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COMMENT

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This article is a comment on Moulin and Benedetti (2018), https://doi.org/10.1029/2018TC004958.

Key Points:

- The chronological constraints and the shortening rates derive from misreading of the available literature and not from new original data
- The description of the tectonic structures do not consider updated geological information available for the study area
- The balanced cross-section is inconsistent with the major crustal models for the Eastern Southern Alps, no alternate discussion is provided

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Comment on "Fragmentation of the Adriatic Promontory: New Chronological Constraints From Neogene Shortening Rates Across the Southern Alps (NE Italy)" by Moulin & Benedetti

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Abstract Moulin and Benedetti (2018), https://doi.org/10.1029/2018TC004958 present a new interpretation of the Neogene-Quaternary tectonic evolution of the Eastern Southern Alps (ESA) in Veneto-Friuli. After the reinterpretation of literature field data by means of remote sensing analysis (Digital Elevation Model interpretation), they calculated deformation rates of the tectonic structures through age interpretation of geomorphological surfaces of the Veneto-Friuli piedmont plain. The authors linked the result of surface analysis to the thrust and fold architecture of the ESA basing on the Castellarin et al. (2006), https://doi.org/10.1016/j.tecto.2005.10.013 interpretation of TRANSALP project and the Friuli geological map at the scale 1:150,000 (Carulli, 2006). Discussing their new architecture of the ESA, the authors finally yielded rates of Europe-Adria plates convergence and suggested fragmentation of Adria over the last 1–2 Ma. The present comment is aimed at discussing several critical points concerning: the use of the geomorphological and chronological data; the misinterpretation of the Digital Terrain Model; the reconstruction of the balanced geological cross section. Moreover, the application of a structural model defined in a certain area to another without considering peculiar structural complexities available in the literature results is geologically and methodologically questionable.

Plain Language Summary The late Quaternary sedimentary successions of Eastern Southern Alps (ESA) recorded important deformations related to the ongoing Europe/Adria collision. Their chronology has been updated in the last years, thanks to detailed surveys and analyses. Our knowledge on the tectonic architecture of the ESA has been recently improved by the new Geological maps of Italy (CARG Project: Zanferrari, Avigliano, Monegato, et al., 2008, Zanferrari, Avigliano, Grandesso, et al., 2008; Zanferrari et al., 2013). However, the bulk of the tectonic and chronological data was discarded or improperly used in Moulin and Benedetti (2018), https://doi.org/10.1029/2018TC004958 in their estimate of the shortening and associated rates and hence in the subsequent discussion on the fragmentation of Adria.

1. Premise

Moulin and Benedetti (2018) (hereafter M&B18) present a new interpretation of the fragmentation of the Adriatic "promontory" based on literature field data that were re-interpreted on the basis of remote sensing analysis (Digital Elevation Model interpretation). Standing on previous ages of geomorphological surfaces of the Veneto-Friuli piedmont plain, they also estimate deformation rates of some tectonic structures within the Eastern Southern Alps (ESA) extending their inferences to the whole fold-and-thrust ESA orogenic wedge between the southernmost thrust (referred to as "Udine Thrust" in M&B18) to the Periadriatic Fault (Lineament). The kinematic-structural architecture suggested by the authors comes from a synthesis of the Castellarin et al. (2006) interpretation of TRANSALP project (see page 14 of M&B18) and the Friuli geological map at the scale 1:150,000 (Carulli, 2006). In the discussion of the newly proposed architecture, they further argue on the Neogene-Quaternary Europe-Adria convergence rates, comparing them to the results of D'Agostino et al. (2008) and Faccenna et al. (2014) based on present-day geodetic measurements.

Figure 1. Tectonic sketch map of the Eastern Southern Alps and neighboring regions (modified from Zanferrari et al., 2013). Legend: AN: Ansiei thrust; AR: Arba-Ragogna th.; BC: Bassano-Cornuda th.; BE: Bernadia th.; BL: Belluno th.; BU: Buia th.; BV: Bassano–Valdobbiadene th.; BFCF: Borgo Faris–Cividale fault.; CA: Cansiglio th.; DA: Dof-Auda th.; DT: Monte Duranno-Tramonti th.; FS: Fella–Sava fault; GK: Gemona-Kobarid th.; HS: Hochstuhl fault; IA: Idrija-Ampezzo fault; IS: Isel fault; MA: Magnano th.; MD: Medea th.; MT: Montello th.; MV: Musi-Verzegnis th.; PA: Palmanova th.; PI: Pielungo th.; PL: Periadriatic Lineament; PM: Polcenigo-Montereale th.; PR: Predijama fault; PV: Pioverno f.; PZ: Pozzuolo th.; RA: Resiutta-Ponte Avons fault; RP: Ravne-Paularo fault; RS: Raša fault; SA: Selva di Cadore-Antelao th.; ST: Susans-Tricesimo th.; SU: Sauris th.; SV: Schio-Vicenza fault; TB: Thiene-Bassano th.; UB: Udine–Buttrio th.; VA: Val d'Astico fault; VB: Valsugana-Val Bordaglia th. FF′ and AA′ geological cross sections of Figures 4 and 5 respectively. Ge: Gemona del Friuli.

The present comment is aimed at highlighting several critical points in the study by M&B18. Due to the articulated and nested arguments and reasoning, we will start discussing the field data available for the investigated area and those used by the authors, following a focus on some specific tectonic structures and their use or interpretation, ending with a discussion on the final crustal interpretation and associated plate convergence rates.

2. Geological and Geodynamic Background

The Southern Alps represent one of the major structural sectors of the broader Alpine Chain and correspond to a late Cretaceous-Quaternary orogen (Castellarin et al., 1992, 2006; Doglioni & Bosellini, 1987; Massari, 1990). The Eastern Southern Alps are the easternmost portion of the Southern Alps, from the Mts. Lessini (Veneto) to NE-Friuli and W-Slovenia (Figure 1). They are bordered to the north by the Periadriatic Lineament representing the polyphased (though mainly oblique-slip) backstop (Castellarin et al., 1992, 2006; Schmid et al., 1996).

The present geological arrangement of the ESA in Veneto and Friuli has been strongly influenced by the Mesozoic and Cenozoic evolution of the Adria microplate. During the Mesozoic, the region was part of the passive margin of Adria, characterized by structural highs (i.e., carbonate platforms and plateaux) and basins associated to the extensional/transtensional tectonics. Since the Late Cretaceous, the ESA has undergone a complex, mainly compressive, polyphasic evolution.

Starting from the Late Cretaceous and during the Eocene, the ESA eastern sector (i.e., eastern Dolomites, Camic and Julian Alps) was affected by the SW-vergence thrusting of the external Dinarides (Caputo, 1996; Castellarin & Cantelli, 2000; Cousin, 1981; Doglioni, 1987; Doglioni & Bosellini, 1987; Massari, 1990; Merlini et al., 2002; Ponton, 2010) causing a strong crustal shortening and stacking (Zanferrari et al., 2013). Meanwhile, the central-western Veneto plain and western Dolomites were representing the corresponding foreland.

Following the late Oligocene-Burdigalian transpressional regime, likely induced by the excape tectonics occurring along the Periadriatic Lineament (Insubric phase in Massari, 1990; Castellarin & Cantelli, 2000), the Veneto-Friuli region was pervasively affected by the Mid-Late Miocene-Quaternary folding and thrusting activity characterized by a mean SSE direction of compression (Caputo et al., 2010; Castellarin & Cantelli, 2000; Doglioni, 1992; Fantoni et al., 2002; Heberer et al., 2016). It is worth to note that several of the Neoalpine ESA structures reactivated inherited Dinaric ones (Zanferrari et al., 2013).

From a broader geodynamic perspective, the end of subduction and slab pull along the eastern edge of the Carpathians in the Early Pliocene (Horváth et al., 2006), coupled with the continuous northward motion of Adria, gave rise to the inversion of extensional structures in the Pannonian basin (Fodor et al., 1998) and, relevant to our investigated region, the onset of a counter-clockwise (CCW) rotation of the Adria microplate (Márton et al., 2003; Vrabec & Fodor, 2006). This geodynamic change affected both ESA and Dinaric realms by inducing, since the Pliocene, a prevailing strike-slip kinematics on preexisting fault systems both in Slovenia and in NE-Italy. Examples are represented by the NW-SE striking Šoštanj and Hochstuhl faults and the WNW-ESE Periadriatic Lineament, Fella-Sava, and Labot faults in the northern sector of the ESA, whereas in central-western Slovenia and easternmost Italy, NW-SE striking dextral faults such as Divača, Raša, Predjama, Idrija, Ravne and Žužemberk (Bled-Mojstrana) were formed (Bajc et al., 2001; Fodor et al., 1998; Geološkj Zavod Slovenije, 2013; Jamšek-Rupnik, 2013; Kastelic et al., 2008; Mlakar, 1969; Placer, 1981, 1982; Placer et al., 2010; Poljak et al., 2000; Vrabec, 2001). These structures cut and displace either the Palaeogene External Dinarides and the Neogene-Quaternary South-Alpine fold and thrust belt inducing widespread transpressional and transtensional kinematics (Falcucci et al., 2018; Poli & Renner, 2004; Zanferrari et al., 2013).

Recent Quaternary tectonic activity is documented not only by the moderate seismicity along the Raša, Idrija, and Ravne faults (Bernardis et al., 2000; Bressan et al., 2018; Kastelic et al., 2008; Poljak et al., 2000), but also by the large dextral offset of geomorphological markers (Cunningham et al., 2006; Moulin et al., 2014; Šušteršič, 1996) and by the formation of pull apart basins along major strike-slip faults (Bajc et al., 2001; Kastelic et al., 2008; Vrabec, 1994).

Note that interseismic geodetic data show a ca. 2–3 mm/yr northward movement of Adria relative to Eurasia (e.g., D'Agostino et al., 2008; Devoti et al., 2011; Serpelloni et al., 2016). It should be noted that shortening is accommodated not only by the WSW–ENE-trending thrust front of the eastern Southern Alps, but also by the NW-SE-trending, right lateral strike-slip faults affecting western Slovenia and NE Italy.

3. (Mis)interpreted Land Surfaces

Concerning the age of the surfaces of the Veneto-Friuli Plain used by M&B18 in their research, we recall that this morphological feature was characterized by widespread aggradation of alluvial fans and fluvioglacial megafans (Fontana, Mozzi, et al., 2014 and references therein) during the Last Glacial Maximum (LGM, 30-16.5 ka sensu Lambeck et al., 2014). However, their deactivation and consequent apex trenching was diachronous among nearby river systems. In particular, the Cormor Megafan was deactivated at 19.5 ka cal BP, as demonstrated by several constraining radiocarbon dates (Fontana, Monegato, et al., 2014), while the Brenta Megafan was deactivated at 17.5 ka cal BP (Rossato & Mozzi, 2016; Rossato et al., 2018). Accordingly, when inferring rates from these ages, these differences solely could induce at least a 10% variation.

The determination of the age of the terrace surfaces is one of the key data used by M&B18 for calculating the deformation rates at different time scales. The authors (a) explicitly do not provide new chronologies,

(b) refer to a study, where uncalibrated radiocarbon ages were deliberately presented (Fontana et al., 2008), (c) neglect or ignore more recent works by the same researchers (Fontana et al., 2010; Fontana, Monegato, et al., 2014; Fontana, Mozzi, et al., 2014) that provided more robust and updated chronologies for same surfaces. For example, the correct chronology of surface "a2" (Figure 6 in M&B18), representing the outwash plain during the LGM, is 26.5–22.0 ka cal BP and not 22.0–18.0 ka BP as reported by M&B18. The terraces of the Cornappo and Lagna valleys, whose age is reported by several radiocarbon datings as being >55 ka BP (Zanferrari et al., 2013), were also erroneously attributed to the same "a2" surface.

The surface "a1" should represent the outwash plain of the withdrawal phase of the Tagliamento glacier within the end-moraine system, whose age was assessed between 22.0 and 19.5 ka cal BP (Fontana, Monegato, et al., 2014; Monegato et al., 2007). This portion of the plain was, however, clearly separated by the one related to the LGM maximum advance (Fontana, Monegato, et al., 2014; Zanferrari, Avigliano, Monegato, et al., 2008), though in M&B18 (Figure 3b) only a small portion of the plain (a2) is attributed to the LGM maximum advance. On the contrary, most of the plain has been considered younger (16.0–14.5 ka) with a difference of 5 ± 1 ka. As a consequence, all subsequent calculations based on the assumed ages are obviously biased.

The age of surfaces "a3" in M&B18 (their Figures 3 and 6b) is considered as <26.5 ka, as if they were related to the LGM peak. Nevertheless, in the same literature cited by M&B18 these surfaces are clearly ascribed to the Middle Pleistocene (Zanferrari, Avigliano, Grandesso, et al., 2008; Zanferrari et al., 2013) and hence much older. In addition, since the 19th century all available geological and pedological literature on the Pozzuolo terrace agrees in attributing at least a Middle Pleistocene age to its top surface (e.g., Comel, 1955; Feruglio, 1925; Fontana, 1999; Pirona, 1861). In this specific case, any calculated deformation rate would be at least five times lower than that presented in M&B18.

A coarse error in their morphotectonic analysis has to be pointed out concerning the surface of the Montebelluna and Brenta megafans, where a scarp located about 9 km south of the Prealpine piedmont is deduced from the digital elevation model (DEM) (Figures 1 and 5 in M&B18) (Figure 2a). As reported in Mozzi (2005), this southern scarp is a clear artifact of the DEM created at the boundary between different sheets of the topographic maps (Carta Tecnica Regionale del Veneto) used for the DEM processing (Figure 2b). Furthermore, M&B18 do not clearly describe the procedure adopted to obtain their DEMs. Focusing on the Veneto one, they state that "*5-m DEM was derived from accurate 1:5,000 topographical maps*" (page 5) and "*5-m DEM derived from 1:5,000 topographical maps (1-m elevation curves and elevation points) provided by the Veneto Region (*http://idt.regione.veneto.it/app/metacatalog/*)*" (page 8). This statement is evidently self-contradicting: topographical maps freely distributed by Veneto Region have 5-m spacing contour lines, and only limited sectors have 1-m spacing contours. On the contrary, the microrelief of the Veneto plain, freely distributed by ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto; http://www.arpa.veneto.it/dati-ambientali/open-data/dati-arpav-in-formato-shp/informazioni-territoriali-di-base/microrilievo-della-pianura-del-veneto) provides 1-m spacing contours. Moreover, if a DEM is built based on contour lines and elevation points, the cell-size is arbitrary, and the authors should have explained their choice (i.e., 5-m size). At the link proposed by the authors (http://idt.regione.veneto.it/app/metacatalog/), the Veneto Region provides also ready-to-use DEMs corresponding to 1:10,000 topographic map sheets, with 5-m cell size, based on the numeric version of 1:5,000 topographical maps. Such DEMs are fairly different from the DEM shown in their Figure 5, as can be noted in our Figure 2c; there indeed, there is no evidence of the linear anomaly, interpreted as a fault scarp by M&B18, probably due to the fact that the elevation data set was newer and corrected from the previous acquisition biases (ASCII files downloadable from the source indicated by M&B18 http://idt.regione.veneto.it/app/metacatalog/ report as date of creation August 2009, while the last issue of elevation data used in Figure 2c is December 2013 sources: https://www.dati.gov.it/dataset/dtm-regionale-celle-5-metri-lato and https://dati.veneto.it/opendata/dtm_regionale_con_celle_di_5_metri_di_lato).

In summary, Figures 1 and 5 in M&B18 contain serious scientific errors and all of the related interpretations and conclusions made by the authors in their section 4.2 "The Montello thrust" (e.g., "*A 35-km-long linear discontinuous 1-to-2 m-high scarp, which deforms the regular surface of the Veneto-Friuli Basin, is also identified 8.5 km further in the south between Bassano and Treviso*") are consequently untenable.

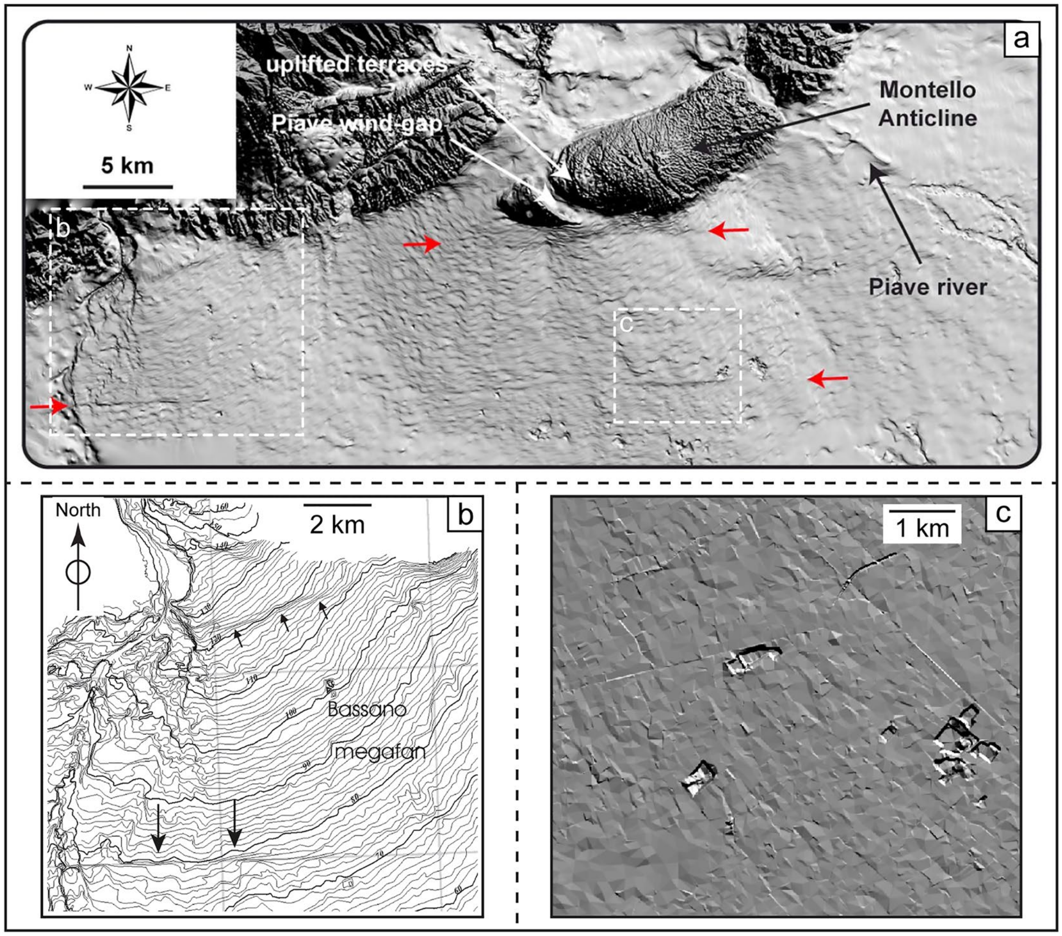

Figure 2. (a) Reproduction of Figure 5 in Moulin and Benedetti (2018) (M&B18), showing with red arrows two linear anomalies in the digital elevation model (DEM) crossing the Montebelluna and Bassano megafans, that are interpreted by the authors as tectonic scarps. (b) reproduction of Figure 6 in Mozzi (2005), reporting the micro-relief map of the apical portion of the Bassano megafan, with 1 m contour lines. Black arrows indicate the foot of a probable tectonic scarp observed also in the field (Favero & Grandesso, 1982; MURST, 1997; Tellini & Pellegrini, 2001), while the light gray grid corresponds to the boundaries of each 1:10,000 topographic map used for contour interpolation. A "false scarp" due to aerophotogrammetric bias, corresponding to an incorrect junction between map sheets, is clearly visible in the lower-left sector of the map, and corresponds to the western sector of the southern linear anomaly evidenced in (a) and interpreted by M&B18 as a scarp of tectonic origin. (c) DEM zoom-in of the eastern box in (a) obtained from the December 2013 data set and showing the lack of any linear morphological feature.

4. (Mis)interpreted Tectonic Structures

Following Carulli (2006), M&B18 show in their Figure 9 the activation and the S-ward propagation of three main contractional structures: Monte San Simeone (MST), Staro Selo (SS), and Tricesimo (TR) thrusts. All these tectonic features deepen northwards into the Adria upper crust, reaching a depth of at least 30 km, and propagate southwards with a ramp-flat geometry in the sedimentary succession. Thrusts root in the staircase-shaped Periadriatic Lineament.

Moreover, in the balanced cross section presented in their Figure 9, M&B18 do not discuss the activity and the kinematic role of the prominent strike-slip fault-systems (Raša, Predjama, Idrija, Ravne, Fella-Sava faults**)** that propagate from W-Slovenia to NE-Friuli (Zanferrari et al., 2013). They similarly never discuss the relationships between reverse and strike-slip structures.

In the following, we report our concerns and comments on the proposed structural model focusing on selected structures.

4.1. Inherited Dinaric Tectonics

In the text and in the drawing of their Figure 9, M&B18 do not adequately consider the presence of the Late Cretaceous-Late Eocene inherited thrusts characterized by a SW-vergence that strongly thickened the eastern Friuli upper crust relative to the western Dolomites and Veneto plain. Deformational structures belonging to the External Dinarides represent a pervasive framework within the ESA in Friuli region, affecting both its alpine and pre-alpine sectors (Merlini et al., 2002; Ponton, 2010; Zanferrari et al., 2013). Based on the detailed geological and structural surveys, the upper crust in Friuli consists of a stack of Upper Cretaceous-Paleogene tectonic units, while the associated thrusts are always strongly cut, folded, and often partially reactivated by the Neogene deformational events (Zanferrari et al., 2013).

In particular, based on the analysis of ENI seismic lines (Amato et al., 1976; S. Venturini, 2002) and/or detailed geological mapping (Venturini, 1987; Zanferrari et al., 2013), several Upper Cretaceous-Eocene tectonic structures clearly belonging to the Dinarides have been identified in the Friuli piedmont area and in the inner ESA Chain in Carnia; examples are the Palmanova (PA in Figure 1), Susans-Tricesimo (ST), and Gemona Kobarid (GK) thrusts. All of these structural features recorded a polyphase history since they have been reactivated during the Neoalpine tectonic phase, while Holocene seismogenic activity still persists on some of them (e.g., ST and GK, Burrato et al., 2008; Galadini et al., 2005; Peruzza et al., 2002; Pondrelli et al., 2001).

On the same issue, some more attention deserves the Monte San Simeone Thrust (or Rio dei Frari Thrust in Zanferrari et al., 2013) given its importance in the structural model proposed by M&B18. The Monte San Simeone Thrust represents the basal detachment of an isolated slice of a Dinaric tectonic inherited unit (see Figures 3 and 4) outcropping near the city of Venzone, where it is cut by the WNW-ESE vertical Pioverno fault belonging to the Idrija-Ampezzo strike-slip system (Zanferrari et al., 2013; see chapter 4.2 in this comment). Originally quoted by Selli (1963) as Monte San Simeone Line, it was tentatively extended both toward the east (MST-Uccea-Saga Thrust in Merlini et al., 2002; Ponton, 2002, 2010) and the west (Dof-Auda-MST Thrust in Venturini & Carulli, 2002), without providing, however, any mesostructural analysis. As a matter of fact, in the "Gemona del Friuli" Explanatory Notes (pages 175–179, Zanferrari et al., 2013) it is clearly documented that this structure (i.e., the Dof-Auda-MST-Uccea-Saga Thrust in Carulli, 2006) does not exist. Although the "Gemona del Friuli" geological sheet is cited in M&B18 (see their Figures 2 and 9), for the geological model they curiously include the Monte San Simeone Thrust sensu Carulli (2006), and neglect the more detailed mapping and newer data provided by Zanferrari et al. (2013).

4.2. Strike-Slip Tectonics

The easternmost sector of the ESA is affected by the activity of several strike-slip faults (Raša, Predjama, Idrija, Ravne, Fella-Sava faults) that formed in Western Slovenia starting from the Pliocene geodynamic rearrangement, and progressively propagated to NE Friuli (Falcucci et al., 2018; Placer et al., 2010; Ponton, 2010; Zanferrari, Avigliano, Monegato, et al., 2008; Zanferrari et al., 2013). It is however crucial the fact that M&B18 never discuss the relationships between reverse and strike-slip structures affecting the investigated area. In particular, there is no explanation about the structural and kinematic relationships between the MST and the NW-SE strike-slip fault system to the east (Figure 2a of M&B18). In this regard, the strike-slip fault system clearly cuts the MST, though the former graphically ended east of the profile trace and hence not considered in their cross-section (Figure 9 in M&B18). It is worth to note that detailed geological and structural mapping (surveys at 1:5,000) carried out also in this specific area for realizing the "Gemona del Friuli" geological sheet (scale 1:50.000), allowed the identification of a steeply dipping, right lateral strike-slip fault zone along the Resia, Fella, and Tagliamento valleys (Zanferrari et al., 2013). This is a broad and anastomosed right lateral N110°–115° strike-slip fault system, coupled with synthetic (N135°–145° striking) and antithetic (N20°–30° striking) faults. NW- or SE-vergence reverse faults, en echelon fold systems, strike-slip duplexes, contractional and releasing bends, as well as positive and negative flower structures integrate the structural association. Zanferrari et al. (2013) and Poli and Zanferrari (2018) define it as Idrija-Ampezzo Fault System (IA in Figure 1), considering it the continuation across the Friuli region of the Idrija strike-slip fault system affecting western Slovenia. In summary, although the "Gemona del Friuli" sheet (Zanferrari et al., 2013) is quoted in the references of M&B18, the really new structural

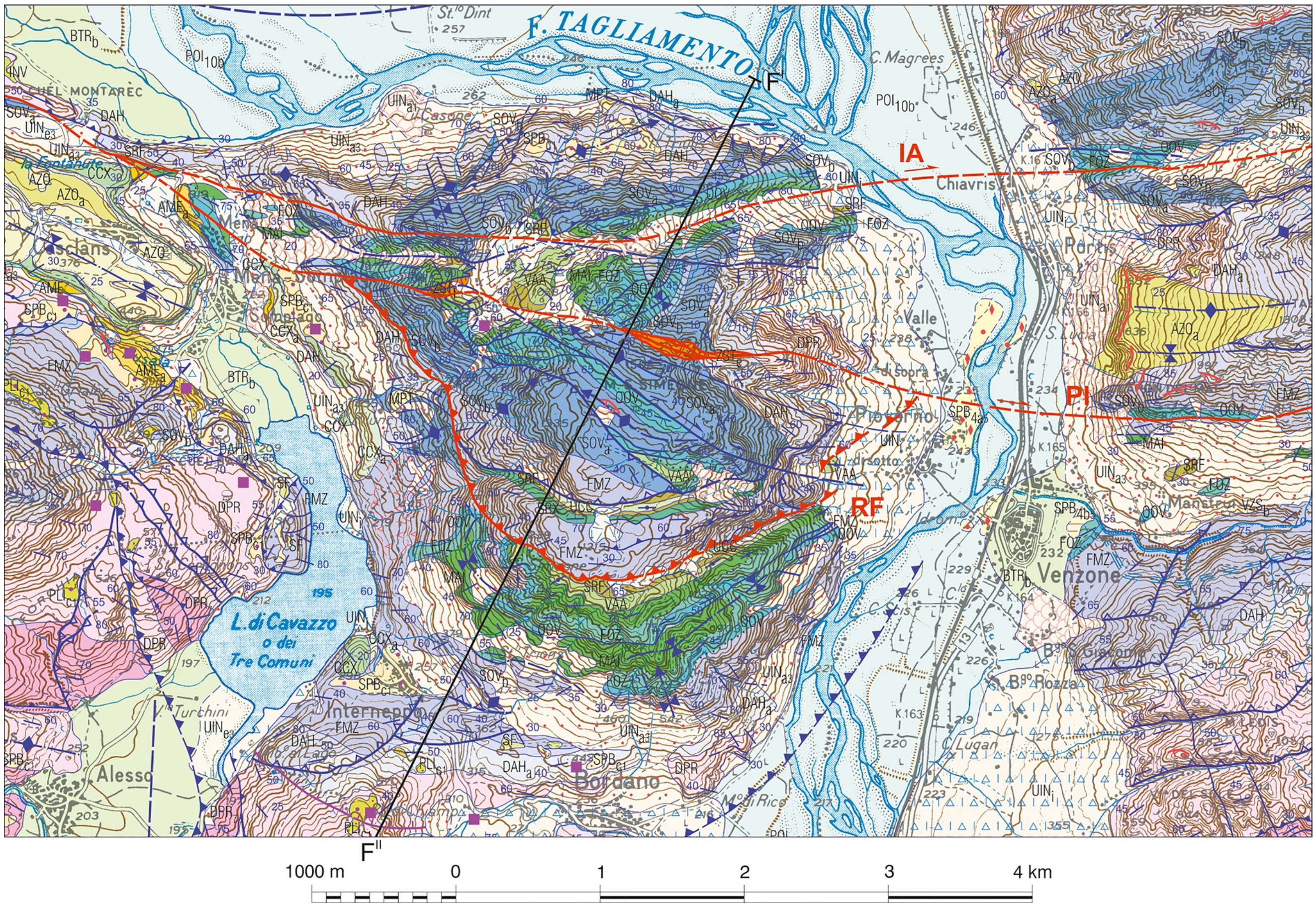

Figure 3. Detail of the Gemona del Friuli geological map (Zanferrari et al., 2013). FF′ black line is the cross section of Figure 4. Red lines: RF (Rio dei Fraris Thrust); PI (Pioverno Fault); IA (Idrija-Ampezzo Fault). Acronyms as in "Gemona del Friuli" sheet.

data seem to have been not considered by the authors and, what is worst, neither discussed. We suspect the "Gemona del Friuli" geological map was only used to report the stratal attitude for their geological profile (Figure 2c) simply because the Carulli (2006) geological map have no such information due to its small scale of representation.

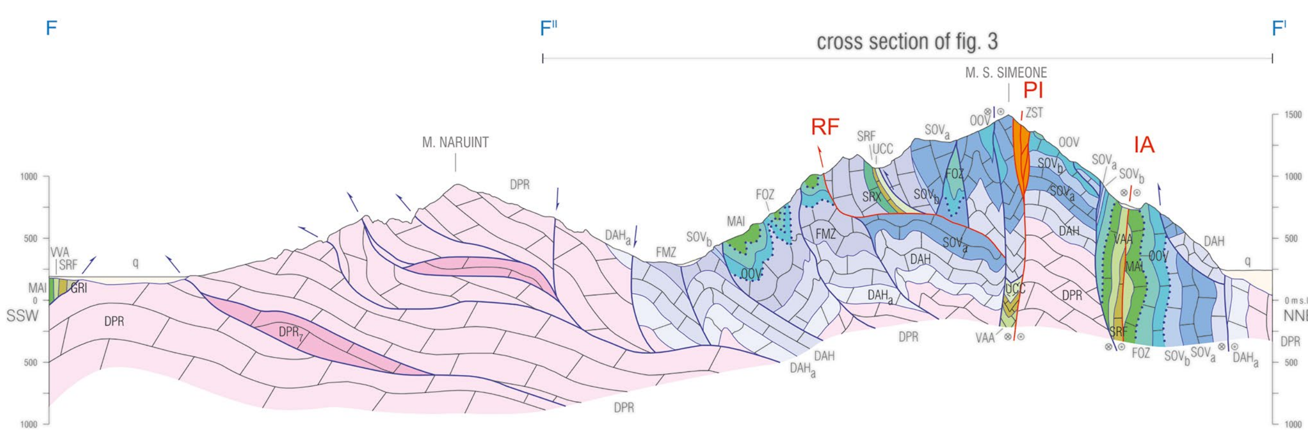

Figure 4. Geological section across the Monte San Simeone (from "Gemona del Friuli" sheet, Zanferrari et al., 2013). See trace in Figure 3. The Dinaric Rio dei Fraris Thrust (RF) is cut by means of the subvertical dextral strike-slip Pioverno Fault (PI), belonging to the Idrija-Ampezzo strike-slip system (IA: Idrija-Ampezzo master fault). Acronyms as in "Gemona del Friuli" sheet.

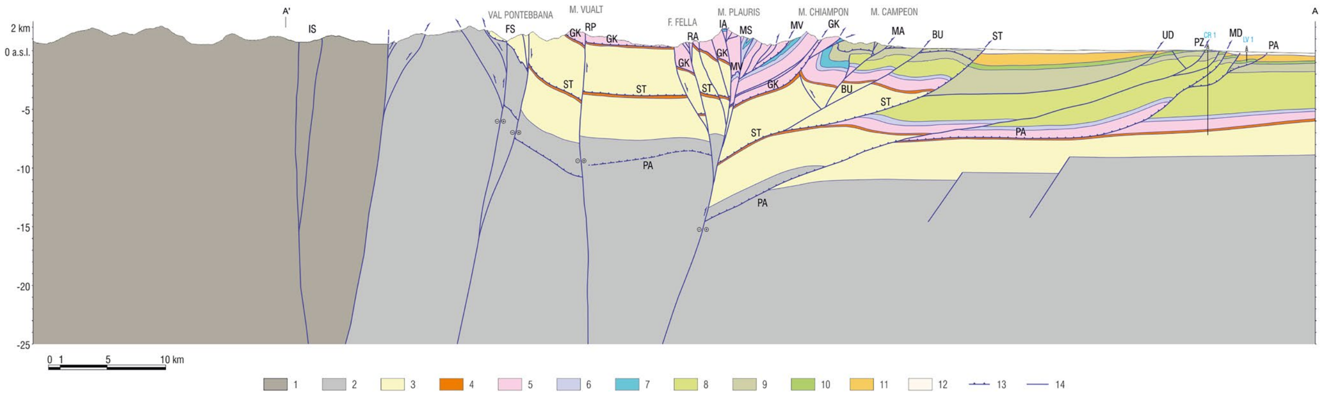

Figure 5. N-S regional geological cross-section across the ESA thrust belt and its foreland in Friuli (modified from Zanferrari et al., 2013, table 2). The cross section benefited from the geological and structural data acquired in the CARG Project (049-Gemona del Friuli and 066-Udine geological sheets) and the interpretation of seismic lines gently supplied by ENI S.p.a. Magnetic basement from Cati et al. (1987). For the structural setting around the Periadriatic Lineament (PL): C. Venturini (2002) and Geologische Karte der Republik Österreich 1:50.000, 198-. Legend: 1. Undifferentiated Austroalpine; 2. Magnetic basement (including the "Permo-Carbonifero Pontebbano"); 3. Upper Permian-middle Triassic successions; 4. Upper Carnian, mostly terrigenous-evaporitic successions; 5. Upper Triassic carbonate platforms; 6. Lower Jurassic carbonate platform; 7. Lower and middle Jurassic-upper Cretaceous *p.p.*, Carnian-Slovenian basin successions; 8. Middle Jurassic-upper Cretaceous p.p., Friuli Carbonate Platform successions; 9. Upper Cretaceous p.p.-lower Eocene, Dinaric Foredeep successions; 10. Aquitanian-Langhian, Cavanella Group successions; 11. Serravallian-lower Messinian successions ("upper Molasse"); 12. Pliocene-Quaternary successions. 13. WSW-verging major Dinaric thrusts (MV: Musi-Verzegnis; GK: Gemona Kobarid; ST: Susans-Tricesimo; PA: Palmanova); 14. Neoalpine faults (f) and thrusts (th) (BU: Buia th.; FS: Fella-Sava f.; IA: Idrija-Ampezzo f.; MA: Magnano th.; MD: Medea th.; PV: Pioverno f.; PZ: Pozzuolo th.; RA: Resiutta-Ponte Avons f.; RP: Ravne-Paularo f.; UD: Udine-Buttrio th.). ENI wells: CR1: Cargnacco 1; LV1: Lavariano 1. IS: Isel fault.

4.3. Buttrio Thrust

The Quaternary most external front of the ESA thrust-belt in Friuli is represented by the Palmanova Thrust (Figure 1). This polyphased tectonic element actually acts with a transpressive kinematics generating the Pozzuolo Thrust that involves not only the Cavanella Group (Lower Miocene), but also the Friuli Supersynthem (Pliocene-Upper Pleistocene p.p.) and the LGM deposits (Fontana, Monegato, et al., 2014; Zanferrari, Avigliano, Monegato, et al., 2008). It is noteworthy that the (Udine-)Buttrio Thrust is not a splay of the Pozzuolo Thrust as interpreted by M&B18 (their Figures 2 and 9), but it consists of two distinct tectonic structures. Their geometric and kinematic relationships have been indeed investigated and described by Galadini et al. (2005; Figure 4), by Burrato et al. (2008; Figure 2), by Zanferrari, Avigliano, Monegato, et al. (2008; Geological map of "Udine" sheet and geological cross sections) and by Zanferrari et al. (2013, plate n. 2). In the aforementioned papers, the interpretation was based on detailed geological and morphotectonic surveys and, above all, on the analysis of industrial seismic lines kindly made available by ENI S.p.a. It is thus clear that also the Palmanova-Pozzuolo Thrust System should have been considered by M&B18 in the attempted Quaternary shortening rate assessment, but we could not find any indication of such discussion in their paper.

Contrary to what mentioned in M&B18, the (Udine-)Buttrio Thrust has not the same structural and seismotectonic meaning of the Montello Thrust in Veneto for the following basic reasons: First, the former is not the most external compressive structure of the ESA thrust belt in Friuli (references above); Second, the Udine-Buttrio Thrust roots at the top of the Friuli Carbonate Platform (i.e., at the base of the Palaeocene-Eocene turbiditic units), that is, to say at a depth of about 3–4 km under the Friuli plain (Burrato et al., 2008; Galadini et al., 2005; Poli et al., 2002; Zanferrari, Avigliano, Monegato, et al., 2008), while the basal branch line of the Montello Thrust is at about 10–12 km depth (Castellarin et al., 2006; Galadini et al., 2005).

4.4. Tricesimo Thrust

Referring to Cheloni et al. (2012), M&B18 assume the (Susans-)Tricesimo Thrust as the causative fault of the 1976 earthquake. Nonetheless, the structure reported in their Figure 2 has a different trace compared to the original paper (Cheloni et al., 2012), where instead a consistent model with a fault plane localized in the Buia area (Buia blind Thrust) is proposed.

Above all and once again, M&B18 do not clarify the structural and kinematic relationships between the Tricesimo Thrust and the regional strike-slip structure E-NE of Udine (as drawn in their Figure 1), referred to by the same authors (Benedetti et al., 2000; Moulin et al., 2014) as an active fault (i.e., Raša Fault Auct.). As it is graphically represented, the reverse and strike-slip faults are kinematically and structurally linked suggesting that a single major unsegmented structure occurs with at least 80 km in length. In the light of the assumption that the Tricesimo Thrust was responsible for the 1976 earthquake, this issue is not a trivial one for defining the seismogenic potential of the region. Despite the subject of their paper, there is no discussion at all about the kinematic relationships between the two "segments" and particularly the location and characteristics of the segment boundary. According to empirical relationships (e.g., Wells & Coppersmith, 1994), a similar unsegmented source would have a seismogenic potential much higher in terms of maximum expected earthquake magnitude also implying that the 1976 event (Mw 6.45 in Rovida et al., 2019) ruptured only a relatively small part of it. If the above represents their view, they should have discussed about (a) why the coseismic rupture halted SE along a straight fault and (b) based on which arguments they rule out the possibility of a complete rupture of the fault with expected magnitude between 7.5 and 8. We think this topic should be treated more cautiously and more in detail that how M&B18 did in their paper.

As a final note, the name "Tricesimo Fault" is misleading and should not be used in this context, since in the literature it refers to another tectonic structure, well defined on the basis of seismic lines interpretation (Amato et al., 1976; Galadini et al., 2005; Zanferrari, Avigliano, Monegato, et al., 2008; Zanferrari et al., 2013). The Susans-Tricesimo Thrust Auct. has been indeed located ca. 1 km to the south in correspondence of the southernmost flysch outcrop, also well constrained by boreholes stratigraphy.

4.5. Fella-Sava Line

The Fella-Sava Line is an active (Jamšek-Rupnik, 2013; Merchel et al., 2014) transregional complex structural element extending from the Carnic area to the Pannonian basin. In Slovenia according to Vrabec and Fodor (2006), the Sava Fault merges with the Šoštanj Fault and the Labot Fault, together forming the continuation of the Periadriatic Lineament shear zone toward the Drava graben. The total cumulative horizontal dextral offset along the Sava Fault was estimated by correlation of various Oligocene formations to be about 25 km (Hinterlechner-Ravnik & Pleničar, 1967), 40 km (Kazmer et al., 1996), and 65–70 km (Placer, 1996). Whatever the exact value, there is a quite huge amount of horizontal offset that likely affected a comparable crustal thickness.

In the Julian area, where it is commonly refered to as Fella Line, the fault was traditionally interpreted as an Alpine (Neogene) high-angle back-thrust (Selli, 1963; Venturini, 1990). In particular, a detailed geological survey between Pontebba and Tarvisio documented that the Fella Line is a complex wrench fault system with both synthetic and antithetic structures (Jadoul & Nicora, 1986), while microstructural analyses carried out in the western Carnic segment (i.e., Paularo-Comeglians Fault) clearly confirmed its mainly strike-slip kinematics (Bartel et al., 2014). Also, Merlini et al. (2002), Carulli (2006), and Ponton (2010) interpreted the Fella Line as a dextral transpressive structure. In spite of the available abundant literature on both geometry and kinematics, M&B18 assume the Fella Sava Fault as a secondary (at the scale of the orogenic wedge) accommodation structure representing it as an oblique-slip reverse fault of the (Susans-)Tricesimo Thrust (see their Figure 9).

Contrary to the interpretation proposed by M&B18, the Fella-Sava Fault is actually one of the major tectonic features of the whole Eastern Alps (Vrabec & Fodor, 2006), though in the M&B18 proposed cross-section there is no argument to explain why a regional high-angle transpressive crustal fault is drawn at depth as a flat secondary decollement. The proposal of such an "innovative" geometric-kinematic setting should have been demonstrated for example, by modeling the deformation field derived from geodetic data (e.g., GPS time series) and check if the low-angle segment at depth of the Fella-Sava Fault would fit the observed regional kinematics. Other problematic issues of the proposed interpretation are (a) the necessary kinematic decoupling between the shallow strike-slip subvertical 'segment" and the deep subhorizontal reverse one; (b) the peculiar kinematic transition with depth that would also imply strong variations of the crustal stress regime in a wider area and the involvement of other tectonic structures.

In conclusion, and notwithstanding the importance of the Fella-Sava Fault as a crustal scale strike-slip feature capable of generating tens of kilometers of horizontal displacement (Hinterlechner-Ravnik & Pleničar, 1967; Kazmer et al., 1996; Placer, 1996), and the transcurrent tectonics strongly affecting the Carnian and Julian Alps and Prealps during Neogene (e.g., Ponton, 2010; Poli & Zanferrari, 2018; Zanferrari et al., 2013), M&B18 clearly assume that the latter is negligible; however, they omit to support their hypothesis and even to discuss it.

4.6. Periadriatic Lineament

According to a wealth of literature, the Periadriatic Lineament is a polyphased strike-slip regional scale shear zone with a subvertical setting (e.g., Massari, 1990; Polino et al., 1990; Schmid et al., 1996, 2004 among many others). Also in the TRANSALP crustal cross section (Castellarin et al., 2006), the Periadriatic Lineament dips about 70°–75° northwards. Regardless of the literature, M&B18 draw it with a staircase geometry and an average dip of about 45° (their Figure 9). No one geological, geophysical, nor geodynamic evidence exists for supporting this choice that, in turn, obviously influences the proposed "balanced" cross section. Concerning this critical point the authors simply state: "*How the three main thrusts connect with the Periadriatic fault at depth is not discussed in the present study*."

Moreover even considering the interpretations of Schmid et al. (2013), Handy et al. (2015), and Hetényi et al. (2018), which strongly questioned the Castellarin et al. (2006) "Crocodile" model suggesting a NE-wards "wrong way" subduction of the Adria lithosphere, the Periadriatic Lineament has been never proposed to have a ramp-flat layout. In particular, Hetényi et al. (2018) show both the Periadriatic Lineament and the Fella-Sava Fault as a subvertical strike-slip structures belonging to the ESA thrust belt.

5. (Un)balanced Cross-Section and Neogene Shortening-Rates

Last but not least, the NNE-trending cross-section proposed by M&B18 (Figure 9) explicitly assumes that the crustal features imaged by the N-S-trending TRANSALP seismic profile (Castellarin et al., 2006), running across the Dolomites 70 km on the west, persist in their study area. At page 14, they in fact declare: "*The structure of the eastern Southern Alps upper crust has been imaged by the TRANSALP seismic profiles running about 70 km west of our study area* (Castellarin et al., 2006) *and could be incorporated into our fault geometry*." Unfortunately, this hypothesis does not hold at all because the Dinaric thrusts in the Dolomites deform only the sedimentary cover, and not the basement (e.g., Doglioni & Bosellini, 1987), while in the easternmost ESA sector (i.e., Friuli and Carnia) representing the M&B18 investigated area, the mountain belt is characterized by a complex nappe architecture mainly built during the Late Cretaceous-Late Eocene Dinaric tectonic phase, that caused the thickening of the upper crust.

Second, the lower plate indicated in their Figure 9 as "*underthrusting of Adria*" is not truncated by any ramp; indeed the segment labeled as R4 is a footwall flat, parallel to the top and base of the crystalline basement and not a ramp. Therefore, the antiformal stack suggested to overlay R4 segment implies a huge amount of shortening along the proposed section: following a trivial graphical exercise the necessary ramp cutting the Adriatic crystalline basement should be located (at least) further left of the section represented in their figure.

Third, when playing and applying thin-skinned models in geological reconstructions some fundamental assumptions must be fulfilled, among which is the conservation of the rock volume (area in plane strain). As a very basic principle, this assumption will not be justified, (a) if oblique-slip occurs on thrust faults, (b) if strike-slip faults intersect the cross-section line, or (c) if the line of section is oblique to the primary movement direction of major rock volumes. None of the above fundamental conditions is satisfied in the M&B18 reconstruction.

It is also hardly comprehensible the reason why, on one hand, M&B18 refer to the Castellarin et al. (2006) model for the 'shallow" part of the TRANSALP Profile and particularly for the Southern Alps. On the other hand, they repudiate the first order geodynamic feature represented by the fact that it is the European plate that undergoes the Adria block and not vice versa. Relative to the shortening and the inferred rates, M&B18 state that:

1. "Although other styles of folding could exist, the poor resolution of the published seismic profiles makes it difficult to estimate how important they are. Therefore, the presented interpretation is thus affected by uncertainties, which cannot be quantified with the available data." (pp. 11–12)
2. "The cross section is hence constructed by assuming that the main decollement horizons lie along D1 and D2 where drastic changes in the rheological properties occur." (p. 12)
3. "Note that the geometry of the ramps as shown in Figure 9 is only indicative and could be better constrained with higher-resolution seismic profiles. Finally, equation 1 indicates that folding of the a1 surface has resulted from 11.6 ± 1.6 m of slip on D1." (p. 13)

Given the uncertainties (1, 2) and assumptions (3) it seems unlikely to evaluate the amount of slip on D1 with the proposed sub-meter resolution, also considering possible graphical errors (their Figure 8b) greater than the resolution of the calculated slip.

From all these considerations, we conclude that the crustal cross-section of M&B18 is essentially wrong because unquestionably unbalanced (and impossible to balance); therefore all consequent calculations relative to the amount of shortening along the profile are not reliable and should be not taken into account. As a further consequence, all proposed rates should be rejected too.

6. Summary

Moulin and Benedetti (2018) propose a new interpretation about the fragmentation of the Adriatic "promontory," reportedly based on the reinterpretation of field data (Zanferrari, Avigliano, Monegato, et al., 2008; Zanferrari et al., 2013) and selected literature (Caputo et al., 2010; Carulli, 2006; Fontana et al., 2008; Monegato et al., 2007), however without considering other available and updated works (Mozzi, 2005; Zanferrari, Avigliano, Grandesso, et al., 2008; Ponton, 2010; Fontana, Monegato, et al., 2014). In some cases, the authors have misinterpreted or over-interpreted the original published data, whereas the reasons for discarding the original interpretations are not discussed and are not supported by any new data. Above all, the changes in age assessment of the terraces without providing new chronological analyses and ignoring the available ones (Fontana, Monegato, et al., 2014; Fontana, Mozzi, et al., 2014; Mozzi, 2005; Zanferrari, Avigliano, Grandesso, et al., 2008) invalidate all of the consequent interpretations on the deformation rates of the tectonic structures.

The alleged balanced cross section on one side embraces the results of the TRANSALP Profile (Castellarin et al., 2006) in terms of shallow tectonic setting, though traced at a distance of ca. 70 km; on the other hand, it assumes that the Adriatic crust underthrusts the European one, at odds with the original TRANSALP Profile.

The proposed structural cross-section also assumes a staircase geometry of the Periadriatic Lineament that was never documented nor suggested in the literature, but that strongly conditions the final results of the paper. Additionally, the proposed overall geometry and kinematics do not consider the huge amount of geological and tectonic information available for the Friuli sector of the ESA and particularly:

1. The Late Cretaceous-Late Eocene Dinaric phase that caused crustal thickening in the investigated area with respect to the central-western Veneto region; as a consequence, the presence of an inherited tectonic stack largely reactivated during the Neogene-Quaternary deformation, hampers and obscures the correlation between tectonic units and therefore the estimate of the relative displacements
2. The major role played by NW-SE to WNW-ESE strike-slip fault systems affecting the area, which are never discussed in M&B18 and that basically make unbalanced the proposed cross section, therefore invalidating all consequent results.

In conclusion, (a) the misinterpreted application of a crustal geological model taken from a distant region, (b) the unsupported assumption of "innovative" geometries and kinematics of major deformational structures, (c) the omission of the role of well-defined regional tectonic features, (d) the neglect of the "local" geological information, and (e) the attribution of wrong ages to fluvial terraces, determined in M&B18 unreliable reconstructions and untenable conclusions both in terms of cumulative shortening and rates.

Data Availability Statement

The present Comment is supported by data of previous works reported in the reference list. The Geological maps and explanatory notes data sets are freely available at http://www.isprambiente.gov.it/Media/carg/friuli.html. Topographic data for the Montello area are freely downloadable from REGIONE VENETO (https://idt2.regione.veneto.it/) and ARPAV (http://www.arpa.veneto.it/dati-ambientali/open-data/dati-arpav-in-formato-shp/informazioni-territoriali-di-base/microrilievo-della-pianura-del-veneto) repositories.

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