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Reply to: Comment by A. Argnani on the paper: "The Strait of Messina: Seismotectonics and the source of the 1908 earthquake" (Earth-Science Reviews 218, 2021, 103,685)

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Reply to: Comment by A. Argnani on the paper: "The Strait of Messina: Seismotectonics and the source of the 1908 earthquake" (Earth-Science Reviews 218, 2021, 103685).

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Abstract

Argnani (2021, hereinafter ARG2021) commented on the paper by Barreca et al. (2021, hereinafter BRC2021) titled: "*The Strait of Messina: Seismotectonics and the source of the 1908 earthquake*", in which a new seismotectonic model and constraints on the possible source fault (the so-called W-Fault) for the 1908 disastrous seismic event were provided. Results from BRC2021 led to a revision of most of the previously published papers on the issue. ARG2021 commented both on the recent activity of the W-Fault and even about its existence in the offshore. In fact, according to the author's inferences: "*it may belong to a fault system that is no longer active*" and, contradictorily, "*the offshore occurrence of the W-Fault is not supported by the data"*. The comment is mostly based on a new tectonic interpretation that the author performed directly on the BRC2021 figures, where the offshore portion of the W-fault is illustrated. In this reply, we demonstrate that the interpretation provided by ARG2021 is affected by several oversights that led the author to erroneous conclusions about the issue. Accordingly, we strongly confirm both the occurrence of the W-Fault in the offshore and the present day activity of this structure, the only active fault capable of producing large earthquakes in the Strait of Messina area.

1. Introduction

We reply to the comment by Argnani (2021), which questions about the occurrence and/or the recent activity of the source proposed by our work (Barreca et al., 2021a, hereinafter BRC2021) for the 1908 earthquake (the so-called W-fault). The inferences of ARG2021 take advance from i) a new tectonic interpretation performed by the author directly on the BRC2021 figures, and ii) from a comparison between the high-resolution seismic data presented by BRC2021 with those previously published by Argnani (see Argnani et al, 2009). Following these points and other "*additional issues*", ARG2021 argues that results of BRC2021 are affected by "*severe uncertainties*" that leads the author to finally state: "*the offshore occurrence of the W-Fault is not supported by the data*" or "*it is not currently active and is likely sealed by late Pleistocene sediments*". Consequently, according to ARG2021, "*the geodynamic implications discussed by BRC* (namely Barreca et al.,2021a) *are speculative*". Likely the ARG2021 comment originates from the critical analysis we made in our original article regarding the previous results published by the author on the 1908 EQ and related tsunami (Argnani et al., 2009). In the latter contribution, the author identified a new active fault in the near-offshore of southern Calabria (i.e., the Southern Calabria Fault, SCF of Argnani et al., 2009) that was associated with the 1908 event. Contrary to what was affirmed by Argnani et al., (2009), we demonstrated that the SCF is instead a sub-horizontal geological boundary (see BRC2021, Fig. 3B-supplementary material), simply by removing the applied, but not declared by the authors, vertical exaggeration.

In the following, we'll demonstrate that the comment of ARG2021 is mostly based on an alternative, and from our perspective incorrect, tectonic interpretation performed by ARG2021 on the presented seismic dataset. The ARG2021 interpretation is in our opinion affected by several oversights, leading to a misinterpretation of our findings. In the following, we want to state, why we consider ARG2021 as obsolete and favour another interpretation of these findings. We revisit the outcomes of BRC2021 and confirm once again i) the occurrence of the W-fault in the offshore, ii) its very recent activity, and iii) its capability of generating large earthquakes in the Strait of Messina area.

2. On the issue 2 "*Seismic data: comparison with previous surveys*"

The comment of ARG2021 begins with a long comparison between our high-resolution seismic dataset and the dataset provided by the author in its previous paper (Argnani et al., 2009). ARG2021 wants to demonstrate that the previously published seismic dataset (i.e., the Taormina 2006 Survey, see Argnani et al., 2009) is equally suitable for resolving active tectonic problems in the Strait of Messina area. We agree that the Taormina 2006 seismic dataset has a deeper penetration but, in addition to the low-medium resolution, most of the lines are affected by strong seismic noise. From our own work, we see the challenges of acquiring and processing seismic lines in this setting, with rough and steep morphologies in a very narrow corridor for navigation. We assume that ARG2009 struggled with these effects during seismic acquisition and processing which resulted in not or only partly removable artefacts. Accordingly, the Taormina 2006 Survey seismic dataset can only allow providing a general overview of the seismo-stratigraphic architecture of the Strait of Messina, whereas the several active tectonic patterns remain unresolved. High-quality seismic datasets such us the one used by BRC2021, capable of illuminating the Quaternary section with greater resolution, are in fact necessary in offshore active tectonic studies. The acquisition and processing of the dataset presented by BRC2021 was especially designed to image the upper ~0.75 s TWT of the sedimentary succession and had not the aim to image deep structures. In this frame, putting the two seismic datasets on an equal level seems at least inappropriate.

3. On the new tectonic interpretation performed by ARG2021

ARG2021 performed a new tectonic interpretation over that provided by BRC2021 exploiting directly the figures published by BRC2021 as supplementary material (e.g., Fig. 5D of B2021). The new interpretation, which represents the core of the comment, allows the author to divide the BRC2021 profiles into two groups: "*a) profiles where there is a fault, which however does not seem to be currently active, and b) profiles where there is no evidence of a fault*". According to ARG2021 results, "*the imaged fault system* (i.e., the W-Fault) *is not active any longer and is unlikely to be related to the recent seismicity of the Messina Strait, including the 1908*", disclaiming, in this way, the main outcomes of BRC2021. In the following, we will demonstrate that ARG2021 interpretation is affected by several oversights. The Profile P204 (i.e., the Fig 5c and d of B2021) is chosen by ARG2021 as an example to illustrate the main problems affecting the BRC2021 interpretation. We would like to note that the new interpretation by ARG2021 is not providing any seismic facies analysis and seismic units' boundaries characterization (the Fig. 4 of BRC2021 for instance), which are essential steps to evaluate prior to a sophisticated tectonic interpretation.

Following his interpretation, ARG2021 rejected the location of the W-fault as traced by BRC2021. The reason for this is that "*the fault plane cut through continuous reflections*". The latter features have been visibly indicated by ARG2021 in its Fig. 2a (black arrow). However, in this figure the black arrow indicating the continuous reflection(s) points straights to a seafloor multiple reflection (clearly labelled with "m" in Fig. 5c of BRC2021), a very common artefact (noise) in seismic data acquisition, which was intentionally not removed from the dataset to generate misleading artefacts. Further, ARG2021 drew another fault plane (the orange dashed line in its Fig. 2a) a little bit NW of the W-Fault. We would like to clarify that the traced fault, which according to the author has its "*tip sealed by sub-horizontal strata*", is not a fault. This misinterpretation probably accounts from the fact that ARG2021 did not consider the clearly state vertical exaggeration (i.e., the Fig. 5c of BRC2021) of the seismic profile. Vertical exaggeration is a standard visualisation routine for high-resolution seismic data and has to be taken into account during interpretation and assessment of such lines. By removing the applied vertical exaggeration, the believed fault is actually a geological limit through which Pliocene-Lower Pleistocene sediments (RMT+MSL, see Fig. 4B of BRC2021) lie unconformably (with on-lap geometry) above SPN (Upper Tortonian), draping a previous contractional feature (see also Fig. 5a of B2021). In order to illustrate this in detail, a new figure (Fig. 1) is here provided to disprove all conjectures made by ARG2021 about the not correct tracing of the W-Fault, its existence, and its recent activity.

ARG2021 also argued that: "*the fault imaged in the profiles shown by BRC is the same previously reported by Argnani et al., (2009a)*". According to ARG2021, the supposed fault has a "*listric*" geometry (Fig. 3 of ARG2021), with *"the fault plane flattening at shallow depth*". Further, "*a middle-late Pleistocene succession is sealing the faulted sedimentary unit*". ARG2021 used a low-

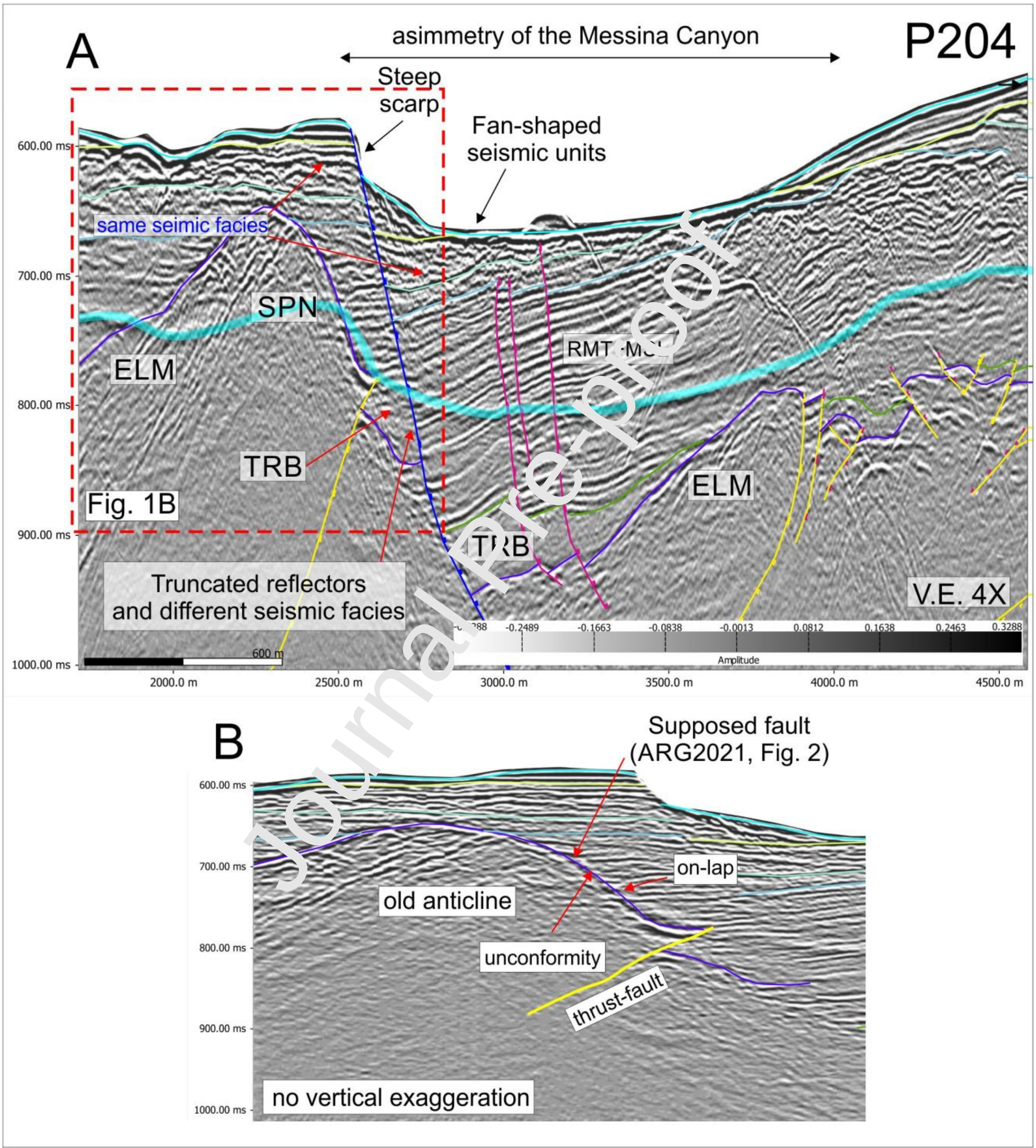


Fig. 1 - A) Original interpretation performed by BRC2021 over the P204 seismic line (in T.W.T.) showing the occurrence of the W-Fault displacing reflectors and juxtaposing different seismic units. Note also the tilting and the fan-shaped geometry of the youngest seismic units in the hanging-wall block of the W-Fault along with the asymmetry of the Messina canyon. The blue transparent line is the seafloor multiple (an artefact that reproduces the seafloor trend at a certain depth, see "m" in Fig. 5 d of BRC2021) that has been mistaken by ARG2021 for a "*continuous reflection*". B)

Zoom on the NW portion of the P204 line where vertical exaggeration has been disapplied. The new fault traced by ARG2021 (see the orange line in Fig. 2 of ARG2021) is instead an unconformity boundary through which RMT+MSL units (see Fig. 4b of BRC2021) mantle an older anticline.

resolution seismic line, the Tao 08, to support a different geometry and age for the W-Fault. However, by looking at the Tao 08 line (i.e., the Fig. 3 of ARG2021), we encountered serious difficulties to see a normal fault plane and other evidence for sealed "*faulted sedimentary unit"*, also considering the low-resolution of the seismic line in its upper part. The "*listric*" fault was probably imaged by ARG2021 (see also Argnani et al., 2009 and black arrows in Fig. 3 of ARG2021) following the Upper Pliocene-Lower Pleistocene grown strata to the East of the supposed normal fault plane. However, during that time, the region was still experiencing tectonic contraction (see Fig. 4 of BRC2021). Accordingly, it is more than likely that the grown strata have deposited syn-tectonically to folding and thrusting within associated piggy-back basins (see Fig.5a and b of BRC2021). On the other hand, also assuming the Tao 08 line with any vertical exaggeration applied, a normal fault with a dip-angle less than 20° appears quite unrealistic at the considered crustal level. Listric faults are generally steeper in the shallow part of the crust and flatten at depth approaching the brittle-ductile transition (thus not "*at shallow depth*"*).* A roll-over anticline is also expected to form in the hanging-wall block of faults with listric geometry. Summing up, ARG2021 did not consider the seismo-stratigraphic model available for the area (see Fig. 4B of BRC2021) and mistook the unconformity boundary between Pliocene sediments and older series with for extensional fault plane. To support what we have affirmed above, a new tectonic interpretation (Fig. 2), in line with the one proposed by Monaco et al. (1996), which is more consistent both with the reconstructed timing of deformation (see BRC2021) and the displaced reflectors, has been performed over the Tao 08 line (i.e., the Fig. 3 of ARG2021). A possible E-dipping acoustically blanked zone has also been identified right where the W-Fault was traced by BRC2021.

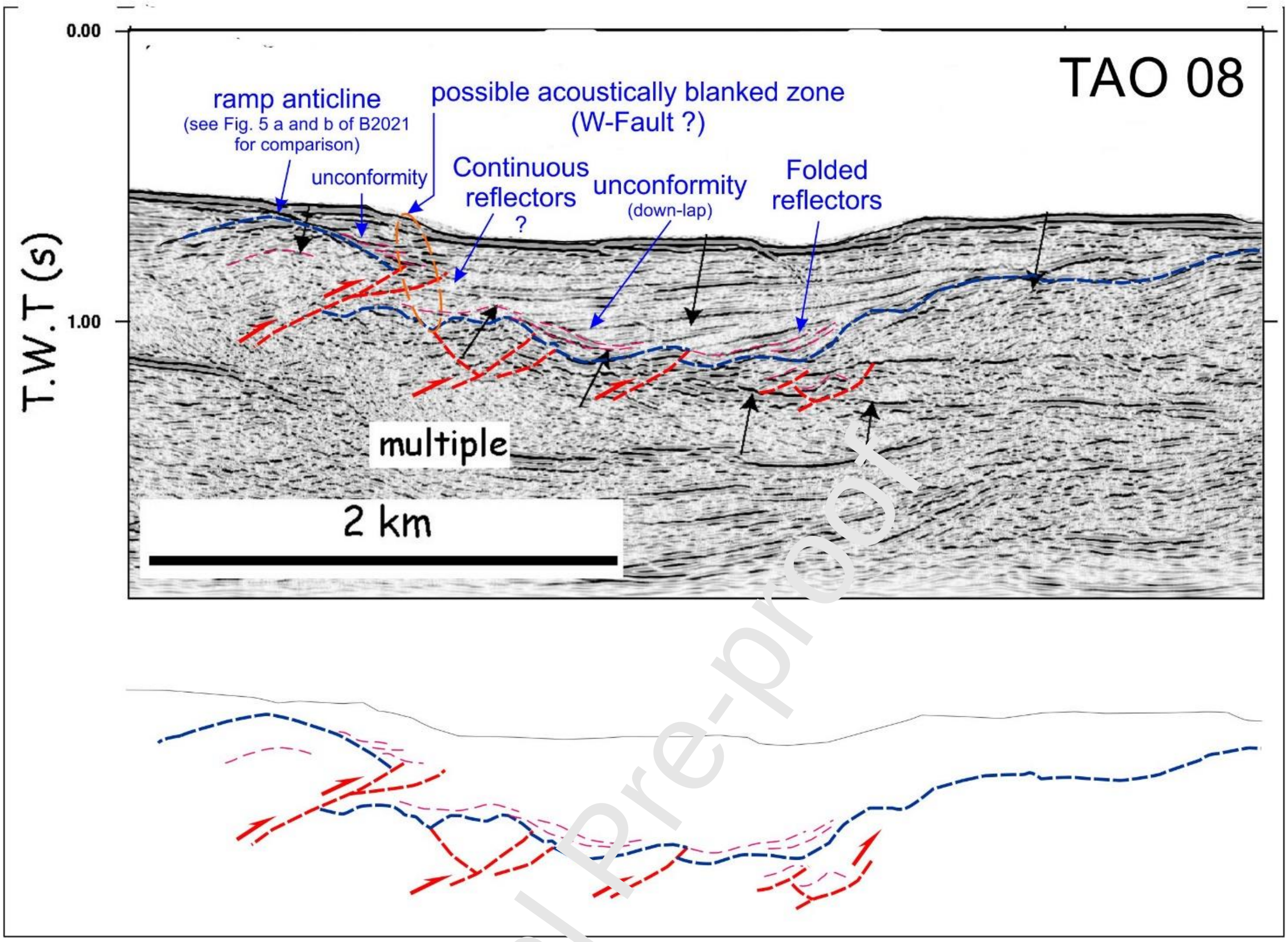


Fig. 2 – Tectonic interpretation performed over the Tao 08 seismic line of Argnani et al., (2009) following outcomes of BRC2021 on the tectono-stratigraphic setting of the Strait of Messina (see Section 3 of BRC2021). Also in this case, an unconformity boundary between Pliocene-lower Pleistocene (?) units and previous rock series (mostly evaporitic units – blue dashed line) was interpreted by ARG2021 as a Listric normal fault (see aligned black arrows).

3.1 on the issue "*Profiles with little evidence of a fault*"

ARG2021 claims that in seismic line P219 the W-Fault "*is traced without evidence of discontinuities in the reflection pattern*". Effectively, along the considered seismic line the W-fault is poorly imaged in the sub-seafloor since discontinuities in the reflection pattern are not sufficiently clear. Nevertheless, the W-fault was equally traced by following i) a series of diffraction hyperboles, which are typical artefacts produced by the occurrence of a fault plane, and ii) the displaced seismic units (Fig. 3a).

The other inferences of ARG2021 about the exclusive erosional origin ("*without a tectonic contribution*") of the steep scarps, which are observables where the W-fault reaches the seafloor are rejected as well. The marked asymmetry affecting the Messina canyon at several points (e.g., Fig. 1b, Fig. 5c and d, supplementary Fig. 2 a and c of BRC2021; Fig. 1 this reply) simply disproves any inferences about the lack of a tectonic contribution in the shaping of the steep scarps. It is also quite clear that the bases of the Messina and Reggio Calabria canyons are not at the same depth. As now evidenced in Fig. 3b, the base of Messina canyon is both tilted towards the W-Fault and about 40 m lower than the base of the Reggio Calabria canyon.

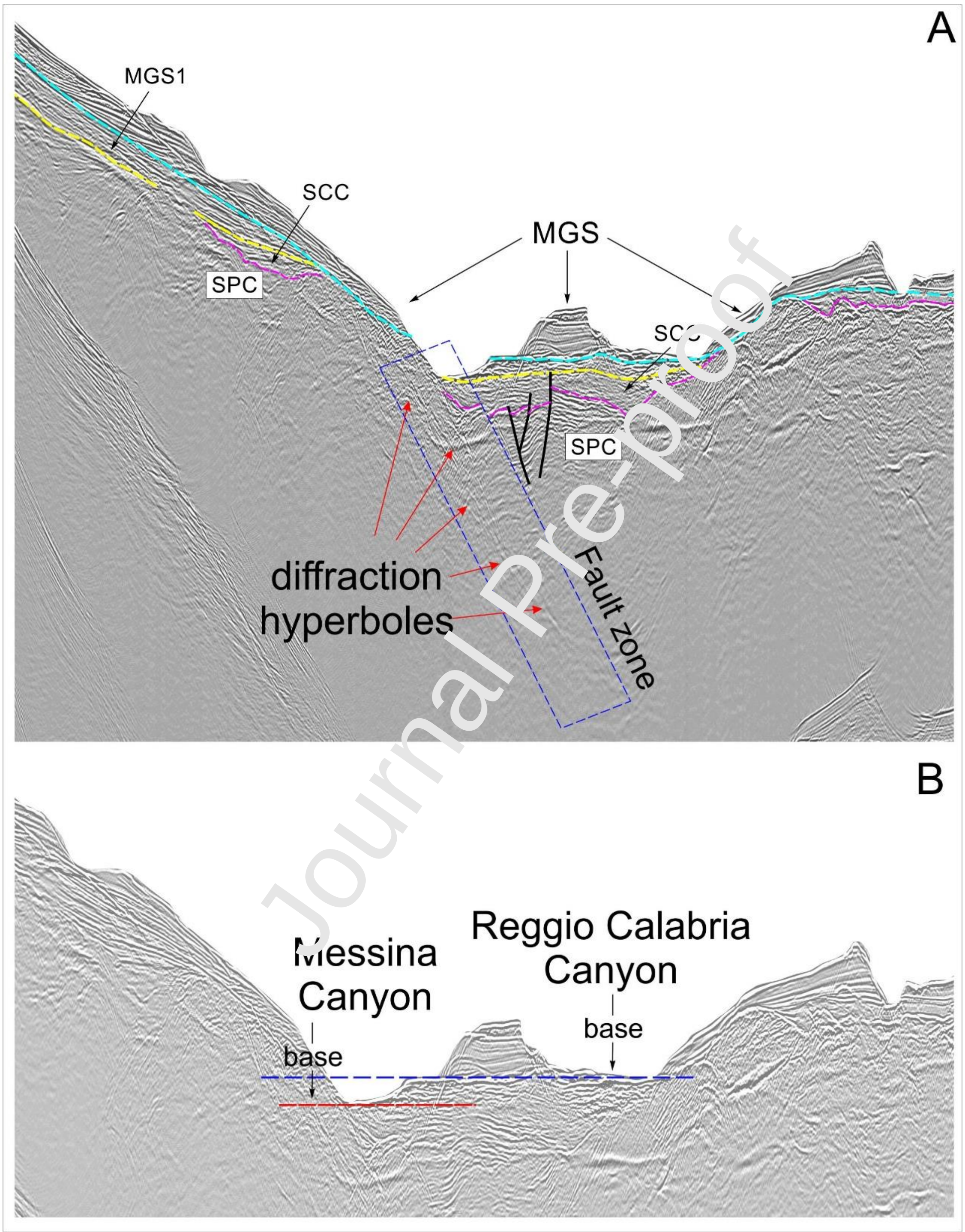


Fig. 3 – A) P219 seismic line (see Fig. 3a of BRC2021 for location) showing a series of diffraction hyperboles exploited by BRC2021 to trace the W-Fault. Note also the displaced youngest seismic units (refer to Fig. 4b of BRC2021 for the age of seismic units). B) Zoom on the P219 line showing the Messina and Reggio Calabria canyons. Note that, contrary to what was stated by ARG2021, the base of Messina canyon (red dashed line) is not at the same

level (about 40 m lower) of the base of Reggio Calabria Canyon (blue dashed line). Further, the tilting of the base of Messina canyon confirms both the location of the W-Fault on the P219 line and its very recent activity.

3.2 on the issue "*Profiles with orientation problems*"

Another major point of the ARG2021comment deals with the orientation of two seismic profiles, the p1007 and p217, that were released as supplementary material by BRC2021 (i.e., Fig. 1A suppl. and Fig. 2B suppl.). We did not notice that the two profiles and the traced fault plane were flipped out, a problem that probably occurred during the exporting and editing process. Obviously, this does not mean that the W-Fault was "*drawn with a dip opposite*" but, more simply, that the two figures are affected by a graphic error. We therefore provide a corrigendum where the two figures are counter-flipped (including the trace of fault) to their correct orientation (see Section 7).

4. On the issue concerning the "*The Southern Calabria fault*"

ARG2021 did not link directly the discovered SCF to the 1908 mainshock. However, the author uses the relocation of the 1908 EQ operated by Michelini et al. (2004), including an ellipse oriented almost parallel to the SCF, to support a significant role of the SCF in the active deformation pattern of the Strait of Messina (see Fig. 7 of Argnani et al, 2008). In fact, Argnani, et al., (2008, 2009) interpreted the SCF as a "*key tectonic feature within the Messina Straits"* and as a part of "*interconnected faults*", an interpretation that "*leaves the possibility to have more than a fault active at the same time to an event that has been inferred for the 1908 earthquake*". Thus, according to Argnani, et al., (2008; 2009), the SCF was activated in December 1908 and contributed to generate the devasting tsunami that inundated the area a few minutes later after the initial seismic event. However, BRC2021 demonstrated that the SCF is instead a geological boundary (see Supplementary Fig. 3b–c of BRC2021), and its associated seafloor fault-scarp (see Fig. 4 and 6 of Argnani et al., 2008) is probably the frontal portion of a submarine landslide (see also Ridente et al., 2014). ARG2021 tries to keep alive his previous outcomes on the Strait of Messina tectonics by asserting that: "*the flat portion of the supposed Messinian surface is not shown (Fig. 6A)* "and "*a seismic profile published by Argnani et al 2009a, that has a longer record length (deeper penetration), shows that the westward dipping surface continues below the Messina Strait cutting across reflection packages (Fig. 6B)*". We provide here a new figure (Fig. 4) to better show the "*supposed Messinian surface",* which was previously interpreted by ARG2021 (see Fig.4 and 6 of Argnani et al., 2008) as an active fault (i.e., the Southern Calabria fault, SCF). The new Fig. 4 also offers the opportunity to better evaluate the seismic facies "*between the trace of the fault and the* *base of the stratified upper succession*" (see Fig. 4 right-bottom). It clearly consists of a transparent and slightly-stratified (thus not "*chaotic*") seismic unit that, for its stratigraphic position and seismic characters, we interpreted as the Lower Pliocene Trubi Formation.

ARG2021 provides another seismic line, the Tao14 (Fig. 6 of ARG2021) to support the existence of the SCF. The line, with an unknown vertical exaggeration and, least of all, a suitable resolution, is close to our high-resolution P233 line (supplementary Fig. 3c of BRC2021 and Fig. 3a of BRC2021 for location). The latter line however does not show, in its eastern part, any evidence of the SCF "*cutting across reflection packages".* The strong reflection indicated by Argnani et al. (2008, 2009) as a "*fault plane*" instead shows an undulated morphology (see Fig. 6 of ARG2021) that typically resembles the eroded top-boundary of Messinian Evaporitic units (the ELM unit of BRC2021).

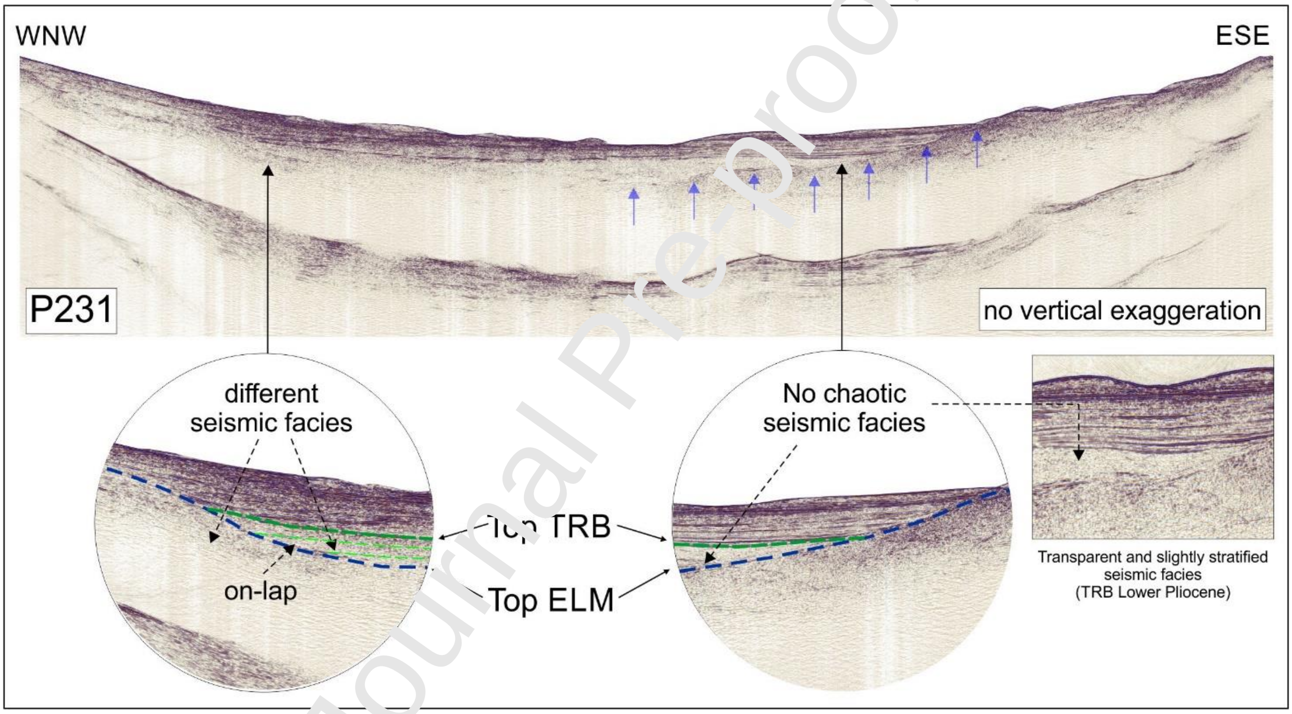


Fig. 4 – The P231 seismic line without vertical exaggeration applied. The blue arrows indicate the "*not shown*" (see Fig. 6 of ARG2021) flat portion of the "*supposed Messinian surface*". The geological boundary between ELM and TRB was previously interpreted as a fault plane, the SCF, by Argnani et al. (2008, 2009). The seismic facies "*between the trace of the fault and the base of the stratified upper succession*" is not chaotic facies (see bottom-right) but a transparent and slightly stratified seismic unit.

5. On the "additional issues"

ARG2021 also poses a question about the possibility of landslide triggering due to the W-Fault seismic shacking and Coulomb stress change. ARG2021 referred to a landslide previously reported by Billi et al. (2008), located about 30 km south of the southern tip of the W-Fault.

The question is already answered in the paper of Billi et al. (2008), where the authors modelled the Coulomb stress change using a seismogenic source that for location, extension, and dipping is very similar to the W-fault. Besides from the coulomb stress change, seismo-induced landslides are generally triggered by ground acceleration. In this context, it is worth nothing that an Intensity VIII-IX (see Baratta, 1910) was estimated for the region right where the landslide was reported (see Fig. 1b of Billi et al., 2008 and Fig. 2a of BRC2021). According to the relationships between macroseismic Intensity and Peak Groud Acceleration (PGA) (see David et al., 1999 among many others), an Intensity VIII-IX correspond to a PGA range of 340-1240 Gal or to a PGV (Peak Groud Velocity) between 31 and 115 cm/s. These data, together with the local geology and the slope gradient, are consistent with the triggering of landslide in the area. ARG2021 also argued that a mismatching occurs between the location of the triangular facets reported for the area (from Ridente et al. 2014), and the southern termination of the W-fault. Even if triangular facets mapped by Ridente et al. (2004) are a little bit south (about 1km) of the southern termination of the W- Fault (but anyway very close to the tip of an extensional fault, the locus where deformation concentrates), other morpho-bathymetric data (the M86-2 bathymetry, see Krastel et al., 2014) support the claim in BRC2021 showing triangular facets all along the trace of the W-Fault (Fig. 5 a and b). As regard the *"demonstrably"* erosional origin of the facets, Ridente et al., (2004) reported: "*the rectilinear segment of the axial Messina Canyon shows well developed flanks, steeper on the western (Sicilian) side where the closely spaced tributaries are suspended, and the interfluves are marked by triangular facet-like scarps*". This statement clearly indicates a tectonic control to the shaping of the western flank of the Messina Canyon, where the W-Fault has been traced by BRC2021. Following Argnani et al. (2009), Barreca et al. (2019) and results from BRC2021, we confirm that there is no evidence of the mapped Taormina (or MTF) fault. It is also the case to remark that in Aloisi et al. (2013), the Taormina fault was reported (with a dashed line and following literature data) only in introductive figures but never considered as a potential seismogenic source for the 1908 event.

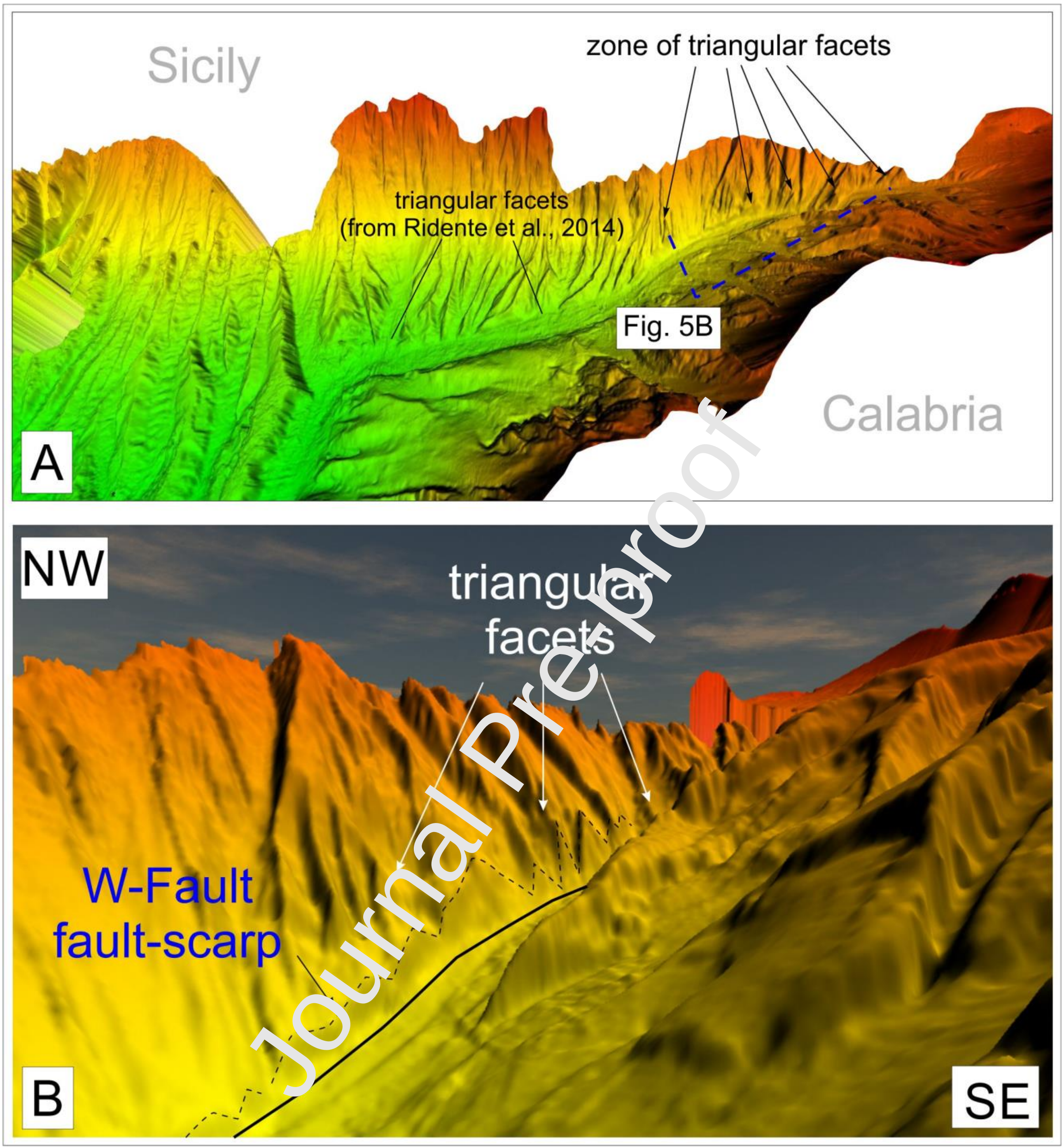


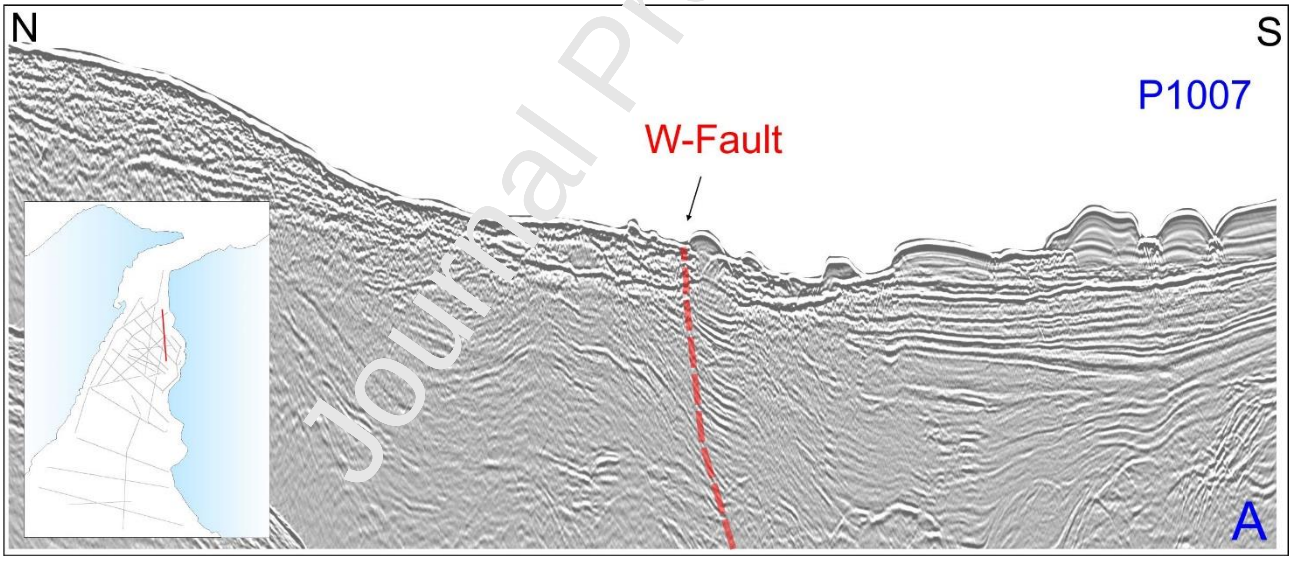
Fig. 5 – A) 3D view from SE of the seafloor morphology of the Strait of Messina (M86-2 bathymetric dataset, see Krastel et al., 2014) with indicated the reported triangular facets (see Ridente et al., 2014) a little bit south of the southern tip of the W-Fault. B) Zoomed view (V.E. 5X) of the central-northern part of the W-Fault displaying, also in this sector, the occurrence of triangular facets on the hanging-wall block.

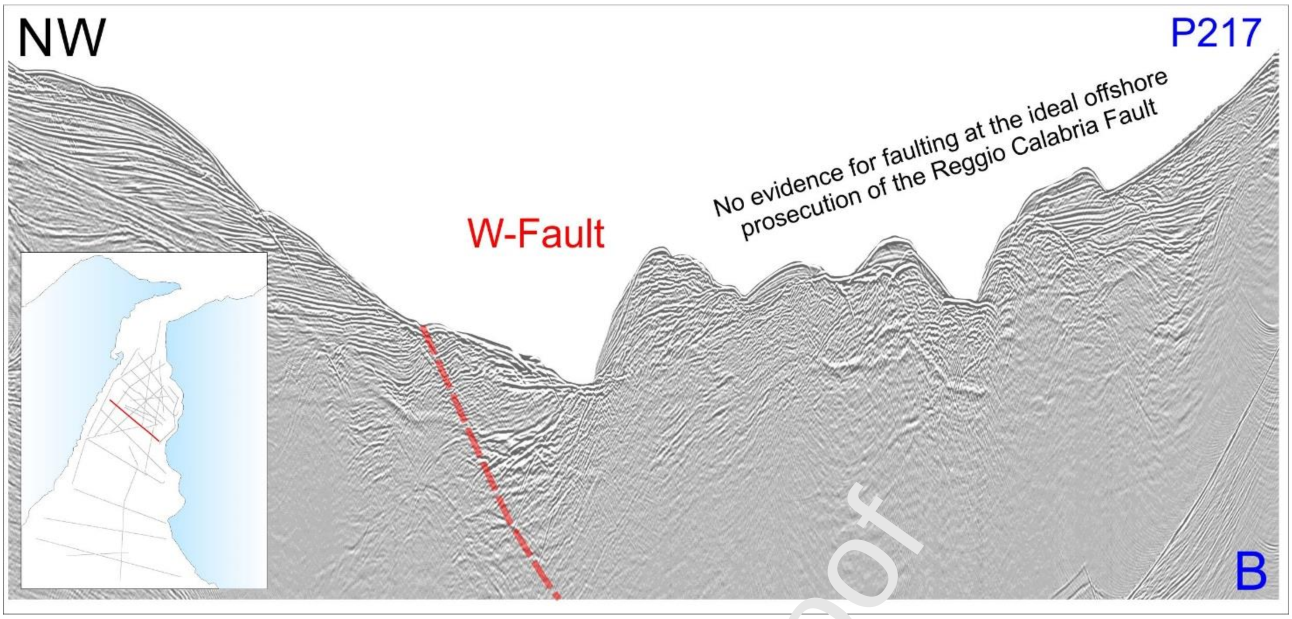
6. Conclusions

We would like to thank ARG2021 for giving us a further opportunity to provide additional pieces of evidence in supporting the outcomes provided in BRC2021. As we demonstrated, the comment of ARG2021 is based on a new tectonic interpretation that is affected by several oversights and supported by medium to low-resolution seismic lines, which do not show the details imaged by our high-resolution profiles. We are aware that an interpretation performed over figures (i.e., with no optimal resolution) and not on the original seismic data is difficult. ARG2021 does not provide any incontrovertible evidence to disprove our previous results or, at least, valid arguments to stimulate the discussion on the issue. Accordingly, we rebut point-by-point the speculative criticisms of ARG2021 confirming both the occurrence of the W-Fault in the offshore realm of the Strait of Messina and its current activity. Coming back to the rationale that pushed ARG2021 to write the comment (i.e., the Section 1 of ARG2021), the author recalled some previously discussed critical points such us the "*poorly evident downward cut-off of seismicity, or the assumption of long-term pre-earthquake creep along the low-angle discontinuity*". We suggest the author to have a read on the reply (Barreca et al., 2021b) we provided to the comment of Pino et al., (2021).

Corrigendum

We provide a corrigendum regarding two figures (supplementary Fig.1a and 2b of BRC2021) that resulted counter-flipped (see Section 3.2 this reply).





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

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