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Fault slip analysis and late exhumation of the Tauern Window, Eastern Alps

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ABSTRACT

Exhumation of the Eastern Alps from the early Tertiary to the late Miocene was localized mainly in the Tauern Window, a thermal and structural dome located in front of the Dolomites indenter. Stress inversions based on new structural investigations over the entire Tauern Window indicate a regional zoning of the paleostress field with a predominance of strike-slip states of stress in the core of the investigated area, and dominant extensional regimes in the eastern and western borders of the dome. Few inverse fault structures have been highlighted. We propose a two-stage deformation history in order to explain the different types of structures that characterise the ductile and the brittle domains. During the first stage of exhumation of the Tauern Window, corresponding to the folding event, the brittle crust was probably dominated by N-S shortening and compression. The second stage of exhumation was marked by normal faulting at the borders of the dome and strike-slip faulting in the core. During the second stage, the brittle part of the crust that was previously affected by compressive structures belonging to the first stage was eroded. Normal faulting associated to E-W extension along the eastern and western borders of the Tauern Window was accommodated by strike-slip faulting located in the core of the Tauern Window, yielding E-W extension and N-S shortening. The orientation of the extensional axes and the nature of the stress tensors are similar to the ones inferred for the late-stage, brittle overprint of the internal basement massifs of the Central Alps pointing to a possible common, large-scale, state of stress acting well beyond the area of the Eastern Alps.

1. Introduction

Present-day deformation in the Alps appears to be controlled by the anticlockwise rotation of the Adriatic plate, whose rotation pole is situated in the western Po Plane (e.g. Noquet and Calais, 2004), thus inducing larger displacements in the eastern part of the Alpine region, where N-S convergence attains ~2 mm.yr^{-1} (Noquet, 2012). This convergence is not only largely absorbed in the seismically active, most external thrusts of the southeastern Alpine chain, but also partly in the thickened, accreted lower plate of the orogen, north of the Dolomites indenter (Fig. 1). Recent GPS measurements in the Eastern Alps (e.g. Caporali et al., 2013; D'Agostino et al., 2005; Grenerczy et al., 2000; Serpelloni et al, 2013) and the records of seismic activity of the past century, (Reiter et al., 2005) indicate that N-directed Adria convergence is partly accommodated by eastward motion of the orogenic wedge east of the Tauern Window (Fig. 2; Caporali et al., 2013). Areas of enhanced seismic activity seem to be associated to fault systems that were already active in the Early Miocene, as the Brenner fault (Fig. 1; Reiter et al., 2005; Rosenberg and Garcia, 2011), the Salzach–Ennstal–Mariazell–Puchberg fault system (SEMP) (Fig. 1; Reinecker and Lehnhardt, 1999), the Mölltal fault (Fig. 1) and the Lavanttal fault (Fig. 1), suggesting a continuous localization of deformation in these structures, from the Miocene to the present. In contrast, the area coinciding to the greatest exhumation in the Mid- to Late Miocene, i.e. the Tauern Window, was barely affected by seismic events (Fig. 1) in the past century (Reinecker and Lehnhardt, 1999), although it is characterized by significant uplift rates (Devoti et al., 2011), high topography and high relief. These observations may point to an ongoing aseismic accommodation of convergence by thickening, or to an active uplift due to isostatic rebound (e.g., Champagnac et al, 2007; Champagnac et al, 2008; Stocchi et al., 2005; Vernant et al., 2013).

Modelling GPS displacement of the Eastern Alps (Caporali et al., 2013) by elastic deformation of a half space containing the major faults inferred to have accommodated Miocene convergence, gives a satisfactory fit to the present-day GPS data. Hence a possible kinematic continuity existed from the Lower Miocene to the present, although large misfits between models and measured GPS data exist in the Tauern Window (Caporali et al., 2013).

Attempts to link the present-day seismicity and displacements inferred from GPS data to the well-investigated Early Miocene

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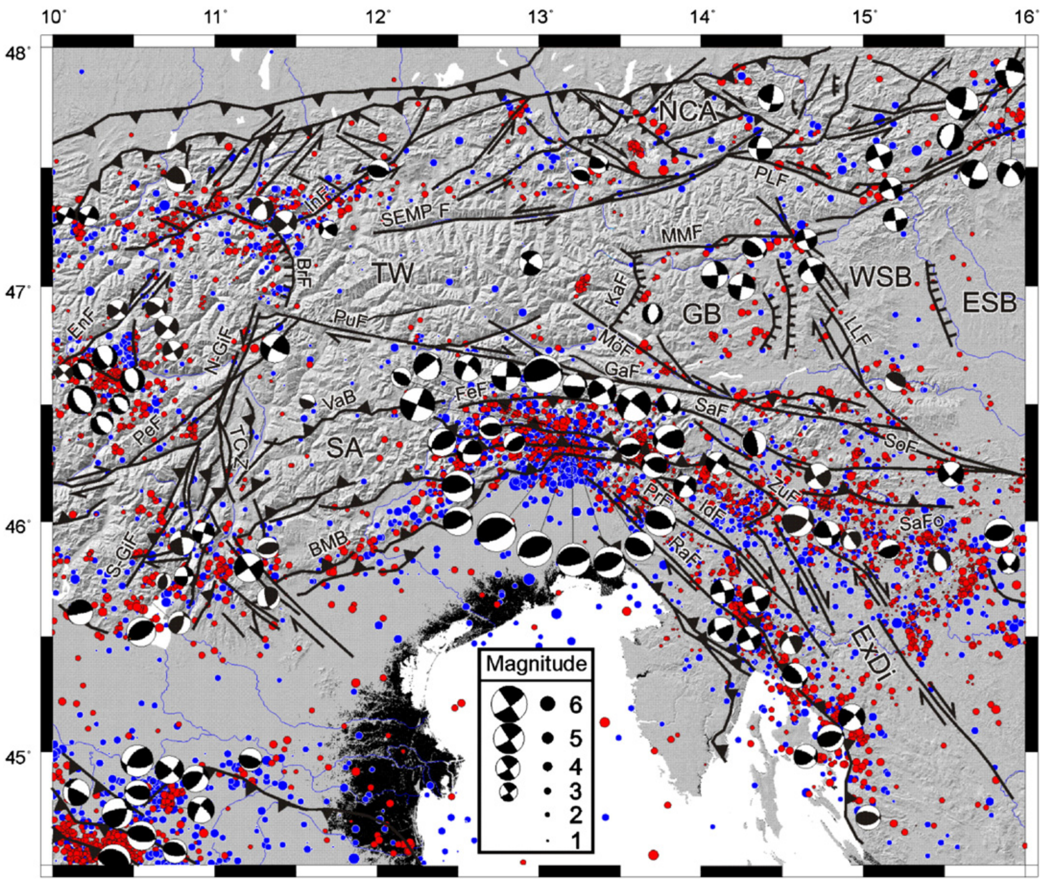

Fig. 1. GPS measurements and main Tertiary faults of the Eastern and Southern Alps. Structural data compiled from Bigi et al. (1990); Burrato et al. (2008); Caporali et al. (2005); Castellarin and Cantelli (2000); Galadini et al. (2005); Linzer et al. (2002); Vrabec and Fodor (2006). BrF: Brenner fault, EnF: Engadin fault, ESB: Eastern Styrian Basin, ExDi: External Dinarides, GaF: Gailtal fault, GB: Gurktal Basin, IdF: Idrija fault, InF: Inntal fault, KaF: Katschberg fault, LLF: Lavanttal fault, MMF: Mur-Mürz fault, MöF: Mölltal fault, NCA: Northern Calcareous Alps, N-GIF: Northen Giudicarie fault, PeF: Peyo fault, PLF: Palten-Liesing fault, PuF: Pustertal fault, SA: Southern Alps, SEMP: Salzach–Ennstal–Mariazell–Puchberg fault, S-GIF: southern Giudicarie fault, TW: Tauern Window, WSB: western Styrian Basin.

tectonics (Behrmann, 1988; Linzer et al., 2002; Neubauer et al., 1999; Peresson and Decker, 1997; Ratschbacher et al., 1989, 1991b; Scharf et al., 2013; Schneider, 2014; Selverstone, 1988) need to fill the information gap existing between the latter studies on the ductile structures of the Tauern Window and the present-day displacements. In order to do so, we investigate the orientation and sense of shear of brittle structures in the Tauern Window and we assess the strain and stress orientations during and after Miocene collision in the Eastern Alps.

Exhumation of the Tauern Window has been interpreted as the result of extensional unroofing along the Brenner and the Katschberg faults (Fig. 3), related to large, orogen-parallel extension, during lateral extrusion (e.g. Frisch et al., 1998). However, this mechanism of exhumation was recently questioned, and a debate centred on the relative importance of folding associated with erosion (Behrmann, 1988; Cornelius, 1940; Glodny et al., 2008; Lammerer, 1988; Laubscher, 1988; Rosenberg and Garcia, 2011, 2012; Rosenberg et al., 2004, 2007), and extensional unroofing located along the normal fault systems bordering the dome (Axen et al., 1995; Frisch et al., 1998, 2000; Fügenschuh, et al., 1997, 2012; Genser and Neubauer, 1989; Kuhlemann et al., 2001; Linzer et al., 2002; Neubauer et al., 1999; Ratschbacher et al., 1989; Wang and Neubauer, 1998) is still ongoing.

Historically, exhumation of the Tauern Window was mainly discussed on the base of ductile structures (Behrmann, 1988; Genser and Neubauer, 1989; Selverstone, 1988) or of brittle structures that nucleated in deep crustal levels mainly behaving as ductile mediums (Axen et al., 1995; Selverstone et al., 1995). Only few studies investigated brittle deformations formed in the upper crust within the Tauern Window (Decker and Reiter, 2006; Kurz et al., 1993; Reiter et al., 2005; Wang and Neubauer, 1998) and these studies are limited to small areas adjacent to the eastern and western borders of the dome. A systematic investigation of brittle structures throughout the Tauern Window is the object of the present work. In addition to the kinematic analysis of brittle structures, we calculate the associated paleostress fields to determine the occurrence of extension and/or compression during the last stages of exhumation of the Tauern Window. Finally, we compare the paleostress fields of the Tauern Window with those inferred for the internal massifs of the Central Alps, to assess whether the late stages of exhumation in the Tauern Window responded to a general state of stress of the Alpine chain or to a more local, East-Alpine tectonic setting.

2. Geologic setting

The Eastern Alps are characterized by a pile of large-scale nappes, whose deepest units consist of European basement with thin relics of their Mesozoic cover, overlain by two oceanic units: the Valais-derived Glockner nappes, and the Piemont–Liguria-derived Matreier nappe (Fig. 3A; Dewey et al., 1989; Schmid et al., 2004, 2013; Termier, 1903). Nappe stacking of the oceanic units started during Cretaceous orogeny, whereas exhumation took place during Tertiary collision (e.g. Schmid et al., 2013). In contrast to the Western and Central Alps, Tertiary collisional exhumation in the Eastern Alps was confined to a small area forming the Tauern Window (Fig. 3A and B). Minor exposures of Valais units also occur within small extensional core complexes at the