Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. **12**, 2003, pp. 55-65. *Copyright ©TÜBİTAK*

Monitoring the Kinematics of Anatolia Using Permanent GPS Network Stations

ONUR LENK[1], ALİ TÜRKEZER[1], SEMİH ERGİNTAV[2],
ALI İHSAN KURT[1] & ALPAY BELGEN[2]

[1] Geodesy Department, General Command of Mapping, TR-06100 Ankara, Turkey
[2] Scientific and Technical Research Council of Turkey, Marmara Research Centre, Earth and Marine Sciences Research Institute, Gebze, TR-41470 Kocaeli, Turkey (e-mail: Semih.Ergintav@posta.mam.gov.tr)

Abstract: The establishment and promotion of three-dimensional geodetic networks supported by continuous Global Positioning System (GPS) data are capable of yielding valuable data in order to enable regional realisation of the International Terrestrial Reference Frame (ITRF) and monitor deformation of the lithosphere. Providing 24-hour continuous data in connection with International GPS Service (IGS) global stations, the Turkish Permanent GPS Network (TPGN) was established in 1999. The main goal of establishing these network stations is to provide adequate information on such an active area, where the collision between African, Arabian and Eurasian plates is occurring. An additional aim is continuous monitoring by TPGN and Marmara Region Continuous GPS Network (MAGNET) sites, for secular variations in the positions of the stations and for the abrupt changes in their positions associated with earthquakes, as were observed during and after the 17 August 1999 İzmit (M_w=7.4) event, to give information on the coseismic deformation field and on postseismic processes. At this preliminary stage in TPGN and MAGNET data analyses, horizontal velocity values have been obtained in the ITRF96 reference frame and have been used to constrain the interseismic velocity field in the region. This analysis includes 900 days beginning from the 230th day of 1999 (18 August) (after the İzmit earthquake) until the end of 2001. In this paper, the TPGN is introduced to the Earth Science community. Its data analysis strategy and results from preliminary analysis of inter-seismic velocities of TPGN stations are also demonstrated and interpreted.

Key Words: permanent GPS networks, Anatolia, coseismic deformation, postseismic deformation

Sabit GPS İstasyonları ile Anadolu Kinematiğinin İzlenmesi

Özet: Sürekli Küresel Konumlama Sistemi (GPS) verileri ile destekli üç boyutlu jeodezik ağların kurulması ve geliştirilmesi, Uluslararası Yersel Referans Sistemi (ITRF) nin bölgesel olarak gerçekleştirilmesi ve litosferdeki deformasyonun izlenmesi kapsamında değerli bir veri grubu sağlamaktadır. Bu çalışmaların ülkemizdeki uzantısı olarak Uluslararası GPS servisinin küresel noktaları ile bağlantılı her gün sürekli olarak 24 saat veri sağlayan Türkiye Sabit GPS İstasyonları (TPGN) 1999 yılında kurulmuştur. Bu ağın kurulmasındaki temel hedef, Afrika, Arap ve Avrasya plakalarının çarpıştığı aktif bir alanda sürekli deformasyonları gözleyerek bölgenin kinematiğini anlamaktır. TPGN ve Marmara Bölgesi Sürekli GPS Ağı (MAGNET) istasyonları ile sürekli izleme faaliyetlerine ilave olarak, nokta konumlarındaki seküler değişimlerin 17 Ağustos 1999 İzmit (M_w=7.4) depremi sırasında ve sonrasındaki kosismik deformasyon alanı ve postsismik sürece yönelik bilgilerin ortaya çıkarılmasında çalışılmıştır. TPGN ve MAGNET verilerinin analizlerinde ilk aşamada ITRF 96 referans sisteminde yatay hız değerleri hesaplanmış ve bunlar bölgenin intersismik hız alanının tanımlanmasında kullanılmıştır. Analizler, 1999 yılının 230'ncu (18 Ağustos) itibaren başlatılmış olup, İzmit depreminden sonra 2001 yılının sonuna kadar 900 günü kapsamaktadır. Bu çalışmada, Yer Bilimleri topluluğuna TPGN tanıtılmakta ve TPGN noktalarının intersismik hızlarına yönelik yapılan analizlerin ilk sonuçları verilerek yorumlanmaya çalışılmaktadır.

Anahtar Sözcükler: Sürekli GPS ağı, Anadolu, kosismik deformasyon, postsismik deformasyon

Introduction

The Eastern Mediterranean/Middle East region has been identified as an excellent natural laboratory for studying the kinematics of plate interactions. The tectonic framework of the region is dominated by the collision of the Arabian and African plates with Eurasia (McClusky *et al.* 2000) as shown in Figure 1. Such active relative motions have necessitated efforts to monitor the deformation of the area by setting up a continuously operating permanent GPS stations in real and/or near real time.

Permanent GPS analysis is a valuable tool for Earth Sciences. Spectral noise analysis of time series, which are obtained from daily based positions of GPS sites (Calais 1999; Zhang *et al.* 1997; Mao *et al.* 1999), and the principal strain accumulation from the interseismic velocities (Sagiya *et al.* 2000) are the most common fields of interest for the analyses of continuous time series, in cases where no abrupt changes have occurred in time series due to earthquakes. Of course, the quality of this spectral analysis depends on the availability of long-term observations, while the quality of stress accumulation maps depends on the density of the distribution of permanent GPS networks.

Coseismic deformation patterns, which provide information about the mechanics of earthquakes, and postseismic time-dependent deformations, which provide information about the rhelogy of the fault zone and surrounding crust, can also be obtained in cases where earthquakes occur, from the continuous time series recorded by dense permanent GPS networks (Ayhan *et al.* 2001; Ergintav *et al.* 2002).

The General Command of Mapping (GCM) has considered the requirement of continuously tracking GPS stations in Turkey for monitoring tectonic activity, given the outcomes obtained from its campaign-based GPS projects held periodically since 1988. The basic motivation behind such a plan is very similar to that of the world's existing permanent arrays considering the high rates of regional and local deformation caused by inter-plate motion between the African, Arabian and Eurasian plates.

Other requirements for establishing permanent stations are based on both off-line and real time data

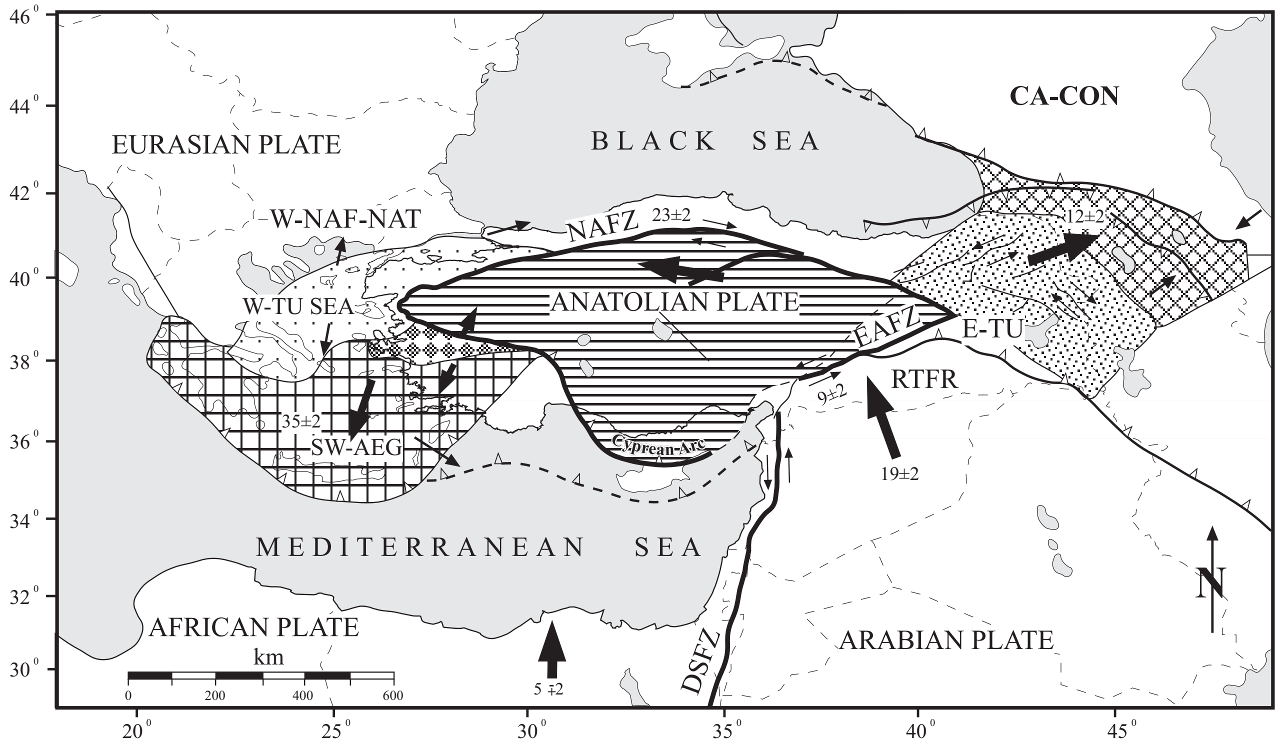

Figure 1. Kinematics of Turkey and surrounding area. Hatched areas show the coherent motion of specific zones of deformation. Heavy arrows indicate the generalised regional motions in mm/yr (after McClusky *et al.* 2000).

availability, imposed by global, regional geodetic and local survey activities. Therefore, the aims of continuously operating stations may be specified as follows:

(a) Data contribution for the global network of permanent stations [e.g., the International GPS Service (IGS), etc.], enabling the realisation of reference systems in the International Terrestrial Reference Frame (ITRF).

(b) Monitoring of local and regional crustal deformation, enabling earthquake prediction and hazard assessment.

(c) Controlling the height system and monitoring sea-level changes by tide-gauge fixing between the Turkish National Fundamental GPS Network (TNFGN) and Turkish National Sea-Level Monitoring Network (TNSMN) stations.

(d) Enabling the integration and connection efforts of the European Reference Frame (EUREF) and the European Vertical Network (EUVN) with National Geodetic Control Networks.

(e) Provision of raw and/or suitably formatted data for other Earth Science research, local cadastral surveys, and Geographic Information System (GIS) activities in both real and near real time, including transmitting Differential GPS (DGPS) corrections through some specific stations with suitably equipped hardware.

Considering these aims, the GCM, as the government institution responsible for geodetic activities in Turkey, initiated the Turkish Permanent GPS Network (TPGN) project in 1999. The preliminary aim of the TPGN is to establish about 16 stations throughout Turkey. The ultimate goal is to install 50 stations, with emphasis on areas with a high rate of crustal deformation. The primary issues dictating site selection are:

(a) Monitoring the complex regime of secular (semi-constant) and episodic (earthquake) crustal motions and aseismic deformations (fault creep) within Anatolia.

(b) Enabling a relatively even distribution to accommodate the increasing demand for dependable, spatially referenced data within the existing control networks: TNFGN and TNSMN.

In the following sections, we first define the present status of the TPGN. We then discuss its data processing strategy and demonstrate secular information relevant to the interseismic velocity field of the network following the last big İzmit (17 August, 1999) and Düzce (12 November, 1999) earthquakes.

The Present Status of the TPGN

The locations of the existing and planned TPGN stations are shown in Figure 2. Being the first permanent global station in Turkey under IGS, the Ankara Permanent GPS Station (ANKR) has been operating since 1991, serving as master station in all GPS geodetic activities worldwide. This station has been operated by the GCM with a receiver provided by Bundesamt Kartographie und Geodasie (BKG). The same institution has provided İstanbul Technical University (İTÜ) and Karadeniz Technical University (Trabzon-KTÜ) with two receivers, which have been operational since 1999. The Marmara Region Continuous GPS Network (MAGNET), a relatively dense network around the Marmara Sea, operated by the Scientific and Technical Research Council of Turkey (TÜBİTAK), Marmara Research Centre, Earth and Marine Sciences Research Institute (EMSRI), was established in 1998–99 (Figure 3). The Gebze (TUBI) and Erdek (ERDT) stations of MAGNET are also incorporated into the TPGN. As part of a collaboration between the GCM, the Massachusetts Institute of Technology (MIT), the University NAVSTAR Consortium (UNAVCO) and Dicle University, the DYR2 (formerly DYAR) station has been operational in Diyarbakır since 1997. As part of the same cooperation, the Erdemli (MERS) site has been operated since 2000 by the Middle East Technical University Institute of Marine Sciences and GCM. Currently in their installation phase, the ANTA and BUCA sites at Antalya and İzmir, respectively, will begin to collect data in 2003. A summary of the TPGN stations with their collaborators is given in Table 1.

TPGN data are collected with various types of receivers. However, the antennas are of the choke-ring design, with precisely defined phase centre offsets and antenna reference points (ARPs). A summary of receiver and antenna information for the TPGN is given in Table 2.

Beginning in late 1999, the data from these stations have contributed to analyses performed by the GCM on a daily basis to fulfil some of the above requirements synchronised with IGS operations, their standards and specifications. All data transfers take place over the Internet and the national integrated communication

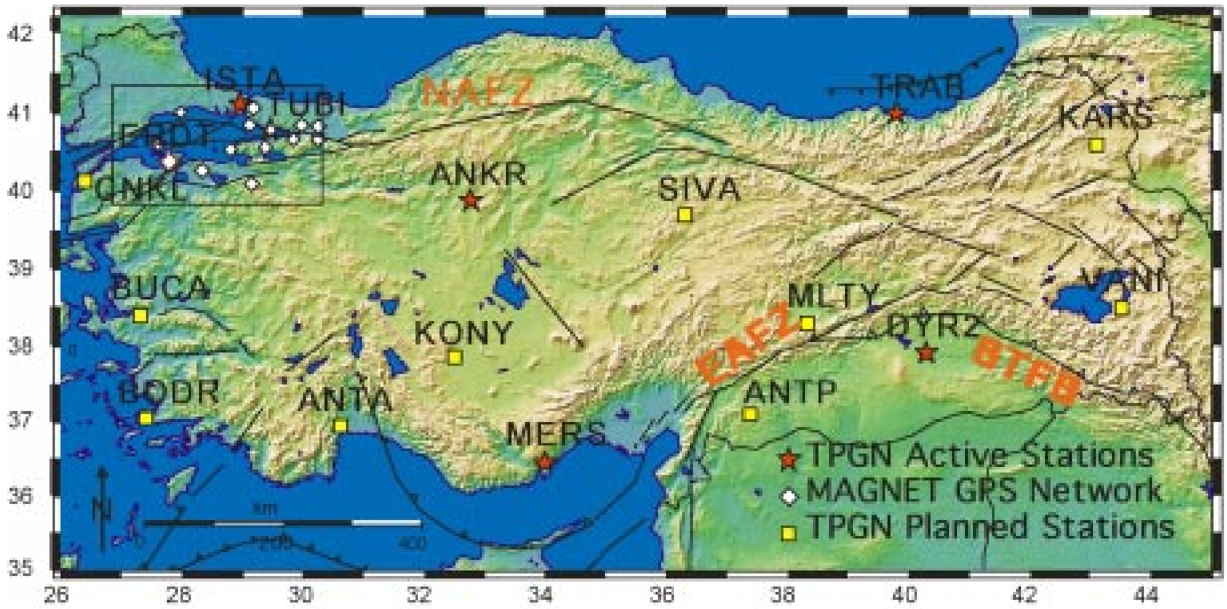

Figure 2. Turkish Permanent GPS Network (TPGN). Those sites marked with red stars are operational and others where yellow squares are the sites to be established in 2002, 2003 and 2004.

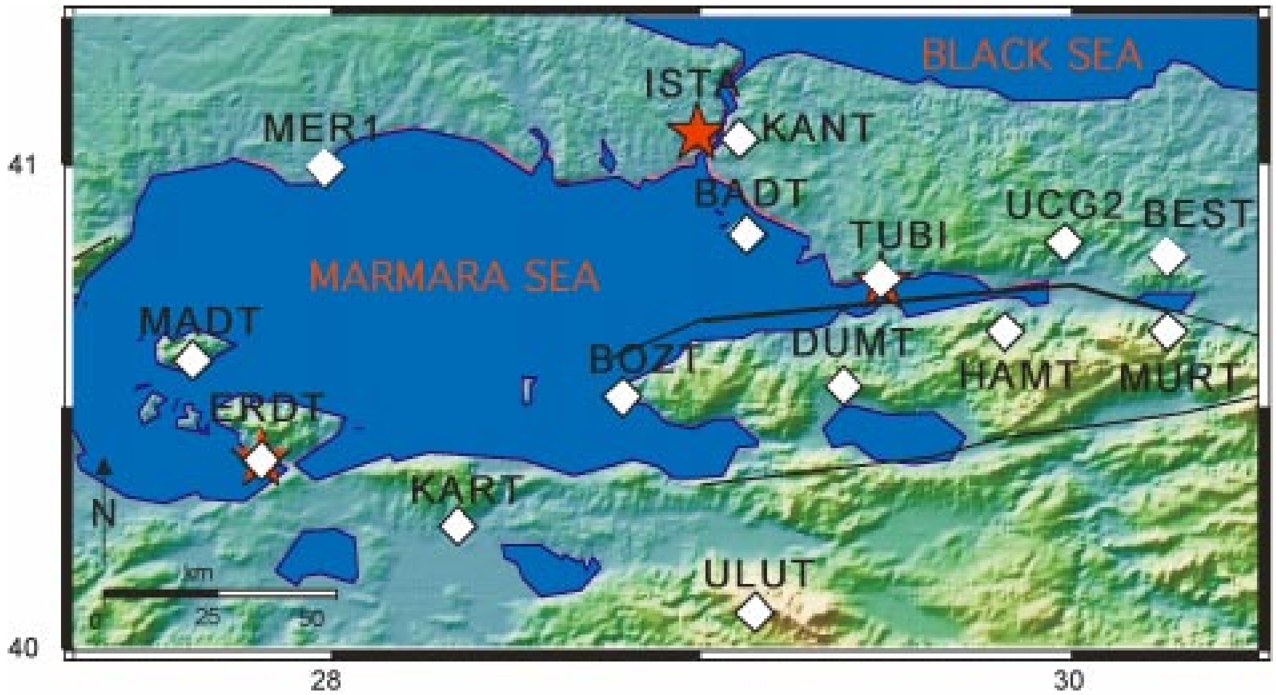

Figure 3. The site distribution of the Marmara Region Continuous GPS Network (MAGNET) of EMSRI.

Table 1. Permanent tracking sites currently providing data for TPGN: (* In installation phase; ** Planned in 2003; Sites to be installed in 2004 are not included).

SITE	NAME	ESTABLISHMENT DATE	LOCAL RESPONSIBLE AGENCY	COLLABORATING AGENCY
Ankara	ANKR	1991	GCM	BKG
Diyarbakır	DYR2	1997	GCM/Dicle University	MIT/UNAVCO
Gebze	TUBI	1998-1999	EMSRI	EMSRI
İstanbul	ISTA	1999	İTÜ	BKG
Trabzon	TRAB	1999	KTÜ	BKG
Mersin/Erdemli	MERS	2000	METU/GCM	MIT/UNAVCO
İzmir/Buca	BUCA	2002 *	Dokuz Eylül University/GCM	MIT/UNAVCO
Antalya	ANTA	2002 *	Akdeniz University/GCM	MIT/UNAVCO
Erdek	ERDT	2002	GCM/EMSRI	GCM/EMSRI
Sivas	SSGİ	2003 **	GCM	GCM
Malatya	MSGİ	2003 **	GCM	GCM
Kars	KAGİ	2003 **	GCM	GCM

Table 2. Receiver and antenna information for TPGN sites.

RECEIVER TYPE	ANTENNA MODEL	TPGN SITES
Turbo Rogue SNR 8000	AOA/Dorne Margolin T	ANKR, MERS, DYR2
Trimble 4700	TRIM29659.00 D_M	TUBI
Ashtech Z-XII3	ASH700936D_M	ISTA, TRAB
Leica Cors 1500	AT504 IGS T Choke Ring	BUCA, ANTA
Trimble 4000 SSI	TRIM29659.00 D_M	ERDT

system through the GCM, and the data are archived in the existing GPS database.

Data Analyses

Data already collected from six permanent GPS stations have been processed on a daily basis using the standard GAMIT/GLOBK GPS processing software (Herring 2000; King & Bock 1998). IGS final orbits and International Earth Rotation Service (IERS) Earth Orientation Parameters (EOP) Bulletin B values have been used, and a set of IGS stations covering the region was included in the analysis to establish a link between the regional and the global solutions. The regional station coordinates, satellite state vectors, and 12 tropospheric zenith delay parameters per site for each day are estimated with the phase ambiguities using doubly differenced phase observations. Loose constraints were applied for the regional and global sites, while relatively tightly constrained IGS final orbit and IERS Bulletin B, Universal Time (UT1) parameters were used in the processing. The processing options, dynamic model and reference system parameters used in these GAMIT analyses are given in Tables 3 & 4.

Having finished the GAMIT stage, regional daily solutions have been combined with the global solutions performed by the Scripps Orbit and Permanent Array Centre (SOPAC). The reference frame was constrained for each day by minimising the position and velocity of a reliable set of IGS stations with respect to a no-net-

Table 3. The dynamic model used in continuous analyses of permanent sites in Turkey.

Gravity Field	GEM-T3
Solid Earth Tides	IERS Second Degree Coefficients including frequency-dependent K1 component (IERS Technical Note: 3).
Ocean Tides (Station Displacement only)	Hans-Georg Scherneck Model of Onsala Space Observatory (IERS Technical Note 21).
Sun Radiation Pressure	The 9-parameter model developed by AIUB.
3rd Body Effects	Numerically integrated orbits of the Earth and Moon from the (10-body) planetary ephemeris of the Harvard-Smithsonian Centre for Astrophysics.

Table 4. The reference system information in data processing.

Station Positions	ITRF96
Earth Rotation Parameters	IERS Final B Bulletin
CIO	mean equinox and Equator J2000
Precession and Nutation	IAU 1976, Nut. Series
Tidal Uplift	applied
Pole Tide	applied
Ocean Loading	not applied
Atmospheric Pressure Loading	not applied

rotation (NNR) frame of the International Terrestrial Reference Frame (ITFR96) (Boucher *et al.* 1998), while estimating the translation, orientation and scale parameters for each day with the origin fixing module (GLORG) of GLOBK. All results of our analysis will be presented in ITRF96 to compare them with global solutions [e.g., products of the International GPS network (IGS)]. For the detailed analysis of any specific tectonic region, a local reference frame can be used. For example, the European reference frame can be used to analyse the deformation fields on the strands of the North Anatolian Fault Zone (NAFZ) in the Marmara region. In this case, the velocities should be minimised, relative to the particular GPS sites that represent velocities of parts with the Eurasia plate (McClusky *et al.* 2000).

Five MAGNET sites were operational before the İzmit earthquake. Because of the rapid deployment of new sites to monitor postseismic deformations following the İzmit earthquake within the MAGNET, nine MAGNET sites were operational at the time of the Düzce earthquake. We did not remove the coseismic steps from time series of the İzmit earthquake using a coseismic deformation model (e.g., Reilenger *et al.* 2000), since our process started on the day following the 18 August earthquake (day of year 230 in 1999). However, the coseismic steps on the time series caused by the Düzce earthquake were removed using a model coseismic deformation pattern (Ayhan *et al.* 2001). To exclude the dominant phase of exponentially decaying postseismic deformation following the İzmit earthquake, we removed the first 100 days after this earthquake from the time series to estimate a reliable set of interseismic linear velocities for the stations. For example, this postseismic effect can be clearly seen on the north and east components of TUBI, DUMT and KANT of the MAGNET in Figure 5. A detailed analysis of the postseismic deformations at MAGNET sites is given in Ergintav *et al.* (2002). No postseismic effects of the Düzce earthquake were observed in our network within its range during data processing and so we did not apply any correction to eliminate them. The total number of days processed is given in Figure 4, and two-dimensional time series of station positions are shown in Figure 5. Error bars represent the 1-sigma deviations of the daily solutions produced by the daily GLOBK combinations. The RMS values represent the weighted RMS scatters of the time series after eliminating the linear trend.

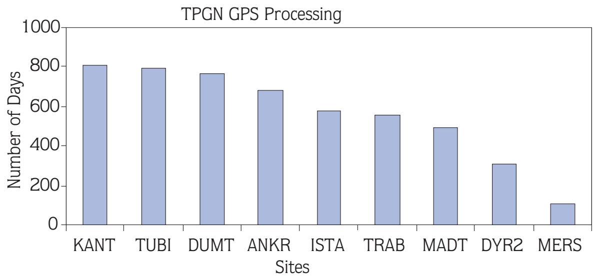

Figure 4. Data availability in terms of total number of days.

A two-year time span is the minimum required to obtain reliable velocities for continuous GPS stations (Calais 1999). Some of our sites thus do not have sufficient data yet to effectively represent the interseismic behaviour of the sites (Figure 4). Interseismic deformation inferred from the site velocities can be estimated by weighted linear regression (1-D) or simultaneous adjustment (2-D or 3-D) of repeated GPS position measurements (Zhang *et al.* 1997). These two solutions are similar at the 95% confidence level with very small velocity residuals (Calais 1999). We calculated the GPS velocities with 3-D simultaneous adjustment of time series to obtain the interseismic velocities for each component, based on our GLOBK solutions. These interseismic velocities were mapped in Figures 6 & 7 for selected network stations.

Because of the white noise assumption for noise characterisation on the time series analysis, the formal uncertainties of the velocities estimated from these time series are not realistic. In fact, the noise component on these time series has nonlinear behaviour. If we use nonlinear noise models like fractal noise, site velocity uncertainties should be 2–4 times larger than uncertainties obtained assuming purely a white noise model (Zhang *et al.* 1997). In our analysis interval, we do not yet have enough time spans to generate a fractal noise model for each site, based on spectral analysis of time series. However, this research is ongoing and results will be generated to show the quality of velocity estimations when we have a minimum of two year observations for each site in the TPGN.

When we compare the interseismic velocities in Table 5 with the pre-earthquake interseismic velocities (McClusky *et al.* 2000) in the epicentral area of the İzmit and Düzce earthquakes, we find that the present-day secular velocities show small differences in magnitude and azimuth relative to pre-earthquake velocities. This difference reflects the continuation of the postseismic deformation and indicates increasing strain and thus seismic risk in the region. To further localise the strain accumulation on the strands of the NAFZ, efforts to increase the number of MAGNET sites are continuing.

The observed continuation of effects of the İzmit and Düzce earthquakes after two years shows that all interpretation about future seismic risk estimation should be re-interpreted based on the results of the TPGN and MAGNET. Some postseismic models have been generated by GPS site velocities to understand the result of strain accumulation on fault strands and the crustal response to tectonic loading (e.g., Bürgmann *et al.* 2002; Ergintav *et al.* 2002). To validate these models and better understand the seismic risk in the region, we need long-term uninterrupted monitoring with the TPGN and MAGNET.

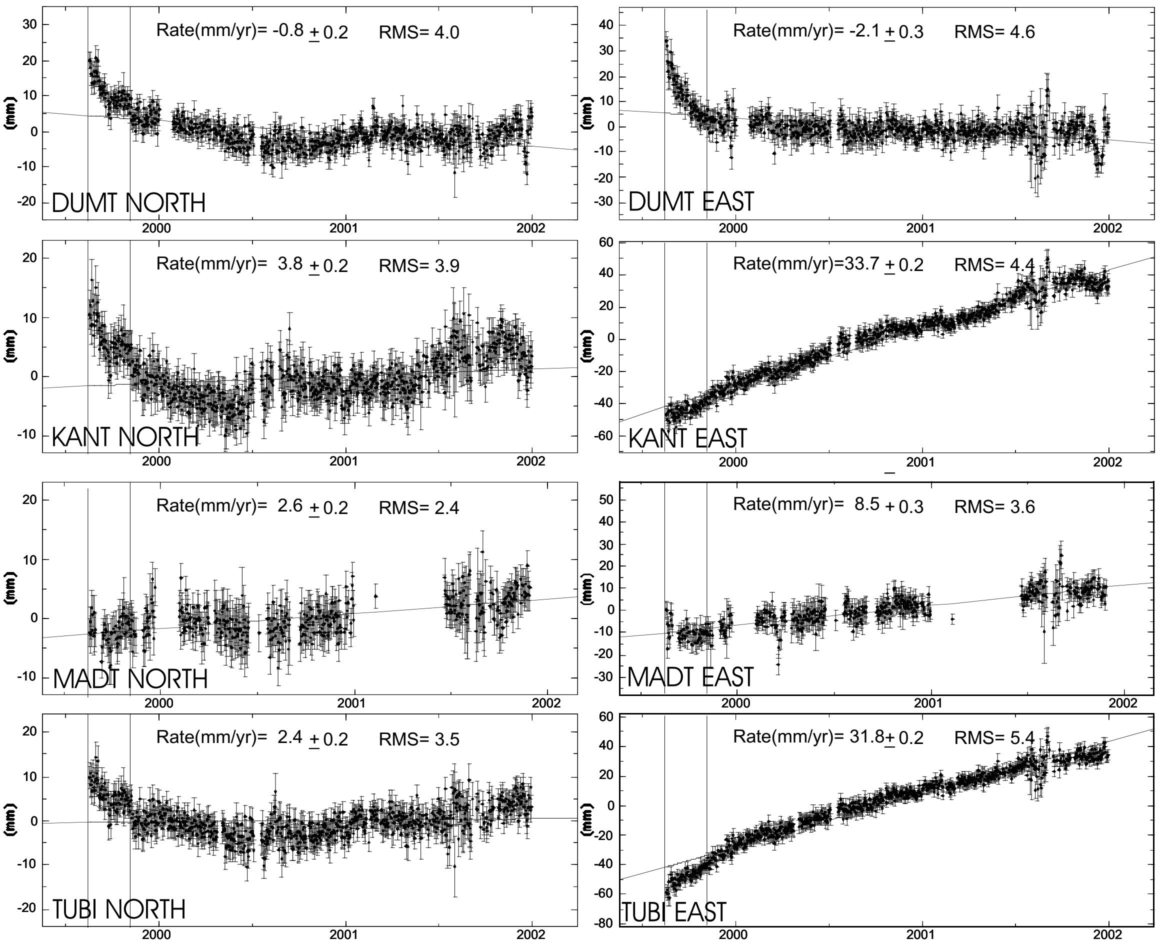

Figure 5. Time series of TPGN and some of the MAGNET sites. The red dashed line represents the time of the İzmit earthquake and the green dashed line represents the time of the Düzce earthquake.

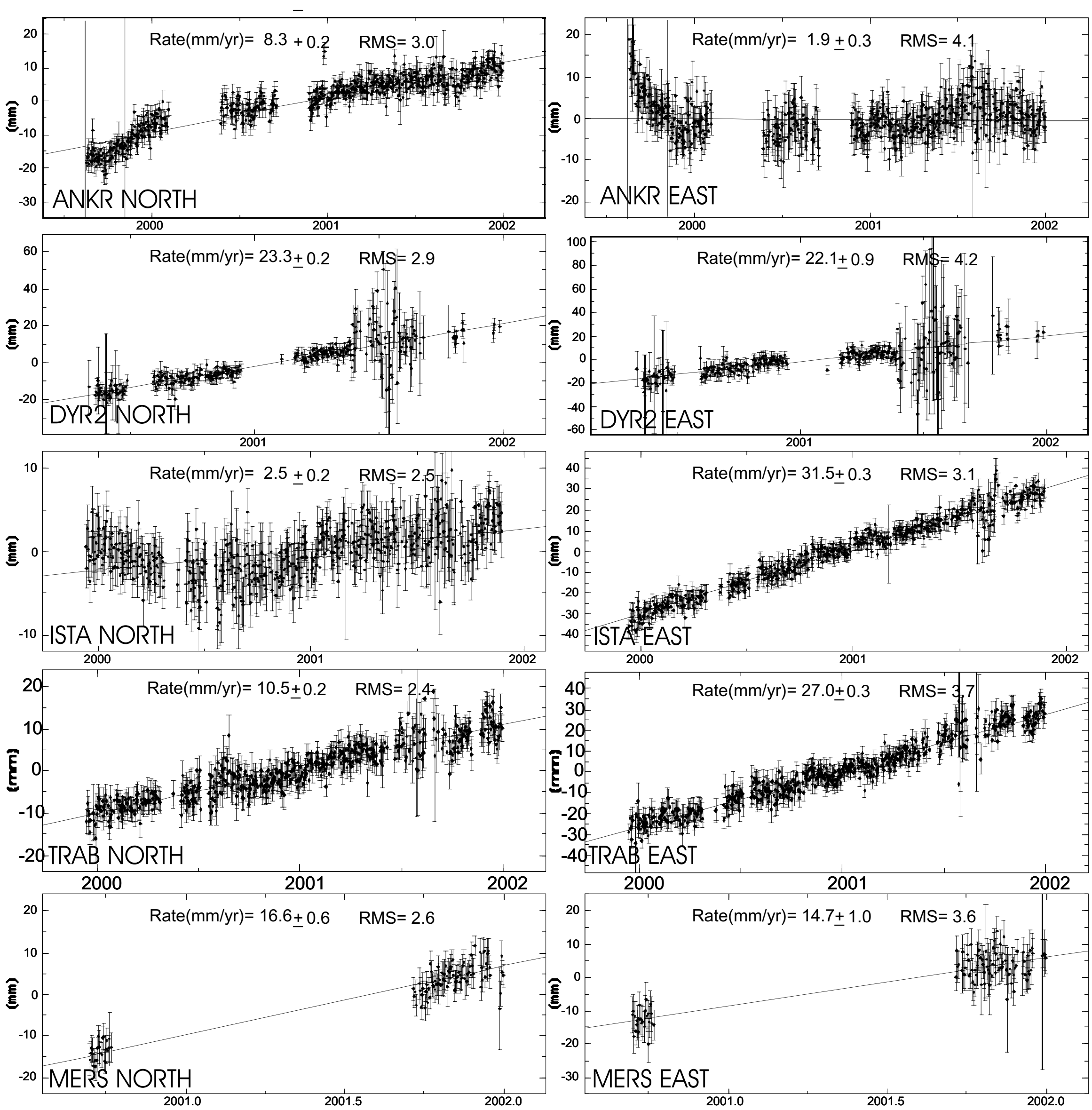

Figure 5. Continued.

In areas far from the epicentral areas, the TPGN sites represent the regional kinematics of Anatolia, not local tectonic deformation rates. The resulting regional velocities show good correlation with the results of McClusky *et al.* (2000) and the horizontal velocities obtained from these scattered stations show details that represent secular motion within the main regional deformation zones in Anatolia. To fill the gap between regional and local deformation rates, GPS campaigns continue to be required in Anatolia. When local campaign data is combined with TPGN sites, all results can be interpreted using the same reference frame.

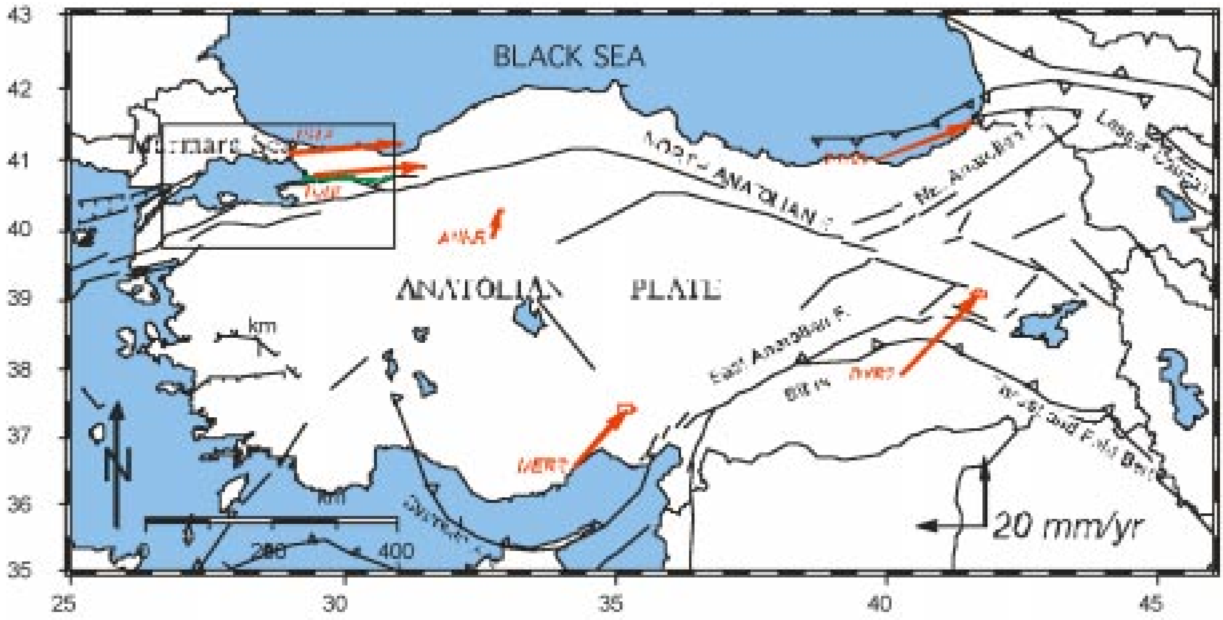

Figure 6. Interseismic velocities of TPGN sites in ITRF96 reference frame. The magnitudes of velocities for each site are given in Table 5. Green lines show the rupture of the İzmit (17 August 1999) earthquake.

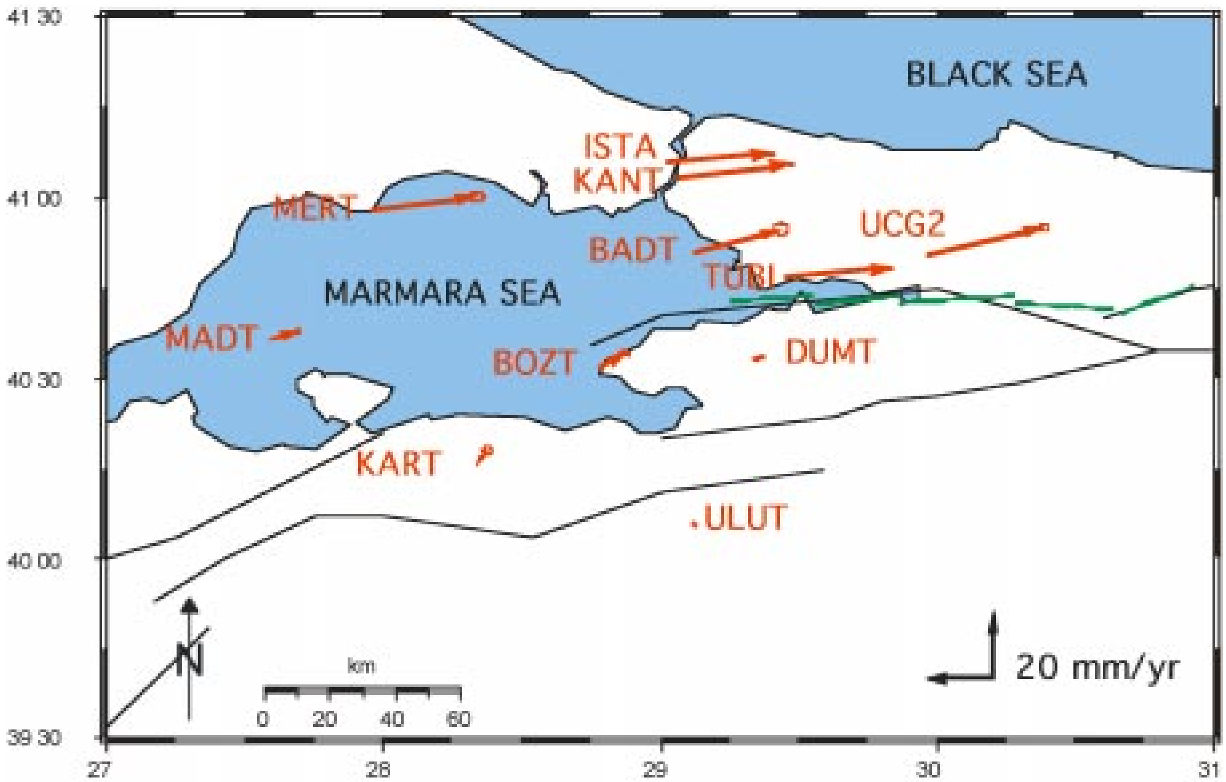

Figure 7. Interseismic velocities of MAGNET sites in IRTF96 reference frame. The magnitudes of velocities for each site are given in Table 5. Black lines show the active faults and green lines show the rupture of the İzmit (17 August 1999) earthquake.

Table 5. Interseismic velocities (ITRF96) estimated from time series.

SITE	V_{EAST} (MM)	σ_{EAST} (MM)	V_{NORTH} (MM)	σ_{NORTH} (MM)	V_{HEIGHT} (MM)	σ_{HEIGHT} (MM)
TUBI	31.8	0.2	2.4	0.2	-7.7	0.6
DUMT	-2.1	0.3	-.8	0.2	-4.5	0.6
KANT	33.7	0.2	3.8	0.2	-2.7	0.6
MERT	30.9	0.8	4.4	0.6	4.4	2.1
MADT	8.50	0.3	2.6	0.2	-2.8	0.9
ULUT	-1.0	0.3	0.3	0.2	-5.9	0.7
BOZT	7.1	0.6	4.2	0.4	-10.2	1.6
KART	3.5	0.6	4.1	0.4	-4.4	1.5
BADT	26.2	0.9	7.2	0.7	-3.8	2.7
UCG2	34.9	0.5	8.6	0.4	-7.9	1.4
DYR2	22.1	0.9	23.3	0.5	-19.4	2.2
MERS	14.7	1.0	16.6	0.6	-25.5	2.7
TRAB	27.0	0.3	10.5	0.2	-5.2	0.8
ISTA	31.5	0.3	2.5	0.2	-0.6	0.7
ANKR	1.9	0.3	8.3	0.2	-4.0	0.5

Conclusion

The interseismic velocities from the TPGN and MAGNET stations have been estimated from a least square analysis of individual time series for each site. The resulting velocity uncertainties of below 1 mm are not realistic as a result of the assumed pure white noise model. As can be seen in Figure 6, the operational TPGN sites do not cover the whole of Anatolia. Given the contributions of planned sites in the future, the TPGN will become an accurate regional reference frame to study the regional crustal deformation in Anatolia. However, local networks should also be installed to study crustal deformation strain accumulation on active fault zones to establish a link between the local and regional scales of deformation. The MAGNET is good example of this. With contributions from the MAGNET, the İzmit earthquake can be studied in detail and we continue to collect data to understand the future seismic risk in the Marmara region.

A close inspection of observed present-day horizontal velocities reveals a good agreement between the magnitudes and direction of the secular motion between TPGN data (spanning an average of 600 days) and the interrupted data at the same sites collected during campaign periods. The findings from continuous data support known earthquake cycle models showing steady interseismic deformation characterised by right-lateral strike-slip motion in the Marmara region on the western NAFZ. In addition, the horizontal velocities obtained from scattered stations show details representative of the secular motion of individual specific zones of deformation in Anatolia.

The differences between the present-day interseismic velocities in Table 5 and the pre-earthquake interseismic velocities (McClusky *et al.* 2000) in the İzmit and Düzce rupture area show the continuation of postseismic effects, and the seismic risk is higher than indicated by previous studies based on pre-earthquake data sets. Because of these differences, the future seismic risk on the strands of the NAFZ in the Marmara region should be re-interpreted, and high strain accumulation should be monitored with the TPGN and MAGNET to understand the interaction between fault strands and stress transfer between them. In addition, the response of the crust under tectonic loading following these recent large earthquakes should be studied with contributions from other disciplines.

The anticipated future work pertaining to the TPGN stations is to perform spectral analyses of GPS-derived coordinate time series in order to recognise time-dependent signals in these time series. Then it will be possible to obtain more reliable information on the differential movements of plates. This will also provide a tool for monitoring the horizontal and vertical displacements associated with future earthquakes during their coseismic and postseismic periods.

Acknowledgements

We would like to thank the efforts of the authors' institutions, General Command of Mapping and TÜBİTAK Marmara Research Centre, for the realisation of TPGN. During many GPS-related projects in Turkey, Aykut Barka installed many sites for campaigns and solved many problems in the field. When we look back at these activities, we see that we could not have accomplished many GPS-related studies without him. Besides Aykut, we would like to thank Tom Herring for his development GLOBK software and Bob King for the GAMIT software, and for their contributions to the analyses. We are also grateful to our collaborators Robert Reilinger, MIT; Rudi Stoeger, BKG; and Karl Feux from UNAVCO. We very much appreciate the valuable efforts of Orhan Kavak at Dicle University and Mehmet Demirel at METU IMU/Erdemli and our colleagues from İstanbul Technical University and Karadeniz Technical University for their support on permanent site data and solutions to numerous problems with these permanent sites in Turkey.

References

AYHAN, E., BÜRGMANN R., MCCLUSKY, S., LENK, O., AKTUĞ, B., HERECE, E. & REILINGER, R.E. 2001. Kinematics of the M_W=7.2, 12 November 1999, Düzce, Turkey Earthquake. *Geophysical Research Letters* **28**, 367–370.

BÜRGMANN, R., ERGİNTAV, S., SEGALL, P., HEARN, L., MCCLUSKY, S., REILINGER, R.E., WOITH, H. & ZSCHAU, J. 2002. Time-space variable afterslip on and deep below the İzmit earthquake rupture. *Bulletin of Seismological Society of America* **92**, 210–223.

BOUCHER, C., ALTAMIMI, Z. & SILLARD, P. 1998. *Results and the Analysis of ITRF96.* International Earth Rotation Service (IERS) Technical Note 24, Central Bureau of IERS, Obs. de Paris, France, p. 166.

CALAIS, E. 1999. Continuous GPS Measurements Across the Western Alps, 1996–1998. *Geophysical Journal International* **138**, 221–230.

ERGİNTAV, S., BÜRGMANN, R., MCCLUSKY, S., ÇAKMAK, REILINGER, R.E., BARKA, A.A., LENK, O. & ÖZENER, H. 2002. Postseismic deformation near the İzmit earthquake (17 August 1999, M=7.5) Rupture Zone. *Bulletin of Seismological Society of America* **92**, 194–207.

HERRING, T.A. 2000. *GLOBK: Global Kalman Filter VLBI and GPS Analysis Program Version 10.0.* Massachusetts Institute of Technology, Cambridge, USA.

KING, R.W. & BOCK, Y. 1998. *Documentation for the Gamit Analysis Software, Release 9.7.* Massachusetts Institute of Technology, Cambridge, USA.

MAO, A., HARRISON, C.G.A. & DIXON, T.H. 1999. Noise in GPS Coordinate Time Series. *Journal of Geophysical Research* **104**, 2797–2816.

MCCLUSKY, S.C., BALASSANIAN, S., BARKA, A.A., ERGİNTAV, S., GEORGIEV, I., GÜRKAN, O., HAMBURGER, M., HURST, K., KAHLE, H., KASTENS, K., KEKELIDSE, G., KING, R., KOTZEV, V., LENK, O., MAHMOUD, S., MISHIN, A., NADARIA, M., OUZOUNIS, A., PARADISISSIS, D., PETER, Y., PRILEPIN, M., REILINGER, R.E., ŞANLI, I., SEEGER, H., TEABLEB, A., TOKSÖZ, N. & VEIS, G. 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. *Journal of Geophysical Research* **105**, 5695–5719.

REILINGER, R.E., ERGİNTAV, S., BURGMANN, R., MCCLUSKY, S., LENK, O., BARKA, A.A., GÜRKAN, O., HEARN, L., FEIGL, K., CAKMAK, R., AKTUĞ, B., ÖZENER, H. & TOKSÖZ, M.N. 2000. Coseismic and postseismic fault slip for the 17 August 1999, M=7.5, İzmit, Turkey Earthquake. *Science* **289**, 1519–1524.

SAGIYA, T., MIYAZAKI, S.I. & TADA, T. 2000. Continuous GPS Array and Present-day Crustal Deformation of Japan. *Pure and Applied Geophysics* **157**, 2303–2322.

ZHANG, J., BOCK, Y., JOHNSON, H., FANG, P., WILLIAMS, S., GENRICH, J., WIDOWINSKI, S. & BEHR, J. 1997. Southern California Permanent GPS Geodetic Array: Error analysis of daily position estimates and site velocities. *Journal of Geophysical Research* **102**, 18035–18055.

Received 06 August 2003; revised typescript accepted 05 February 2003