Structural Nexus and Divide: the Western Tauern Window, Eastern Alps

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Key Points:

- The western Tauern Window forms a mature transpressive wrench zone with a sigmoidal vortex geometry
- The western Tauern Window links the Giudicarie Belt to the SEMP Fault, translating orogen-perpendicular shortening into -parallel extension
- The western Tauern Window decouples the Ötztal Basement in the west from the extruding wedges of the Eastern Alps in the east

Abstract

The western Tauern Window of the Eastern Alps constitutes a mature transpressive wrench zone generated by Oligocene-Miocene convergence between the Dolomites Indenter and the European foreland. As a major structural divide, it translates convergence-parallel north-south shortening into convergence-perpendicular eastward lateral extrusion. About 7000 foliation, lineation, fold-axis, axial-plane, shear-zone, and shear-band measurements at ~1800 sites detail the structural geometry and evolution during indentation and transpression, modeled by numerical and analogue-material experiments. The results outline the western Tauern Window as an orogen-scale zone of localized deformation, consisting of tight, upright folds, reactivated by a sinistral shear-zone network. It connects the Giudicarie Belt southwest of the indenter salient with the Salzach-Ennstal-Mariazell-Puchberg Fault (SEMP) in the northeast. This transpressive zone has a sigmoidal vortex geometry, decoupling the Ötztal Basement in the west from the extruding wedges of the Eastern Alps in the east.

Shortening was successively absorbed by nappe stacking, upright folding, and dome formation and then maintained by transpressional shearing that led to lateral extrusion, probably promoted by a change in the lithospheric configuration. The western part of the SEMP likely rotated 20° clockwise around a pole approximately halfway along its entire length during the indentation.

Plain Language Summary

The Alps constitute one of Earth's best-studied continent-continent collision orogens. There, the Apulian plate, a continental sliver of the African plate, started to collide with the European plate ~66 million years ago. In the north, the Apulian plate has a triangular shape, the Dolomites Indenter. The Tauern Window at the tip of the Dolomites Indenter deformed stronger than its neighboring areas, exposing deeply-buried European-plate rocks that are surrounded by Apulian-plate upper crustal rocks. We studied the deformation within the western Tauern Window and found that it connects two major fault zones, i.e., the Giudicarie Belt in the southwest that accommodates orogen-perpendicular shortening, and the SEMP Fault in the northeast that accompanies orogen-parallel extension. Based on kinematic models and field data, the western SEMP Fault likely rotated clockwise 20°.

1 Introduction

Salients or oroclines (e.g., Bandar Abbas, Pamir-Hindu Kush, Hazare-Kashmir, Namche Barwa, Nanga Parbat), where promontories advance into weak crust, are studied to deduce the kinematics of indenter tectonics and the associated displacements in the lithosphere (e.g., Critelli & Garzanti, 1994; Kufner et al., 2016; Molinario et al., 2004). Commonly observed processes are strain partitioning and localization, decoupling between tectonic blocks, deep-crustal exhumation, transpression, transtension, and slab breakoff (e.g., Chopin et al., 2012; Dewey et al., 1998; Fossen et al., 2013; Frehner, 2016; Kufner et al., 2016; Reiter et al., 2011; Reiter et al., 2018; Robin & Cruden, 1994). The structural evolution at indenter fronts has been modeled by numerical and analogue-material experiments, but controversies on the boundary conditions, reference systems and directions, and displacement amounts and rates in orogens hinder the transfer of their results to the natural systems (Burg & Podladchikov, 1999; Ratschbacher et al., 1991a, 1991b; Reiter et al., 2011; Rosenberg et al., 2004, 2007; Schueller & Davy, 2008). In addition, pre-existing anisotropies, common in orogens, may induce a structural evolution that deviates from the predicted one. Another difficulty is the quantification of shortening at the indenter fronts. Shortening in transpressional zones is often overestimated, as the wrench component of deformation remains underconsidered due to the lateral material movements out of the cross sections used to quantify the shortening (Tikoff & Peterson, 1998). To overcome this problem, we herein derive the kinematic vorticity number W_k to estimate the amounts of convergence-parallel shortening (contraction) and fold-hinge-parallel extension (stretching) based on the convergence angle , measured between the convergence direction and the active shear plane (Supporting Information Figure S1); this reflects the ratio between the simple and pure shear components of the bulk deformation (Fossen & Tikoff, 1993; Tikoff & Fossen, 1993).

We studied the western Tauern Window (TW) in front of the Dolomites Indenter in the European Alps (Figure 1a). The structural maps outline areas of dominate transpression and subordinate transtension, for example outlined by non-cylindrical folds and transecting foliations. In the field, we took foliation, lineation, fold axis, fold axial plane, shear zone, and shear band measurements. Based on their orientation, we defined five structural domains (A to E). We focus on the spatial distribution and relative temporal evolution of these structures and calculate the dihedral angles (section 4 Methods and section 5 Results) between the mean values of two distinct structures that formed in kinematic succession. We use the rotational direction of the dihedral angles (being clockwise or counterclockwise) and the kinematic vorticity number W_k to (1) deduce the kinematic connections between major fault systems, (2) discriminate between wrench-dominated and pure-shear-dominated transpressional domains, and (3) quantify the amounts of shortening and extension within the transpressional folds of the western TW. We review the existing hypotheses on the structural development of the TW and, based on our findings, modify them regarding the role of indentation, lateral extrusion, and fault linkage and rotation. Finally, we discuss the coupling between major fault zones, the decoupling of tectonic blocks, and complement the ongoing discussion about fault linkage and absolute displacements in the western TW by developing the Proto-SEMP hypothesis.

2 Geological Setting

The TW (Figure 1a) is the largest tectonic window of the Eastern Alps (Frisch, 1976), where lower plate rocks have been exhumed from >35-km-depth in the Cenozoic (e.g., Kurz et al., 2008; Selverstone & Spear, 1985; Spear & Franz, 1986). In this east-west elongate structural and metamorphic dome, the arcuate dome axis coincides with rocks recording the peak temperatures of high-grade Barrovian metamorphism (Grundmann & Morteani, 1985; Rosenberg et al., 2018; Selverstone, 1985; Schneider et al., 2015) and the youngest cooling ages (Bertrand et al., 2017; Luth & Willingshofer, 2008; Most, 2003; Rosenberg & Berger, 2009). We subdivided the TW into the eastern, central, and western sub-domes; the eastern and western sub-domes are characterized by elongate and concentric metamorphic isograd trajectories (Grundmann & Morteani, 1985; Scharf et al., 2013b) and intersecting and bordering shear zones (Figure 1a; e.g., Linzer et al., 2002; Neubauer et al., 1999; Rosenberg et al., 2004; Scharf et al., 2013a; Schneider et al., 2013). Framing shear zones are absent in the central dome; there, only structurally high nappes are exposed (e.g., Bousquet et al., 2012a; Schmid et al., 2013), partly folded into a map-scale sheet fold (Groß et al., 2020).

Two end-member models are debated for the formation of the TW. One emphasizes orogen-parallel, large-scale extension, exhuming the rocks of the TW along low-angle normal faults (e.g., Frisch et al., 2000; Neubauer et al., 1999), the other upright folding associated with erosional denudation (e.g., Cornelius, 1940; Laubscher, 1990). Yet, most authors agree on the activity of two kinematically-coupled processes, namely shortening due to the northward displacement of the Dolomites Indenter and eastward lateral material transport, associated with orogen-parallel extension; Ratschbacher et al. (1991a, 1991b) defined these as lateral extrusion, encompassing extension collapse, i.e., gravitational spreading of thickened and uplifted crust in an orogen, and tectonic escape. However, the amounts of shortening, displacement, and extension remain controversial (Frisch et al., 2000; Fügenschuh et al., 2012; Linzer et al., 2002; Luth et al., 2013; Neubauer et al., 1999; Pomella et al., 2011, 2012; Rosenberg & Berger, 2009; Rosenberg & Garcia, 2011, 2012; Scharf et al., 2013a; Schmid et al., 2013; Wolff et al., 2020). We contribute to this discussion with a compilation of structural measurements in the western TW to distinguish structural domains, and to assess the traces and interconnections of major shear zones.

2.1 Tectonostratigraphic Framework

Mesozoic ocean-derived and ophiolite-bearing units of the Glockner Nappe and Matreier Zone and siliciclastic rocks of the European distal margin were imbricated during European continental margin subduction (Figure 1a). The deepest structural units of the TW consist of Europe-derived, late-Variscan intrusions and their para-autochthonous, pre-Variscan host rocks covered by post-Variscan metasediments (Figure 1a), forming the Venediger Duplex, an antiformal stack generated by north-vergent nappe emplacement during the Adria-Europe collision. Above the intervening ocean-derived units of the Glockner Nappe and Matreier Zone, the hanging, Adria-derived Austroalpine nappes include the Meran-Mauls Basement, Ötztal Basement, Northern Calcareous Alps, Niedere Tauern, Gurktal Alps, and the DAV Basement (Figure 1a). All these units were thrusted over the European continental-margin units with the units in the TW shortened due to nappe stacking (D_1) and upright folding (D_2) during the Alpine collision in the Eocene to Oligocene. This resulted in a thickened European crust (e.g., Frisch, 1976; Lammerer et al., 2008; Lammerer & Weger, 1998; Rosenberg et al., 2014, 2018; Schmid et al., 2013) with a declining thickeness east of the TW (Spada et al., 2013). In the late stage of the orogenic evolution, in the Oligocene-Miocene, east-west extension and strike-slip motion (D_3) have accompanied shortening.

2.2 Structural Framework

The western TW consists of the (D_2) upright Ahorn-, Tuxer-, and Zillertaler antiforms that fold the Early Alpine (D_1) foliation of the Venediger Duplex (Figure 1a; Schmid et al., 2013; Lammerer & Weger, 1998). Estimates of the amount of shortening accommodated by these folds vary between ~60 km (Rosenberg et al., 2015), ~49 km (Rosenberg & Berger, 2009), and ~32 km (Schmid et al., 2013), based on line-length balancing and assuming constant nappe thicknesses. The tight folds strike ENE, show sub-horizontal, doubly-plunging fold axes and sub-vertical axial planes; they are often associated with axial-plane foliations, and have up to ~17 km amplitudes (Figure 1b). In contrast, the upright folds in the central and eastern TW strike east to ESE, are open and flat-topped (box-type) with amplitudes of up to ~10 km, and lack axial-plane foliations (Figures 1c to 1d). These structural differences point to an abrupt along-strike change in the way shortening has been accommodated (Figure 2a).

The Brenner Fault at the western margin of the TW (Figure 1a) is subdivided in this study into the Brenner Mylonites (BM) and the Silltal Fault (SF, Figure 2b; Behrmann, 1988; Schmidegg, 1953; Selverstone, 1988). The top-west, normal-slip Brenner Fault detaches the Ötztal Basement from the underlying Glockner nappe. The steep limbs of the antiforms and the cores of the tight synforms in the westernmost TW are overprinted by sinistral shear zones, striking sub-parallel to their axial planes. From north to south, the map-scale sinistral shear zones are the Ahorn (ASZ), Greiner (GSZ), and Ahrntal (AhSZ) Shear Zones, each ~1 to 3-km-wide and tens of kilometers long (Figures 1a and 2b). In addition, several 10s to 100s of meters wide sinistral shear zones, e.g., the Tuxer (TSZ) and the Olperer (OSZ) Shear Zones, occur.

2.3 Surrounding Fault Zones

2.3.1 Giudicarie Belt The sinistral transpressive Giudicarie Belt (GB, Figure 1a) forms the western margin of the Dolomites Intender, a ~77-km-long, N30°E-striking fault system, that offsets the ESE-striking Periadriatic Fault System. Displacement estimates along the GB vary between 15 to 30 km (e.g., Müller et al., 2001; Picotti et al., 1995; Viola et al., 2001) and ~70 km (e.g., Laubscher, 1988; Ratschbacher et al., 1991b; Werling, 1992) due to differing assumptions on its pre-indentation orientation and the amount of shortening accommodated at its southwestern tail. The former group of authors assumes an originally bent Periadriatic Fault System and therefore argues for moderate displacement along the GB, whereas the latter group assumes a straight, pre-indentation Periadriatic Fault System, requiring a larger displacement. Based on balanced cross-sections across the Southern Alps (Nussbaum, 2000; Schönborn, 1992), we favor an originally straight Periadriatic Fault System, hence a sinistral displacement of ~70 km along the GB. The GB includes the Pejo (PeF) and the Northern (NGF) and Southern Giudicarie Faults (SGF), and terminates in the north in the Jaufen (JF), Meran-Mauls (MMF), and Passeier Faults (PaF); the latter delimit, together with the southwestern corner of the TW, the N55°E-striking Meran-Mauls Basement (Figure 1a) (Pomella et al., 2011, 2012). The PaF cuts the JF and the MMF (Müller et al., 2001; Pomella et al., 2011). The thrust geometries inside the Dolomites Indenter exhibit an arcuate shape, indicating north-south (±10°) shortening when applying the bow-and-arrow rule (e.g., Elliot, 1976) to its major thrusts. GNSS measurements of the present-day Alpine kinematics indicate a counterclockwise rotation of Adria against Europe (Caporali & Martin, 2000; Le Breton et al., 2017).

Seismic tomography outlined two lithospheric slabs whose lateral terminations spatially coincide with the GB. The eastern slab was interpreted as the Adriatic plate subducted northward down to 250 km depth; the western slab, likely part of the European plate, features incipient slab break-off (Kästle et al., 2020; Lippitsch et al., 2003; Mitterbauer et al., 2011; Zhao et al., 2016). This discontinuity in the lithospheric structure coincides with a change in seismic anisotropy (Bokelmann et al., 2013; Hetényi et al., 2018; Qorbani et al., 2015). Earthquakes with a magnitude M_L 5 (Richter scale) and hypocentral depths of 20 km have strike-slip focal mechanisms along the GB (Reiter et al., 2018).

2.3.2 Salzach-Ennstal-Mariazell-Puchberg Fault The sinistral transpressive (west) to transtensive (east) Salzach-Ennstal-Mariazell-Puchberg Fault (SEMP, Figure 1a) strikes N70°E from Mittersill along the northern margin of the TW to the Vienna Basin (e.g., Cole et al., 2007; Frost et al., 2009; Linzer et al., 1995). Currently, the SEMP is a structural divide between the seismically active Northern Calcareous Alps in the north and the low-seismicity TW in the south (Reiter et al., 2018). Piercing points imply ~60 km displacement along the SEMP (Linzer et al., 2002), equivalent to ~56 km of east-west extension. Analogue-material models (Ratschbacher et al., 1991a; Rosenberg et al., 2004), simulating the indentation of the Dolomites Intender into the Eastern Alps, suggest that the sinistral faults along the northern boundary of the extruding wedges, e.g., the Proto-SEMP (chapter 6.5), initiated in the earliest stages of indentation and then rotated clockwise during progressive indentation. For the west-central SEMP, Wang and Neubauer (1998) inferred six evolution stages from paleostress analysis. Two involve predominantly strike-slip faulting and four are dominated by fault-normal compression; the maximum compressive stress axes rotated counterclockwise from NE to NW over time. Throughout the evolution of the SEMP, its northeastern tail has been confined to the southeastern salient of the European Platform, the southeastern tip of the Bohemian Massif (Ratschbacher et al., 1991b). At present, the southeastern tip of the Bohemian spur is located below the subparallel Mur-Mürz Fault (Figure 1a) at the Semmering Pass, close to Glognitz (16°00'East, 47'40'North; van Gelder et al., 2020). Geophysical data outline its subsurface extent (Grad et al., 2009; Baroň et al., 2019; Reinecker & Lenhardt, 1999) and suggest that the Bohemian spur is still acting as a buttress.

2.3.3 Pustertal-Gailtal Fault The dextral, N100°E-striking Pustertal-Gailtal Fault (PGF), a segment of the Periadriatic Fault System, divides the Eastern from the Southern Alps (Figure 1a, Polinski & Eisbacher, 1992) and defines the southern margin of the extruding wedges of the Eastern Alps (Ratschbacher et al., 1991b). Estimates of the Oligo-Miocene displacement along the PGF are indefinite. Frisch et al. (1998) and Laubscher (1988) argued for 100 150 km, pre-Miocene dextral displacement along the entire Periadriatic Fault System based on apparent map-view offsets and palinspastic reconstructions. The dextral, NE-dipping Sprechenstein-Mauls Fault (SMF, Figure 2b), the youngest and westernmost, purely brittle segment of the PGF, offsets the western ductile tail of the PGF by ~2 km (Bistacchi et al., 2010). Earthquakes with focal mechanisms $\mathrm{M_L}$ 4 and hypocentral depths 10 km indicate dextral strike-slip along the PGF (Reiter et al., 2018).

2.3.4 Brenner Mylonites and Silltal Fault First estimates of east-west extension across the west-dipping BM varied between ~9 and 14 km (Behrmann, 1988) and "several to tens" of kilometers (Selverstone, 1988). Recent estimates are ~70 km (Fügenschuh et al., 1997), 4 to 12 km (Rosenberg & Garcia, 2011, 2012), 35 ± 10 km (Wolff et al., 2020), and ~44 km (Fügenschuh et al., 2012). The throw across the BM varies continuously along strike (Rosenberg & Garcia, 2011, 2012), with a maximum of ~17 km in the area of the Brenner Pass along the hinge of the Tuxer Antiform (Figure 1a); there, the BM are thickest (Axen et al., 1995; Behrmann, 1988; Selverstone, 1988). Towards the northern and southern tails of the BM and SF, the throw decreases to ~5 km, which cannot be explained by folding of the footwall (Rosenberg & Garcia, 2011). Reassessment (Fügenschuh et al., 2012; Rosenberg & Garcia, 2011, 2012) showed that extension was overestimated because exhumation was entirely attributed to normal faulting, ignoring the contributions of folding and erosion (Axen et al., 1995; Fügenschuh et al., 1997; Selverstone et al., 1995; Wolff et al., 2020). Following structural arguments (Rosenberg & Garcia, 2011, 2012) and using the average 29° dip of the BM obtained in this study (chapter 5.7.5 Extensional Shear Zones), we calculated 10 km extension across the BM, in agreement with the first estimates (Behrmann, 1988; Selverstone, 1988).

The moderately west-dipping SF strikes ~30 km from Innsbruck to Sterzing (Figure 2b and 2c). North of Steinach (Figure 2c), syn- and antithetic normal faults occur in the hanging wall of the SF (Figures 1a and 2b; Reiser, 2010; Reiter et al., 2018). The seismically active Brenner-Inntal Transfer zone connects the SF with the Inntal Fault System (Figure 1a) with transtensive and transpressive faults in the hanging and footwall of the SF, respectively (Ortner et al., 2006). The hypocentral depths of the $\mathrm{M_L}$ 4 earthquakes are between 5 and 15 km (Reiter et al., 2018).

2.3.5 Tauern-Northern-Boundary Fault

The Tauern-Northern-Boundary Fault (TNBF) between the Glockner Nappe and the Lower Austroalpine nappes in the northwestern TW was interpreted to link the BM to the SEMP (Töchterle et al., 2011), to transform extensional into strike-slip displacements (Fügenschuh et al., 2012), and to have a throw of ~3 km, deduced from the TRANSALP seismic section (Lammerer et al., 2008). The TNBF is an outcrop-scale, 50-m-thick, poorly exposed fault zone with varying shear sense indicators, perhaps with dominant top-north reverse and minor sinistral displacements (Bergmeister, 2010; Töchterle et al., 2011).

3 Deformation Fabrics

In the following, we present new and published structural data from the western TW (Figure 2) (Angel & Staber, 1950; Becker, 1993; Exner, 1956, 1962a, 1962b, 1979, 1980, 1983, 1989; Frank & Pestal, 2008; Frank et al., 1987; Giese, 2004; Höck et al., 1994; Karl et al., 1979; Lichtenheld, 2004; Moser, 2006; Rockenschaub & Nowotny, 2009, 2011). These data highlight a structural difference between the central and eastern and the western TW. Based on the mean orientation of the structures, we subdivided the western TW into five structural domains (Figure 2c, Domains A to E) and discriminated three deformation phases (D_1 to D_3), associated with foliations S_1 to S_3.

S_1 foliations formed prior to the upright folds (D_2; Figure 2d). Although of possibly varying ages, S_1 are associated with D_1 nappe stacking and Eocene/Oligocene metamorphism (Bousquet et al., 2012b; Glodny et al., 2005; Nagel et al., 2013; Schmid et al., 2013). The widespread sub-vertical axial-plane foliations (S_{2a}) of the D_2 tight and upright folds strike ENE and cut the folded nappe contacts in the tight D_2 synforms of the western TW (Figure 2d and 2c). The micro- and meso-scale D_2 folds are disharmonic passive shear folds, with thickened hinges, thinned limbs (measured perpendicular to bedding), and Z- and S-shaped second-order folds. Along the margins of the western TW and in the Austroalpine nappes, flexural-slip folds dominate. Along the western margin of the TW, the anticline hinges plunge west, indicated by the circular strike of the nappe contacts with outward pointing bedding. There, the folded S_1 are cut by or form composite foliations with moderately west-dipping S_{2b} foliations, part of the normal-slip shear zones along the BF. S_{2a} and S_{2b} are spatially separated, occurring NE and NW of the indenter salient, respectively (S_{2a} and S_{2b} appear as solid and dashed trajectories in Figure 2d).

D_2 folds and S_2 foliations are overprinted by D_3 km- to meter-scale, subvertical strike-slip and extensional shear zones (Figure 2b). Major NNE- to ENE-striking, sinistral (C_{sin}) shear zones and minor ESE- to ENE-striking, dextral (C_{dex}) ones occur (Pennacchioni and Mancktelow, 2007; Bistacchi et al., 2010). The west-dipping extensional shear zones (C_{nor}) along the western margin of the TW (Figure 2b) formed contemporaneously with the strike-slip shear zones because of mutual overprinting relationships (Axen et al., 1995; Behrmann, 1988; Fügenschuh et al., 1997; Selverstone, 1988). All D_3 shear zones are mylonitic, often brittle-ductile, have higher mica content and smaller grain size than the host rocks, and show clear shear-sense indicators (e.g., Mancktelow & Pennacchioni, 2005; Pennacchioni & Mancktelow, 2007; Schneider et al., 2013; Selverstone, 1993).

4 Methods

We first summarize the geometry, kinematics, and metamorphism associated with the major shear zones of the western TW (Figure 2b). Most of these structures have been described (e.g., Behrmann, 1988; Behrmann & Frisch, 1990;

Lammerer and Weger 1998; Neubauer et al., 1999; Müller et al., 2001; Pomella et al., 2011; Reicherter et al., 1993; Schneider et al., 2013; Spiess, 1995; Steffen & Selverstone, 2006; Viola et al., 2001), but their extent and location differ in the literature. Therefore, we reassess the structures and the shear-zone pattern based on our new structural data and a literature compilation. Then, we present and discuss the field measurements and mean orientation values of specific structures shown in equal area, lower hemisphere stereoplots (created by Stereo32 version 0.9; Röller & Trepmann, 2008). When the data show a preferred orientation and number >15, we contoured them using a cosine exponential equation. If lineations and foliations are shown together, we contoured only the foliations. Mean values were deduced graphically from the data maxima. The individual field measurements of the Domains A to E are listed in the Supporting Information Dataset S1. Rotation of these structures during transpression led to deactivation and replacement by new structures representing the prevailing deformation field during the progressive deformation. The rotational sense of the successively formed structures is opposed to the material paths. We calculated dihedral angles between the mean values of structures, which formed in the prevailing deformational field, and that we infer to have formed in kinematic succession. This illustrates and quantifies their transpressional character and yielded different rotational senses for Domains A to E during transpression (Borradaile, 1987; Treagus and Treagus, 1981). ’s algebraic sign is positive (blue arrows) or negative (purple arrows) when the rotation from one mean value to the succeeding one is clockwise or counterclockwise, respectively (Figure S1).

5 Results and Interpretation

5.1 Ahorn Shear Zone

The ~2.5-km-wide and ~50-km-long, ~ENE-striking Ahorn Shear Zone (ASZ) is a transpressive mylonitic belt located along the northern limb of the western TW (Rosenberg & Schneider, 2008), extending the SEMP westward into deeper crustal levels (Figure 2b; Cole et al., 2007). The ASZ shows sinistral-oblique, south-side-up kinematics with a sub-vertical to steeply SSE-dipping mylonitic foliation and a shallowly west-plunging stretching lineation (Rosenberg & Schneider, 2008). The ASZ transitions into the SEMP in the area of Mittersill and Krimml where sinistral, brittle-ductile and ductile shear zones strike ~NNE and turn abruptly into the east-striking SEMP (Figure 2b and 2c; Cole et al., 2007; Reicherter et al., 1993). The metamorphic grade of the mylonites increases westward along-strike and southward perpendicular to the ASZ strike from 300°C to 400 500°C based on the quartz and feldspar recrystallization mechanisms and the stability of biotite (Schneider et al., 2013).

5.2 Tuxer Shear Zones

Lammerer & Weger (1998) described two sinistral shear zones of >40 km length within the Tuxer Antiform (Salzach-Riffler Fault), striking ESE from the Olperer and Riffel summits in the west to Krimml in the east (Figure 2b and 2c). At Lammerer & Weger's (1998) locations, we mapped an interconnected network of outcrop-scale, 1- to 10-m-thick, lower amphibolite-facies, sinistral shear zones, the Tuxer Shear Zones (TSZ, Figure 2b). The TSZ strike NE to east, dip sub-vertically to steeply south, and connect to the ASZ and the Greiner Shear Zone (see chapter 5.4) at their northeastern and southwestern tails, respectively (Figure 2b).

5.3 Olperer Shear Zones

We divided Lammerer & Weger's (1998) shear zones in the Tuxer Antiform into the TSZ (section 5.2) and the Olperer Shear Zones (OSZ) because of their different orientations and kinematics. In agreement with Ebner et al. (2004), the OSZ constitute two shear zones of 10 to 15 km length, NE to north strike, and moderate to sub-vertical NW to west dip. Sinistral and top-NW normal shear occurred within these ~300-m-thick zones at their western tails. Feldspar ductility and biotite stability indicate syn-kinematic flow at amphibolite-facies conditions.

5.4 Greiner Shear Zone

The ~1-km-thick and ~50-km-long Greiner Shear Zone (GSZ) cuts all D_1 nappe contacts of the western TW and attains a maximum thickness in the Glockner Nappe (Figure 2b and 2e; Selverstone, 1993; Steffen et al., 2001). It strikes east to ENE, is sub-vertical, and has a sub-horizontal stretching lineation. Kinematic indicators imply sinistral (Behrmann & Frisch, 1990; De Vecchi & Baggio, 1982) and dextral (Barnes et al., 2004) shear. Metamorphism in the GSZ mylonites increases eastward along strike from greenschist to amphibolite facies, controlled by the west-plunging Greiner Synform (Figure 1a; e.g., Selverstone, 1985; Selverstone & Spear, 1985).

5.5 Ahrntal Shear Zone

The ~2-km-wide and ~70-km-long transpressive Ahrntal Shear Zone (AhSZ) at the southern limb of the western TW strikes NE to ENE, dips sub-vertically to steeply NNW, and shows sinistral and minor dextral and north-side-up shear (Figure 2b; Behrmann & Frisch, 1990; Reicherter et al., 1993; Schneider et al., 2009). The AhSZ cuts all D_1 nappe contacts and shows predominantly shallowly east-plunging stretching lineations. Metamorphism increases eastwards along strike from greenschist to lower amphibolite facies and northward, perpendicular to the strike, from 300°C to 400 500°C based on quartz and feldspar recrystallization mechanisms, biotite stability, and epidote composition (Kitzig, 2010; Reicherter et al., 1993; Wollnik, 2012). Hence, the metamorphic trends are complementary to the ASZ. Key outcrops in the Vals Valley, south of the Grabspitz summit (Figure 2c), show upright, open to tight folds in the north progressing into isoclinal and rootless folds with axial-plane foliations in the south, overprinted by sinistral shear zones (Figure 3a to 3d).

5.6 Jaufen Fault and Meran-Mauls Basement

The ~200- to 300-m-wide, >15-km-long JF strikes ~ENE; its ductile-brittle mylonites formed at lower greenschist-facies conditions (Müller et al., 2001; Spiess, 1995, 2001; Viola et al., 2001). The JF splits into two branches, one with top-west normal shear in the area of Gasteig (Viola et al., 2001), and one with sinistral-transpressive shear at the Penserjoch road NW of Elzenbaum (Figures 2b and 4; Müller et al., 2001). Our structural data, collected in the Meran-Mauls Basement and summarized in chapter 5.7 as Domain C, indicate that the upright folds of the western TW can be traced into the Austroalpine nappes (Figures 2c to 2d and 4).

5.7 Structural Elements of the Western Tauern Window

5.7.1 S_1 Foliation In Domains A to C (Figure 2c), the folded S_1 strike ENE and dip moderately to steeply NNW but locally SSE (Figure 3a and 3b), indicating an upright to slightly south-vergent sub-dome structure. The sub-vertical -circle of S_1 in Domain A traces a sub-horizontal, WSW-trending fold axis, whereas the -circles of S_1 in Domains B and C indicate gently ENE- and WSW-plunging fold axes, respectively (Figure 5a to 5c; -circle: great circle that fits best the distribution of poles to a folded surface). S_1 and S_2 form a composite foliation along the steep limbs of the D_2 antiforms. A crenulation cleavage, comprising the folded S_1 cut by the axial-plane S_{2a} foliation (Figure 3a and 3b), dominates the fold hinges.

5.7.2 D_2 Fold Axes and Axial Planes The D_2 axial planes (AP_2) of Domains A and B strike ENE, whereas those of Domain C strike NE, sub-parallel to the northwestern margin of the Dolomites Indenter (Figure 5k to 5m). In a cylindrical fold, the -circle and the mean axial plane should be orthogonal to each other and the -axis should be the fold axis (Ramsay & Huber, 1987, p. 334). However, the values for $_1$ (mean AP_2 − -axis; i.e., angle between the strike of the mean D_2 axial planes and the pole to the -circle) in Domains A and B show a -5° (counterclockwise) deviation from being orthogonal, whereas the $_1$ value in Domain C indicates a +11° (clockwise) deviation (Figures 5a to 5c, 5k to 5m, and S1a to S1c, S1g in the supporting information). The D_2 fold axes (FA_2) of Domain A are sub-horizontal and trend ENE, whereas the fold axes in Domains B and C plunge moderately ENE and SW, respectively (Figure 5a to 5c and 5f to 5h). Further, the $_2$ values (mean FA_2 − -axis) indicate a deviation of -8° and -6° in Domains B and A, in contrast to a deviation of +8° in Domain C (Figures 5f to 5h, 5k to 5m, and S1). The orientation of successively formed structures (deformation fields) during the D_2 folding of S_1, indicated by $_1$ and $_2$, thus rotated counterclockwise in Domains A and B and clockwise in Domain C; the corresponding material paths rotated opposite to the deformation field, i.e., counterclockwise in Domain C and clockwise in Domains A and B (chapter 6.4).

The FA_2−-axis deviations ($_1$ and $_2$) in Domains A, B, and C indicate non-cylindrical folding in the western TW, which is diagnostic for transpressional or transtensional folding (Dewey et al., 1998; Ramsay & Huber, 1987; Tikoff & Peterson, 1998; Treagus & Treagus, 1981). The opposite rotations in Domains A and B respectively Domain C (Figures 5a to 5c, 5k to 5m, and S1) reflect the different strikes of the indenter margins causing dextral transpressive folds in domain C and sinistral ones in domains A and B (Figure S1). The different strikes are governed by the orientation of indenter margins and their angle to the convergence direction.

5.7.3 $\mathbf{S_2}$ Foliation and $\mathbf{L_2}$ Stretching Lineation In Domain A, the sub-vertical S_{2a} axial-plane foliations strike ENE, whereas in Domains B and C, they strike ENE–NE, i.e., slightly more to the north, and dip oppositely, SE and NW, respectively (Figure 6a to 6c). The angle $_3$ (mean AP_2–mean S_{2a}) describes the transection of the axial planes (AP_2) by the axial plane foliation (S_{2a}); S_{2a} deviates counterclockwise from AP_2 in Domains A and B and clockwise in Domain C (Figures 5k to 5m, 6a to 6c, and S1). Equally, the $_4$ values (mean FA_2–mean S_{2a}) in Domains A to C deviate clockwise in Domain C and counterclockwise in Domains A and B. According to Borradaile (1978), the $_3$ and $_4$ values obtained from cleavage-transected folds indicate dextral transpressive shear for Domains A and B, and sinistral one for Domain C. However, Treagus and Treagus (1981) showed that the relationship between cleavage-transected folds and transpressive shear sense rather depends on the initial orientation of the convergence direction to the shear zone boundary. Accordingly, the dihedral angles $_1$ to $_4$ indicate clockwise rotation of the deformation field in Domain C west of the indenter salient and counterclockwise rotation in Domains A and B east of the indenter salient during the same transpressive event. The dihedral angles $_5$ (-axis–S_{2a}) of Domains A to C are -6°, -4°, and -5°. The L_2 stretching lineations are sub-horizontal in Domain B (Figure 6b), sub-horizontal to gently WSW-, rarely ENE-plunging in Domain A, and mostly shallowly WSW-plunging in Domain C, with an increasing WSW-plunge along-strike from Domain B to C (Figure 6a to 6c).

5.7.4 Transcurrent Shear Zones In Domains A, B, and C, the values for $_6$ (mean S_{2a}–mean C_{sin}) are -7°, -15°, and -18°, respectively; these are typical but especially for Domain A relatively small angles for sinistral S-C fabrics (Figures 6a to 6c, 6f to 6h, and S1; Passchier & Trouw, 2005). The values for $_7$ (mean C_{sin}–mean C'_{sin}) are -20°, -16°, and -18°, indicating typical C-C' angular relationships in all Domains (Figures 6f to 6h, 6k to 6m, and S1). The relatively small $_6$ angle in Domain A and the typical $_7$ angles suggest a mature shear zone system formed by prolonged activity. In Domain A, the sinistral shear zones (C_{sin}) are sub-vertical and strike ~ENE; in Domain B and C, they strike NE with opposing dips, steeply SE and NW, respectively (Figure 6g to 6h). Stretching lineations (L_{sin}) are sub-horizontal in Domain B, plunge shallowly SW in Domain A, and moderately SW to WNW in Domain C (Figure 6f to 6h). In Domains A, C, and D, conjugate dextral shear zones (C_{dex}) are associated with variably-oriented stretching lineations (L_{dex}, Figure 7a, 7e, and 7i). The mean strike of C_{dex} changes from ENE to E to SE across the Domains C, A, and D, forming an arc around the indenter salient.

5.7.5 Extensional Shear Zones Extensional shear zones (C_{nor}) in Domains A and E show a large orientation scatter, but are, in general, sub-parallel to the S_{2b} foliation in Domain E (Figure 7c, 7m, and 7o). Based on the spatial distribution of S_{2b} (Figure 2d), the west-plunging FA_2 (Figures 2c and 5j), and the westward increasing plunge of L_2 (Figure 6e), we infer that the C_{nor} nucleated along the hinges and limbs of the west-plunging D_2 folds, ultimately forming the BM. In the areas of the OSZ and the JF (Figure 2b), outcrop-scale shear zones show sinistral-oblique, top-west normal kinematics, i.e., transtension, connecting the BM to the sinistral shear zones of the western TW. The extensional shear zones dip moderately NW in Domain A and gently NE in Domain C, where they are associated with shallowly NW-plunging stretching lineations (Figure 7c and 7g), parallel the Sprechenstein-Mauls Fault (Bistacchi et al., 2010).

5.7.6 Shear Bands Sinistral shear bands (C'_{sin}) in all five Domains (A to E) have a similar appearance, strike in average N34°E, and dip steeply to sub-vertically, indicating a homogeneous deformation field in and around the western TW (Figure 6k to 6o). Assuming that shear bands form at angles of 15 35° to the shear-zone boundary (Passchier and Trouw, 2005), the MMF (N55°E) with an angle of 21° to the average C'_{sin} strike may constitute the structure that is closest to the shear zone boundary during the C'_{sin} formation. The dextral shear bands (C'_{dex}) in Domains A, C, and D strike east; in Domain E, they strike ESE (Figure 7b, 7f, 7j, and 7l). Moderately west-dipping extensional shear bands (C'_{nor}) are common in Domains E and C, where they parallel the BM (Axen et al., 1995); they are rare in Domain A (Figure 7d, 7h, and 7n).

5.7.7 Structural elements in Domain D: Incipient Extruding Wedge Structural elements like the S_2 foliation (S_{2a} and S_{2b}) and the D_3 shear zones are less developed in Domain D than in Domains A to C. The folded S_1 predominantly dip gently to steeply south, i.e., opposite to those in Domains A to C (Figure 5a to 5d). The sub-horizontal FA_2 trend east (Figure 5d and 5i) and the sub-vertical AP_2 strike east (Figure 5n). Towards the west, the D_2 folds tighten and axial-plane foliations become frequent. The rarely observed, sub-vertical S_{2a} strikes east and the related L_2 lineation plunges gently east (Figure 6d), i.e., opposite to Domain C (Figure 6c). The sub-vertical sinistral shear zones (C_{sin}) strike ENE, show gently west-plunging L_{sin} (Figure 6i); the sub-vertical dextral shear zones (C_{dex}) strike east (Figure 7j). Both the C_{sin} and C_{dex} are more eastward oriented than those in Domains A to C.

5.7.8 Structural elements in Domain E: Western Margin of the Tauern Window The major difference between Domain E and the other Domains is that none of its structural elements is sub-vertical. The folded S_1 dip mainly NNE, indicating south-verging folds (Brandner et al., 2008; Rosenberg & Garcia, 2011); the FA_2 plunge gently west, and the AP_2 dip moderately north (Figure 5e, 5j, and 5o), similar to the D_2 folds in Domain D (Figure 5i and 5n). The S_{2a} axial-plane foliations strike ENE and mainly dip moderately NNW; the associated stretching lineations plunge gently west (Figure 6e). In Domain E and along its transition to Domain A, the shallowly WNW-dipping S_{2b} dominate the structural grain (Figures 5e and 7m o), following the west-plunging hinge of the Tuxer Antiform. We observed only few NE-striking sinistral and ESE-striking dextral shear zones, but numerous, top-west normal shear zones, paralleling the BM, with down-dip stretching lineations (Figures 6j, 7k, and 7m) (e.g., Axen et al., 1995). In our field study, we could not find convincing evidence for the existence of the TNBF (Bergmeister, 2010; Fügenschuh et al., 2012; Töchterle et al., 2011).

A key outcrop in St. Jodok (Figure 2c) exhibits NNW-dipping normal shear zones (C_{nor}) associated with D_3 folds with gently NNW-dipping axial planes (AP_3) (Figure 8a to 8c). The D_3 folds refold the tight, south-verging D_2 folds and are accompanied by subvertical, NE-striking tension gashes (Figure 8d). These relationships indicate that the normal shear zones along the western margin of the TW post-date the D_2 folds. Additionally, the C_{nor} and AP_3 follow the arcuate strike of the folded S_1 along the northern limb of the Tuxer Antiform, delimiting the BM to the north, and connecting them to the ENE-striking sinistral-transtensive OSZ. To the south, the BM are delimited by the sinistral-transtensive JF.

5.8 Estimates of the Amounts of Shortening, Stretching, and Sinistral Strike-Slip

A critical parameter for estimating the amounts of shortening, stretching, and sinistral strike-slip is the movement direction of the Dolomites Indenter; the latter has been assumed to be NNW to N (e.g., Laubscher, 1988; Scharf et al., 2013; Schmid et al., 2013). Based on the analogue-material modeling results of Rosenberg et al., (2007) and the interpretation of the PaF, NGF, and SGF as strike-slip faults formed in a wrench-dominated transpressional regime, we argue for a convergence direction of N20°E; we include a ±10° uncertainty in our calculations (Figure S3). In section 6.3 (Transpressional Hypothesis), we detail the geometry of the western TW as transpressive zone and anticipate the structural orientation of its center, Domain A, as being representative for this zone. The angle   between the mean strike (N60°E) of the sinistral shear zones (C_{sin}) in domain A and the inferred N20°E convergence direction is 40°. This indicates pure-shear-dominated transpression with a kinematic vorticity number W_k of 0.22, estimated using the graph proposed by Tikoff & Peterson (1998, Figure S3). Hence, 22% of the N30°E-displacement of ~70 km along the GF, which caused the shortening in the TW in front of the Dolomites Indenter (amount of contraction) (Laubscher, 1988), can be attributed to the hinge parallel stretch and 78% to folding (true amount of contraction). According to Tikoff & Peterson (1998) and using the ±10° uncertainty in the convergence direction, we calculated 55 +6/-9 km of shortening accommodated by folds and 15 +9/-6 km hinge parallel stretch (Figure S3). Our result for shortening is larger than the estimate of ~32 km (Schmid et al., 2013) but similar to the estimates of ~49 km (Rosenberg and Berger, 2009) and ~60 km (Rosenberg et al., 2015) based on balanced cross sections. According to Tikoff & Peterson (1998), the amount of hinge parallel stretch equals the wrench component in transpressive systems. Therefore, sinistral strike-slip together with the hinge parallel stretch in the western TW is 15 +9/-6 km, together contributing 13 +8/-5 km to E-W extension.

6 Discussion

In the following, we discuss three hypotheses for the localized exhumation in the western TW. We also discuss the rotation of the Proto-SEMP during transpression, and wrench zone formation across the Eastern Alps.

6.1 Transtension Hypothesis

The TW was interpreted as a pull-apart structure in a transtensional setting (e.g., Genser & Neubauer, 1989; Neubauer et al., 1999). Strain modeling shows that upright open folds can form during transtension (Fossen et al., 2013). Such experiments indicate that the axial planes of transtensional folds strike perpendicular or at a high angle to the extension direction (Rey et al., 2011), and rotate toward the divergence vector ( ), that is the vector sum of the simple and pure shear components in transtensive (and transpressive) strain fields (Fossen et al., 2013). In sinistral transtension, the orientation of the divergence vector, approximated by the transtensional fold axes, has a clockwise deviation from the shear zone boundary (Fossen et al., 2013, their Figure 2a).

We used the mean strike (N60°E) of C_{sin} in Domain A as approximating the shear zone boundary during the D_2 and D_3 deformation. The mean trend (N57°E) of the FA_2 fold axes is sub-parallel to the shear zone boundary in Domain C (Figure 5h), and deviates 14° and 8° clockwise in Domains A and B, respectively (Figures 5f and 5g). These fold axes–shear zone boundary relationships exclude the formation of D_2 folds as transtensional folds (Fossen et al., 2013). In addition, the geometry of transtensional folds is different from those observed in the western TW, where D_2 fold hinges are sub-parallel, not sub-perpendicular to the extension direction. The axial planes of D_2 folds in the western TW strike at high angles to the BM and are therefore kinematically unsuitable to accommodate large amounts of east-west extension. Only small-scale D_3 folds in Domain E have an appropriate orientation to accommodate east-west extension and could be interpreted as collapse folds (Froitzheim, 1992; Fossen et al., 2013).

6.2 Extensional Unroofing Hypothesis

Exhumation of the western TW by extensional unroofing requires that extension along the BM and SF are transferred to transcurrent sinistral and dextral strike-slip faults at the northern and southern tails of the Brenner Fault, respectively (Fügenschuh et al., 1997; Scharf et al., 2013a; Schmid et al., 2013). Our fieldwork shows that neither a sinistral strike-slip fault at the northern boundary of the western TW nor a km-scale, dextral strike-slip fault at the southern tail of the BM exists. The dextral PGF nucleates at the salient of the Dolomites Indenter that is located ~10 km ESE of the Brenner Fault. We traced the westernmost occurrence of the dextral PGF to the Valler Jöchl that is ~13 km away from the Brenner Fault. In spite of the widespread occurrence of sinistral shear zones throughout the western TW and the Meran-Mauls Basement (Figures 2b and 6f to 6i), Domain E lacks such structures (Figures 2b and 6j). The TNBF is a small-scale structure (section 2.3.5). The northwestern margin of the TW is characterized by south-verging, asymmetric F_2 folds (Figures 2c, 5e, 5j, and 5o) and the folded S_1 of the northern limbs are reactivated/overprinted by S_{2a} and S_{2b} (Figures 6e and 7o). The brittle SMF that possibly connects to the BM at the southwestern margin of the TW (Bistacchi et al., 2010), has no ductile precursor. Hence, it never was part of the pre-indentation Periadriatic Fault System. We predominantly found sinistral and normal-sense shear indicators in the field. Dextral shear indicators along the Meran-Mauls Fault document the pre-existence of dextral strike-slip along the Periadriatic Fault System.

6.3 Transpression Hypothesis

We interpret the large sinistral shear zone network within the western TW as a first-order structure linking the GB to the SEMP, transferring indentation into lateral extrusion. The mean orientation of the structural elements within Domains A to C show four along-strike trends from SW to NE in the western TW (Figures 2b to 2d). First, the S_{2a} foliations and C_{sin} strike NE at the lateral terminations of the western TW (Domains B and C) and ENE in its center (Domain A, Figures 6a to 6c, 6f to 6h, and 9a). Second, these foliations and shear zones show a steepening of the average dip from the lateral terminations (Domains B and C) to the center (Domain A), and third, an along-strike flip in dip direction (Figures 6a to 6c, 6f to 6h, and 9a). Fourth, the fold axes are doubly plunging towards the lateral terminations of the western TW (Domains B and C) and sub-horizontal in its center (Domain A, Figures 5a to 5c, and 5f to 5h). This sigmoidal foliation pattern resembles that of a transpression zone in a sinistral strike-slip system, e.g., a restraining bend or a strike-slip duplex, in which Domain A is the transpression zone and Domains B and C approximate the bordering wrench zones (Dewey et al., 1998; Sanderson & Marchini, 1984; Woodcock & Fischer, 1986). The vortex of the foliation is located in the central Domain A (Figure 9b), as described for transpressive systems (Robin & Cruden, 1994).

Generally, the stretching lineations are shallowly plunging but scatter between sub-horizontal and steeply westward plunging along the axis of the western TW. The variable bearing and plunge agree with numerical model results of stretching lineations formed in transpression (Robin & Cruden, 1994). Further, the fold amplitudes decrease and the fold wavelengths narrows from the central Domain A towards the outer Domains B and C, indicating non-cylindrical (conical) folds; such style is predicted by numerical models of transpressional folds (Frehner, 2016).

The dihedral angles $_1$ to $_4$ in Domains A to C, which mainly describe the geometric evolution of the D_2 folds, indicate a deviation of the mean strike/trend of the different structures formed in kinematic succession that is consistently clockwise in Domain C and counterclockwise in Domains A and B (Figures S1a to c, S1g). This indicates counterclockwise material-plane rotations in Domain C and clockwise rotations in Domains A and B and can be explained by the orientations of the two margins of the Dolomites Indenter, parallel to the MMF and PGF, causing different deformation fields east and west of the indenter salient, e.g., bending the preexisting S_1 foliations. The dihedral angles $_5$ to $_7$, which mainly describe the geometric evolution of the D_2 shear zones, indicate exclusively counterclockwise deviations during sinistral shearing in all three Domains (A to C; Figures S1d to f, and S1g). The mean strike of the C'_{sin}, sub-parallel to the PaF, NGF and SGF, is constant in all domains, indicating a similar, late-stage deformation field related to the Dolomites Indenter (Figures 6k to 6o). As the sinistral shear zones (C_{sin}) in Domains A to C reactivate the AP_2 axial plane foliation, we argue that they are kinematically linked to the D_2 folds and can be interpreted as part of the transpressive zone (Woodcock & Fischer, 1986; Dewey et al., 1998). This transpressive zone initiated during non-cylindrical folding during indentation and progressed by the reactivation of the $S2_2$ as slip planes during sinistral transpression. The switch in the rotational sense of the structures from opposing directions during non-cylindric folding in Domain C compared to Domains A and B into a uniform rotation sense during shearing in all three Domains supports the two-stage evolution within a constant deformation field.

6.4 Corner Effect, Partitioning, and Decoupling

The sinistral transpressive zone of the western TW established a structural connection between the GB and the SEMP with a kinematic continuity between NNE-ward indentation and eastward extrusion. Indentation induced a transpressive zone with upright folding and hinge-parallel stretching that transitioned into deformation governed by strike-slip shear zones. Outside the transpressive zone, conjugate sinistral and dextral strike-slip faults formed in Domain D along the NNE-facing indenter margin, and extensional shear zones formed in Domain E. Partitioning of NNE-SSW shortening caused a divergence of material flow away from the indenter salient within Domains D and E (cf. Ježek et al., 2002; Reiter et al., 2011).

Kinematically, the BM, JF, and OSZ (Figure 2b) decouple the Ötztal Basement from the western TW by transtensional to extensional deformation west of the transpressive zone. East of the indenter salient conjugate shear zones, i.e., the sinistral AhSZ, DAV, SpSZ and the dextral PGF, Iseltal, and Mölltal faults (Figure 1a) and other small-scale, conjugate faults in Domain D decouple the eastward extruding wedge from the transpressive zone. Hence, the transpressive zone is not part of the eastward extruding wedge, instead it comprises a restraining-bend structural junction between the GB and the SEMP (Figure 9b).

Analog-material and numerical experiments showed that within sinistral transpressive zones, transpressive fold axes initiate parallel to the maximum instantaneous stretching axis and with increasing strain, rotate clockwise and stay parallel to the long axis of the strain ellipse (Frehner, 2016; Ratschbacher et al., 1991a, 1991b; Rosenberg et al., 2004, 2007). The mean orientation of fold axes in the western TW, especially in Domain A, form an angle of ~44° to the GB, suggesting—at first glance—a rather juvenile transpressive structure, where transpressional folds only initiated and started to rotate clockwise towards the indenter margin (Fossen et al., 2013; Frehner, 2016; James & Watkinson, 1994; Tikoff & Peterson, 1998; Treagus & Treagus, 1981). However, the western TW combines transpression due to the connection of two fault zones (GB and SEMP) and the indentation imposed by the Dolomites Indenter. Numerical indentation models (Ježek et al., 2002) show that the deformation pattern in front of an indenter changes little through time, supporting the interpretation of the western TW as a rather mature sinistral transpressive zone that has clear borders in Domains D and E and connects the GB to the SEMP (Ježek et al., 2002).

6.4.1 Decoupling to the West Rocks north of the GB (Figure 1a; Ötztal Basement) were shortened little because of two geometric aspects. First, the angle of 10 to 25° between the N20°E convergence direction and the N30°E strike of the PaF, SGF, and NGF caused a rather oblique deformation field west of the indenter margin compared to the nearly orthogonal shortening in the northern margin of the indenter (the PGF; Figure 9b). Second, the Dolomites Indenter experienced a net eastward movement, which promoted extension in front of the indenter salient. The FA_2 and AP_2 in Domain C strike NE, subparallel to the northwestern margin of the Dolomites Indenter, and rotated counterclockwise during ongoing shortening, indicated by consistently positive dihedral angles $_1$ to $_4$ (Figure S1). The FA_2 and AP_2 in Domains A and B strike ENE and rotated clockwise during ongoing shortening indicated by exclusively negative dihedral angles $_1$ to $_4$ (Figure S1). We argue that this opposing rotation of the material planes/lines NW and NE of the indenter salient caused additional, about convergence-perpendicular extension, necking the D_2 folds (Figure 9b, stereoplots of the D_2 folds). The S_{2b} foliation is restricted to the west-plunging dome axis and the BM (Domain E). Together with the westward increasing steepness of the L_2 stretching lineation within the transpressive zone, it likely is a structural expression of this local extension. The S_{2b} foliation pre-dates the top-west extensional shear zones/bands (C_{nor}, C'_{nor}), that detach and decouple the Ötztal Basement from the transpressive zone. The OSZ (Ebner et al., 2004; Lammerer & Weger, 1998), structures observed at St. Jodok (Figure 8), and partly the JF (Müller et al., 2001; Viola et al., 2001), are transtensive, transferring sinistral displacement of the western TW into east-west extension along the BM (Figure 2b). Extensional shear zones within the TW in the area of Steinach (Figures 2b and 2c) dip NNW (Figure 8a), tracing the BM in a convex arc northeast-ward (Fügenschuh et al., 1997; Töchterle et al., 2011). Therefore, the ENE-striking normal shear zones in the area of St. Jodok separate the thick BM in the south from the brittle SF in the north (Behrmann, 1988; Fügenschuh et al., 1997; Reiser, 2010; Reiter et al., 2018; Schmidegg, 1953). Finally, the NNE-SSW shortening caused a component of eastward motion of the indenter, promoting maximum east-west extension in front of the indenter tip (Rosenberg et al., 2004, 2007). Hence, Domain E marks a decoupling zone between the shortened western TW and the Ötztal Basement (Figure 9b). The BM are coupled with and the SF together with syn- and antithetic faults in its hanging wall are decoupled from the transpressive zone of the western TW (Figure 9b). Thus, how to explain the extension along the SF? We speculate that it is part of a late-stage releasing band connecting the sinistral shear along the IF in the north with that along JF and PaF in the south; these would involve up to a few kms of late brittle normal faulting along the BF.

6.4.2 Decoupling to the East The AhSZ bounds the central TW in the west that lacks high-amplitude folds, subvertical foliations, and transcurrent shear zones (Figures 2a to 2e). Accordingly, the exhumation level is less deep than in the western TW and large areas expose rocks of the structurally high units. North of the PGF (Figure 1a), the convergence in Domain D was mainly accommodated by upright D_2 folds; their axial planes (AP_2) and the rarely developed S_{2a} have an angle of ~20° to the PGF and the latter fade out eastward (Figure 5n). The folds are overprinted by conjugate sinistral and dextral shear/fault zones implying NNE-SSW shortening and eastward material transfer away from the indenter salient (Figure 9b). Domain D, bound by the AhSZ in the north and the PGF in the south, forms the western tip of an eastward extruding wedge (Ratschbacher et al., 1991b).

The ENE-striking transpressive zone of the western TW (Domain A) turns into a NE-strike in Domain B. There, the number of D_2 folds is reduced to two major antiforms, indicating less localized shortening. Several NE-striking sinistral shear zones delimit the transpressive zone to the east from the central TW, where it enters the SEMP with a sudden change in strike (Figures 2b, 2d, 2e; Cole et al., 2007; Rosenberg & Schneider, 2008). We argue that Domain B marks the area where the distributed transpressive deformation expressed by non-cylindric folding and sinistral shearing of the western TW was transferred into more localized sinistral shear zones south of Mittersill (e.g., RSZ, Figure 2b; Cole et al., 2007) and ultimately to the brittle-ductile SEMP (Frost et al., 2011). The fault/shear zones south and east of the western TW that connect to the SEMP and the PGF decouple the extruding central and eastern TW from the stationary western TW (Linzer et al., 2002; Peresson & Decker, 1997). Based on the following observations, we interpret that shortening inside the western TW is at maximum and gradual decreases eastward, and strike-slip motion and extension is minimum in the western TW and gradually increases eastward. First, the location of the western TW—at the tip of the indenter—accommodated maximum shortening and minimum lateral translation. Second, east of the western TW, shortening is localized along the SEMP and PGF, given the large displacements of both faults east of the western TW. Third, the SEMP and numerous conjugate strike-slip faults south and east of the TW nucleate east of the western TW. Forth, the SEMP shows a succession from transpression in the west to transtension in the east along strike.

6.5 Proto-SEMP Hypothesis

In accordance with the results of the analogue-material models (Ratschbacher et al., 1991a, 1991b; Rosenberg et al., 2007), we propose that the N70°E-striking SEMP had a more northerly initial strike and nucleated northeast of the indenter tip, i.e., it never was connected to the GB in the first place (Figures 9b and S4). We present two approaches to restore its orientation to the time of early indentation (Proto-SEMP). The first approach (Proto-SEMP$_1$) is a counterclockwise back-rotation of the present-day western SEMP around a vertical rotation pole close to Liezen (Figure 1a), using the 55-km NNE-SSW shortening and 13-km eastward extension suggested in this study for the western TW. In this restauration, the Proto-SEMP$_1$ had an initial N50°E strike, subparallel to the present-day strike of the Meran-Mauls Basement, and rotated 20° clockwise together with the sub-parallel IF and MMzF (Figures 1a and S4). Palinspastic restorations of Fodor (1995) and Linzer et al. (1995) also imply a N50°E strike of the Proto-SEMP. The Northern Calcareous Alps in between rotated counterclockwise along antithetic Riedel faults, deduced from paleomagnetic analyses of intramontane basins interpreted as domino-block rotation (Haubold et al., 1999; Márton et al., 2000).

The second approach uses the results of paleostress analysis along the western SEMP; these yielded six deformational events, two (D_3 and D_5) involved mostly strike-slip deformation, four mainly thrusting (Wang & Neubauer, 1999). Against the authors' interpretation, we kept the orientation of the principal stress axes constant and rotated the present-day SEMP 55° counterclockwise towards a Proto-SEMP$_2$ orientation of N15°E (Figure 9b), using the rotations derived by Wang & Neubauer (1999); we consider this rotation value an extreme. Both approaches support our hypothesis of a clockwise rotating SEMP during indentation under a stable convergence direction (Figures 9c and S4).

6.6 Wrench Zone Hypothesis

The TW consists of upright folds, delimited by conjugate transpressive shear zones (Ratschbacher et al., 1991a, b; Rosenberg et al., 2004; 2007), forming an arcuate culmination in front of the Dolomites Indenter. This arcuate dome of the

TW with a triangular crustal block south of it (Figure 1a) is consistent with the majority of indentation models (Schueller & Davy, 2008, for a review), which show localized shortening and conjugate shear in front of a triangle pointing away from the indenter margin. However, the western TW accumulated more deformation as the central and eastern TW, indicating a different evolution in the late stage. We defined the Domains A to C as a mature sinistral transpressive zone, connecting the initially separated GB and the SEMP via a restraining bend (Figure 9b). The western TW forms the western margin of the stable triangle in front of the Dolomites Indenter. In an early stage of indentation, the western TW developed as a right step-over between the independently existing GB and the Proto-SEMP with localized high-strain shortening accommodated by upright folds (Figure S4); it evolved over time into a zone dominated by sinistral wrenching. We argue that this transpressive zone together with the GB and the SEMP constitutes a sinistral wrench zone translating Dolomites indentation into lateral extrusion. By that, it decouples the Ötztal Basement in the west, experiencing normal shear/faulting along the Brenner Fault and sinistral transtension along the OSZ and the JF, and the central and eastern TW in the east, experiencing eastward extrusion along conjugate shear zones, e.g., the PGF, SEMP and minor strike-slip faults in between (Ratschbacher et al., 1991a, 1991b; Rosenberg et al., 2007).

7 Conclusions

The western Tauern Window shows a structural evolution distinct from the central and eastern Tauern Window. Tight, upright folds of high-amplitude, subvertical axial plane foliations, and sinistral shear zones indicate absorption of orogen-perpendicular shortening. The western Tauern Window constitutes a right step-over connecting the sinistral transpressive Giudicarie Belt, subparallel to the indentation direction of the Dolomites Indenter, with the sinistral SEMP Fault, a major fault zone related to the eastward lateral extrusion of the central and eastern Eastern Alps. The ~70 km indentation by the Dolomites Indenter has been manifested within the western Tauern Window by upright folds and sinistral shear zones, accommodating 55 +6/-9 km of shortening, and 15 +9/-6 km hinge parallel stretch and likewise 15 +9/-6 km sinistral shear zones, resulting in 13 +7/-5 km of east-west extension. Farther east, the SEMP Fault has accommodated ~56 km of eastward lateral extrusion. At the salient of the Dolomites Indenter, the western Tauern Window forms a relatively stationary structural divide, decoupling the western Eastern Alps along the top-west, normal-slip Brenner Fault from the central and eastern Eastern Alps that extrude eastward. In the central Tauern Window, north-south shortening decreases in comparison to the western Tauern Window, as seen from the preservation of higher tectonostratigraphic units, the lower amplitude of folds, and the lack of axial plane foliations. In turn, the amount of lateral extrusion increases, as indicated by the increasing abundance of conjugated strike-slip shear/fault zones within the Austroalpine nappes south and east of the Tauern Window. The structures and the inferred displacements within the western Tauern Window are consistent with exhumation dominated by erosional denudation during transpressive folding. We interpret the western Tauern Window as a transpressive, right step-over between the sinistral Giudicarie Belt and a sub-parallel Proto-SEMP, which was pinned by the West-European Platform at the southern salient of the Bohemian massif. During indentation, the western Proto-SEMP progressively rotated clockwise around a vertical axis close to Liezen, attaining its present day orientation.

8 Acknowledgments and Data

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This data set contains 6965 structural data from 1774 outcrops in the western Tauern Window, collected during July to August, 2007, June to September, 2008, June to September, 2009, July to October, 2010, using a Breithaupt "GEKOM" Stratum Compass, provided by the Freie Universität Berlin, Germany. The raw data, plotted in the lower hemisphere and equal area plots of Figures 5a to 5o, 6a to 6o, and 7a to 7o are given in the Supporting Information Dataset S1. The Supplementary Information Figures 1a to g, 2, and 3 contains the different dihedral angles between the mean values of the respective structural elements of the Domains A to C. The georeferenced raw data are available in the open access research data base OpARA of the Technische Universität Dresden and Technische Universität Bergakademie Freiberg.

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10 Figure Captions

Figure 1a. Simplified tectonostratigraphic map of the Tauern Window and surrounding units modified after (Bousquet et al., 2012b). **b.** to **d.** Structural sections of the western, central, and eastern sub-dome of the Tauern Window simplified after Brander (2013) and Schmid et al. (2013).

Figure 2a. Foliation map of the Tauern Window shows the main foliation (undifferentiated). Compiled literature and new data (see paragraph 2 for references). **b.** to **e.** Close ups of the western Tauern Window based on (Bigi et al., 1994) showing **b.** Traces of the macro-scale sinistral shear zones; **c.** Outcrops of this study, definition of the five structural Domains (A to E), and traces of the structural sections (Figure 4); **d.** Interpreted traces of the S_{2a} axial-plane (solid lines) and the S_{2b} foliations (dashed lines); **e.** Interpreted traces of the F_2 upright folds and the tectonostratigraphic units.

Figure 3. Field photographs along the Vals valley from north to south. **a.** Folded S_1 upright, tight folds, Width of the photo is approximately 4 m; **b.** Rootless S_1 folds and newly formed sub-vertical S_{2a} axial-plane foliation; **c.** S_{2a} axial-plane foliation and localized sinistral shear zones (C_{sin}), having an additional north-side-up component; **d.** Top view on sub-vertical S_{2a} axial-plane foliation and localized sinistral shear bands C'_{sin}.

Figure 4. SE-trending structural cross section running from Rosskopf to Onsberg (see Figure 2a for trace). Lithological units based on the Geologische Karte 1:50.000, Blatt 175 Sterzing.

Figure 5. Stereoplots of contoured data in ten contouring intervals, number of data, maximum, minimum, mean densities ( ), cosine exponent, and mean values are given in the bottom-left columns. **a.** to **e.** S_1 foliation, great circles indicate -circles. **f.** to **j.** D_2 fold axes (FA_2). **k.** to **o.** D_2 axial planes (AP_2).

Figure 6. Stereoplots of contoured data in ten contouring intervals, number of data, maximum, minimum, mean densities ( ), cosine exponent, and mean values are given in the bottom-left columns and the lower right corner. **a.** to **e.** S_{2a} axial-plane foliations and L_2 lineations, great circles indicate S_{2a} mean values. **f.** to **j.** Sinistral shear zones (C_{sin}) and stretching lineations (L_{sin}) , great circles indicate C_{sin} mean values. **k.** to **o.** Sinistral shear bands (C'_{sin}), great circles indicate C'_{sin} mean values.

Figure 7. Stereoplots of contoured data in ten contouring intervals, number of data, maximum, minimum, mean densities ( ), cosine exponent, and mean values are given in the bottom-left columns and the lower right corners. **a., e., k., j.** Dextral shear zones (C_{dex}) and stretching lineations (L_{dex}), great circles indicate C_{dex} mean values. **b., f., l., i.** Dextral shear bands (C'_{dex}), great circles indicate C'_{dex} mean values. **c., g., m.** Extensional shear zones (C_{nor}) and stretching lineations (L_{nor}), great circles indicate C_{nor} mean values. **d., h., n.** Extensional shear bands (C'_{nor}), great circles indicate C'_{nor} mean values. o. Composite foliations (S_{2b}), great circles indicate S_{2b} mean value.

Figure 8. a. Sketch of a key outcrop near St. Jodok (outcrop length ~100 m) and stereoplots; from left to right: S_1 foliations, AP_2 axial planes, C_{nor} extensional shear zones, and AP_3 collapse folds. **b.** to **d.** South-verging, tight D_2 folds (F_2) are sheared by normal-sense shear zones along their limbs. Collapse folds (F_3) and tension gashes overprint steep F_2 folds.

Figure 9. a. Block model of the western Tauern Window. Structural map and sections are based on Brandner (2013) and Schmid et al. (2013). Map is displaced and view is parallel to the wrench zone (~NE) to illustrate the along strike variation of the sinistral shear zones (red lines). **b.** Structural summary of the wrench zone highlighted in red. Mean great circles and mean vectors based on data shown in Figures 5, 6, and 7. Sectors with upper-right-to-lower-left stripes indicate the assumed N20°E ($\pm$ 10°) convergence direction of the Dolomites Indenter with respect to the major faults forming the wrench zone (GF, MMF, and Proto-SEMP). Sectors with upper-left-to-lower-right stripes indicate the conver-

gence vector of the respective shear zone boundary (-20°), in which transpression is wrench-dominated. For the MMF and the western TW, the convergence angles are 35° and 40°, respectively, indicating pure-shear-dominated transpression (Tikoff and Peterson, 1998). For the GF, the Proto-SEMP$_1$, and the Proto-SEMP$_2$, the convergence vectors are towards N10°E, N30°E and N15°E, respectively, indicating mostly wrench-dominated transpression (Tikoff and Peterson, 1998). **c.** Structural reinterpretation of the deformation stages of Wang and Neubauer (1998), left: Wang and Neubauer's (1998) interpretation of counterclockwise rotation of principle stress axes around a fixed SEMP, right: reinterpretation in this study assumes a fixed (~N) direction of principle stresses and a ~55° clockwise rotation of the SEMP into the Proto-SEMP orientation.