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Present geodynamics of the northern Adriatic plate

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ABSTRACT

The northern Adriatic plate is surrounded and squeezed by three orogens (i.e. Apennines, Alps and Dinarides). Therefore, in the same area, the effects of three independent subduction zones coexist and overlap. This supports the evidence that plate boundaries are passive features.

The northeastward migration of the Apennines subduction hinge determines the present-day faster subsidence rate in the western side of the northern Adriatic (>1 mm/yr). This is recorded also by the dip of the foreland regional monocline, and the increase SW-ward of the depth of the Tyrrhenian layer, as well as the increase in thickness of the Pliocene and Pleistocene sediments. These data indicate the dominant influence of the Apennines subduction and the related asymmetric subsidence in the northern Adriatic realm. The Dinarides front has been subsided by the Apennines subduction hinge, as shown by the eroded Dalmatian anticlines in the eastern Adriatic Sea. GPS data show the horizontal pattern of motion along the front of the three belts surrounding the northern Adriatic plate. Values of shortening along the prisms are in the order of 2-3 mm/yr (Northern Apennines), 1-2 mm/yr (Southern Alps) and <1mm/yr (Dinarides). The pattern of the new GPS velocities relative to Eurasia account for different tectonic domains and the estimated strain rates are within 0.1 µstrain/yr. The shortening directions tend to be perpendicular to the thrust belt fronts, as expected. The areas where the strain rate sharply decreases across a tectonic feature (e.g., the Ferrara salient) are considered structures seismically loading the brittle layer.

Key words: *Adriatic plate, Plate boundaries, thrust tectonics, subsidence, strain rate*

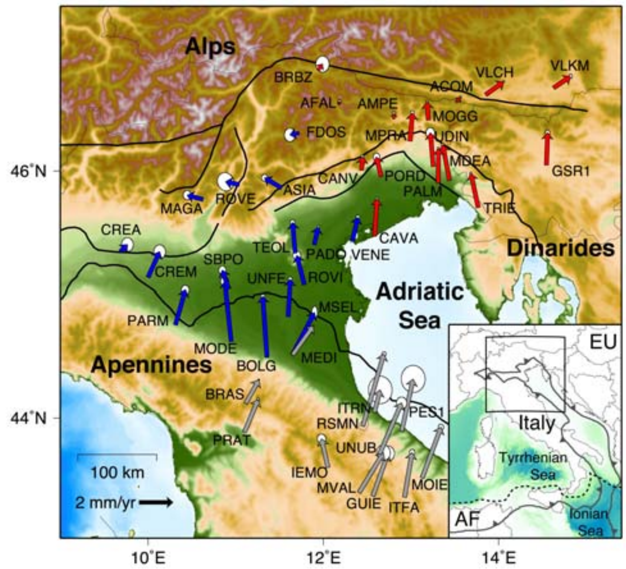

Fig. 1 – GPS velocities relative to Eurasia and the rescaled error ellipses, in the northern Adriatic realm, where three subduction zones interacts (Apennines, Alps and Dinarides). Velocities are divided in three clusters (red cluster 1, blue cluster 2, and gray cluster 3) to estimate local strain rates.

GPS DATA AND STRAIN RATE

The largest GPS time span covers an interval of 11 years (1998–2008), nevertheless most of the data come from the recent RING network (http://ring.gm.ingv.it) settled in Italy in the last five years by INGV. The GPS data processing follows basically the procedure proposed in DEVOTI *et alii* (2008).

We have analyzed the GPS observations at 30 s sampling rates in the framework of the processing of all the Italian permanent stations. We have processed the data with the Bernese Processing Engine (BPE) of the Bernese software, version 5.0 (BEUTLER *et alii*, 2007) based on the double difference observables. We have estimated each daily cluster in a loosely constrained reference frame, imposing a priori uncertainties of 10 m to obtain the so–called loosely constrained solution. The daily *loosely constrained* cluster solutions are then merged into global daily *loosely constrained* solutions of the whole network applying the classical least squares approach (DEVOTI *et alii*, 2008). The daily combined network solutions are then rigidly transformed into the ITRF2005 frame (ALTAMIMI *et alii* 2007), estimating translations and scale parameters.

The velocity field is estimated from the ITRF2005 time series of the daily coordinates, with the complete covariance matrix, simultaneously estimating site velocities, annual signals and offsets at epochs of instrumental changes, as in DEVOTI *et alii* (2008) and in RIGUZZI *et alii* (2009).

We have scaled the formal errors of the GPS rates using the mean scale factors estimated for each velocity component, as in DEVOTI *et alii* (2008), according to the approach developed in WILLIAMS (2003).

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The GPS site positions and velocities with respect to the Eurasian fixed reference frame, as defined in DEVOTI *et alii* (2008), with their re-scaled uncertainties are reported in Fig. 1.

We estimate the strain rate field solving the two–dimensional velocity gradient tensor equations, with an inverse procedure, based on the standard least squares approach. The GPS velocities are separated in 3 clusters, accounting for the main tectonic domains (Fig. 1). We use a regularly spaced gridded interpolation method, based on the distance weighted approach (SHEN *et alii*, 1996; ALLMENDINGER *et alii*, 2007; CARDOZO & ALLMENDINGER, 2009). We define a regular grid (30´30 km) estimating the strain rate principal axes at the center of each cell, using all the GPS velocities pertaining to each cluster. The velocity of each station is weighted by the factor $W = \exp(-d^2/2\alpha^2)$, where d is the distance between each GPS site and the center of the cell, and *a* (22 km) is the damping parameter defining how the contribute of each station decays with distance from the cell center.

The pattern of the strain rate principal axes (Fig. 2) shows that most of shortening directions tend to be perpendicular to the thrust belt fronts, reaching 82±11 nstrain/yr in cluster 1 (Eastern Veneto, Friuli, Southern Austria), 44±8 nstrain/yr in cluster 2 (Western Veneto, Lombardy, Emilia-Romagna) and with lower values offshore, in cluster 3 (Marche), where the GPS velocities are not able to constrain with good accuracy the deformation rate. The extension rate axes reach the maximum value of 45±19 nstrain/yr in cluster 1; minor rates are 35±15 nstrain/yr in cluster 2 and 56±18 nstrain/yr in cluster 3.

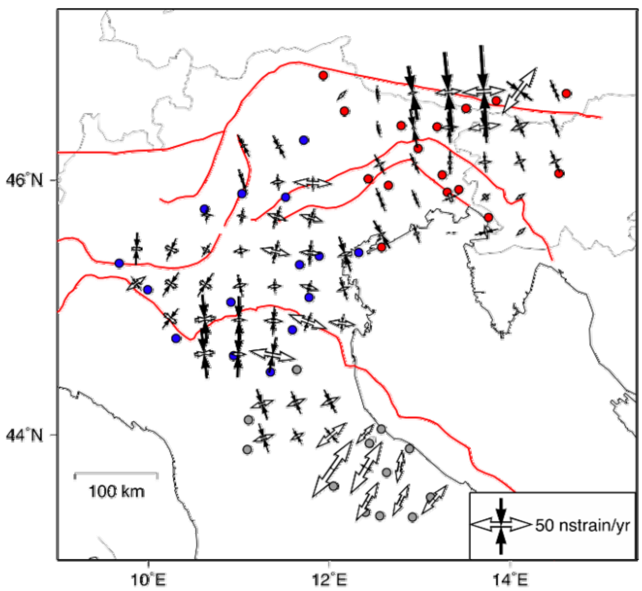

Fig. 2 – Principal axes of strain rates from GPS velocities in the northern Adriatic area estimated on a regularly spaced grid (30´30 km). Black and white arrows represent shortening and extension rate principal axes. Red, blue, and gray dots are the GPS stations of the cluster 1, cluster 2 and cluster 3 respectively. Note the smaller strain rate along the Ferrara salient, which may indicate tectonic loading.

TECTONIC SETTING

The northern Adriatic is the foreland area of three different orogens, i.e., the Apennines, the Alps, and the Dinarides. In fact it represents the foredeep and foreland of the W-directed Apennines subduction (CARMINATI *et alii*, 2003), the retrobelt foreland of the SE-directed Alpine subduction (CARMINATI & DOGLIONI, 2002; DAL PIAZ *et alii*, 2003; KUMMEROW *et alii*, 2004), and the foreland basin of the NE-directed Dinaric subduction (DI STEFANO *et alii*, 2009). These three belts are currently active, although at different rates (D'AGOSTINO *et alii*, 2005; DEVOTI *et alii*, 2008). Each subduction has its own vertical rates, e.g., subsidence in the foreland basin and uplift in the belt. All three belts propagate toward the Adriatic lithosphere (PANZA *et alii*, 1982; 2003; 2007), which was stretched and thinned by the Tethyan rift during the Mesozoic (e.g., WINTERER & BOSELLINI, 1981). Therefore, the northern Adriatic is contemporaneously undergoing the effects of three independent subduction zones that surround it. However, among the three belts, the Apennines are the only subduction where the slab hinge is migrating away relative to the upper plate. This kinematic character is typical of W-directed subduction polarity, and have fast (>1 mm/yr) subsidence rate in the depocenter of the foredeep basin (DOGLIONI *et alii*, 2007). In fact, the underlying section of Pleistocene sediments thickens when moving from NE to SW, toward the Apennines (Fig. 3). The dip of the regional monocline (1.5°) underlies this asymmetric subsidence, supporting the steepening of the lithospheric top when moving towards the subduction hinge (Fig. 4). The pinch-out of the Pleistocene sediments points for syn-tectonic deposition. The faster subsidence recorded by the Tyrrhenian layer towards the Apennines confirms the whole Pleistocene record, highlighting an asymmetric subsidence. Therefore, in spite of the three competing subductions acting along the northern Adriatic plate boundaries, the Apennines slab is the most effective geodynamic process in determining the subsidence of the northern Adriatic area (CARMINATI *et alii*, 2003; 2005). The NE-ward migration of the subduction hinge in the northern Apennines determines a corresponding trend in the subsidence rates, which decrease moving toward the foreland from >1 mm/yr, to less than 0.5 mm/yr (Fig. 4). In the central part of the northern Adriatic Sea, the Tyrrhenian layer has been found at shallower depth than expected. This is consistent with the local uplift due to an active anticline at the front of the Apennines accretionary wedge, as documented by industrial seismic reflection profiles. The Dinarides front has been shown active both from surface, seismic reflection and seismological data (e.g., MERLINI *et alii*, 2002; Galadini *et alii*, 2005). The Southern Alps front is also notoriously very active as proved by seismicity (BRESSAN *et alii*, 1998; SLEJKO *et alii*, 1999) and geological and geophysical evidences (DOGLIONI, 1992; GALADINI *et alii*, 2005; CASTELLARIN *et alii*, 2006).

The hinge of the northern Apennines slab is still moving toward the NE, away from the upper plate, determining the subsidence in the downgoing lithosphere that decreases moving toward the foreland. The northern Adriatic lithosphere is also suffering the effects of the subductions of the Alps and the Dinarides. The asymmetry of the Pleistocene subsidence, however, indicates that the Apennines have the most relevant role in shaping the vertical rates in the northern Adriatic realm.

In fact, the Dinarides have been tilted by the Apennines subduction hinge, and the thrust-belt front, after being sub-aerially eroded, it has been subsided (Fig. 5). This is marked by the thinning toward the east of the Pliocene-Pleistocene sediments thickness in the Adriatic Sea, and the subsidence of the previously eroded anticlines of the Dinarides front, as visible along the Dalmatian islands.

Therefore the northern Adriatic is an area undergoing the overlap of three independent geodynamic mechanisms. The coexistence in the same area of more than one plate boundary effects can be read as evidence that plate boundaries are passive features.

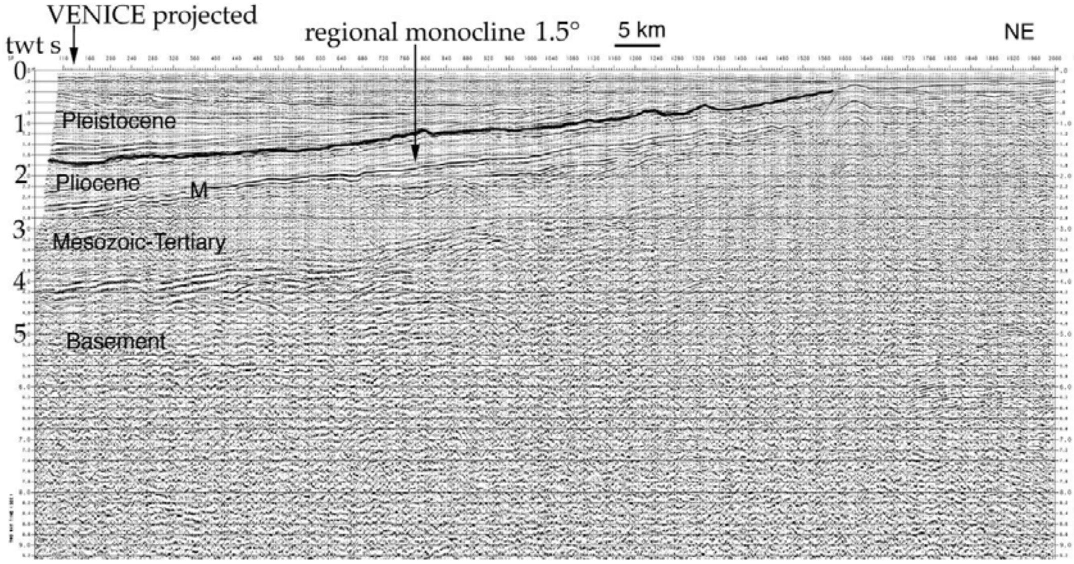

Fig. 3 – Seismic reflection profile (CROP M-18) of the northern Adriatic Sea. Location in Fig. 4. Note the regional dip of the basement and the overlying cover up to the Pliocene toward the southwest. The Pleistocene sediments pinch-out moving northeastward, indicating syn-tectonic deposition coeval to the differential subsidence in the underlying rocks. M, Messinian unconformity. Vertical scale in seconds, two way time (after CARMINATI *et alii*, 2003).

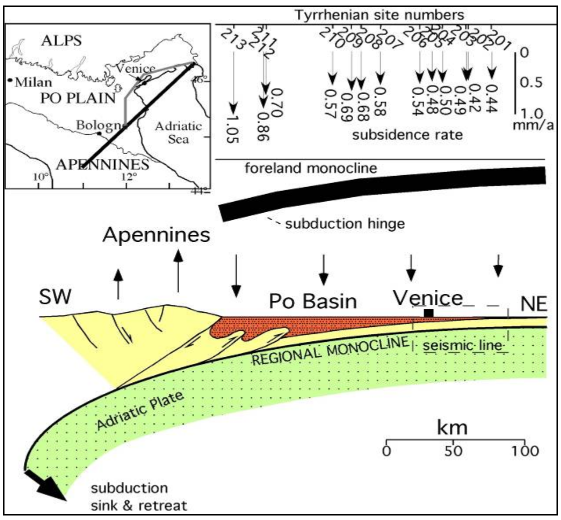

Fig. 4 – The values below the Tyrrhenian site numbers indicate the subsidence rates determined by the depth of the Tyrrhenian layer cored mostly along the grey line along the coast (data after ANTONIOLI *et alii*, 2009). This indicates faster subsidence in the southwestern part of the profile, i.e., an asymmetric active subsidence. The dip of the regional monocline in the northern Adriatic Sea recorded the faster subsidence to the left and it can be associated to the northeastward slab retreat of the Adriatic slab. The seismic line location shows the position in this profile of the cross-section shown as Fig. 3.

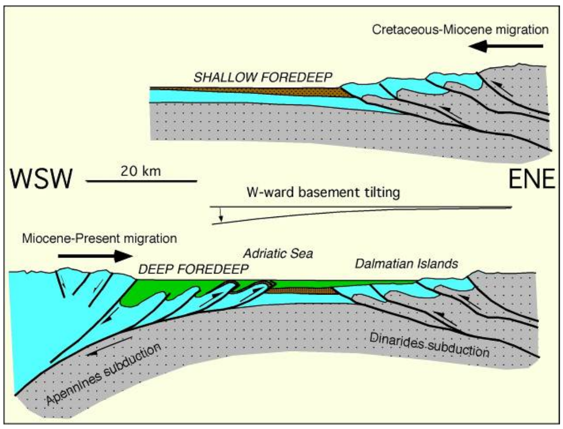

Fig. 5 – Schematic cross section from the western to the eastern Adriatic Sea, showing the two accretionary prisms at the front of the Apennines and Dinarides subduction zones. The Dinardides are older and have been downward tilted by the regional monocline of the Apennines subduction hinge retreat.

REFERENCES

ALLMENDINGER R.W., REILINGER R., & LOVELESS J. (2007) - *Strain and rotation rate from GPS in Tibet, Anatolia, and the Altiplano*. Tectonics, **26**, doi:10.1029/2006TC002030.

ALTAMIMI Z., COLLILIEUX X., LEGRAND, J., GARAYT B., & BOUCHER C. (2007) - *ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters*. J. Geophys. Res., **112**, doi:10.1029/2007JB004949.

ANTONIOLI F. ET ALII (2009) – *Relative sea-level rise and asymmetric subsidence in the northern Adriatic*. Submitted.

BEUTLER ET ALII (2007) – Bernese GPS software. In: Dach R., Hugentobler U., Fridez P. & Meindl M. (Eds), Astronomical Institute, University of Bern.

BRESSAN, G., SNIDARCIG, A. & VENTURINI, C. (1998) - *Present state of tectonic stress of the Friuli area (eastem Southern Alps)*. Tectonophysics, **292**, 211-227.

CARDOZO N. & ALLMENDINGER R.W. (2009) - *SSPX: A program to compute strain from displacement/velocity data*. Computers & Geosciences, **35**, 1343-1357.

CARMINATI E., DOGLIONI C. & SCROCCA D. (2003) - *Apennines subduction-related subsidence of Venice*. Geophys. Res. Lett. **30**, 13, 1717, doi:10.1029/2003GL017001.

CARMINATI E., DOGLIONI C. & SCROCCA D. (2005) - *Magnitude and causes of long-term subsidence of the Po Plain and Venetian region*. In: Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge, ed. C. A. Fletcher and T. Spencer with J. Da Mosto and P. Campostrini. Cambridge University Press.

CASTELLARIN A., NICOLICH R., FANTONI R., CANTELLI L., SELLA M. & SELLI L. (2006) - *Structure of the lithosphere beneath the Eastern Alps (southern sector of the TRANSALP transect)*. Tectonophysics, **414**, 259-282.

D'AGOSTINO N., CHELONI D., MANTENUTO S., SELVAGGI G., MICHELINI A. & ZULIANI D. (2005) - *Interseismic strain accumulation in the eastern Southern Alps (NE Italy) and deformation at the eastern boundary of the Adria block observed by CGPS measurements*. Geophys. Res. Lett., **32**, L19306, doi:10.1029/2006GL024266.

DAL PIAZ G.V., BISTACCHI A. & MASSIRONI M. (2003) - *Geological outline of the Alps*. Episodes, **26**, 3, 175-180.

DEVOTI C., RIGUZZI F., CUFFARO M. & DOGLIONI C. (2008) - *New GPS constraints on the kinematics of the Apennines subduction*. Earth Planet. Sci. Lett., **273**, 163–174.

DI STEFANO R., KISSLING E., CHIARABBA C., AMATO A. & GIARDINI D. (2009) - *Shallow subduction beneath Italy: Three-dimensional images of the Adriatic-European-Tyrrhenian lithosphere system based on high-quality P wave arrival times*. J. Geophys. Res., **114**, B05305, doi:10.1029/2008JB005641.

DOGLIONI C. (1992) - *The Venetian Alps thrust belt*. In: K.R. McClay (Ed), Thrust Tectonics, Chapman & Hall, 319-324, London.

DOGLIONI C. (1992) - *Relationships between Mesozoic extensional tectonics, stratigraphy and Alpine inversion in the Southern Alps*. Eclog. Geol. Helv., **85**, 1, 105-126.

DOGLIONI C. & CARMINATI E. (2002) - *The effects of four subductions in NE Italy*. Transalp Conference, Mem. Sci. Geol., **54**, 1-4.

DOGLIONI C., CARMINATI E., CUFFARO M. & SCROCCA D. (2007) - *Subduction kinematics and dynamic constraints*. Earth Sci. Rev., **83**, 125-175, doi:10.1016/j.earscirev.2007.04.001.

GALADINI F., POLI M.E. & ZANFERRARI A. (2005) - *Seismogenic sources potentially responsible for earthquakes with M>6 in the eastern Southern Alps (Thiene-Udine sector, NE Italy).* Geophys. J. Int., **160**, 1-24, doi: 10.1111/j.1365-246X.2005.02571.x.

KUMMEROW J., KIND R., ONKEN O., GIESE P., RYBERG T., WYLEGALLA K., SCHERBAUM F. & TRANSALP WORKING GROUP (2004) - *A natural and controlled source seismic profile through the Eastern Alps: TRANSALP*. Earth Planet. Sci. Lett., 225, 115- 129.

MERLINI S., DOGLIONI C., FANTONI R. & PONTON M. (2002) - *Analisi strutturale lungo un profilo geologico tra la linea Fella-Sava e l'avampaese adriatico (Friuli Venezia Giulia-Italia)*. Mem. Soc. Geol. It., **57**, 293-300.

PANZA, G.F., MUELLER, S., CALCAGNILE,G. & KNOPOFF, L. (1982) - *Delineation of the north central Italian upper mantle anomaly*. Nature, **296**, 238–239.

PANZA, G.F., PECCERILLO, A., AOUDIA, A., & FARINA B. (2007) - Geophysical and petrological modelling of the structure and composition of the crust and upper mantle in complex geodynamic settings: the Tyrrhenian Sea and surroundings, Earth Sci. Rev., **80**, 1-46.

PANZA, G.F., PONTEVIVO, A., CHIMERA, G., RAYKOVA, R., AOUDIA, A. (2003) - *The Lithosphere–Asthenosphere: Italy and surroundings*. Episodes, **26**(3), 169–174.

RIGUZZI, F., PIETRANTONIO, G., DEVOTI, R., ATZORI, S., ANZIDEI, M. (2009) - *Volcanic unrest of the Colli Albani (central Italy) detected by GPS monitoring test.* PEPI, in press, doi:10.1016/j.pepi.2009.07.012.

SHEN Z.-K., JACKSON D.D. & GE B.X. (1996) - *Crustal deformation across and beyond the Los Angeles basin from geodetic measurements*. J. Geophys. Res., **101**, 27957–27980.

SLEJKO, D., NERI, G., OROZOVA, I., RENNER, G. & WYSS M. (1999) - *Stress Field in Friuli (NE Italy) from fault plane solutions of activity following the 1976 main shock.* Bull. Seismol. Soc. Am., **89**, 4.

WINTERER L. & BOSELLINI A. (1981) – *Subsidence and Sedimentation on Jurassic Passive Continental Margin, Southern Alps Italy.* AAPG Bull., **65**, 394-421.