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Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (Northern Italy)

Vincent F. Verwater[1], Eline Le Breton[1], Mark R. Handy[1], Vincenzo Picotti[2], Azam Jozi Najafabadi[3], Christian Haberland[3]

[1]Institut für Geologische Wissenschaften, Freie Universität, Berlin, Germany
[2]Department of Earth Sciences, ETH-Zürich, Switzerland
[3]German Research Centre for Geosciences, GFZ, Potsdam, Germany

Correspondence to: Vincent F. Verwater (vincent.verwater@fu-berlin.de)

Abstract

Neogene indentation of the Adriatic plate into Europe led to major modifications of the Alpine orogenic structures and style of deformation in the Eastern Alps. Especially, the offset of the Periadriatic Fault by the Northern Giudicarie Fault marks the initiation of strike-slip faulting and lateral extrusion of the Eastern Alps. Questions remain on the exact role of this fault zone in changes of the Alpine orogen at depth. This necessitates quantitative analysis of the shortening, kinematics and depth of decoupling underneath the Northern Giudicarie Fault and associated fold-and thrust belt in the Southern Alps. Tectonic balancing of a network of seven cross sections through the Giudicarie Belt parallel to the local shortening direction reveals that it comprises two kinematic domains with different amounts and partly overlapping ages of shortening. These two domains are delimitated by the NW-SE oriented strike-slip Trento-Cles – Schio-Vicenza fault system, cross-cutting the Southern Alpine orogenic front in the south and merging with the Northern Giudicarie Fault in the north. The SW kinematic domain (Val Trompia sector) accommodated at least ~18 km of Late Oligocene to Early Miocene shortening. Since the Middle Miocene, the SW kinematic domain experienced a minimum of ~12-22 km shortening, whereas the NE kinematic domain underwent at least ~25-35 km shortening. Together, these domains contributed to an estimated ~53-75 km of sinistral strike-slip motion along the Northern Giudicarie Fault, implying that (most of) the offset of the Periadriatic Fault is due to Late Oligocene to Neogene indentation of the Adriatic plate into the Eastern Alps. Moreover, the faults linking the Giudicarie Belt with the Northern Giudicarie Fault reach ~15-20 km depth, indicating a thick-skinned tectonic style of deformation. These fault detachments may also connect at depth with a lower crustal Adriatic wedge that protruded north of the Periadriatic Fault and was responsible for N-S shortening and eastward escape of deeply exhumed units in the Tauern Window. Finally, the east-west lateral variation of shortening indicates internal deformation and lateral variation in strength of the Adriatic indenter, related to Permian - Mesozoic tectonic structures and paleogeographic domains.

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1 Introduction

The fold-and-thrust belt of the eastern Southern Alps formed due to indentation of the Adriatic plate into the Eastern Alps (Schönborn, 1992; 1999; Picotti et al., 1995; Frisch et al., 1998; 2000; Castellarin and Cantelli, 2000; Linzer et al., 2002; Rosenberg et al., 2007; Pomella et al., 2011; 2012; Favaro et al., 2017). Indentation is defined as the post-collisional penetration of a relatively stiff upper plate into a weaker, already existing orogenic edifice (e.g., Tapponier et al., 1986). In the Alps, indentation modified the early Tertiary nappe structure of the orogen (Schmid et al., 2004), including post-nappe folding and exhumation of Alpine metamorphic units in the Tauern Window (Rosenberg et al., 2018), eastward lateral extrusion of the Austroalpine nappes (Ratschbacher et al., 1991; Rosenberg et al., 2007; Scharf et al. 2013) and south-directed folding in the Southern Alps (Doglioni and Bosellini 1987; Castellarin et al. 2006b). The Giudicarie Fault, subdivided into a northern (NGF) and a southern (SGF) branches, is a prominent structure that offsets sinistrally the Periadriatic Fault (PF) by ~75 km in map view (Figure 1). It ends to the north at the western boundary of Neogene post-nappe folding of the Tauern Window and lateral escape of the Eastern Alps (Scharf et al., 2013). Previous studies have established a direct kinematic link between sinistral motion along the NGF and Neogene exhumation in the Tauern Window (Ratschbacher et al., 1989; Frisch et al., 1998; 2000; Linzer et al., 2002; Rosenberg et al., 2007 Scharf et al., 2013; Schmid et al., 2013; Handy et al., 2015; Favaro et al., 2015, 2017). This complex response of the orogenic crust to indentation calls for detachment of both sedimentary cover and metamorphic units above one or more detachments located at or above the Moho-discontinuity (Oldow et al., 1990). To the south, the Giudicarie fold-and-thrust belt trends obliquely to the dominantly south-verging thrusts in the Southern Alps and consists of (1) N-S to NNE-SSW trending thrusts and strike-slip faults and (2) E-W trending thrusts (e.g. Valsugana Thrust and Southern Alps orogenic front; Figure 1). The question arises of how oblique-sinistral shortening accommodated by the Giudicarie Belt is linked to Neogene displacements on the Giudicarie Fault, the Periadriatic Fault and in the Tauern Window. In particular, the kinematic link of this belt to the northern and southern segments of the Giudicarie Fault remains poorly constrained and is the focus of this study.

The Giudicarie Fault coincides also with significant changes in the mantle structure, as imaged by tomographic P-wave models that show a SE-dipping slab anomaly beneath the Central Alps and a steeply dipping enigmatic slab anomaly beneath the Eastern Alps (Lippitsch et al., 2003, Mitterbauer et al. 2011; Karousova et al. 2012). The model of Lippitsch et al. (2003) shows that the slab anomaly beneath the Eastern Alps dips towards the NNE, which would suggest a subduction of the Adriatic plate, with a length varying from 50 km in the west to 210 km in the east. The exact dip, length and plate tectonic affinity (Adriatic, European or mixed) of this slab anomaly remains however under strong debate (Mitterbauer et al., 2011; Handy et al., 2015; Qorbani et al., 2015; Kästle et al., 2020). Any amount of Adriatic subduction should be reflected in both Neogene shortening estimates across the eastern Southern Alps and Neogene estimates of lateral extrusion of the Eastern Alps. Proposed estimates for the amount of shortening across the Giudicarie Belt and Southern Alps range from 30 to 100 km (Laubscher, 1990; Doglioni, 1992; Roeder, 1992; Schönborn, 1992; 1999; Picotti et al., 1995; Castellarin and Cantelli, 2000; Nussbaum, 2000). This wide range reflects the complexity in the kinematics and strain partitioning between thrusts and strike-slip faults within the Giudicarie Belt. Therefore, this study aims to provide new constraints on the kinematics of shortening within the Giudicarie Belt,

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as well as on the depth of deformation within the Adriatic indenter, to discuss its relationships to Neogene exhumation in the Tauern Window and lateral extrusion in the Eastern Alps. To do so, we first review the Permian to Jurassic pre-existing structures and paleogeography of the eastern Southern Alps that affect the kinematics and partitioning of the deformation related to the Alpine Orogeny (chapter 2). Structural observations on the field (chapter 3) and deformation ages (chapter 4) along the Giudicarie belt are then used to construct a series of balanced geological cross-sections (chapter 5). Based on the calculated amount of shortening, we propose a kinematic sub-division of the Giudicarie Belt (chapter 6) and discuss the relationship between Neogene shortening along the Giudicarie Belt and Neogene motion along the NGF, a topic which has fascinated many researchers in the past (Castellarin and Vai, 1981; Picotti et al., 1995; Prosser; 1998, 2000; Müller et al., 2001; Viola et al., 2001; Linzer et al., 2002; Stipp et al., 2004; Pomella et al., 2011; 2012).

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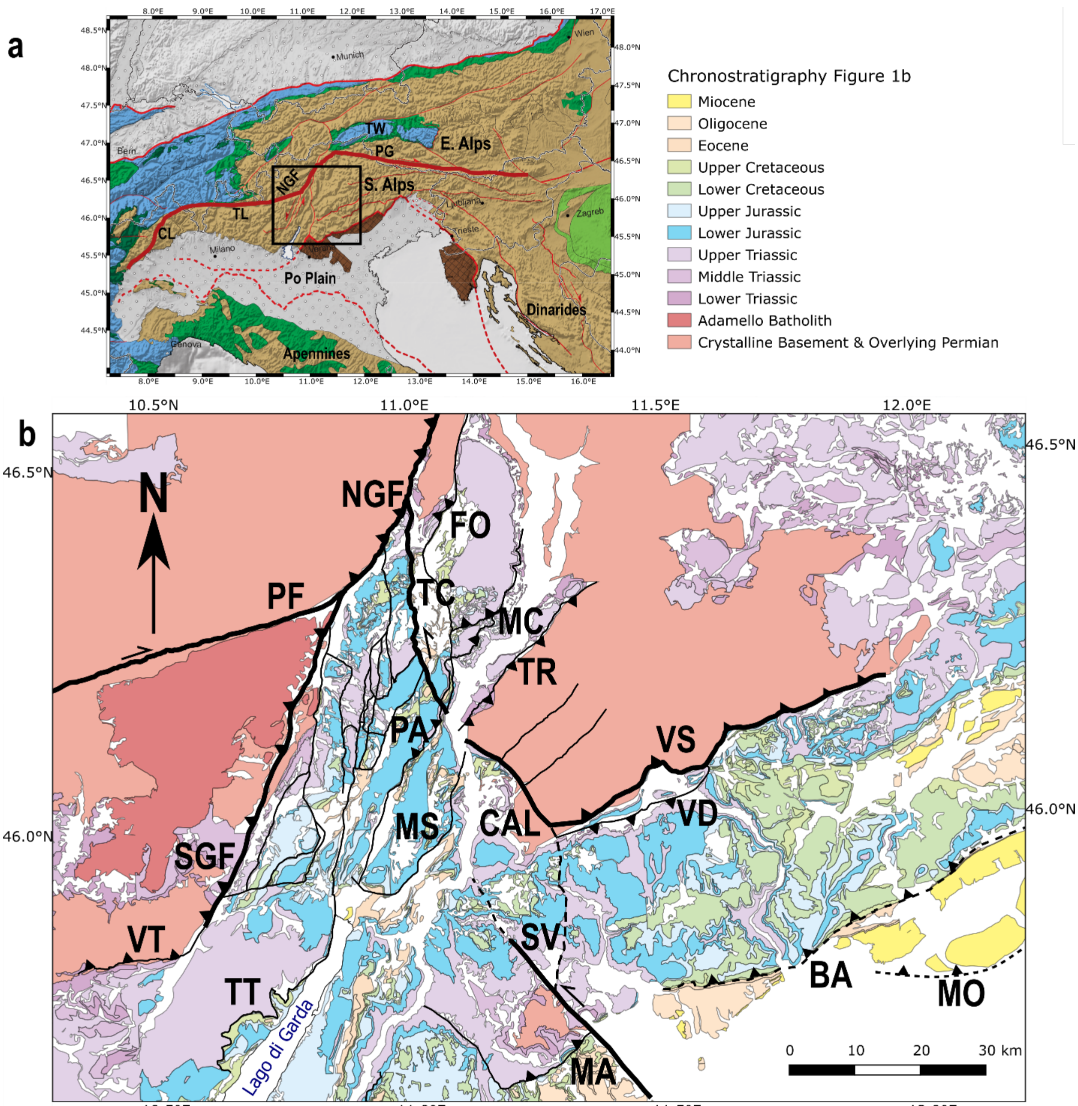

Figure 1: (a) Tectonic provenance map of the Alps (Handy et al., 2010 simplified from Schmid et al., 2004; 2008). The Southern Alps and Dinarides are accreted units derived from the Adriatic plate (brown). The Southern Alps are bounded to the north by the Periadriatic Fault (PF), which is sinistrally offset by the Northern Giudicarie Fault (NGF). The PF is divided into a western segment (Tonale and Canavese Lines, TL and CL, respectively) and eastern segment (Pusteria-Gailtal Line, PG). (b) Geological map of our study area (Giudicarie Belt) in the eastern Southern Alps indicated by a black square in (a). Abbr.: TW=Tauern Window; Fault abbreviations: BA=Bassano, CAL=Calisio, FO=Foiana, MA=Marana, MC=Mezzocorona, MO=Montello, MS=Monte Stivo, PA=Paganella, SGF=Southern Giudicarie, SV=Schio-Vicenza, TC=Trento-Cles, TR=Truden, TT=Tremosine-Tignale, VD=Val di Sella, VS=Valsugana, VT=Val Trompia.

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2 Geological setting

2.1 The eastern Southern Alps

The Southern Alps are a predominantly south-vergent fold-and-thrust belt, at the leading edge of the Adriatic plate indenting the European plate to the north. The Giudicarie Fault is the boundary between eastern and western parts of the Southern Alps (Schönborn, 1999; Castellarin and Cantelli, 2000). In the Late Cretaceous, the tectonic regime shifted in the Alps from E-W extension to N-S shortening due to convergence between Adria and Europe (e.g., Dewey et al. 1989). The western Southern Alps record a Late Cretaceous compressional phase (documented by the so-called Lombardian Flysch; e.g. Doglioni and Bosellini, 1987; Bernoulli and Winkler, 1990; as well as thrusting that pre-dates the Paleogene Adamello intrusive body, see Brack, 1981) followed by Oligocene to Middle Miocene shortening (e.g. Schönborn, 1992; Schmid et al., 1996). Only the western Southern Alps have recorded this Late Cretaceous deformation (Castellarin et al., 1992), as within the eastern Southern Alps evidence of this phase is lacking. The eastern Southern Alps comprise actively accreting cover units of the Adriatic plate and are bounded to the north by the PF, to the west by the NGF and SGF, to the east by Dinaric thrusts and active strike-slip faults, and to the south by the Po Plain (Figure 1). Paleostress analyses (Castellarin et al., 1992; Castellarin and Cantelli, 2000; Zampieri et al., 2003) and structural analysis of the NGF (Prosser, 1998; 2000; Viola et al., 2001) show that during the Middle to Late Miocene, the eastern Southern Alps were dominantly affected by NNW-SSE shortening, which reactivated many Permo-Jurassic faults. This Neogene NNW-SSE shortening was preceded by a minor phase of Eocene E-W extension related to the opening of a volcanic graben, which was only recorded locally in the southernmost part of the Trento Platform (Zampieri, 1995).

Directly north of the Giudicarie Belt and Periadriatic Fault, nappes in the Tauern Window were affected by km-scale upright folding and orogen-parallel extrusion towards the Pannonian Basin in Miocene time (Ratschbacher et al., 1991; Frisch et al., 1998; Scharf et al., 2013). The northern Alpine front west of Munich (northwest of the Tauern Window) was active until the Pliocene (Von Hagke et al., 2012), whereas east of Munich it ceased propagating northwards after ~20 to 15 Ma (Ortner et al., 2015). This cessation coincides broadly with the onset of sinistral transpression along the Giudicarie Belt, as well as south-directed thrusting in the eastern Southern Alps (Castellarin and Cantelli, 2000; Schmid et al., 2013 and references therein). During this time, rapid exhumation of Penninic and Subpenninic nappes in the Tauern Window commenced (Fügenschuh et al., 1997), although slower exhumation in the Tauern Window may already have started earlier, in the late Oligocene time (Pomella et al., 2012; Scharf et al., 2013; Favaro et al., 2015). Taken together, these events have been interpreted to indicate that Adriatic indentation triggered the orogen-parallel extrusion of the Eastern Alps towards the Pannonian Basin (Ratschbacher et al., 1989; Frisch et al., 1998; 2000; Linzer et al., 2002; Rosenberg et al., 2007; Favaro et al., 2017). Contrasting estimates have been proposed for the amount of lateral extrusion, ranging from 14-62 km (Rosenberg and Garcia, 2011; disputed by Fügenschuh et al., 2012), 65-77 km (Favaro et al., 2017), 100 km (Scharf et al., 2013), to as much as 120 km (Linzer et al., 2002) and 160 km (Frisch et al., 2000).

The NGF and its northern prolongation, the Meran Mauls Fault, sinistrally offset the PF by 75 km, dividing the PF into the Tonale Fault (western segment) and the Pusteria Fault (eastern segment; Figure 1). Discussion has focused on whether the NGF is an exclusively Neogene fault that sinistrally offsets a formerly straight PF, or if the NGF formed a pre-Neogene bend of the PF that was reactivated under transpression during the Neogene (Castellarin and Vai, 1981; Picotti et al., 1995; Prosser; 1998, 2000; Müller et al., 2001; Viola et al., 2001; Linzer et al., 2002; Stipp et al., 2004; Pomella et al., 2011; 2012). The latter hypothesis is supported by Picotti et al. (1995), who estimated that the amount of strike-slip (30-40 km) along the NFG, extrapolated from the amount of Neogene shortening calculated within the southwestern part of the Giudicarie Belt, was less than the 75 km offset of the PF. In addition, several studies (e.g. Doglioni and Bosellini, 1987; Castellarin et al., 2006b) have interpreted the lateral termination of the Cretaceous pre-Adamello deformation phase along the NGF, as a late Cretaceous lateral ramp. However, the interpretation of a pre-Neogene offset PF is incompatible with the proposed 100-150 km of Paleogene dextral strike-slip along this fault (Laubscher, 1991; Schmid and Kissling, 2000) based on offset correlative features on either side of it, i.e. the Ivrea- and Pejo-zones (Laubscher, 1991) and the Sesia-Dent Blanche and Margna units (Laubscher 1991; Schmid et al., 1996; Handy et al., 2005). In addition, a paleomagnetic study of Pomella et al. (2011) convincingly shows that the Periadriatic granitoid intrusions along the NGF underwent counterclockwise rigid-body rotation into their current NNE-SSW striking orientation in Neogene time, suggesting the NGF can be interpreted as a rotated segment of the PF (Pomella et al., 2011; 2012). Although a paleomagnetic study across the Southern and Eastern Alps possibly indicates a larger-scale coherent Oligocene to Miocene rotation rather than a local reorientation (Thöny et al., 2006). Potential links between Neogene shortening in the Giudicarie Belt and strike-slip motion across the NGF and adjacent Tonale and Pusteria fault segments are therefore of great relevance for a better understanding of Neogene collision processes in the Eastern and Southern Alps.

To assess the amount of Neogene shortening within the eastern Southern Alps, it is important to constrain the role of inherited Permian to Mesozoic structures. Indeed, many of the Neogene fault structures were inherited from earlier tectonic events, which include Permian to Jurassic rifting phases.

2.2 Permian to Jurassic paleogeography

Based on Permo-Mesozoic stratigraphic variations, we divide our study area into six different paleogeographical domains (Figure 2) which, as we show below, exert important controls on the partitioning of Neogene shortening. Within the eastern Southern Alps, the Atesina Volcanic Complex (Figure 2) is a good example of a Permian basin filled with volcanic sediments, with the Valsugana fault interpreted as a dextral Permian feature (Zampieri et al., 2003) and the Calisio and Truden faults recording a Permian normal faulting history (Selli et al., 1996). Another minor unit in the eastern Southern Alps containing evidence of this interpreted Permian transtensional phase (Zampieri et al., 2003) is exposed in the hanging wall of the Foiana Fault (Figure 1).

From the Late Triassic to Jurassic, a rifting related to the opening of the Alpine Tethys west and north of Adria (Piemont-Liguria Ocean) affected the Adriatic plate (e.g. Handy, 1987; Handy and Zingg, 1991; Bertotti et al., 1993;

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Picotti and Cobianchi, 2017; Le Breton et al., 2020). The rifting of Alpine Tethys led to the formation of carbonate platforms and basins bounded by N-S trending faults that are still well preserved within the Southern Alps (Bernoulli and Jenkyns, 1974; Winterer and Bosellini, 1981). The main N-S trending faults divided the area into four different domains from west to east (Bernoulli and Jenkyns, 1974; Winterer and Bosellini, 1981): the Lombardian Basin, the Trento Platform, the Belluno Basin and the Friuli Platform (Figure 2). The Lombardian Basin recorded the most Triassic to Jurassic subsidence (Winterer & Bosellini 1981; Bertotti et al., 1993), reaching ~5 km of sedimentary thickness, and is bounded in the east by the Ballino-Garda and Tremosine-Tignale Faults (Figure 1 and 2). Differential subsidence caused significant stratigraphic thickness variations within the Jurassic paleogeographic domains (Picotti et al., 1995). Within the Trento Platform, thicknesses decrease from ~3 to ~2 km both towards the SE and NE dividing the Trento Platform itself into sub-domains: the Trento Platform (numbered 2 on Figure 2), the Reduced Recoaro High (2a), the Reduced Trento Platform (2b), the Atesina Volcanic Complex (2c) and the Asiago Plateau (2d). These thickness variations broadly coincide with Neogene faults, including the Trento-Cles Fault, Truden Fault, Calisio Fault, Valsugana Fault and Schio-Vicenza Fault (Figure 1 and 2). The Atesina Volcanic Complex forms the most prominent Permian paleogeographical domain with a 2 km thick Permian sequence, with no overlying Triassic to Cretaceous sedimentary cover outcropping (Figure 2). Based on the occurrence of Miocene conglomerates with Mesozoic carbonate clasts in the footwall of the Valsugana Fault (Castellarin et al., 1992), it is assumed that this domain (2c) had a similar Mesozoic cover as along the nearby and paleogeographically comparable Reduced Trento Platform (2b) (Selli, 1998), which was later eroded in the Miocene. Another paleogeographic domains containing thinner Permian volcanic successions (up to ~1 km thick; Figure 2) is the Reduced Trento Platform. Further small-scale thickness variations across Mesozoic faults occur within the paleogeographic domains defined here (Franceschi et al., 2014). However, these are beyond the aim of this paper and are neglected in order to simplify the construction and balancing of cross sections (section 5).

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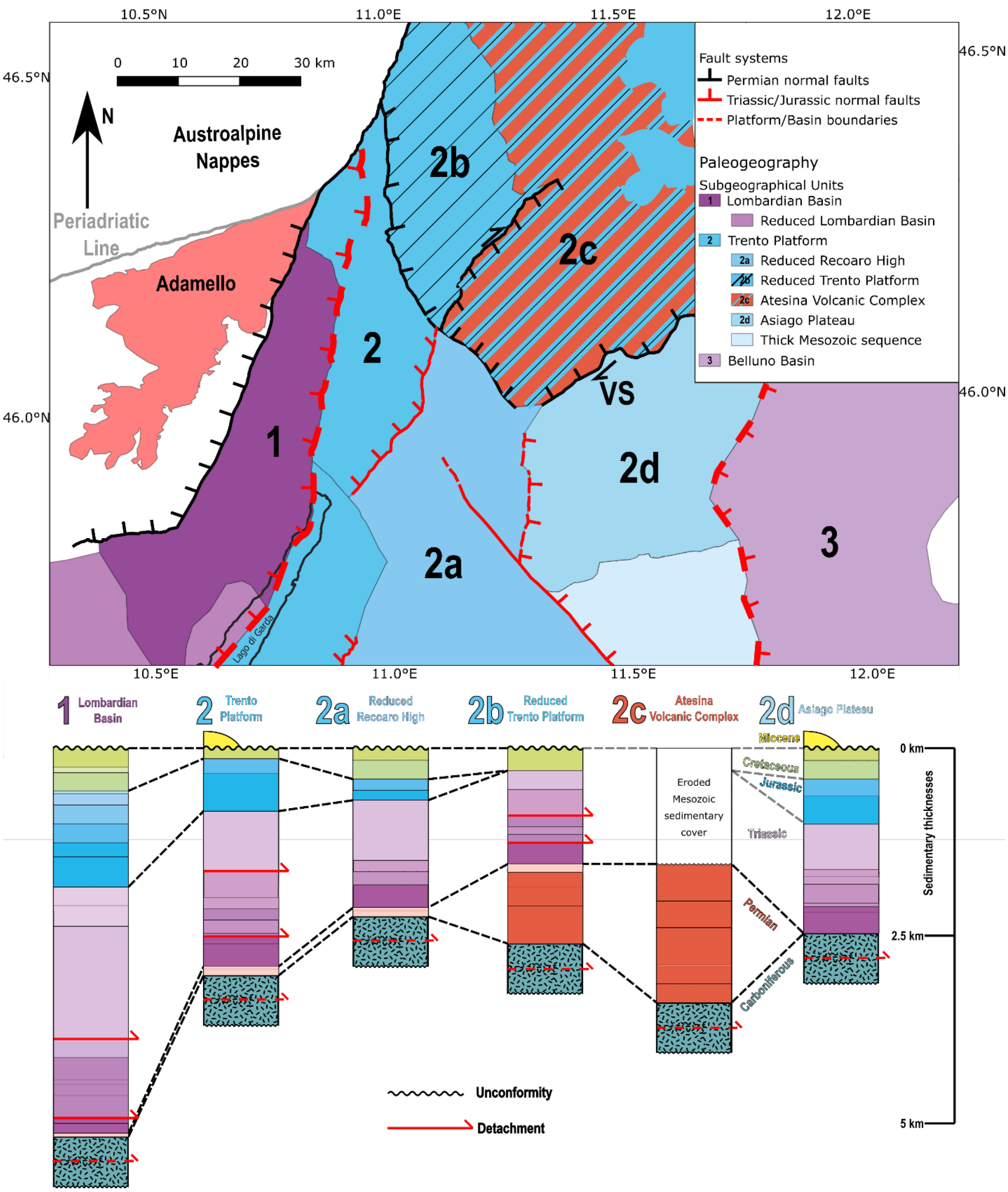

Figure 2: Triassic to Jurassic paleographic basinal (1, Lombardian Basin; in violet) and platform domains (2, Trento Platform in blue). Based on Mesozoic thickness variations, the Trento Platform is subdivided into units 2a-d. Note that within domain 2c no Mesozoic sediments are exposed and the thickness of the eroded Mesozoic sequence is extrapolated from domain 2b, based on the occurrence of Miocene conglomerates with Mesozoic clasts unconformably overlying Mesozoic strata in domain 2d. Domain 2 also includes a Cenozoic sequence unconformably overlying Mesozoic strata outcropping at Monte Brione (see discussion Chapter 4). Simplified stratigraphic columns (below) for each paleogeographic domain 1-2d.

3 Structural observations and fault-slip analysis

Structural data from the eastern Southern Alps were collected as input for fault-slip analysis to calculate the main Neogene shortening direction. This was necessary to estimate the amount of shortening parallel to the shortening direction in the balanced cross sections. Special attention was paid to fault systems coinciding with paleographic variations (the Trento-Cles, Calisio, Valsugana and Schio-Vicenza Faults; Figures 1, 2 and 3) to test if these features coincide with variations in structural style and amount of shortening.

Structural analysis in the Giudicarie-Valsugana sector of the eastern Southern Alps included measuring fault surfaces, their striations and shear-sense, fold-axial planes, as well as bedding planes near folds and faults. These data formed the input for fault-slip analysis, which was performed in the WinTensor software version 5.8.8 (Delvaux and Sperner, 2003). An angle of 30° between the maximum principal stress and the shear plane based on the Mohr-Coulomb failure criterion was assumed. However, given the proximity of the measured fault striations to major fault structures (Figure 3), this angle might have been different due to strain complexities. The maximum principal stress sigma-1 was calculated in the WinTensor software for various fault systems, assuming that structures measured in the field reflect the principal incremental strain direction and principal stress direction sigma-1. The final stereoplots with results of the fault-slip analysis calculated with WinTensor were drawn using FaultKin 8.0.0 software (Figure 3; Marrett and Allmendinger, 1990).

Bedding and striation measurements (Figure 3) were collected along the Bassano (Figure 3a) and Marana (Figure 3b) thrust faults on either side of the Schio-Vicenza Fault (Figure 3c) to test for variations in structural style. The Schio-Vicenza Fault represents an inherited Mesozoic feature associated with stratigraphic thickness variations (Figure 2). Along the Borcola Pass Fault zone, a branch of the Schio-Vicenza Fault, steeply dipping NW-SE to N-S trending fault surfaces containing sinistral striations cut Eocene mafic dikes (Figures 3c and 3e). Striation steps indicating sinistral motion related to local NNW-SSE incremental strain (Figure 3e) parallel to the main shortening direction (Castellarin & Cantelli, 2000) indicate that the Schio-Vicenza Fault was reactivated during post-Eocene time. These striations are overprinted by younger striations indicating downthrow of the NE-block that are interpreted to be related to flexural extension of the foreland bulge of the Apennines (Pola et al., 2014). Contrasting deformation styles east and west of the fault may indicate the Schio-Vicenza Fault acted as a transfer fault. Indeed, directly east of the Schio-Vicenza Fault, strata in the hanging wall of the Bassano Fault (Figure 1) are steeply dipping, strongly folded and form the forelimb of the ENE-WSW trending Monte Grappa ramp anticline (Figure 3a), whereas to the west, the Marana thrust emplaces cataclastically deformed Norian Dolomia Principale on Hettangian to Pliensbachian Calcari Grigi (Figure 3b). No thrust associated with the Monte Grappa ramp anticline is exposed; the anticline is therefore interpreted as a fault-propagation fold above the blind Bassano Fault, in agreement with earlier studies (Doglioni, 1990; Roeder, 1992; Pilli et al., 2012; Pola et al., 2015). The Schio-Vicenza Fault is only observed as far north as the Adige Valley. However, previous studies argued for either a continuous Trento-Cles – Schio-Vicenza (TC-SV) fault system (Semenza, 1974) or a contractional strike-slip stepover with the Calisio Fault connecting the Trento-Cles and Schio-Vincenza Faults (Zampieri et al., 2003). The TC-SV fault system will be further discussed in Chapters 5 and 6.

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Strike-slip deformation along the Schio-Vicenza Fault ends towards the NW in the vicinity of the Valsugana Fault (Figure 1). This fault was reactivated as a Neogene thrust and emplaced Variscan basement onto Mesozoic sediments of the Trento Platform in its western part and Triassic onto Jurassic strata in the east. Striations in the field show thrust motion with a component of dextral strike-slip (Figure 3e). Cross-cutting relationships show that the Valsugana Fault was later once more reactivated as a dextral strike-slip fault (Figure 3d). The lateral ramp of the Valsugana thrust is the Calisio Fault (Figure 1), which merges with the Trento-Cles Fault, thereby inverting a major Permian paleographic boundary (Figure 2). Striations from the Valsugana, Marana, Bassano and Schio-Vicenza faults, ENE-WSW trending axial planes and axes of the Monte Grappa ramp anticline, and striations in the footwall of the Marana Fault and results from a literature compilation (Figure 3e) are all consistent with NNW-SSE shortening.

We note that Castellarin and Cantelli (2000) presented fault-slip data indicating three distinct orientations of shortening through time: Chattian-Burdigalian NNE-SSW shortening, Serravallian-Tortonian NNW-SSE shortening and Messinian-Pliocene NW-SE shortening. However, the Chattian to Burdigalian phase of NNE-SSW shortening occurred mainly west of the SGF, between the cities of Brescia and Bergamo (Schönborn, 1992; Picotti et al., 1997) and has not greatly affected our study area. Messinian to Pliocene shortening is recognized along the Schio-Vicenza Fault and the Bassano and Montello faults along the Southern Alpine orogenic front (Castellarin and Cantelli, 2000). Late Tortonian to Messinian conglomerates were deposited in a syn-tectonic wedge in the hanging wall of the Bassano and Montello Faults (Massari et al., 1986). However, field observations along the Bassano Fault show that folds trend WSW-ENE (Figure 3e), which is more consistent with a NNW-SSE shortening direction.

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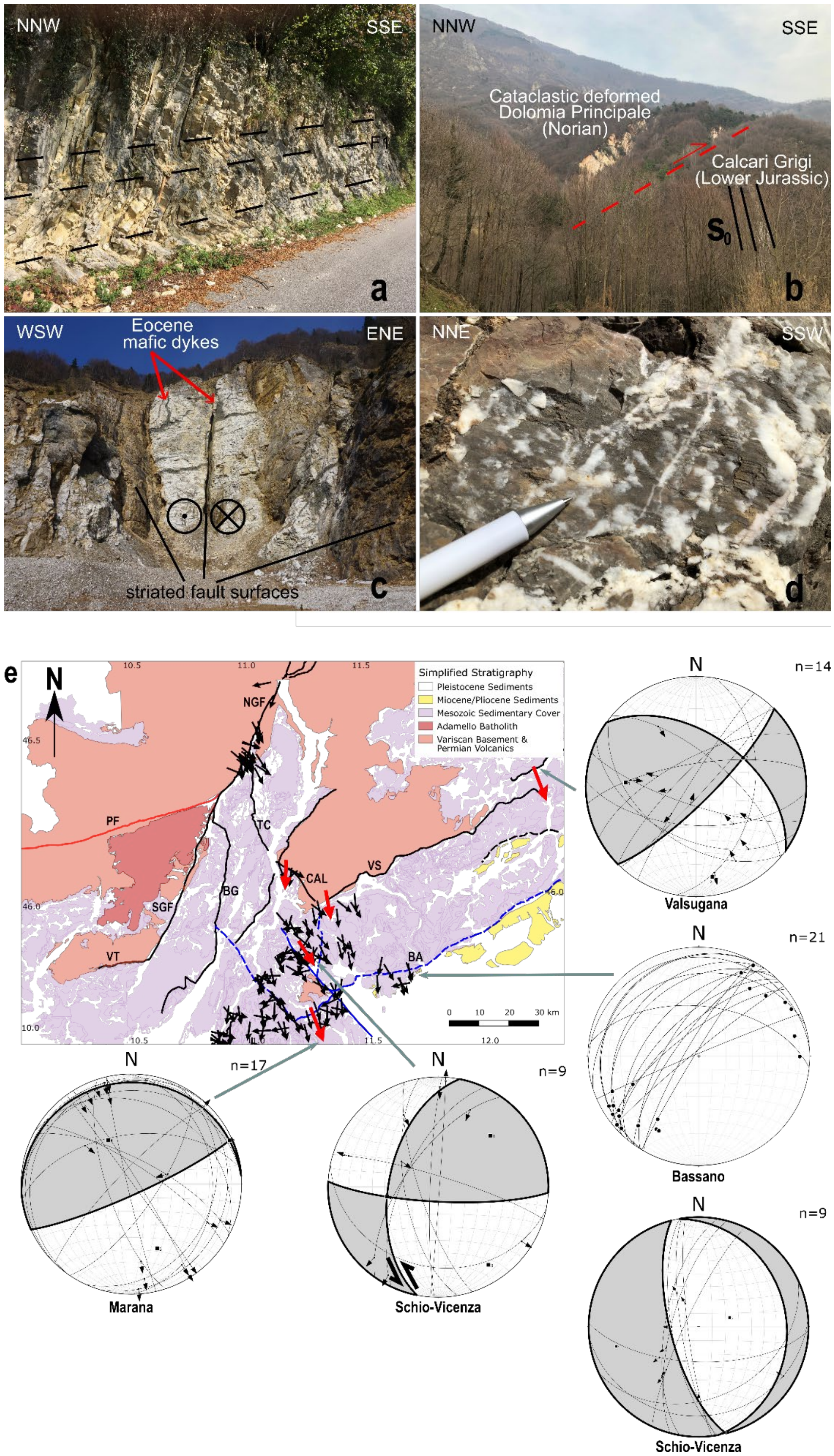

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Figure 3 (previous page): (a) Steepened and kinked Lower Cretaceous strata (Majolica) in the forelimb of the Monte Grappa ramp anticline forming the hanging wall of the blind Bassano Thrust; (b) The Marana Thrust at Zanconati emplaces Norian Dolomia Principale on Lower Jurassic Calcari Grigi; (c) The Schio-Vicenza Fault at Passo della Borcola, offsetting Norian Dolomia Principale and Eocene mafic dykes. Striations on fault surfaces indicate oblique sinistral down-dip motion; (d) Dextral strike-slip slickenfibres at the eastern end of the hanging wall of the Valsugana Fault (near Pieve di Cadore) where the Valsugana Fault branches into several fault splays and becomes transpressive. (e) Fault-slip analyses with paleostrain directions from own data (red) at field locations a to d, and from regional (Castellarin and Cantelli, 2000; Zampieri et al., 2003) and local paleostrain analyses (Prosser, 1998; 2000; Viola et al., 2001) from the literature (indicated in black). The data indicate a dominant NNW-SSE shortening direction. The geological map is a compilation of own field data and published geological maps (Bartolomei et al., 1967; Bosellini et al., 1967; Castellarin et al., 1968; 2005; Braga et al., 1971; Dal Piaz et al., 2007; Avanzini et al., 2010). See Figure 1 for fault abbreviations.

4 Age of deformation in the eastern Southern Alps

Individual thermochronological dated faults within the eastern Southern Alps include the NGF, SGF, Valsugana and Val Trompia faults, which are broadly coeval with stratigraphic age constraints indicating Neogene deformation (Figure 4). Deformation in the eastern Southern Alps initiated during late Oligocene time (27.8-23.0 Ma), indicated by a detailed seismic survey beneath the Po Plain that documented Chattian to Burdigalian deposits affected by Late Oligocene to Neogene thrusts sealed by Messinian strata (e.g. Fantoni and Franciosi, 2010; and references therein).

A maximum age for the onset of thrusting within the Giudicarie Belt itself is given by the youngest sediments below a thrust that accommodated NNW-SSE shortening. At Monte Brione, at the northern end of Lake Garda (Figure 1), the base of an arenitic-pelitic sequence dated at 21.5 Ma (Luciani and Silvestrini, 1996) shows westward divergent onlaps suggestive of growth in a footwall syncline (Castellarin et al., 2005). Directly east of Monte Brione, similar stratigraphic age constraints are found within deformed sediments of 28-16 Ma in the footwall of the Monte Stivo thrust (Figure 4). Yet further to the east in the footwall of the Valsugana thrust, deformed Serravallian (~14-12 Ma) sediments date south-directed thrusting (Castellarin et al., 1992; Selli, 1998). Similar ages (17-9 Ma) were obtained with apatite fission-tracks from the hanging wall of the Valsugana Thrust and several faults along the Giudicarie Belt (Pomella et al., 2012; Heberer et al., 2016). This main phase of Neogene shortening has been termed the Valsugana Phase, and was coeval with shortening along the Giudicarie Belt (Castellarin et al., 1992; Castellarin and Cantelli, 2000). Several former Mesozoic structures were reactivated during this phase, including the Schio-Vicenza Fault (Figure 2).

A younger phase of Messinian to Pliocene shortening has been recognized along the Bassano and Montello faults of the Southern Alpine orogenic front (Massari et al., 1986; Castellarin et al., 1992). Late Tortonian to Early Pliocene fossils (Dal Piaz, 1912, Massari et al., 1986) are found in mudstones interbedded with conglomerates in a syn-tectonic wedge in the hanging wall of the Bassano and Montello Faults (Massari et al., 1986). Historical seismicity (e.g. Galadini et al., 2005) and clustering of (micro-)seismic hypocenters (Romano et al., 2019; Anderlini et al., 2020; Jozi Najafabadi et al., 2020) along these fault systems and morphological evidence of fault surface rupture (Moratto et al., 2019; Romano et al., 2019) indicate that this younger phase of shortening is still active.

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The Adamello granitoids, the Variscan basement and overlying Permian volcanics are better suited for geochronological studies, as reflected in the clustering of age data within these rock units (Figure 4). Early to Late Miocene thermochronological ages along the NGF (Viola et al., 2001; Pomella et al., 2011; 2012) and within the Val Trompia-sector of the Giudicarie Belt (Heberer et al., 2016; VT in Figure 4) fall within the same age interval as the stratigraphic constraints above, indicating the coeval evolution of the NGF and Giudicarie Belt.

In addition, pre-Oligocene ages of shortening have been reported in the eastern Dolomites (Doglioni and Bosellini, 1987) based on similarities with Dinaric thrust directions and Oligocene deposits unconformably overlying Mesozoic strata (Doglioni and Bosellini, 1987; Keim and Stingl, 2000). However, these faults only occur east of our study area. West of the SGF, a pre-Adamello phase of shortening is recognized along the Val Trompia-sector of the Giudicarie Belt (Brack 1981; Doglioni and Bosellini, 1987; Picotti et al., 1995; Castellarin et al., 2006b). Relative age constraints are provided here by the observation that the Gallinera Fault is cross-cut by the western side of the Adamello batholith (Brack, 1981; Picotti et al., 1995; Castellarin et al., 2006b), which indicates a pre-Adamello age of deformation, possibly Cretaceous. However, within our study area east of Adamello, no such indications for pre-Adamello deformation can be found. This suggests the presence of a Cretaceous lateral ramp between the western and the eastern Southern Alps (Doglioni and Bosellini, 1987; Castellarin et al., 2006b).

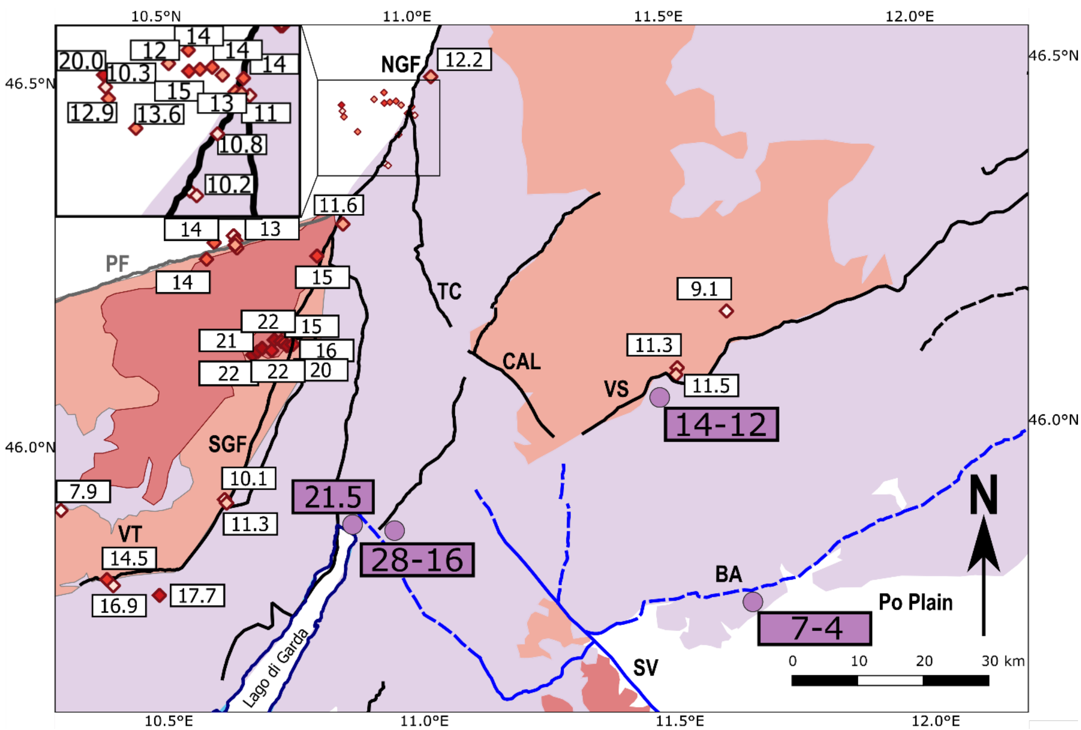

Figure 4: Compilation of stratigraphic and AFT age data in the eastern Southern Alps from Luciani and Silvestrini, (1996); Martin et al. (1998); Castellarin and Cantelli (2000); Viola et al. (2001); Stipp et al. (2004); Pomella et al., (2011; 2012); Heberer et al. (2016). Purple boxes mark biostratigraphic ages of deformed sediments (Castellarin et al., 1992). The inset

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map outlines the Adamello-Giudicarie area at the junction of the NGF and TC faults, with the locations of many, tightly spaced age data. See Figure 1 for fault abbreviations.

5 Shortening estimates and depth of detachment in the eastern Southern Alps

5.1 Assumptions for structural analysis and cross section balancing

All kinematic models of the Giudicarie Belt agree that deformation involved Neogene transpression with strain partitioning between strike-slip and thrust faults (Picotti et al., 1995; Prosser, 1998; 2000). To obtain reliable estimates of shortening across the belt, it is necessary to account for rock volumes moving into and out of 2-D sections traces. Seven cross sections were constructed parallel to the NNW-SSE Neogene direction of principle shortening direction obtained from fault-slip analysis above (Figure 3e). These cross sections straddle the Schio-Vicenza, Trento-Cles and Ballino-Garda faults (Figure 5), which as we have shown above, coincide with the main boundaries of paleogeographic domains (Figure 2). In addition, seven perpendicular (orogen-parallel) cross sections were constructed to assess stratigraphic variations across these faults (Figure 5). Stratigraphic and tectonic contacts were projected into the sections using structural contours constructed from published geological maps (Bartolomei et al., 1967; Bosellini et al., 1967; Castellarin et al., 1968; 2005; Braga et al., 1971; Dal Piaz et al., 2007; Avanzini et al., 2010). In addition, publicly available bore-hole data for the southern part of the studied area beneath the Po Plain (Paese, Scaldaferro, Travettore and Villaverla wells; VIDEPI-database) constrain the thickness of the sedimentary cover. Thickness variations within the paleogeographic domains of Figure 2 are neglected and only variations across these major paleogeographic boundaries are incorporated in the cross sections. Thicknesses within the profiles were extrapolated to depth and above the current erosional level using the kink-band and dip-domain methods (Boyer, 1986).

Line-length balancing was performed with the Move software package (provided by Petex) using the flexural slip algorithm for unfolding the horizons. We assumed a flat top-Cretaceous horizon and used this as a marker to estimate the fault displacements. This is admittedly a simplification given the lateral facies and thickness variations in Cretaceous strata (Doglioni and Bosellini, 1987). Modelled fault geometries at depth were tested using a trial-and-error, forward modelling approach until a best-fit with the present-day surface geology was found. We assumed that all the observed folds along the profiles are fault-related and employed a fault-bend-fold algorithm (Suppe, 1983) in Move. This algorithm treats faults as brittle, discrete discontinuities, even at depths below ~10 km where ductile behavior is expected in natural systems. The fault-bend-fold algorithm maintains line length and area in forward modelling, in contrast to its alternative, fault-parallel flow, which only maintains line length when a correct angle of angular shear is specified. We avoided fault-parallel flow modelling because this angle is not well constrained in the studied area. It is inferred that the Northern Giudicarie Fault (NGF) forms the backstop of the south-vergent Neogene deformation of the eastern Southern Alps and that all interpreted detachments are connected at depth with the NGF. This is in line with the absence of any significant Neogene deformation in the Austroalpine basement to the NW of the NGF. It is clear that sinistral strike-slip motion of up to 75 km along the NGF itself was coeval with thrusting in the Giudicarie Belt (e.g., Pomella et al. 2011), but transpressional movement cannot be incorporated in the fault-bend-

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folding algorithm of Move. Thus, in forward modelling of all cross sections, the NGF is progressively offset as a passive marker along the fault detachments (Figures 6, 7 and 8).

The 3D Move database including all 14 cross-sections, as well as descriptions of selected cross sections 1, 5, 6 and details on the forward modelling approach, are available as supplement in Verwater et al. (2021; see data availability section below). Our obtained shortening estimates should be considered minimum estimates, given the possibility of eroded hanging wall cutoffs and potential tectonic erosion.

5.2 Results of shortening estimates from cross-section balancing

Amounts of shortening in orogen-normal profiles vary laterally along the Giudicarie Belt (Figure 5). To the south-west (Profiles 1 and 2), balancing yield 18-22 km of shortening. Similarly, to the northeast (Profiles 6 and 7), shortening estimates range from 17 to 25 km. However, shortening is only 8 to 12 km in the central part of the Giudicarie Belt (Profiles 3, 4, 5). The largest variation in shortening occurs between profiles 5 (11 km) and 6 (25 km) across the TC-SV fault system (Figures 5, 7 and 8). We infer a dominantly thick-skinned style of deformation, with detachments reaching down to ~15 km depth based on exposure of basement in the hanging wall of steep thrusts, recent seismicity clustering at depths of 10 to 20 km (Vigano et al., 2015; Jozi Najafabadi et al., 2020) and forward modelling in Move (Figs. 6, 7, 8 and 9; Supplement in Verwater et al. 2021).

These minimum shortening estimates are fairly well constrained, as the fault displacement observed at the surface provides the most important constraint for the amount of shortening and uncertainties of fault structures at depth have errors of 2-3 km (see discussion supplementary material). Although the Giudicarie Belt exposes several long decollements within the sedimentary cover (e.g. Tremosine-Tignale, Paganella and Tosa Faults; Figures 6 and 7), field observations show that, with the exception of the Mezzocorona antiformal stack along profile 6 (Figure 8a), there are no large-scale duplexes exposed. This suggests that kinematic models with several putative duplexes at depth are inconsistent with field observations. However, the geometries in the footwall of the Paganella (profile 5; Figure 7) and Valsugana Faults (profile 6; Figure 8) allow for alternative interpretations in which possible duplexes at depth are linked with shortening at the surface. These duplexes would increase shortening along profiles 5 and 6 by ~2 to 3 km (see alternative interpretations of profiles 5 and 6 in data repository of Verwater et al. 2021). In addition, the clustering of seismic events along modelled fault structures in the basement propagating southward in profiles 1, 5 and 6 (Figures 6, 7 and 8; Jozi Najafabadi et al., 2020) is consistent with thick-skinned tectonics featuring ramps that root in the basement units.

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Profile	1	2	3	4	5	6	7
Shortening	18 km	22 km	8 km	12 km	11 km	25 km	17 km

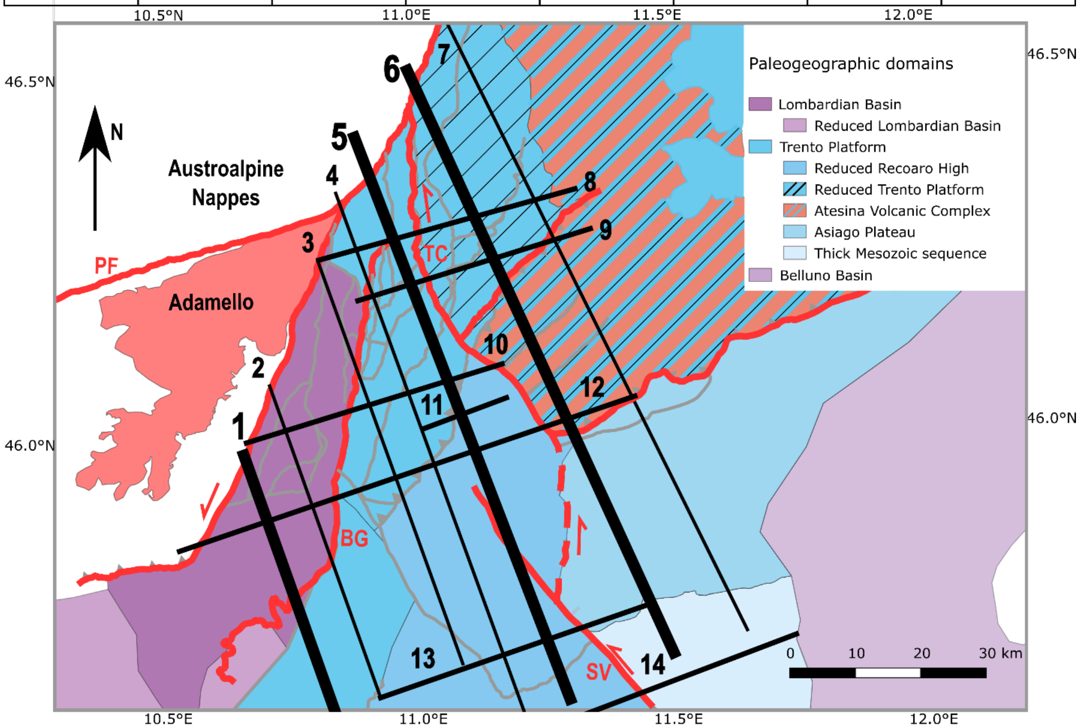

Figure 5: Traces of cross sections constructed and balanced in this study. Details of profile reconstructions for profiles 1, 5 and 6 (thick black lines) is shown on Figures 6, 7 and 8, respectively. Profiles not shown in Figures 6, 7, 8 and 9 are available in the supplementary material. Abbr. BG: Ballino-Garda Fault; PF=Periadriatic Fault; SV: Schio-Vicenza Fault; TC: Trento-Cles Fault.

5.3 Forward modelling of fault detachments at depth

Sub-surface faults in profiles 1-7 (Figures 6, 7, 8 and 9) were determined from forward modelling of an initial undeformed state involving layer-cake stratigraphy (Figures 6b, 7b and 8b). This assumption is necessary for balancing, though in light of the aforementioned Mesozoic rifting in this area (chapter 3), layer-cake stratigraphy is only an approximation of the pre-Neogene structure. All the NNW-SSE profiles were tested with one, two, or three basements nappe slices involved in thrusting. Within the Lombardian Basin and Trento Platform along profiles 1 and 5, the surface geology was best reproduced with two basement thrust sheets (Figures 6c and 7c). We interpret the Mesozoic Ballino-Garda Fault (Fig. 2) to ramp down to Pre-Permian basement and connect at depth with a basement detachment (Figure 6c). However, for the Reduced Trento Platform and Atesina Volcanic Complex along profile 6 (Figures 8c), the surface geology was best reproduced with three basement thrust sheets. The 10-12 km depth of the lower detachment in profile 1 suggests a possible connection with the lower detachment in profile 5 and the middle detachments of profile 6, both situated at 10-12 km depth (Figures 6, 7 and 8). A possible correlation between the

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bottom detachments of profiles 5 and 6 is suggested by similar detachment geometries and depths down to 15 to 20 km. Lateral jumps of a few km in detachment level (Figure 9) are interpreted to occur along major steep Permo-Mesozoic faults. These fault jumps could be an artefact produced by the uncertainty of the fault geometries at depth within the forward modelling in Move. Such a deeper basement level is required in forward models to reproduce the structures associated with the Bassano Fault west of the Schio-Vicenza Fault.

Recently, the SWATH-D seismic network (Heit et al., 2020) provided accurate hypocenters in the study area (average vertical and horizontal resolutions of ~1.7 km and of ~0.5 km, respectively; Jozi Najafabadi et al., 2020), basically confirming existing seismicity patterns (e.g., Vigano et al., 2015). The seismicity indicates that the most frontal fault systems within the eastern Southern Alps are active (figures 6a, 7a and 8a). Plotted onto the cross sections, the hypocenters provided an additional independent constraint on the depth of basement fault nappes and indicate a possible blind thrust system propagating southward in profiles 1-7 (figures 6a, 7a and 8a), (Jozi Najafabadi et al., 2020). Note that seismicity does not necessarily delineates all active faults, as deformation may occur aseismically (section 6.2) or occur along different structures than the main basement thrust.

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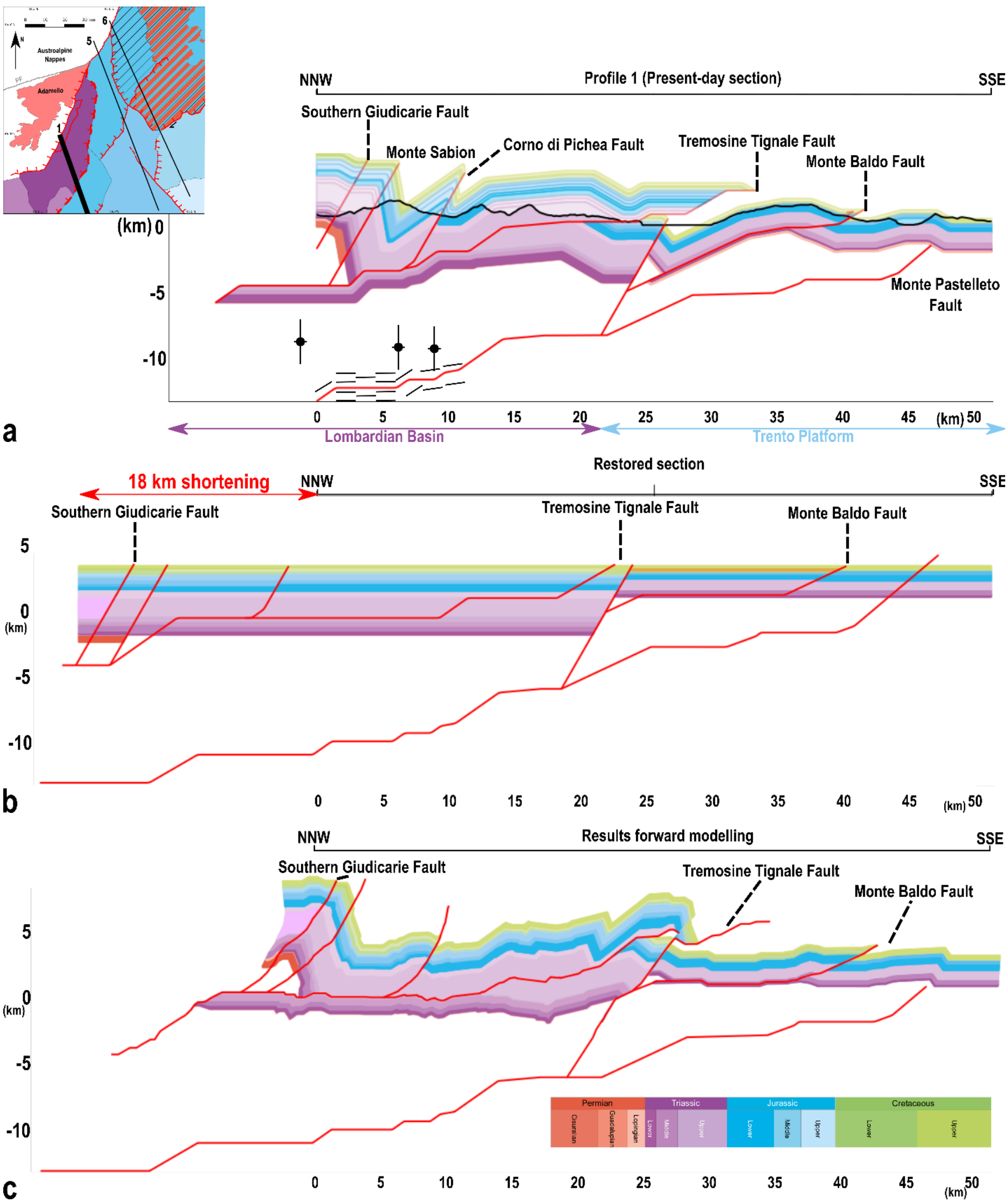

405 **Figure 6: a) Profile 1 across the Lombardian Basin and Trento Platform; b) Profile 1 retro-deformed to a layer-cake stratigraphy; c) Results of forward modelling. Colors in legend modified after the International Chronostratigraphic Chart with pre-Permian basement beneath in white. Black dots indicate earthquake hypocenters during 2017-2018 (SWATH-D Network; Jozi Najafabadi et al., 2020; vertical bars indicate the average error range on hypocenter depths), projected from a swath covering 6 km on either side of the profile. Dashed lines below ~10 km indicate ductile deformation.**

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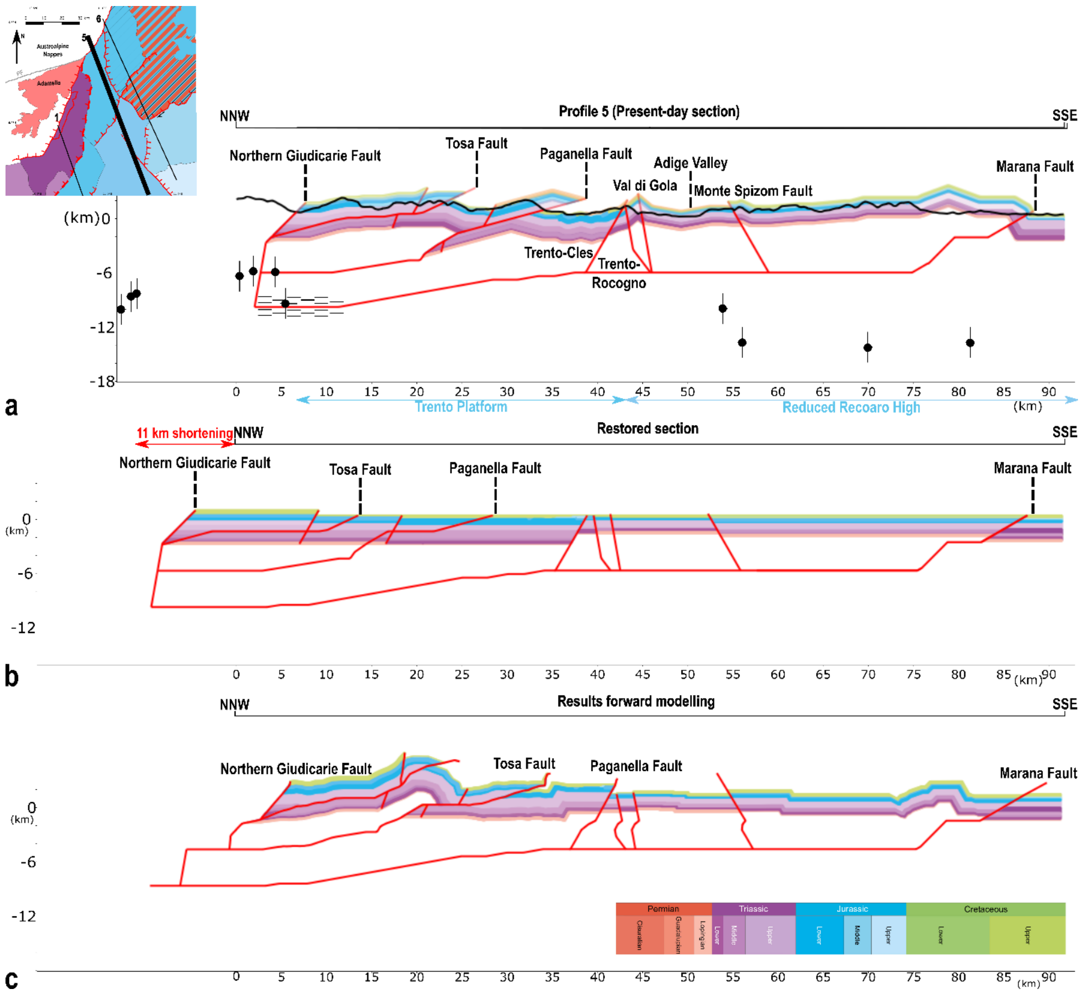

Figure 7: (a) Profile 5 across the Trento Platform and its structural Recoaro High; (b) Profile 5 retro-deformed to a layer-cake stratigraphy; (c) Results of forward modelling. Colors in legend modified after the International Chronostratigraphic Chart with pre-Permian basement beneath in white. Black dots indicate hypocenters of seismic events during 2017-2018 (SWATH-D Network; Jozi Najafabadi et al., 2020; vertical bars indicate the average error range on hypocenter depths), projected from a swath covering 6 km on either side of the profile. Dashed lines below ~10 km indicate ductile deformation.

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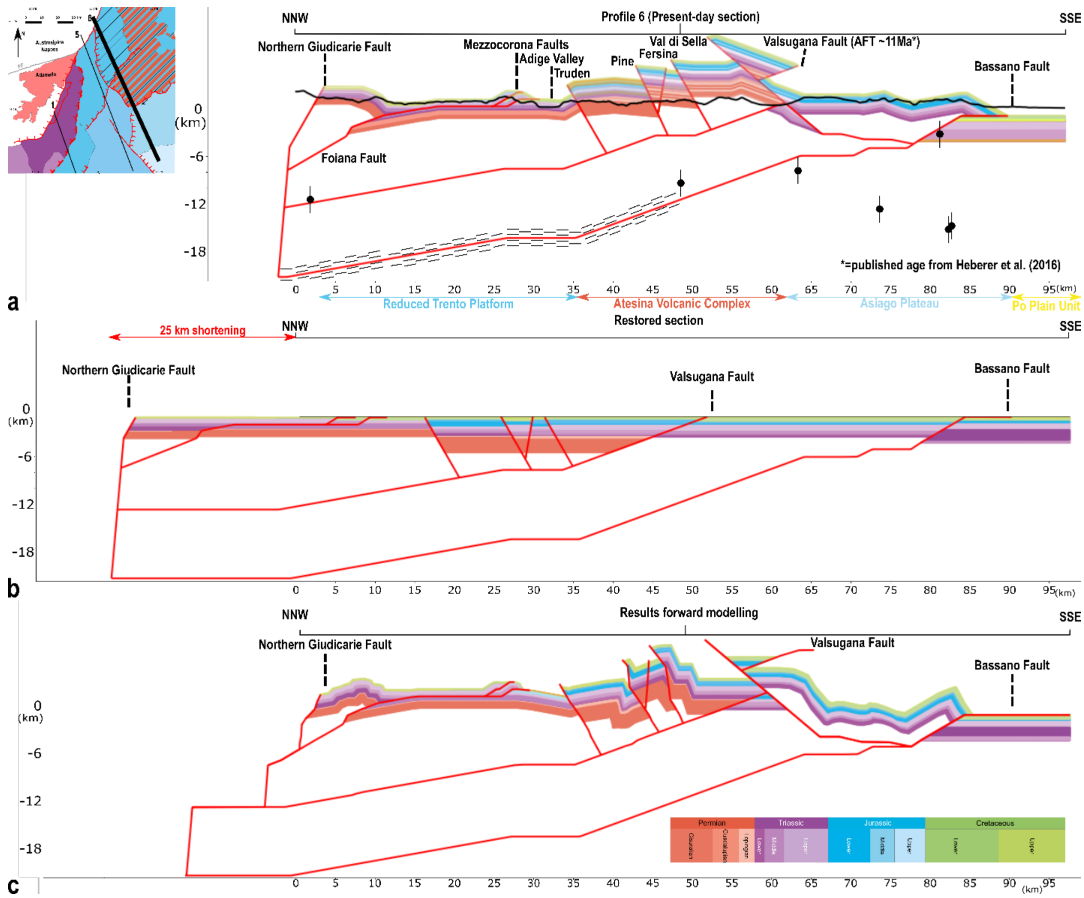

Figure 8: (a) Profile 6 across the Reduced Trento Platform, Atesina Volcanic Complex and the Asiago Plateau; (b) Profile 6 retro-deformed to a layer-cake stratigraphy; (c) Results of forward modelling. Colors in legend modified after the International Chronostratigraphic Chart with pre-Permian basement beneath in white. Black dots indicate hypocenters of seismic events during 2017-2018 (SWATH-D Network; Jozi Najafabadi et al., 2020; vertical bars indicate the average error range on hypocenter depths), projected from a swath extending to 6 km on either side of the profile. Dashed lines below ~10 km indicate ductile deformation.

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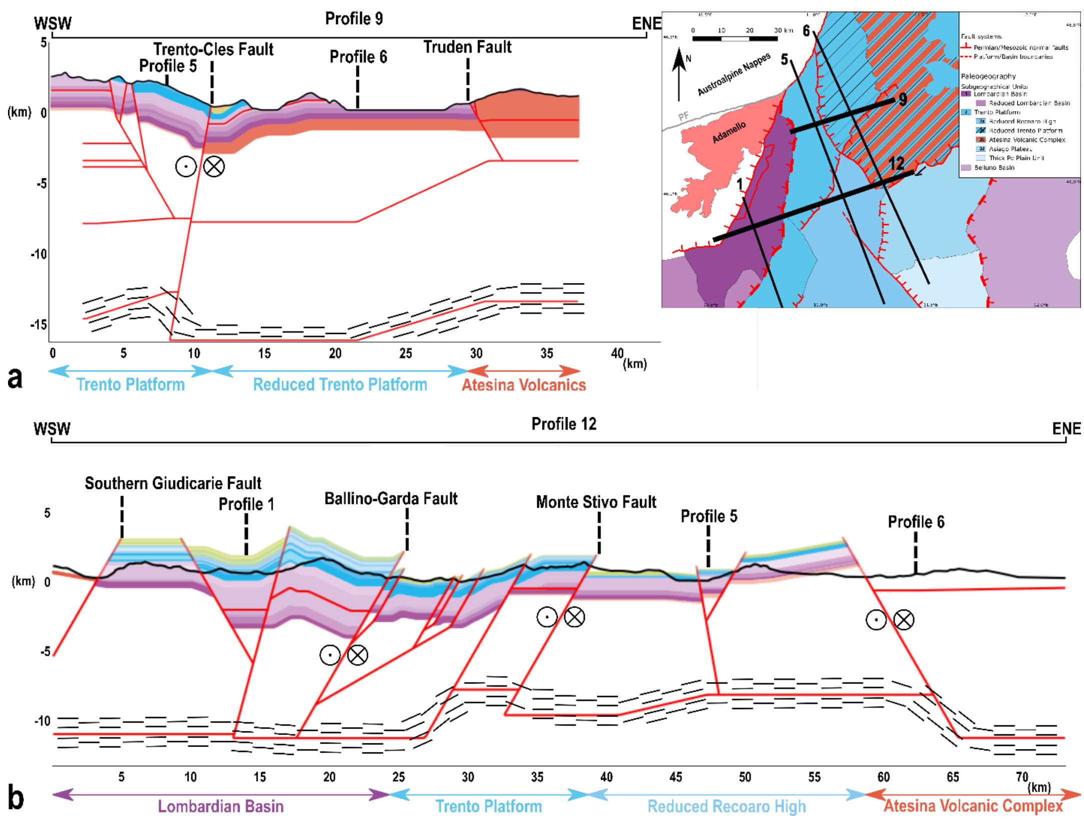

Figure 9: (a) Profile 9 across the Trento-Cles Fault separating the Trento Platform and Reduced Platform; (b) Profile 12 across the Ballino-Garda Fault between the Lombardian Basin and Trento Platform. Dashed lines at and below ~10 km indicate ductile flow.

6 Discussion

6.1 Kinematic divisions of the Giudicarie Belt

The lateral variation in shortening described above follow Permian-Mesozoic paleogeographic domains (Figure 5), whose boundaries were reactivated as strike-slip faults during the Neogene. This is consistent with field observations along the Ballino-Garda, Schio-Vicenza and Trento-Cles faults and fault-slip analysis indicating strike-slip motion along these faults (Figure 3e). We interpret the TC-SV fault system to act as a major sinistral transfer zone (Figure 10), accommodating the largest variation of shortening along the Giudicarie Belt (between Profiles 5 (11 km) and 6 (25 km); Figure 5) and therefore subdividing the area into two kinematic domains (1) and (2), west and east of the TC-SV fault system, respectively (Figure 10).

Based on age constraints (section 4), we subdivide furthermore the shortening phases along each cross section into southern (actively deforming) and northern (inactive) segments. We estimate the amount of strike-slip motion along the TC-SV fault system by comparing shortening on either side of the fault (Figure 10), which results in minimum estimates of 4 km along the SV and 9 km along the TC.

The difference in shortening within the three sectors is attributable to changes in stratigraphy across these faults that are inherited from Permo-Mesozoic time. For example, in the western sector within the Lombardian Basin, most shortening is taken up by the thin-skinned Tremosine-Tignale Fault, which has a long detachment at the base of the Calcare Di Zu and consequently stacks the Dolomia Principale (Figure 6a). The Ballino-Garda Fault is its lateral ramp (Picotti et al., 1995) and therefore does not continue to the Trento Platform. The sedimentary cover is much thicker in the Lombardian Basin than in the Trento Platform (Figure 2) and comprises a thick Jurassic sequence of slope and deep-water deposits that favor the development of extended decollements. In the Trento Platform similar stacking of the Dolomia Principale can be observed along the Tosa, Mezzocorona and Paganella Faults (Figures 7 and 8). However, their fault displacements are much smaller, possibly due to the presence of different decollement layers within the sedimentary cover.

Another example is in the eastern sector (northeast of TC-SV fault system), where most shortening is taken up by the Valsugana Fault and the inversion of a Permian graben containing the Atesina Volcanic Complex. The Calisio Fault represents the lateral ramp of the Valsugana Fault, which is connected with the Trento-Cles Fault (Figure 1; Selli et al., 1996), indicating the Valsugana Fault cannot be traced to the Trento Platform. Although the Valsugana Fault exhumes Pre-Permian basement in its hanging wall, the sedimentary cover of the Atesina Volcanic Complex is much thicker than that of the Trento Platform and contains competent volcanic and pyroclastic deposits of the Lower Permian Formazione di Ora and Formazione di Gargazzone, which are less abundant within the Trento Platform. We propose that the thick sedimentary cover of the Atesina Volcanic Complex favored a different tectonic style with a contrasting amount of shortening due to the reactivation of former Permian normal faults as steep Neogene thrusts.

We argue that these local variations in shortening in the eastern Southern Alps are related to inherited paleogeographic features from Permian to Jurassic times with the majority of the deformation focused within the Lombardian Basin and the Atesina Volcanic Complex, that have a thicker sedimentary cover than the Trento Platform, which is composed of mainly competent carbonate platforms. Moreover, internal fragmentation of the Adriatic indenter along the NGF and TC-SV fault system played a major role in strain partitioning (discussed in section 6.2)

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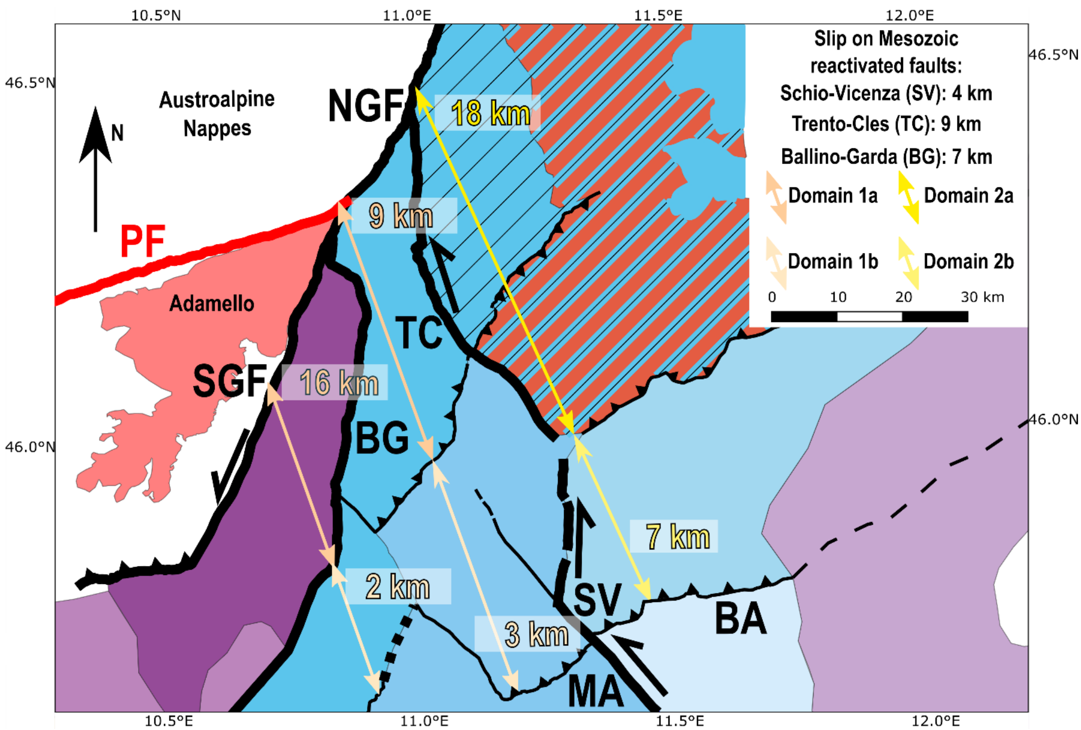

Figure 10: Lateral variation of shortening coincide with paleogeographic domains (Figure 4), bounded by Mesozoic faults (BG, SV, TC) that were reactivated as Neogene strike-slip faults. The TC-SV fault system accommodated the largest variation of shortening and subdivides the area in two kinematic domains (1) and (2), west and east thereof, respectively. Each profile is furthermore subdivided into a northern and southern segment based on the age of deformation, with the northern domains indicating older deformation of the Giudicarie/Valsugana phase, and southern domains with a younger to active phase of shortening along the Southern Alpine orogenic front (labelled as the Marana (MA) and Bassano Faults (BA) (see Figure 11)). See Figure 1 for fault abbreviations.

6.2 Lateral variations in Neogene shortening across the eastern Southern Alps

The presented model of dominantly thick-skinned tectonics with three basement thrust sheets is in agreement with the cross section across the Dolomites of Schönborn (1999). However, Schönborn (1999) estimated twice more shortening in his profile across the Dolomites (> 50 km; orange line on Figure 11). Although his cross section transects the Belluno Thrust, which is not considered in our study, the 4-5 km of displacement along this system (Schönborn, 1999) remains insufficient to explain the difference in shortening (c. 25 km). In fact, shortening estimated by Schönborn (1999) along the Valsugana-Belluno system (22 km) is similar to our estimate of 18 km along the Valsugana system (Figure 8). The difference between Schönborn (1999) and our study is mainly due to different interpretations of the Bassano Fault, which Schönborn associated with 33 km of shortening, while we only propose 7 km. Schönborn (1999)'s 33 km estimate is based on hinterland-dipping panels above footwall ramps, which must be matched with hanging wall geometries. Other profiles transecting the Bassano Fault published by Selli (1998) (close to the TC-SV fault system; parallel to our profile 6) and Castellarin and Cantelli (2000) (parallel to the section of Schönborn, 1999;

orange section in Figure 11) indicate 33 and 35 km of Neogene shortening, respectively, of which 14 km and 19 km were accommodated by the Bassano Fault. Along profile 6 (Figure 8) surface measurements of layer dips indicate that several hinterland-dipping strata of Schönborn (1999) are not observed at the surface in the hanging wall of the Bassano Fault. Therefore, we prefer the 7 km shortening estimate in our study area (Figure 8) and the 19 km towards the east from Castellarin and Cantelli (2000), to the 33 km of Schönborn (1999).

More to the east, Nussbaum (2000) presented cross sections with several basement thrust sheets and an estimated minimum of 50 km shortening (blue line on Figure 11). To the west of the Giudicarie Belt, Picotti et al. (1995) obtained shortening estimates of 30 to 40 km (purple line on Figure 11). The main difference between cross sections h, g and f of Picotti et al. (1995) and cross sections 1 to 7 of this study is the major thin-skinned component of shortening beneath the Po Plain west of Lake Garda (Picotti et al., 1995; and references therein); this shortening decreases towards its lateral ramps up to the Adige Valley. Such buried thin-skinned shortening is not present further to the east, as shown by a seismic survey across the Po Plain directly east of the Schio-Vicenza Fault (Pola et al., 2014).

In addition, the TC-SV fault system seems to be the boundary for most thrust systems, as thrusts merge with it and cannot be traced across. It also coincides with contrasting (though partly overlapping) ages of shortening (Figure 10), which forms the basis for a distinction between kinematic domains 1 and 2 (Figure 11). Kinematic domain 1 contains the Val Trompia-sector of the Giudicarie Belt with ~18 km of Late Oligocene to Early Miocene shortening along thrusts that merge with the NGF and SGF (Picotti et al., 1995; Figure 11). The same thrusts then accommodated ~12-22 km of Middle Miocene to recent shortening. In kinematic domain 2, a minimum of 25 km of post-Middle Miocene shortening (Figures 5, 8, 10 and 11) was accommodated directly east of the TC-SV fault system, simultaneously with shortening in kinematic domain 1. Given the proximity of profile 6 to the TC-SV fault system, a major strike-slip corridor, significant out-of-plane motion along these profiles may have occurred. Therefore, we have included the estimated 35 km of Neogene shortening of Castellarin and Cantelli (2000) in the Neogene displacement vector triangle of domain 2 (Figure 11).

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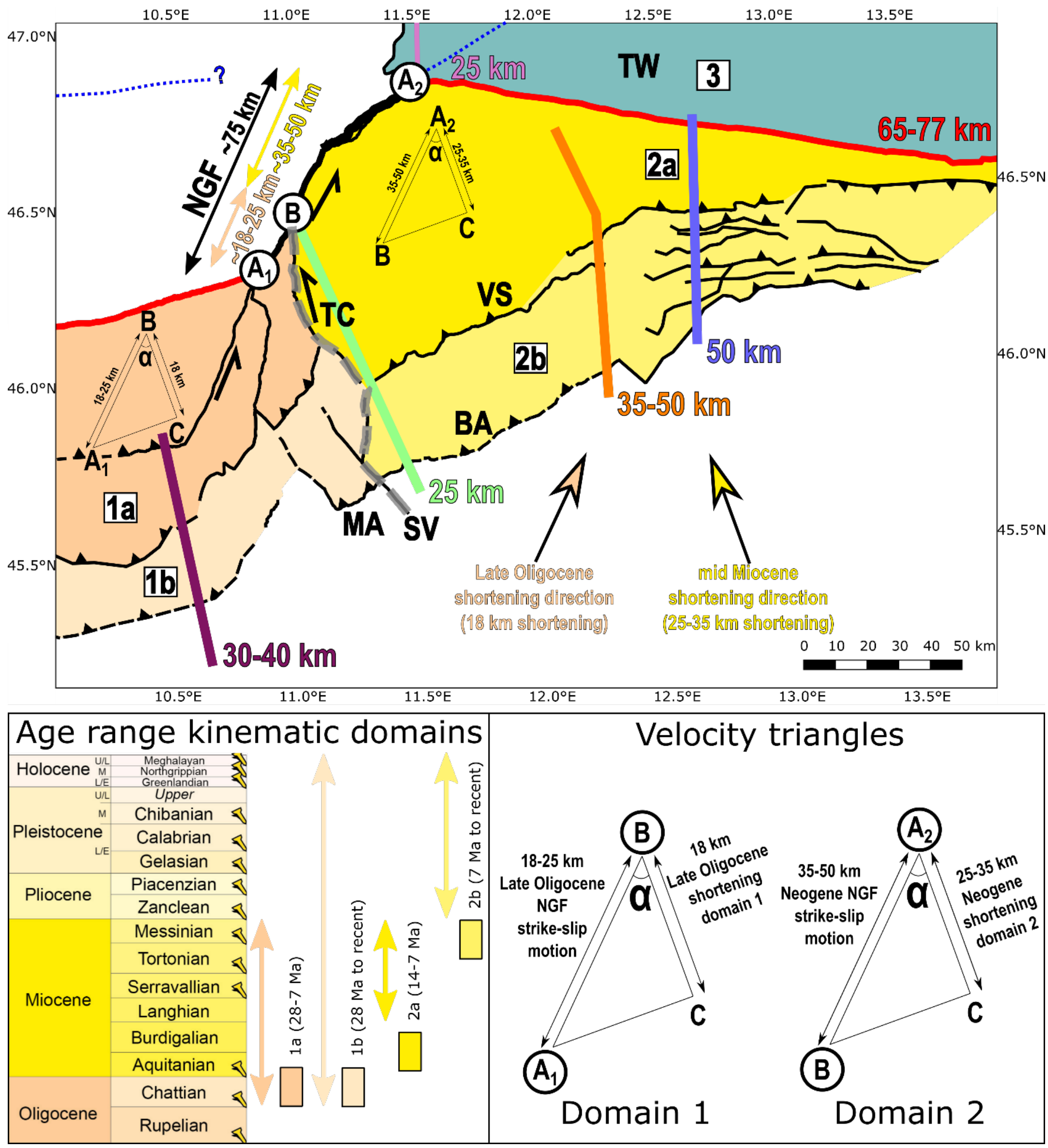

525 **Figure 11: Kinematic map of the eastern Southern Alps, subdivided in two domains east and west of the TC-SV fault system (dashed in grey). These made contrasting and partly overlapping kinematic contributions to sinistral strike-slip offset along the NGF. The subdivision into domains a and b is based on the age of deformation (see legend and section 4). Seismicity in domains 1b and 2b indicates that shortening is still ongoing. Profile traces from this study (green), Picotti et al., (1995, purple), Schönborn (1999, orange; parallel to cross section of Castellarin and Cantelli, 2000), Nussbaum (2000, blue),**
530 **Favaro et al., (2017) (pink), and the inferred surface trace of a putative Adriatic crustal wedge (Gebrande et al., 2002, blue dashed) are indicated. Triangle A$_1$BC depicts the geometrical relationship between Late Oligocene to Early Miocene shortening in kinematic domain 1 of the Giudicarie Belt (vector BC) and motion along the NGF (vector AB), which is estimated to be ~18-25 km. This was obtained by projecting 18 km of shortening along the Val Trompia sector of the Giudicarie Belt (Picotti et al., 1995, purple). Triangle A$_2$BC depicts the geometrical relationship between Middle Miocene**

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shortening in kinematic domain 2 of the Giudicarie Belt (vector A$_2$C) and motion along the NGF (vector AB), which is estimated to be ~35-50 km. This was obtained by projecting 25-35 km (green) of shortening along the Giudicarie Belt east of the TC-SV fault system. Fault abbreviations: BA=Bassano, MA=Marana, NGF=Northern Giudicarie Fault SV=Schio-Vicenza, VS=Valsugana

Based on stratigraphic and radiometric age criteria (section 4), we further subdivide domains 1 and 2 into sub-domains a and b (Figure 11), with ongoing shortening in domain b indicated by seismicity. Low instrumental seismicity and high strain rates in the central part of domain 2b (Figure 12; Serpelloni, 2016) might indicate a seismic gap (Anselmi et al., 2011) where deformation is aseismic. Note that strain rates are also relatively high in the Friuli area where there is a prominent cluster of seismicity (Figure 12; see e.g. Bressan et al., 2016). This could be due to its junction with the Dinaric system, and/or an increase of shortening towards the East (Nussbaum, 2000) due to counterclockwise rotation of Adria with respect to Europe (e.g. Channell et al., 1979; Ustaszewski et al. 2008; Le Breton et al. 2017).

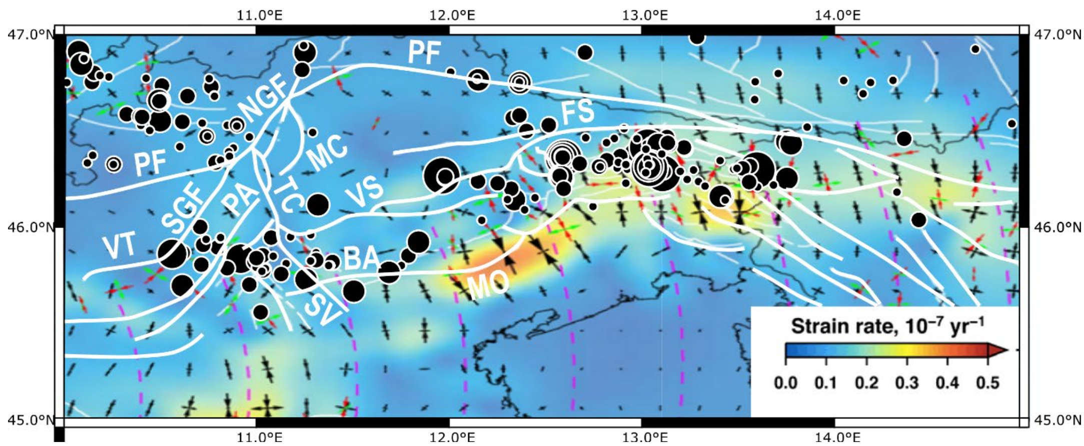

Figure 12: Epicenters of seismic events from 2017-2018 ($M_L \geq 1$; size of black dots indicates earthquake magnitudes up to M_L 4.2) compiled from the SWATH-D Network (Jozi Najafabadi et al., 2020) superposed on strain rates determined from GPS velocities (after Serpelloni et al., 2016). Note that the area in the center with the highest strain rates (vicinity of the Montello Thrust) coincides with lower seismic activity, although clustering of low-magnitude events has been reported (Moratto et al., 2019; Romano et al., 2019). Abbr.: FS=Fella-Sava Fault; see Figure 1 for the other fault abbreviations.

6.3 Kinematic link between shortening along the Giudicarie Belt and sinistral motion along the NGF

Variations in lateral shortening along strike of the Giudicarie Belt may be attributed to large-scale strain partitioning resulting from strike-slip motion along the TC-SV fault system (Figure 11). This system merges with the NGF and the transferred shortening therefore partly accounts for some of the total 75 km sinistral offset along the NGF (Figures 11 and 12). Figure 13 shows a reconstruction from Late Oligocene to present and how shortening has contributed to the observed sinistral offset along the NGF using displacement vector triangles. During the Late Oligocene to Early Miocene, 18 km of shortening along domain 1 was transferred into 18-25 km of motion along the NGF (see displacement vector triangles in Figure 13). Subsequently, coeval shortening along domains 1 and 2 since the Middle Miocene contributed an additional of 35 to 50 km of motion along the NGF (Figure 13). The range of 35 to 50 km

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motion along the NGF since the Middle Miocene reflects the uncertainty in shortening estimates within kinematic domains 1 and 2 related to the presence or absence of putative duplexes at depth along profiles 5 and 6 (Figures 7 and 8; see discussion in supplementary data repository, Verwater et al. 2021). Combining the estimates of 18 to 25 km of Late Oligocene to Early Miocene sinistral slip and another 35 to 50 km of Middle Miocene to Recent slip on the NGF yields a total of 53 to 75 km of sinistral offset along this fault since the Late Oligocene. These 53 to 75 km of Oligocene to Neogene strike-slip displacement along the NGF are insufficient to solve the question whether the 75 km of sinistral displacement on the NGF is exclusively Oligocene, such that the dextral PF would acquire its interpreted straight pre-Oligocene geometry, as discussed above in section 1 (Laubscher 1991; Schmid and Kissling 2000; Handy et al. 2015). We note that some previous workers regard the NGF to have accommodated no more than 30-40 km of sinistral displacement (Picotti et al., 1995; Castellarin et al., 2006b) or even less (15 km, Viola et al., 2001), which are significantly lower than our estimate for displacement on the NGF. These authors used small-scale markers and only considered motion along parts of the Giudicarie Fault System (Viola et al., 2001; Castellarin et al., 2006b) or used slightly lower shortening estimates (Picotti et al., 1995). These studies further based their view on Mesozoic paleogeographical variations on either side of the NGF (Castellarin and Vai, 1981; Picotti et al., 1995; Prosser, 1998) that are generally colinear with the NNW-striking, early Mesozoic facies change going from the Trento Plateau to the Lombardian Basin. They interpret this linear coincidence as evidence for a pre-Alpine (Mesozoic) offset, thus rendering the map-view kink of the PF to be partly an artifact of Mesozoic rift tectonics. In addition, Müller et al. (2001) estimated a shortening of more than 40 km based on jumps in metamorphic grade across the NGF, which if valid, would suggest only ~40 km of Paleogene dextral motion along the PF and allow a pre-Oligocene offset of the NGF. This is however incompatible with the interpreted late Paleogene dextral motion on the PF of some 100-150 km (Laubscher 1991, Schmid and Kissling 2000), which would have been accommodated by a roughly equivalent amount of the late Paleogene E-W shortening at high angles to the NGF. Shortening of such magnitude along the NGF has not been observed.

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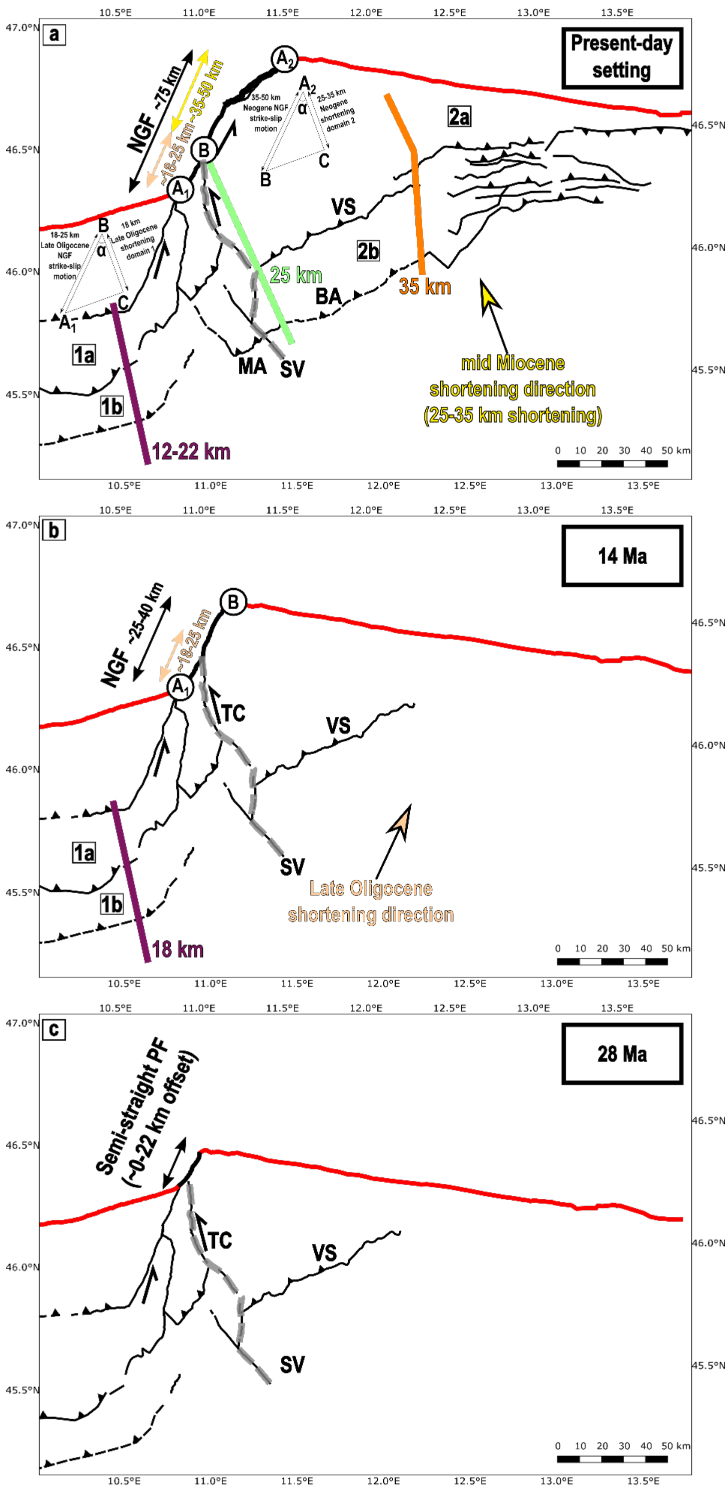

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Figure 13 (previous page): Kinematic evolution of the eastern Southern Alps from the present day (a) to Late Oligocene time (c): (a) Present configuration of the eastern Southern Alps with ~75 km sinistral offset of the PF along the NGF. There are two kinematic contributions to the ~75 km of strike-slip motion: (1) 25-35 km of Middle Miocene NNW-SSE shortening across kinematic domain 1 and 2 (Figure 11), which when projected onto the NGF corresponds to ~35-50 km of sinistral strike-slip (displacement vector triangle A_2BC); (2) 18 km of Chattian to Middle Miocene, NNE-SSW to NNW-SSE shortening west of the TC-SV fault system, which when projected onto the NGF corresponds to ~18-25 km of sinistral strike-slip (see discussion in section 3); (b) At ~14 Ma the NGF sinistrally displaced the PF by ~25-40 km. Since the Middle Miocene (≥14 Ma), ~20-35 km of shortening both east and west of the TC-SV fault system were transferred into motion along the NGF at ≥ 14 Ma and are therefore subtracted from the 75 km displacement budget. The ~25-40 km offset along the NGF at ~14 Ma is partly attributable to 18 km of Late Oligocene to Middle Miocene shortening along the Val Trompia-Giudicarie Belt ('kinematic step 1' of Picotti et al., 1995); (c) At ~28 Ma the Periadriatic Fault was only partly offset (~0-22 km) and restores to a relatively straight Periadriatic fault showing only a minor bend north of the Adamello batholith.

6.4 Transfer of motion along the NGF to the Eastern Alps

The minimum 53 to 75 km of sinistral motion on the NGF must have been transferred into the Alpine orogenic lithosphere north of the Pustertal-Gailtal part of the PF and south of the Northern Calcareous Alps. The northern Alpine Front is not offset by an equivalent amount. The obvious structures to accommodate this displacement is in the Tauern Window, as already proposed by numerous authors (e.g., Laubscher 1991, Scharf et al. 2013). Based on 2-D map view kinematic reconstructions, Favaro et al. (2017) estimated at least 25 km of N-S Neogene shortening (Figure 11) associated with km-scale upright folding in the Western Tauern Window, located just north of the angular junction of the NGF and PF defining the tip of the eastern Adriatic indenter. This implies that a remaining amount of N-S shortening was transferred into orogen-parallel, lateral escape of the Eastern Alps towards the Pannonian Basin (Ratschbacher et al., 1989; Frisch et al., 1998; 2000; Linzer et al., 2002; Rosenberg et al., 2007 Scharf et al., 2013; Handy et al., 2015). Estimates of lateral extrusion vary between 65-77 km (Favaro et al., 2017) and 160 km (Frisch et al., 2000). The latter amount is probably an overestimate because the latter authors assumed that Austroalpine units exposed at the western and eastern ends of the Tauern Window were in contact prior to Neogene extension, effectively neglecting the contributions of km-scale post-nappe upright folding to denudation (see discussion in Favaro et al. 2017). The amount of eastward motion can be roughly estimated by balancing the amount of shortening within the Southern Alps with shortening within the Tauern Window, although the amount of lateral escape as a function of indentation also depends on the depth of detachment underneath the Tauern Window, which remains rather uncertain. Our minimum estimates for Middle Miocene to recent NNW-SSE shortening within the Giudicarie Belt (~25 km) combined with Late Oligocene to Early Miocene NNE-SSW shortening estimates across the Val-Trompia fold-and-thrust belt (Picotti et al., 1995) would suggest that the amount of lateral extrusion is much more modest than proposed values in the order of 160 km (Frisch et al., 2000). We therefore favor the estimate of 65 to 77 km (Favaro et al., 2017) of E-W directed, orogen-parallel extension of the Eastern Alps since 21 Ma (Favaro et al., 2017). Assuming that 53 to 75 km motion along the NGF was transferred to the Tauern Window (Laubscher, 1990) and resulted in 25 km N-S shortening in the Tauern Window (Favaro et al., 2017), a total of 69 to 100 km N-S Neogene Alpine shortening can be depicted. This range of shortening estimates provides a minimum amount of Adria-Europe plate convergence and is in good agreement with plate tectonic reconstructions (~70 km, Van Hinsbergen et al., 2020; ~135 km, Le Breton et al., 2017).

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6.5 Transfer of motion at lower crustal – mantle depths

The contribution of shortening along the Giudicarie Belt to offset along the NGF requires that the basal detachment of the former roots in the latter. Alternatively, the basal detachment of the Giudicarie Belt and NGF occupy different depths, implying the absence of a kinematic link between shortening along the Giudicarie Belt and motion along the NGF. Additional shortening could be accommodated by a lower crustal Adriatic wedge, which according to reflection seismic studies extends 25 km north of the PF beneath the Tauern Window (Figure 11; Gebrande et al., 2002; Lüschen et al., 2004; Castellarin et al., 2006a). This would necessitate decoupling between relatively weak orogenic crust and rigid denser lower Adriatic crust. The shortening associated with this sub-Tauern wedge can be no more than its 25 km length, which is less than the minimum amount in our sections and along other transects of the eastern Southern Alps (Schönborn 1999; Castellarin & Cantelli 2000, Nussbaum 2000). Our results show that lateral variations in Neogene shortening occurring along the eastern Southern Alps coincide with strain partitioning within the Giudicarie Belt along pre-existing structures, indicating a main detachment horizon exists beneath the Giudicarie Belt. This detachment horizon could either be linked at depth with the NGF, PF and a lower crustal Adriatic wedge underneath the Eastern Alps (sub-Tauern wedge; Lüschen et al., 2004; Castellarin et al., 2006a) or alternatively could extend northwestward of the NGF and linked with the Adriatic lower crustal wedge beneath the central Alps (Rosenberg and Kissling, 2013). We consider the latter hypothesis to be rather unlikely given the wide E-W extent of this wedge towards the Western Alps (Rosenberg and Kissling, 2013) and the modest amount of shortening along the Giudicarie Belt. The Eastern Alpine crustal wedge may be shorter than the lower crustal Adriatic wedge in the Central Alps (Schmid et al. 1996; Rosenberg and Kissling, 2013). Nevertheless, its relationship with Neogene shortening across the eastern Southern Alps remains enigmatic. Possibly, the amount of shortening observed at the surface and within the Adriatic crust is an expression of lateral variations in the strength of the Adriatic upper and lower crust, as also proposed for the Central Alpine lower crustal Adriatic wedge (Rosenberg and Kissling, 2013). To test this hypothesis, future studies using local earthquake tomography are necessary to image and delineate a potential lower Adriatic crustal wedge beneath the Tauern Window and Eastern Alps. Such studies may also constrain the dip of the NGF at depth, which in existing Moho maps, does not extend down to the mantle lithosphere (e.g., Spada et al. 2013). The model of Adriatic indentation offsetting a straight PF would require a deep sub-vertical fault dip.

Previous studies have also suggested the presence of an Adriatic slab underneath the Eastern Alps (Lippitsch et al., 2003; Handy et al., 2015). However, shortening within the eastern Southern Alps ranging between 25 km (this study) and 50 km (Schönborn, 1999) is significantly less than the ~50-210 km NNE-dipping segment beneath the Eastern Alps imaged by Lippitsch et al. (2003), suggesting that this slab cannot be considered to be exclusively, if at all, related to Adriatic subduction underneath the Eastern Alps.

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7 Conclusion

The Giudicarie Belt and associated Giudicarie Fault at the transition from the western to eastern Southern Alps is an important junction within the Alpine orogen. This study focuses on constraining its Neogene kinematics and depth of deformation, in particular the kinematic link between shortening in the Giudicarie Belt and motion along the NGF, and their connection to deeper structures.

Fault-slip analysis confirms that the main Neogene shortening direction is NNW-SSE. Balancing of 7 geological cross sections within the Giudicarie Belt indicates a dominant thick-skinned structural style of deformation, as shown by ramp anticlines exposing Pre-Permian basement in the hanging wall of faults, and clustering of recent seismicity at ca. 15 to 20 km depth within the basement. This thick-skinned tectonic implies a modest amount of shortening (8-25 km) within the studied area. The variations in Neogene shortening coincide with major Permian-Mesozoic paleogeographic domains that divide the studied area into two kinematic domains, west and east of the Trento-Cles – Schio-Vicenza transfer fault system that accommodated about 13 km of sinistral slip. The lateral variation in shortening reflects competence contrasts and sedimentary thickness variations across the paleogeographic domains. Domains of thickest sedimentary cover, comprising relatively incompetent slope deposits, has accommodated more Neogene shortening (8-11 km), whereas domains of thinnest sedimentary cover, with competent platform carbonates, accommodated the least amount of shortening (17-25 km).

Projecting the amount of shortening onto the NGF yields a minimum of 53 to 75 km of sinistral slip along this fault since the Late Oligocene. This amount may be insufficient to fully explain the apparent 75 km of sinistral offset of the Periadriatic Fault, indicating a possible additional source of Neogene shortening within a potential Adriatic lower crustal wedge. Future work using local earthquake tomography is necessary to test this hypothesis and determine its potential lateral extent and relationship to shortening within the upper crust. Here, we follow the interpretation that Adriatic indentation into the Eastern Alps is responsible for most, if not all, of the 75 km sinistral offset along the NGF, triggering lateral escape of the Eastern Alps. Furthermore, we interpret the lateral variation of shortening (11-28 km, this study; 35 km, Castellarin and Cantelli, 2000; 50 km, Schönborn, 1999 and Nussbaum, 2000) within the eastern Southern Alps to reflect lateral variations in strength of the Adriatic indenter due to inherited Permian to Mesozoic tectonic structures and paleogeographic domains.

Data Availability

All reconstruction and forward modelling files, as well as the complete set of cross sections of this study are available in the following data repository website:
https://dataservices.gfz-potsdam.de/panmetaworks/review/3c9729f2be33ab6678f45a7f3e2a7f21bfc6b711bd8b1632bad231e75df52be8/

Author contribution

The project was conceived by MH, ELB and CH as part of the German Research Priority Program (SPP-2017) "Mountain Building in 4-Dimensions, an interdisciplinary arm of the European *AlpArray* Project. Fieldwork, fault-slip analysis, drawing of stratigraphic columns, construction and balancing of cross sections were performed by VF under the supervision of ELB, MH and with the advice of VP. VF wrote the manuscript with major contributions from ELB and MH. AJN and CH provided the earthquake catalogue and participated in the discussion on seismicity and active structural domains of the Southern Alps.

Competing interests

The authors declare that they have no conflict of interest.

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