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Kinematics, seismotectonics and seismic potential of the eastern sector of the European Alps from GPS and seismic deformation data

E. Serpelloni [a,*], G. Vannucci [b], L. Anderlini [a], R.A. Bennett [c]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy
[c] Dept. of Geoscience, University of Arizona, Tucson, AZ, USA

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ABSTRACT

We present a first synoptic view of the seismotectonics and kinematics of the eastern sector of the European Alps using geodetic and seismological data. The study area marks the boundary between the Adriatic and the Eurasian plates, through a wide zone of deformation including a variety of tectonic styles within a complex network of crustal and lithospheric faults. A new dense GPS velocity field, new focal mechanisms and seismic catalogues, with uniformly re-calibrated magnitudes (from 1005), are used to estimate geodetic and seismic deformation rates and to develop interseismic kinematic and fault locking models. Kinematic indicators from seismological and geodetic data are remarkably consistent at different spatial scales. In addition to large-scale surface motion, GPS velocities highlight more localized deformation features revealing a complex configuration of interacting tectonic blocks, for which new constraints are provided in this work accounting for elastic strain build up at faults bonding rotating blocks. The geodetic and seismological data highlight two belts of higher deformation rates running WSW-ENE along the Eastern Southern Alps (ESA) in Italy and *E*-W in Slovenia, where deformation is more distributed. The highest geodetic strain-rates are observed in the Montello-Cansiglio segment of the ESA thrust front, for which the higher density of the GPS network provides indications of limited interseismic locking. Most of the dextral shear between the Eastern Southern Alps and the Eastern Alps blocks is accommodated along the Fella-Sava fault rather than the Periadriatic fault. In northern Croatia and Slovenia geodetic and seismological data allow constraining the kinematics of the active structures bounding the triangular-shaped region encompassing the Sava folds, which plays a major role in accommodating the transition from Adria- to Pannonian-like motion trends. The analysis of the seismic and geodetic moment rates provides new insights into the seismic potential along the ESA front.

1. Introduction

Continental earthquakes are one of the most widely observable indicators of active intraplate deformation. Although sparser in time than large earthquakes occurring at the edges of oceanic and continental plates, the economic and social impacts of earthquakes within diffuse zones of continental deformation is huge, because of the presence of important and ancient human and industrial settlements, key transportation infrastructures, and a unique historical and monumental heritage, with consequent high exposure to significant damages (e.g., Bilham, 2013). Diffuse deformation, slow tectonic rates, and long repeat times of large earthquakes make the estimates of seismic hazard at continental plate boundaries a challenging task. This is the case of the Alps, which are a classic example of a broadly deforming continental collisional belt (Schmid et al., 2004). Present-day convergence between the Adriatic microplate and the Eurasian plate is mainly accommodated in the eastern European Alps (D'Agostino et al., 2005; Bechtold et al., 2009; Cheloni et al., 2014), where the Adriatic lithosphere underthrusts the Alpine mountain belt. The northernmost tip of this convergent margin is located at the border between Italy, Austria and Slovenia. Here, the S-verging fold-and-thrust belt of the Eastern Southern Alps (ESA), the W-SW-verging Dinaric belt and the ~*E*-W structures belonging to the Carpathians system interact, creating a puzzlingly diffuse tectonic boundary.

The ESA is the locus of strong (M > 6) earthquakes occurred in the past (Fig. 1). Information from historical sources and modern earthquake catalogues show that there were at least 12 earthquakes with a magnitude of ≥6 in the past thousand years. The last one took place in 1976 in northern Italy (Mw 6.46, Rovida et al., 2011), followed by two aftershocks with magnitudes >6 within a few months (Pondrelli et al., 2001). This earthquake sequence claimed 989 lives and injured 2400 people; about 45,000 were left homeless as a result. Although the extent

* Corresponding author at: Istituto Nazionale di Geofisica e Vulcanologia, Via D. Creti 12, 40128 Bologna, Italy.
E-mail address: enrico.serpelloni@ingv.it (E. Serpelloni).

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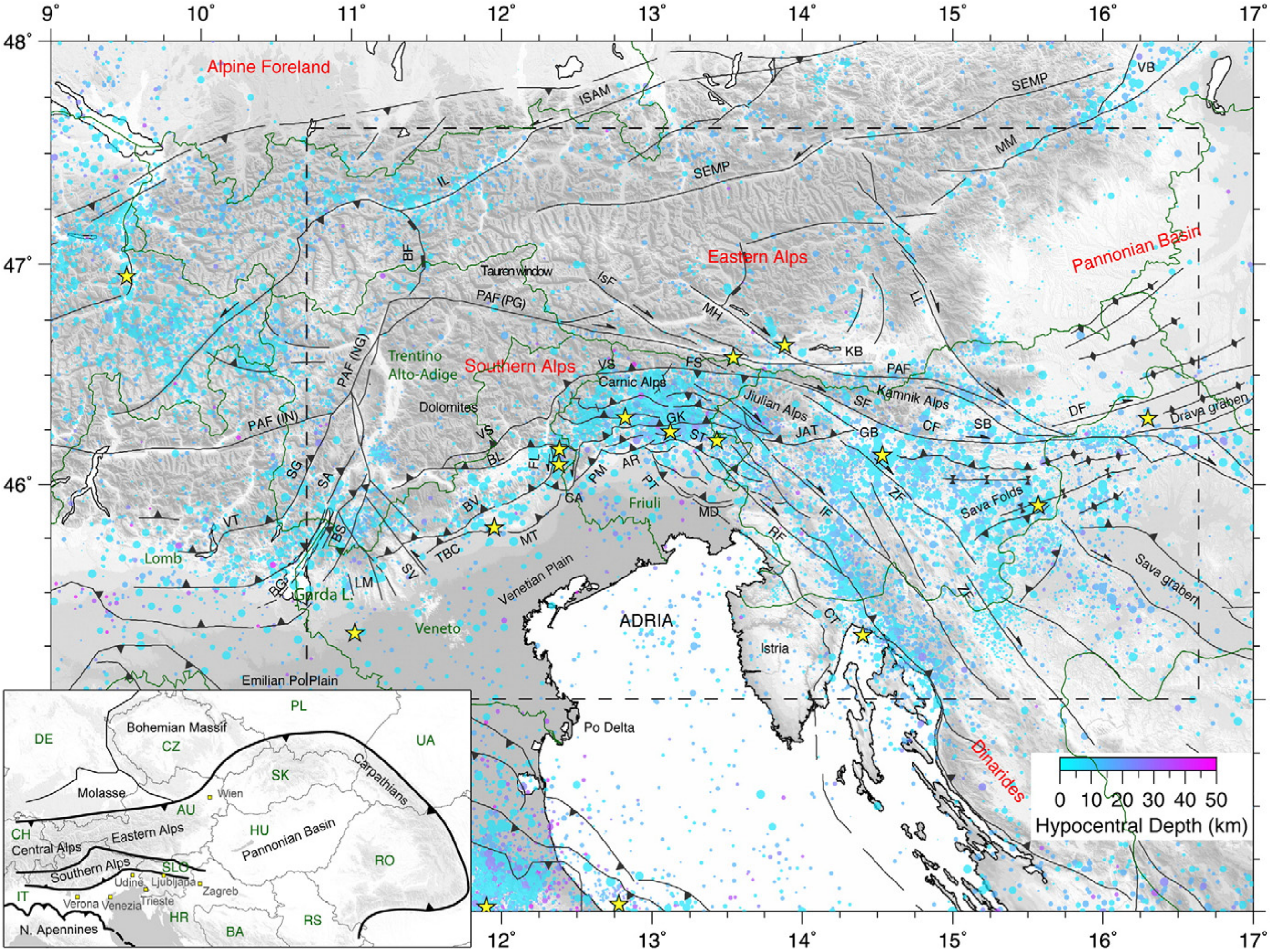

Fig. 1. Tectonic map of the study area, with the major tectonic lineaments shown in black. The seismicity since 1000 is extracted from the integrated catalogue discusses in Section 3. Major historical events (Mw > 6) are shown as yellow stars. The green lines show national boundaries (regional boundaries only for Italy). AR: Arba-Ragona thrust; BF: Brenner fault; BG: Ballino Garda thrust; BL: Belluno thrust; BS: Mt. Baldo-Mt. Stivo thrust; BV: Bassano-Valdobbiadene thrust; CA: Cansiglio thrust; CF: Celje fault; CT: Cicarija thrust; DF: Donat fault; FL: Fadalto line; FS: Fella-Sava line; GB: Gorenjska basin; GK: Gemona-Kobarid thrust; IF: Idrja fault; IsF: Iseltal Fault; IL: Inntal line; PAF (IN): Periadriatic fault - Insubric line; ISAM: Innsbruck–Salzburg–Amstetten fault; JAT: Julian Alps thrust; KB: Klagenfurt basin; LL: Lavanttal line; LM: Lessini Mountains; MD: Medea thrust; MH: Möll Hochstuhl fault; MM: Mur-Mürz fault; MT: Montello thrust; PAF (NG): Periadriatic fault - North Giudicarie line; PAF (PG): Periadriatic fault - Pusteri-Gailtal line; PM: Polcenigo-Maniago thrust; PT: Pozzuolo thrust; RF: Raša fault; SA: Sarca faults; SB: Savinja basin; SEMP: Salzachtal-Ennstal-Mariazell-Puchberg line; SF: Sava fault; SG: South Giudicarie line; ST: Susans-Tricesimo thrust; SV: Schio-Vicenza line; TBC: Thiene-Bassano-Cornuda thrust; VB: Vienna basin; VS: Val-Sugana thrust; VT: Val Trompia thrust; ZF: Žužemberk fault.

of damage for historical events can sometimes be difficult to estimate, it is likely that at least three of the quakes shown in Fig. 1 caused > 10,000 deaths. While for some of these earthquakes authors generally agree that the fault sources belong to the ESA thrust fault system, emerging at the boundary between the Venetian plane and the mountain front in northeastern Italy (Benedetti et al., 2000; Burrato et al., 2008; Galadini et al., 2005; Cheloni et al., 2012), for others, the fault sources are still uncertain. This is the case of the 1117 (Mw ~6.7) Verona earthquake, the 1348 (Mw ~7) Carinzia earthquake and the 1511 Slovenia (Mw ~6.9) earthquake (Rovida et al., 2011, Stucchi et al., 2012). Uncertainties on the location, geometry and seismic potential of active faults in the Eastern Alps persists due: i) to the complex structural framework of the region, inherited by the geodynamic evolution of this area and resulting in deformation distributed over a vast area, ii) slow deformation rates at mainly blind faults, iii) sparse instrumental seismicity, causing some areas where strong historical earthquakes occurred to appear presently almost aseismic (see Fig. 1). In this framework Global Positioning System (GPS) data provide fundamental constraints on the kinematics of continental deformation. GPS observations, in fact, have provided increasingly more details on the kinematics of this area (e.g., Grenerczy et al., 2005, Caporali et al., 2013), fault slip-rates (e.g., D'Agostino et al., 2005; Bechtold et al., 2009; Barba et al., 2013) seismic potential (e.g., Bus et al., 2009; Cheloni et al., 2014) and geodynamics (e.g., Metois et al., 2015).

The kinematic boundary conditions in the ESA of Italy are well known, with ~N-S convergence rates increasing from west to east as resulting from the counterclockwise rotation of the Adriatic microplate around a pole of rotation located in the western Po Plain (Nocquet and Calais, 2003; Battaglia et al., 2004; Serpelloni et al., 2005; D'Agostino et al., 2008). Deformation indicators from geodesy and seismotectonics are in fairly good agreement in the Italian ESA, making assumptions on the kinematics and location of active faults there more robust. On the contrary, at the boundary between Italy, Austria and Slovenia, where different tectonic regimes coexist (e.g., Bressan et al., 2003; Poli and Renner, 2004; Herak et al., 2009) and GPS stations are sparser, uncertainties on the location and kinematics of major active faults are larger.

This work focuses on the Eastern Southern Alps (ESA), south of Lat. 48°N, where the number of geodetic and seismic data is greater and both tectonic rates and seismic hazard are higher than the Eastern Alps. We use a new earthquake catalogue, with original and proxies (i.e., recalibrated) moment magnitudes (Mw), from 1005 to present-