser et al., 2009(Trench study)	6.0

Figure 6. 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)

177

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

Geoscientific Instrumentation Methods and Data Systems
Discussions
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Aseismic creep ratio estimated by interpolation through the profiles using surface velocities except the 3rd profile (Table 7). At the Ismetpasa segment, repeatability of the ORMN and KDZU stations indicates abnormal deformation. Therefore, creep estimation for that profile unfeasible. Actually, this is not a drawback for block modelling, because the remaining station velocities are all used to model the region uneventfully.

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

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

Block Modelling

Station velocities are suitable to predict surface and block motions around them locally. On the other hand, observations inside the blocks provide adequate long-term block velocities and rotations with high precision. Blocks generally demonstrate a regular movement, but their motion differ at their boundaries from this overall velocity. They cannot move freely around the faults because of the friction of rocks, generally infer underspeed, may down to none (Fig 7). This difference in the velocity is called “slip deficit”, and causes earthquakes after the friction threshold surpasses (Kutoglu&Akcin 2006, McCaffrey 2014, Yavasoglu et al. 2015).

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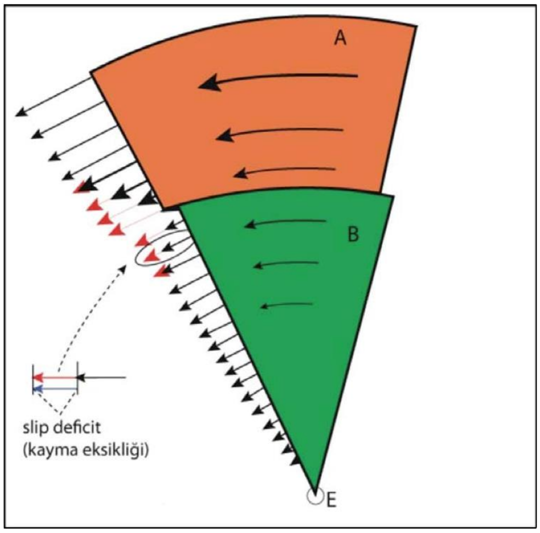


Figure 7. Motions of tectonic blocks around the same Euler pole and slip deficit at their boundaries. Long-term block velocities evolve at the fault zones and gap between them is responsible for strain accumulation and earthquakes (from Cakmak 2010).

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

Basic input for the software includes GPS velocities, blocks with Euler poles, user's fault geometry prediction and locking depth, generally acquired after seismic researches. Interacting blocks represented as elastic blocks and assumed to have elastic deformation because of their rotation around Euler poles. All of the defined system assumed to float inside a half-space where one of the blocks is fixed and have zero strain or movement. Fault geometry defined by the user with nodes, and their locking ratios (phi) can be defined manually or as a function of depth (Fig. 8). Then, the software predicts the underground velocities based on the routines of *Okada* (1985), and estimates the surface velocities according the defined values. Fault geometry estimation is the key feature to minimize the difference between observed and predicted surface velocities with the help of χ^2 test result, which represents the accuracy of the entire model (McCaffrey 2002, Aktuğ ve Çelik 2008, Yavasoglu et al. 2011).

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

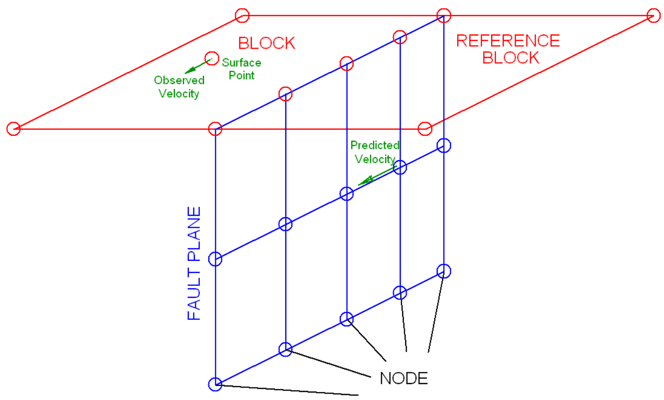


Figure 8. Fault plane geometry defined to the control file of TDEFNODE. Nodes divides the fault plane into sub-regions to defined depths and their locking ratio may differ from each other.

TDEFNODE can be 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. This allows user to define the fault plane with layers by using depth contours, and to predict the fault plane if these layers are partially or fully locked (Url-2).

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 and an interseismic movement. Thus, the observation network around the fault plane should be planned carefully regarding the ±3-10 km station locations mentioned before (Fig 9).

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

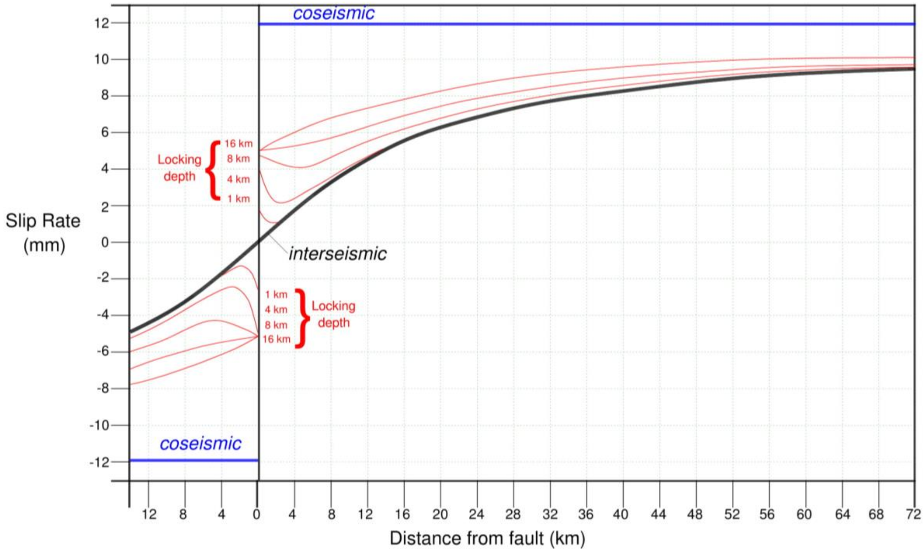


Figure 9. Slip rate along a fault plane during interseismic and coseismic events. Blue lines represents the coseismic, and black line represents the interseismic behaviour, where red lines demonstrates the aseismic creep ratios at two sides of the fault for different locking depths (after Yavasoglu et al. 2015).

Figure 9 demonstrates the suitable distances to detect aseismic creep. If an aseismic creep suspected on a fault plane, then the optimum locations for the observation stations should be around 3 and 10 km on both sides of the fault, and can be resolved from the interseismic movements. Therefore, observation stations, mentioned before, established around the fault as profiles to detect this discrepancies, and to detect the main locking depth of the fault and attenuation depths for the creep event. Their locations are suitable to evaluate both creeping ratios and locking depths of the faults.

Discussion

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

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

Geoscientific Instrumentation Methods and Data Systems
Discussions

Inspected segments' special features revealed by the network established near the fault plane. Regarding the surface velocities of the observation points, profiles on both Ismetpasa and Destek segments indicates movements. This ranges between 10.1-14.9 mm/year and 10.6 mm/year for Ismetpasa and Destek segments, respectively.

On the other side, modeled fault plane evaluation for observed and calculated station movements demonstrates similar results with the locking depths of the both creeping and seismogenic layers (Fig. 10). Station velocities on the south of the NAF faster than the north-end as expected (Fig. 11). Regarding the long-term geodetic block motions, modeled weighted locking ratios indicates a 13.0±3.3 mm/year of aseismic creep all over the Ismetpasa segment. This movement does not include the whole fault plane, thus the creeping layer seems to slip freely to 4.5 km depths from the surface and decays between 4.5-6.75 km. The seismic data and previous studies (Cakir et al. 2005, Yavaşoğlu et al. 2011, Hussain et al. 2019) indicates the locking depth all over the fault as ~15 km. This result demonstrates the fully locked portion of the fault plane is between 6.75-15 km, which supported by the χ^2 test result.

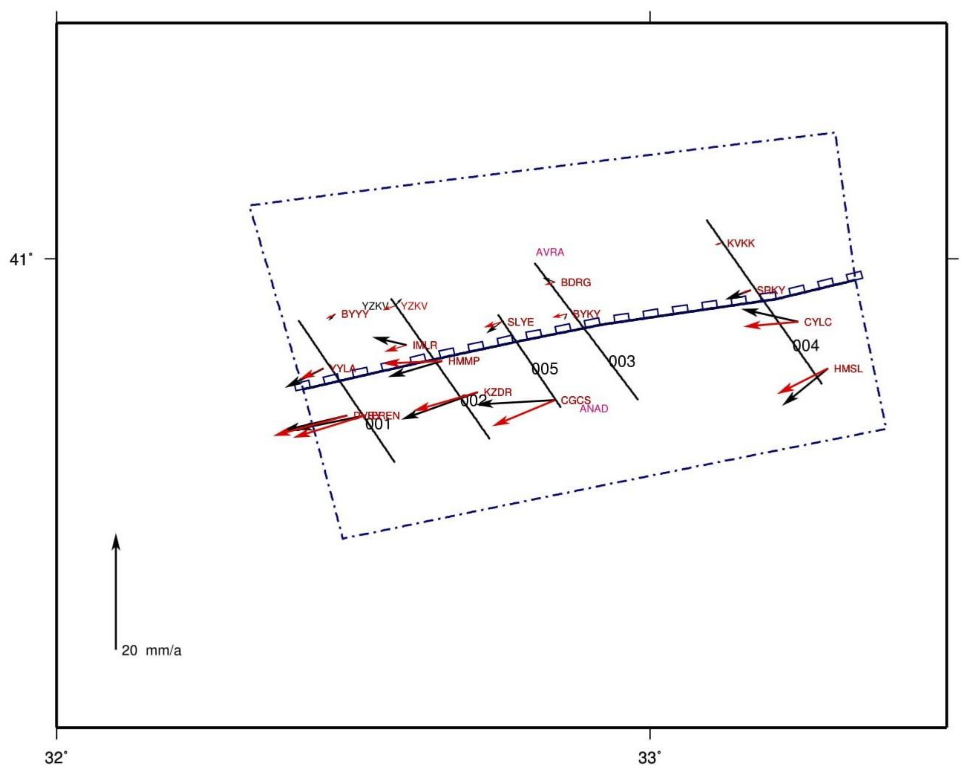


Figure 10. Model area for Ismetpasa segment with Eurasian plate (AVRA) on the north and Anatolian plate (ANAD) on the south (dashed lines), divided by the creeping segment of the NAF. Black and red arrows represent the observed and modeled velocities respectively, obtained from GAMIT/GLOBK

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

and TDEFNODE. Five profiles are numbered from west to east with 001 to 004, where 005 represents the intermediate profile established during the 1st campaign. Two stations (SLYE and CGCS) on the south-end of the profile 003 removed from the model due to unexpected velocities.

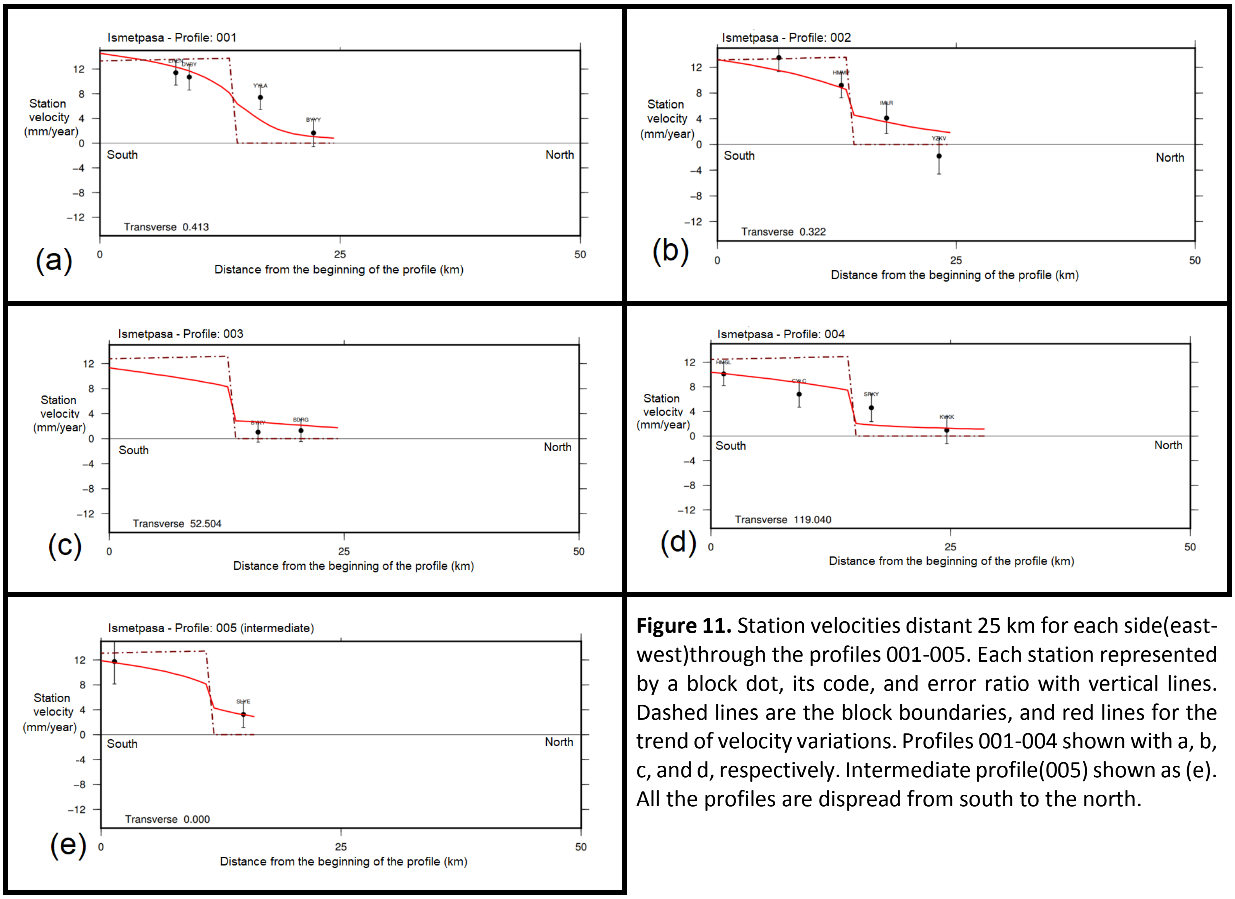
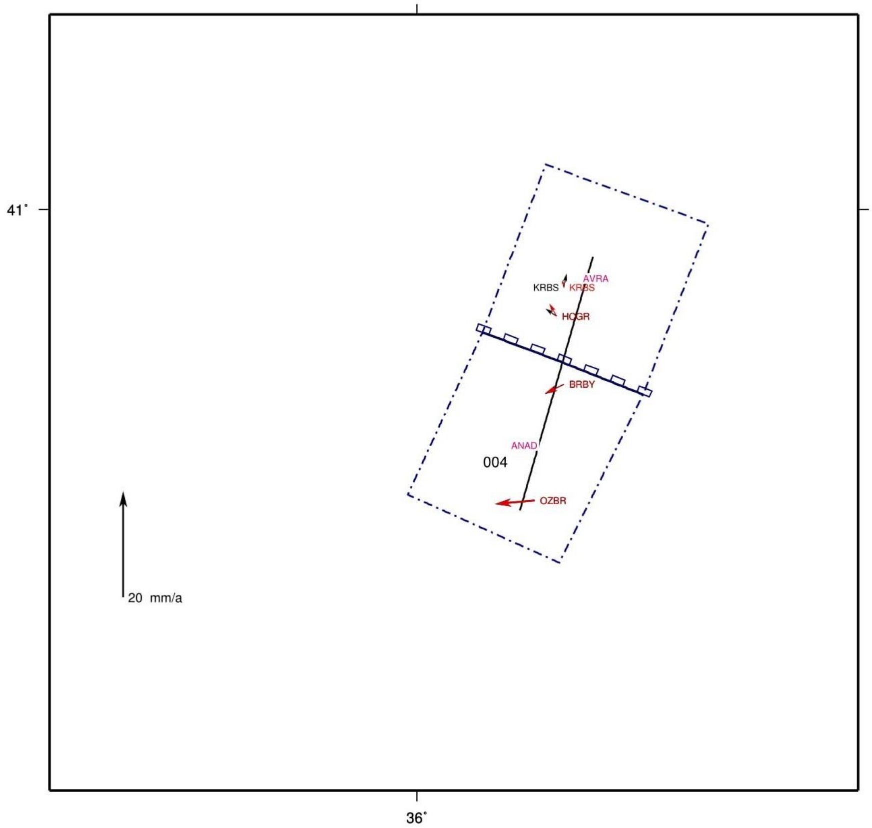


Figure 11. Station velocities distant 25 km for each side(east-west)through the profiles 001-005. Each station represented by a block dot, its code, and error ratio with vertical lines. Dashed lines are the block boundaries, and red lines for the trend of velocity variations. Profiles 001-004 shown with a, b, c, and d, respectively. Intermediate profile(005) shown as (e). All the profiles are dispread from south to the north.

Destek segment also have similar results for the observed and modeled velocities (Fig 12). The surface velocities for the profile (006) at this region indicates velocity differences (Fig 13). On the other hand, modeled fault plane indicates the creeping segment to 4.3 km depths and decays linearly between 4.3-6.0 km. The remaining layer of the part seems to be fully locked down to the seismogenic layer. Free slipping portion have a 9.6 mm/year which is similar with the estimated surface velocities (10.6±3.1 mm/year). The χ^2 test result and the seismic data confirms the accuracy of the model.

Geoscientific Instrumentation Methods and Data Systems
Discussions



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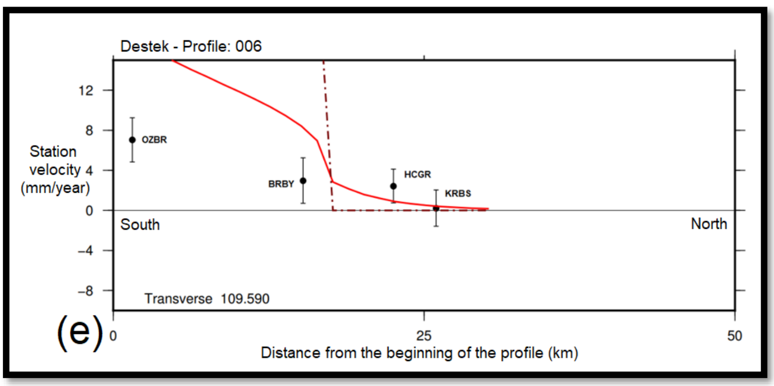
279 **Figure 12.** Model area for Destek segment with Eurasian plate(AVRA) on the north and Anatolian
280 plate(ANAD) on the south(dashed lines), divided by the creeping segment of the NAF. Black and red
281 arrows represent the observed and modeled velocities respectively, obtained from GAMIT/GLOBK
282 and TDEFNODE. 004 represents the profile in the area.



283

284 **Figure 13.** Station velocities and profile (006) for the Destek profile. Each station represented by a
285 block dot, its code, and error ratio with vertical lines. Dashed lines are the block boundaries, and red
286 lines for the trend of velocity variations. Profile dispread from south to the north.

https://doi.org/10.5194/gi-2019-24
Preprint. Discussion started: 2 October 2019

On the other hand, Paleomagnetic data indicates a predominantly clockwise rotation of the blocks bordered by the faults between Ismetpaşa and Destek segments. Examining the results with this study promotes this behaviour with the GPS field of the region, especially on the Anatolian side of the NAF (Figure 10&12) (İşseven & Tüysüz, 2006).

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

Conclusion

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

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

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

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

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

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