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Unravelling polyphase brittle tectonics through multi-software fault-slip analysis: The case of the Voltri Unit, Western Alps (Italy)

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A B S T R A C T

We have analyzed the brittle structures in a key area of the Alps–Apennines transition zone (NW-Italy): here two orogens have interfered with each other since Oligocene times, producing a complex structural evolution and a heterogeneous fault population. Only relative chronologies can be reconstructed as stratigraphic constraints are lacking. We have performed the inversion of fault-slip data with two softwares for paleostress calculations, combined with field observations at selected structural stations and photo-interpretation. The resulting incompatible stress tensors can be grouped in this sequence: i) a strike-slip tensor, with NNW–SSE trending σ_1 (Event A); ii) a strike-slip tensor, with NE–SW trending σ_1 (Event B) and iii) an extensional/transtensional tensor, with NW–SE or NE–SW trending σ_3 (Event C). We correlated our results with structures of known age from adjacent areas. Event A is possibly Rupelian –early Chattian, linked to far-field incipient rifting in the future Ligurian-Provençal basin. Event B fits Oligo–Miocene shortening: the faults may belong to a sinistral strike-slip zone that accommodated the oblique component of deformation during the rotation of the Corsica–Sardinia block. Event C is attributed to a Pliocene/Quaternary? (neotectonic) event. Therefore combining different inversion procedures with a detailed structural analysis has successfully unravelled the polyphase brittle tectonics.

1. Introduction

The inversion of fault-slip data is now a well-established technique that has increasingly been used to separate heterogeneous fault populations linked to the superposition of different tectonic events (e.g., Wang and Neubauer, 1998; Lamarche et al., 1999; Matenco and Schmid, 1999; Saintot and Angelier, 2002; Burg et al., 2005; De Paola et al., 2005; Bergerat et al., 2007; De Vicente et al., 2009; Laó-Dávila and Anderson, 2009; Sippel et al., 2009, 2010). By considering the fault-slip attitudes of at least four independent faults, this technique makes it possible to calculate the corresponding "reduced stress tensor" (Angelier et al., 1982), which is made up of: *i)* the orientations of the three mutually perpendicular principal stress axes σ_1, σ_2 and σ_3 and *ii)* the ratio of principal stress differences (stress ratio).

In this study we have applied fault-slip analysis to the meta-ophiolitic Voltri Unit (Western Alps, Italy; Capponi and Crispini, 2008a,b) that is characterized by polyphase late orogenic brittle tectonics, still unresolved and undated. As fault-slip inversion methods have a number of critical assumptions such as considering rocks as being initially homogeneous and isotropic, deforming as rheologically linear material (Dupin et al., 1993; Pollard et al., 1993; Twiss and Unruh, 1998; Marrett and Peacock, 1999), we have applied two different inversion procedures, performed with two open-source computer programmes, namely Fsa v. 33.9 by Célérier (1999) and Win-Tensor 4.0.3 by Delvaux (2011), in order to reduce the uncertainties. Few attempts to cross-check the results of different inversion procedures have been undertaken on natural datasets (e.g. Sippel et al., 2009; Federico et al., 2010) and, to our knowledge, none testing these two programmes. We, moreover, combined paleostress calculations with structural analysis in the field (involving the study of cross-cutting relationships, mesoscale fault geometries, fault-rock type and fault-slip data collection) and with photo-interpretation.

The study area was chosen as, being a part of the Ligurian Alps (Fig. 1), it is a key area in the transition between two opposite verging mountain chains: the Western Alps and the Northern Apennines (Italy). This transition has been considered a complicated tectonic issue for a long time (e.g. Elter and Pertusati, 1973; "Ligurian knot" in Laubscher et al., 1992; Schumacher and

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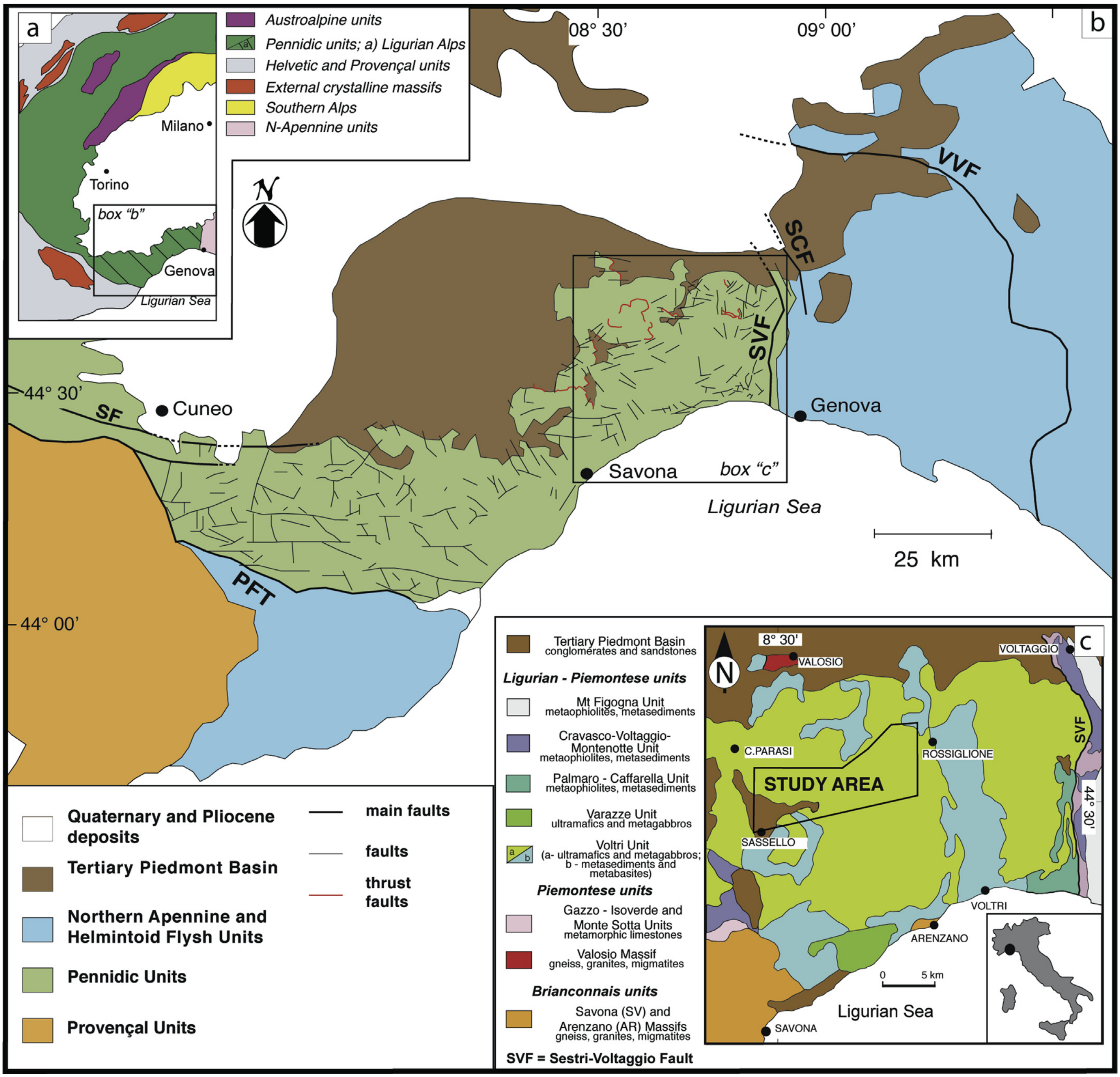

Fig. 1. a) Main geological units of the NW Alps; b) simplified geological map of the Ligurian Alps with the distribution of the main faults (data inside the area of box “c” from Capponi and Crispini, 2008a; Capponi et al., 2013b,c,d,e; data outside the area of box “c” from Maino et al., 2013), PFT = Penninic Front Thrust; SF = Stura Fault; SVF = Sestri–Voltaggio Fault; VVF = Villalvernia–Varzi fault; c) simplified geological map of the Voltri Unit and location of the study area.

Laubscher, 1996). At present, some consensus exists (see Molli et al., 2010 for a review) on this transition occurring in an area approximately 100 km-wide (according to Mosca et al., 2009) and its position changing over time (i.e. an evolving linkage; Molli et al., 2010; Molli and Malavieille, 2011). This study explores the kinematic framework active during the Tertiary in the linking area between the two orogens. During the Oligocene and Miocene the area was indeed affected by major geodynamic events, such as the late-orogenic processes of the Alps, the eastwards/northeastwards migration of the Ligurian Alps (see Fig. 1a) and the Apennines and the opening of the Ligurian-Provençal basin (e.g. Castellarin, 2001 and references therein).

The area investigated in this study is located in the north-western sector of the Voltri Unit (Fig. 1b, c) where a new geological mapping campaign at 1:10.000 scale (Capponi et al., 2013a,b,c,d,e) has revealed the occurrence of a large number of brittle structures, both inside the basement rocks and in the post-orogenic Oligocene cover; this is also testified to by the fact that a km-scale fault zone had already been mapped in the 1:100.000 geological map of the Italian Geological Service (the Prà Vallarino-Tiglieto Line after