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OPINION
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Response: Commentary: Deformation Pattern of the Northern Sector of the Malta Escarpment (Offshore SE Sicily, Italy): Fault Dimension, Slip Prediction, and Seismotectonic Implications

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INTRODUCTION

Argnani (2021) provides a commentary (hereafter ARGN) on our paper titled: "Deformation Pattern of the Northern Sector of the Malta Escarpment: Fault Dimension, Slip Prediction, and Seismotectonic Implications," which was published in the journal Frontiers in Earth Science in January 2021 (Gambino et al., 2021, hereafter GAMB). Through the interpretation of eight new seismic profiles (six of which are reported in Supplementary Figure S1 of GAMB) crossing the Malta Escarpment, GAMB pointed to a better definition of the geometry of three active faults (F1, F2, F3) and their seismic potential by employing slip tendency modeling and forward analysis. The results suggest that F3 is prone to be reactivated under the achieved stress field and has the capacity of generating M > 7 earthquakes. ARGN raises concerns about the higher resolution and less penetration of the eight newly acquired high-resolution multichannel reflection seismic profiles and the seismic-stratigraphic pattern proposed by GAMB. According to ARGN, "the seismic profiles analyzed by GAMB belong to different sets and have very different seismic characters and resolution, making seismic facies correlation pretty difficult, also because no tie lines are available. As a result, stratigraphic correlations are highly speculative and the ensuing uncertainties undermine the timing of the tectonic evolution envisaged by GAMB, as well as the age and rate of activity of tectonic structures." Furthermore, ARGN argues on the hypothesis of an early large-scale slope instability affecting the area. Most of the statements of ARGN seem to be based on his available older multichannel reflection seismic profiles, which have, indeed, a higher penetration but less resolution. We also agree that high-resolution digital multichannel seismic profiles are not easily comparable with low-resolution multichannel seismic lines, but we see the clear advantage of a state-of-the-art technology to image the upper strata of sedimentary systems. The used system proved its robustness in many different settings worldwide and has been successfully used for many pre-site surveys for drilling campaigns for the IODP and ICDP. As a result, we rebut point-by-point ARGN's comments and stand by our model on the active deformation pattern and seismotectonics of the northern sector of the Malta Escarpment.

On the Issue "Stratigraphy: The Aftermath of Uncertainties"

ARGN claims that GAMB provided a "highly speculative" seismic-stratigraphic interpretation since "The seismic profiles analyzed by GAMB belong to different sets and have very different seismic characters and resolution." We would like to clarify that ten high-resolution seismic lines (two from CIRCEE-HR and eight from the unpublished POS496 dataset, see Figure 2 and Supplementary Figure S1 of GAMB) with a comparable resolution were exploited by GAMB to achieve the proposed seismic-stratigraphic model. In addition, ARGN's statement "no tie lines are available" is unfounded since a tie line (P701, see Figure 2 of GAMB), crossing transversally most of the E-W trending seismic lines, was interpreted to correlate laterally (N-S direction) the various units recognized in the GAMB seismic dataset (CIRCEE-HR and POS496). The other published lines (Argnani and Bonazzi, 2005, 2012; Polonia et al., 2016, 2017) were only considered to constrain fault geometry at depth, since a comprehensive seismic facies characterization along them is problematic considering their lower resolution. In the absence of deep drilling data from the sediment package, only a basic lithological and chronological interpretation of the detected seismic units may be supplied as stated by GAMB (see *Seismic Stratigraphy*).

Concerning the correlation between PQ1 and PQ2 units of GAMB with units PQb and PQa of Camerlenghi et al. (2020), considered speculative by ARGN, we reply that the age attribution of PQ1 and PQ2 was primarily based on their stratigraphic position and seismic characters; subsequently, we made a comparison with the seismic and stratigraphic features shown by Camerlenghi et al. (2019) and by Micallef et al. (2018) for the PQa–PQb units and "unit one," respectively. The PQ2 unit of GAMB shows quite similar seismic character (e.g., amplitude, frequency, and lateral continuity) and stratigraphic position to the PQa unit of Camerlenghi et al. (2019). Furthermore, both PQ2 and PQa are bounded at the bottom by an erosive surface (see Figure 4G of GAMB and Figures 2, 4 of Camerlenghi et al., 2019). All these aspects enabled us to consider the two units (PQ2 and PQa) as comparable, a standard method in seismic interpretation. It is also clear that the Panchina Formation outcropping on land and the PQ2 unit are only currently "physically disconnected" since major active faults occur in-between. We interpreted the PQ2 unit as the distal part of the Panchina Formation also considering the submarine canyons excavated in the MESC slope (Micallef et al. (2019), Figure 1C of GAMB), which may have contributed to sediment supply from the uplifted footwall-block of the Malta Escarpment. In addition, even considering an eventual physical mismatching between the two units (i.e., the Panchina Fm. and the PQ2 unit), this aspect would not disprove the interpreted age of the PQ2 unit and the consequent estimate of deformation rates.

Another critical point raised by ARGN on this issue concerns the age attribution to PQ2 on the base of drill core (DSDP Site 374, Hsü et al., 1978). We are aware that the core at DSDP Site 374 is away from the studied sector but anyhow located within the same foreland basin (i.e., the Ionian abyssal plain out of the Calabrian accretionary wedge, see Gutscher et al. (2016) where the PQ2 unit was deposited. The same core DSDP Site 374 has been recently exploited by Rebesco et al. (2021) to constrain the age (~ 500 kyr) of the same sediment package (i.e., the PQ2 unit) at the base of the Malta Escarpment. As regards the speculations that ARGN attribute to GAMB about the correlation of far away seismic units, we would like to underline that, in Argnani and Bonazzi (2005), the age of the Trubi Formation (Zanclean) in the Western Ionian Basin was assigned on the basis of a seismic facies correlation with a unit found in the Gela Nappe (Argnani, 1987), more than 120 km to the west and in a quite different structural domain. So, the authors agree with us that high-distance correlation of seismic/stratigraphic units is possible if a reflector with good lateral continuity can be followed.

Furthermore, according to ARGN, the "most critical issue" affecting GAMB outcomes is the attribution of the MES unit to the Messinian sequence. In this regard, ARGN states "the seismic facies do not resemble the typical Messinian units" or "often the top surface lacks a high reflectivity." We reject this inference since from our point of view the MES top-reflector is quite evident in most of the analyzed seismic dataset (see Supplementary Figure S1 of GAMB, for instance). Attribution of the MES unit to the Messinian sequence was based not only on its seismic character, which locally could appear as less reflective (probably due to the attenuation of the seismic signal with depth), but also mainly on its stratigraphic position (see Figure 3D 1-2-3-4 of GAMB) immediately below the semitransparent PQ1a sub-unit (Zanclean-Trubi Formation, see also Butler et al., 2015). The local "lacking high-reflectivity top surface" is not surprising if we consider the available literature on the issue (e.g., Lofi et al. (2011) and references therein). Moreover, the MES internal stratigraphic pattern (three internal sub-units) along the seismic lines presented by GAMB shows strong similarities to the Messinian subdivision provided by previously published papers concerning the seismic stratigraphy of the Western Ionian Basin (see Camerlenghi et al., 2020; Butler et al., 2015, among many others).

Finally, ARGN states that "the growth strata to the west of the fold (see Figure 4G of GAMB) could well be of Quaternary age" and that the interpretation provided by Argnani and Bonazzi (2005) is to be preferred. However, in Argnani and Bonazzi (2005), several speculations are provided about the age of the considered sediment package. The authors assert the following on the issue: "direct dating [. . .] is not available," "sediments correlate pretty well with the facies of Plio-Quaternary," "we can therefore constraint, conservatively, the timing of deposition [. . .] within the late Pliocene- Quaternary." They conclude the following: "more likely the majority of the sediments deposited during the Quaternary," without providing any evidence for this.

On the Issue "Fault Parameters and Seismotectonic Implications: To What Extent Can We Stretch the Data?"

According to ARGN "impression," GAMB does not adopt a hierarchical approach in correlating the interpreted faults. Even if it is not clear to which kind of correlation ARGN refers (e.g., along-strike or along depth), we would like to point out that a hierarchical approach was instead followed by GAMB. Accordingly, sentences such as "the simultaneous activity observed with the fault displacement analysis leads to interpret such faults (i.e., the F1, F2, and F3 fault-structures) as merging down-dip into a single tectonic structure" or "detected faults should be therefore thought as low hierarchical-order splay structures through which the strain accumulated by the deeper and larger tectonic structure is partitioned at a shallow crustal level" (see *Discussion* on page 15 of GAMB) show our consideration on fault hierarchy. The F2 fault has been well constrained all along the GAMB high-resolution seismic dataset (CIRCEE-HR and POS496) and following its clear bathymetric expression (see Figures 4B,F of GAMB). Effectively, along the MESC-09 profile of Argnani and Bonazzi (2002, 2005), the F2 fault is not detectable, but this is simply due to the lower resolution of this line. Not by chance, GAMB does not report any data about F2 displacement in correspondence with the MESC09 profile (see the graph of Figure 5B in GAMB). ARGN also claims that GAMB does not provide a vertical scale in Figures 7, 8. The depth to which the faults have been projected is reported in Table 1 of GAMB and was estimated following the max depth that can be appreciated along the MESC seismic dataset of Argnani and Bonazzi (2005). For clarity, an indication of the projected depth of the faults is also reported in the pressure–depth graphs of Figure 8 of GAMB (right panels), where the horizontal violet line represents the mean depth of the fault plane to which stress load is applied.

ARGN is concerned about the GAMB outcomes addressing the 1693 earthquakes, sustaining that they were already stated by Argnani and Bonazzi (2005). Apart from the fact that other authors had previously proposed the same solution (see Bianca et al. (1999) and references therein), we are aware of this, and accordingly, Argnani and Bonazzi (2005) have been properly quoted by GAMB. However, about the 1693 issue, Argnani and Bonazzi (2005) use the findings by Piatanesi and Tinti (1998) to assert that the Western fault has "the same trend" of the fault matching the tsunami numerical modeling. In addition, GAMB faces the open question left by Argnani and Bonazzi (2005) (i.e., "the seismogenic potential of the structural architecture outlined with this new survey is still to be worked out") by redefining the geometry of faults (i.e., length, depth), and estimating their seismic potential by forwarding methods. These aspects have never been treated before in the study area. Even considering the expected uncertainties in the stratigraphic framework due to the lack of deep drilling data in the area, the throw analysis is an important step in evaluating fault segmentation, a significant parameter in seismotectonic studies and particularly in the estimation of the maximum expected magnitude.

On the Issue "Inferred Tectonic Evolution: Is Complication Really Necessary?"

According to ARGN, GAMB "propose a rather complicated tectonic evolution of the Malta Escarpment." From our perspective, the two-stage tectonic evolution proposed by GAMB for the area appears not so complicated and is data-driven. ARGN rejected GAMB hypothesis of a deep-seated gravitational deformation affecting the area during the Pliocene. This hypothesis was simply based on the late-Miocene–Pliocene grown strata west of the folded structural culmination (Figure 4G of GAMB) when the deformation front of the Calabrian accretionary wedge was located far away (> 100 km) to the NW. This latter aspect rules out that the observed folding was produced by the accretionary processes as proposed by Argnani et al. (2002) and Argnani and Bonazzi (2005). Thus, excluding contraction at the front of the accretionary wedge, GAMB inferred a deep-seated gravitational deformation affecting the area during the considered time interval. The topic was intentionally not faced by GAMB, and accordingly, it remained only a hypothesis since a flat decollement level connecting extensional and reverse structures is difficult to observe. Nonetheless, the inferred gravity process has strong similarities to the formation of the so-called DW-FTS (deep water fold and thrust system), widespread all over the world, mainly along passive margins (see Figure 1 of Morley et al., 2011). Furthermore, the GAMB hypothesis was partly inspired by the tectonic setting of the area imaged by Argnani et al. (2002), where main extensional faults are represented as changing their trajectory at a depth approaching the boundary (a decollement level?) between carbonate and the overlying younger units. This latter interpretation (supporting the GAMB hypothesis) was later abandoned by Argnani and Bonazzi (2005), where instead the same faults are imaged to cut through the carbonate layer (Figure 1C of ARGN, lower panel), even if the carbonate top-reflector appears not displaced by the westernmost fault (see Figure 4 of Argnani et al., 2002). ARGN compares this last interpretation (Figure 1C of ARGN, lower panel) with very simple sketch models concerning gravity sliding and gravity spreading processes (as proposed by Morley et al., 2011) to reject the GAMB hypothesis. Although any scaling factor is provided, ARGN sustains that both gravity deformation mechanisms (never mentioned by GAMB) have no application for the studied sector for the following reasons: 1) "The overall geometry observed in seismic profile CIR-01 (GAMB, Figure 4A) does not fit with a gravity sliding, as the stratal geometry depicts a basin over the translational sector, where there should be no subsidence," 2) "Gravity spreading is also unlikely because of the lack of a large sedimentary load and of a basal mobile unit (salt or overpressured shale) in the Mesozoic succession," and 3) "mobility of Messinian salt can be ruled out, as seismic facies recalling salt are not present in this part of the Malta Escarpment."

About the first comment on the gravity sliding model, ARGN claims that a basin over the translational domain cannot develop since "there should be no subsidence." However, by looking at Figure 1C of ARGN (upper panel), subsiding basins are, on the contrary, expected to form both above the left part of the translational domain (i.e., close to the normal fault) and above its right sector (i.e., to the left of the compressional toe), where subsidence should be maintained by the growth of adjacent compressional features. We would also like to point out the strong similarity between the listric normal fault geometry shown in Figure 1C of ARGN and those traced along the MESC09 line (Figure 3 of Argnani et al., 2002). Substantially, ARGN argues on the issue using a simplistic, stationary, and maybe out-of-water model, as dynamic and sedimentation over time are not considered. In other words, moving forward with time the provided model (i.e., Figure 1C of ARGN, upper panel), and rightly considering deformation and sedimentation through time, more accommodation space is expected at the hanging wall of normal faults and to the left of the compressional toe, with the consequent formation of a continuous and variable thickness basin all over the translational domain. The final sedimentary and tectonic pattern should not have a dissimilar geometry with respect to that shown in Figure 4A of GAMB.

About the second comment on the gravity spreading model, ARGN states that "large sedimentary load and a basal mobile unit (salt or overpressured shale) in the Mesozoic succession" are lacking. We do not see why ARGN refers to Mesozoic succession neglecting to consider the Cenozoic series and why ARGN excluded the presence of salt or overpressured shale in the invoked sediment section (Mesozoic). The "large sedimentary load" expected by ARGN for mobilizing mobile units is not supported by any literature known to us. For instance, by studying salt deformation buried by pulse of progradational sediments (i.e., a setting like that studied by GAMB), Rojo et al. (2020) demonstrated that migration of salt can occur also for thin sediment wedges. A higher thickness of the sediment wedge would eventually affect the velocity of the mechanism (i.e., the mechanism would be faster when the sediment wedge is thicker and vice versa). Furthermore, Peel (2014) stated that spreading is linked to depositional pulse by analyzing the contribution of spreading vs gliding in gravity-driven sliding mechanisms. The available literature on the issue (the gravity spreading model) stands in contrast to ARGN. 2D sequential restoration analysis performed on the CIR-01 and P607 profiles (see Gambino et al., 2022) revealed that, in the early stage of deformation (i.e., from MES to PQ1b, see Figure 7B of Gambino et al., 2022), the extension component of deformation measured on the faults (F1, F2, and F3 of GAMB) prevails over the vertical one. This evidence supports the notion that the Messinian–lower Pliocene diffuse extensional strain was controlled by spreading of ductile layers in the Messinian unit.

The statement by ARGN that salt layers lack close to the Malta Escarpment is entirely in contrast to the previous literature. Salt deposits have been found elsewhere in the various sectors of the Western Ionian Basin (Lofi et al., 2007, 2011; Valenti, 2010; Mocnik et al., 2013; Camerlenghi et al., 2020) as well as close to the MESC slope (Butler et al., 2015; Micallef et al., 2018, 2019). It is worth noting that, along the P202 line of the GAMB dataset (see Supplementary Figure S1D of GAMB), the recognized transparent and chaotic seismic facies forming a diapiric body is consistent with a salt deposit.

Finally, we would like to underline that ARGN does not mention the mixed gravity gliding/spreading model presented in Figure 6C of Morley et al. (2011) that appear to fit better with the Pliocene tectonic and sedimentary pattern provided by GAMB.

CONCLUSIONS

ARGN stated his concerns on some parts of GAMB on the active deformation pattern and seismotectonics of the Malta Escarpment's northern region. We clearly see the need to interpret high-resolution multichannel seismics in a more sophisticated way than lower resolution data. The result of such interpretation will always be more complex as it is an important role in earth sciences that scaling down makes everything more complicated. Many structures, invisible on lower resolution data, are hence a matter of concern for the interpreter of high-resolution data. If we want to understand complex systems, we must use these state-of-the-art technologies to challenge and prove available hypotheses on earth's processes.

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GB and SG: response writing, conceptualization,review of the literature data, FG, SK, M-AG: critical reading of the manuscript. CM: review of the literature data, critical reading of the manuscript.

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