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A seismotectonic picture of the inner southern Western Alps based on the analysis of anomalously deep earthquakes

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ABSTRACT

The anomalously deep seismicity beneath the Western Po Plain is here analyzed to shed light on the complex and still poorly understood tectonic configuration of the internal side of the Western Alps area. The original dataset, including 590 earthquakes deeper than 20 km recorded during the last 25 years, has been accurately relocated with HypoDD using both catalog and cross-correlation differential times. We found that the distribution of seismic events faithfully mirrors the presence of two distinct tectonic domains (axial belt domains 1 and 2), originally belonging to the Paleogene Alpine wedge and now anomalously juxtaposed beneath the sedimentary infill of the Western Po Plain. Shallow, low-magnitude earthquakes (<20 km depth) are concentrated in domain 1, and are possibly triggered by the isostatic reequilibration of the accretionary wedge. Earthquakes between 25 and 75 km depth, instead, define a NNW–SSE linear cluster along the boundary between domains 1 and 2, and mark an apparent plane steeply dipping to the ENE. We propose that this plane may represent a major tectonic boundary of Neogene age, here referred to as the Rivoli–Marene deep fault. Focal mechanisms along the Rivoli–Marene deep fault are invariably transpressional, and suggest ongoing left-lateral motion in agreement with available plate motion constraints. The normal throw inferred from surface geology data (>8 km), and accommodated in correspondence of the fault, could be linked to its Neogene activity, coeval with the northward translation of the retreating Adriatic slab.

1. Introduction

The Western Alps are one of the best studied orogenic belts worldwide, structured in Cretaceous to Paleogene times within the framework of European subduction beneath the Adriatic microplate (Handy et al., 2010; Polino et al., 1990; Schmid and Kissling, 2000). This orogen displays a relatively simple tectonic arrangement in the external zones (Dumont et al., 2012; Ford and Lickorish, 2004) that sharply contrasts with the more complex and only partly understood configuration characterizing the Adriatic side (Cassano et al., 1986; Schumacher and Laubscher, 1996) (Fig. 1A). Along the internal boundary of the Western Alps, in fact, major variations in structural arrangement are documented from the northern to the southern segments of the orogen (Lardeaux et al., 2006; Malusà et al., 2009; Michard et al., 2004). In the northern Western Alps segment, the Paleogene metamorphic wedge, including the double vergent Frontal wedge and the Eocene Eclogite belt (Malusà et al., 2011), is directly juxtaposed against Adriatic units also including the Adria-derived Cretaceous wedge (section X–X′ in Fig. 1A). In the southern Western Alps segment, instead, the Eocene Eclogite belt is juxtaposed against greenschist-to-blueschist facies metamorphic units originally belonging to the Frontal wedge (Bertotti and Mosca, 2009; Polino et al., 2010), and now buried beneath the Cenozoic sediments of the Tertiary Piedmont basin (axial belt domains 1 and 2 in Fig. 2A). Such a complex tectonic configuration can be ascribed to the northward migration of the retreating Adriatic slab since the Oligocene (Dewey et al., 1989; Jolivet et al., 2003; Malusà et al., 2015a,b) (Fig. 1B), when part of the Alpine orogenic wedge was affected by transpressional tectonics in the Adriatic forearc (section Y–Y′ in Fig. 1A) (Cerrina Feroni et al., 2004; Elter and Pertusati, 1973; Malusà and Balestrieri, 2012), by lithospheric extension in the Adriatic backarc (Faccenna et al., 2001; Jolivet et al., 1994; Malinverno and Ryan, 1986), and by major block rotations (Carrapa et al., 2003; Collombet et al., 2002; Maffione et al., 2008). As a result, the Alpine orogenic wedge is now partly dismembered and exposed not only in the Western Alps, but also in Corsica (Caron, 1994) and beneath the Tertiary Piedmont Basin (axial belt domain 2 in Fig. 2A), where it is anomalously juxtaposed against the main segment of the Paleogene metamorphic wedge (axial belt domain 1 in Fig. 2A).

To date, the geological boundary between domains 1 and 2 is poorly investigated. It is buried beneath the thick Quaternary infill of the Western Po Plain (Cassano et al., 1986; Pieri and Groppi, 1981; Rossi et al., 2009), and its surface expression is represented by the sharp morphological contrast between the Viso ophiolites, exposed ~4 km a.s.l. in front of

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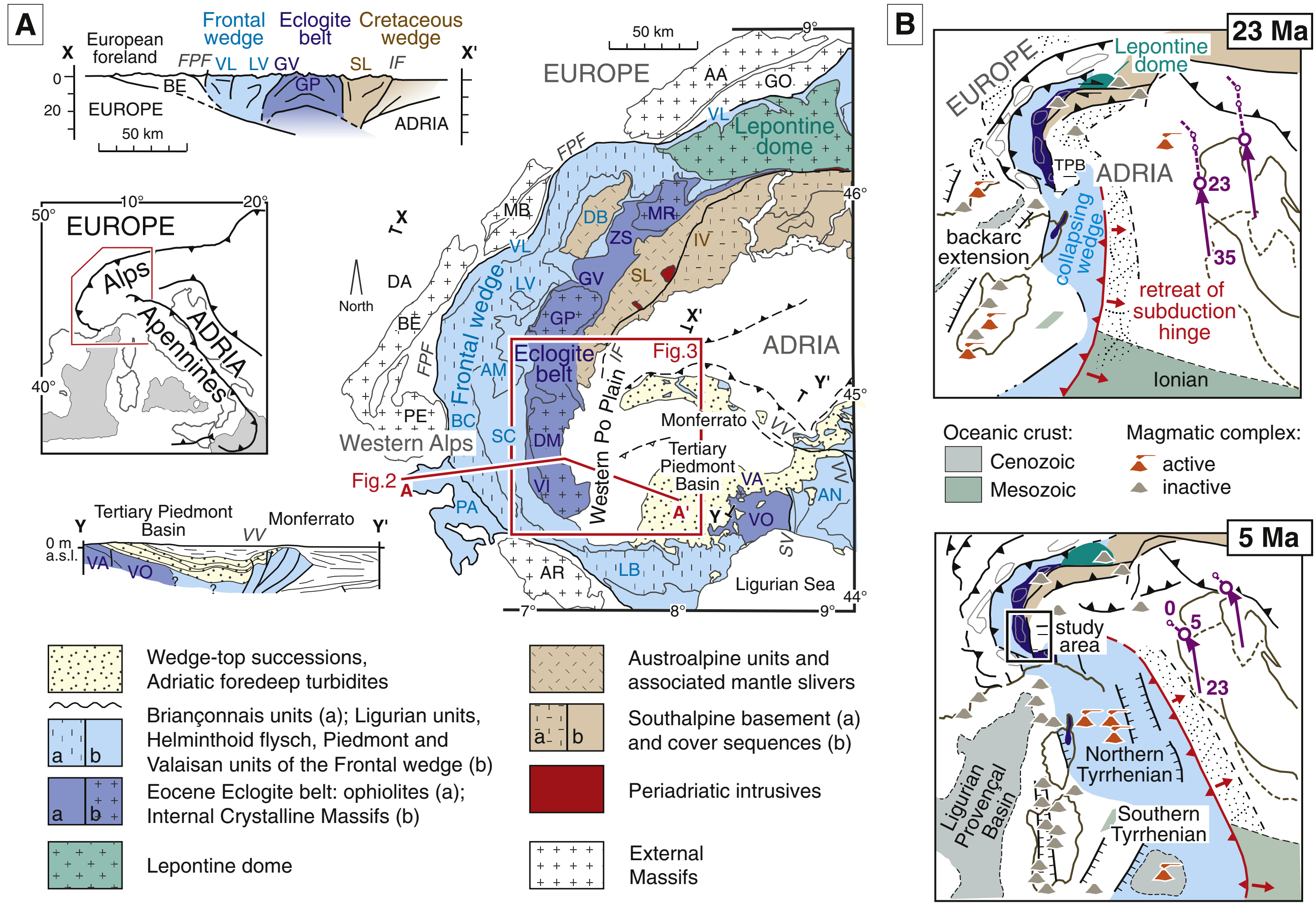

Fig. 1. A) Geodynamic setting (inset), tectonic sketch map of the Western Alps, and representative cross sections across the northern Western Alps and the Alps–Apennines transition zone (major tectonic domains according to Malusà et al., 2011): X–X′, based on crustal seismic data along the ECORS-CROP traverse (Polino et al., 1990), and modified after Malusà et al. (2011); Y–Y′, based on seismic data in Rossi et al. (2009), modified after Malusà and Balestrieri (2012). Acronyms: AA, Aar; AM, Ambin; AN, Antola; AR, Argentera; BC, Briançonnais; BE, Belledonne; DA, Dauphinois; DB, Dent Blanche; DM, Dora–Maira; GO, Gotthard; GP, Gran Paradiso; GV, Grivola; IV, Ivrea–Verbano; LB, Ligurian Briançonnais; LV, Leverogne; MB, Mont Blanc; MR, Monte Rosa; PA, Parpaillon; PE, Pelvoux; SC, Queyras calcschists; SL, Sesia–Lanzo; VA, Valosio; VI, Viso; VL, Valaisan; VO, Voltri; ZS, Zermatt–Saas. Major faults (italics): FPF, Frontal Pennine; IF, Insubric; SV, Sestri–Voltaggio; VV, Villalvernia–Varzi–Ottone. B) Neogene to present evolution of the Alps–Apennines system (modified after Malusà et al., 2015a,b). Active subduction zones are marked in red, Adria trajectories relative to Europe are indicated in purple (from Dewey et al., 1989; Jolivet and Faccenna, 2000); TPB, Tertiary Piedmont Basin.

the Western Po Plain (Lombardo et al., 1978; Schwartz et al., 2000), and the top of the metamorphic basement to the east, which is buried beneath ~4 km thick sediments (Fig. 2B). At least 8 km throw was thus accommodated along this geological boundary, and differential rock uplift is possibly still ongoing, as suggested by GPS data (Serpelloni et al., 2013). However, it is still unclear whether the boundary between domains 1 and 2 is sharp or distributed, and little constraints concerning its attitude and kinematics are available. Information provided by oil industry surveys is limited to the uppermost 3–4 km of the crust (Pieri and Groppi, 1981; Rossi et al., 2009), whereas existing local tomography studies were chiefly focused within domain 1 (e.g., Paul et al., 2001).

In this work, we shed light on these issues by the analysis of seismicity recorded in the last 25 years in the inner Western Alps. In particular, we focus our attention on the >20 km depth earthquakes recorded beneath the Western Po Plain. Our results provide useful indications on the attitude and kinematics of this first-order geological boundary, which will be later discussed within the framework of recent geodynamic reconstructions (Malusà et al., 2015a,b).

2. Seismicity in the Western Alps

Seismicity typically shows low to moderate energy in most of the Alps (2 < Ml < 4 magnitude). Although the focal depth of earthquakes observed in intraplate regions is usually confined to the upper crust (down to 15–20 km; e.g., Meissner and Strehlau, 1982; Chen and Molnar, 1983; Solarino and Cassinis, 2007), evidence of relatively deep events is reported from the Alpine area. Deichmann (1987), for instance, demonstrated the occurrence of earthquakes in the lower crust beneath northern Switzerland down to the Moho.

The picture in the Western Alps is very similar to the rest of the belt, with shallow earthquakes on the external side (e.g., Béthoux et al., 1998; Eva and Solarino, 1998; Eva et al., 1997, 1998; Godano et al., 2013; Jenatton et al., 2007; Sue et al., 1999, 2007) and a few deeper events on the internal side. The occurrence of "anomalously deep earthquakes" in the Western Alps was already pointed out in a pioneering work by Cattaneo et al. (1999), who attempted a seismotectonic interpretation of such deep events. However, the reliability of seismic locations at that time was weakened both by the small number of available seismograms for phase picking, and by the limitations in computational capacity. Nowadays, the increasing number of digital seismograms, also including additional intermediate-depth seismic events for the study area, and the availability of more sophisticated algorithms, allowed us to improve the relocation of such earthquakes, and to propose a seismotectonic explanation for their occurrence within the framework of the geodynamic evolution of the southern Western Alps region.