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RESEARCH ARTICLE

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3D architecture of the northern Hellenides fold and thrust belt of Albania, and implications for maximum moment magnitude estimation for the southern Albanide Frontal Thrust

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ABSTRACT
Based on a series of balanced cross-sections, we present the first 3D structural model of the northern part of the outer Hellenides active fold and thrust belt exposed in Albania and its adjacent offshore areas. This sector of the Hellenides includes Permian to Eocene pelagic basin and carbonate platform successions, overlain by synorogenic strata and deformed since the Oligocene. The tectonic setting of this area results from a structural style change that occurred around the Miocene-Pliocene boundary, shifting from thin-skinned to thick-skinned thrusting. Active basement faulting, highlighted by the Mw 6.4 November 2019 Dürres earthquake, indicates the presence of deeper seismogenic sources in addition to shallow thrusts within the sedimentary cover. Integrating well-established scaling relationships with fault parameters extracted from our 3D structural model which includes active basement thrusts in the frontal part of the fold and thrust belt, the seismic potential associated with the major seismogenic source in the region (i.e. the Southern Albanide Frontal Thrust) was estimated, bearing major implications for seismic hazard evaluation in this densely populated area.

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KEYWORDS
Fold and thrust belt; northern hellenides; balanced geological sections; 3D model; earthquake magnitude estimation

1. Introduction

Albania includes an important segment of the Africa-vergent portion of the Mediterranean Alpine orogenic system, constituted by the Hellenides mountain belt. Recent seismicity (e.g. the Mw 6.4 November 2019 Dürres earthquake) provides an emerging picture of crustal, predominantly reverse faults controlling active tectonics in the coastal areas of Albania and the adjacent offshore (Figure 1; Caporali et al., 2020; Ganas et al., 2020; Govorčin et al., 2020; Pezzo et al., 2022; Santini et al., 2020; Teloni et al., 2021; Vittori et al., 2020). Furthermore, a recent interpretation of receiver function images by Rossetti et al. (2024) suggests the occurrence of a basement-involved thrust system. According to the latter authors, deep-seated thrusting occurred in Albania since the latest Miocene-Pliocene and triggered a pulse of exhumation amounting to ca. 3–4 km. These findings fit within a broader regional framework in which the Dinarides – Albanides – Hellenides orogen experienced a late Miocene – Pliocene phase of crustal accretion driven by deep crustal underplating, as demonstrated through integrated thermochronologic and structural analyses (Rossetti et al., 2025). Their results indicate that crustal-scale thrusting and underplating beneath Albania governed both the distribution of deformation and the recent uplift of the belt, providing the deep geodynamic framework for the basement-involved frontal thrust system investigated in this study. On the other hand, available catalogues of seismogenic sources (Basili et al., 2008) include exclusively shallow thrusts – essentially hosted in sedimentary cover rocks – in the coastal areas of Albania and adjacent offshore. Consequently, these catalogues fail to provide a complete and fully satisfactory account of active structures in the coastal offshore areas of Albania. In this study, surface geology and a series of balanced cross-sections are integrated in the building of a structural model

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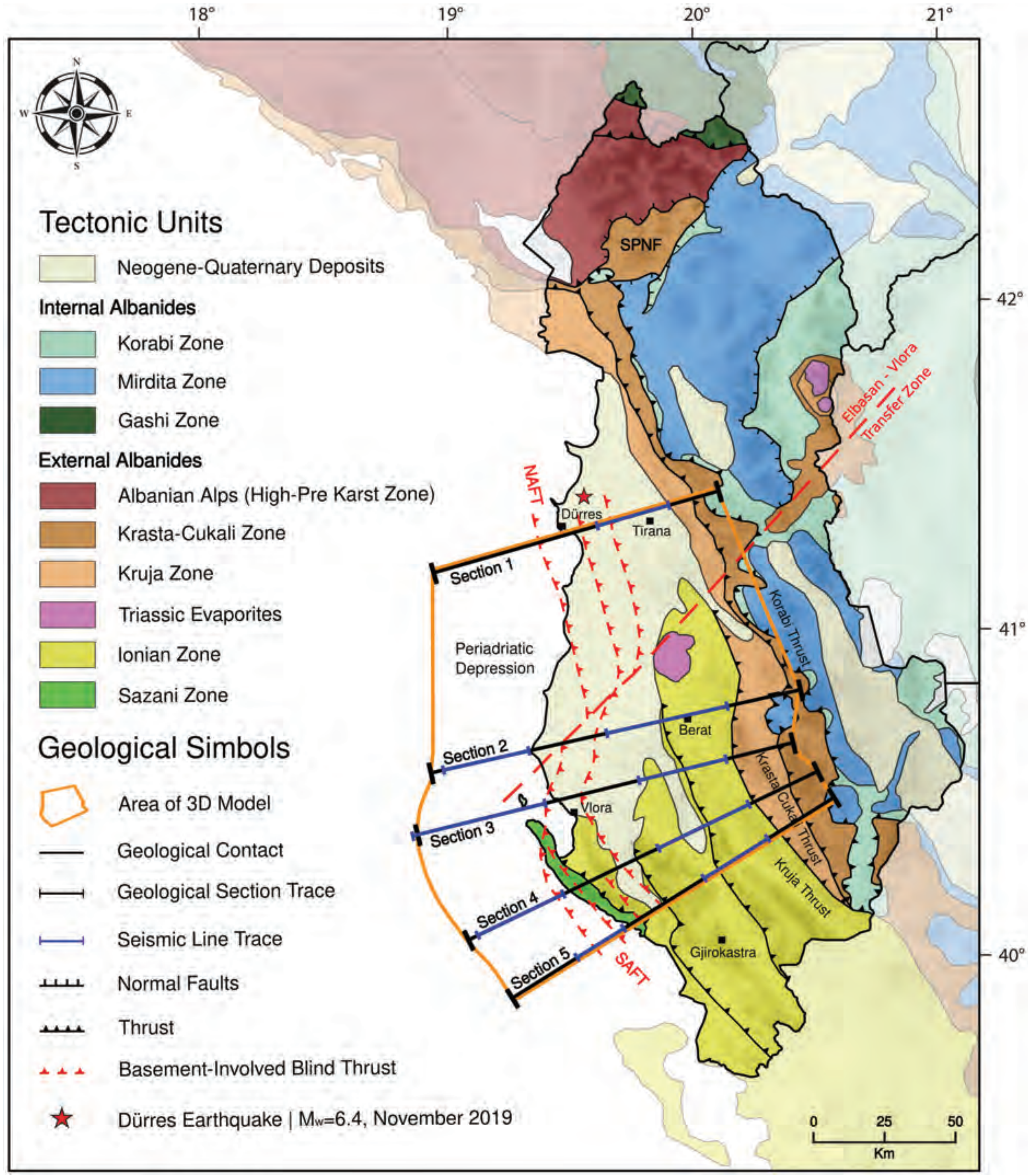

Figure 1. Tectonic sketch map of Albania and surrounding regions (modified after Grund et al., 2023; Handy et al., 2019; Mazzoli et al., 2022; Muceku et al., 2006; Nieuwland et al., 2001; Roure et al., 2004; Teloni et al., 2021), draped over a hillshade derived from a 30 m resolution digital elevation model (Source: https://www.eea.europa.eu). The map shows the location of the Mw 6.4, November 2019 Dürres earthquake (Teloni et al., 2021), traces of geological section by Mazzoli et al. (2022) modified in this study, and the area of the presented 3D model. NAFT indicates the northern Albanide Frontal Thrust, SAFT indicates the southern Albanide Frontal Thrust.

aimed at unravelling the 3D architecture of the outer northern Hellenides. An enhanced understanding of this thrust system is pivotal not only for gaining new insights into the structural response to slab dynamics in an area of strong coupling between the downgoing and overriding plates (Handy et al., 2019), but also for obtaining a comprehensive picture of potential seismogenic sources in the Adriatic region of Albania. This, in turn, has major implications for seismic hazard evaluation in this densely populated area of the Mediterranean region.

2. Geological background

The northern Hellenides fold and thrust belt in Albania (Figure 1) results from the deformation of a segment of the former Adria continental margin (e.g. Robertson & Shallo, 2000, and references therein), including a series of shallow- and deep-water domains. The Sazani carbonate platform domain, located to the west, represents the continuation of the Apulia carbonate platform exposed in Italy. The Ionian basin, currently folded and thrusted, was originally situated between the Sazani platform and another carbonate platform (Kruja) to the east (Figure 2). The Kruja platform was located between the Ionian basin and the oceanic-continent transition to the east, known as the Krasta-Cukali hyperextended domain.

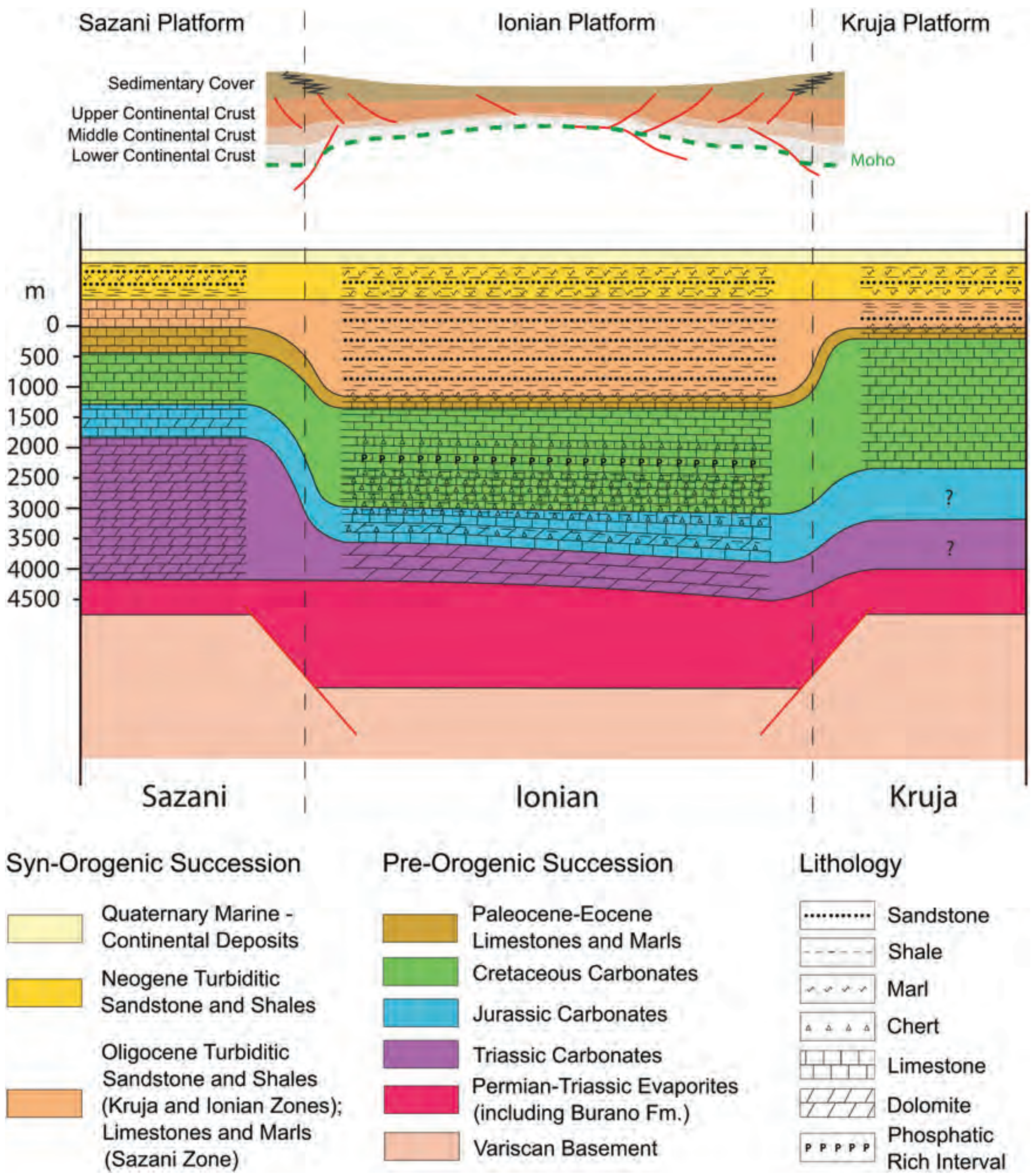

Figure 2. Stratigraphic template for the Kruja, Ionian, and Sazani Zones of Albania (modified after Mazzoli et al., 2022). The upper diagram schematically shows the palaeotectonic setting of the Adria rifted continental margin. The middle crust is depicted as a décollement level, which is envisaged to be reactivated during subsequent orogenic evolution, as upper crustal thrust ramps are interpreted to root into it during thick-skinned thrusting.

The base of the stratigraphic succession of the Ionian basin (Figure 2) is formed by Permian-Triassic evaporites (also referred to as the Burano Anhydrites Formation; Velaj, 2001) resting on top of the crystalline basement (Kamberis et al., 2022, and references therein). The evaporites are overlain by a Jurassic calcareous succession including both shallow-water and pelagic basin formations, followed upward by Cretaceous and Palaeogene pelagic limestones, marls, and shales (Mecaj & Mahmutaj, 1995; Zappaterra, 1990), and then by clastic sediments that were deposited within a subsiding foreland basin system (Bega & Soto, 2017; Roure et al., 2004).

The rifting phase started during the Triassic and finished during the Early Jurassic (Velaj et al., 1999). Since the Oligocene, crustal shortening has affected the area, producing the present-day ENE-directed fold and thrust belt controlled by a system of NNW-SSE striking thrusts (Frasheri et al., 2009; Mazzoli et al., 2022; Nieuwland et al., 2001; Velaj et al., 1999). Presently, the Ionian Zone exhibits an overall plunge to the northwest, as also highlighted by the present-day topography (Figure 1). In the northern sector, characterised by a subdued topography, the entire calcareous succession of the Ionian Zone is covered by a thick (locally > 10 km) succession of Cenozoic clastic sediments that accumulated in the so-called Periadriatic depression (Velaj et al., 1999). On the other hand, the folded and thrusted Mesozoic succession of the Ionian Zone is well exposed in the southern, mountainous sector. The boundary between the northern and southern sectors is marked by the NE-trending Elbasan-Vlora Transfer Zone (Mazzoli et al., 2022; Nieuwland et al., 2001). This zone is commonly interpreted as a major Cenozoic transfer zone of the thrust belt (Durmishi et al., 2014), probably controlled by an inherited Triassic/Jurassic strike-slip fault (Lacombe et al., 2009; Nieuwland et al., 2001). The relatively deep-water environment characterising the northern sector during the Middle and Late Triassic prevented the massive deposition of evaporites. Consequently, north of the Elbasan-Vlora Transfer Zone, the thickness of the Permian-Triassic evaporites is considerably less than in the southern sector (Nieuwland et al., 2001). This is evidenced by the lack of salt diapirs in the northern sector and by the different deformation style of the two sectors of the Ionian Zone in response to the contractional tectonic regime that acted throughout Albania: while the southern sector is characterised by extensive basement-cover detachment and thin-skinned imbrication, in the northern sector the Mesozoic-Cenozoic succession is essentially attached to the substratum (Durmishi et al., 2014; Frasheri et al., 2009; Mazzoli et al., 2022; Nieuwland et al., 2001; Robertson & Shallo, 2000; Roure & Sassi, 1995; Velaj, 2015; Velaj et al., 1999). Mazzoli et al. (2022), based on the interpretation of seismic lines calibrated with deep borehole logs and field observations, published five balanced and restored geological sections across Albania. Such sections show ramp-dominated thrusting involving both the basement and the overlying sedimentary cover north of the Elbasan-Vlora Transfer Zone. To the south the thick Permian-Triassic evaporites beneath the carbonate succession provide an efficient décollement throughout most of the thrust system, resulting in detachment-dominated thrusting of the sedimentary cover. However, a late-stage basement involvement in thrusting characterises also this southern sector, where the basement is substantially uplifted above the regional level in the frontal part of the fold and thrust belt (Mazzoli et al., 2022). The fact that the frontal part of the fold and thrust belt in Albania is governed by crustal ramp-dominated, basement-involved thrusting, was confirmed by the Mw 6.4 November 2019 Dürres earthquake (Caporali et al., 2020; Ganas et al., 2020; Govorčin et al., 2020; Pezzo et al., 2022; Santini et al., 2020; Teloni et al., 2021; Vittori et al., 2020).

3. Methodology

As first demonstrated by Dahlstrom (1969), 2D balanced cross-sections do not account for out-of-plane displacements nor for along-strike variations in fault geometry. Consequently, they inevitably approximate fault planes as surfaces with constant dip and strike within the section plane, which may lead to an oversimplified representation of fault geometries and kinematics. In non-cylindrical fold and thrust belts such as the Albanides, where major thrusts display pronounced along-strike curvature, variable dip angles, and lateral segmentation, only a full 3D model can correctly capture these geometric variations and provide a reliable architectural reconstruction of the thrust system (Balestra et al., 2019; Basilici et al., 2020, 2023; Castelluccio et al., 2016; Deville & Sassi, 2006; Mazzoli et al., 2022; Roure & Sassi, 1995; Santini et al., 2020, 2021; Tavani et al., 2021). In recent years, numerous efforts have been made to develop geological models that depict the subsurface arrangement of rock formations and faults in three dimensions, thereby taking into account out-of-plane movements (e.g. Balestra et al., 2019; Basilici, 2021; Basilici et al., 2020, 2023; DiBucci et al., 2021; Santini et al., 2021).

To construct a 3D structural model of the area, we relied on published geological maps (Viti, 2014; Xhomo et al., 2002), and published balanced cross-sections (Mazzoli et al., 2022) modified by incorporating new constraints provided by the seismic lines published by Scrocca et al. (2022). These seismic lines themselves are derived from subsurface datasets provided by the Albanian National Agency of Natural Resources (AKBN, 2025). The resulting sections were placed in a 3D environment using Move software (Petroleum Experts) to build the 3D structural model and estimate the maximum earthquake potential of major seismic sources in the area. With this respect, it is worth noting that the scaling relationship by Leonard (2014), commonly used to estimate the potential seismic source in an area, utilised a rectangular-shaped fault. Such a geometry, traditionally adopted for the parametrisation of deep seismogenic source, often leads to overestimating the seismic potential of active faults. In this study, using the 3D structural model, we are also able to define a symmetric fault shape that provides a more realistic and accurate geometry for the seismogenic source.

3.1. Balanced cross-sections

The balanced sections we considered for constructing the 3D model are based on those published by Mazzoli et al. (2022), modified considering new seismic lines published by Scrocca et al. (2022; Figure 3) derived from subsurface datasets provided by the AKBN and new field observations (Figures 4 and 5). Geological sections across the southern outer Albanides were developed using a combination of published geological maps (Viti, 2014; Xhomo et al., 2002), our own fieldwork observations, available stratigraphic data,

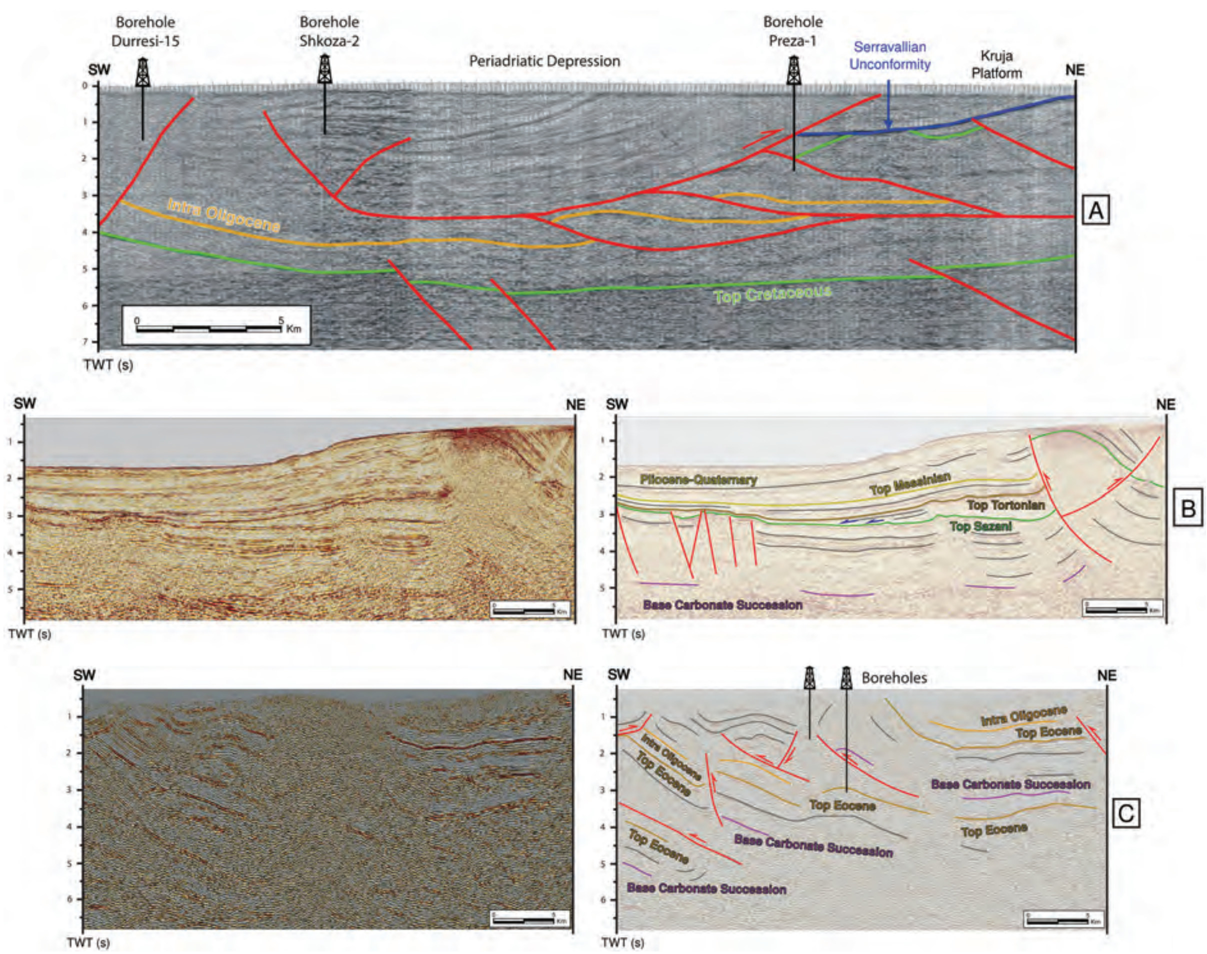

Figure 3. Examples of seismic lines. (a) Interpreted seismic profile (from Roure et al., 2004) across the northern sector of the study area, used to constrain section 1. (b) Seismic profile (from Scrocca et al., 2022) across the frontal southern portion of the Fold and thrust belt, and interpretation used to constrain the relevant part of section 3. (c) Seismic profile (from Scrocca et al., 2022) across the interior southern portion of the Fold and thrust belt, and interpretation used to constrain the relevant part of section 2.

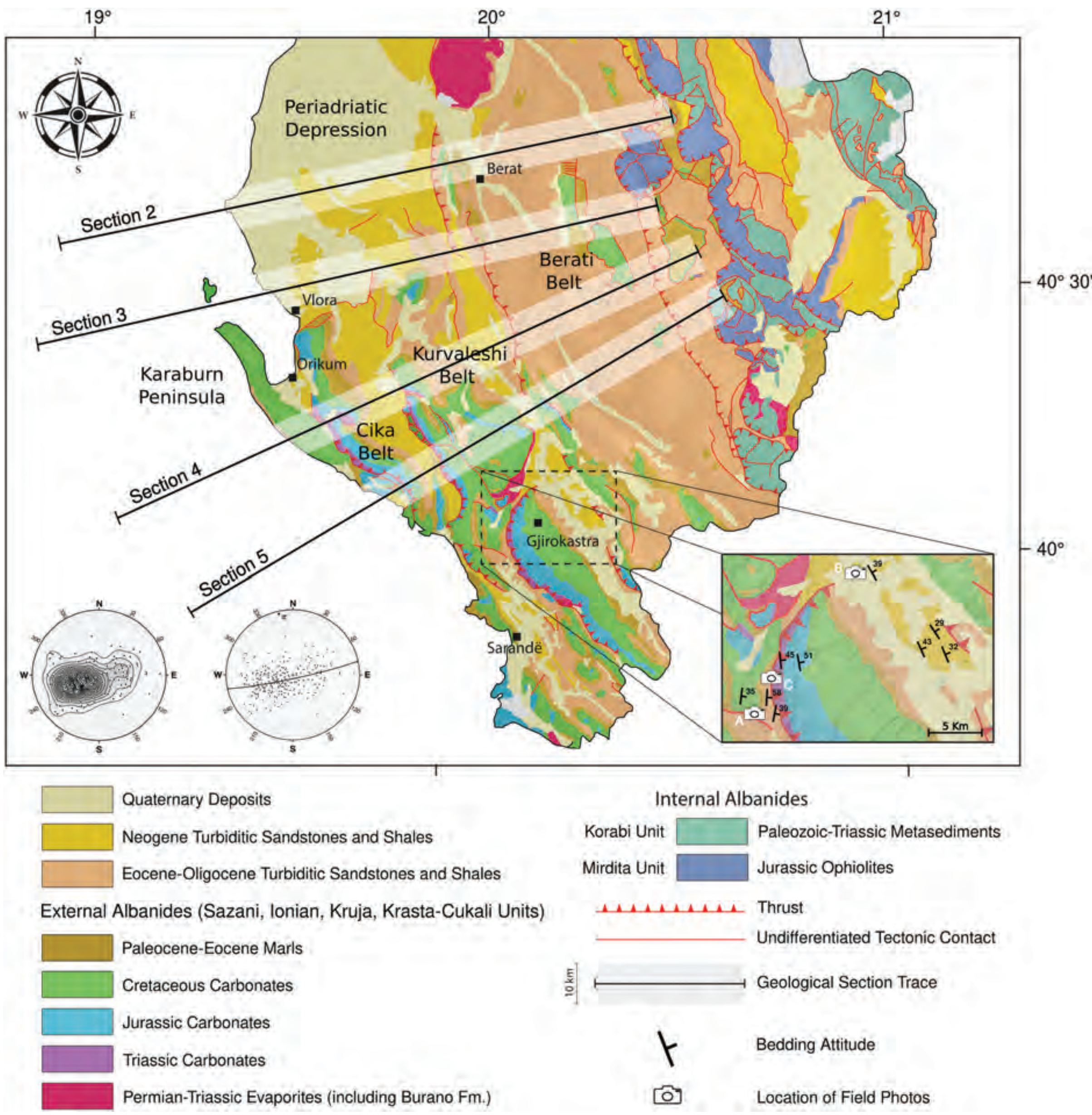

Figure 4. Geological map of southern Albania (modified after Muceku et al., 2006; Roure et al., 2004; Teloni et al., 2021; Mazzoli et al., 2022) draped onto a 30 m resolution digital elevation model (Source: https://www.eea.europa.eu), showing location of the southern cross-sections of this study. Bedding attitude data are plotted on lower hemisphere, equal area projections (on the right-hand diagram, poles to bedding are shown together with the best-fit great circle approximating their distribution and the related Pole, which provides the π statistical Fold axis). Plots related with individual cross-sections include data collected from the 10 km wide grey boxes surrounding each cross-section trace. The location of the field pictures of Figure 5 is also shown.

and seismic interpretations, all calibrated with deep well log data. Bedding data from the southern sector of the study area show sub-cylindrical folding (Ramsay & Huber, 1987) around a nearly horizontal, NNW-trending statistical axis (Figure 4. The larger folds exhibit wavelengths that range from several kilometres, as seen in the regional anticline of the Sazani platform carbonates in the Karaburn Peninsula-Mt. Llogarase region, to only a few hundred metres for the folds within the Ionian Basin succession. In the Ionian Basin, smaller folds with wavelengths of tens to a few metres appear as parasitic structures linked to the major folds. The Ionian Basin's predominantly calcareous beds show widespread evidence of flexural-slip folding, as bedding-parallel slip is recorded by striae and calcite shear fibres generally perpendicular to the bedding-cleavage intersection lineation. Regional folds within the Ionian Basin succession are commonly associated

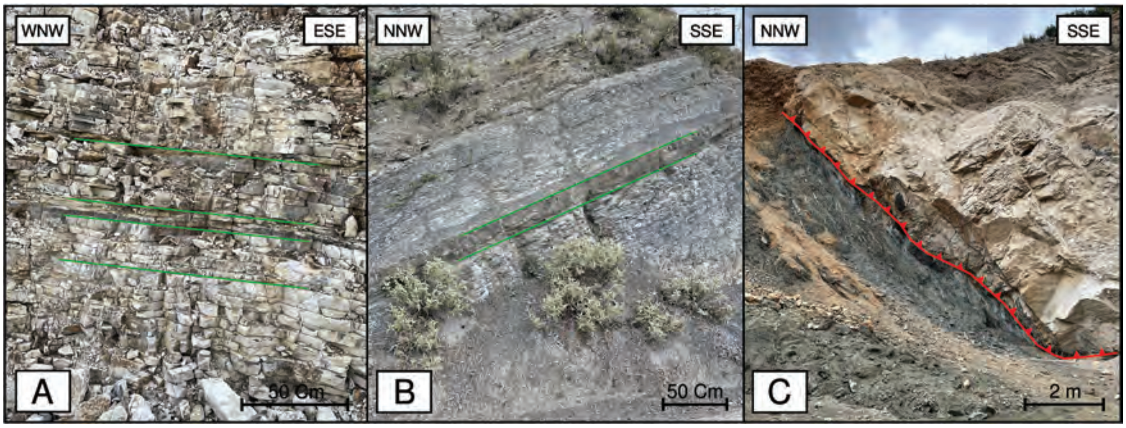

Figure 5. Field pictures from the Ionian Zone units exposed in the Gjirokastra area (located in Figure 4). (a) ESE dipping strata consisting of cretaceous micritic limestones exposed in the footwall of the main thrust in the Gjirokastra area. (b) NNW dipping beds consisting of Neogene turbiditic sandstones and Shales outcropping at the northern tip of the main thrust in the Gjirokastra area. (c) Detail of the previous tectonic contact, showing intense deformation in the Eocene-Oligocene turbiditic sandstones and Shales of the footwall block.

with thrusts transporting the hanging-wall block towards the W (Figure 4). A field example of a well exposed thrust fault is shown in Figure 5.

The balancing procedure was performed using the balancing analysis tool available in Move software, which primarily follows the classical approach by Dahlstrom (1969). However, this suite also allows for checking the quality of interpretations and identifying locations where horizons are missing or incorrectly interpreted, thereby reducing uncertainty in the resulting geological model. Specifically, the balancing analysis tool automatically unfolds all the horizons in the section into horizontal lines and calculates the area differences between fault blocks (e.g. Basilici et al., 2023).

3.2. 3D structural model

In this work, the first 3D model of the Ionian and Sazani Zones of Albania was constructed based on the integration of the available geological map of the region (Viti, 2014; Xhomo et al., 2002), draped onto a 30 m cell-size digital elevation model (source: https://www.eea.europa.eu), with the new five balanced cross-sections. Following the procedure recently outlined in Basilici et al. (2023), model building involved the construction of a dense grid of additional projected sections (n. 38 for the present work) perpendicular to the main structural trends (Figure 6). The process for constructing projected sections involves projecting a section onto its nearby section, constrained by the digital elevation model and geological maps.

This procedure allowed us to reconstruct the main fault surfaces (Figure 7(a)), taking into account the lateral variability of geological features observed from the map and occurring among the five original balanced sections. Finally, using spline interpolation, the following surfaces were constructed: (i) top basement (Figure 7(b)), (ii) top Permian-Triassic evaporites, and (iii) top Eocene of the Sazani, Ionian, and Kruja zones (Figure 7(c)).

The 3D model includes the NW-SE striking Southern Albanide Frontal Thrust (SAFT) south of the Elbasan-Vlora Transfer Zone. A symmetric elliptical shape was attributed to this structure for the sake of simplification in seismogenic source modelling. This approach helped overcome the overestimation made by using a rectangular shape in the scaling relationship by Leonard (2014).

4. Results

The first result of this study is the construction of five balanced cross-sections across the outer Hellenides of Albania (Figure 8), using sections published by Mazzoli et al. (2022) and modified based on new seismic lines provided by Scrocca et al. (2022), derived from subsurface datasets of the AKBN. While sections 1, 4, and 5 do not show significant differences compared to those published by Mazzoli et al. (2022), sections 2 and 3 exhibit substantial modifications in the offshore

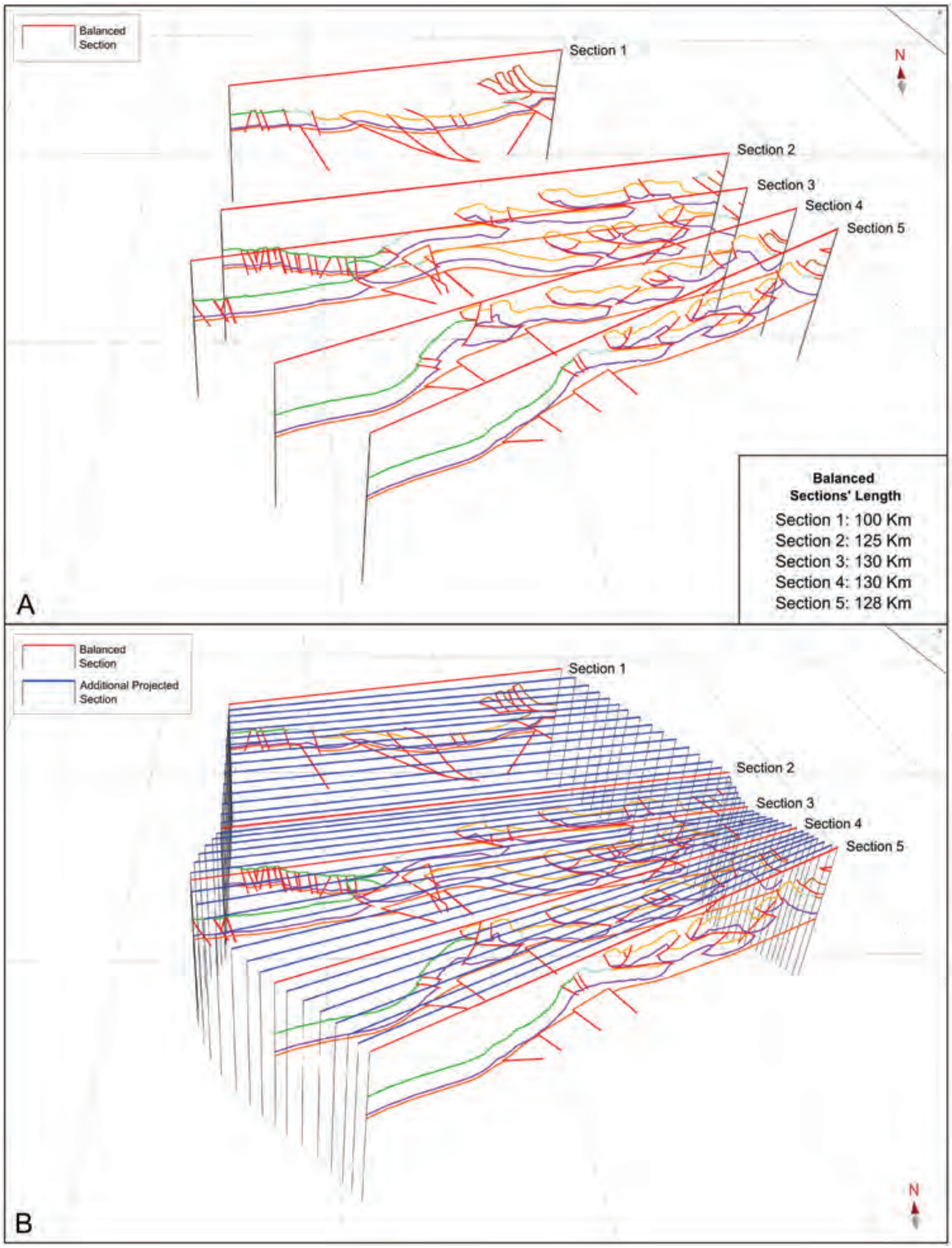

Figure 6. Steps for the construction of the 3D model using Move software (Petroleum Experts; see Figure 2 for the location of the 3D model). (a) Location of the five balanced sections in a 3D environment. (b) Generation of a dense grid of 38 additional projected sections.

areas due to new seismic sections. In the offshore area of section 2, the basement is located at a depth of ca. 10 km, defining a broad synclinal structure. The overlying cover is dissected by multiple NE-dipping normal faults, making it more consistent with section 1 located to the north. The Periadriatic depression in section 2 is completely filled by Neogene turbiditic sandstones and shales, and Quaternary deposits. Oligocene limestones and marls occur above the Mesozoic to Eocene sedimentary cover and are dissected along with it, clearly indicating that normal faulting occurred during Neogene foreland basin deposition. A similar architecture is visible in the offshore area of section 3. Here, the basement is almost horizontal at a depth of ca. 10 km in the footwall of the frontal thrust that carries the Sazani unit in the hanging wall, at variance with the previous interpretation provided by Mazzoli et al. (2022) that involved further thrusting offshore. The sedimentary cover follows the basement, with some NE-dipping normal faults. In this case, the

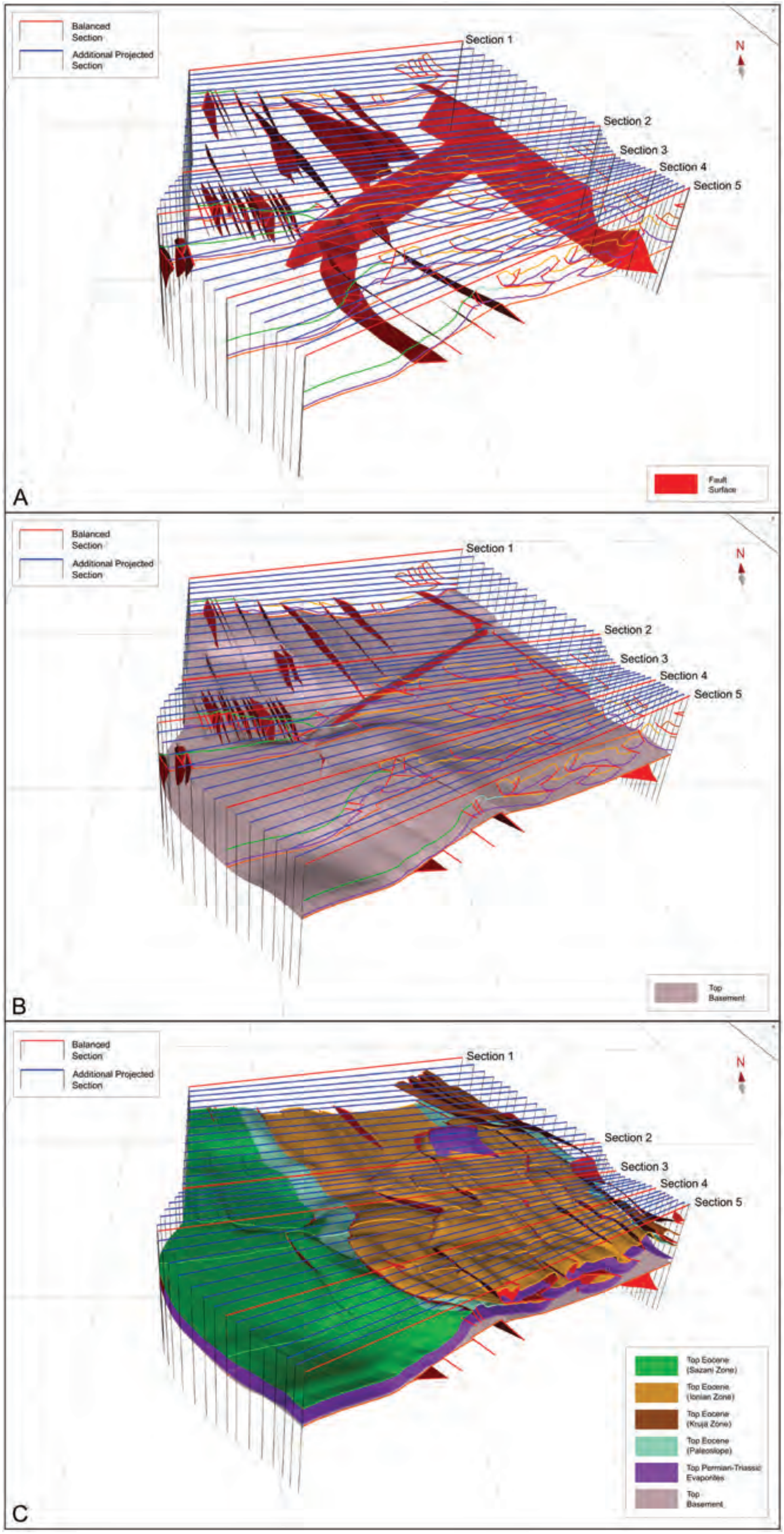

Figure 7. Steps for the construction of the 3D model using Move software (Petroleum Experts; see Figure 2 for the location of the 3D model). (a) Fault surfaces building. (b) Top basement building. (c) Sedimentary cover building.

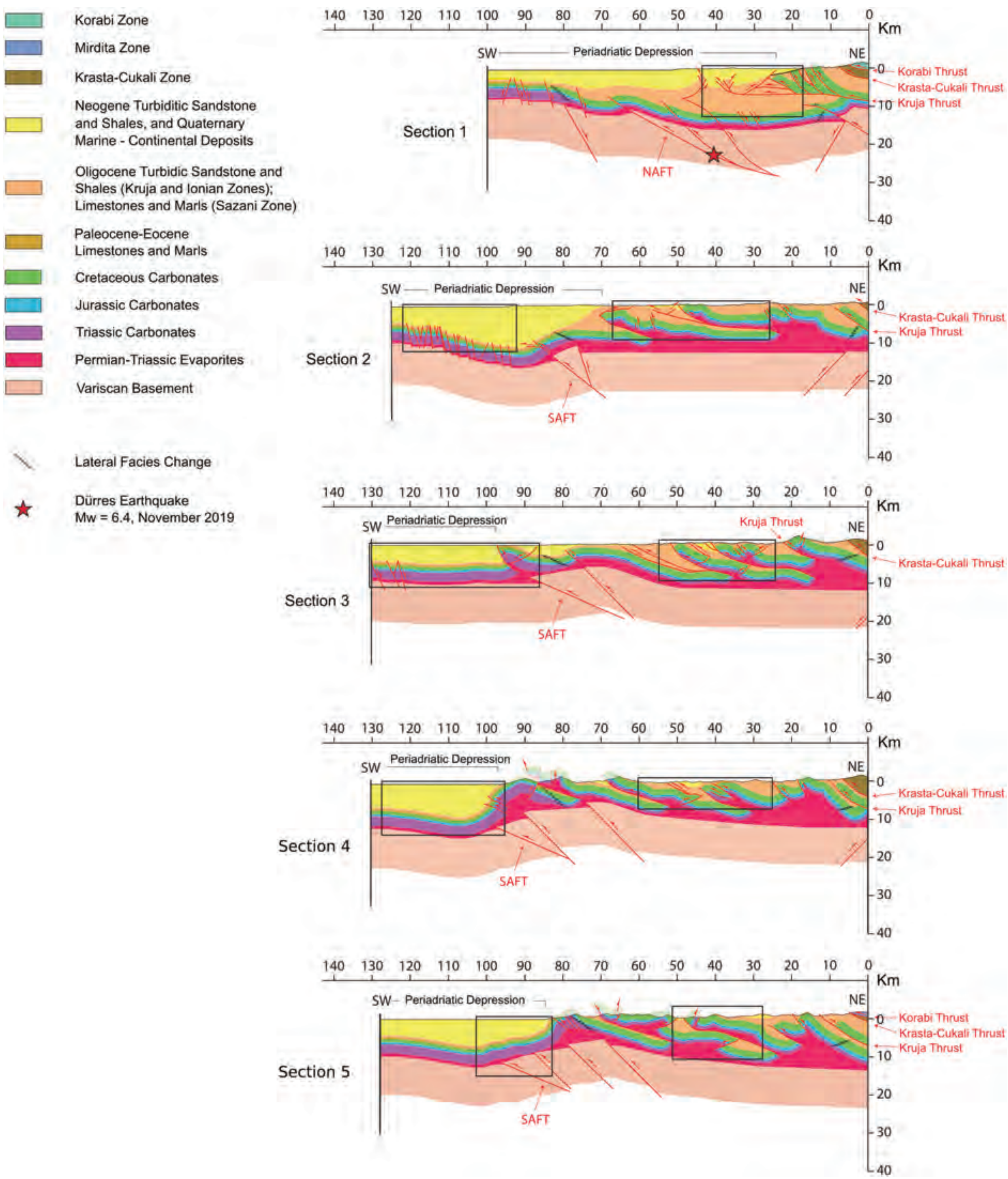

Figure 8. Balanced sections across the outer Hellenides of Albania (located in Figure 2, modified after Mazzoli et al., 2022 and Scrocca et al., 2022) used to construct the 3D structural model. No internal stratigraphy is shown for the Krasta-Cukali zone and internal zone units, which tectonically overlie the outer units forming the subject of this study. Boxes show areas constrained by seismic interpretation. NAFT indicates the northern Albanide Frontal Thrust, SAFT indicates the southern Albanide Frontal Thrust.

Periadriatic depression is also filled by Neogene turbiditic sandstones and shales, and Quaternary deposits.

The second result of this study is the 3D structural model (Figure 9). Observing the deformation style in three dimensions the following features emerge: (i) the Ionian Zone succession is intensely folded and imbricated south of the Elbasan-Vlora Transfer Zone, whereas it is mildly deformed to the north, where it is offset by thrusts ramping up from the basement; (ii) the Kruja Thrust is more advanced in the northern

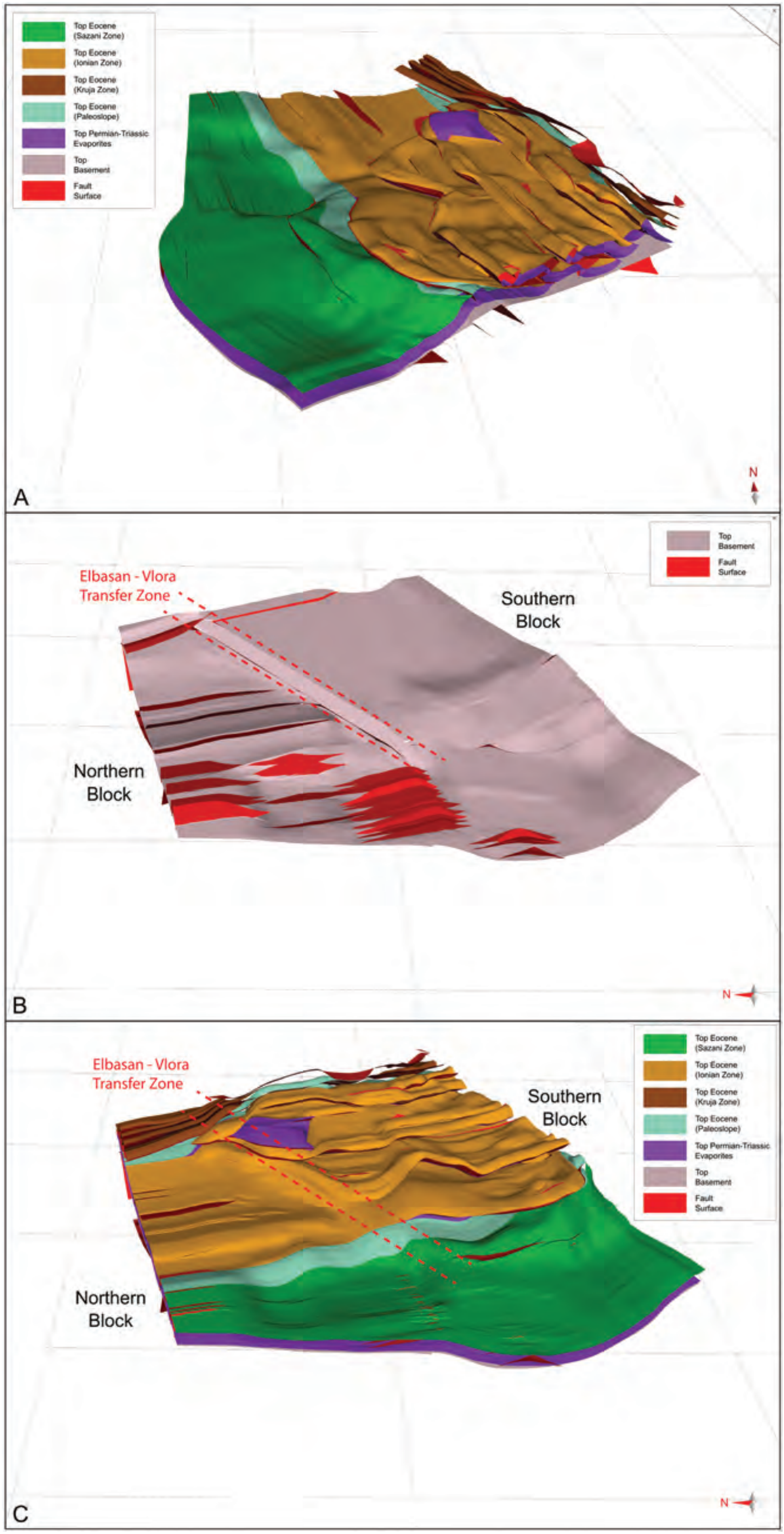

Figure 9. Completed 3D structural model of the outer Hellenides Fold and thrust belt of Albania and adjacent offshore (see Figure 2 for its location) based on balanced sections of Figure 8 and surface geological maps (Viti, 2014; Xhomo et al., 2002). (a) View from S, showing top basement, top Permian-Triassic evaporites, top Eocene (different colours used for this horizon show Ionian and Sazani Zones, and the paleoslope between them), and fault surfaces. (b) View from east of top basement and fault surfaces. (c) View from the east of the complete 3D model.

sector, having propagated within the foredeep succession of the Periadriatic depression; (iii) the Kruja Thrust is less advanced in the south, where shortening is accommodated by the detached Ionian Zone succession; (iv) the basement is significantly uplifted above the regional level in the frontal zone of the southern block; and (v) frontal basement uplift in the northern block is limited and insufficient to raise it above the regional level, since the thrust front is located along the flexed outer edge of the Periadriatic depression.

5. Discussion

Despite outlining a marked difference in the fold and thrust belt architecture between the north and south of the Elbasan-Vlora Transfer Zone, the sections indicate that a switch from detachment-dominated thrusting of the sedimentary cover to ramp-dominated, basement-involved thrusting affected the entire fold and thrust belt. The difference in deformation style between the northern and southern parts of the fold and thrust belt is due to the differing thickness of Permian-Triassic evaporites. In the north, the low amount of Permian-Triassic evaporites inhibited thrust belt propagation within the Ionian basin succession, favouring further advancement of the detached Kruja units in its hanging wall. In the south, the greater amount of Permian-Triassic evaporites produced intense shortening of the Ionian basin (e.g. Mazzoli et al., 2022 and references therein).

These along-strike differences in deformation style are consistent with the regional orogenic evolution proposed by Rossetti et al. (2025), who documented that late Miocene – Pliocene crustal thickening and exhumation in the Albanides were driven by deep crustal underplating. Their results indicate that a crustal-scale thrust system has been active since the late Miocene, providing the deep-seated framework for the basement-involved frontal thrusting documented in our 3D model.

Our 3D structural model documents a mixed tectonic style characterising the southern Albanian sector of the Hellenides fold and thrust belt. In addition to the dominant detachment-dominated thrusting controlled by the weak Permian-Triassic evaporites, basement thrusting occurs in the frontal part of the chain. Previous work based on seismic interpretation has highlighted dramatically different thicknesses of Permian-Triassic evaporites characterising the Ionian Zone on either side of the Elbasan-Vlora Transfer Zone (Lacombe et al., 2009; Nieuwland et al., 2001; Robertson & Shallo, 2000). Furthermore, substantial changes in evaporite lithology (more dolomitic in the northern block; Velaj, 2001) have resulted in a degraded quality of detachment. These features control marked along-strike variations in structural style in the outer Hellenides of Albania (Mazzoli et al., 2022; Velaj, 2011). Despite these major changes, the accommodation space filled by synorogenic sediments in the Periadriatic depression to the north is similar to that occupied by the imbricated Ionian Zone thrust sheets to the south (considering the flexural depocentre in front of the Kruja Thrust; see section 1 and section 5 in Figure 8). This reflects a roughly uniform flexure of the foreland lithosphere along the entire Albanian sector of the Hellenides. In the southern block, the substratum of the Oligocene-Miocene flexural depression (i.e. the Ionian Zone) was affected by substantial imbrication, thereby minimising the accommodation space for synorogenic sediments (Figure 8). The rapid accumulation of such synorogenic deposits is also thought to have hindered earlier inner thrust activity (Mazzoli et al., 2022). This eventually led to the locking of the Kruja Thrust, which controlled the thrust front in the northern block until late Miocene times. A comparison between the architecture of the northern and southern crustal blocks shown in Figure 9(c) suggests that, while late Miocene thin-skinned thrusting was affecting the Ionian Zone to the south, the Kruja Zone imbricate fan was scarcely advancing within the thick synorogenic deposits of the Periadriatic depression to the north, resulting in the development of a triangular zone at the leading edge of the Kruja Thrust.

Subsequent basement-involved thrusting was accompanied by the reactivation of the inherited deep-seated fault controlling the Elbasan-Vlora Transfer Zone. The oblique-slip reactivation of this southeast-dipping fault involved a reverse dip-slip component of motion accompanied by right-lateral strike-slip. This is consistent with transpressional deformation along the boundary between the northern and southern crustal blocks, effectively visualised by our 3D model (Figure 9). The Sazani Zone remained unaffected by shortening in the foreland of the northern block. On the other hand, the southwestward motion of the southern block was accompanied by basement-involved thrusting beneath the Sazani Zone. Our 3D structural model shows a 20 km dextral offset of the thick-skinned thrust front between the northern and southern blocks (Figure 10).

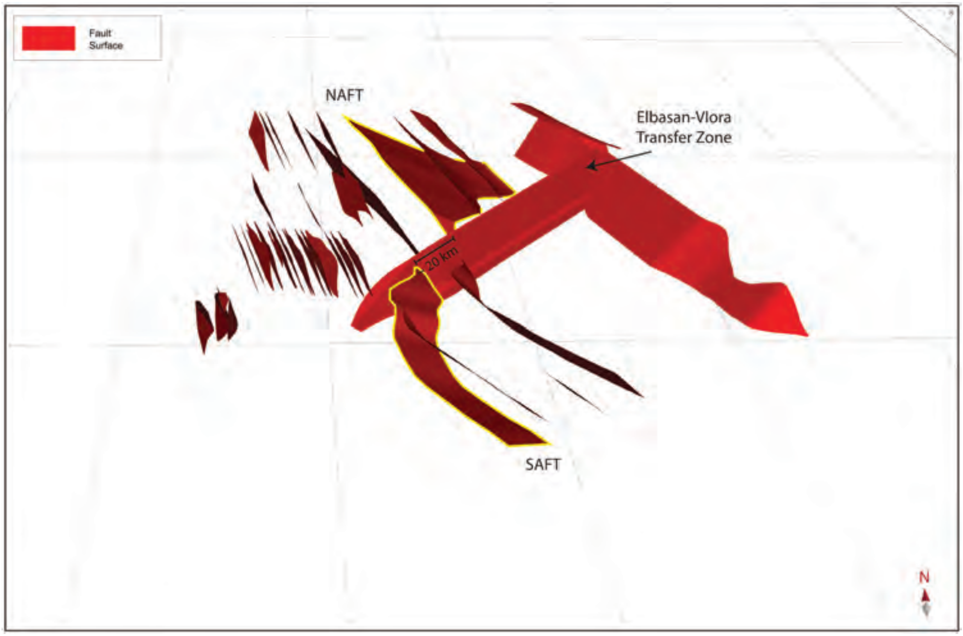

Figure 10. 3D structural model of the outher Hellenides Fold and thrust belt of Albania and adjacent offshore, showing fault surfaces and display between northern and southern Frontal Thrust (see Figure 2 for its location), based on balanced sections of Figure 8 and surface geological maps (Viti, 2014; Xhomo et al., 2002). NAFT indicates the northern Albanide frontal thrust, SAFT indicates the southern Albanide Frontal Thrust.

This is not significantly different from the previously estimated amount of right-lateral displacement along the Elbasan-Vlora Transfer Zone (28 km; Handy et al., 2019).

However, we do not imply that the thrust front was faulted, but rather that the basement-involved frontal thrust system developed at separate locations on either side of the transfer zone, coeval with its oblique-slip (dextral and reverse) motion. According to our interpretation, the uniform flexure of the downgoing Adria plate in the footwall of the Kruja Thrust (as described above) largely predated the ~5 Ma (Mazzoli et al., 2022) switch from thin-skinned to thick-skinned thrusting in the study area and the associated oblique-slip reactivation of the basement fault controlling the Elbasan-Vlora Transfer Zone. A new Pliocene-Quaternary foredeep formed ahead of the basement-involved frontal thrust in the southern sector of the study area, while thick-skinned thrusting just reached the outer edge of the Periadriatic depression to the north (Figure 9). This latter flexural basin continued to host clastic sedimentation throughout the entire Neogene-Quaternary, reaching the substantial thickness of synorogenic strata observed today (see section 1 in Figure 8).

The reconstruction of the 3D structural architecture and tectonic evolution of the northern Hellenides, highlighting the important role of late thick-skinned thrusting, has major implications for the active tectonic setting of Albania. Within this framework, the three-dimensional structural model also provides a geological basis for discussing the potential seismogenic significance of basement-involved thrusting in the frontal part of the Albanides, without implying a direct assessment of seismic hazard. Basement-involved, predominantly reverse faulting controlled the Mw 6.4 November 2019 Dürres earthquake. The main shock of this event was located at a depth of 22 ± 1 km according to seismic catalogues (INGV catalogue available at http://terremoti.ingv.it/search; USGS catalogue available at https://earthquake.usgs.gov/earthquakes/search/). Proposed source models include either a moderately west-dipping thrust (Ganas et al., 2020; Teloni et al., 2021; Vittori et al., 2020) or a steeply east-dipping reverse fault (Govorčin et al., 2020), the latter also involving a significant strike-slip component of motion according to Pezzo et al. (2022). In any case, the occurrence of a seismogenic basement fault in the frontal part of the fold and thrust belt is indicated by this earthquake. Recent crustal seismicity in the Greek offshore suggests that active basement-involved thrusting characterises the frontal part of the Hellenides south of our study area as well (Kamberis et al., 2022; Kokkalas et al., 2013). Since basement-involved fault activity is not equally well constrained by recent seismicity along the thrust front of southern Albania (i.e. south of the Elbasan-Vlora Transfer Zone), our 3D reconstruction may be used to model major – yet silent – potential seismic sources in that area. This, in turn, may have substantial implications for seismic hazard assessment in a densely populated region of Europe.

According to the INGV Database of Individual Seismogenic Sources (Basili et al., 2008), the southern Albanian offshore hosts a composite seismogenic source (named 'Sazani' and located near the frontal thrust of this study) characterised by a depth range of 1–15 km and an estimated maximum magnitude of Mw 7.6. On the other hand, our 3D geological model (Figures 9 and 10) includes a basement-involved frontal thrust extending in depth from ca. 9 km to ca. 20 km. Although discontinuous thrust faults also occur in the overlying sedimentary cover, indicating heterogeneous basement-cover interaction (folding/faulting) along the strike, the major structure here consists of a NW-SE striking crustal thrust ramp extending from the Elbasan-Vlora Transfer Zone to the Othoni-Dhermi Transfer Fault (located in Greece, south of the study area). This basement fault is termed here the Southern Albanide Frontal Thrust (SAFT). In detail, this ENE-dipping structure shows a variable strike (ranging from N346 to N328) and a moderate angle of dip (22–24°). The 3D reconstruction of the SAFT crustal ramp depicts an along-strike heterogeneous fault width (Figure 10). Since the overall geometry is characterised by a wider fault plane in its central portion, pinching out at the fault tips, a symmetric elliptical shape was attributed to this structure for the sake of simplification in seismogenic source modelling. The maximum expected moment magnitude, Mw, was derived from the fault area, A, using the fault scaling relation documented by Leonard (2014):

$$Mw = 4(\pm 0.3) + 1 \times \log(A)$$

Assuming an elliptical fault geometry of the SAFT with the long axis (fault length) of 70 km, and the short axis (maximum fault width) of 23 km, the resulting maximum moment magnitude is Mw = 7.1 ± 0.3. This is consistent with pre-instrumental seismic records (Grünthal & Wahlström, 2012; ISIDe Working Group, 2007; Pondrelli, 2002), which testify the occurrence of large historical earthquakes (Mw > 6.0) likely related to major basement-involved thrust structures within the studied fault system. The highest reported magnitude (Mw 6.82 ± 0.3) is assigned to an event that occurred in 1851 with an epicentre near the coastal city of Vlora (Grünthal & Wahlström, 2012), in the region of the NW termination of SAFT. Although, the proposed magnitude estimate should be regarded as a first-order approximation, as it is based on simplified geometric assumptions and does not account for possible fault segmentation, heterogeneous slip distribution, or temporal variations in fault activity.

6. Conclusions

This study provides new insights into the structural architecture of the outer northern Hellenides fold and thrust belt in Albania through the integration of balanced geological cross-sections and 3D structural modelling. The main results include the reconstruction of five balanced cross-sections across the belt, the development of the first 3D structural model of the Ionian and Sazani Zones, and the evaluation of the potential seismogenic implications of the Southern Albanide Frontal Thrust (SAFT). The balanced cross-sections highlight marked along-strike variations in the architecture of the fold and thrust belt across the Elbasan – Vlora Transfer Zone, documenting a transition from detachment-dominated thrusting of the sedimentary cover to ramp-dominated, basement-involved thrusting towards the frontal part of the belt. These differences are primarily controlled by variations in the thickness of Permian – Triassic evaporites, which exert a first-order influence on the deformation style of the Albanides. The 3D structural model allows a more comprehensive visualisation of these along-strike variations and confirms that shortening is partitioned differently between the northern and southern sectors of the belt. In particular, the model shows a more advanced propagation of the Kruja Thrust in the northern sector, whereas in the southern sector deformation is largely accommodated within the Ionian Zone, resulting in significant uplift of the basement in the frontal part of the belt. These results are consistent with a regional framework involving late-stage basement-involved thrusting beneath the Albanides. On the basis of the reconstructed 3D geometry, we explored the potential seismogenic significance of the SAFT. A first-order estimate of the maximum moment magnitude was obtained by applying established fault-scaling relationships to the modelled fault geometry. Although this estimate relies on simplified assumptions and should therefore be regarded as indicative, it suggests that basement-involved frontal thrusts may represent important, yet still poorly constrained, potential seismic sources in southern Albania. Overall, this work demonstrates the value of integrating balanced cross-sections within a three-dimensional framework to better characterise the architecture of non-cylindrical fold and thrust belts and to improve the geological basis for assessing the seismic potential of complex thrust systems.

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Author contributions

CRediT: **Matteo Basilici:** Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft; **Federico Cella:** Conceptualization, Data curation, Methodology, Supervision, Validation, Visualization; **Elia Leonardi:** Data curation, Investigation, Resources, Software, Visualization; **Stefano Mazzoli:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing; **Pietro Paolo Pierantoni:** Data curation, Investigation, Methodology, Resources, Supervision; **Vincenzo Spina:** Conceptualization, Data curation, Funding acquisition, Supervision, Validation; **Emanuele Tondi:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Supervision; **Tiziano Volatili:** Conceptualization, Data curation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing.

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