PLATE TECTONIC FRAMEWORK AND GPS-DERIVED STRAIN-RATE FIELD WITHIN THE BOUNDARY ZONES OF THE EURASIAN AND AFRICAN PLATES

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ABSTRACT

The Adriatic microplate forms the central part of the Alpine-Mediterranean plate boundary area located between the African and Eurasian Plates. The Eurasia/Africa collision is closely related to continental subduction. Superimposed on the relatively slow counterclockwise rotation of the African Plate, complex dynamic processes affect lithospheric blocks between the two major plates. Seismic results indicate the presence of subducted lithosphere below the Alpine-Mediterranean collision belt. The belt displays pronounced differences in structural style. Compressional deformation and mountain building can be traced around the Adriatic block including the Calabrian and Hellenic arcs. Recent GPS results reveal large motion for the Anatolian/Aegean microplates directed towards west-southwest, relative to the Eurasian Plate. In the Calabrian Arc and Ionian Sea area, there is a complex distribution of compressional and tensional stress regimes. Most recent GPS results indicate a relatively strong compressional strain regime to the north of Sicily, which is concordant with fault-plane solutions of recent earthquakes and which is indicative of the position of the actual kinematic boundary of the African Plate. The Tyrrenhenian Sea and its surroundings move like the Eurasian Plate. The boundaries of the Anatolian/Aegean Plates are characterized by large strain rates due to rapid W-SW oriented movement that reaches 35 mm/y.

INTRODUCTION

New geodetic instrumentation and improved spaceborne measuring techniques permit a more accurate interpretation of recent crustal movements. At the same time, synthesis of multidisciplinary quantities and inversion of observations for geodynamically relevant parameters form part of current and future international activities, such as pursued by the Working Group of European Geoscientists for the Establishment of Networks for Earth-Science Research (WEGENER; Plag et al., 1998). In hazardous areas, either continuous GPS or repetitive measuring campaigns at shorter time intervals have been continued and strengthened. This allows for the determination of space and time variations in the regional strain tensors.
The results achieved so far can be considered as a first important step towards a better understanding of the geologic evolution, geophysical structure and present-day dynamics of the Alpine-Mediterranean region (Kahle and Mueller, 1998). However, most of the deformation processes are not yet fully understood. Mapping the kinematic pattern (horizontal and vertical motions) in specific areas where lithospheric detachment seems to be active or may have faded out will yield important kinematic data as boundary conditions for modeling arc evolution and back-arc basin development. The current height components of deformations are, to date, almost completely unknown, but as time passes the signals of vertical motions will become recognizable in long-term time series of GPS observations. With modern space-geodetic techniques, it will become possible to provide data which ultimately will enable us to shed light on the plate tectonic processes of the Alpine-Mediterranean region and better assess the pattern of current crustal deformation around the Adriatic microplate.

The purpose of this paper is to summarize the present-day crustal movements and geodetic strain field for the wider European area, and to focus on the southern and southeastern boundary of the Adriatic microplate, in particular.

PLATE TECTONIC FRAMEWORK

In a simplistic picture, the recent major tectonic processes in the Mediterranean-Alpine region can be understood as a consequence of sea-floor spreading in the Atlantic Ocean, the Red Sea and the Gulf of Aden. Higher spreading rates in the South Atlantic as compared to the rates in the North Atlantic cause a gradual counterclockwise rotation of the African Plate resulting in a northwestward directed push against Eurasia.

Seismic activity in the Mediterranean-Alpine regions (Figure 1) impressively illustrates the existence and dimensions of the so-called "Adriatic promontory" of the African Plate proposed by Channell and Horvath (1976). Figure 1 also clearly demonstrates the existence of the Aegean-Anatolian microplate.

The Mediterranean-Alpine region has been shaped by numerous episodes of destruction and creation of oceanic lithosphere. From Ocean Drilling Program data across the Tyrrhenian Sea, Kastens et al. (1988) inferred that tilting, subsidence and rifting had occurred on the margin near Sardinia. Emplacement of basaltic crust in the central Tyrrhenian Sea started in the Tortonian. In contrast, the formation of basaltic crust in the southeastern part of the Tyrrhenian Sea began not earlier than Late Pliocene. This later date of initiation of basaltic crust formation is in agreement with suggestions that the Tyrrhenian Sea has grown southeastward towards the
Calabrian arc. A key issue in the assessment of recent crustal movements around the Tyrrhenian Sea is the analysis of GPS observations. Recent results will be shown below.

Subduction of the African Plate is still going on today beneath the Hellenic, Calabrian and Gibraltar arcs, resulting in the extension and subsidence of the Aegean, Tyrrhenian and Alboran basins (see Figure 2). Mapping of the Mohorovicic discontinuity (the "Moho"), which separates the crust from the upper mantle, has been carried out by many investigators based on seismic refraction and reflection surveys. Deep crustal roots have been found under the Betics, Pyrenees, Alps, Dinarides, Hellenides, and Caucasus mountain ranges. The regions with the smallest crustal thickness correlate with episodes of recent subsidence, such as in the Pannonian basin. A third feature are the "oceanized" basins, including the Alboran Sea, the Tyrrhenian Sea, the Ionian Sea, the southern Aegean Sea, and the Black Sea. The Ionian Sea is underlain by an oceanic type of crust. The Mediterranean Ridge, extending from the Apulian plateau to the island of Rhodes and the southern part of the Antalya basin, has an intermediate-type crust. The margins of the Eastern Mediterranean Sea are bound by normal continental crust. While the southern and eastern coastal regions of the Eastern Mediterranean are typical passive continental margins, the northern boundaries are active continental margins comprising the Calabrian, Hellenic and Tauric arcs associated with compressional processes.
To map the gross features of the lithosphere-asthenosphere system, dispersion of surface waves has been analyzed (Panza et al., 1980). Significant deviations from the average European thickness value of 90 to 100 km were found in the Balearic and Tyrrhenian basins (each with a thickness of about 30 km). The considerable increase in lithospheric thickness (up to 130 km) beneath the central and eastern part of the Southern Alps suggests subduction of the Eurasian Plate under the Adriatic microplate. Due to the plate collision south of the Alps, the lithosphere reacts by a pronounced thickening, producing high-velocity, high-density, cold and slowly subsiding "lithospheric roots". The actual plate boundary between Africa and Eurasia is characterized by deep structural features in the Alpine area and in the northernmost part of Africa.
In eastern and northern Turkey, seismic activity is primarily associated with the East and North Anatolian Transform fault zones. The East Anatolian and Dead Sea Transform fault zones exhibit predominant left-lateral motion, while the North Anatolian fault motion is governed by right-lateral strike slip. Horizontal displacement on these faults is determined by the relative motion between the Eurasian and Arabian Plates, with the Anatolian plate moving to the west (McClusky et al., 2000). In the western part of Turkey as well as in central and southern Greece, tensional earthquake mechanisms dominate, due to normal faulting in the Aegean graben system.

An Alpine orogenic belt can be traced from the Dinarides and Hellenides in the west through the Hellenic island arc and the Aegean archipelago to the Taurides in Turkey. The geological framework of the Aegean Sea is characterized by thrusting of the Hellenic nappes over the stable pre-Apulian zone along a NW-SE-trending front. The outward growth of the Mediterranean Ridge complex as a function of time has been elucidated by Kastens (1991). She concluded that the seaward migration of the Mediterranean Ridge has accelerated since its initiation from about 6 mm/y to 22 mm/y.

Under the southern Aegean Sea, the slab seems to be uninterrupted, with a clear outline of the Wadati-Benioff zone. Detailed neotectonic studies on the Ionian islands, the Gulf of Corinthis and the Peloponnesus have revealed a complex strain pattern for the Quaternary (Spakman, 1990). Compression dominates in the external part of the Hellenic arc, north-south extension is observed around the Gulf of Corinthis, while east-west extension has been found in the southern Peloponnesus and in western Crete. In the internal part of the Hellenic, arc-normal faulting is observed from the Gulf of Corinthis to Crete. The strain-rate field in the Hellenic-Aegean region is most likely due to the superposition of back-arc spreading in the Aegean Sea and the collision with the Apulian microplate. Recent GPS results are displayed and discussed below.

Lowrie (1980) suggested that the Apennine peninsula, the island chain of Corsica and Sardinia as well as the Iberian peninsula have all undergone counterclockwise rotations to a varying degree. Whether this slow rotation is still in progress will have to be tested in the future by dedicated GPS measurements. The first complete repetition of GPS measurements at stations in the western Hellenic Arc tied across the Strait of Otranto to an additional station in southern Apulia was carried out in 1991. The results – if compared to the 1989 GPS measurements, a high-class triangulation in the 1970’s and distance measurements in the 1930’s – suggest a shortening of the distance between Othoni island in northwestern Greece and Specchia Cristi in southern Apulia of 9 mm per year over the past 60 years (Kahle et al., 1993). Repeated GPS measurements have been carried out to reveal whether this trend can be confirmed (see below).
Along the southeastern margin of the Tyrrhenian Sea bordering the Apennine peninsula and Sicily, there is a chain of elongated peripheral basins filled with thick sediments. Based on combined seismic-refraction and reflection experiments carried out in the central Tyrrhenian Sea, a depth of 12 km to the crust-mantle transition zone was found, corresponding to a total crustal thickness of 8 to 9 km (Finetti and Morelli, 1972) which points towards an intermediate (rifted) to oceanic type of crust.

RECENT CRUSTAL MOVEMENTS AND STRAIN RATE FIELDS

Based on 6 years of continuous GPS data of the European IGS (International GPS Service), EUREF (European Reference Frame) and Greek stations, a kinematic field has been derived and plotted relative to the rotation of the North American Plate (Figure 3). It is remarkable that almost all of the resulting velocity vectors of crustal motion follow small circles about a pole that had been deduced from geophysical information (DeMets et al., 1990).

Figure 3. GPS-rates of crustal motion relative to the North-American Plate. The rotation of the North-American Plate was subtracted, using a rotation rate of 0.195°/My around a pole located at 2.3°N and 79.7°W (Heflin and Argus, pers. commun., 1998). N-Pole is the geographical North Pole, while R-Pole (63.2°N, 134.5°E) and the corresponding gridlines represent a geophysical pole of rotation of the Eurasian Plate (DeMets et al., 1990).
In order to visualize the rates of crustal motion relative to Eurasia, the rotational part of the Eurasian Plate (relative to ITRF97) was subtracted using a rotation rate of 0.262°/My around a pole located at 59.0°N and 97.1°W (Heflin and Argus, pers. commun., 1998; Figure 4).

As a result, it can be seen that the Eurasian stations (except those in Greece, Turkey and bordering regions) have only small motions (on the order of 1 mm/yr). So there is almost no internal deformation within the Eurasian plate. The African Plate motion is visible in the southwest, as documented by stations in southwest Spain, Morocco, Sicily and the island of Lampedusa. The Arabia Plate motion is seen in the southeast for the station Bahrain. Most striking are the large westward and southwestward velocities of the Anatolian and Aegean microplates, respectively. But the Adriatic microplate also clearly shows a different kinematic behavior compared to the Eurasian Plate.

Figure 4. Rates of crustal motion relative to Eurasia, derived from continuous GPS data of IGS, EUREF and Greek sites between 1995 and 2001.

In the following discussion, more detailed GPS velocity and strain-rate results are presented for the central and eastern Mediterranean. The strain-rate field is calculated from the velocities at GPS sites by least-squares collocation. Collocation is a general method of least-squares adjustment which includes parameter estimation, filtering and prediction/interpolation. The displacements, the signal-to-noise ratio of the displacements, and a covariance function are used as input. Details are given in Kahle et al. (2000). Since the velocities and the strain rates are directly interrelated by a
differential equation, the strain-rate field (Figure 6) can be determined without explicitly gridding the velocity field. To visualize the deformation attributed to seismotectonic processes active on major fault systems, the normal and shear strain rates associated with the major faults in the eastern Mediterranean were calculated (Figs. 7 and 8). Details of this calculation can be found in Straub (1996). The locations of faults do not influence the strain-rate results, they only defines the points at which we calculate and show the strain rates. Removing a fault or introducing a new one, does not change the results along the other faults. No fault does not mean that there is no strain; we simply do not show it.

In Figure 5a, the velocity results from continuous and repeated GPS measurements in southern Italy between 1994 and 2001 after Hollenstein et al. (2003) are shown. The velocities in Figure 5b show the integration of recent GPS data from a number of GPS campaigns in the eastern Mediterranean. Fig 6 represents the collocated strain-rate fields for the two areas overlain with fault plane solution of major earthquakes. The strain-rate field for the central Mediterranean (Figure 6a) is based on the velocities of Figure 5a. Due to the lack of GPS data on the African side of the Hellenic arc, the strain-rate field along this trench is only weakly constrained. To obtain realistic strain rates in the eastern Mediterranean (Figure 6b), the velocities of Figure 5b therefore were supplemented by velocities representing the motion of the African Plate. The corresponding points were introduced to the south of the seismic belt, and we used rates calculated from a rigid Africa (Nubia) rotation (Sella et al., 2002).

Seismicity and fault-plane solutions for southern Italy show active deformation, which varies between N-S shortening and NE-SW extension on normal faults along the Apennine Chain (Anderson and Jackson, 1987). The Dinaric coast region is deforming on strike-slip and thrust faults. A belt of NE-SW shortening continues into northwestern Greece along numerous transcurrent fault systems (Mantovani et al., 1992). NE-SW-oriented compression is also seen in the GPS-based strain rates in northwestern Greece (Figure 7). There are too few GPS stations in this region and to the north for one to go into further detail.

The GPS velocities and the strain rates in the region of southern Italy support the following results of previous work. Compression between Apulia and northwestern Greece (5 mm/y), extension across the southern Apennines (Amato and Montone, 1997; Hunstad et al., 2003) right-lateral movement between Vulcano and Lipari (Bonaccorso, 2002), as well as extension and dextral strike slip in the Sicily Rift Zone (Cello, 1987).
Figure 5. GPS velocity fields relative to Eurasia. The error ellipses represent the 1-sigma confidence region. a) For southern Italy, based on results from Hollenstein et al. (2003). Inset: velocities relative to Africa. b) For the eastern Mediterranean, combined velocity field based on GPS results from McClusky et al. (2000), Kotzev et al. (2001), and Cocard et al. (1999). Notice the different scales in a) and b). KFZ: Kephalonia Fault Zone, MF: Maghrebian front, SRZ: Sicily Rift Zone, TS: Tyrrhenian Sea, WHA: West Hellenic Arc.
Figure 6. Principal values and axes of strain rates calculated from the velocities shown in Figure 5 and – for 6b – some additional virtual rates representing the motion of the African Plate. The scales are given in nanostrain/yr; they equal a relative motion of 1 mm/yr over a distance of 1000 km normal to the fault. If the width of the deformation zone is multiplied by the strain rates, the total relative motion is obtained. The focal mechanisms of larger earthquakes are from Harvard CMT solutions (http://www.seismology.harvard.edu), Jackson et al. (1992) and Pondrelli et al. (2002; http://www.ingv.it/seismoglo/Rcmt/). a) For southern Italy (Hollenstein et al., 2003). Insets: Normal and shear strain rates associated with selected faults. b) For eastern Mediterranean. Notice the different scales in a) and b). There is large compression to the north of Sicily. The regions around the Gulf of Corinth are characterized by large extensional strain rates. The SW Aegean Sea is nearly strain free. Along the West Hellenic Arc, significant compression is observed. The focal mechanisms correspond quite well to the type of deformation identified by GPS observations. Especially remarkable is the relatively quiet of the central Aegean.
In addition, new kinematic constraints have been obtained. The Eurasian Plate extends beyond Corsica and Sardinia to the Tyrrhenian Sea. Statistically insignificant displacement for Corsica and Sardinia were also found by Oldow et al. (2002). Whether these new, short-term GPS results are indicative of a tectonic reorganization in the Tyrrhenian/Calabrian area is under discussion and will remain an open interesting question (Faccenna et al., 2004; Pondrelli et al., 2004; Goes et al., 2004; Rosenbaum et al., 2004). The island of Lampedusa is situated on the African shelf and moves like the African Plate. Also, the Sicily Rift Zone and the southwestern coast of Sicily are dominated by the African Plate motion. The compression between the African and Eurasian Plates seems to be concentrated along the Maghrebian front to the northwest and north of Sicily, which is consistent with compressional focal mechanisms of earthquakes which have occurred along this belt. Large north components of the velocities in northeastern Sicily (up to 8 mm/yr) enhance compression to the north and cause extension in the interior of Sicily.

The velocity field in the eastern Mediterranean is separated into two main parts by the North Anatolian Fault Zone (NAFZ), North Aegean Trough (NAT) and the Kephalonia Fault Zone (KFZ). To the north and northwest, relatively small and Eurasia-like motions are observed. Northern Greece and southern Bulgaria move to the south and southwest with rates between 2 and 5 mm/yr, while the area to the northeast of the KFZ shows westward to northwestward motion. To the south of the above mentioned line, Anatolian-Aegean block is moving rapidly, turning from westward direction along the NAFZ to southwestward direction in the Aegean Sea. The rates reach 40 mm/yr. A large increase of velocities is found along the KFZ, from less than 10 mm/yr in the north up to more than 30 mm/yr in the south within a distance of 200 km.

Our results indicate a relatively strain-free region in the central southern Aegean, between the volcanic and the non-volcanic Hellenic arc (37° to 38°N and 35° to 36°N, respectively). High extensional strain rates are confined to the northern Aegean Sea and to western Anatolia. Maps of in-situ stress measurements compiled by Rebai et al. (1992) show mainly N-S extensional horizontal stress in central Greece, which is also seen in the GPS results.

The seismic cluster in the south-eastern Aegean Sea, coincides with NW-SE-oriented extension, also accompanied by recent active volcanism. Comparison with the seismic strain-rate fields derived from an inversion of moment tensors of seismic events show that this area is characterized by a pronounced seismic strain deficit (Jenny et al., 2004).

Normal deformation rate components on the major fault zones reveal large extension in central Greece, centered around the Gulf of Corinthos (Figure 7). The West Hellenic arc is associated with strong compression. The
relatively small compression to the southwest of Crete is caused by a measurement point which is located very close to the arc. It shifted the large compression more to the south, which is not shown on this map.

Northwest Anatolia is dominated by the both extension and compression. The SW-trending portions of the NAFZ are associated with compression, whereas the NW-oriented segments show mostly extensional activity. This can be related to the restraining and releasing stress behavior along the NAFZ which changes its strike on several well-defined fault segments. The western part of Anatolia is characterized by N-S-oriented extensional strain rates, coincident with W-E-trending graben structures, that are also associated with large normal earthquakes.

The southwestern margin of Greece is dominated mainly by the subduction of the African Plate along the Hellenic trench. The most important fault zone taking up this motion is the KFZ (Kahle et al., 2000). The dextral nature of the KFZ is clearly illustrated by the shear strain rates shown in Figure 8. This area shows intense seismicity as well. Devastating earthquakes with magnitudes of M>7, associated with dextral fault-plane solutions (FPS), occurred on the central Ionian islands in 1945 and 1953 (Stiros et al., 1994), in 1972 (Anderson and Jackson, 1987), and in 1983 (Kiratzi and Langston, 1991).
The northern and central Aegean area is governed by distributed right-lateral strike-slip faulting (Taymaz et al., 1991). The GPS strain-rate analysis reveals that these features are dominated by right-lateral components of shear (Figure 8) accompanied by extension, ranging between NNE-SSW to NNW-SSE directions. The dextral sense of motion along the NAFZ, clearly visible in the GPS results, is also documented on the FPS (Figure 6). Sinistral shear strain is dominant in the area beginning east of the island of Crete, running along the island of Rhodes and into southwest Turkey, identifying the Strabo and Pliny troughs, which act as transcurrent faults, separating the moving Aegean Plate from the eastern Mediterranean basins.

CONCLUSIONS

- The kinematic field in the Eastern Mediterranean is characterized by W-WSW-SW motion of 20-40 mm/yr for Anatolia-Aegean, relative to Eurasia. A distinct right-lateral strike-slip boundary is aligned with the zone following the Black Sea–Marmara–Epirus–central Ionian Islands. The Tyrrhenian Sea block moves like Eurasia, and the Sicily rift zone
like Africa. The KFZ right-lateral strike-slip delineates the end of the West Hellenic subduction.

- Results of the strain-rate field calculation reveal pronounced extension in western Anatolia, the Aegean region and in central northern Greece, where normal faulting earthquakes are predominant. Significant compression is found perpendicular to the West Hellenic arc, between Apulia and northwestern Greece, and to the north of the coastline of Sicily. Maximum dextral shear has been found along the NAFZ-NAT-KFZ line. N-S-oriented extensional strain rates dominate in central Greece, accompanied by normal faulting earthquake mechanisms.
- The calculation of normal and shear components of the deformation rates on major fault systems show that three main types of strain distribution dominate: extension in the Aegean region and central northern Greece, compression perpendicular to the Hellenic arc, and shear along the NAFZ-NAT-KFZ line. In the southern Ionian islands, compression occurs in a N34°E direction across the Hellenic arc. The Central Southern Aegean is strain-free.
- Deficits in seismically-released strain are apparent in the Eastern Mediterranean (Kahle et al., 1999, 2000; Jenny et al., 2004).
- In summary, we conclude that the strain-rate field in the central and eastern Mediterranean is further constrained by GPS data. The results are considered as a first preliminary step towards a better understanding of the complex present-day dynamics of the eastern Mediterranean-Alpine region, with a focus on the southeastern boundary of the Adriatic microplate, in particular.

ACKNOWLEDGEMENTS

This study benefited greatly from discussions and cooperation with M. Cocard, now University of Laval Quebec, Canada, and D. Giardini, S. Goes and S. Jenny, Institute of Geophysics, ETH Zürich. We thank G. Grenerczy and O. Odalovic for critically reviewing the manuscript and helpful suggestions for its improvement. This work was financed by ETH research grant 41-2647.5 and EU grant ENV4-CT97-0519. The GPS measurements in Italy were supported by ETH Zürich and Centro Spaziale di Matera, Italy.

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