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Article

Generation of the Quaternary Normal Faults in the Messina Strait (Italy)

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Abstract: It is widely recognized that since the Early–Middle Pleistocene, the Messina zone, the site of strong earthquakes, has undergone extension, but the geodynamic context which determined this deformation is still a matter of debate. This work suggests that such a tectonic event was caused by the interaction of northern Calabria with the continental Adriatic domain. The suture of that consuming boundary produced major changes in the microplate mosaic and the related kinematic pattern in the Southern Italian zones, which was triggered by the activation of the Sibari and Vulcano faults. In the new context, the Peloritani belt sector, dragged by the Hyblean block, rotated clockwise and then moved northward, causing its divergence from southern Calabria. The normal faults which have accommodated that separation may be the main seismogenic source in the Messina Strait.

Keywords: Messina Strait; seismic source; Quaternary evolution; tectonic setting; central Mediterranean

1. Introduction

Since the Messina Strait could become the site of a long bridge between Sicily and Calabria, recognizing the location and geometry of the main seismic sources in that area may be particularly useful. Several attempts to get this information have been made by studying the effects of the last two main earthquakes which affected the area, one in the northern Messina trough (M = 6.2) on 6 February 1783 (e.g., [1]) and one in the Messina sphenocasm (M = 7.1) on 28 December 1908 [2–15]. Some of the fault models indicated by the above authors for the most studied event, the 1908 shock, are shown in Figure 1. The variety of the proposed solutions testifies to the poor constraining power of the evidence now available, mostly represented by coseismic effects, with particular regard to levelling data from 1907 to 1909 [16]. The most striking ambiguity is given by the fact that the set of proposed solutions involves both onshore and offshore fault locations. Such difference mostly derives from the choice of considering or not the capable faults identified by morphological and geological observations (Figure 2, e.g., [13,17–20]). To mitigate the above uncertainty, it would be necessary to identify further possible constraints. In this work, we approach this problem by trying to recognize the geodynamic context that generated the normal faults in the Messina area. Since several hypotheses have been advanced about that problem, involving the gravitational sinking of the Ionian slab [21–24], deep-seated asthenosphere processes [25,26], extrusion processes [27–29] or other tectonic mechanisms (e.g., [20,30]), we report some remarks on how the implications of the proposed geodynamic models can account for the observed deformation pattern in the study area. To increase the constraining power of this analysis we have imposed that the tectonic context that determined the Pleistocene evolution of the study area was compatible with the processes that controlled the Pliocene deformation pattern in the central Mediterranean area.

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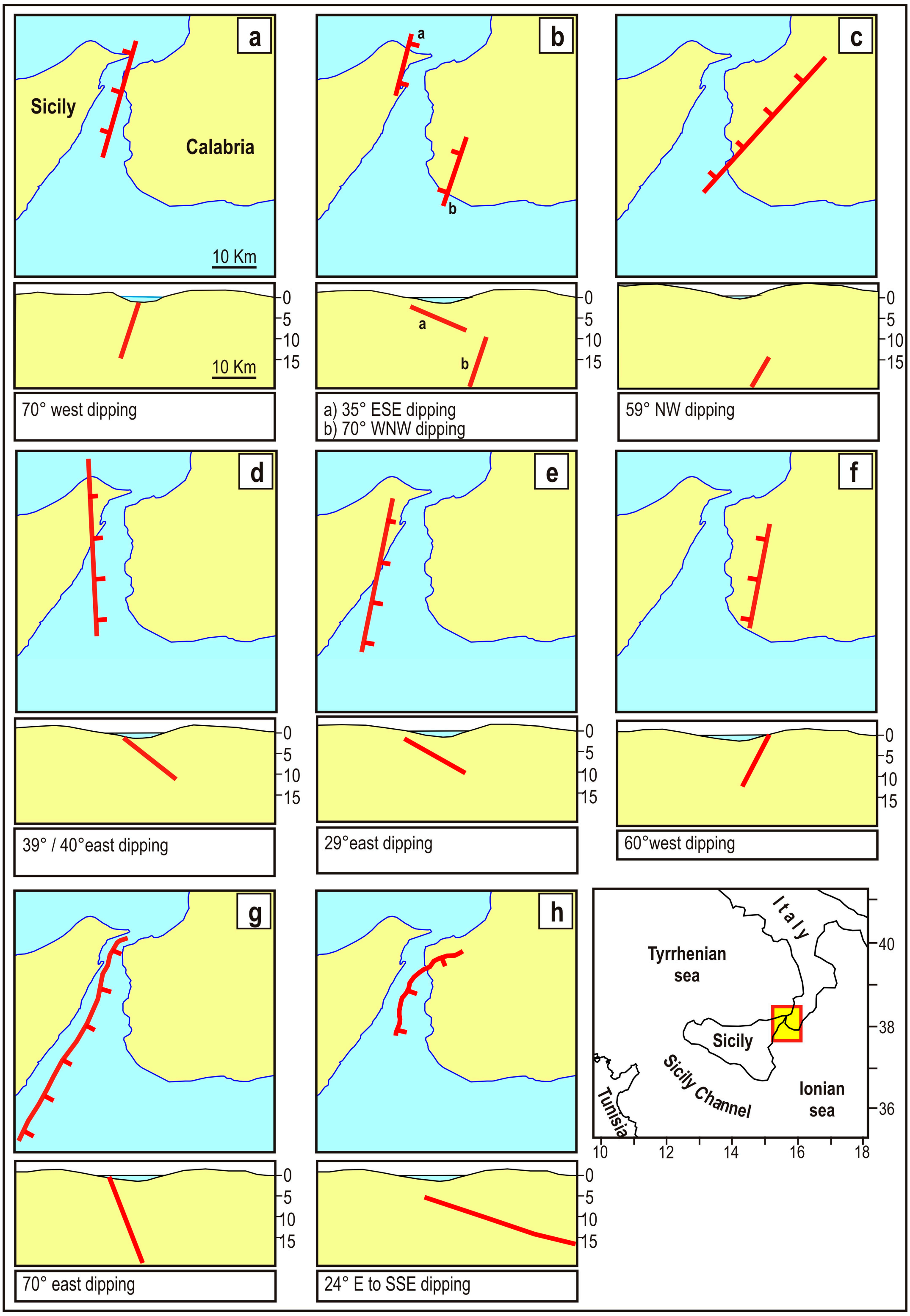

Figure 1. Fault locations (red lines) and cross sections, with related deep fault geometries, adopted in the previous literature ((**a**) [2]; (**b**) [3]; (**c**) [4]; (**d**) [5,7,10]; (**e**) [6,8,12]; (**f**) [11]; (**g**) [13]; (**h**) [14]) to model the geodetic levelling dataset [16] carried out before and after the 1908 earthquake ([13,14] and references therein). The location of the area here considered is shown in the last picture (yellow box).

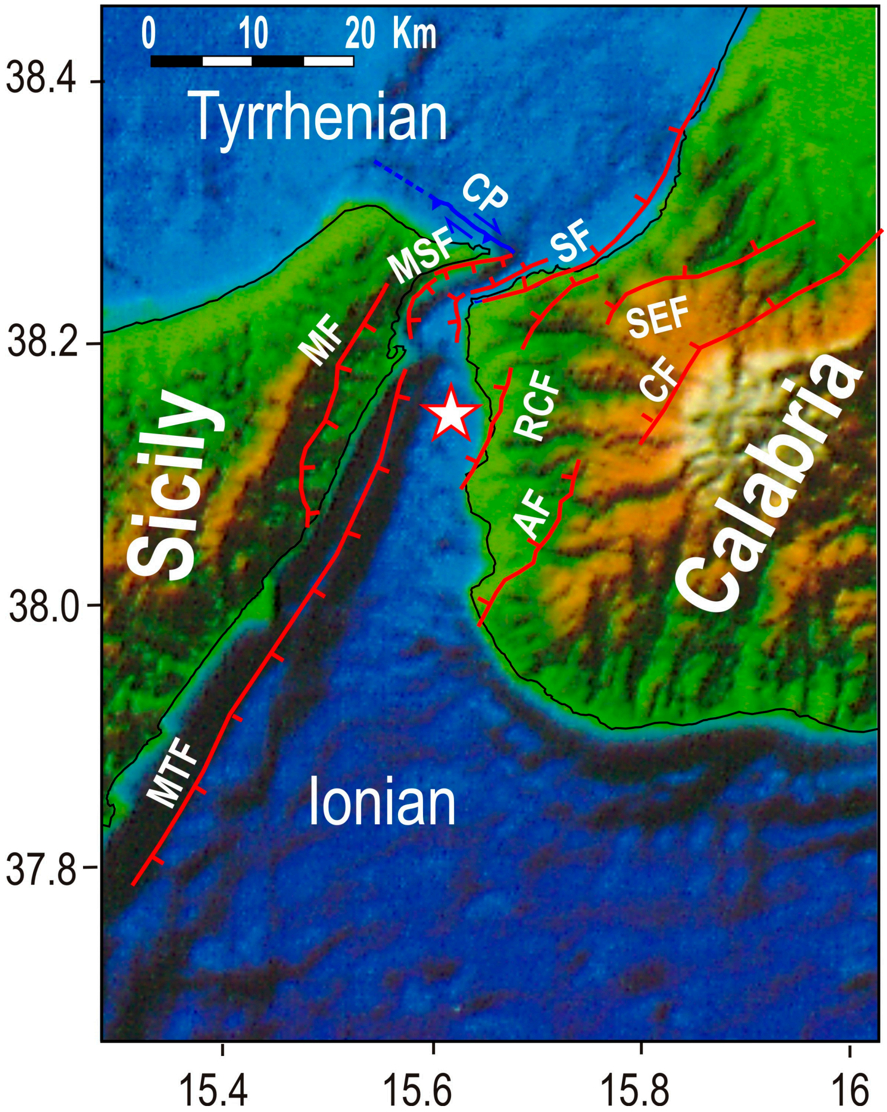

Figure 2. Quaternary normal faults (red lines) in the Messina Strait and surroundings indicated by geological and morphological evidence (e.g., [20,31–33]. AF = Armo fault; CF = Cittanova fault; CP = Capo Peloro fault; MF = Messina fault; MTF = Messina–Taormina fault; MSF = Messina Strait fault; RCF = Reggio Calabria fault; SEF = Sant'Eufemia fault; SF = Scilla fault. The star indicates the epicentre of the 1908 earthquake.

2. Pliocene

The Neogene evolution of the Mediterranean region has been driven by two main kinematic boundary conditions: the Nubia–Eurasia convergence and the westward escape of Anatolia (induced by the Arabia indentation [34–37]. Until the Late Miocene–Early Pliocene, the evolution of the central Mediterranean area was scarcely influenced by the escape of Anatolia since the convergence between these two major systems was mainly accommodated by the consumption of the interposed thinned zone (Pindos, [28,29,38–40]). The tectonic context changed considerably since the Early Pliocene when the Aegean system (Hellenides) collided with the Adriatic foreland. After the consequent suture of this consuming boundary, the westward push of the Anatolian–Aegean–Pelagonian system (AAPS) caused the decoupling of a large part of the Adriatic promontory (Adria plate) from Nubia, by the activation of a major fracture, constituted by the Victor Hensen–Medina–Sicily Channel fault systems. Once decoupled, this plate underwent a clockwise rotation accompanied by a NNW ward motion (Figure 3B, [27–29,41]).

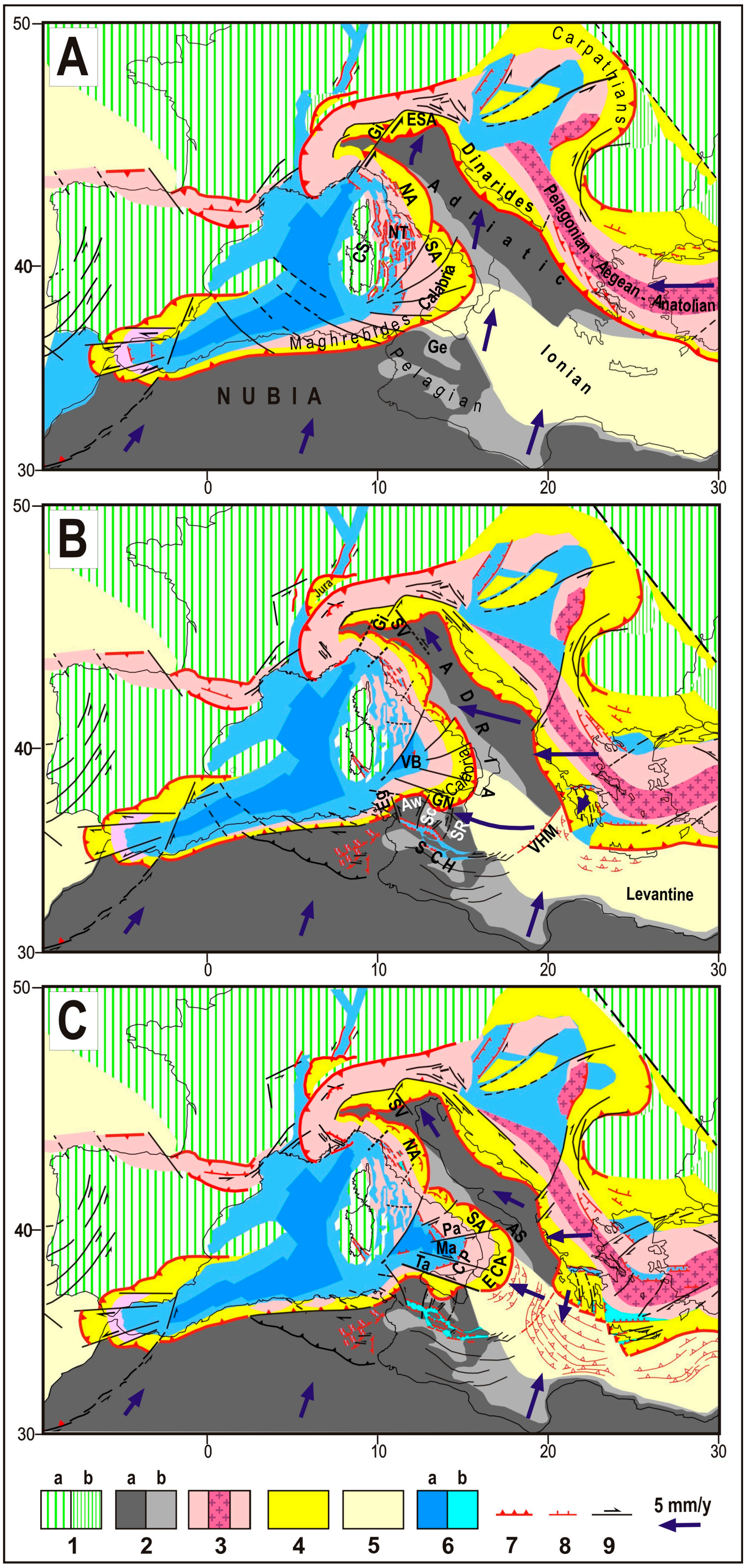

Figure 3. (**A**) Tectonic configuration of the study area in the Late Miocene–Early Pliocene, after the formation of the Northern Tyrrhenian basin. Ge = Gela basin; NA, SA = Northern and Southern Apennines. (**B**) Middle Pliocene. After the collision of the Anatolian–Aegean–Pelagonian system (AAPS) with the continental Adriatic domain, a large part of the Adriatic promontory (Adria plate) decoupled from Nubia by the activation of the Victor Hensen–Medina (VHM) and Sicily Channel (SCH)

fault system. Once decoupled, the Adria plate underwent clockwise rotation and minor NW to NNW ward motion. The consequent convergence between the Adria plate and Northwestern Nubia was accommodated by major E-W shortening in the Pelagian zone, as well as in the Alpine–Maghrebian belt. Aw = Adventure wedge; Eg = Egadi fault; GN = Gela nappe; Sc = Sciacca fault; SR = Scicli–Ragusa fault; SV = Schio–Vicenza fault; VB = Vavilov basin (Central Tyrrhenian). (**C**) Early Pleistocene. After the collision of the Southern Apennine extruding wedge with the Apulian swell (AS), accretionary activity along the outer Calabrian front formed the External Calabrian accretionary belt (ECA), while crustal extension developed in the wake of the migrating Arc, forming the Marsili basin (Ma). In this strong compressional context, the Calabria–Peloritani (CP) wedge underwent fast uplift and bowing. Pa = Palinuro fault, Ta = Taormina fault. (1) Continental (a) and thinned continental; (b) Eurasian domains. (2) Continental (a) and thinned continental; (b) African/Adriatic domains. (3) Tethyan belt (AAPS). (4) Other orogenic belts. (5) Old oceanic domains. (6) Zones affected by intense (a) or moderate (b) crustal thinning (7–9). Compressional, extensional and strike-slip tectonic features. Blue arrows indicate the kinematic pattern with respect to Europe [42,43].

This evolutionary phase involved a considerable change in the tectonic setting in the southern part of the central Mediterranean area, as shown in greater detail in Figure 4.

The roughly E-W convergence between the southernmost Adria plate and Northwestern Nubia (Tunisia) induced strong compression in the Pelagian–Hyblean domain, which was accommodated by some major shortening processes [27–29,44–49]. A major one was the roughly northward escape of the Adventure wedge, guided by the Sciacca and Egadi lateral faults (Figure 4B). The extension that developed in the wake of this extruding wedge formed the Pantelleria trough, while the compressional deformation that occurred along the front of the wedge was accommodated by thrusting and northward bending/displacement of the adjacent Alpine–Maghrebian belt (Figure 5). Such deformation caused the interaction of the Maghrebian belt with the Corsica–Sardinia block [28,29]. This hypothesis can explain why during that evolutionary phase (Lower-middle Pliocene to the Pleistocene) tectonic activity affected the southwestern edge of the Corsica–Sardinia block, with the formation of the Campidano trough (e.g., [50–52]). An alternative explanation of that event can hardly be found, since the Corsica–Sardinia block did not experience any other interaction with the surrounding structures after the Middle Miocene [53–55].

Another major effect of the convergence between the Adria plate and northern Nubia was the consumption of the inner thinned part of the Hyblean domain (Gela basin, Figure 3A), which was accommodated by two opposite processes. One was the southward oroclinal bending of the Sicilian Apennines (Gela nappe) and the other resulted from the northward displacement of the fragments (Empedocle, Girgenti, Linosa, Malta, Selinunte, Urialo in Figure 4A) generated by the breaking of a narrow Hyblean plateau. The extension that developed in the wake of the escaping fragments generated the Linosa and Malta troughs (Figure 4B, [28,29]).

The present shape of the Kabylides–Calabrides and Maghrebides–Apennines belts, determined by the northward escape of the Adventure–Hyblean wedge, and other main tectonic features in the Pelagian–Hyblean domain are shown in Figure 5. The proposed interpretation, involving the lateral escape of the Adventure wedge and the consequent deformation of the Maghrebian belt, can account for a peculiar aspect of the Central Mediterranean tectonic setting, i.e., the fact that the Maghrebian belt lying in front of the Adventure wedge is the only sector of the peri-Tyrrhenian belts that moved towards the Corsica–Sardinia block, while all the other belt sectors (Calabrian Arc and Apennines) moved away from Corsica–Sardinia.

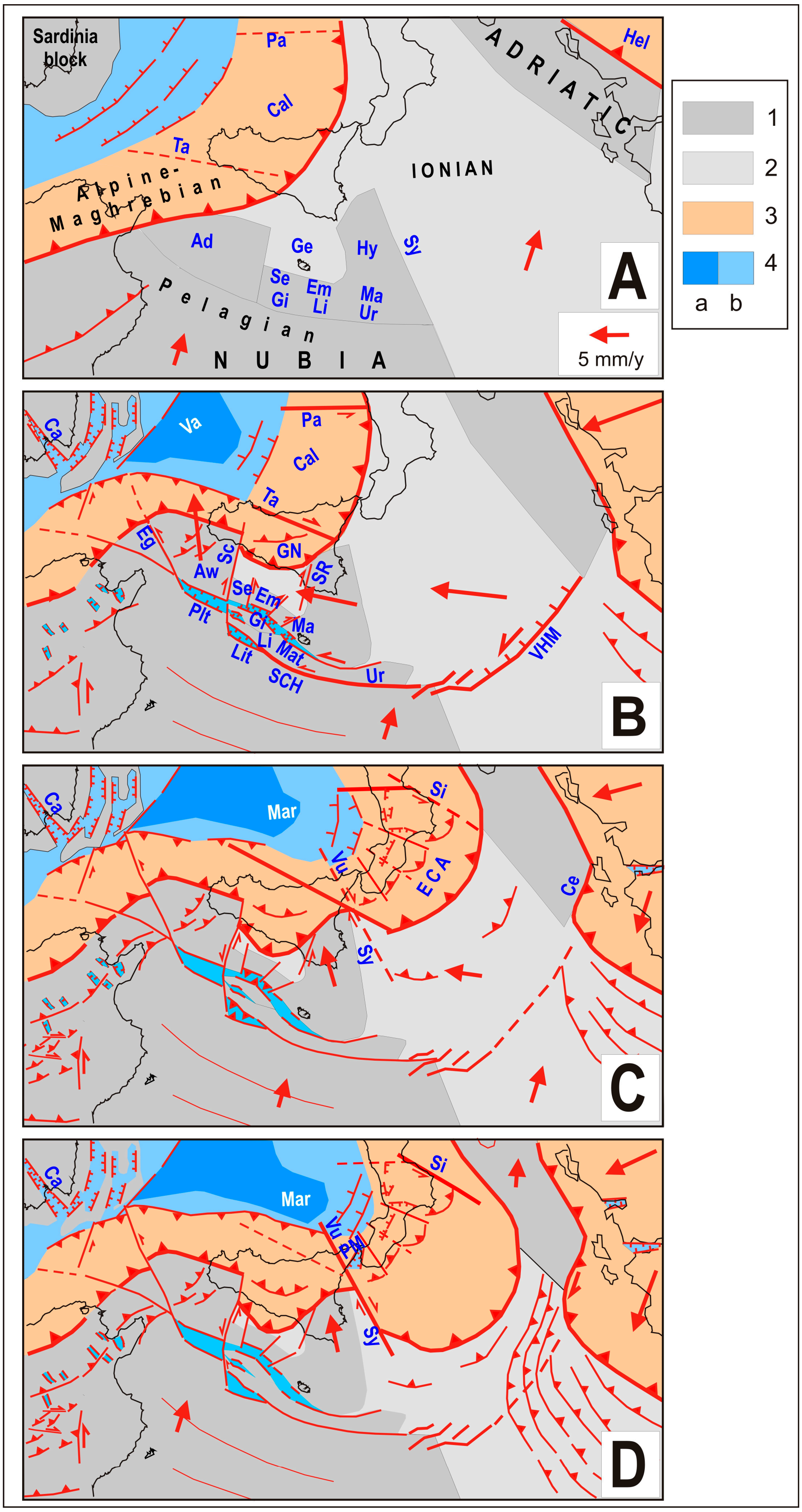

Figure 4. Evolutionary reconstruction of the Hyblean–Pelagian domain and the adjacent Alpine–Maghrebian belt, as effect of the convergence between the Adria plate and northwestern Nubia. (1) Continental domains. (2) Thinned continental and oceanic domains. (3) Orogenic belts. (4) Zones of intense (a) or moderate (b) crustal thinning. (**A**) Late Miocene. Initial configuration of

the study area. Cal = Calabrian wedge; Ad, Em, Gi, Hy, Li, Ma, Se, Ur = Empedocle–Girgenti–Linosa–Malta–Selinunte–Urialo original parts of the Hyblean plateau; Ge = Gela basin (thinned Hyblean domain); Hel = Hellenides; Pa = Palinuro fault, Sy = Syracuse escarpment, Ta = Taormina fault. (**B**) Middle-upper Pliocene. Aw = Adventure wedge, Ca = Campidano graben, Eg = Egadi fault, GN = oroclinal Gela Nappe; Lit, Mat, Plt = Linosa, Malta and Pantelleria troughs; SCH = Sicily channel fault, Sc = Sciacca fault; SR= Scicli–Ragusa fault; Va = Vavilov basin; VHM = Victor Hensen–Medina fault (**C**) Late Pliocene-Early Pleistocene. The suture of the Southern Apennines consuming boundary accelerated the lateral escape of the Calabrian wedge, triggering the formation of the Marsili basin (Mar) and the External Calabrian Arc (ECA), Ce = Cefalonia fault, (**D**) Middle Pleistocene-Present. The collision of the northern Calabrian wedge with the Adriatic foreland triggered the formation of the Sibari (Si) and Vulcano (Vu) faults. The geometries and locations of the Hyblean plateau fragments have been taken from [56]. PM = Peloritani microplate. Other symbols as in Figure 3. More details about the Pleistocene evolution are reported in Figures 6 and 7.

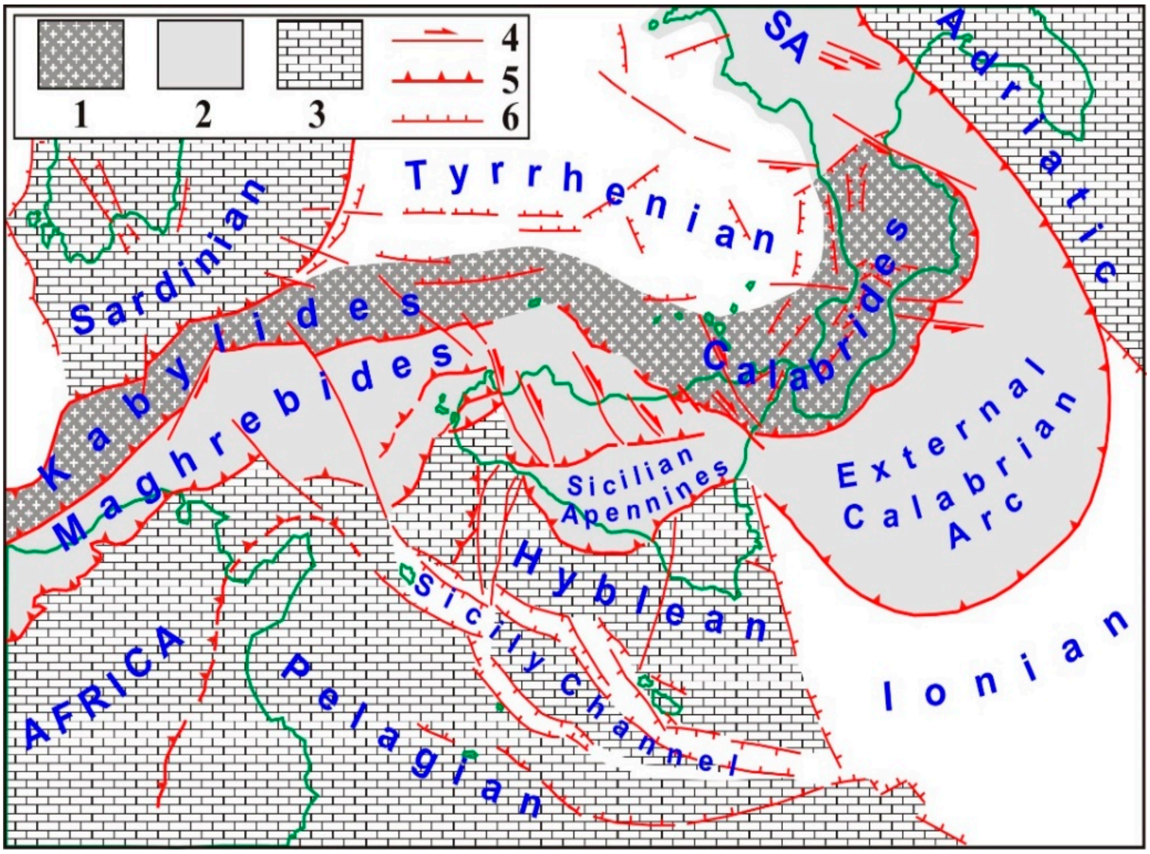

Figure 5. Present tectonic setting in the study area. Kabylides–Calabrides (1) and Maghrebides–Apennines (2) belts (modified after [46,57,58]); (3) foreland domains, (4–6) strike-slip, compressional and tensional features. SA = Southern Apennines. The fact that the Kabylides–Calabrides and Maghrebides–Apennines belts, deformed by the escape of the Adventure wedge have reached the Corsica–Sardinia block may explain why this last structure underwent tectonic activity in the Pliocene.

3. Early Pleistocene–Present

Another major reorganization of the tectonic pattern occurred around the Early–Middle Pleistocene when the lateral escape of the Calabrian wedge reached the Adriatic foreland (Figure 4d). After this continental collision, the extrusion trend of that wedge had to change, to favour the consumption of the remaining Ionian thinned domain (e.g., [28,29]). This deviation was allowed by the activation of two new lateral guides, the Sibari and Vulcano faults (Figure 6b, e.g., [18,20,59–64]), which replaced the previous guides (Taormina and Palinuro faults). The formation of the Vulcano fault also had major effects on the kinematics of the Hyblean block, which accelerated and moved with a greater northward component. Initially, the dextral transpression at the Vulcano fault did not allow a complete decoupling between the Hyblean block and the Peloritani belt sector (PM = Peloritani microplate). As a consequence, this microplate, partially dragged by the Hyblean block, rotated clockwise with a minor northward component, so diverging from southern Calabria (Figures 4, 6a and 7). This reconstruction can account for the generation of faults in the Messina sphenocasm (MF, MTF, RCF and AF faults in Figure 2) and then of the northern trough (MSF and SF faults in Figure 2). The supposed northward motion of PM can also explain the occurrence, since the Early–Middle Pleistocene, of compressional deformation along the outer front of this microplate, as indicated by the development of the Capo Peloro transpressional fault (Figure 2, e.g., [20]). Moreover, in the same period, a NE-trending anticline grew up a few km north of the Messina strait [20]. This structural high is considered by some authors [65] as the submarine prolongation of an uplifting area (1.1 mm/y) in PM. It is noteworthy that this anticline developed in the southernmost sector of the internal Calabrian arc, which was previously characterized by extension. This evidence and the formation of ridges characterized by high uplift rates [65] clearly reveal that such a zone underwent an inversion of strain regime since the Middle Pleistocene. The Quaternary compressional deformation observed in the Maghrebian belt lying offshore northern Sicily (e.g., [46,66–71]) is compatible with the supposed roughly northward motion of the Hyblean block (Figure 6). The important decoupling role that is still played by the Syracuse fault is testified by the occurrence of strong historical earthquakes offshore eastern Sicily (e.g., the 1169 M = 6.5 and 1693 M = 7.3 shocks) [72].

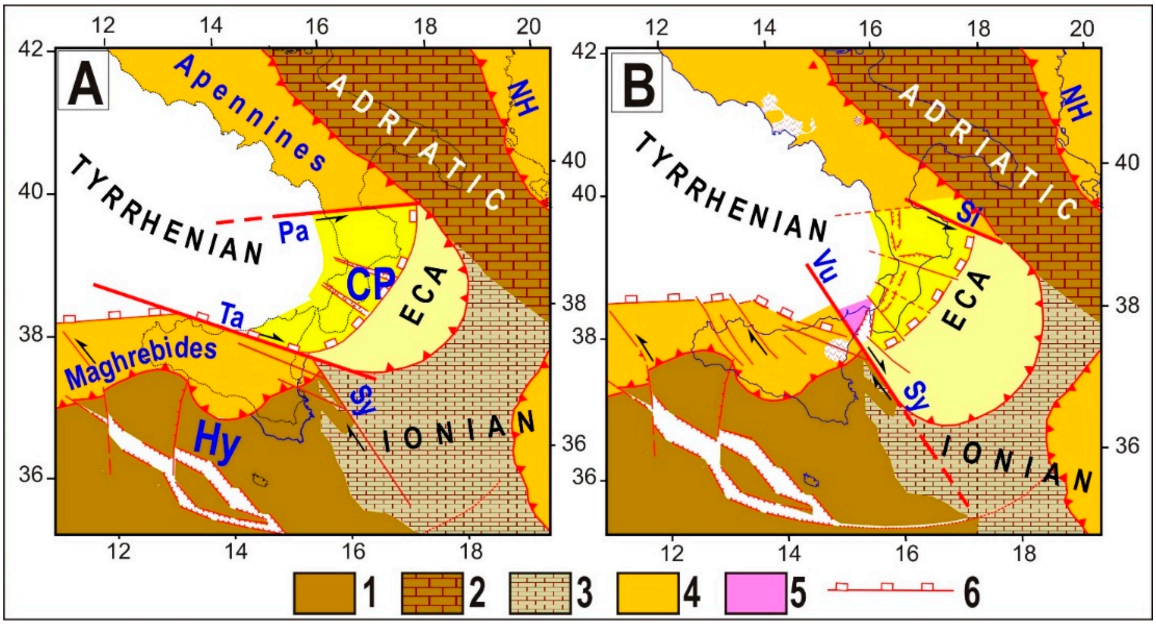

Figure 6. Tectonic sketch of the Calabria–Peloritani (CP) and Hyblean (Hy) wedges before (**A**) and after (**B**) the collision of Northern Calabria with the Adriatic continental domain. (1) Nubian continental domain; (2) Adriatic continental domain; (3) Ionian oceanic domain; (4) Orogenic belts (5); Peloritani microplate (6). Outer fronts of the Alpine belt. (**A**) Early-Middle Pleistocene. The lateral escape of the CP wedge is guided by the Taormina (Ta) and Palinuro (Pa) faults. ECA = External Calabrian Arc; NH = Northern Hellenides; Sy = Siracuse fault; Pe = Peloritani. (**B**) Post Middle Pleistocene. The extrusion trend of the CP wedge changed significantly by the activation of two new lateral guides (Sibari (Si) and Vulcano (Vu) faults (e.g., [18,46,56])).

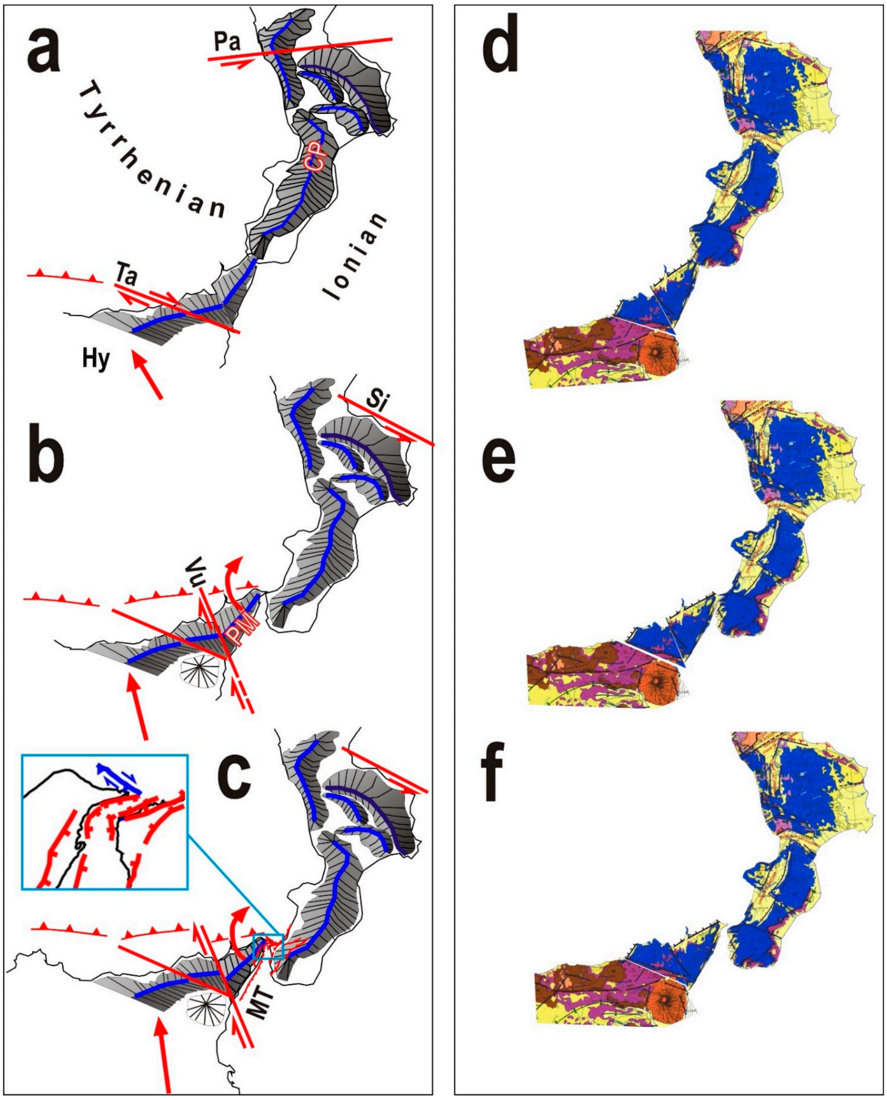

Figure 7. Tentative reconstruction of the microplate kinematics and tectonic setting which led to the formation of the Messina trough (MT). (**a**) Late Pliocene. The Calabria–Peloritani wedge (CP) extrudes laterally, guided by the Palinuro (Pa) and Taormina (Ta) faults at the expense of the Ionian domain. Hy = Hyblean domain. (**b**) Early-Middle Pleistocene. After the activation of the Vulcano (Vu) and Sibari (Si) faults, the extrusion trend of CP changes, while Hy accelerates, moving with a greater northward component. PM = Peloritani microplate. (**c**) Late Pleistocene-Present. Stressed by the transpressional interaction with Hy, PM undergoes clockwise rotation and then a minor northward motion. The consequent divergence of this microplate from Southern Calabria generates normal faults in the Messina zone (Figure 2). The present tectonic setting shown in (**f**) is taken from the Tectonic Map of Italy [73]. Using the same Map, the location of that tectonic setting is tentatively reconstructed for the previous evolutionary phases (**d**,**e**).

4. Discussion

This work describes the Plio–Quaternary tectonic evolution of the central Mediterranean region that in our opinion can best account for the Pleistocene occurrence of extension in the Messina Strait. Since various alternative geodynamic interpretations have been so far proposed for this region, it may be useful to explain why the solution proposed here can be preferred to the hypotheses previously advanced.

The interpretation most cited in the literature (under the name of the slab-pull model, e.g., [44–47]) suggests that a primary role in the Plio–Quaternary evolution of the central Mediterranean was played by the gravitational sinking of the Ionian slab, which determined the migration of the Calabrian Arc and the opening of the Tyrrhenian basin. The main difficulties in reconciling the implications of this driving force with the available evidence are discussed in various papers (e.g., [27–29,41,43,74]). Here, we report further considerations about some major tectonic features that can impose important constraints on the geodynamic context.

The fast uplift that since the middle Pleistocene, the Calabrian Arc has undergone (more than 1200 m, with an increasing rate, e.g., [31,75–79]) cannot easily be reconciled with the implications of the slab-pull model that are predicted by modellings, with particular regard to the occurrence of major subsidence in the migrating arc (e.g., [80–84]).

An important piece of evidence that can help us to identify the driving force of the Calabrian wedge is provided by the cross-section shown in Figure 8A, which shows a vertical bending of crustal layers in the Calabrian Arc. This peculiar deformation, indicated by upward and downward displacements, testifies to the very strong horizontal compression that such a structure must have undergone during the development of the Tyrrhenian–Calabrian arc-trench-back arc system. Such shortening is clearly incompatible with the horizontal extension of the migrating arc that is expected from the slab-pull driving force [80,81,83,84]. In our opinion, the above major features should discourage any attempt to invoke the slab-pull mechanism as the driving force of the Calabrian evolution.

It is widely recognized that the northern Tyrrhenian basin developed from the Tortonian to the late Miocene, the central Tyrrhenian (Vavilov basin) from the Early Pliocene to the Late Pliocene and the southernmost Tyrrhenian (Marsili basin) since Pleistocene (e.g., [56,85–89]). Explaining this peculiar space–time evolution of that basin as an effect of slab sinking must face many difficulties, as discussed in some papers [27–29,41,74]. In particular, one should explain why the gravitational sinking of the subducted lithosphere first developed in the northern Tyrrhenian sector, despite that during such period (upper Miocene) the underlying slab was more developed in the southernmost sector of the migrating arc.

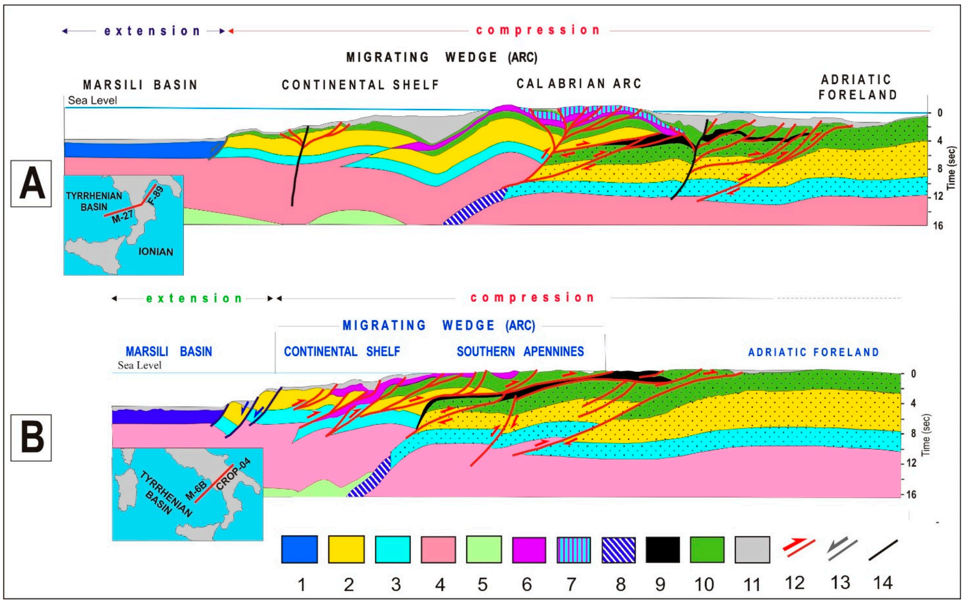

Figure 8. Cross sections from the southernmost Tyrrhenian to the Adriatic foreland, through Northern Calabria (**A**) and the Southern Apennines (**B**), modified after [90,91]. (1) Oceanic crust; (2) upper continental crust; (3) lower continental crust; (4) lithospheric mantle; (5) asthenospheric mantle; (6) remnants of the Alpine Tethys; (7) Kabylo–Calabrides units; (8) Ionian Tethys oceanic slab; (9) Ionides; (10) pre-Pliocene sedimentary cover; (11) Pliocene–Quaternary sediments; (12–14) major thrust, normal and strike-slip faults. Dots indicate the Adriatic crustal units (from [29], modified).

The tectonic features cited above are instead compatible with the hypothesis that the trench-arc-back arc systems in the central Mediterranean region developed as effects of extrusion processes (e.g., [27–29]), induced by the convergence of the confining plates (Nubia, Eurasia and Arabia). In fact, both the considerable uplift of Calabria and the vertical bending of its crustal structure may be explained as a consequence of the strong constriction that stressed the Calabrian wedge after the suture of the Southern Apennines consuming boundary. In that context, the above wedge was forced to escape laterally through a narrow corridor, confined by lateral continental domains (Hyblean plateau on one side and Adriatic domain on the other side, Figure 3). It can be noted that the section crossing the southern Apennine wedge (Figure 8B) does not show the vertical bending of the crust given in Figure 8A, indicating that the compressional stress which drove the lateral escape of that Apennine sector was less intense than the one controlling the extrusion of the Calabrian wedge.

Some authors tentatively interpret the uplift and extension in the Messina zone as an effect of deep-seated asthenospheric processes (e.g., [92–94]), with particular reference to mantle upwelling (e.g., [25,95]). However, it is very difficult to believe that such kind of process, involving the mobility of large deep structures, may have created the observed upper crustal tectonic setting, characterized by coeval extensional and compressional strain regimes within some tens of km. In particular, mantle upwelling cannot easily explain why the Messina trough was generated in the Pleistocene, considering that the presumed retreat of the Ionian slab and the related mantle upwelling under the Calabrian Arc was already active in the Pliocene, as suggested by the timing of the Vavilov basin.

Another important aspect of the tectonic setting that can help recognize the driving force in the study area is the occurrence of compressional deformation along the outer border of the Peloritani sector in the Pleistocene [20,65]. Since this belt sector was affected by extensional deformation in the Pliocene, any proposed driving force must provide a plausible explanation of why that regime completely changed in the Pleistocene. The geodynamic interpretation adopted here (Figures 6 and 7) can account for this change, as discussed earlier, whereas mantle upwelling can hardly account for the timing of the above strain regimes.

Another hypothesis about the tectonic mechanism responsible for the generation of the Messina trough is advanced by [20], which suggests that such deformation may be related to a transfer zone located between the SE ward retreating Ionian slab and the advancing slab under the Hyblean-Sicilian domain. The tectonic scheme shown in the inset of Figure 1 of [20] indicates that the transition from the thrust front (along the Tyrrhenian offshore of Sicily) and the extensional zones (in Calabria) corresponds to the Messina trough. However, no shear faults are reported in that zone, where only normal faults are recognized (Figure 2). It seems to be more plausible supposing that the decoupling between the Sicilian and Ionian slabs is accommodated by the Vulcano fault, where a dextral transpressional regime is clearly recognized (e.g., [26,59]). However, this fault does not mark the transition from the northern Sicilian compressional front to the Calabrian extensional zones (Figure 2), as it cuts the long compressional front that runs from Ustica to the Messina zone, and thus it cannot support the geodynamic interpretation mentioned above.

The deformations cited above are compatible with the tectonic reconstruction here proposed (Figures 3, 4, 6 and 7) since the expected northward motion of the Peloritani microplate (stressed by the Hyblean block) implies thrusting along the northern boundary of this belt sector since the Early–Middle Pleistocene. In this view, the expected divergence between Peloritani and Calabria is supposed to have driven extension in the Messina zone (Figure 2). The angular shape of the Messina sphenocasm (Figure 7) is compatible with the genetic mechanism we propose (involving a clockwise rotation of the Peloritani sector) and with the fact that the most intense extension in such trough migrated from the southern branch, in the Early Pleistocene, to the northern one, in the Middle–Late Pleistocene (e.g., [18]).

5. Conclusions

The tectonic mechanism that generated the Messina trough was triggered by the Early Pleistocene interaction between the Calabrian wedge and the continental Adriatic domain. This event determined the activation of two major decoupling zones, the Sibari and Vulcano faults. By these new lateral guides, the Calabrian wedge changed its escape trend, at the expense of the remaining Ionian domain, while the Hyblean block accelerated its northward motion, dragging the Peloritani belt sector. As a consequence, such a sector ceased to be a part of the Calabrian wedge and became an almost independent microplate, undergoing northward motion and clockwise rotation. The proposed kinematic pattern of the Peloritani belt sector can explain why since the Early Pleistocene the outer border of this structure has undergone compressional deformation [20].

This microplate kinematics involved the divergence between the Peloritani and the Calabrian wedge, which was undergoing an outward migration. The above interpretation may help to identify the genetic mechanism of the normal faults recognized in the Messina area (Figure 2), most probably representing the main seismogenetic sources of the last two major earthquakes.

The longest normal fault recognized by geological evidence in the Strait zone (Messina–Taormina fault), lying offshore the Sicilian coast, may be the source of the 1908 earthquake. Assuming this east dipping fault location, with a 5 m dip-slip at depth, it is possible to reproduce the coseismic vertical movements caused by the 1908 earthquake [13]. The same fault can explain the uplift of the shorelines that outcrop between the Messina and Taormina towns. Seismic soundings show that the above fault offsets the pre-Pleistocene basement in the Messina sphenocasm. The location of the above seismic source can explain why no ruptures have been observed onshore [96]. Moreover, the uplifted marine terraces on the footwall of the Messina–Taormina fault [97] imply a marked throw-rate change at about 50 ka (acceleration from 0.96 to 2.34 mm/y), while the slip rate decreased in the other late Quaternary faults, as the Armo and Reggio Calabria ones. This implies a recent re-organization of strain in the Messina Straits and, therefore, provides relevant information about seismic hazards in this area. In this regard, it is useful to point out that the macroseismic field of the 1783 (6 February) earthquake suggests an epicentre located in the northern part of the Messina trough, perhaps related to the Scilla fault [9].

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