The Adriatic region: An independent microplate within the Africa-Eurasia collision zone

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[1] We use GPS measurements and block modeling to investigate the present-day deformation of the Adriatic region, whose kinematics within the Nubia-Eurasia plate boundary zone is not well constrained and remains controversial. Block modeling allows us to compute rigid-plate angular velocities while accounting for elastic strain accumulation along block-bounding faults. Results suggest that the Adriatic is a microplate (Adria) and that the southern boundary with the Nubia plate and the Aegean domain may be located along the Apulia Escarpment and the Kefallinia fault. Geodetic data alone cannot discriminate between a single block (AP) or a two blocks (GDAP) description of Adria, but the GDAP model predicts boundary slip rates that are in better agreement with observations from previous studies. *INDEX TERMS:* 1208 Geodesy and Gravity: Crustal movements—intraplate (8110); 1243 Geodesy and Gravity: Space geodetic surveys; 3210 Mathematical Geophysics: Modeling; 8107 Tectonophysics: Continental neotectonics; 9335 Information Related to Geographic Region: Europe. **Citation:** Battaglia, M., M. H. Murray, E. Serpelloni, and R. Bürgmann (2004), The Adriatic region: An independent microplate within the Africa-Eurasia collision zone, *Geophys. Res. Lett.*, *31*, L09605, doi:10.1029/2004GL019723.

1. Introduction

[2] The tectonics of the Mediterranean is shaped by deformation related to the collision between the Nubia (Africa), Eurasia, and Anatolia plates. In this study, we use block modeling of surface velocities recorded by GPS measurements to investigate the present-day deformation of the Adriatic (Figure 1, Figure A1[1], and Table A1). The tectonics of the Adriatic is not well constrained and remains controversial [*Mantovani et al.*, 1990; *Van Dijk and Scheepers*, 1995; *Wortmann et al.*, 2001]. The region includes the relatively stable Adriatic basin (Po Valley, Adriatic Sea and Apulia), surrounded on the eastern, northern, and western margins by the Albanides and Dinarides, the Alps, and the Apennines, respectively (Figure 1). Focal mechanisms from historical and recent earthquakes and geodetic observations show NE-SW extension on normal faults across the Apennines, N-S convergence across the Alps, and deformation on strike-slip and thrust faults resulting in NE-SW shortening along the eastern coast of the Adriatic Sea [*Anderson and Jackson*, 1987; *Pondrelli et al.*, 2002; *Hunstad et al.*, 2003]. Given the lack of significant seismic activity along the southern margin of the Adriatic Sea, the boundary with the Nubia plate, if it exists, is not well defined [*Anderson and Jackson*, 1987, *Oldow et al.*, 2002]. Geomagnetic data averaged over several Myr and *Sn* shear wave propagation observations suggest that Nubia extends as a promontory into the Adriatic region [*Mantovani et al.*, 1990, *Channell*, 1996; *Mele*, 2001], whereas historic geodetic and seismic evidence suggest that the Adriatic is an independent microplate (Adria) within the Nubia-Eurasia plate boundary zone [*Anderson and Jackson*, 1987; *Ward*, 1994; *Nocquet and Calais*, 2003]. *Oldow et al.* [2002] propose that Adria is divided by the Gargano-Dubrovnik fault into two blocks. Northwestern Adria has little or no motion relative to Europe and is part of the Alpine collage of southern Europe. Southeastern Adria is moving together with Nubia and is continuous from Sicily to Apulia. Other studies suggest that the Adriatic is an area of distributed deformation [*Nocquet et al.*, 2001].

[3] To test different tectonic models for the Adriatic region, we develop a block model of regional deformation (Figure 1). This approach incorporates secular velocity and fault geometry estimates, as well as elastic strain accumulation. With this model we can assess whether different hypotheses are compatible with geodetic data, estimates of fault slip rates and locking depths, areas of rigid block

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL019723.

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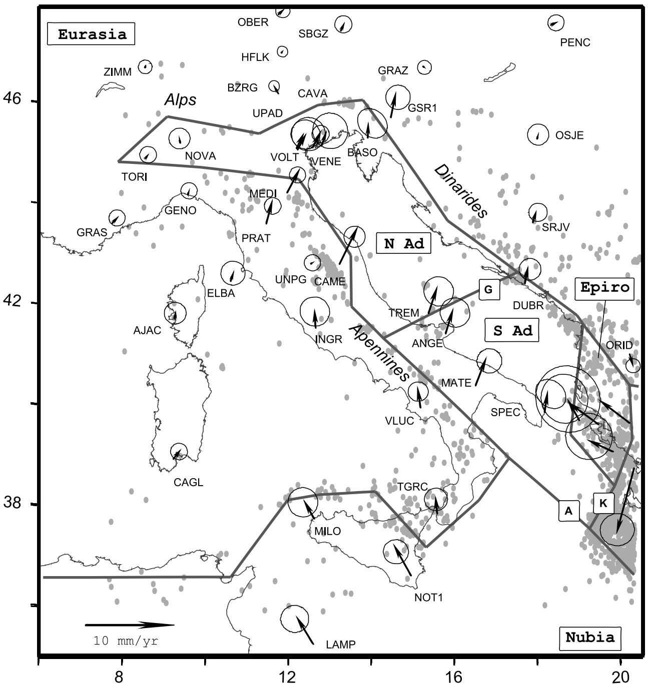

Figure 1. Location of the segments (solid lines) and blocks used to model the Adriatic region. [N Ad] North Adria, [S Ad] South Adria. [G] Gargano-Dubrovnik fault zone; [K] Kefallinia fault zone; [A] Apulia escarpment. GPS velocities and their 95% confidence ellipses, referenced to the stable Eurasian frame realized by *McClusky et al.* [2000]. The grey dots indicate the location of the shallow seismicity from 1975 to 2000 (M > 3.5) (*Bulletin of the International Seismological Centre*, http://www.isc.ac.uk/Bull, 2001).

rotation, and regions of anomalous strain accumulation [*Meade et al.*, 2002].

2. GPS Measurements of Deformation

[4] We use publicly available observations made at 30 continuous GPS stations of the European Reference Permanent Network (EUREF) and Italian Space Agency networks to estimate deformation in the Adriatic region (Figure 1). We analyze the data using the GAMIT/GLOBK software in a three-step approach described by *McClusky et al.* [2000].

[5] To improve the realization of a stable reference frame for the velocity solution, additional sites from the International GPS Service and EUREF networks are included as loosely constrained solutions provided by the Scripps Orbit and Permanent Array Center. Our solution includes data spanning 4 years from 102 stations, including 50 in the Mediterranean area (Figure 1, Figure A1, and Table A1). We incorporate velocities from 38 episodic GPS (EGPS) sites from *McClusky et al.* [2000] and 10 EGSP sites from *Serpelloni et al.* [2001, 2002] to better constrain deformation in the Eastern Mediterranean (Aegean and Anatolian plates) and southern Adriatic regions.

[6] The 1σ uncertainties of the GPS velocities were derived by scaling the formal error by the square root of the residual chi-square per degrees of freedom of the solution, and by assuming a random walk of 1 mm/$\sqrt{}$yr to take into account possible monument instability [*Langbein and Johnson*, 1997]. The velocities are relative to the stable Eurasian frame realized by *McClusky et al.* [2000].

3. Block Model

[7] Although determining the angular velocity of a rigid block on a sphere is usually sufficient to study plate kinematics, the short interval spanned by our GPS observations and proximity of some stations to the block boundaries require us to consider the effects of interseismic elastic strain accumulation [*Murray and Segall*, 2001]. We assume the block boundaries are dislocations in an elastic half-space with a Poisson's ratio of 0.25, and they are vertically oriented with no dip slip along the fault surfaces. The strike-slip and extension/contraction components of the back-slip rates are derived from the projection onto the fault-plane geometry of relative motions derived from the angular velocities of the blocks [*Meade et al.*, 2002].

[8] Our block model of the Adriatic includes the interaction between the Eurasia, Nubia, Adria, Anatolia, Aegea, and Arabia plates. The plate boundaries are based on the description of the tectonic settings of the Mediterranean after *Van Dijk and Scheepers* [1995], the REVEL plate velocity model [*Sella et al.*, 2002] and seismicity distribution in the Mediterranean basin (*Bulletin of the International Seismological Centre*, http://www.isc.ac.uk/Bull, 2001). Velocities at sites in the Ionian Islands are more northwesterly oriented than at sites in Greece or southern Adriatic [*Cocard et al.*, 1999]. For simplicity, we assume that this region is an independent block (Epiro) in all our models (Figure 1). Plate boundary strain is determined from single continuous faults along the Calabrian coast, the Apennines, the Alps, the Dinarides, and the Hellenic Arc (Figure 1). This approach provides a first-order kinematic description in areas with more broadly distributed deformation, where the station distribution is insufficient for detailed study.

[9] We evaluate several possible representations of Adria and the Adria-Nubia margin (Figure 1 and Figure A2): (EU) the Adriatic is a region of continuous deformation within the Eurasian plate [*Nocquet et al.*, 2001]; (EUgd) Northwestern Adria is part of the Alpine collage of southern Europe with the southern boundary with Nubia being the Gargano-Dubrovnik fault [*Oldow et al.*, 2002]; (PR) Nubia extends as a promontory into the Adriatic region [*Jiménez-Munt et al.*, 2003]; (GD) Adria is divided from Nubia by the Gargano-Dubrovnik fault [*Calais et al.*, 2002]; (AP) Adria is divided from Nubia and Aegea by the Apulia Escarpment and the Kefallinia fault; (GDAP) Adria consists of two blocks separated by the Gargano-Dubrovnik fault in the middle and divided from Nubia and Aegea by the Apulia Escarpment and the Kefallinia fault.

4. Results

[10] We compare the proposed models, assuming a regional fault locking depth of 20 km, by performing F-ratio tests [*Gordon et al.*, 1987] on the residual χ^2_ν (chi square per degree of freedom) fit (Table 1). The F-test determines if the reduction in χ^2_ν is greater than would be expected simply because additional model parameters were added. Table 1 gives values of the experimental (Fe) and theoretical (Ft) F-ratios of GDAP against the other models. All the models,

Table 1. Models Statistics Based on 103 Sites From Europe (36), Nubia (13), Adria (12), Aegea (19) Arabia (7), Epiro (4) and Anatolia (12)[a]

Model	Blocks	v	χ^2_v	Fe	Ft (99%)
EU	6	188	3.3	6.2	2.9
EUgd	6	188	3.4	6.5	2.9
PR	6	188	3.4	7.0	2.9
GD	7	185	3.3	10.2	3.9
AP	7	185	2.8	−0.7	3.9
GDAP	8	182	2.9	–	–

[a]We compare the fit of the GDAP model against all the others using the F test. v: degrees of freedom, Fe: experimental value of F, Ft: theoretical value of F, 99% confidence bound.

except for AP, show values of Fe larger than Ft at the 99% confidence level (Fe has only 1% probability of exceeding Ft by chance). We conclude that the microplate models AP and GDAP fit the data significantly better than any other model proposed, but are not statistically different at 99% confidence level.

[11] Considering the effect of elastic strain accumulation at the block bounding faults improves the fit to geodetic data. If we allow the regional fault locking depths to vary, we find an optimal locking depth of 20 km both for the GDAP and AP models with a residual χ^2_v of 2.8 and 2.9, respectively. The χ^2_v value for a regional fault locking depth of 0 km (i.e., no strain accumulation) is 3.7 for both models.

[12] Inversion of the geodetic velocities at the 12 sites belonging to the Adriatic domain (Table A1) gives a counterclockwise rotation of Adria with respect to stable Europe (Table 2). The location of the northern Adria pole (GDAP model) can be compared with that derived by *Calais et al.* [2002], but our pole has a larger rotation rate. On the other hand, the location of the Adria pole estimated by the single block AP model is different from that proposed by *Ward* [1994], which is derived using 2 sites only (Figure A3).

[13] Both the AP and GDAP models predict extension in the Apennines, shortening in the central Alps, Dinarides and Ionian Island (Epiro coast), and right-lateral slip along the Kefallinia fault zone, (Table 3, Figure A4, and Table A3), in agreement with previous studies [*Anderson and Jackson*, 1987; *Cocard et al.*, 1999; *D'Agostino et al.*, 2001; *Thatcher*, 2003]. The GDAP model predicts mainly right-lateral strike-slip motion along the Gargano-Dubrovnik fault zone. This is only in partially in agreement with previous studies indicating that the actual fault plane is the one striking ENE-SSW with a left-lateral strike-slip component [*Console et al.*, 1993]. Geological observation and seismological results [*Montone et al.*, 1999; *Calais et al.*, 2002; *Benedetti et al.*, 2003] indicate that the northern Apennines accommodates <1mm/yr deformation and predict shortening in the western end (southern western Alps). Both the single block (AP) and the two block (GDAP) models overestimate the extension in the northern Apennines, but the GDAP model predicts shortening in the southern western Alps and extension in the central western Alps, in agreement with previous work by *Calais et al.* [2002].

Table 2. Rotation Poles Relative to Stable Eurasia

Plate	Lon., °E	Lat., °N	Corr., ρ_{EN}	Rate, °/Myr	Model
Adria	−22 ± 13	49 ± 2	0.146	0.11 ± 0.05	AP
Adria	6 ± 4	49 ± 2		0.29 ± 0.06	*Ward* [1994]
N Adria	8.1 ± 0.7	46.3±0.4	−0.599	0.9 ± 0.2	GDAP
N Adria	9	45		0.5	*Calais et al.* [2002]
S Adria	−2 ± 17	46 ± 5	−0.946	0.2 ± 0.2	GDAP

Table 3. Segments Slip Rate (mm/yr) and Their 1σ Uncertaintiesss: strike-slip (right-lateral is negative); ts: tensile slip (extension is negative); So: Southern; Ce: Central; No: Northern; FZ: Fault Zone

AP model				GDAP model				Reference
ss	1σ	ts	1σ	ss	1σ	ts	1σ	
1	1	−5	0	2	1	−5	1	So Apennines
2	1	−4	0	2	1	−6	1	Ce Apennines
−1	1	−4	1	−2	1	−3	1	No Apennines
−2	1	−4	1	−2	1	0	1	We Alps – So
4	1	2	1	1	1	−1	1	We Alps – Ce
1	1	4	1	1	1	2	1	Ce Alps
4	1	3	1	3	1	3	1	Ea Alps
−3	1	4	1	−5	1	6	1	Dinarides
−39	1	1	1	−39	1	0	2	Kefallinia FZ
−6	1	−4	1	−5	1	−4	1	Apulia Escarpment
6	2	1	2	6	3	0	2	Epiro coast
–	–	–	–	−6	1	−3	2	Gargano FZ
−4	1	6	1	−4	1	6	1	Tunis-Egadi FZ
−6	1	1	1	−6	1	1	1	Vergilio-Etna FZ

[14] Modeling results suggest that a possible location of the southern Adriatic/Nubia boundary could be the Apulia Escarpment. This boundary has a clear topographic mark [*Van Dijk and Scheepers*, 1995] and should accommodate about 5 mm/yr of deformation. *Catalano et al.* [2001] suggest that the abrupt morphology of both Apulia and Maltese escarpments should be related to recent reactivations of such structures. While the Iblean-Maltese lineament shows seismicity and recent tectonic activity, the picture is more complicated for the Apulia escarpment. The relatively higher heat flow in the area or the fact that this lineament is partially covered by the soft sediments of the Calabrian wedge could imply aseismic deformations.

5. Conclusions

[15] We use simple models to investigate the deformation in the Mediterranean basin, and determine the kinematics of the Adriatic and other blocks located within the Eurasia-Nubia plate boundary zone. It is clear from the geodetic data and the models presented here that the Adriatic block is neither part of the Eurasia nor the Nubia plate. Geodetic data show that the Nubia plate is moving NW with respect to Eurasia with a velocity of 6 mm/yr, while the Adriatic microplate moves NE at a rate of 4–5 mm/yr [*McClusky et al.*, 2000; *Fernandes et al.*, 2003; *McClusky et al.*, 2003; *Nocquet and Calais*, 2003]. Our results show that independent microplate models of Adria offer a better fit to GPS velocities than models considering Adria as continuous with the Nubia or Eurasia plate. Geodetic data alone cannot discriminate between a single block (AP) or a two block (GDAP) description of Adria (Figure 2), but the GDAP model predicts boundary slip rates that are in better agreement with observations from previous studies. Modeling results suggest that a possible location of the southern Adriatic/Nubia boundary could be the Apulia Escarpment lineament.

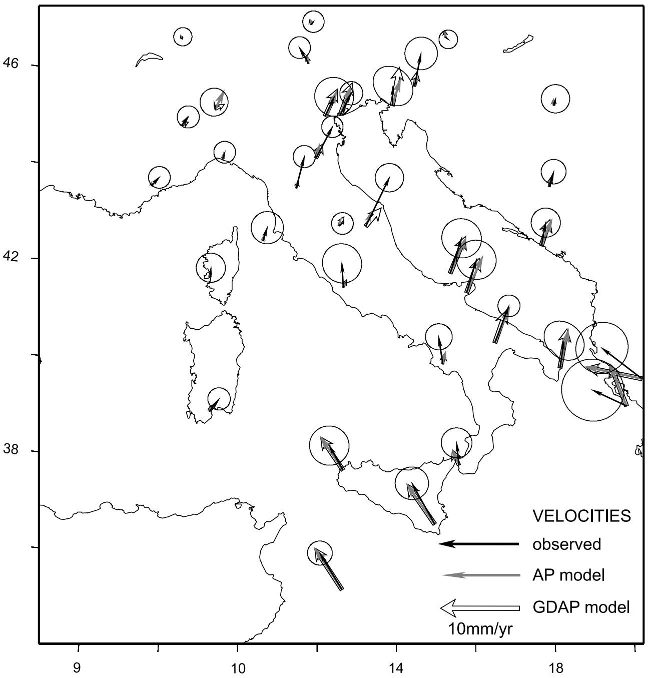

Figure 2. Observed and modeled GPS velocities for the single block (AP) and the two blocks (GDAP) model of Adria. To avoid clutter, we have omitted plotting some sites in Epiro and northeastern Adria.

[16] Although the description of the block bounding faults may be simple, it provides a first-order account of the total deformation that is being accommodated within these microplates and useful boundary conditions for more detailed models.

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