Review Letter to the Topical Editor of "Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (Northern Italy)" by Verwater et al.

Dear Prof. Molli,

Thank you for your careful handling of the manuscript. We, as authors, hereby submit a revised version of the manuscript including tracked changes, updated figures and reply letters to the reviewers with our responses to their comments (please find these attached below).

The most important comment of Prof. Zampieri was on Fig. 11, where the Late Oligocene shortening direction and the decomposition of the displacement triangles needed further clarification. Therefore, we included an additional paragraph in Sect. 6.2 (lines 574-583) discussing the Late Oligocene shortening direction as determined from mesostructural analysis and tectonic reconstructions (Castellarin et al., 1992; Picotti et al., 1995) based on field data (Schönborn, 1992; Picotti et al., 1997) and subsurface data (e.g. Fantoni and Franciosi, 2010). This shift in shortening directions is an important constraint on the decomposition of the displacement triangles (Fig. 12), as the hypotenuse of these should be parallel to the motion direction. Consequently, the hypotenuse of the Late Oligocene displacement triangle is oriented NNE-SSW (Fig. 12; parallel to NGF and oblique to the profile from Picotti et al., 1995), whereas the hypotenuse of the Middle Miocene displacement triangle is oriented NNW-SSE (Fig. 12; parallel to profiles 1 to 7). Using this triangular approach, we obtained a new estimate of 40-47 km of Late Oligocene to Middle Miocene displacement along the NGF, a calculation we discuss step by step in Sect. 6.4. We thus corrected our previous estimate of 53-75 km of displacement along the NGF since Late Oligocene. Therefore, we accept the helpful criticism from Prof. Zampieri that our previous conclusion on the motion along the NGF was not fully supported by our data and we changed our conclusions accordingly.

The most important comment of Dr. Von Hagke was on the uncertainties of the balancing method presented in the manuscript. To discuss this adequately, we added an additional paragraph (lines 355-372) to explain why our shortening estimates should be considered minima and what the source of errors could be. We calculated that these sources could introduce errors to our shortening estimates of 27% or even more (lines 393-397). We hope that this clarifies what the possible errors are of our shortening estimates.

We would like to thank both reviewers as their insightful suggestions significantly improved the quality of the manuscript. We look forward to the manuscript being accepted for final publication in Solid Earth and hope that it will form a fruitful basis for future discussions.

Yours sincerely,

Vincent Verwater, On behalf of all the co-authors

Reply on interactive comment on "Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (Northern Italy)" by Verwater et al.

Referee: Dario Zampieri

Dear Prof. Zampieri,

We would like to express our appreciation for your positive review of our submitted manuscript and acknowledge your insightful comments that helped to improve the manuscript. Below, please find our responses to your valuable remarks highlighted in blue.

General comments

The manuscript presents tectonic balancing of a network of seven cross sections parallel to the local shortening direction through the Giudicarie Belt, which is the boundary between eastern and central-western Southern Alps. In the area, several amounts of Neogene shortening have been proposed by different authors, but the use of forward modelling performed using 3-D MOVE software and different kinematic scenarios provides new robust insights to the problem. The manuscript is generally consistent and well-written, while the conclusions aren't fully justified by data. Within the work the section 3 is a bit weak. The main issues of the manuscript to be clarified are the Oligocene shortening direction, the decomposition of the shortening vector and the lack of the Thiene-Bassano fault (ITIS127 in DISS 3.2). In fact, several minor uncertainties are mainly related to the figures.

Specific comments and typographical corrections to the manuscript

Text

Line 204-217: the presumed contrasting styles to the east and west of the Schio-Vicenza fault may be just due to different levels of erosion of the hanging wall of the frontal thrusts (Bassano and Marana), which exposes rocks with different physical properties. In fact, the steepened and folded Lower Cretaceous strata of the thin-bedded Maiolica Fm in Fig. 3a are located on the forelimb of the M. Grappa ramp anticline where the steep mountain slope faces the foreland plain. By contrast, the cataclastic Dolomia Principale of Fig. 3b is located inside a valley, which deeply cuts the Marana thrust. Therefore, the Dolomia outcrop represents a deeper structural level, which is not exposed in the Bassano frontal slope. In fact, the Lessini block (southern part of Domain 2a) are a structural high interpreted as a foreland wedge separating the central-western from the eastern Southern Alps (see the Structural map of Italy, Bigi et al., 1990), also called the Adige embayment by Laubscher (1990).

The contrasting styles across the Schio-Vicenza Fault, may indeed be partly related due to different levels of erosion in the hanging wall of the Bassano and Marana thrusts and this point is now discussed in lines 220-225. However, our forward modelling indicates that the deeper geometries of the Bassano and Marana faults are not entirely the same. They both represent a ramp-flat fault system at depth with hanging wall ramp anticlines (Recoaro and Monte Grappa anticlines). However, the shape of these anticlines and their associated displacement along the Bassano and Marana faults are quite different and can be observed along profiles 5 and 6 (Figures 8 and 9).

Lines 226-227: "Striations in the field show thrust motion with a component of dextral strike-slip". A close inspection of the stereoplot of Fig. 3e shows that most of the NE-trending mesofaults, i.e. the faults subparallel to the mean trend of the Valsugana fault, have a sinistral strike-slip component. The same is inferred from the structural map, where the red arrow of the Valsugana stop is oblique to the mean trend of the fault. Is the information on the strike-slip component relevant to the text development?

The 'thrust motion with a component of strike-slip' was measured along steep fault fractures conjugate to the Valsugana trend. NE-trending fractures show striations with sinistral component and NW-trending faults show dextral striations. Given the presence of both dextral and sinistral striations on secondary conjugate fault surfaces, we interpret that the main Valsugana Fault has not accommodated strike-slip motion. In addition, fault-slip analysis on the striations (Figure 4) is consistent with NNW-SSE shortening, exactly perpendicular to the main trend of the Valsugana Fault. This suggests that there is no kinematic requirement for a major strike-slip component along the Valsugana Fault. This is now discussed in lines 236-239.

Lines 227-228: "Cross-cutting relationships show that the Valsugana Fault was later once more reactivated as a dextral strike-slip fault (Figure 3d)". The photo 3d really shows one NNE-trending fault plane with dextral transtensional synkinematic calcite fibers, which is represented also in the stereoplot. However, the fault has a trend different from that of the Valsugana fault. In the photo the two cross-cutting lineations are not evident: please insert two arrows.

The cross-cutting relationships are unfortunately not clearly evident on the picture and were only observed in the field with a hand-lens. Also, these cross-cutting relationships have been observed on fault surfaces conjugate to the Valsugana trend. Therefore, we chose to remove this sentence.

Line 691: I'm not convinced about the "if not all". See comment to Fig. 11.

Please see our response in this letter to your comment on figure 11 below.

Line 715: Alfio instead of Alfi.

Done

Figures

Figure 1. In the right half of the geological map, south of BA a blind frontal thrust is lacking (see comment to Figure 8).

This blind frontal thrust (the Thiene-Bassano thrust) has been added to the geological map.

Figure 3. This figure and the related caption require several improvements.

The exact location of the structures in the photos from a) to d) isn't declared. Please specify.

The exact location of the structures in photos a to f is now indicated by yellow stars on the structural map.

a) the significance of the horizontal dashed black lines (F1) is not explained in the caption. They seem axial planes of chevron parasitic folds. In the forelimb of the ramp anticline of the Bassano thrust they are very common in the thin-bedded Maiolica unit. These folds are produced by flexural slip rather than by kinking.

The significance of the horizontal dashed black lines is now added to the caption.

c) the strike-slip fault shown isn't the Schio-Vicenza fault, which is NW trending, but a conjugate fault ca N-S trending. In the text the fault is correctly labelled as Borcola Pass Fault zone. Stereolpots of e) confirm the trend of the faults. In fact, the Schio-Vicenza fault trace follow the axis of the Posina valley and passes through the Borcola pass, which is 250 m away from the inactive quarry of the figure (see also Fondriest et al. (2012). Fault Zone Structure and Seismic Slip Localization in Dolostones, an example from the Southern Alps, Italy. J. Struct. Geol., 45, 52-67, http://dx.doi.org/10.1016/j.jsg.2012.06.014).

Therefore, the structures shown in c) belong to the damage zone of the true Schio-Vicenza fault.

Agreed and the labels of the Schio-Vicenza stereoplots have now been labelled as the Borcola Pass Fault Zone in the figure caption and the reference to Fondriest et al. (2012) has been included.

e) the graphical quality of the stereonets can be improved. The strain axes are not legible, please enlarge the labels. The stereonet Bassano seems a plot of NW-dipping faults with variable dip angle (reverse faults?) reactivated by strike-slip movements (the plunge of the lines contained on the fault planes is small). It seems that two deformation phases have occurred, a phase of contraction with reverse faults (lineations not recorded) followed by a strike-slip regime reactivating the same faults and originating some new sub-vertical faults. Please explain what you are showing. Some lines fall outside the planes!

There are two Schio-Vicenza plots. The first presents a fault plane solution consistent with a transpressional stress regime, while the second (from the same Borcola pass stop?) shows an extensional character. Are the plots representative of two different stress fields? In the inactive quarry of fig. c there are Paleogene basaltic dikes injected along some faults. The wall of the dikes is generally overprinted by striations.

The graphical quality of the stereonets is improved by enlarging the labels and in addition the previous figure 3 is now split in two distinct figures to further improve the image quality by enlarging their sizes. The stereonet of Bassano does not show fault surfaces, but fold axes plotted on their respective fold axial planes. Some fold axes indeed fall outside their fold axial planes, but we chose to preserve this error in the stereoplot to show the true field measurements. Yes, we interpret the two different fault plane solutions from the same Borcola pass stop to represent two different stress fields. We observed in the field that sinistral striations are overprinted by striations indicating downthrow of the

NE-block of the BPFZ (see lines 210-215) and therefore added additional field pictures in figure 3 to show these two generations of striations.

Fig. 5. The trace of the Cross section 14 (see Cross section 14 in Fig. A1.1 of Supplementary material) seems truncated on its western part. Therefore, I am not able to understand if the fault in the mid of the cross section is the Schio-Vicenza fault or another normal fault placed outside Fig. 5 (the Paleogene graben boundary Castelvero fault?).
The trace of cross-section 14 was indeed truncated in its western part and the map extent has been widened to incorporate its complete trace.

Fig. 7. In the cross-section 5 I can't see the Schio-Vicenza fault, which is undoubtedly crosscut by the profile trace in its northwestern tract (see Fig. 5). Clearly, the crossing of the strike-slip fault is irksome, because out-of-plane movements occur. Probably, the amount of movement is small compared to that of the fault system separating Domain 1 from Domain 2. However, I think you must discuss this problem and insert the subvertical Schio-Vicenza fault into the cross section.
Agreed, we added the Schio-Vicenza Fault to cross-section 5 (figure 8a) and this problem is now discussed in lines 496-499.

Fig. 8. In the footwall of the Bassano fault a blind fault does exist. The surface expression of this thrust is the Montecchio Precalcino hill, interpreted to as the hinge of the hanging wall anticline isolated into the plain. It was recognized from a N-trending seismic section performed by Agip in the Eighties and consequently drilled by the 4 km deep Villaverla 1 well (see also Viganò et al., 2017. Past to present deformation of the central-eastern Southern Alps: from the foreland to the Giudicarie 3 belt. Annual Meeting of the Structural Geology Italian Group (GIGS) of the SGI. Geological Field Trips and Maps, vol. 10, 1.1, (2018). doi 10.3301/GFT.2018.01
In the DISS v. 3.2 the thrust is known as Thiene-Bassano fault (from the works of Galadini et al. 2005 and Burrato et al. 2008) and is therefore considered an individual seismogenic source (ITIS127) belonging to the composite source Thiene-Cornuda (ITCS007).
In the Profile 6 this blind thrust is neglected, although some seismic events are reported in the footwall of the Bassano fault. Therefore, I suspect that four basement thrust sheet, not three, best represent the profile 6. This would produce an additional, although limited (1-2 km?), shortening of the crosssection.
We agree that Profile 6 may be better represented by a 4th blind and deeper fault detachment, which would imply an additional amount of shortening. However, as no offset sediments can be observed at the Montecchio Precalcino hill, we are lacking clear constraints on the amount of shortening and stratigraphic markers necessary for the cross-section balancing method. Therefore, we chose to include this 4th detachment in Profile 6 as a dashed line (Figure 9) and we discuss the potential additional shortening associated with this 4th detachment and the deeper seismic events in lines 432-442 (with a reference to Viganò et al., 2018).

Fig. 11. It's unclear if the arrow labelled Late Oligocene shortening direction refers to Adria - Europe plate convergence or to the strain partitioning among the Giudicarie structures or simply to the field measurement. The cited works from Pomella et al. (2011, 2012) show a Late Oligocene/Earliest Miocene NNW-ward movement of the Southalpine indenter (large arrow) (Fig. 11 and 9, respectively). If the Late Oligocene shortening direction is NNW, then the 18-25 km of slip along the NGF requires a shortening of the domain 1 larger than 18 km. The same could be said for the mid Miocene shortening, since the hypotenuse of the triangle should be the shortening direction and not the strike-slip component along the NGF, which is the catheter. Applying different triangles with shortening corresponding to the hypotenuse (calculated by cross section balancing), the bend of the Periadriatic fault is at least half pre-existing to the Adria indentation. Therefore, while the calculation of the differential shortening in different domains seems correct, the conclusions of the manuscript that "Adriatic indentation into the Eastern Alps is responsible for most, if not all, of the 75 km sinistral offset along the NGF" would not be justified.

Please explain and insert some citation of papers from which the Late Oligocene shortening direction is taken.

We agree and corrected the displacement triangles, in which now the hypotenuse correspond to direction of shortening; however this direction changed with time. The Mid Miocene shortening direction for domains 1 and 2 is NNW-SSE (at an angle of 45° to the NGF fault trend) and in the displacement triangle, this results in a new motion estimate of at least 18 to 25 km of Mid Miocene along the NGF.

The Late Oligocene shortening direction in domain 1 is however NNE-SSW (Castellarin et al., 1992; Picotti et al., 1995; Castellarin and Cantelli, 2000) and trends at N025° (Castellarin and Cantelli, 2000), parallel to the NGF fault trend. Therefore, the NGF fault trend corresponds to the hypotenuse of the Late Oligocene displacement triangle. However, the minimum 18 km of Late Oligocene shortening was obtained along a NNW-SSE transect of Picotti et al. 1995 at an angle of 35° to the NGF fault trend. Therefore, this 18 km is inserted on the cathetus of the Late Oligocene displacement triangle and implies 22 km of Late Oligocene motion along the NGF.

Combining the 18 to 25 km Mid Miocene NGF motion and the 22 km Late Oligocene NGF motion, we obtain a new minimum estimate of 40 to 47 km motion along the NGF since the Late Oligocene. This implies a pre-Oligocene bend of the PF along the NGF of maximum 28 to 35 km and that 37%-47% of the current bend of the PF is pre-Oligocene based on minimum shortening estimates.

All above points are now added to the discussion in the text (please see lines 574-583).

We accept the criticism that our data does not support the idea that all displacement along the NGF is related to Adriatic indentation and therefore we removed the 'if not all.'. However, we would like to emphasize that our shortening estimates represent absolute minima and are less than proposed values for Neogene convergence between Adria and Europe, a point we discuss in lines 697-705.

Fig. 13. See previous comment to the late Oligocene shortening direction.

In figure 13 the sense of movement of SV and TC remains unchanged from a) to c). However, the indicated Late Oligocene shortening direction requires a dextral strike-slip kinematics of the SV and TC. In addition, the post Eocene CCW rotation of Adria relative to Europe casts doubts on the sketch of Fig. 13, where since the Late Oligocene the structures are shifted to the north, while their orientation remains fixed.

We found no evidence for dextral strike-slip motion along the SV and TC faults and there is no published Late Oligocene deformational age for these faults, therefore we assume these faults were not active in the Late Oligocene and we removed them from the sketch of figure 14c.

The Neogene CCW rotation of Adria (see text lines 606-610) was not more than 5° (Le Breton et al., 2017), therefore its effect on the orientation of the fault structures would be minimal.

Comments to the Supplementary material:

Balanced cross sections along the Giudicarie Belt (Southern Alps, Northern Italy) in 3-D Move

p. 7:

Figure A1.9: The small red arrows indicating the kinematics of the faults with apparent downthrow of the hanging wall show a reverse kinematics. Is this the result of a partial inversion of the faults or of the stratigraphic dip subparallel to the faults?

The arrows were mistakenly pointing in the wrong direction as they should indicate a normal sense of motion and have been adjusted accordingly.

Figure A1.10: The trace of the Cross section 14 in Fig. A1.1 seems truncated on its western part. As a consequence, I am not able to understand if the fault in the mid of the cross section is the SchioVicenza fault or another normal fault (the Paleogene graben-bordering Castelvero fault?). The small red arrows indicating the kinematics of the faults show uplift of the hanging wall relative to the footwall, exactly the contrary of the stratigraphic offset.

The trace of the cross-section 14 was indeed truncated in its western part and the map extent has been widened to incorporate its complete trace. This means that the fault in the middle of the cross-section is indeed the Schio-Vicenza Fault. Along this fault, the displacement arrows were mistakenly pointing in the wrong direction as they should indicate a normal sense of motion and have been adjusted accordingly.

Fig. A.12: see comment to Fig. 7 of the manuscript.

Done

p. 9: A1.3 Description of Cross section 5 second line: Cross section 5 instead of 6.

Done

I hope these comments are helpful, and I look forward to seeing the paper published in revised form

Dario Zampieri (Padova, Italy)

Reply on interactive comment on "Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (Northern Italy)" by Verwater et al.

Referee: Christoph von Hagke

Dear Dr. Von Hagke,

We would like to express our appreciation for your positive review of our submitted manuscript and acknowledge your constructive comments that helped us improve the manuscript. Please find below our responses to your remarks highlighted in blue.

This mansucript adresses the amount of shortening associated with the Giudicarie Belt, a key structure for understanding the Neogene evolution of the Alps. Using balanced cross sections, the authors find that most of the offest of the Periadriatic Fault can be linked to shortening in the Giudicarie Belt. They place their findings in the ongoing discussion on the deep structure of the Alps.

This manuscript is well written, and well structured. The constructed cross sections are sensible, and it is great to see that the authors published the full models as supplement. The study is an important contribution and can be published after some minor revisions.

General comments:

While the authors state that it is necessary to take into account strike slip movements during balancing, their modeling in fact is 2-D, and the respective error remains unknown. Second, I find it unfortunate that the forward modeling approach is discussed in the supplement only. Even though the manuscript would be longer, I find it important to show the approach and the uncertainties in the main text. These cross sections are the heart of the manuscript. Hypocenters of earhtquakes partly do not plot on faults (Fig. 6), and it would be important to explain that.

Yes, we agree that we need to take into account strike slip movements during balancing and that we need to elaborate on the respective errors. In line 496-499 we added a statement describing that most of the strike-slip motion out of the 2-D section traces occurred along profiles 3, 4 and 5 and therefore our shortening estimates for these profiles may be underestimated by a few km yielding errors of up to 27% (discussed in lines 393-397). An additional paragraph discussing possible errors associated with our balancing method was added at the end of section 5.1 (lines 355-372)

Although we agree on the great importance on the forward modelling approach for the manuscript, we choose to not show the figures of all the different forward models for every profile to maintain a reasonable length of the paper. The different forward models for profiles 5 and 6 can be found in the supplementary file, which is open-access to all interested readers. In addition, we would like to refer the reviewer and the reader to lines 338-351, where all the key assumptions for forward modelling are discussed in detail. The uncertainties related to the forward modelling approach are discussed in detail in lines 384-399.

It is correct that some hypocenters do not plot on faults and in the case of profiles 5 and 6 even deeper than the deepest interpreted fault detachment. We interpret these hypocenters to represent deformation associated with a deeper, blind, developing fault system, which may be linked to the Thiene-Bassano Fault for Profile 6, as pointed out by reviewer 1 (Dario Zampieri) to this contribution. We discuss this in lines 432-442 and added dashed-lines on Figures 8 and 9.

Revermann et al. 2012 provide AHe data from the Adamello showing exhumation increasing at 10-8 Ma, which is slightly younger than the Valsugana Phase. This should be included and discussed.

We agree this study is an important contribution to the discussion of exhumation in the Southern Alps and we added this paper to our discussion age of deformation in the eastern Southern Alps (section 4), lines 283-285.

Figure 3 can be improved. 3a: show an uninterpreted version + the interpreted version including S0 and say what the stippled lines mean (fold axes). Image size should be enlarged. 3B: indicate S0 also for the Dolomia Principale. Also here a separate interpretation wold be good. 3d: a more oblique view on the plane would have been good to show more clearly the shear sense. Generally more field pictures with more extensive descriptions would have been appreciated.

In the updated version of figure 3 two additional field pictures are included to highlight the two generations of striations observed along a branch of the Schio-Vicenza Fault (discussed in lines 210-215).

To enlarge the quality and the image size of figure 3 we separated the field pictures from the fault slip stereoplots to two different subsequent figures. In addition, we added uninterpreted versions for every field picture in the supplementary material.

The stippled lines in figure 3a indicate fold axes of chevron folds in the hanging wall of the Bassano Fault and are now labelled along with S0 on the figure. Unfortunately, at the location of figure 3b S0 for the Dolomia Principale could not be observed as the bedding was completely destroyed by intense cataclastic deformation.

For the previous figure 3d (now figure 3f) a field picture with a more oblique view is unfortunately not available.

Minor comments:

Line 39: this has been said earlier than in Scharf et al. 2013

We agree and added references in line 40.

Lines 68 ff: replace "chapter"

We agree and adjusted this.

Line 120: Tonale Fault and Pusteria Fault are named Tonale line & Pusteria Gailtal Line in Fig. 1. Both is acceptable, but should be used consistently.

We now use Tonale and Pusteria Lines consistently.

Line 144: references missing

We included references describing the Permian to Jurassic rifting events (lines 146-147).

Line 172: sth went wrong with this sentence (?)

We rephrased the sentence to improve its clarity.