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DISCUSSION

Comment on Rosenberg and Garcia: Estimating displacement along the Brenner Fault and orogen-parallel extension in the Eastern Alps, Int J Earth Sci (Geol Rundsch) (2011) 100:1129–1145

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Introduction

The western end of the Tauern window is marked by what we refer to as the Brenner Normal Fault Zone. The Brenner Fault—since the late eighties—is known as a textbook example of a normal fault. Already in (1934), Dünner proposed west-directed normal faulting related to updoming of the footwall (i.e. the Tauern window). These earlier publications (e.g. Schmidegg 1953) mainly focussed on a brittle normal fault known as Silltal Fault that represents a northern segment of the Brenner Normal Fault Zone. Behrmann (1988) and Selverstone (1988) were the first to also describe ductile components of normal faulting in an area further south, referred to as Sterzing-Steinach mylonite zone (Behrmann) or Brenner line (Selverstone). In (1997), Fügenschuh et al. presented a two-stage model for the evolution of the Brenner Normal Fault Zone. Thereby ductile normal faulting was restricted to an area between Sterzing and Matrei during stage 1 (referred to as Brenner Normal Fault s.str. in this contribution), while brittle faulting during stage 2 not only overprinted the earlier mylonites of the Brenner line s.str. but extended further north into the entirely brittle Silltal Fault. This model involved coeval N–S compression and E–W extension during stage 1.

The published calculated total amounts of related E–W extension, derived from metamorphic data and distinct exhumation histories in footwall and hanging wall and from the estimated dip of the overall fault zone, varied significantly between 10 and 20 km (e.g. Behrmann 1988) and up to 70 km (e.g. Fügenschuh et al. 1997). The contribution of exhumation by erosion as a consequence of coeval N–S compression has never been explicitly considered and calculated so far.

The Silltal Fault (late stage brittle component of the Brenner Normal Fault Zone, Fig. 1)

Rosenberg and Garcia (2011), after providing a nice introduction to the local geology of the Brenner Fault Zone, present an approach to calculate the relative contributions of extension and erosion in footwall exhumation that unfortunately fails to take account of such a two-stage evolution in terms of ductile faulting followed by brittle faulting. The whole paper, including the derived numbers, exclusively deals with only the brittle component of the Brenner Normal Fault Zone, i.e. the higher angle Silltal Fault component (stage two in Fügenschuh et al. 1997), which overprints the low-angle ductile (mylonitic) Brenner Fault s.str. that is located further south. When writing ‘We use the term Brenner Fault to address both the latter mylonites and their northern continuation into the Silltal Fault’ Rosenberg and Garcia not only ignore the fission track evidence provided by Fügenschuh et al. (1997) that led to this two-stage evolution but also make a direct geometric and kinematic link between ductile mylonites and brittle faulting. This contradicts the observation that the more

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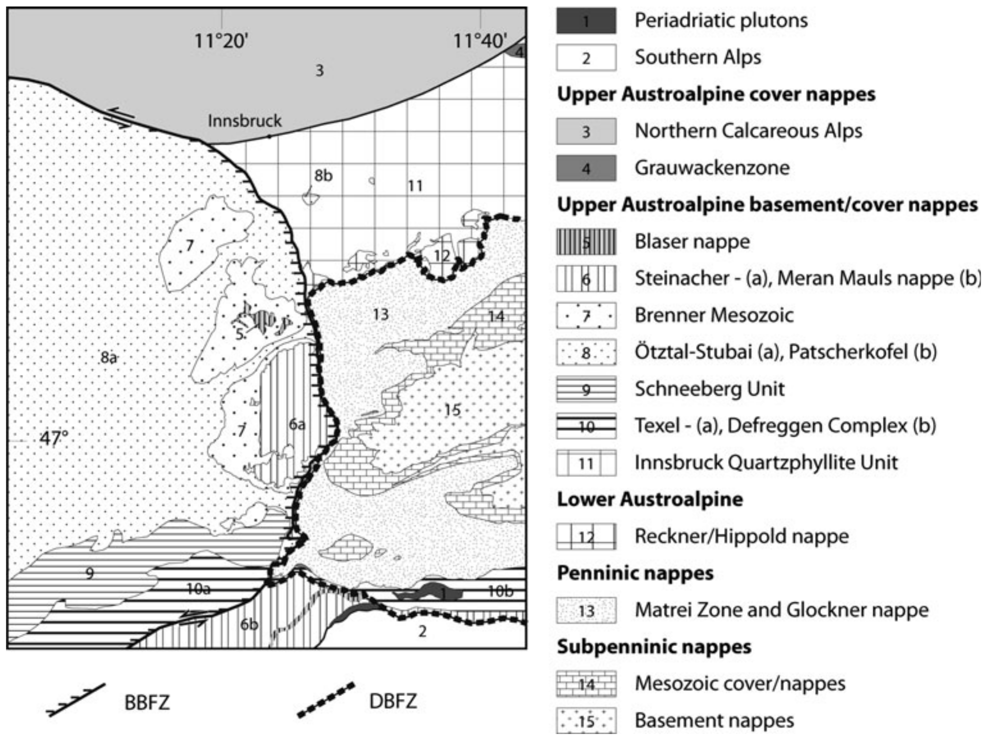

Fig. 1 Tectonic overview of the western end of the Tauern window redrawn after Schmid et al. (2011). Trace and continuation of the ductile (stage 1, DBFZ) and brittle (stage 2, BBFZ) components of the Brenner Fault Zone are indicated

steeply inclined brittle stage 2 Silltal Fault clearly offsets the earlier formed more shallowly dipping mylonites along the length of the western termination of the Tauern Window, from Matrei all the way south to Sterzing (e.g. Prey 1989).

For their calculation of tectonic omission, they chose a tectonic marker horizon, namely the base of the Ötztal nappe located in the hanging wall of the brittle Silltal Fault, and its equivalent in the footwall, namely the base of the Patscherkofel crystalline unit. Thereby they implicitly only calculate tectonic omission due to stage two faulting since the Patscherkofel unit is only located in the footwall of the brittle Silltal Fault, while it resided, as evidenced by the fission track data, together with the Ötztal nappe, in the hanging wall of the ductile Brenner Fault during stage 1 (Fügenschuh et al. 1997). Hence, it is obvious that the calculation of tectonic omission by the authors only deals with the brittle stage 2 component. This is also evident from their contoured map of what they refer to as Brenner Fault (their Fig. 3), which traces the brittle Silltal Fault all the way into the brittle fault that cuts the ductile Brenner mylonites further south. From this map, the authors correctly conclude that their exclusively brittle Brenner Fault is barely folded. Moreover, they argue that any omission (or vertical offset) larger than the 5 km they calculated from their exercise, namely some 10 km additional exhumation in the Brenner pass area indicated by the difference in degree of metamorphism, would be exclusively due to N–S shortening and associated erosional denudation (see their Fig. 4). Note that they geometrically and kinematically strictly separate N–S compression from E to W extension, in spite of postulating that these two components of strain operate contemporaneously.

The vertical offset of 5 km along the Brenner Fault calculated by Rosenberg and Garcia (which actually is that along brittle Silltal Fault) is in perfect agreement with the number given by Fügenschuh et al. (1997) for the brittle stage 2 of the Brenner Fault activity and leads to, depending on the dip angle, a horizontal extensional displacement of barely 2–14 km. Note, however, that the onset of this brittle faulting is dated at around 13 Ma, while the western Tauern window starts to fold and cool much earlier, i.e. at some 20 Ma ago (see Fügenschuh et al. 1997 and references given therein). According to the available information, the southern prolongation of the brittle Brenner Fault has to be looked for along the Jaufen Fault, where a brittle overprint, together with a jump in zircon fission track ages, has been documented (Viola et al. 2001).

The ductile mylonites of the Brenner Normal Fault Zone south of Matrei (Fig. 1)

The Brenner Fault mylonites, as described and kinematically interpreted by Behrmann (1988) and Selverstone (1988) are mentioned several times by Rosenberg and Garcia (2011). However, their role is not further discussed, nor are they considered in their calculations. Due to their particular approach that strictly separates brittle normal faulting from predominantly ductile folding, they do not consider the more important ductile component of normal faulting to be related to normal faulting at all. Any E–W oriented extension is taken to simply be the result of differential vertical displacements of material points within the dramatically shortened Tauern window and in front of the 'Dolomites indenter' (Rosenberg et al. 2007).

The mylonites of the Brenner Normal Fault Zone contain a strong E-W trending stretching lineation with consistently top-to-the-west sense of shearing (e.g. Axen et al. 1995; Fügenschuh 1995). Reported mean values for the stretching lineation are 262/17° (Axen et al. 1995) and 266/14° (Fügenschuh 1995), respectively. Although there are no strain estimates, it is difficult to understand how such mylonites could possibly form in the absence of substantial E–W extension by normal faulting. It is a fact, however, that the mylonitic foliation became progressively folded during shearing in the footwall of the ductile Brenner Normal Fault during stage 1 activity along the Brenner Normal Fault Zone (e.g. Axen et al. 1995, their Fig. 3a, b). Fold axes on all scales are parallel to the stretching lineation; their orientation constructed from foliation poles are 276/17° (Axen et al. 1995) and 266/16° (Fügenschuh 1995), respectively. These folds progressively affect the evolving mylonites of the footwall of the normal fault, with axial planes that are both at a high angle and sub-parallel to the fault zone, as was demonstrated in comparable examples by Mancktelow and Pavlis (1994, their Figs. 5, 10). In summary, we estimate that a considerable part of the estimated total of 23–25 km post-20 Ma differential exhumation of the Tauern Window was accommodated by normal faulting and associated erosion of the footwall, as modelled in Fügenschuh et al. (1997, Fig. 2). On the other hand, we certainly agree with the important point made by Rosenberg and Garcia that erosion is critical for exhumation in such models, as is implicit in all 2D kinematic models with planar fault surfaces and a planar surface topography of constant height (e.g., Grasemann and Mancktelow 1993; Fügenschuh et al. 1997; Campani et al. 2010—JGR). We agree that estimates of fault-parallel slip from such purely 2D models based on the angle of dip and the relative difference in pre-displacement burial from petrological data (e.g. Fügenschuh et al. 1997) will lead to an overestimate of the amount of E–W extension since it neglects the contribution of denudation of the hanging wall by erosion associated with such folding; it does not consider the potentially important component of folding and shortening perpendicular to the 2D profile considered (Bartley et al. 1995; Mancktelow and Pavlis 1994; Avigad et al. 2001).

The transformations of displacements across the ductile Brenner Normal Fault into strike-slip faulting at its northern and southern terminations

So far we only discussed strain partitioning between normal faulting and N–S compression. The complexity of the 3D kinematic picture is enhanced by the necessity of transforming ductile normal faulting across the Brenner Normal Fault Zone into strike-slip displacements at the northern and southern terminations of the overall N–S striking Brenner mylonitic belt.

Since the north-western margin of the Tauern window exhibits a distinct jump in fission track ages between overlying Austroalpine units in the Patscherkofel area and the Penninic Bündnerschiefer, Fügenschuh et al. (1997) postulated a transformation of the normal faulting component and part of the N–S shortening into sinistral strike-slip faulting along the E–W striking northern boundary of the Tauern Window. Regionally, this boundary is marked by the SEMP line that is kinematically linked with N–S compression (see Rosenberg and Schneider 2008), enabling lateral extrusion (Ratschbacher et al. 1991) of the core of the Eastern Alps to the east. While a part of this transformation takes place over almost the entire western Tauern window (Rosenberg and Schneider 2008), Töchterle et al. (2011), in the context of the geological investigations for the planned Brenner railway tunnel, highlighted the important role played by the Tauern Northern Boundary Fault, which joins the northern termination of the N–S striking ductile Brenner Normal Fault near Matrei. He showed that the Tauern Northern Boundary Fault represents the former continuation of the ductile Brenner Normal Fault, reoriented by N–S folding and associated tilting and dissected by brittle sinistral strike-slip faults. This brings these mylonites into an orientation favourable for sinistrally transtensive faulting. Further to the east along the northern boundary of the Tauern window, the sinistral strike-slip component takes over, here coupled with N–S compression and hence transpression, as convincingly shown by Rosenberg and Schneider (2008).

We also disagree with the suggestion of Rosenberg and Garcia that the southern kinematic prolongation of the Brenner Normal Fault, more specifically that of the ductile Brenner mylonites, has to be looked for along the Jaufen Fault rather than along the dextral Periadriatic Fault as suggested by Fügenschuh et al. (1997). This suggestion, originally proposed by Selverstone (1988) is taken up by Rosenberg and Garcia again who argue, based on the apparent lack of substantial offset across what they consider their Brenner Fault by only considering its brittle component. It is certainly correct that the Jaufen Fault is kinematically linked to stage 2 brittle faulting (Viola et al. 2001) and we cannot exclude that it may have taken up a minor component of stage 1 ductile faulting. However, the south-westernmost tip of the Tauern window is surrounded by ductile Brenner mylonites within the Penninic Bündnerschiefer, which cannot be followed into the Jaufen Line at all but, instead, become dextral as they curve into an E–W orientation (Fig. 1). They overprinted all earlier structures and can be followed further eastwards for a short distance along the Tauern window in the area of Sterzing (Stöckli 1995). As shown by the same author (see also Mancktelow et al. 2001), these dextral mylonites cut across the Austroalpine units east of Sterzing in order to join the coevally active and predominantly brittle dextral Periadriatic Fault. This points to a kinematic transformation of ductile normal faulting into brittle dextral faulting near the southern tip of the ductile Brenner mylonites. Hence, the Periadriatic Fault can be regarded as the major dextral conjugate fault in respect to the sinistral SEMP line during lateral extrusion (Ratschbacher et al. 1991). It must be said, however, that the exact mode of transformation of coeval N–S shortening and E–W extension into large-scale strike-slip movements along SEMP and Periadriatic Line still awaits further studies.

Conclusions and independent estimate of E–W extension based on an estimate of tectonic omission across the Brenner Normal Fault

We accept the criticism of Rosenberg and Garcia pointing out that Fügenschuh et al. (1997) employed an oversimplified 2D model to estimate the amount of E–W extension. For a truly 3D interplay between normal faulting, ongoing orogen convergence and erosion, this will indeed lead to an overestimation of the horizontal extension (and the amount of crustal thinning), especially if the out-of-plane shortening (as manifested in upright folding with axes parallel to the fault movement direction) is significant and provided the folds themselves do not stretch parallel to their axes (Grujic and Mancktelow 1995—J. Struct. Geol.). However, we reject the simple calculation of Rosenberg and Garcia that ignores the two-stage evolution of the Brenner Normal Fault Zone and, additionally, finds no role for the spectacular stage 1 mylonites found along the Matrei-Sterzing segment of that fault zone. In view of the extremely complex 3D interaction of normal faulting, folding and strike-slip faulting, it is difficult to determine the exact amount of extension produced across the Brenner Fault Zone. We emphasize, however, that a very substantial part of the total vertical offset, which reaches a maximum of 23–25 km across the Brenner Normal Fault, must have been accommodated by E–W extension.

This can be roughly quantified by estimating the total thickness of omitted tectonic units. In the Brenner pass area, the westernmost tip of outcropping Zentralgneiss of the footwall lies within 2 km horizontal distance and hence less than 1 km absolute distance from the base of the Steinacher nappe in the hanging wall. The tectonic omission over this negligible distance amounts to a total of at least 17 km: (1) Some 6 km thickness of the Pennnic nappes as indicated in Fig. 4 of Rosenberg and Garcia, based on upward extrapolation of the thicknesses from the well-constrained profile of Brandner et al. (2008); (2) at least an additional 2 km of the Lower Austroalpine nappe system, still preserved in the NE corner of the Tauern window (Häusler 1988 and Becker 1993); (3) the total thickness of the Upper Austroalpine Silvretta-Seckau nappe system (Schmid et al. 2004) represented by the Innsbrucker Quartzphyllite in the Tauern section with a minimum estimated thickness of 3 km (Brandner et al. 2008); (4) some 6 km thickness represented by the Texel, Schneeberg and Ötztal tectonic units (the entire Koralpe-Wölz and Ötztal-Bundschuh nappe systems of Schmid et al. 2004), preserved southeast of the Brenner Line and north of the Jaufen Line (Pomella et al. 2010). Hence, a minimum of 17 km out of an estimated total of 23–25 km exhumation of the western Tauern window, i.e. at least between 68 and 74% of the exhumation occurred by normal faulting, the rest by erosional denudation induced by N–S shortening. Taking an average dip of 17° for the Brenner mylonites that omit 12 km out of the total of 17 km plus an average dip of some 45° for the brittle part of the Brenner Normal Fault (between 20° and 70° according to Rosenberg and Garcia) that omit an additional 5 km, we obtain 39 km + 5 km = 44 km E–W minimum extension by normal faulting across the Brenner Normal Fault Zone. A similar number can be calculated from petrological data from units on either side of the Tauern Window Northern Boundary Fault (Töchterle et al. 2011). These authors suggest a minimum of about 10 km of vertical offset that must be solely attributed to the ductile stage and can be converted into 33 km of E–W extension along a 17° westward dipping fault plane.

This is admittedly less than the 70 km of extension estimated by Fügenschuh et al. (1997) that only consider ductile low-angle normal faulting and ignore the brittle high-angle faulting and the effect of erosional denudation, but by far more than the 2–14 km proposed by Rosenberg and Garcia.

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