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“Gravity modeling reveals a Messinian foredeep depocenter beneath the intermontane Fucino Basin (Central Apennines)”, reply to the comment from Florio et al. (2022).

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Cover Letter for the reply to the comment from Florio et al. (2022) on the paper "Gravity modeling reveals a Messinian foredeep depocenter beneath the intermontane Fucino Basin (Central Apennines)", by Mancinelli et al. (2021).

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Dear Editor,

Please consider the manuscript attached to this cover letter as the reply to the comment from Florio et al. (2022) on the paper "Gravity modeling reveals a Messinian foredeep depocenter beneath the intermontane Fucino Basin (Central Apennines)", by Mancinelli et al. (2021). The comment was submitted with the reference number TECTO15654, the manuscript we are submitting replies to that comment.

These very same files were attached to the review report I made on April 13, 2022 regarding the revision of the aforementioned comment. Since it was never asked to me to reply in a formal new article submission until today, I would like to request that the submission date for this reply to be shown in the published final reply is April 13, 2022.

Best regards

Paolo Mancinelli and co-authors

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Highlights

This short communication replies to the comment made by Florio et al. (2022) to the work by Mancinelli et al. (2021) where the gravity anomaly in the intermontane Fucino basin (Central Italy) is investigated.

We welcome the discussion on our work, the debate is always useful when dealing with complex geological scenarios such the Fucino basin. However, in the comment presented by Florio et al. (2022) there is a fundamental misinterpretation of the geological context in which our work is framed (i.e. the presence or not of a Miocene siliciclastic flysch beneath the Plio-Quaternary deposits). Furthermore, Florio et al. (2022) comments on the poor quality of the gravity data used in Mancinelli et al. (2021) while strongly supports the model proposed by Cella et al. (2021) that is based on the same dataset (i.e. the Bouguer anomaly map of Italy, Carrozzo et al., 1986) as clearly stated in Cella et al. (2021).

Misreading of the available literature and of our work was evident throughout the comment, in the following we try to address the main points raised by the authors of the comment.

Best regards

Paolo Mancinelli and co-authors

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Introduction

This short communication replies to the comment made by Florio et al. (2022) to the work by Mancinelli et al. (2021) where the gravity anomaly in the intermontane Fucino basin (Central Italy) is investigated.

We welcome the discussion on our work, the debate is always useful when dealing with complex geological scenarios such the Fucino basin. However, in the comment presented by Florio et al. (2022) there is a fundamental misinterpretation of the geological context in which our work is framed (i.e. the presence or not of a Miocene siliciclastic flysch beneath the Plio-Quaternary deposits). Furthermore, Florio et al. (2022) comments on the poor quality of the gravity data used in Mancinelli et al. (2021) while strongly supports the model proposed by Cella et al. (2021) that is based on the same dataset (i.e. the Bouguer anomaly map of Italy, Carrozzo et al., 1986) as clearly stated in Cella et al. (2021).

Misreading of the available literature and of our work was evident throughout the comment, in the following we try to address the following main points:

- Gravity data;
- Modeling approach;
- Seismic data and interpretation;
- Geological evidences that led to the models presented in Mancinelli et al. (2021).

Gravity data

The dataset used in Mancinelli et al. (2021) is the same as the one used in Cella et al. (2021), or at least the one they mention in their published work. The only difference between the two works lies in the processing of such data to calculate the residual anomaly maps. On one side, Cella et al. (2021) use the method proposed by Mickus et al. (1991) whilst, conversely to what stated in the comment where a band-pass filtering is recalled, Mancinelli et al. (2021) subtract a regional planar trend (e.g. Mancinelli et al., 2020) and anomalies with wavelengths > 100 km. Unsurprisingly, these two approaches result in slightly different residual anomaly maps (Fig. 2 in Cella et al. (2021) and Fig. 2d and 3 in Mancinelli et al. (2021)). However, conversely to what stated in the comment, the residual anomaly proposed by Mancinelli et al. (2021) locates well-developed gravity lows in the Varri and Roveto valleys (Figs. 2d and 3 in Mancinelli et al., 2021).

The location of gravity stations presented in figure 3 of Mancinelli et al. (2021) demonstrates the good coverage of the original data that were used, among thousands other stations, to produce the Bouguer anomaly map of Italy (Carrozzo et al., 1986). This latter map, i.e. the interpolation of the original gravity stations, represents the only publicly available gravity anomaly data over the study area and we are confident about its robustness for the investigation of the Fucino basin thanks to the dense distribution of gravity stations in this area.

The dataset proposed in figure 1 of the comment by Florio et al. (2022) is not publicly available, otherwise, different filtering approaches such the one adopted by Cella et al. (2021) would have been tested by Mancinelli et al. (2021). Obviously, a total anomaly map such the one in figure 1 of Florio et al. (2022), should not be compared with a residual anomaly map because, regardless of the filtering procedure adopted, there will always be significant differences in amplitudes and spatial trends of the residual anomalies. Nevertheless, regardless that any discussion about their map is precluded to those who do not have access to such data, Florio et al. (2022) compares the full anomaly map produced from proprietary data (their figure 1) with the residual map produced in figure 3 of Mancinelli et al. (2021). Furthermore, the full anomaly map produced by Florio et al. (2022) from proprietary data is not suitable for the comparison proposed in their figure 3 because, once again, a full anomaly data (the green line) is compared against observed (black continuous line) and calculated (dashed lines) residual anomalies. Such a comparison would be inappropriate particularly when a regional planar trend has been removed as done in Mancinelli et al. (2021). In Central Italy, the removal of the first-order contributor (i.e. the Moho discontinuity) from the observed gravity anomaly likely induces a tilt of the residual such that observed between the green and black continuous lines in figure 3 of Florio et al. (2022). On the SW-NE striking sections, the counterclockwise tilt from the green line (full-anomaly) to the black line (residual anomaly), likely represents the contribution due to the northeastward-thickening of the crust, from ~20 km crustal thickness in the Tyrrhenian domain to ~30 km in the Adriatic domain (e.g. Piana-Agostinetti and Amato, 2009; Mancinelli et al., 2020) because the first-order planar trend removal was performed on a regional-scale (Fig. 2d in Mancinelli et al., 2021) rather than on a local-scale.

Following the above discussion and considering the differences in the filtering procedures proposed by Cella et al. (2021) and Mancinelli et al. (2021), we fully reject the comment by Florio et al. (2022) about the gravity data being used in our work.

Modeling approach

We are aware of the limitations that every 2D model carries and this is recalled in several parts of the paper by Mancinelli et al., (2021). The comparison provided by the authors of the comment in their figure 2 suggests that some 3D contributions can be responsible for the observed gravity anomaly. However, we note that the maximum misfit between the 2D and the 2.5D models is not widespread along the modeled profile but rather it distributes only in the central Fucino basin (Fig 1b this work, Fig. 2 in Florio et al., 2022). Interestingly, despite the model proposed by Florio et al. (2022) should cover the entire basin (Fig. 1), the misfit between the two models immediately approximates zero mGals both toward the SW and NE edges of the basin. This imply that the source for such misfit is not fully related to the Miocene block but adjunct contributions can be related to the other units (i.e. the green, blue, orange and yellow blocks). Furthermore, if a third-dimension component was the causative source for such misfit, the two models should show some differences also on the LS ridge, where strong NW-SE striking components (i.e. orthogonal to the modeled profile) should be related to low-density carbonates. Instead, the misfit is only located in the central portion of the basin, where the major thickness of low-density blocks is modeled. This evidence suggests that the misfit reported by Florio et al. (2022) is related to the infilling units rather than to a third-dimension component.

Figure 1 mimics the modeling approach used by Florio et al. (2022) to evaluate contributions from a third dimension component orthogonal to the modeled section G in Mancinelli et al. (2021). Florio et al. (2022) modeled the infilling units of the Fucino basin as a bowl-shaped horizontal layering with concentric sections (black squares in figure 1c) whose lateral extent regularly decrease with depth (figure 1a). They do not specify neither the center of their model nor the thickness of the sections, but in figure 1 we hypothesized a constant thickness (~ 400m) of each section and centered the concentric sections on the geographic center of the basin. Despite this setup (Figure 1a, 1c) allows to cover most of the vertical thickness of the Miocene-Quaternary deposits in the central part of the basin, it demonstrates that, regardless of the thickness and location of the sections used to approximate the bowl-shaped model proposed by Florio et al. (2022), their model is neglecting significant volumes of infilling deposits that certainly contribute to the misfit they report. Furthermore, the comparison provided in figure 1c highlights the significant approximation introduced by a horizontal-layering model such that proposed in Cella et al. (2021) and in the comment by Florio et al. (2022). In fact, the visual comparison (Fig. 1c) between the lateral extent of the colored blocks and of the black rectangles representing constant-density blocks such those modeled in figures 5b, 9-12 in Cella et al. (2021), suggests that the latter approach is neglecting significant vertical and lateral (both SW-NE and NW-SE striking) density contrasts that should be expected in a half-graben basin such the Fucino. Finally, we argue that such vertical and lateral density contrasts provide significant contribution also to the misfit reported by Florio et al. (2022).

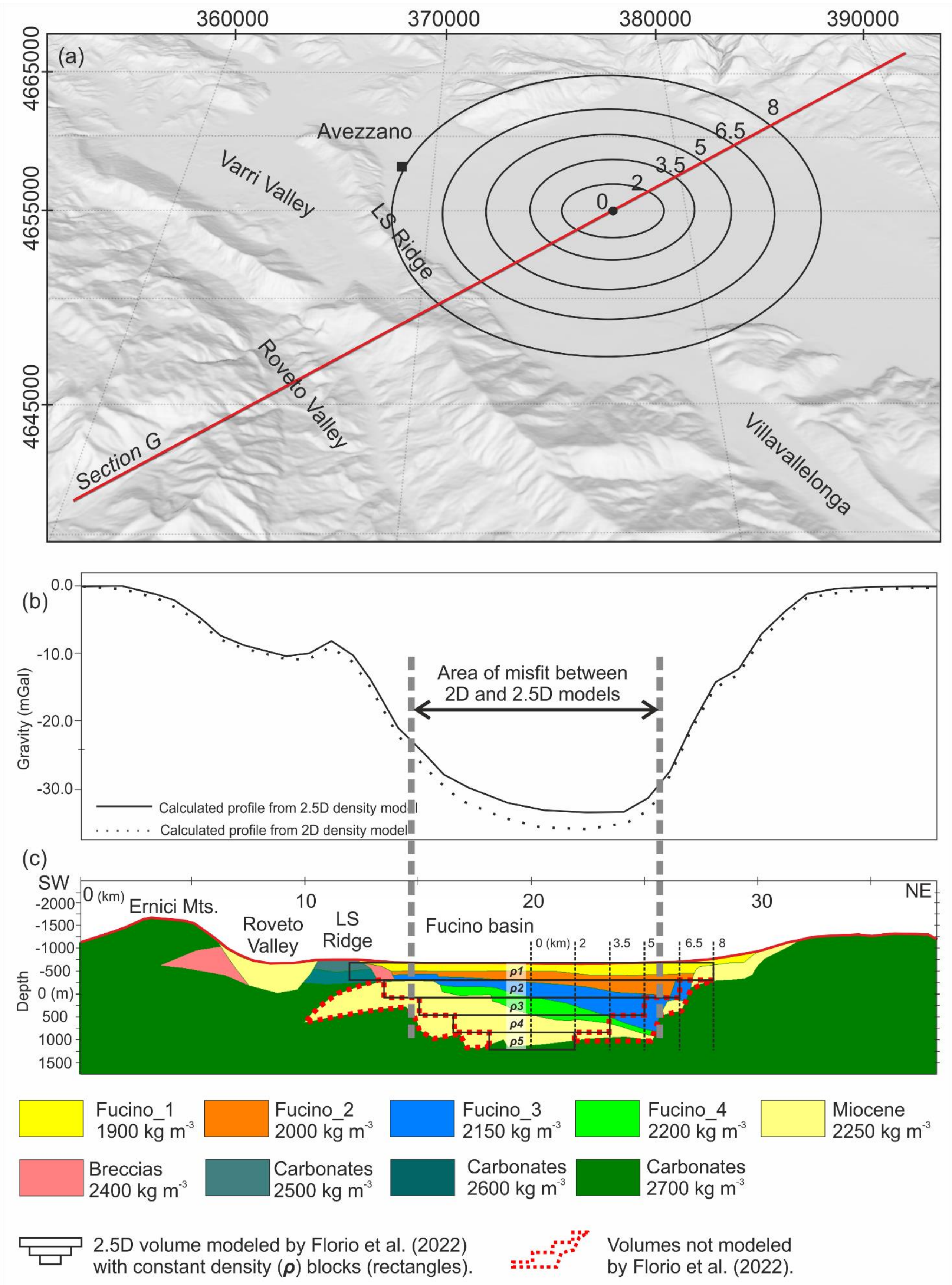

Figure 1. (a) Location of the modeled section G overlying a shaded-relief topography of the Fucino basin and surroundings. Black circles mimic the horizontal extent of the sections used for the bowl-shaped basin model by Florio et al. (2022) – i.e. black rectangles in (c). (b) Calculated profiles

according to a 2.5D (continuous line) and 2D (dotted line) approach as shown in Florio et al. (2022). (c) Modeled section in Mancinelli et al. (2021) (colored blocks) compared against the black constant-density rectangles modeled by Florio et al. (2022). In this figure the dashed red polygons denote deposits neglected by the model in Florio et al. (2022).

Some uncertainties about the depth to the bottom of the Miocene deposits are related to the modeled densities, in the following we try to estimate the possible range. Given the lack of deep borehole data, to retrieve the density values used in the modeling, Mancinelli et al. (2021) started from the best-fitting velocity estimates proposed in Patruno and Scisciani, (2021) that were calculated after the interpretation of migrated seismic sections (see the following section). The resulting velocity ranges were converted in density values using the well-known Gardner relation (Gardner et al., 1974), providing density ranges for each unit (Table 1 in Mancinelli et al., 2021). Modeling of the Miocene and Plio-Quaternary blocks was achieved using unique density values per each block that were kept as much constant as possible in the several modeled sections, in order to minimize density differences for the same unit across the sections. However, density variations within the block and within each unit across the sections are, of course, possible within the ranges provided in Table 1 of Mancinelli et al. (2021). Thus, considering the ranges of densities for the five modeled units (Fucino_1-4 and Unit 5, Table 1 in Mancinelli et al., 2021), the calculated gravity anomaly can range ~±5% due to possible density changes of the modeled units. This, in turn, lead to a possible error in the depth of the bottom of the basin in section G of ±80 m.

According to the above discussion, we reject the comment from Florio et al. (2022) because they do not provide convincing evidences demonstrating that a significant 3D contribution should be expected when modeling the Fucino basin on 2D sections.

Seismic data and interpretation

Seismic quality and reflection strength

In several parts of the comment by Florio et al. (2022), the authors define the seismic data as low quality. Land seismic shot in areas of complex topography and structural settings, like the Apennines, commonly shows lower signal-to-noise ratio compared to poorly deformed foreland basins imaged by marine seismic acquisitions. However, through the Apennines, onshore seismic data acquired in areas characterized by a near-flat topography and where poorly-deformed Plio-

Quaternary or Miocene siliciclastic deposits are outcropping, generally show a good penetration and clear imaging of reflections up to 3-4 s in TWT at depth in industrial seismic profiling (e.g., Mirabella et al., 2008; Mirabella et al., 2011; Scisciani and Motefalcone, 2006). The Fucino basin is one of such cases, where primary reflections, even if locally interrupted by tectonic structures and related artifacts, are visible up to 2-2.5 s in TWT of depth. Clearly these seismic data have been acquired in a preliminary phase of the hydrocarbon exploration and are too sparse and low-resolution for potential prospects delineation (e.g., Compagnia Mediterranea Idrocarburi, 1999). However, they are still good to unequivocally define the typical asymmetric basin geometry which is completely misinterpreted by the unrealistic flat-lying and bowl-shaped infill modelling by Cella et al. (2021) and Florio et al. (2022), which is in deep contrast with all the seismic stratigraphic architecture ever published for the Fucino Basin (e.g., see the fault-related syn-rift wedges interpreted under the Fucino by Cavinato et al., 2002 – see their figures 11 to 16 – and by Patacca et al., 2008 – see their figures 14-15). Indeed, no other authors, to our knowledge, has ever proposed that flat-lying and bowl-shaped units are present under the Fucino Basin, which is universally known to represent a well-documented example of present-day normal fault-driven (post-orogenic) continental half-graben.

We would also like to directly quote Cavinato et al. (2002), as they, again, write the precise opposite of what has been implied in the comments by Florio et al. (2022): "*The data available include surveys carried out by Elf Italiana at the beginning of the 1980, and data acquired later by Agip, Chevron Oil and Fiat-Rimi. The Consortium CNR-ENEL-AGIP CROP Project (Subproject CROP11 Tarquinia-Vasto; Director: Prof. M. Parotto) has recently acquired additional deep seismic data. […] The seismic signal was* ***<u>fair to poor quality</u>*** *and the data were processed only to a stack product without applying data migration. The shallow data recorded allow the* ***<u>recognition of the geometry of the Plio–Quaternary deposits and the top of the Meso–Cenozoic carbonates. It is also possible to recognize the Neogene shortening structures geometries (thrust features) with the control of the surface geological mapping</u>****."* Indeed, the good quality of the seismic utilized, and particularly of the two reprocessed and migrated seismic lines published by Patacca et al. (2008) and successively utilized by Patruno and Scisciani (2021) for their velocity modelling (c.f., lines 1 and 2, shown in Figures 5-6 of Patruno and Scisciani, 2021 and by figures 14-15 of Patacca et al., 2008) is confirmed by the observation of the un-interpreted versions of such lines (see figures 7-8 of Patruno and Scisciani, 2021).

It is surprising that Florio et al. (2022) cite the CMI company seismic processing and interpretation report to justify their assertion that the seismic data are characterized by low quality. In the CMI document, the scarce quality of seismic is not referred to their newly re-processed data and to other higher-resolution profiles acquired by other companies (e.g., the two lines utilized by both Patacca et al. (2008) and Patruno and Scisciani, (2021) for their main interpretation – see Figures 14-15 by Patacca et al., 2008), but to data acquired back in the 1980's with low values of fold coverage.

Another point addressed by Florio et al. (2022) regards the hypothesized absorption of the seismic wave at the base of the Pliocene-Quaternary units and the resulting absence of penetration in the deeper medium. Even if we assume the existence of a direct contact between Plio-Quaternary and carbonate bedrock, the presumed "total" reflection hypothesized by the authors is completely unrealistic for people familiar with the interpretation of industrial seismic. In the Apennines context, several seconds of reflective intervals and key markers are undoubtedly visible underneath the contact between Neogene siliciclastic deposits and Top Apulian carbonates in the Southern Apennines or below Messinian evaporites in the Adriatic foreland (e.g., Mancinelli and Scisciani, 2020).

Florio et al. (2022) state: "*the strong reflection strength at the base of the Pliocene-Quaternary units implies a strong impedance contrast and a strong increase of P-wave velocity with the depth, which is not detected by the velocity analysis, as the reflected wave do not penetrate the deeper medium*". Thus, the authors are proposing an "a priori" existence of a strong impedance contrast produced by the inferred interface between Pliocene-Quaternary units and the underlaying carbonates (Cella et al., 2021). We fully disagree with the authors' statement citing 'strong reflection strength at the base of the Plio-Quaternary'. All the seismic profiles clearly show an evident discontinuous characteristic of the reflection marking the base of the Pliocene-Quaternary Fucino units, which is inconsistent with an abrupt change in acoustic impedance between the "slow" Pliocene-Quaternary deposits and the "fast" and dense carbonates. In most places at the base of the Plio-Quaternary fill, the reflection amplitude is, in fact, moderate to weak. Generally, there is the complete lack of a single strong "hard-kick" reflection, as it would be expected in the case of a single siliciclastic-on-carbonate contact, particularly if unconformable. Indeed, the strength of the reflection at the base of the Plio-Quaternary package is similar or even weaker than many intra-Quaternary reflections! For reference to this discussion on reflection strengths, please see figures 5-6-7 of Patruno and Scisciani (2021). In addition, the 'a priori' assumption of 'strong reflection strength' at the base of the Pliocene-Quaternary fill due to a direct Plio-Quaternary on carbonate bedrock contact is inconsistent with the geological evidence, and in particular with the widespread occurrence around the Fucino Basin of Messinian flysch siliciclastic deposits between carbonate 'bedrock' and Plio-Quaternary Fucino units (see the geological evidence section).

Supposed 'multiples' in the deep part of the seismic lines and velocity analysis

Florio et al. (2022) have cautioned that the velocity modelling shown by Patruno and Scisciani (2021) may be tainted by the existence of multiples under the Pliocene-Quaternary sedimentary fill.

Multiples are well-known artifacts producing noise in seismic data processing and interpretation and considerable effort is spent during processing to remove or attenuate their effects (e.g. Sheriff, 1984). Long-path multiples show persistent hyperbolic curvatures after normal move-out (NMO) correction, when the velocity of shallower intervals is smaller than those of deeper reflective intervals. This results in steeper signals compared to primary reflections; consequently, they are easily detected during processing and routinely suppressed by seismic data migration, a procedure adopted by all the Fucino lines interpreted by Patruno and Scisciani (2021). Moreover, the stacking processing allows to discriminate against multiples because, during NMO corrections, the velocity spectrum shows significantly different values compared to primary reflections received at the same time, with lower velocity necessary to flatten multiples signals (Yilmaz, 1987). It is a basic rule during processing to take care to avoid erroneous picking of multiples and to select the higher values of the contoured semblance panel. In addition, applying an erroneously picked interval velocity produce evident artifacts in the final stacking (e.g., the typical "smiles" in this case) which are evident to both the geophysical company, the contractor and the interpreters.

Multiples may still be subtle, especially when they are short-path (i.e., the arrival time of the multiple seismic signals is very close the primary reflection), but their presence and noise are still evident with closer inspection on CMP gathers or stacked seismic sections. This is particularly true when acoustic interfaces producing primary reflection are not horizontal, like in the deeper part of the Fucino Basin. Assuming that this particular artifact has occurred in our data, the extra wave travel path must have occurred in the high-velocity carbonates supposed by Florio et al. (2022) to directly underly the Plio-Quaternary Fucino basin infill. In such case, the NMO curves belonging to multiples are very gentle and similar to flattened primaries occurring at the same time, without a significant reduction of the velocity values that are typical of carbonate (i.e., of at least c. 4000 m/s). Therefore, in the case where the stacking process is unsuccessful to identify the artifact during the

NMO correction, multiples will still be ineffective at significantly altering the estimated interval velocity.

In addition, we note good evidence of primary reflections being present under what we interpret as the base of the Plio-Quaternary Fucino basin infill (corresponding to the same interpretation carried out, on the same lines, by Patacca et al., 2008 – see their figures 14-15).

In the Fucino seismic lines, a clear package of continuous, roughly concordant, medium-to-high amplitude reflection is well-imaged under the basal unit of the Plio-Quaternary Fucino infill (e.g., see Fig. 5, 6 and 7a in Patruno and Scisciani, 2021). This seismic unit sometimes shows internally-concordant high-amplitude reflections that are more prominent with respect to the overlaying basal contact of the Pliocene-Quaternary deposits (i.e., the contact tentatively equated by Cella et al. (2021) to a presumed direct Pliocene-on-carbonate bedrock unconformity). This characteristic, which is evident both on stack and migrated version of the seismic profiles, conflicts with the interpretation proposed by Florio et al. (2022) of widespread multiples at this depth, due to the lower amplitude and the identical dip compared to the overlying primary reflection.

The methodology adopted to derive the mean seismic interval velocity has been explained by Patruno and Scisciani (2021) in page 9 of their paper: "*In lines 1 and 2, interval velocity profiles were reconstructed for the 26 common depth points (CDPs) for which Vrms velocity data were available (Figures 5 and 6). Due to the absence of any velocity measurement from deep penetrations (e.g. sonic logs, check shots, VSP's and refraction seismic), Vrms-derived interval velocity is the only seismic velocity information for the Fucino. We have therefore derived a velocity model from the analysis of seismic data using the formula of Dix (1955).*"

In Figures 5-6 of their paper, Patruno and Scisciani (2021) show in black the velocity interval profiles for a number of CDPs along the two most recent lines (Line 1 and 2). These interval velocity data were calculated for these 26 CPDs based on the VRMS data collected by the company who acquired the seismic data. Therefore, this seismic velocity analysis is completely independent from the interpretation of the horizons shown by Patruno and Scisciani (2021), which in turns adheres to the previous interpretation of the same two lines shown by Patacca et al. (2008) (see the Figures 14-15 of Patacca et al., 2008). If one looks at these interval velocity profiles displayed by the figures 5-6 of Patruno and Scisciani (2021), it is possible to qualitatively ascertain that there are no strong contrasts in interval velocity between the deepest interpreted Plio-Quaternary unit (Unit Green) and the inferred deeper Meso-Cenozoic basement. Overall, the interval velocity increases with depth (as expected), but not that much. It should be again remarked, that the Plio-Quaternary Fucino units interpreted by Patruno and Scisciani (2021) in their lines 1-2, including the base of the Plio-Quaternary sedimentary fill, are exactly the same ones as those interpreted by Patacca et al. (2008) on the same lines.

Patruno and Scisciani (2021) have then proceeded at depth-converting the 4 interpreted horizons along these two lines, by utilizing the interval velocity data at the location of the 25 CDP points. They then extracted, for each of the 26 CPD points, 'averaged' interval velocity and thickness data for the 4 interpreted seismic units, plotted in the isochron vs. isopach graph shown in Fig. 11A, which is then utilized to extract equations to depth-convert all the lines. The statistical data showing the spread of the 'averaged' interval velocity data for each CDP and each of the four intervals, is shown in Fig. 11B of Patruno and Scisciani (2021).

It is important to notice that the "black ball" bar shown at the far right in Fig. 11B shows the spread of interval velocity data from the undefined 'basement' below our deepest interpreted Fucino unit (Unit Green). So, this particular data-unit is very likely corresponding to Messinian flysch and/or older carbonate rocks, down to the deepest points where Seismic lines 1 and 2 reported VRMS data. This composite 'basement' unit, it is fair to say, is independent from any possible difference in views of horizon interpretation that other authors may have, including any discussions regarding artifacts. This composite 'basement' unit under the base of the Plio-Quaternary sediments is still showing remarkably low interval velocity data for carbonate rocks – average of 2750 m/s, with a maximum of less than 3100 m/s.

As explained above, the velocity analysis is simply based on the Vrms data collected/elaborated by the original companies. The maximum depths of these Vrms data are significantly deeper than the base of our deepest interpreted Plio-Quaternary unit (i.e. our 'Unit Green'), as it may be confirmed by simply looking at the black interval velocity profiles for the 26 CPDs shown by Patruno and Scisciani (2021) in their figures 5-6. So, the only way to 'explain away' these interval velocity data for the deeper units would be to state that the Vrms data for these depths were unreliable for some reasons, although Florio et al. (2022) have made no attempt to prove this, nor could they have. Finally, we have previously argued that eventual multiples in the deepest parts of the basin cannot possibly explain such a strong inferred reduction in interval velocities compared to the values expected for carbonate rocks (of at least c. 4000 m/s).

Geological evidence

The two most significant failures of the model published by Cella et al., (2021) are the assumptions that: (1) the Plio-Quaternary Fucino sediments are directly underlain by the carbonate bedrock; and (2) the density-depth trend shows a horizontal layering, which is then used to constrain their 3D model. There is, in fact, broad scientific consensus on the asymmetric nature of the Plio-Quaternary infill and the presence of Miocene flysch units interposed between the Plio-Quaternary sediments and the carbonate bedrocks, with plenty of geologic evidence backing these up.

All the published seismic interpretations of the Fucino basin (except that proposed by Cella et al., 2021) clearly show a fault-related wedge-shaped geometry of the Plio-Quaternary infill deposits that is typical of a half-graben continental basin filled by alluvial and lacustrine continental deposits (e.g., figures 11-16 of Cavinato et al., 2002; figures 14-15 of Patacca et al., 2008; figures 5-9 of Patruno and Scisciani, 2021). This seismic-stratigraphic architecture was controlled by the complex tectonic evolution of the Fucino Basin in the wider framework of the Apennine orogen (e.g., also see Gori et al., 2017 for nearby Quaternary basins), resulting in significant fault-driven lateral heterogeneities striking both SW-NE and NNW-SSE, regardless of the adopted evolutionary model (e.g., Cavinato et al., 2002; Patruno and Scisciani, 2021). Similarly, the flysch deposits beneath the Pliocene sequence, should also carry an asymmetrical, westward-thickening geometry, inherited from the feeding Simbruini thrust sheet to the west (Mancinelli et al., 2021).

Cella et al. (2021), for the first time ever, are apparently showing persistently horizontal layering for the Fucino sedimentary units. To do so, they have only relied on "*…reflective segments whose evidence is unquestionable*", and have censored and ignored the other, supposedly unreliable segments. Had they at least shown the ignored seismic segments, the readers would have been able to weigh their models against the supporting evidence and evaluate their outcomes. In our opinion, it is likely that this "*unquestionable selection*" has resulted in the horizontal layering of the Plio-Quaternary deposits in the Fucino basin (see figures 5b, 9, 10, 11, 12 of Cella et al., 2021). This is not the simplest representation of the geological model that would meet the Occam's razor principle, but rather it is a wrong one, resulting from 'selectively' neglecting and ignoring the data contrasting the horizontal layering model. As previously outlined, the typical half-graben asymmetry of the Fucino Basin is indicated by plenty of previous geological and geophysical investigations.

A second misleading geological view presented in the comment by Florio et al. (2022), perhaps representing the very foundation of their doubts, is that the work by Mancinelli et al. (2021) is attempting to *confirm* a model in which "…*the Pliocene-Quaternary units infilling the basin overlies an older (Messinian) siliciclastic flysch, instead of a carbonate substrate as hypothesized in previous studies (e.g., Cavinato et al, 2002; Cella et al., 2021).*" suggesting that the majority of the available literature supports a model where the Plio-Quaternary deposits directly overly the carbonate substrate. In the following, we provide evidence that, as a matter of fact, such view is proposed only in the work by Cella et al. (2021).

The Fucino basin is geographically surrounded by Messinian flysch deposits outcropping in the Roveto valley to the west, in the Giovenco valley to the east, and NE of the Tremonti mounts to the north (Cipollari et al., 1999; Cavinato et a., 2002; Cara et al., 2011; Patacca et al., 2008; Carminati et al., 2014; Mondati et al., 2021; Scisciani and Patruno, 2021), with outcropping thicknesses of at least 200 m. In particular, in the north-eastern margin of the Fucino basin, extensive exposures of Messinian flysch are located in the hangingwall block of the Pescina-Celano Fault (near Celano and Aielli villages). This sector corresponds to the footwall block of the San Benedetto-Serrone-Gioia Fault and analogous flysch deposits are obviously expected in the hangingwall block (i.e., underneath the Fucino basin). Exposed thickness of at least 200 m (Cerchio and Collarmele area in the hangingwall of the Pescina-Aielli east Fucino boundary fault, e.g., Fig.1 in Patruno and Scisciani, 2001 and references therein) unconformably overlaid by Pliocene-Quaternary deposits and overlaying concordant Miocene marls (e.g., east of Celano, in the hangingwall block of the north-easterly prosecution of the Tre Monti fault system) with carbonates more at depth.

In remarkable contrast to what the authors of the comment state when they say that *"The presence of carbonate basement at the base of the Fucino basin is supported by several authors (e.g., Cavinato et al., 2002; Cella et al., 2021; Cara et al., 2011; Boncio et al., 2016)"*, Cavinato et al. (2002) clearly describe **<u>at least 200 m of flysch deposits found inside the basin</u>** by borehole S5, located ~ 1 km south of Paterno (Fig. 5 and section A-A' in Fig. 7 of Cavinato et al., 2002). Cavinato et al. (2002), in agreement with a vast body of published literature and geological maps (e.g., ISPRA, 2007; Mondati et al., 2021) also report outcropping Miocene flysch units around the Fucino Basin (e.g., Collarmele and Paterno areas), lying just below the Plio-Quaternary Fucino units (Fig. 5 of Cavinato et al., 2002). Both in their stratigraphic framework images and in their text, Cavinato et al. (2002) **<u>clearly show a Miocene "Lazio-Abruzzi Flysch" unit, about 700 m in thickness, between the Plio-Quaternary Fucino units and the deeper carbonate sequences</u>** (see figures 6 and 10 of Cavinato et al., 2002). A direct quotation of Cavinato et al. (2002) is also very clear (their page 5): "*The synorogenic terrigenous units (Lazio–Abruzzi flysch; Messinian age) (Patacca et al., 1992; Cipollari et al., 1997),* *which consist of calcirudites and which grade upward to flysch units (sandstone and mudstone bodies), are well exposed along the Val Roveto and Val di Varri valleys and in the northern and eastern areas of the Fucino Basin (Ovindoli, Goia dei Marsi and Giovenco Valley) (Fig. 2). Evaporites (gypsum) are found at the top of the Lazio–Abruzzi Flysch in the Val Roveto valley and in the Marsica range. […] The carbonate and terrigenous marine sequences are interpreted to represent the two different main source areas during the Plio–Pleistocene basin evolution. These sequences are largely covered, in the studied area, by the Plio–Pleistocene and Holocene deposits of the ancient Fucino lake.*" ("These sequences", meaning both the carbonate and the siliciclastic flysch sequences, of course). In figure 8 of Cavinato et al. (well correlation panel), we can see an onlapping contact between Plio-Quaternary Fucino units and carbonate bedrock (which is perhaps what has misled Florio et al., 2022), but only at the very edge of the basin itself. Indeed, if one observes the geological cross-sections reconstructed by Cavinato et al. (2002), these clearly show Miocene flysch (the dotted unit, corresponding to their 'sequence 2'), sometimes very thick, clearly interposed between the Plio-Quaternary Fucino fill and the underlying carbonate rocks (please see figures 7 and 16 of Cavinato et al., 2002). The Messinian flysch sequence identified by Cavinato et al. (2002) is correlated with marine foredeep sedimentation whose seismic facies overlies the carbonate ramp sequence (Figure 7 in Cavinato et al., 2002). Similar results are obtained by Cara et al. (2011) where the flysch deposits overly the carbonate units throughout the basin (e.g. Fig. 1 and 14 in Cara et al., 2011) and likely represent the resonant layer (i.e. the bedrock for the seismic modelling of the basin). The work by Boncio et al. (2016) also reports a basin-wide distribution of Miocene siliciclastic deposits overlying the carbonate facies (Figs. 1, 5, 6 in Boncio et al., 2016) and such deposits represent the bedrock for the seismic modelling of the basin. The only seismic interpretation where the flysch deposits are not clearly located beneath the Plio-Quaternary is the one proposed by Patacca et al. (2008). However, this latter work was focused on the Plio-Quaternary deposits neglecting the "*Pre-Pliocene Apennine units*" (e.g. Figs. 14-16 in Patacca et al., 2008). Therefore, Patacca et al. (2008) are not at all excluding the possibility that flysch deposits are interposed between the deeper carbonate facies and the Plio-Quaternary Fucino deposits.

Based on the above sets of evidence, we can objectively conclude that only the work by Cella et al. (2021) assumes a Plio-Quaternary infill directly overlying the carbonate facies, although the origin of such assumptions are shrouded in mystery.

All the points described above suggests that the flysch deposits are not only ubiquitous beneath the Plio-Quaternary deposits, but they also play a significant role in controlling the seismic response of the basin. Thus, every modeling approach in the Fucino basin should consider such deposits.

Regarding the comment about the relationship between the Luco fault and the Miocene deposits, we interpreted the NE-dipping western faults (including the Luco fault) as representing an intermediate evolutionary step in the extensional post-orogenetic evolution of the basin. In the discussion section of the work by Mancinelli et al. (2021), it is clearly stated that this is an interpretative view, and we welcome any alternative interpretation. Similarly, we discuss the carbonate blocks with densities of 2500-2600 kg m^{-3} on the Luco-Salviano (LS) ridge, to avoid repetition we warmly invite the reader to please refer to chapter four of the work by Mancinelli et al. (2021). Regarding the breccias blocks modeled in section G and sections 1-3 we confirm that their geometries and densities are inferred from the residual gravity modeling. Furthermore, we take advantage from this reply to suggest the speculative interpretation that these deposits as modeled in section G, may represent the south-eastern continuation of the Renga breccias (Carminati et al., 2014 and references therein). These coarse massive breccias are widely exposed northwest of the Roveto valley (Fig. 2 in Carminati et al., 2014) with thickness > 200 m and their lateral southeastward continuation would overlap with the modeled sections G and 2 in Mancinelli et al. (2021).

Conclusions

The comment from Florio et al. (2022) proposed some discussion about the data, methods and results of the work by Mancinelli et al. (2021) suggesting that the model from Cella et al. (2021) would represent a "*reliable representation of the geological-structural setting of the Fucino basin*". We are here showing that these comments are based on the erroneous assumption that there is neither data nor literature supporting a Miocene flysch sequence beneath the Plio-Quaternary deposits. Therefore, the comments of Florio et al. (2022) do not seem to genuinely improve our knowledge about the Fucino basin and severely compromise the results proposed by Cella et al. (2021), which are based on the same erroneous assumption. Furthermore, Cella et al. (2021) modeled the same dataset as the one modeled in Mancinelli et al. (2021) but they assumed constant-density horizontal layers of the Plio-Quaternary infill, which has no geological evidence and is in obvious conflict with the tectono-sedimentary evolution of the basin as clearly documented by several previous geological and geophysical investigations.

The aim of our work was to present an interpretative scenario, in which the geological and structural evidence arising from the complex evolution of the Fucino basin would help to constrain the modeling of the observed intense gravity signature. We feel that we succeeded in achieving this goal and, if our model is correct, future geophysical and/or borehole data will confirm it.

On one point we fully agree with Florio et al. (2022): new deep borehole and/or high-resolution geophysical data are required to investigate the Miocene deposits beneath the Fucino basin and such data would help us to further constrain the spatial-temporal evolution of the Apennine belt-foredeep system.

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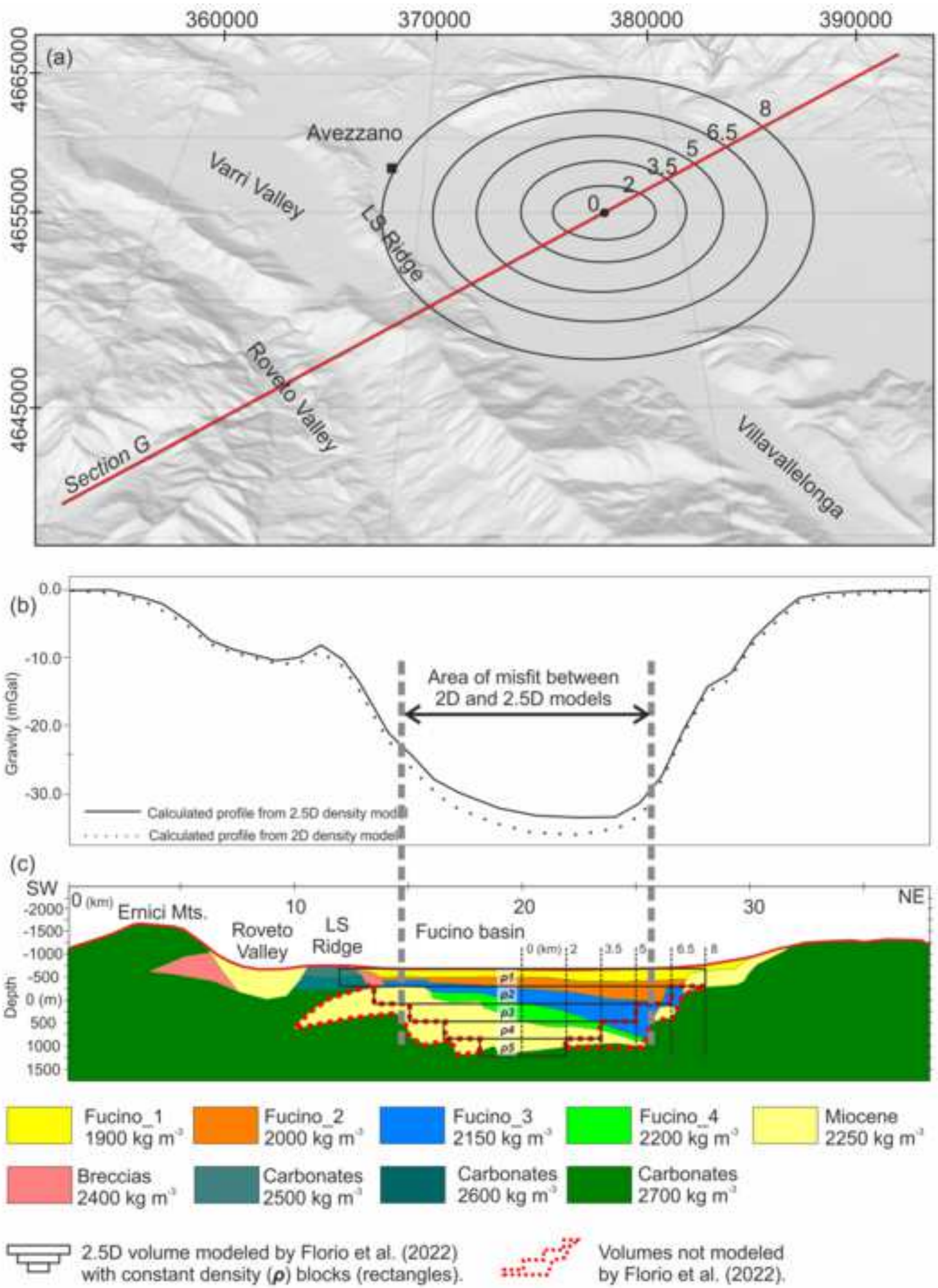

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: