# Eocene to present subduction of southern Adria mantle lithosphere beneath the Dinarides

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## ABSTRACT

**We modeled global positioning system measurements of crustal velocity along a N13°E profile across the southern Adria microplate and south-central Dinarides mountain belt using a one-dimensional elastic dislocation model. We assumed a N77°W fault strike orthogonal to the average azimuth of the measured velocities, but we used a constrained random search algorithm minimizing misfit to the velocities to determine all other parameters of the model. The model fault plane reaches the surface seaward of mapped SW-verging thrusts of Eocene and perhaps Neogene age along the coastal areas of southern Dalmatia, consistent with SW-migrating deformation in an active fold-and-thrust belt. P-wave tomography shows a NE-dipping high-velocity slab to ~160 km depth, which reaches the surface as Adria, dips gently beneath the foreland, and becomes steep beneath the Dinarides topographic high. The thrust plane is located directly above the shallowly dipping part of the slab. The pattern of precisely located seismicity is broadly consistent with both the tomography and geodesy; deeper earthquakes (down to ~70 km) correlate spatially with the slab, and shallower earthquakes are broadly clustered around the geodetically inferred thrust plane. The model fault geometry and loading rate, ages of subaerially exposed thrusts in the fold-and-thrust belt, and the length of subducted slab are all consistent with Adria-Eurasia collision involving uninterrupted subduction of southern Adria mantle lithosphere beneath Eurasia since Eocene time.**

**Keywords:** Adria microplate, continental collision, crustal deformation, mountain building.

## INTRODUCTION

It is widely accepted that collision of Adria with Eurasia since mid-Mesozoic time created important components of the Alpine-Himalayan chain, including the southern Alps, the Apennines, and the Dinarides (Rosenbaum and Lister, 2005) (Fig. 1). However, the nature of Adria motion and its tectonic interactions with the European margin, past and present, remain poorly understood. Although most agree that Adria was a promontory of Africa from Jurassic through Cretaceous time (Channell et al., 1979), the gamut of hypotheses regarding the Cenozoic kinematics of Adria has been proposed. Previous studies have considered Adria as a single microplate kinematically distinct from Nubia (Anderson and Jackson, 1987), northern Adria as forming part of the Eurasia plate and southern Adria as forming part of the Nubia plate (Oldow et al., 2002), northern and southern Adria microplates kinematically distinct from both Nubia and Eurasia (Battaglia et al., 2004; Grenerczy et al., 2005), and there have been more complex scenarios proposed. Uncertainty regarding the first-order kinematics of Adria hampers understanding of a broad range of fundamental issues in central Mediterranean tectonics, including the role and evolution of microplates in the closing of the Tethys ocean basin, the formation of the peri-Adriatic orogens, Mediterranean seismic hazards, and a variety of geodynamic processes such as slab rollback and upper plate retreat, subduction and/or accretion of continental crust, and slab break-off.

Because the majority of Adria is currently submerged beneath the Adriatic Sea, inaccessible to direct geologic and geodetic field studies, its motion and possible internal deformation have been inferred indirectly through geological and geodetic studies of its deformed margins (e.g., Herak, 1986; Tari Kovačić and Mrinjek, 1994; Tari, 2002; Pamić et al., 1998; Oldow et al., 2002; Battaglia et al., 2004; Altiner et al., 2005; Grenerczy et al., 2005), slip vectors and moments of large historic earthquakes (e.g., Anderson and Jackson, 1987), and the spatial pattern of seismicity (e.g., Herak et al., 2005). The External Dinarides, which record the history of Adria-Eurasia collision since Late Cretaceous time, represent one of the least studied portions of the Adriatic margin and thus present one of the best opportunities for a significant advance in our understanding of Adria kinematics.

Dinarides orogenesis from Eocene through Miocene time is evident from tectonically derived sediments along the present-day foreland

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*Geology*, January 2008; v. 36; no. 1; p. 3–6; doi: 10.1130/G24136A.1; 3 figures; Data Repository item 2008005.

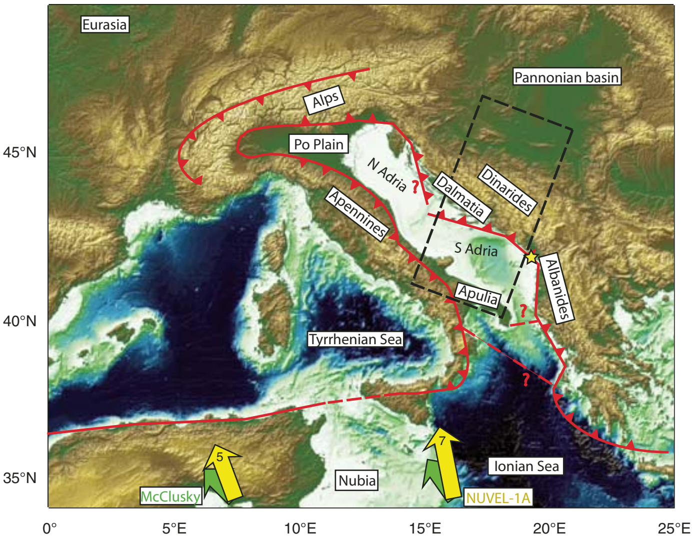

**Figure 1. Major tectonic elements and topographic and bathymetric relief for Adria region. Thick red lines approximate major tectonic boundaries (modified from Wortel and Spakman, 2000). Barbs point into hanging wall of thrust structures. Question marks and dashed lines identify boundaries not well resolved by current data sets. Dashed rectangular box identifies location of Figure 2. Yellow and green vectors show Nubia-Eurasia plate motion predicted by NUVEL-1A (DeMets et al., 1994) and McClusky et al. (2003). Numbers on vectors show approximate rates of NUVEL-1A velocities (in mm/yr). Yellow star shows location of 1971 $M_w$ 7.1 Montenegro thrust earthquake.**

deposited in orogen-parallel foredeep basins (Herak, 1986; Tari-Kovačić and Mrinjek, 1994; Tari, 2002; Pamić et al., 1998). Sparse geodetic measurements of crustal velocity and earthquake focal mechanisms reveal present-day shortening within the External Dinarides, consistent with contemporary Adria-Eurasia collision (Anderson and Jackson, 1987; Battaglia et al., 2004; Altiner et al., 2005; Grenerczy et al., 2005). The relationship between these diverse observations, which represent vastly different epochs of time, has not previously been addressed in detail.

The goal of this work is to improve understanding of the post-Eocene kinematics of southern Adria and its relationship to Dinarides orogenesis using new measurements of crustal velocity determined from campaign and continuous global positioning system (GPS) measurements in southern Adria and the Dinarides. We use a model for crustal deformation and a recently published tomographic model for central Mediterranean mantle P-wave velocity structure to formulate a new tectonic interpretation of Adria-Dinarides interaction since Eocene time. This interpretation, with implications for the kinematic history of Adria, relates contemporary deformation to orogenesis on the scale of millions of years.

## OBSERVATIONS

We concentrate on campaign measurements from a subset of stations belonging to the CRODYN GPS network (Fig. 2). The subset of stations is located primarily in southern Dalmatia, and forms a transect across southern Adria and the south-central Dinarides. The CRODYN network was observed in 1994, 1996, 1998, and 2005. Supplementary observations for sites CSRA and HVAR were also conducted as part of the Central European GPS Geodynamic Reference Network (CEGRN) project (Grenerczy et al., 2005). All measurement campaigns typically consisted of multiple 24 h observation sessions. Our analysis represents an update of the results reported by Altiner et al. (2005), who used CRODYN data from 1994 to 1998. The density of CRODYN stations in southern Dalmatia is significantly higher than for the CEGRN GPS network used by Grenerczy et al. (2005). In addition to CRODYN measurements, we also use continuous GPS data from stations located throughout the study region for the period of 1994–2006 (Fig. 2), which represents a longer period of observation than previous continuous GPS-based studies of Adria microplate motion and/or peri-Adriatic crustal deformation (e.g., Battaglia et al., 2004).

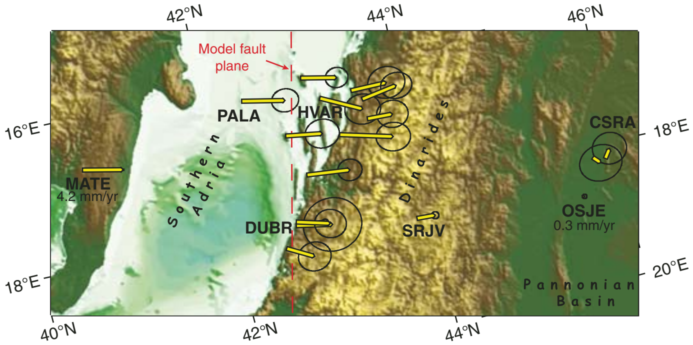

**Figure 2. Velocity estimates for select sites from CRODYN network and continuous global positioning system stations in southern Adria and the south-central Dinarides. Error ellipses represent 95% confidence. Velocity reference frame is Eurasia fixed. Some sites are identified by four characters. Oblique map projection is parallel to the average of site velocities and the profile of Figure 3.**

We estimated secular site velocities using the GAMIT/GLOBK software, version 10.2, following the procedure outlined by Bennett and Hreinsdóttir (2007). Velocity estimate uncertainties were determined by least squares propagation of an empirically determined elevation-angle dependent phase noise model, and the velocities were realized in a Eurasia fixed reference frame (Bennett and Hreinsdóttir, 2007). Horizontal velocity estimates relative to the Eurasia frame are shown in Figure 2 with 95% confidence ellipses. Velocities in southern Adria, southern Dalmatia, and the south-central Dinarides are generally oriented NE relative to the Eurasia frame, orthogonal to the general trend of the Dinarides chain. The rates decrease from SW to NE; the rate at site MATE in Apulia, Italy, is 4.17 ± 0.03 mm/yr, whereas the rate at OSJE in Osijek, Croatia, is 0.3 ± 0.1 mm/yr (see GSA Data Repository Table DR1[1]). The difference in these rates provides a first-order estimate for the amount of present-day shortening accommodated across southern Adria and the Dinarides. A gradient in the GPS velocity field is apparent across southern Dalmatia, but the rate of motion observed as far inland as site SRJV is 1.9 ± 0.1 mm/yr.

We resolved the GPS velocity estimates onto coordinate axes oriented N13°E and N77°W, which are parallel and orthogonal, respectively, to the average azimuth of the crustal velocity measurements. Figure 2 shows the velocities in an oblique projection aligned with this system. The root mean square scatter of the N77°W components of velocity is 0.2 mm/yr, an order of magnitude smaller than for the N13°E range-perpendicular components. Figure 3 shows the N13°E components versus N13°E distance along the profile. Velocity gradients in the N77°W direction are insignificant (±2 µm/yr km$^{-1}$) and indicate negligible out-of-plane strain.

We used a constrained random search algorithm (Brachetti et al., 1997) and a one-dimensional model for interseismic strain accumulation on a buried dip-slip fault in an elastic half-space (Savage, 1983) to determine the slip rate, dip, location, and locked zone for a best-fit

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[1] GSA Data Repository item 2008005, Table DR1, Adria–southern Dalmatia crustal velocity estimates, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

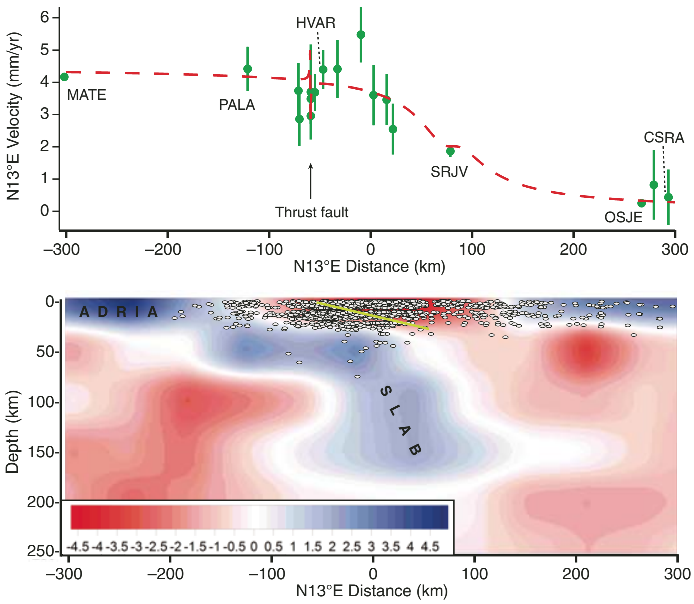

**Figure 3. Thrust fault model for the southern Dinarides. A: The N13°E components of global positioning system velocity as a function of N13°E distance. Error bars represent one standard deviation. Dashed line represents best-fit crustal velocity model determined by constrained random search. Spike in the curve near –59 km indicates location of surface trace of the fault and represents short wavelength deformation associated with creeping near surface portion of model fault. CRODYN sites are indicated by four characters (see Fig. 2). B: Two-dimensional (2-D) slice through the 3-D mantle tomography model of Piromallo and Morelli (2003) showing subduction of a slab of southern Adria affinity beneath the Dinarides to ~160 km depth. Circles show precisely located earthquakes. Color scale shows percent velocity variation. We filtered out all earthquakes in the depth bands defined by <2 km, 8.5–11.5 km, 18.5–21.5 km, and 28.5–31.5 km, because events with poorly determined locations were biased toward these depths due to a priori constraints applied in the location algorithm. Deeper earthquakes (>30 km) generally correlate with location of the slab. Thick dashed line represents location of the geodetically inferred thrust plane, which correlates with top of shallowly dipping portion of the slab.**

model to the N13°E components of velocity. The only parameter of the fault model not determined by random search was the strike of the fault, which was assumed to be N77°W, orthogonal to the profile. Figure 3 shows the model for crustal velocities calculated using the estimated model parameters. The square root of the chi-square per degree of freedom of the misfit to the crustal velocity data, which we use as an a posteriori estimate for the data variance scale factor, is 1.1. This value indicates that the uncertainties associated with our velocity estimates adequately represent the errors in the measurements, and that the dislocation model does a reasonable job of representing the deformation signal recorded by the data to within their uncertainties.

## RESULTS AND CONCLUSIONS

The estimated location of the model fault trace is ~0.3 km southwest of GPS site DUBR, which is located on the Dalmatia coast. The location is within the densest part of the GPS network and is thus well determined (±1 km with 95% confidence). The best-fit model thrust reaches the surface seaward of mapped SW-verging thrust faults. The mapped faults place Cretaceous and Tertiary carbonates over Eocene flysch along the coastal areas of southern Dalmatia. The geometric relationship between the modern deformation front and these older thrust faults is consistent with SW-migrating deformation in an active fold-and-thrust belt.

The best-fit model creeps freely across the upper 0.8 km of the model fault, possibly representing the effect of a near-surface layer of unconsolidated sediments (Marone and Scholz, 1988). The 95% confidence region for the width of this creeping zone covers the range ~0.5–3 km. There is no apparent topographic expression of the thrust fault in the available bathymetry for the region. The inferred loading rate and fault plane dip are positively correlated, but the 95% confidence regions cover the narrow ranges of 4.2–5.0 mm/yr and 8°–15°, respectively. The best-fit loading rate is 4.5 mm/yr. The best-fit dip is 9°. The locking depth measured vertically from the surface is 22 km, with 95% confidence region covering the broad range of 21–37 km. Based on these values, we calculate a downdip width for the locked portion of the model fault of 138 km.

All known earthquakes within the Dinarides have magnitude ≤~M7 (Kuk et al., 2000). Dinarides seismicity is most intense in the southern Dalmatia fold and thrust belt. The largest known earthquakes may have involved slip on our geodetically inferred model thrust plane. The 1667 Dubrovnik earthquake had an epicentral intensity of X on the Modified Mercalli scale, which may underestimate the size of the event because the city was subsequently devastated by fire. High-intensity shaking and damage occurred across at least 100 km of the coast, and there were eyewitness accounts of harbor-docked ships touching the seafloor multiple times following the event (M. Herak, 2007, personal commun.). These observations are consistent with an event of magnitude ~M7 that likely displaced the seafloor near Dubrovnik.

The 1979 $M_w$7.1 Montenegro earthquake could also have occurred on the same fault plane off the coast of Montenegro, ~120 km SE of Dubrovnik. The 1979 earthquake involved a pure thrust mechanism with a maximum slip of 2.7 m (Benetatos and Kiratzi, 2006). The most recent estimate for the strike of the rupture plane based on available teleseismic records is 120° (Benetatos and Kiratzi, 2006), similar to but somewhat larger than the 103° (N77°W) strike of our model thrust plane. This difference could indicate an ~17° obliquity between the thrust belt strike and the plate convergence direction, but uncertainties in both the seismological and geodetic inferences currently preclude more conclusive statements. The focal mechanism of the Montenegro earthquake indicates either a fairly steep (SW dipping) or shallow (NE dipping) rupture; the most recent estimate for the dip of the shallow rupture plane is 14° NE (Benetatos and Kiratzi, 2006), similar to our 9° NE-dipping model thrust.

Earthquakes of M ≤ 7 are probably not capable of rupturing the entire width that we have estimated for the locked portion of the fault all at once during a single earthquake. Anderson and Jackson (1987) estimated a seismic strain accumulation rate for the southern Dinarides of half our geodetically inferred slip rate based on summed moments of earthquakes over the past two decades, but such estimates depend critically on the short duration of the seismic record. Extension of the analysis to earthquakes that are known to have occurred prior to instrumental seismology is difficult because we do not have an accurate indication of the moments of these past events. The seismic versus geodetic moment deficit indicates either accumulation of elastic strain that will be released by one or more future earthquakes, or it could represent the amount of strain accumulated by aseismic deformation.

The location and geometry of the model thrust plane correlate remarkably well with the recent tomographic model for the central Mediterranean lithosphere of Piromallo and Morelli (2003) (Fig. 3). The tomography shows subducting southern Adria lithosphere beneath the Dinarides. The imaged slab shallows near the Dalmatian coast, consistent with the location of the Dalmatian fold and thrust belt and the surface trace of the model thrust plane. The slab dips gently NE beneath the foreland, and then more steeply below the topographic crest of the mountain belt. The location of the locked portion of the geodetically inferred thrust plane correlates remarkably well with the top of the shallowly dipping portion of the tomographically imaged slab; the downdip edge of the locked zone marks the change in slab dip from gentle to steep.

The tomographically imaged slab extends to a depth of ~160 km, which at the current rate of southern Adria–Eurasia convergence implies initiation of subduction during middle to late Eocene time, consistent with the ages of mapped thrusts along the southern Dalmatia coast. These observations support uninterrupted subduction of Adria mantle lithosphere beneath the Dinarides. The emergence of Quaternary right-lateral strike-slip faults in the External Dinarides may indicate a slight counterclockwise rotation of the convergence direction since ca. 2 Ma (Picha, 2002).

The southern Adria microplate is covered by a thick layer of buoyant carbonate rocks (~10 km), which are likely underlain by another ~20–30 km or more of continental basement. However, the thickness of continental crust is difficult to quantify for southern Adria because the Moho is poorly defined; seismic velocities typical of continental crust transition into velocities typical of mantle material over a wide (~30 km) zone (Venisti et al., 2005). Nevertheless, it is unlikely that buoyant crustal material would be able to subduct uninterruptedly since Eocene time (e.g., Molnar and Gray, 1979). We speculate that subduction of Adria mantle lithosphere must involve detachment and transfer of an appreciable thickness of crustal material from Adria to the Dalmatian fold-and-thrust belt.

## ACKNOWLEDGMENTS

CRODYN campaigns were funded by the Croatian Geodetic Administration. We used some data from the Central European GPS Geodynamic Reference Network project and stations of the EUREF Permanent Network (EPN) and other continuous global positioning system networks. The U.S.-based authors were supported by National Science Foundation grants EAR-0441965 and EAR-0533089 to the University of Arizona and EAR-0208299 to University of Washington associated with Continental Dynamics Program project RETREAT. C. Piromallo provided data files and software aiding our analysis of the Piromallo and Morelli (2003) tomography model. M. Herak provided precise earthquake locations and relayed historical accounts of the Dubrovnik earthquake. We benefited from informative conversations with N. Fay, M. Brandon, B. Tomljenović, I. Vlahović, and V. Tari-Kovačić. M. Brandon provided software subroutines for constrained random search. Some figures were made in part with the Generic Mapping Tools (GMT) software. We thank Maurizio Battaglia and Seth Stein for constructive reviews.

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Manuscript received 11 June 2007
Revised manuscript received 3 August 2007
Manuscript accepted 11 August 2007

Printed in USA