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Geodynamics of the South Balkan and Northern Aegean Regions Driven by the Westward Escape of Anatolia

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Abstract

The Plio-Quaternary deformation pattern of the northern Aegean and south Balkan regions is interpreted as an effect of the interaction between the Anatolian-Aegean-Pelagonian system (Tethyan belt), undergoing westward extrusion and strong deformation, and the surrounding plates (Nubia, Europe and Adriatic). Since the middle-late Miocene, the collision of the Tethyan belt with the continental Adriatic domain has caused strong E-W shortening in the outer Hellenides and Albanides, also involving the southward extrusion of the Peloponnesus wedge, at the expense of the Ionian oceanic domain. The roughly E-W extension recognized in the western South Balkan zones (Macedonia and eastern Albania) is related to the divergence between the Pelagonian belt (Albanides and Hellenides) and the Rhodope-Moesia domain. Stressed by the westward displacement of the central Anatolian plateau and by the southward bowing of the Cycladic Arc, the northern Aegean zone has contemporaneously undergone E-W compression and N-S extension, which has generated a series of dextral shear faults, delimiting a number of slats. The westward displacement and deformation of such slats can explain the morphological features of the northern Aegean zone. During this phase, the push of the central Anatolian plateau also caused the separation of the Rhodope massif from the Moesian European domain, with the consequent formation of the upper Thrace basin. This hypothesis can explain the Plio-Quaternary compressional deformations recognized in a sector of the North Anatolian fault system, the Ganos-Gelibolu zone. The proposed geodynamic/tectonic interpretation may help to explain some features of the time-space distribution of major earthquakes in the study area.

Keywords

South Balkan, North Aegean, Geodynamics, Tectonics, Seismicity

1. Introduction

The Plio-Quaternary evolution of the northern Aegean and south Balkan zones (**Figure 1**) has been characterized by a complex distribution of tensional and compressional stress regimes (e.g., [1]-[6]). The central South Balkan zones (Bulgaria, eastern Macedonia and northern Greece) have been affected by a roughly S-N extension, while the trend of this regime changes to about E-W in western Macedonia and inner Albania. Roughly E-W compression has dominated in the outer sector of the Albanides and northern Hellenides (Epirus). The central part of Greece has undergone S-N extension, with the formation of E-W troughs in the Corinth, Ambracique and Thessaly zones. Roughly NE-SW extension formed the Upper Thrace graben, while SE-NW compression is recognized in the Ganos-Gelibolu sector of the North Anatolian fault system (NAF). A series of dextral E-W shear faults developed in the Northwestern Anatolian and northern Aegean zones, delimiting some westward sliding slats.

Many attempts have been made to recognize the geodynamic framework responsible for such complex tectonics, but a widely accepted interpretation is not yet available. Some authors suggest a dominant role of slab-pull forces induced by the retreat of the Hellenic trench (e.g., [2] [6] [7]). Other hypotheses involve gravitational spreading of thickened crustal zones (e.g., [4] [8]). In this work we argue that plausible and coherent explanations of the observed deformation pattern can be found by supposing that tectonics has been driven by the convergence of the confining plates (Nubia, Adriatic, Arabia and Eurasia) and in particular by the displacement and deformation that such kinematic boundary conditions have produced in the Anatolian-Aegean-Pelagonian system.

Some considerations are then made about the possible connection between the proposed present tectonic context (**Figure 2**) and the spatio-temporal distribution of major earthquakes (1800-2023) in some zones. In particular, some comments are reported about the possible influence of post seismic relaxation on the seismicity patterns of the periAdriatic and Balkan zones.

2. Late Cenozoic Evolution and Proposed Geodynamics

Since the Miocene, the indentation of Arabia has caused the westward escape of the Anatolian-Aegean-Pelagonian system (AAP), a heterogeneous belt constituted by an inner metamorphic and crystalline core (Tethyan belt), flanked by accretionary chains of European and African affinity (**Figure 3(a)**). During the Miocene, the convergence between this system and the Adriatic promontory was accommodated by the consumption of the interposed thinned domains (mainly the Pindos zone, [20] and references therein). When the Aegean-Pelagonian sector of AAP collided with the continental Adriatic domain (**Figure 3(b)**), around the late Miocene-Early Pliocene, the above consuming boundary sutured (e.g., [21] [22]). This caused a major reorganization of the tectonic setting in the central Mediterranean area [20] [23] [24] [25] [26] and a considerable increase of E-W compression in the Anatolian-Aegean belt, which produced the formation of two main oroclinal bendings (the Cyprus and Hellenic Arcs), at the expense of the Levantine and Ionian oceanic domains respectively (**Figure 4(a)**, **Figure 4(b)**).

These bowings were accommodated in a ductile way by the inner metamorphic core, whereas in the more rigid external orogenic belts bending produced major breaks. The most evident example of the different responses of the above belts can be recognized in the Hellenic Arc (**Figure 4(a)**, **Figure 4(b)**), where bending caused the break of the Hellenides belt, with the formation of two major fragments, the western Arc (Peloponnesus) and the eastern Arc (Crete-Rhodes). The separation of these fragments from each other and from the inner ductile core (Cycladic arc) generated the Western Cretan basin [9] [10] [20].

After the activation of the decoupling Scutari-Pec fault in the Middle-Late Miocene, the westward displacement of the Pelagonian belt lying south of that discontinuity accelerated (**Figure 4**). This caused a clockwise rotation (of about

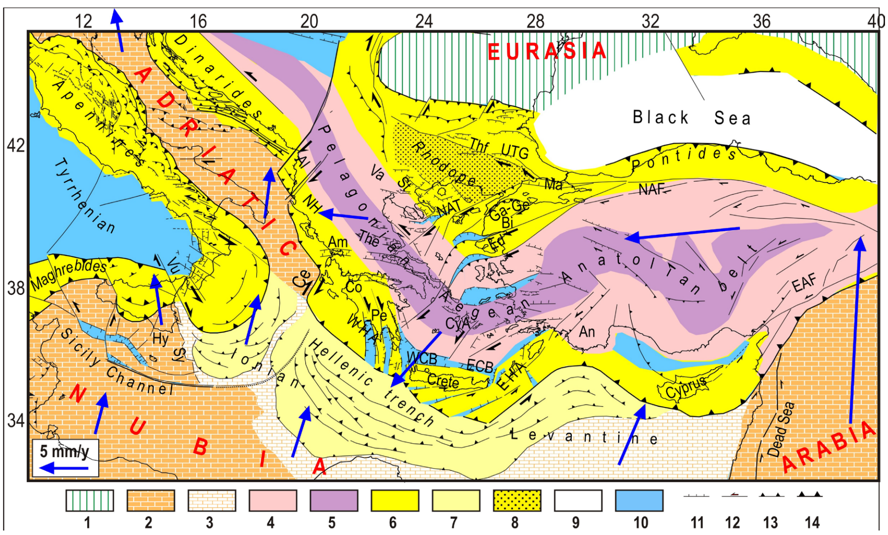

Figure 1. Tectonic scheme of the central and eastern Mediterranean area. 1) European continental domain 2) Nubia-Adriatic continental domain, 3) Ionian-Levantine oceanic domain, 4, 5) Outer and inner Tethyan belts 6) Orogenic belts 7) Calabrian and Mediterranean ridges 8) Rhodope massif, 9) Black Sea thinned domain 10) Cenozoic basins 11, 12, 13) Tensional, transcurrent and compressional features, 14) Outer fronts of the orogenic belts. Blue arrows indicate the Quaternary kinematics pattern with respect to Europe [9] [10] [11]. Al = Albanides; Am = Ambracique trough; An = Antalya peninsula, Bi = Biga peninsula, Ce = Cephalonia fault, Co = Corinth trough, CyA Cyclades Arc, EAF = Eastern Anatolian fault, ECB = Eastern Cretan Basin, Ed = Edremit fault, EHA = Eastern Hellenic Arc, Ga-Ge = Ganos-Gelibolu thrust fault, Hy = Hyblean block, Ma = Marmara trough, NAF = North Anatolian fault, NAT = North Aegean trough, NH = Northern Hellenides, Pe = Peloponnesus wedge, St = Struma fault zone, Sy = Syracuse fault, The = Thessaly, ThF = Thrace fault, UTG = Upper Thrace graben, Va = Vardar zone, Vu = Vulcano fault, WCB = Western Cretan basin, WHA = Western Hellenic Arc.

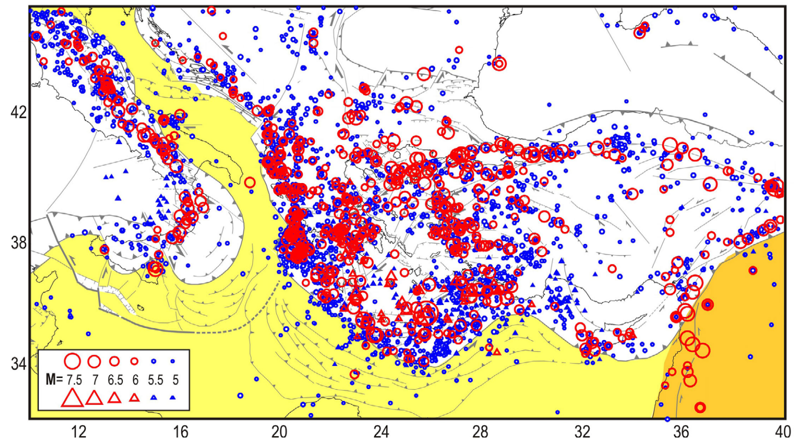

Figure 2. Major earthquakes (M ≥ 5) since 1000 A.D. in the central-eastern Mediterranean region [12]-[19]. The Nubia-Adriatic domain and Arabia are evidenced in yellow and brown respectively. Circles and triangles indicate hypocentral depths lesser than and greater than 60 km respectively.

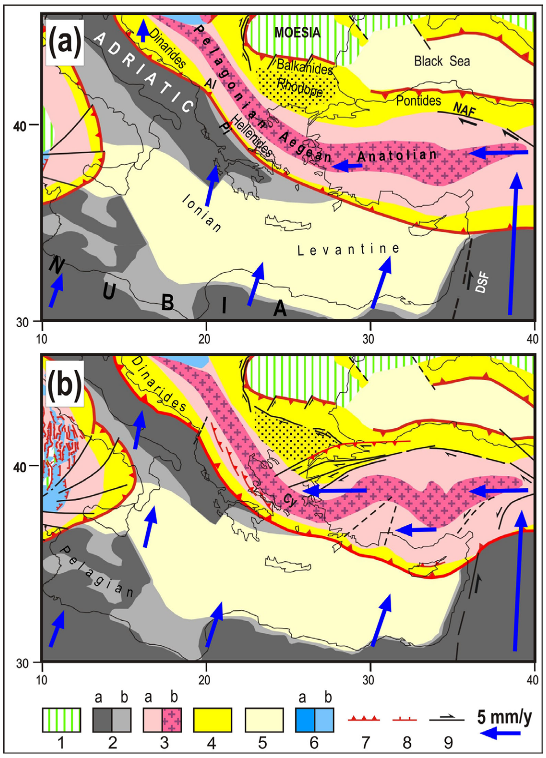

Figure 3. (a) Middle Miocene paleogeographic setting, dominated by the westward extrusion and deformation of the Anatolian-Aegean-Pelagonian system. The average long-term kinematics pattern with respect to Europe [9] [10] [11] is indicated by blue arrows (scale in the legend). Present geographical contours (thin black lines) are reported for reference. 1) Eurasian domain 2) Continental (a) and thinned (b) Nubia/Adriatic domain 3) Tethyan belt, constituted by ophiolitic and metamorphic units (a) and crystalline massifs (b) 4) Other orogenic belts 5) Mesozoic oceanic domains 6) Zones affected by intense (a) or moderate (b) Neogenic crustal thinning, 7, 8, 9) Compressional, tensional and strike-slip features. Al = Albanides, DSF = Dead Sea fault system, NAF = North Anatolian fault system, Pi = Pindos zone. (b) Late Miocene paleogeographic setting: the Aegean-Pelagonian system collided with the continental Adria domain. Cy = Cycladic Arc.

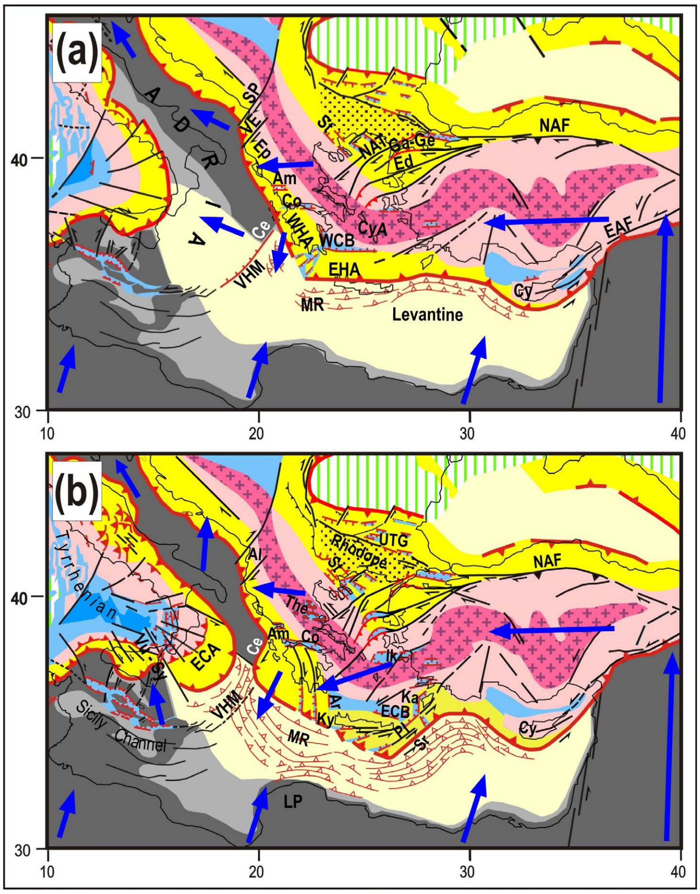

Figure 4. (a) Middle Pliocene tectonic setting. After the collision with Adria the deformation of the Anatolian-Aegean belt strengthened, forming the Hellenic and Cyprus Arcs. Am = Ambracique trough, Ce = Cephalonia fault, Co = Corinth trough, Cy = Cyprus; CyA = Cycladic Arc, EAF = East Anatolian fault system, Ed = Edremit fault, EHA=Eastern Hellenic Arc (Crete-Rhodes); Ep = Epirus, Ga-Ge = Ganos-Gelibolu fault, MR = Mediterranean Ridge, NAF = North Anatolian fault system, NAT = North Aegean trough, SP = Scutari-Pec fault, St = Struma fault system, VE = Vlora-Elbasan fault, WCB = Western Cretan Basin, WHA = Western Hellenic Arc (Peloponnesus); VHM = Victor-Hensen-Medina fault. (b) Pleistocene paleogeographic setting. After the complete consumption of the surrounding thinned domains the Adria plate moves NNE wards in almost close connection with Nubia. The collision between the Libyan promontory of Nubia (LP) and the Crete-Rhodes sector causes the SE ward bending of this wedge, with the formation of the Eastern Cretan Basin (ECB). Al = Albanides, Ar = Argolides trough, ECA = External Calabrian Arc, Ik = Ikaria basin, Ka = Karpathos trough, Ky = Kythira slice, Pl = Pliny fault, Sr = Strabo fault, The = Thessaly, UTG = Upper Thrace graben, Vu-Sy = Vulcano-Syracuse fault. Colours, symbols and other abbreviations as in Figure 1 and Figure 3.

20˚ - 25˚) of the Albanides belt sector with respect to the southern Dinarides, accompanied by an NW-SE scissor-like extension (≤11 km) in the Scutari-Pec fault system [6] [27] [28]. The above tectonic process is also testified by the fact that the amount of post mid-Miocene shortening in the Albanides belt increases from 10 km, north to the Scutari-Pec, to about 120 km, south of the Vlora-Elbasan fault [6].

The above evidence implies that a tear fault must have developed under the

Scutari-Pec faut system (as tentatively shown in Figure 5) to decouple the Adriatic margin underlying the Albanides from the Adriatic margin underlying the southern Dinarides. A decoupling tear may also be present under the Vlora-Elbasan fault, whose lateral displacement is estimated in about 28 km [6].

The extensional deformations observed in the inner part of the Albanides [28] [29] [30] may be an effect of the clockwise rotation of this belt.

Since the late Miocene, the convergence between the AAP system and Adria caused the roughly southward escape of the Peloponnesus wedge, laterally guided by the Cephalonia transpressional fault. Some authors (e.g., [31]) suggest that in the late Miocene the Cephalonia fault did not exist and that the Hellenides belt sectors lying north and south of that feature were aligned. The S-N extensional deformation that developed in the wake of the Peloponnesus wedge formed some troughs, as the Corinth, Ambracique and Thessaly ones (Figure 4, e.g., [32] [33]). In the Thessaly zone, the occurrence of extensional deformation was also favoured by the clockwise bending of the Aegean-Pelagonian belt (Figure 4(b)). This deformation pattern may also explain the time evolution of extensional trends in the Thessaly troughs and the coeval occurrence of extension and uplift in that zone (Figure 6).

Since the late Miocene, the consumption of the Ionian oceanic domain in front of the Peloponnesus escaping wedge led to the formation of the western Mediterranean ridge ([36] [37], Figure 4(b)).

Driven by the westward push of the central Anatolian plateau and by the coeval southward bowing of the inner Aegean belt (Cycladic Arc), the northwestern Anatolian and northern Aegean zones underwent E-W shortening and S-N extension, with the formation of a series of dextral transpressional and transtensional faults (Figure 4(a), Figure 4(b)), delimiting a number of slats.

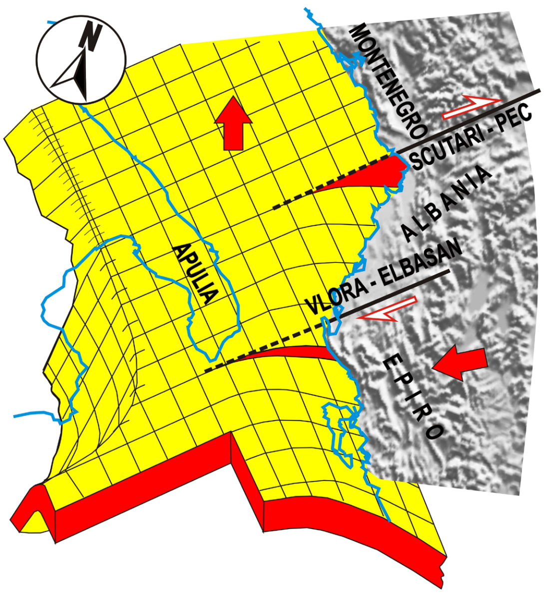

Figure 5. Tentative perspective view of the subducted Adriatic margin under the Albanides and northern Hellenides, based on geophysical data (e.g., [34]) and cross-sections [6]. The red arrows indicate the Quaternary kinematic pattern with respect to Europe [9] [10] [11].

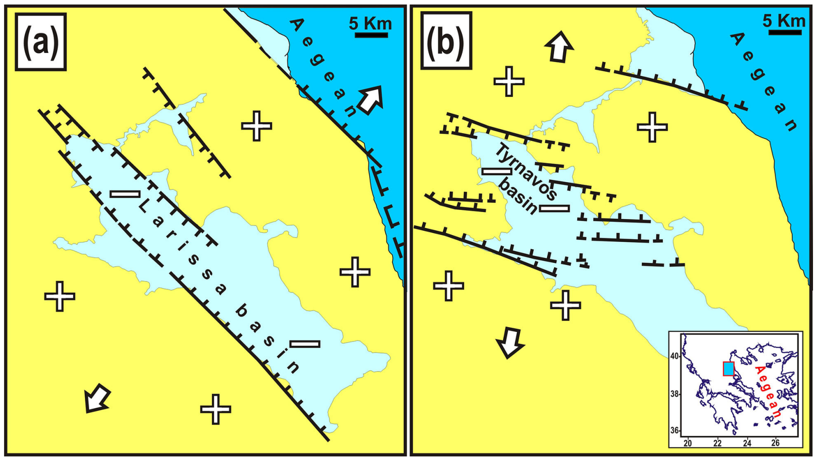

Figure 6. Trends of extension (white arrows) and vertical motions (+ and −) in two evolutionary phases of the Thessaly zone [35] (blue square in the insert). (a) Pliocene-Early Pleistocene (b) Middle Pleistocene-Holocene.

The westward displacement of the northernmost slat, including the Biga peninsula, formed the pull-apart Marmara trough, where a SW-NE extension of about 30 km and a considerable reduction of crustal thickness is recognized [1]. The convergence of the other slats with the Aegean-Pelagonian belt was accommodated by northward bendings and fragmentation, as tentatively reconstructed in **Figure 4(b)** and evidenced in **Figure 7**. The divergence between the southernmost slat (undergoing northward bending) and the Cycladic Arc (undergoing southward bending) may have caused the formation of the Ikaria basin (**Figure 7**).

The tectonic reconstruction proposed in **Figure 4(b)** for the northern Aegean zone is compatible with the present morphology of that area (**Figure 7**). In the late Pliocene, after the formation of the southern branch of the North Anatolian fault (the Edremit fault in **Figure 1**), the northern Marmara zone was characterized by a pure E-W dextral strike slip motion and the previous pull-apart basin was affected by thrusting (e.g., [1]).

Another major effect of the westward displacement and deformation of the Anatolian system was the separation of the Rhodope massif (undergoing a clockwise rotation) from the Moesian European domain, with the consequent formation of the Upper Thrace trough (e.g., [2] [38], **Figure 4(a)**, **Figure 4(b)**. The zone where the push of Anatolia was mainly exerted may be identified by considering the compressional deformation that since the late Miocene-Early Pliocene has developed in the Ganos-Gelibolu fault system (**Figure 1** and **Figure 4**, e.g., [3] [39] [40]). Geological evidence indicates that the flower structure in that zone (Dardanelles) formed during an intense and rapid compressional phase in the Early Pliocene and was later shifted laterally by a 70 km right-lateral offset during the last 5 My [3] [5]. The timing of such tectonic event supports the hypothesis that it was considerably influenced by the coeval collision of AAP with the continental Adria domain.

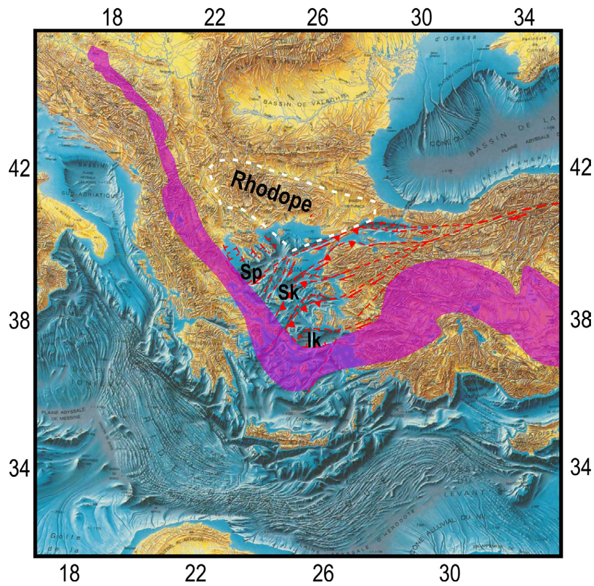

Figure 7. Marine and terrestrial morphological features in the study area (From [41]). The violet band indicates the inner Anatolian-Aegean-Pelagonian belt, constituted by crystalline massifs (see **Figure 1**, **Figure 3** and **Figure 4**). Red lines delimitate the slats cited in the text. IK = Ikaria trough, Sk = Skiros trough, Sp = Sporades trough.

The roughly E-W extension that since the Pliocene has affected the Macedonia and eastern Albania zones ([2] [28] [42] [43] and references therein, [29] [30]) may be an effect of the divergence between the Pelagonian belt (moving westward as a part of the AAP system) and the Rhodope massif.

3. Present Kinematics, Tectonic Setting and Seismic Activity

At present, the Adriatic plate is moving roughly NE to NNE ward in almost close connection with Nubia, as suggested by geological and geodetic data [10] [11] [25]. For the Anatolian-Aegean wedge instead, the present kinematic pattern, inferred from geodetic data (**Figure 8**), may be significantly different from the long-term pattern indicated by the observed Plio-Quaternary deformation pattern [10] [25] [26] [44]. This is because the present kinematics of the above wedge may be a transient accelerated phase, triggered by the series of strong decoupling earthquakes that occurred along the entire North Anatolian fault since 1939 (e.g., [45]). The numerical modeling of the post-seismic relaxation [46] [47] induced by the above seismic sequence shows in fact that the expected present kinematic pattern of the Anatolian-Aegean system is compatible with the kinematics indicated by geodetic data.

In the zones lying North of the NAF and NAT fault systems, the present motion rates are fairly low (some mm/y) and mainly oriented southward (**Figure 8**). In the Albanides the rates are low as well, but the motion trends go from westward to NW ward, suggesting that the displacement of the outer zones is more influenced by the motion trend of the Adria plate.

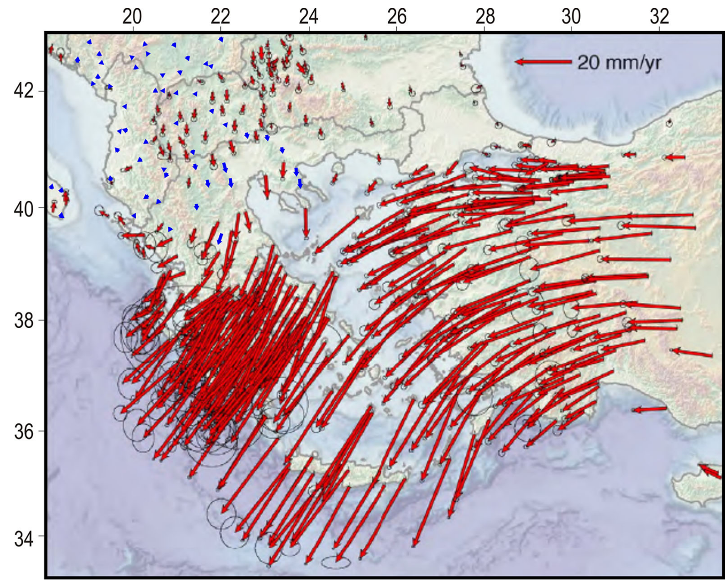

Figure 8. Present kinematic pattern in the study area from geodetic data. Red vectors from [48] (modified). Blue vectors from [49]. Thin black lines indicate States boundaries.

Since the south Balkan zones are decoupled from the Anatolian-Aegean system by the NAF and NAT faults, it is reasonable to suppose that present kinematic pattern of the south Balkan zones has not been significantly influenced by the post 1939 Anatolian displacement (**Figure 4(b)**).

In the region here considered some major seismogenic zones can be identified: the Cephalonia transpressional fault, the central Greece troughs (Corinth, Ambracique and Thessaly), the Epirus thrust zone, the outer Albanides thrust front, the Vlora-Elbasan and Scutari-Pec faults, the inner Albanides extensional zone, the southern Dinarides, the Rhodope zone, the upper Thrace graben, the northern Aegean fault systems.

3.1. Cephalonia Fault

Major earthquakes in this dextral transpressional fault relate to the overthrusting of the Peloponnesus wedge on the Adria plate (**Figure 9**, e.g., [9] [20] [50] [51] and references therein, [52]). This transversal discontinuity marks the transition from the continental collision at the Epirus thrust front to the oceanic subduction under the western Hellenic Arc (e.g., [53]). Some authors (e.g., [54]) interpret this fault system as the surface expression of a slab tear between the Hellenic subduction zone and the roughly vertical Epirus lithospheric fragment, detached from the deeper slab. Several strong earthquakes, with magnitudes up to 7.2 (e.g., [16] [18] [20] and references therein, [9] [53]), took place in this zone. The most recent occurred in 2003 (M = 6.2), 2014 (M = 6.0), 2015 (M = 6.4) and 2018 (M = 6.8). Earthquake focal mechanisms and geological evidence reveal a dextral strike-slip, associated with a significant thrust component and uplift (e.g., [55] [56] [57]).

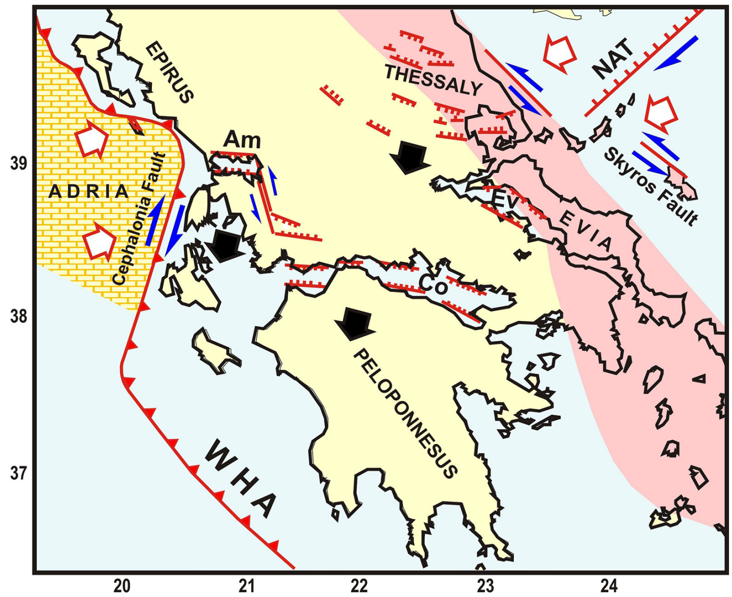

Figure 9. Sketch of the extrusion process recognized in this zone (from [50], modified). The big black arrows show the motion of the extruded wedges. The pink band indicates the inner Aegean-Pelagonian belt (**Figure 7**). The convergence between this belt and the Adriatic domain (big white arrows) is responsible for the strong E-W compression in Greece. Am = Ambracique trough, Co = Corinth trough, Ev = Evia Gulf, NAT = North Aegean trough, WHA = Western Hellenic Arc.

3.2. Central Greece

Seismic activity affects the Corinth, Ambracique and Thessaly fault systems. Geological, geodetic and seismicity data suggest a mostly S-N oriented extensional regime (**Figure 9**, e.g., [33] [58] [59]), with rates up to about 15 mm/y (e.g., [51] [60] [61]). The high potentiality of these seismic sources is indicated by the occurrence of several shocks with M > 7 (e.g., [62] [63]). Active tectonics in northern Thessaly and Evia zones is dominated by NE-SW to N-S extension (e.g., [35] [64]). Strong earthquakes (M > 6) occurred in 1781 and 1941. The southern Thessaly zone was affected by a strong event (M = 6.8) in 1733 [18] and by intense seismicity from 1954 to 1980 (e.g., [16] [65] [66]). In the Evia zone the analysis of the 2001 Skyros earthquake (M = 6.4, e.g., [67]) shows that significant strain is accommodated by slip along NW-SE left lateral faults (**Figure 9**). Three strong earthquakes (Mw = 6.3, 6.2, 5.7) occurred in 2021, in northern Thessaly, activating blind normal faults which form a graben-like structure oriented roughly NW-SE [66].

3.3. Epirus Thrust Front

Quaternary deformation and seismicity data (e.g., [68] [69]) indicate E-W compression in the outer belt, where major shocks allow the chain to overthrust the Adria domain. Some tectonic models (e.g., [70]) suggest the presence of a trench-parallel tear in the underlying Adriatic lithosphere, which could explain the lack of intermediate earthquakes in this zone. [54] suggests that the semi-horizontal slab detachment cited above started developing around the middle Pliocene. A continuous slab is instead recognized under the western Hellenic Arc, where earthquakes occur up to a depth of 160 - 185 km (e.g., [71] [72]).

3.4. Albanides

This belt sector involves various seismic sources: the outer thrust front, affected by roughly SW-NE to E-W compression, the inner zone, undergoing a roughly perpendicular extension, and the Scutari-Pec and Vlora-Elbasan strike-slip faults, (**Figure 1**). This last fault was hit by major events in 1833 (6.2), 1843 (6.2), 1848 (6.4), 1851 (6.8, 6.6, 6.4, 6.1), 1859 (6.2), 1860 (6.2), 1862 (6.2), 1865 (6.3), 1866 (6.6, 6.2, 6.1, 6.1), 1869 (6.0), 1896 (6.2), 1920 (6.0), 1942 (6.1), 1959 (6.3), 1962 (6.1) and 1967 (6.7). At the Scutari-Pec, major shocks occurred in 1852 (6.2), 1855, M = 6.8, 1869 (6.2), 1870 (6.5), 1905 (6.7, 6.1, 6.0), 1926 (6.3), 2019 (6.2). These events could be associated with the tear faults that decouple the subducted Adriatic margin under the Albanides from the margin underlying the southern Dinarides (**Figure 5**). The source geometry of the last Durres earthquake (2019, 6.4, [29] [73] [74]) is consistent with a low angle thrust fault dipping towards east, which can be related to the outer compressional front of the Albanides. The complex strain pattern in this zone (**Figure 10(a)**), inferred from focal mechanisms (**Figure 10(b)**) and GPS data (**Figure 10(c)**), may be explained by the proposed geodynamic/tectonic setting: the outer Albanides tend to move roughly Northward, in connection with the Adria plate, while the motion of the inner zones is mainly driven by the southward bowing of the Hellenic Arc. The relative motion between the above zones induces the extensional deformation recognized in the eastern Albanides (e.g., [28] [29]).

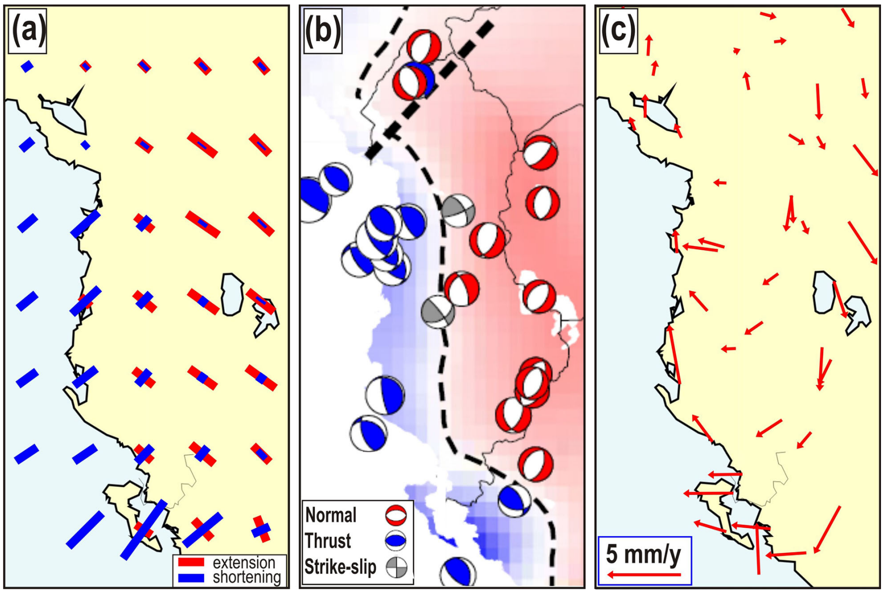

Figure 10. Strain field (a), Focal mechanisms (b) and GPS data (c) in the Albanides (from [49] modified).

3.5. Southern Dinarides

This thrust zone marks the collisional boundary between Adria and the Pelagonian-Dinarides belt. E-W shortening in this zone is evidenced by geological and geophysical evidence (e.g., [75] [76] [77]). Major evidence on the very strong E-W compression that affected the southern Adriatic plate is also provided by the considerable upward flexure of the Apulian carbonatic platform (**Figure 11**). The last major earthquake that hit this zone (Montenegro) occurred in April 1979 (M = 7.1). This event may have released the shortening accumulated at the collisional boundary between the Adria plate and the Pelagonian-Dinarides belt, triggering the propagation of post seismic relaxation through the Adriatic domain. The extensional character of this migrating stress perturbation is supposed to have favored the 1980 shock (23 November, M = 6.8) in the southern Apennines [78] [79]. The possibility that this tectonic connection systematically influences the time pattern of major earthquakes in the southern Apennines is based on the comparison of the seismic histories of the Southern Dinarides and Southern Apennines zones (e.g., [80]).

3.6. Rhodope Zone

Plio-Quaternary tectonic activity in this zone is mainly associated with NE-SW extensional deformation (e.g., [2] [42] [82]). Major earthquakes occurred in 1904 (M = 7.8), in the northern sector (SW Bulgaria), and in 1932 (M = 7) and 1978 (M = 6.5) in the southern sector, near the Thessaloniki zone (NE Greece). Some authors (e.g., [42] [83]) suggest that the Strymon fault system has been generated by N-S extension and is characterised by dip-slip movement on E-W trending normal faults, while other authors consider it as a NW-SE left-lateral strike-slip or transtensional fault system, on the basis of geothermal fields, borehole data, focal mechanisms of microearthquakes and GPS data (e.g. [43] and references therein, [84]).

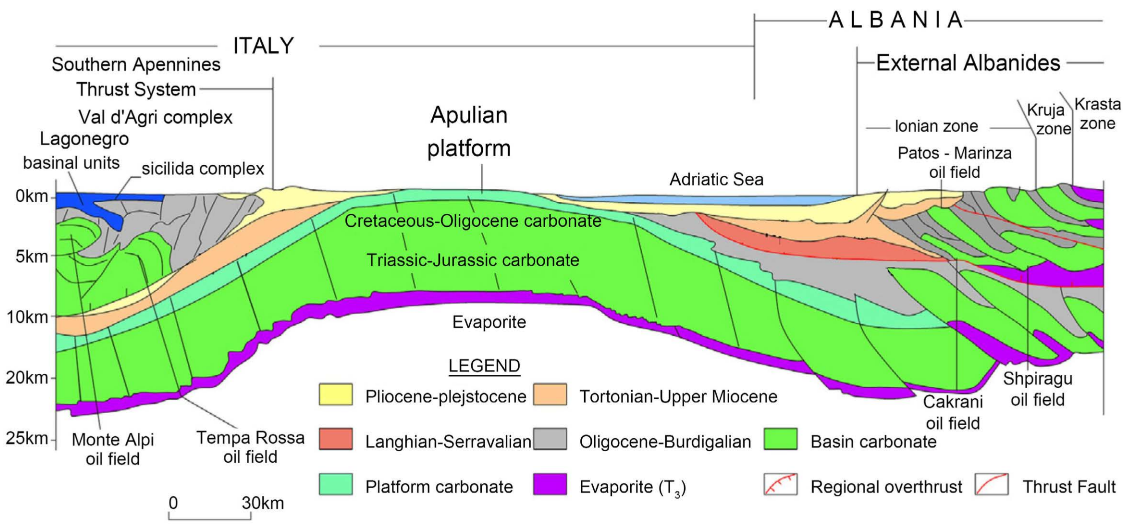

Figure 11. Section across the southern Adriatic domain (From [81], modified). The upward flexure of the Apulian carbonate platform testifies a very intense E-W compression.

3.7. Upper Thrace Graben

Two destructive earthquakes occurred in 1928 (M = 6.8, 7.1), in a roughly E-W graben located along a preexisting transcurrent fault system (Maritsa, e.g., [2]). The available focal mechanism for the strongest event indicates WNW-ESE extension with a significant dextral component. Geological, geophysical and paleoseismological investigations suggest that normal faulting was active throughout the Pleistocene and Holocene ([85] and references therein). GPS data and long-term slip rates of the active faults in this region suggest a roughly N-S to NE-SW extension at rates running from 1 to 3 - 5 mm/y ([38] and references therein).

3.8. Northern Aegean Fault Systems

This zone is characterized by dextral strike-slip faults, evidenced by seismological and geodetic data [59] [86] [87]. Some of them are the boundaries of morphological depressions (as the Sporades, Skiros and Ikaria basins, see, e.g., **Figure 7**). This complex structural setting could result from the differentiated extrusion and arching of the crustal slats that lie north of the Cyclades Arc. In the last three centuries, this zone experienced several strong earthquakes (1719 6.7, 1860 6.2, 1893 6.8, 1905 7.5, 1968 7.1, 1975 6.6, 1982 6.6, 1983 6.8, 2014 6.9, e.g., [65] [87]). The above fault system is connected with the North Anatolian fault, through the Ganos transpressional lineament and the Marmara pull-apart region (e.g., [1] [5] [88]). The most recent strong earthquakes in these zones involved the Ganos (1912, M = 7.3) and Izmit (1999, M = 7.4) fault sectors, both characterized by dextral strike slip focal mechanisms (e.g., [89] [90] [91]).

4. Possible Tectonic Connections between Main Seismic Sources and Space-Time Distribution of Major Earthquakes

The geodynamic/tectonic context proposed in this work may help to explain some features of the spatio-temporal distribution of major earthquakes. For this purpose, it may be useful to consider the period 1850-1935, when seismic activity in the study area was quite strong. The data reported in **Figure 12** indicate that the collision zone between the Adria plate and the Aegean-Pelagonian belt

(Cephalonia fault, Epirus and Albanides thrust fronts, Vlora-Elbasan and Scutari-Pec faults) was affected by strong shocks in the time intervals 1850-1870 (**Figure 12(a)**), 1889-1907, 1890-1907 (**Figure 12(e)**, **Figure 12(f)**) and 1920-1930 (**Figure 12(h)**), while the Rhodope zone was hit by major earthquakes in the time intervals 1858-1867 (**Figure 12(a)**, **Figure 12(b)**), 1900-1906 (**Figure 12(f)**) and 1931-1933 (**Figure 12(h)**). The fact that the main crises in the second zone show a significant overlapping on the ones in the first zone might suggest that the perturbation triggered by major shocks in the periAdriatic zones may increase stress and thus the probability of earthquakes in the Rhodope zone, after periods controlled by the rheological properties of the zones involved. The role of post-seismic relaxation in seismicity patterns of tectonic zones is described for other regions of the World (e.g., [78] [80] [92] [93] [94] [95]).

A more complete data set about the possible time correlation discussed above is provided by the seismic histories of the two zones involved in the last two centuries (**Figure 13**). The comparison of these seismicity patterns points out some interesting features, which could be not merely casual. In particular, the fact that the most intense seismic phases in the second zone are coeval with or just follow the main seismic periods in the first zone. The correspondence between the periods of minor seismicity in the two zones is particularly evident in the latest period, when the almost complete cessation of seismic activity in the Epirus-Albanides was followed by very low activity in the Rhodope zone.

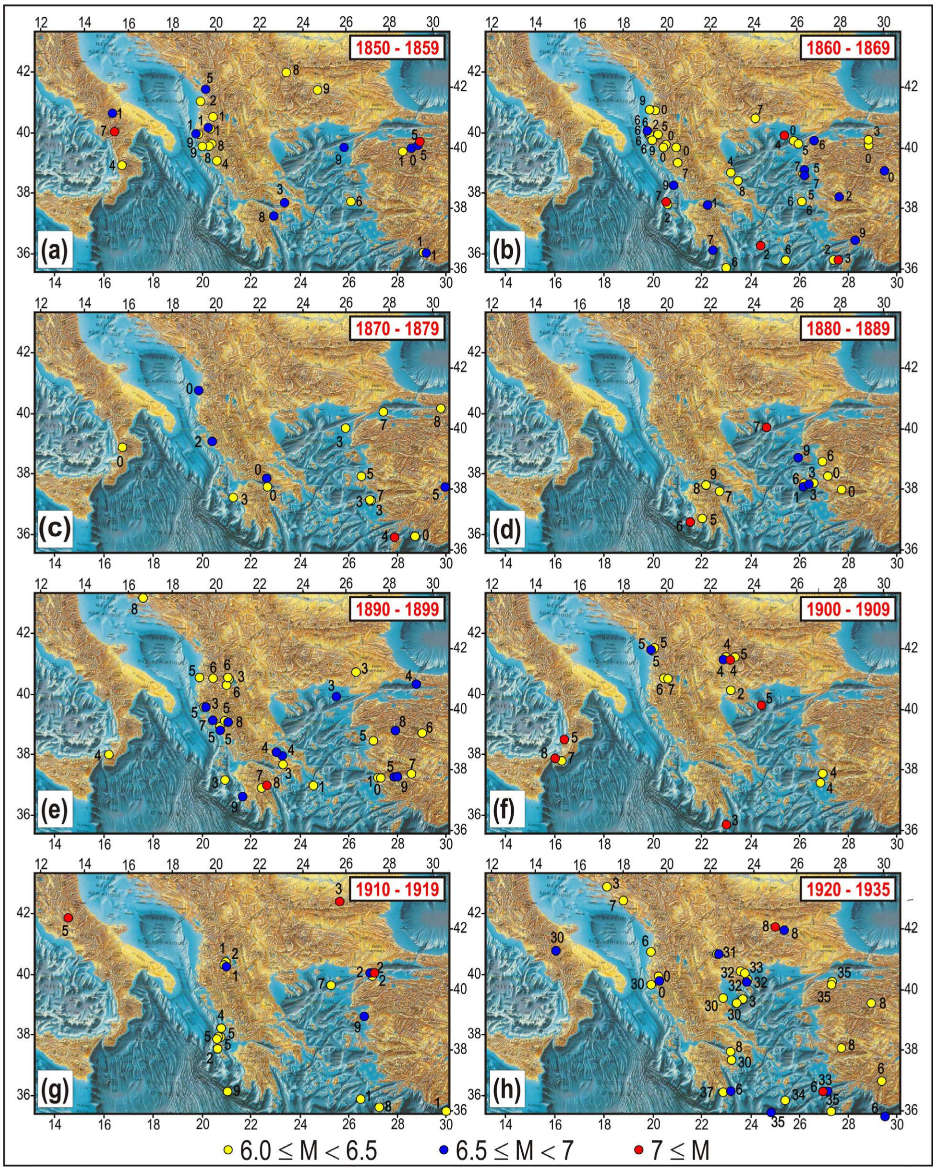

Figure 12. Distribution of major earthquakes in the period 1850-1935 (Seismicity data as in **Figure 2**). In each decade the year is indicated by the number close to each symbol (circle). Magnitude scale at the bottom of the figure.

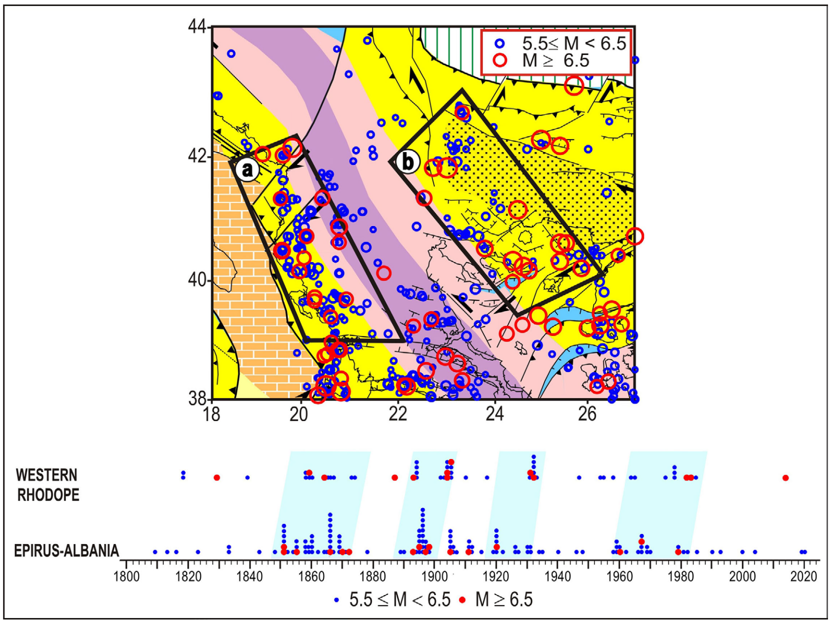

Figure 13. The map reports the location of major earthquakes (circles) in the study area (Seismicity data as in **Figure 2**) and the geometries of the presumably connected seismic zones Epirus-Albania (a) and Rhodope (b). Seismicity time patterns in the two zones are shown at the bottom. See text for comments.

The evidence given in **Figure 12** and the tectonic context we propose for the study area, might suggest that major earthquakes in the Scutari-Pec and Vlora-Elbasan fault systems can favour thrusting activity in the Albanides and Epirus. This tentative hypothesis is based on the following consideration. The westward displacement of the Aegean-Pelagonian belt (**Figure 1**) is accommodated by the overthrusting of the Albanides and Hellenides on the southern Adria domain and by the consequent sinking of this domain. However, this retreat cannot occur without the decoupling of the subducting margin from the Adriatic domain underlying the southern Dinarides. Since such decoupling is allowed by the activation of the Scutari-Pec and Vlora-Elbasan tear faults, one can suppose that after major earthquakes at those faults the probability of strong shocks in the Albanides-Epirus thrust front may increase. For instance, this hypothesis could explain why the 1850-70 seismic phase in the Albanides-Hellenides zones (**Figures 12(a)-(c)**) was preceded by the strong events that occurred in the Vlora-Elbasan fault in 1851 (6.8, 6.6, 6.4, 6.1) and in the Scutari-Pec fault in 1855 (6.8). Other strong events hit the Vlora-Elbasan fault in 1865 (6.3) and 1866 (6.6, 6.2, 6.1, 6.1). Another major example of the presumed connection may be given by the fact that the strong 1905 (M = 6.7, 6.1, 6.0) earthquakes in the Scutari-Pec fault and the 1906-07 (M = 6.4, 6.2) events in the Vlora-Elbasan fault preceded a major seismic phase in the Albanides-Epirus thrust front: 1920 (6.5), 1926 (6.3), 1930 (6.2) (**Figure 12(h)**).

5. Conclusions and Discussion

The Plio-Quaternary evolution of the south Balkan, northern Aegean and Hellenides-Albanides zones is explained as an effect of the westward displacement and deformation of the Anatolian-Aegean-Pelagonian belt, driven by the indentation of Arabia. The convergence between this system and Adria was accommodated by thrusting and uplift in the Hellenides and Albanides and by southward escape of the Peloponnesus wedge, at the expense of the Ionian domain. The S-N extension that occurred in the wake of that wedge generated E-W troughs in central Greece (Corinth, Ambracique and Thessaly). The lateral decoupling of the Peloponnesus wedge from Adria has been allowed by dextral transpression at the Cephalonia fault. The divergence between the Pelagonian-Aegean belt sector and the Rhodope massif has induced NE-SW to N-S extension in the south Balkan zones. The extension in the inner part of the Albanides has been induced by the clockwise rotation of this belt sector. Tectonic activity in the northern Aegean zone has been controlled by E-W compression, driven by the westward displacement of the Central Anatolian plateau, and by S-N extension, induced by the southward bowing of the Cycladic Arc (**Figure 4**). This regime generated a system of dextral transpressional faults which have allowed the westward sliding and escape of slats. The westward motion of northernmost slat caused the formation of the Marmara trough by a pull-apart mechanism. The other slats underwent various bendings, due to their convergence with the Pelagonian belt sector (Thessaly), as evidenced by morphological features in the northern Aegean zone (**Figure 7**). The roughly NW push of Anatolia (Biga peninsula) on the Rhodope massif, evidenced by the deformations and uplift observed in the Ganos-Gelibolu fault zone, caused the clockwise rotation and NW ward displacement of the above massif. The consequent separation of this block from the European domain (Moesia) caused the formation of the upper Thrace graben.

Any attempt at identifying the geodynamic context in a given zone should also explain why the proposed solution can better explain the observed deformation pattern with respect to the alternative interpretations. In this work, we mainly discuss the most cited geodynamic solution, which suggests a dominant role of slab-pull driving forces. This kind of interpretation mainly concerns the gravitational sinking of the Hellenic slab under the Hellenic trench (e.g., [2] [6] [7] [77]). As discussed in previous papers [9] [10] [20] [26], we suggest that the implications of this driving mechanism can hardly account for the observed Plio-Quaternary deformation pattern in the study area. Further considerations about this problem are reported in the following:

- The E-W compressional regime and the strong uplift observed in the outer Hellenides and the Albanides is not compatible with the South to SW ward pull presumably induced by the retreat of the Ionian slab. The importance of this argument is supported by the fact that the outer Hellenides are affected by the most intense shortening and seismicity in the Mediterranean area.

- The southward pull of the Hellenic slab can hardly explain why the southern Balkan zones lying between the Pelagonian and Rhodope belts have been affected by roughly E-W extension.

- The retreat of the Hellenic slab evidenced by subcrustal earthquakes cannot easily explain the oroclinal bending of the Aegean Arc and the very complex time space evolution of the western and eastern Cretan basins.

- Since the Anatolian-Aegean belt does not show any significant structural interruption (**Figure 1**, **Figure 6**, **Figure 7**), one should suppose that the presumed slab-pull mechanism did not only cause the southward displacement of the Aegean Arc, it must have also dragged the Anatolian wedge.

- The separation between the Rhodope massif and the European domain (Moesia), with the generation of the Upper Thrace graben, can hardly be explained as an effect of southward pull in the Hellenic Arc, especially if one considers that the Ganos-Gelibolu zone, lying south of the Rhodope massif, has been affected by roughly NW ward compression since the late Miocene [3] [40].

- The formation of a series of dextral mainly transcurrent faults in the northern Aegean zone (**Figure 4**), can hardly be interpreted as an effect of the Hellenic southward pull, since it clearly requires the contribution of E-W compression, as suggested in this work. Furthermore, the hypothesis that the S-N pull is induced by the retreat of the Hellenic slab during the Pliocene is not compatible with the present dimensions and the amphitheater shape of the subducted lithosphere indicated by the distribution of subcrustal earthquakes. In this regard, some authors suggest that the Hellenic subduction started not before the middle-late Miocene, and that the Hellenic boundary at that time was rectilinear, while, afterwards, it underwent a strong curvature, also in the deep sectors of the slab (e.g., [71] [96]).

Some authors even suggest that slab-pull forces may be induced by the retreat of the subducted Adriatic lithosphere under the Hellenides-Albanides belt (e.g., [6]). However, the available evidence (in particular the lack of intermediate-deep seismicity under the Epirus-Albanides region and the evidence suggesting a slab detachment since about 4 My, e.g., [54] [70]) cannot easily be reconciled with the presence of a well developed rigid slab under that zone, such context is only envisaged on the basis of tomographic investigations (e.g., [6]). However, one should explain why subcrustal earthquakes under the Calabrian Arc (where the subducting lithosphere is the same that sinks below the Hellenic Arc) occur up to depths of about 500 km, whereas under the Hellenic Arc (where a long slab is supposed to exist) such seismicity stops at a depth of about 150 km.

In our opinion, what has led many authors to neglect the difficulties pointed out above is the fact that they assume the present kinematic pattern inferred from geodetic data (**Figure 8**), indicating a faster motion of the Aegean zone (30 - 40 mm/y) with respect to the Anatolian wedge (15 - 20 mm/y), as representative of the long-term kinematic behaviour. In this view, the retreat of the Hellenic slab is considered the only driving force compatible with the above kinematic field in the Aegean and Anatolian regions. However, this interpretation does not consider that the present geodetic kinematics can be a transient pattern, triggered by the seismic activation of the entire North Anatolian fault since 1939, as provided by numerical modellings [46] [47]. This possibility would allow to explain the present kinematics in the Anatolian-Aegean area without invoking slab-pull forces.

Some support to the reliability of the geodynamic/tectonic setting here proposed may be provided by the spatio-temporal distribution of major earthquakes in the study area. In particular, by the fact that in the last two centuries the main seismic crises in the Epirus-Albanides collision zone were followed by the main seismic periods in the western Rhodope area. This evidence could support the hypothesis that the extensional deformation in the south Balkan region mainly develops in the wake of the Pelagonian belt sector, once the westward acceleration of this structure is triggered by major earthquakes in the Epirus-Albanides thrust front. We also advance the speculative hypothesis (mainly based on tectonic considerations) that seismic activity in the Albanides and Epirus thrust fronts is favoured by strong decoupling earthquakes in the Scutari-Pec and Vlora-Elbasan transpressional faults (**Figure 5**). Since the seismic activation of the underthrusting fault system under the Epirus-Albanides is also expected to trigger the NEward acceleration of the southern Adriatic domain one can expect significant consequences in the seismic hazard of the southern Italian zones (southern Apennines and Calabria). This hypothesis could explain the time-space distribution of major earthquakes in these two zones [80] [97].

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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