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Tectonic Inversion and Deformation Differences in the Transition from Ionian Basin to Apulian Platform: The Example from Ionian Islands, Greece

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Abstract: The studied areas (the Ionian Islands: Paxoi, Lefkas, Kefalonia and Zakynthos), are situated in the western ends of Ionian Basin (IB) in contact with the Apulian Platform (AP) and named as Apulian Platform Margins (APM). The proposed model is based on fieldwork, previously published data and balanced geologic cross-sections. Late Jurassic characterizes Ionian Basin to Early Eocene NNW–SSE extension followed by Middle Eocene to Middle Miocene compression (NNW–SSE directed). The space availability, the distance of Ionian Thrust from the Kefalonia strike-slip fault (KSSF) and the altitude between Apulian platform and Ionian basin that produced during extensional regime were the main factors for the produced structures due to inversion tectonic. In Zakynthos Island, the space availability (far from KFT), and the reactivation of normal bounding faults formed an open geometry anticline (Vrachionas anticline) and a foreland basin (Kalamaki thrust foreland basin). In Kefalonia Island, the space from FKT was limited and the tectonic inversion formed anticline geometries (Aenos Mountain), nappes (within the Aenos Mountain) and small foreland basins (Argostoli gulf), all within the margins (APM). In Lefkas Island, the lack of space, very close to KFT, lead to the movement of the Ionian basin over the margins, attempting to overthrust the Apulian platform. Because the obstacle between basin and platform was very large, the moving part of Ionian Basin strongly deformed producing nappes and anticlines in the external part of the Ionian basin, and a very narrow foreland basin (Ionian Thrust foreland basin).

Keywords: inversion tectonic; thrust faults; Kefalonia strike-slip; mesozoic sequence; Apulian platform; Ionian basin; Apulian platform margins

1. Introduction

The term "inversion" refers to areas whose evolution has been influenced by reversal from subsidence to uplift due to contraction and subsequent reactivation of previously extensional faults and basins. Plenty of sedimentary basins formed in the continental crust, before, during, or after the oceanic spreading, have been influenced by inversion tectonics such as basins along the North-East Atlantic margins of Norway and Britain, and has many different interpretations [1–5]. These basins formed as a response to either local stress induced by shearing [5], or far-field stress in relation to Alpine compression [1,6], oceanic ridge-push [7], or oceanic transform motion [8].

Inversion tectonics also emerges to a large extent in continental rifts, and areas of inversion in the reference Cenozoic East African rift system are reported to the Afar [9,10], and Rukwa sectors [11,12], as well as to the Turkana area [13]. The several kinematic models so far proposed for inverted basins imply disturbances of the stress field in relation with transform fault in the Afar rift [10], plate-scale mechanisms in the Turkana rift [13], and permutation and/or rotation of stress axes in the Rukwa rift [14].

For several decades, the Mesozoic-Cenozoic tectonic evolution of the Ionian basin was in a thorough debate, particularly regarding the nature of deformations and the problem of correlating structural events with the Apulian platform margins, located west of the Ionian basin. Lefkas, Kefalonia and Zakynthos Islands, are the keys to this study as both the Ionian thrust and the Kefalonia strike-slip fault outcropped in the Islands. This remote area has been the target of previous expeditions resulting in diverging structural interpretations. The Hellenic FTB dominates the External Hellenides and is mainly controlled by collision and continued convergence of the African and Eurasian plates since the Mesozoic [15,16]. Western Greece was part of the Apulian continental block on the southern passive margin of the Tethys Ocean from the Triassic to Late Cretaceous. During early Jurassic (Pliensbachian), extensional stresses associated with the opening of the Tethys Ocean, resulted in the Ionian Basin's opening [17,18], while further Neogene extension has been observed as well [19]. The most important structural control is contractual deformation, as suggested by the constant occurrence of evaporites throughout the thrust boundary between the Apulian platform margins and the Ionian basin. Evaporites represent the lowest detachment level of individual thrust sheets and form a major decollement level.

The aim of this paper is to present a structural model of the tectonic evolution of the Ionian basin and Apulian platform margins, from Late Jurassic to Pleistocene. Moreover, through this papers will be seen the impact of the Late Jurassic to early Eocene NNW–SSSE extension, followed by middle Eocene to middle Miocene NNW–SSE compression, and finally by middle Miocene to present NNE-SSW extension, on the stratigraphy and basin evolution of the Ionian Basin and the Apulian platform margins. The models are based on fieldwork, previously published data, detailed and validated 3D-modeling, and balanced geologic cross-sections.

2. Geological setting/Materials and Methods

The studied areas of Lefkas, Kefalonia and Zakynthos Islands are suitable areas for the study of regional structural evolution as both Ionian Thrust fault (IT) and Kefalonia strike-slip fault (KSSF) have been outcropped. This remote area has been the target of previous expeditions resulting in diverging structural interpretations.

The Hellenic Fold and Thrust Belt (FTB) dominates the External Hellenides (Figure 1) and is mainly controlled by collision and continued convergence of the African and Eurasian plates since the Mesozoic [15].

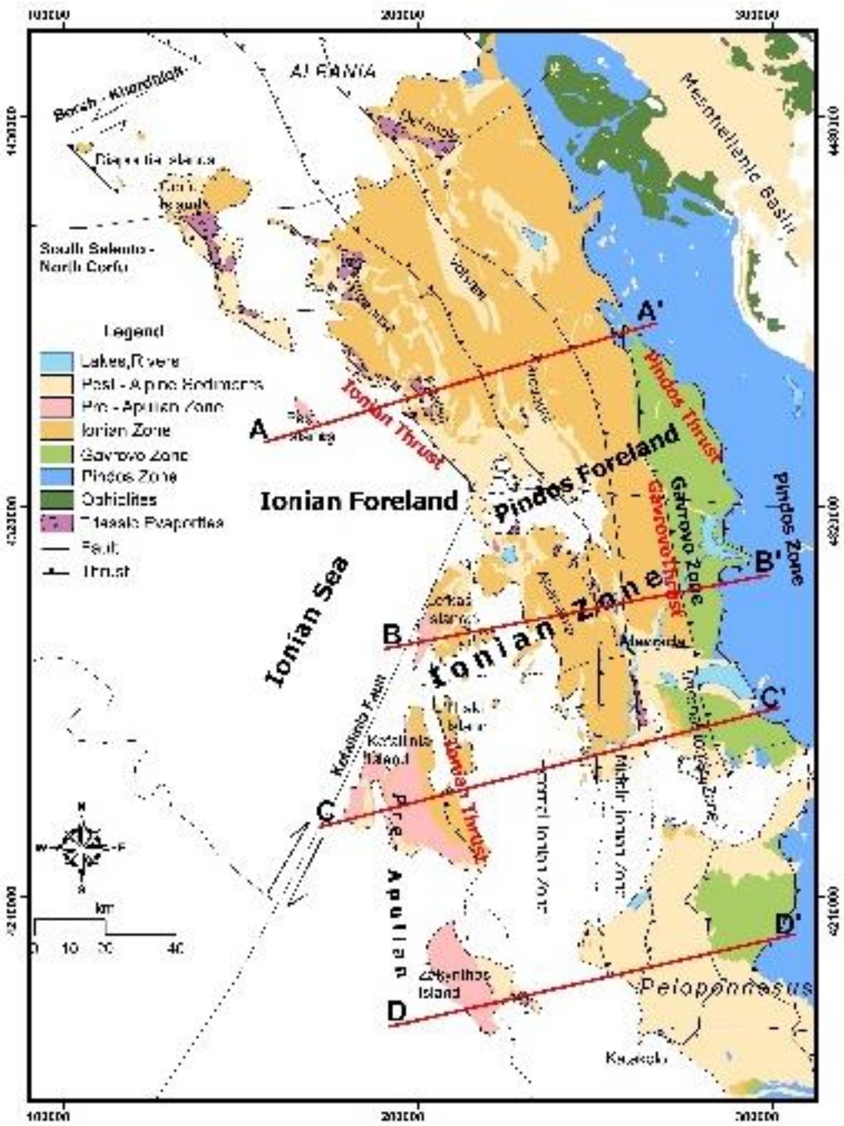

Figure 1. Geological map of the studied area with the four studied cross-sections [20].

Western Greece was part of the Apulian continental block on the southern passive margin of the Tethys Ocean from Triassic to Late Cretaceous. In early Jurassic (Pliensbachian), extensional stresses associated with the opening of the Tethys Ocean, resulted in the Ionian Basin's opening [20]. The most important structural control is contractual deformation, as suggested by the constant occurrence of evaporites throughout the thrust boundary between the Apulian platform margins and the Ionian basin. Evaporites represent the lowest detachment level of individual thrust sheets and form a major decollement level [21].

Ionian thrust is the major tectonic feature throughout Western Greece and Ionian Islands, a crustal-scale thrust fault that pushes the lower stratigraphic Ionian Zone over the Pre-Apulian, and has been active since the early Miocene. The NW margin of the Hellenic FTB, represents a geotectonically complex area of collision, subduction and transform faulting activity [22]. This corresponds to a compressional zone placed upon the boundary between the Adriatic and Aegean microplates and the Eurasian-African plates, which in turn corresponds to a general NNW-SSE convergence between Eurasian-African plates.

Moreover, the activity of different branches of the main Ionian Thrust led to the evolution of smaller, confined sub-basins [23]. The pre-Apulian (or Paxoi) zone is the continuation of the Apulian Platform and its transition to the Ionian Basin through some edge-slope facies. It is exposed in several Ionian Islands, mainly in the southwestern margins of the Hellenic FTB (e.g. Kefalonia, Zakynthos)

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and south of Corfu (Paxoi Islands). This transitional zone is absent in NW part (Corfu Island), suggesting that the Ionian units are directly over -thrusting South Apulia basin [24] (Figure 2).

Strike-slip faults have also controlled the regional tectonic setting and smaller scale strike-slip faults have dissected the Ionian Thrust [25] (Figure 2). Further, the Kefalonia strike-slip fault to the south bisects the Western Greece in an ocean-continent subduction and a continent-continent collision regime, and the Borsh-Khardhiqit strike-slip to the north of Corfu control the evolution of the broad region.

Observed uplift in the southern parts of the island suggests that the southern part of the Ionian Thrust in Corfu is still active. Furthermore, in the hangingwall of the southern section of the thrust, evaporites are covered by Middle to Upper Miocene deposits, suggesting tectonic activity towards the Miocene-Pliocene boundary (Figure 2).

Based on seismic data [26] suggested that normal faults, that influenced Mesozoic deposits, reactivated as thrust faults, during Eocene to Miocene, and further reactivated as normal faults during Plio-Quaternary. In addition, it is recommended that Mesozoic normal and transfer faults were re-activated during the compressional stage as thrust or back-thrusts and strike-slip faults, respectively [20,27] (Figure 3).

Deformation due to collision, based on seismic lines across the Ionian Islands, showed the different structures close and far from Kefalonia strike slip fault [21,22,28]

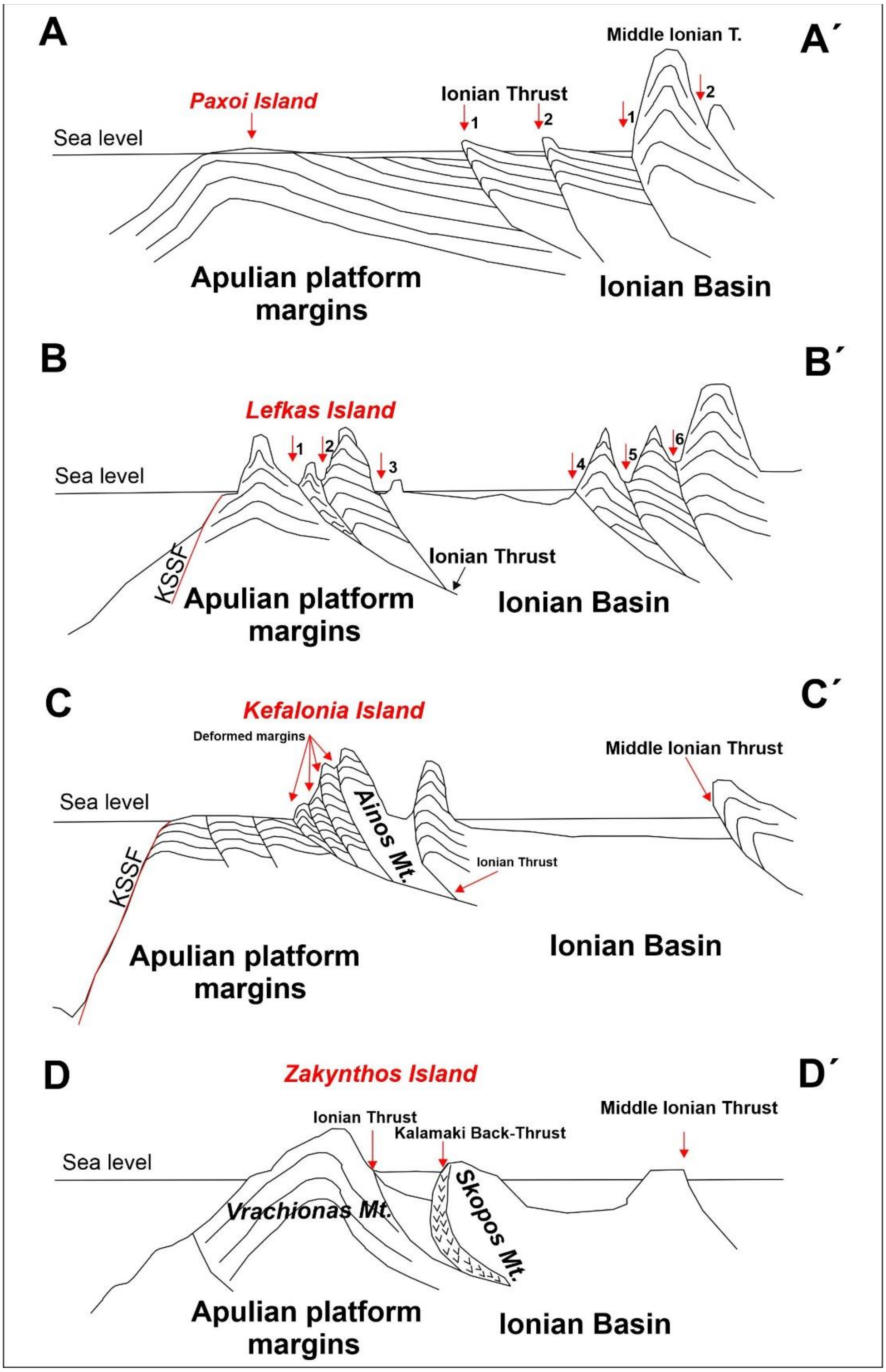

Figure 2. Four cross-sections depict the major structures based on google earth relief. For the abbreviations see the text and for the locations see Figure 1.

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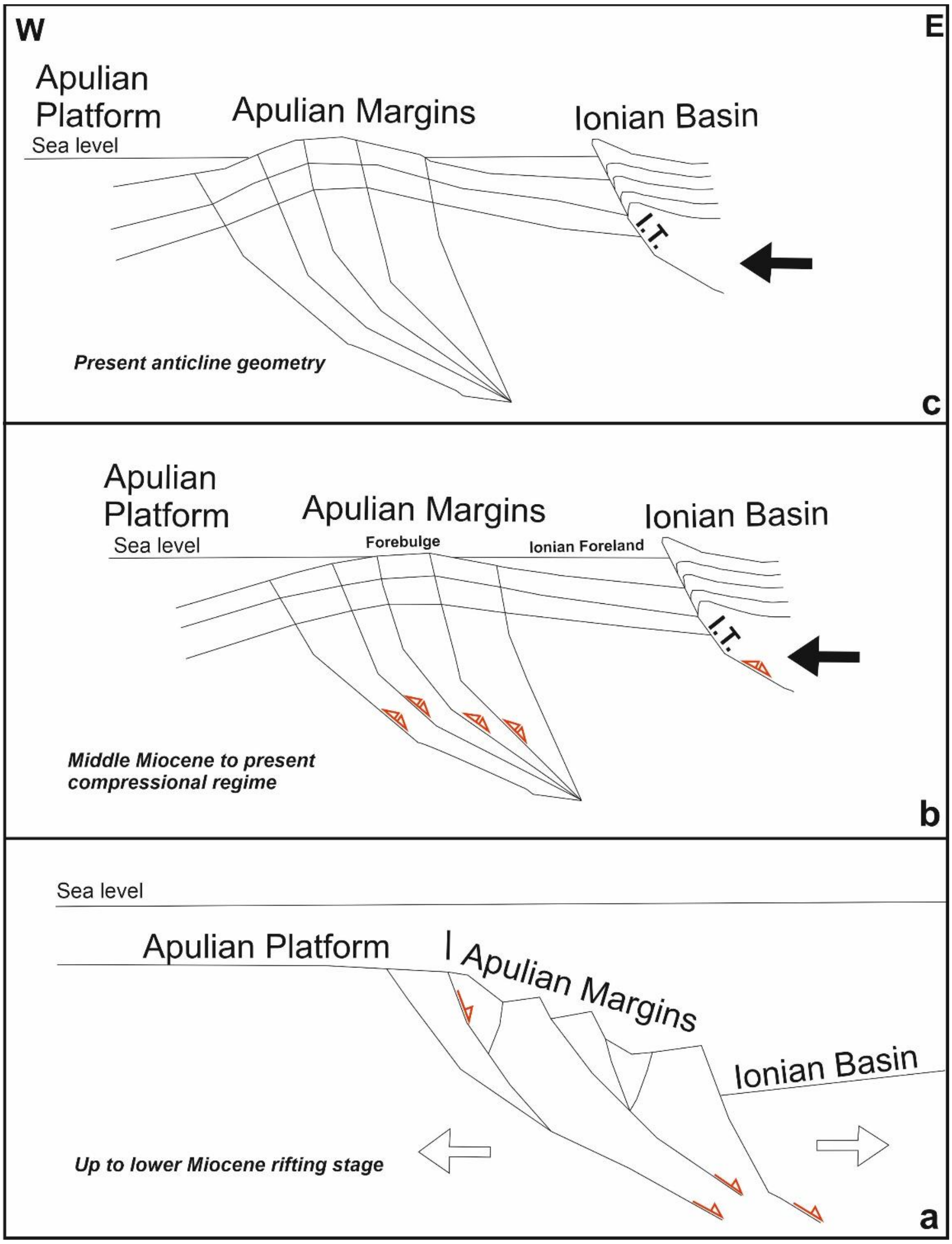

Figure 3. Evolutionary stages of development from rifting stage to present, applied to Paxoi/Anti-Paxoi Islands [29].

3. Results

The A-A′ and D-D′ sections (Figure 2) suggest that when the area influenced by the Ionian Thrust (IT) is situated remotely from the Kefalonia strike-slip fault (KSSF) then the deformation is the same. As the IT affected the margins of the Apulian platform, a high angle anticline was formed in both cases (Paxoi Anticline – PA), with up to 200 m altitude, and Vrachionas Anticline (VA), with up to 550 m altitude, in Zakynthos Island). In Paxoi (Figure 2 A-A′), the KTF is not present and therefore sufficient space is available, a conventional foreland basin was formed, below sea-level. In Zakynthos Island (Figure 2 D-D′), the Ionian fault pushes the margins of the Apulian platform towards the KTF. In this case, the space was limited resulting to margin uplift, and producing the VA. The Ionian thrust gradually evolved into the Kalamaki Back Thrust (KBT).

In addition, when the deformation is at close proximity to the KTF (Figure 2 cross sections B-B′ and C-C′) then the results differ.

In the case where IT is very close to the KTF (Figure 2 B-B') and limited preserved space exists, only the pre-existing deposits of the Ionian basin were deformed, producing numerous synclines and anticlines, with highest altitudes up to 1150 m. Additionally, the restricted or protected from the KTF margins of the Apulian platform were deformed generating altitudes up to 750 m, between KTF and IT.

In Kefalonia Island (Figure 2 C-C'), the Apulian margins present the most interesting structures, because they were deformed from the compression of the IT producing several small foreland basins. The Paliki Peninsula (PP) (up to 450m altitude) is at close proximity to the KTF and exhibits slumped blocks to opposite direction (eastward directed) over younger deposits. This so most likely because to limited space available Aenos Mountain (AM) with up to 1650 m altitude (the highest in Ionian Islands) was formed as a result of the westwards movement of the IT. Although space from AM to PP peninsula is available, the strong uplifted block of AM could be related to the high angle of the pre-existing normal fault and its great displacement, as well as the coexistence of another thrust fault in Argostoli Gulf (AG). This suggests that AM could represent the wedge top of the Argostoli thrust.

4. Discussion

The boundaries-margins between the stable Apulian Platform and the Ionian Basin display changes in tectonic regime from extensional to compressional regime, with showed characteristic structures [2,3,26] (Figure 4). During Eocene, the pre-existing normal faults reactivated as thrust faults and the transfer faults as strike-slip faults producing different structures. of the type of tectonic structures generated by the inversion tectonics depend of both the existing displacement of the marginal normal faults and the proximity of the IT to the KTF.

Parameters, such as, the pre-existing displacement of normal faults, the frequency of normal faults and the proximity to transfer faults that could be reactivated as strike-slip faults are important in the study of inversion tectonic structures.

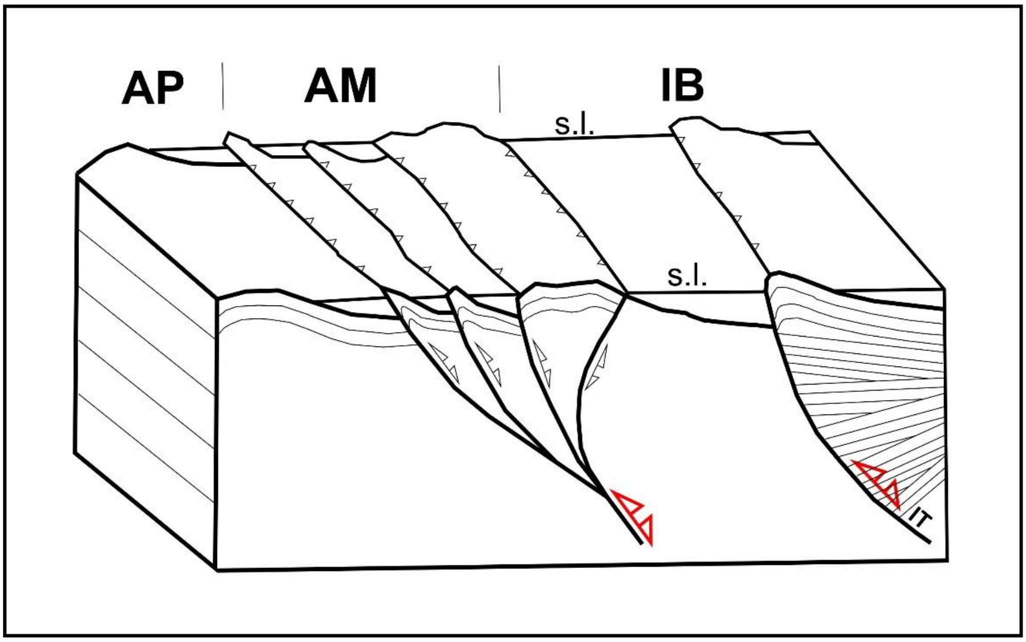

Figure 4. The block diagram illustrates how the tectonic inversion influenced the Apulian Platform Margins producing small restricted foreland basins.

5. Conclusions

Apulian platform margins represents the transition margins from Apulian Platform to Ionian Basin and was formed because of extensional tectonic activity associated with normal faults during the Mesozoic. The aerial differences in the displacement of the marginal faults and the influenced area from north to south generated areas that differ in size and bathymetry. During Eocene, the

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normal faults reactivated as thrust faults and the produced deformation was influenced by the existing displacement and the presence of KTF.

In case of limited space between KTF and margins, the Ionian basin deposits were deformed, whereas in cases of space availability, the reactivation of marginal normal faults generated small foreland basins with often back-thrusts.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, A.Z. and N.B.; methodology, N.B.; software, N.B.; validation, A.Z.; formal analysis, A.Z.; N.B.; investigation, A.Z. N.B. E.Z. AG.M.; data curation, A.Z.; writing—original draft preparation, A.Z. N.B.; E.Z.; AG.M.; writing—review and editing, A.Z. N.B.; E.Z.; AG.M; visualization, A.Z.; supervision, A.Z.; project administration, A.Z. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

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