MIGRATING EARTHQUAKE SEQUENCES ON MAJOR FAULT SYSTEMS IN SOUTHERN AND EASTERN ALBANIA (1851- - 1942)

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ABSTRACT

Albania is located within the complex tectonic framework of the external Dinarides and Hellenides, where multiple active fault systems accommodate ongoing crustal shortening. However, significant uncertainties persist regarding fault segmentation, kinematics, and surface expression. This study integrates tectonic geomorphology, field observations, and historical data to reassess the relationships between active structures and destructive seismicity in southern and eastern Albania during the period 1851 to 1942. Remote sensing data (satellite imagery and digital terrain models (DTM)), high-resolution topographic data, and field surveys were combined with earthquake catalogues and focal-mechanism datasets to identify and evaluate seismogenic sources in two representative case studies. The first case concerns the Vlora–Elbasani Line and the southern frontal thrust system of the Ionian Zone, which produced a prolonged seismic sequence including more than twelve Mw > 6 earthquakes, culminating in the 1930 event. This sequence is interpreted as a migrating rupture process that facilitated the thrusting of the Ionian Zone over the Sazani Zone. Detailed analysis of the 1897 Dhiver earthquake reveals well-documented coseismic ruptures and highlights the persistence of oral traditions that preserve seismological memory. The second case study focuses on eastern Albania (1894-1942), where strike-slip deformation along the Peshkopi–Bilisht fault system is associated with pull-apart basins and major historical earthquakes within the Ohrid graben.

Keywords: Active faults, historical seismicity, seismotectonics, migrating earthquake sequences, crustal deformation, Albania

1. INTRODUCTION

Albania, located within the complex deformational framework of the external Dinarides and Hellenides, hosts numerous active fault systems that primarily accommodate southwest-directed crustal shortening. However, significant uncertainties remain regarding the surface expression, segmentation, and seismogenic potential of many of these faults. Although instrumental seismicity provides valuable constraints on the recent activity of certain structures, the historical earthquake record, when critically reassessed in the context of fault geometry, past surface ruptures, and regional tectonics, offers additional and often essential constraints for identifying and characterizing seismogenic sources. The data presented in this study were collected within the framework of the Scientific Cooperation Agreement between the National Research Council of Italy (CNR) and the Ministry of Education and Sports of the Republic of Albania, entitled "*Earthquakes, active tectonics and seismogenic sources in Albania*" (2021-2022). This initiative involved multiple Italian and Albanian institutions, including the Institute of Geosciences and Earth Resources (CNR), the Geological Survey of Italy (ISPRA), Institute of Geosciences of the Polytechnic University of Tirana, Academy of Sciences of Albania, Albanian Geological Survey (EATA project, https://seismotectonics-albania.com). Additional results from the same framework are presented in this volume by Di Manna *et al*. (2025), who focus on the active tectonics of the central seismotectonic province, and by Vittori *et al*. (2025), who describe the new integrated earthquakes catalogue developed within this collaborative project.

Migrating earthquake sequences are spatiotemporal patterns in which seismicity propagates systematically along a fault, or through a network of faults, over time. This migration is typically driven by static stress transfer from preceding events, pore-fluid diffusion, or aseismic slip transients. As strain accumulates on faults, rupture occurs when rock strength is exceeded, releasing stored elastic energy. The initial rupture not only relieves stress locally but also redistributes stress to adjacent fault segments or nearby faults, either promoting or inhibiting subsequent failure. When stress transfer promotes failure, it may generate a cascade of earthquakes in which one event triggers another (e.g. Mogi, 1968; Bonini *et al*. 2016). This process— variously termed migrating earthquake sequences, earthquake triggering, or static and dynamic stress transfer—is widespread in active tectonic regions. A classic example is the 1939-1992 earthquake sequence along the North Anatolian Fault, where ten major earthquakes with magnitude exceeding 6.7 ruptured approximately 1.000 km of the fault system over six decades (e.g., Stein *et al*. 1997). In this sequence, nine of ten major earthquakes occurred on fault segments brought closer to failure by stress transfer from preceding ruptuers. Similar behaviour was observed during the 2016 central Italy earthquake sequence (e.g., Pizzi *et al*. 2017) and the Turkey 2023 earthquake sequence (e.g., Núñez-Jara *et al*. 2025), although progressive fault failure may also occur at local scale (Fischer *et al*. 2023). Recognizing and modelling progressive rupture is therefore essential for seismic hazard assessment, as it helps to identify where future large earthquakes may occur and to estimate possible rupture lengths and maximum magnitudes. This approach also aids in identifying possible seismic gaps, that is segments of active fault systems known to produce significant earthquakes that have not slipped in an unusually long time compared with other segments along the same structure, considered likely to produce large shocks during the next few decades (e.g., Lay and Nishenko, 2022, and references therein).

In this study, we present two case histories from the southern and eastern seismotectonic provinces of Albania for the period 1851-1942. These examples illustrate how active fault systems, defined through remote sensing, morphotectonic analysis, and field observations, correlate with major historical earthquakes and provide insight into the interaction of seismic sources. The attribution of large earthquakes to mapped faults is based on both spatial relationships and on documented coseismic effects described in historical reports. Earthquake magnitudes, locations, and uncertainties were homogenized in the integrated Earthquake Catalogue of Ormeni *et al*. (2022) and Vittori *et al*. (2025), from which the seismic data in this study are derived. The analysed case studies provide clear evidence of the progressive rupture process in the development of earthquake sequences, emphasizing their importance for seismic hazard analysis and the design of effective risk mitigation strategies. They also contribute to a better understanding of active deformation and regional geodynamics in the broader Alpine–Dinaric–Hellenic region, particularly regarding the interaction between the Ionian Zone and the Sazani Zone (Adria) (e.g., Mantovani *et al*. 2023).

The overall objective of this work is to present an integrated analysis of selected active faults as case studies in order to develop a workflow applicable at both national and local scales. Based on a multidisciplinary approach, this workflow enhances the interpretation of major active tectonic zones and their relationship to seismicity, enabling the assessment of the seismic potential, fault interconnections, and the identification of seismic gaps and areas of elevated future seismic hazard.

These case studies provide concepts and methodologies that can support the development of a much-needed future national seismotectonic synthesis for Albania. Updating the active-fault and characterizing seismic sources using new data and modern analytical approaches are fundamental for producing an improved seismotectonic framework, which is essential for more reliable seismic-risk assessment and safer land-use and urban-planning strategies.

2. MATERIALS AND METHODS

The NW-SE trending Albanides represent a typical fold and thrust belt system (De Celles and Giles, 1996) characterized by a west-verging thrusting over the Apulia-Adriatic foreland. Based on variations in tectonic style, as well as in the rate and timing of deformation along the vergence direction, three different geological units are distinguished (Aliaj, 2006; Velaj, 2015): i) Apulia-Adriatic foreland, ii) the Albanides orogen, and iii) the peri-Adriatic depression. The review of active tectonics of Albania presented here builds upon a critical appraisal of published literature combined with original investigations.

The structural-geomorphological analysis is based on the premise that active faults intersecting the topographic surface generate ground ruptures, producing characteristic landforms that accumulate over time and leave persistent geomorphic signatures. The degree of preservation or sharpness of these morphological features is commonly interpreted as an indicator of their relative recency. Our approach integrates tectonic geomorphology and structural geology through the analysis of remote sensing imagery and digital terrain models at multiple spatial scales, targeted field mapping in key areas, and geological information derived from the literature, with the aim of identifying features of tectonic significance. Where possible, the mapped faults were checked directly in the field along their most accessible traces in search of evidence of Late Quaternary or historical co-seismic ruptures. This approach has been successfully applied also in Albania, in the context of both active normal and reverse faulting (Hoffman *et al*.2010; 2012; Biermann *et al*. 2019, 2021; D'Agostino *et al*. 2022; Aliaj and Mesonjesi, 2023).

The morphotectonic study was conducted at the regional scale, through the interpretation of satellite imagery (Google Earth) and digital terrain models (DTM) with spatial resolution of 30 m (ALOS 3D World, SRTM) and 10 m (COPERNICUS EU-DEM). At the local scale, higher-resolution topographic maps and orthophotos available via Web Map Services (WMS) from Albanian geportals (http://geoportal.asig.gov.al/map/?auto=true and http://www.gsa.gov.al/en) were analysed, complemented by targeted field surveys. At specific sites (e.g., Dhiver; see Section 3.1.1.), high-precision drone-based photogrammetry was used to image and quantify fault scarps in detail.

From a seismological perspective, a first step consisted of homogenizing the various earthquake catalogues compiled for Albania and neighbouring regions into a single integrated dataset (Ormeni *et al*. 2022; Vittori *et al*. 2025). A similar integration and homogenization procedure is currently being applied to develop a unified focal-mechanism catalogue. These datasets have been further updated with additional information from 2023–2024. Particular attention was devoted to the critical revision of historical earthquake reports describing coseismic surface ruptures along major active faults and other associated coseismic phenomena.

Based on the integration of these datasets, ground ruptures described in the contemporary sources as particularly significant—showing lateral continuity along strike and located within the epicentral areas of strong earthquakes—were interpreted as the surface expression of seismic ruptures at depth and were associated with the corresponding active faults.

3. RESULTS AND DISCUSSION

The results of this study were synthesised into a preliminary map of potential capable faults and fault systems of Albania, compiled using QGIS (Fig. 1). In the following sections, we present two representative examples of fault systems characterized by ongoing seismicity and well-defined kinematics in the southern and eastern Albanides, with particular emphasis on their possible structural linkages and progressive activation.

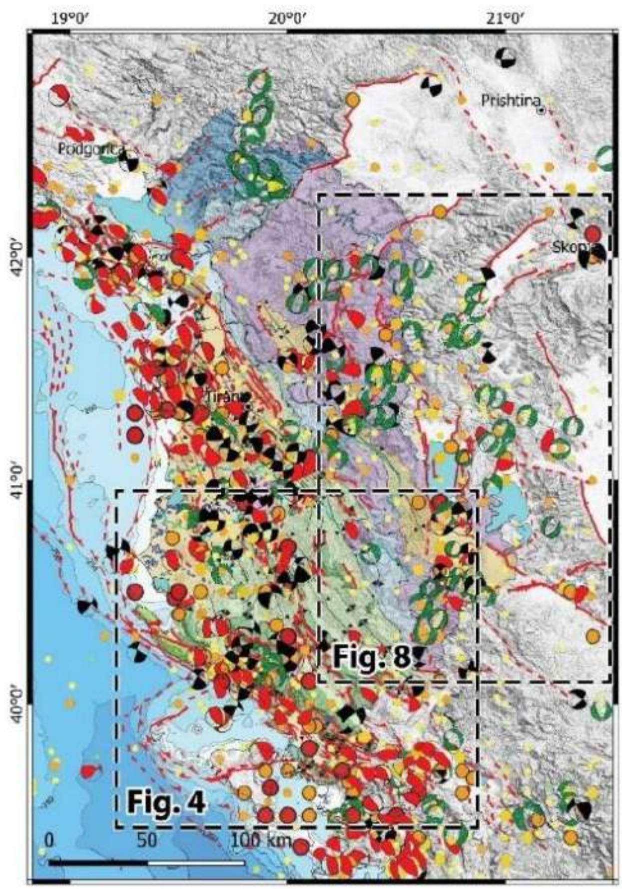

Fig. 1: Schematic map of active fault systems, earthquakes and focal mechanisms of Albania.

3.1. Vlorë-Elbasan Line and frontal thrust system of the Ionian Zone (1851 to 1930)

The N50°E- trending crustal structure known as the Vlora-Elbasani-Dibra Line, hereinafter referred to as the Vlora-Elbasani Line (VEL), is recognised as one of the most hazardous active fault systems in Albania. The VEL is characterized by predominantly oblique normal-dextral movement (Sulstarova *et al*. 2000).

The fault zone is exposed in a quarry NE of Kanina, where the fault plane strikes 325° and dips 75° toward the northwest (Fig. 2). Slickensides preserved on the fault surface indicate normal-dextral oblique slip, with a rake of approximately 135°. Also crops out outside the quarry, the fault plane can also be traced at the base of the cumulative fault escarpment (Figs 2B and 2C). In this southern sector, the normal component of motion along the VEL, which contributed to the development of the peri-Adriatic basin, is expressed by a large NW-dipping monocline south of Selenica. The structure reflects the tilting of the Pliocene-Pleistocene deposits associated with basin subsidence (Fig. 3).

In 1851, the VEL generated a destructive seismic sequence comprising five earthquakes with M > 6 earthquakes occurring in the same year, three of which took place within an interval of 8 days (Vlora on October 12, Mw 6.6/6.82, Elbasani on October 17, Mw 6.6, and Berati on October 20, Mw 6.1) (Fig. 4A). This sequence was preceded by an Mw 6.3 earthquake near Elbasani on January 20 and followed by an Mw 5.74 event near Berat on 29 December. Together, these events indicate progressive rupture along the fault system. Seismic activity continued in Vlora area in 1859 and 1862, with two earthquakes of Mw 6.1, culminating in the strong earthquakes of 1866. During that year, a sequence of three major shocks (Mw 6.6, 6.24 and 5.89) struck the region over a two-month period (January 2, February 28 and March 2, respectively) (Figs 3 and 4B), producing extensive surface faulting between Vlora and Kanina.

Mihailovic (1927) referred to the 1866 earthquake as "*the Seventh destruction of Vlora and Kanina* If this expression is interpreted as referring to the destructive events over the past two millennia, it would imply an average recurrence interval of approximately 285 years. This estimate is consistent with the timing of the previous strong earthquake documented in the Vlora area on April 26, 1601 (Mw 6.6), which occurred roughly 250-265 years before the 1851-1866 seismic sequence.

Fig. 2: (**a**) The Vlora fault zone near the surface. (**b**) Cumulative fault scarp. (**c**) Vlora fault plane cropping out at the base of the scarp, where it reaches the topographic surface.

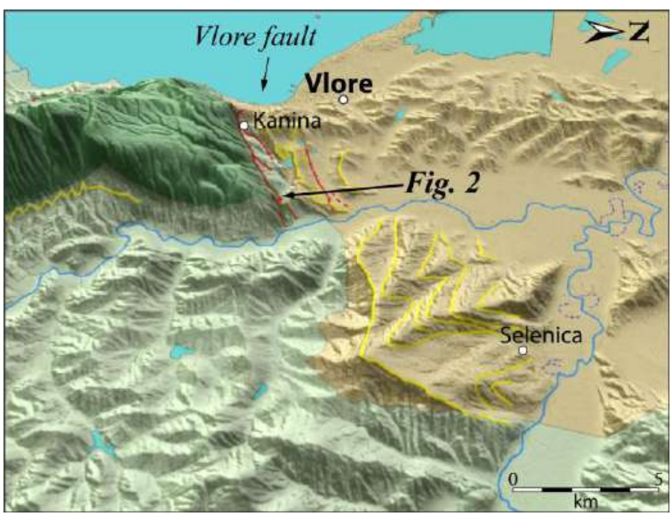

Fig. 3: Perspective view toward the southwest on the Vlora fault and the monocline at Selenica.

The southern frontal thrust system of the Ionian Zone, extending between Borshi (Albania) and Paramythia (GR), was also activated during a seismic series lasting several years, with major earthquakes occurring in 1893, (Mw 6.62), in 1895 (two events of Mw 6.2 and Mw 6.8), and in 1897 (Mw 6.2 and Mw 6.58) (Fig. 4C). Although surface faulting is clearly documented only for the 1897 event, the entire sequence is consistent with the activation of the frontal thrust belt, here referred to as the Maja e Frasherit thrust front, after its most prominent topographic expression.

Seismic activity resumed in 1920, concentrating in Tepelena and Vlora regions. On November 26, 1920**,** an Mw 6.2 earthquake almost completely destroyed the town of Tepelena, caused severe damage to villages along the Shkumbini River valley, from Adalit to Pekini including Bença, Turani, Dhemblani, Memaliaj, Kashishti, Salari, Dragoti, and Luzati. On 18 December 1920**,** a further earthquake (Mw 5.6) struck Vlora and also damaged Elbasani. The epicenter of this event was located offshore (40.5N, 19.5E), and it generated a tsunami in the Gulf of Vlora that flooded Sazani Island and inundated extensive coastal areas, resulting in numerous fatalities (Morelli, 1942).

The two fault systems described above —the Vlora-Elbasani Line and the southern frontal thrust system are not independent structures. Instead, they form part of a single major fault system that defines the margin of the Ionian Zone thrust pile, which overthrusts the Sazani Zone. The 1930 earthquake effectively filled the seismic gap between Borshi and Vlora along this margin (Fig. 4D). Despite the complexity of the event, historical descriptions of the earthquake effects and ruptures (Novack, 1931, 1933) allow the identification of the principal coseismic faulting, which corresponds spatially to this previously unruptured segment.

Overall, the available evidence suggests that a complete earthquake cycle unfolded over a period of 79 years (1851 - 1930), during which more than twelve earthquakes with M > 6 activated a fault system exceeding 250 km in length, extending from Elbasani to Paramythia. This progressive activation likely accommodated a discrete increment of thrusting of the basal fold-and-thrust system of the Ionian zone over the Sazani Zone (i.e., Adria) (Fig. 4E). Within this framework, the Vlora-Elbasani Line (VEL) functions as a major tear fault within the thrust pile, characterized by a right-lateral component of slip and downthrow of the northwestern block, at least southwest of the Dumrja salt diapir. The right-lateral displacement along this structure also offsets the main seismically active frontal thrust belt of Albania (Fig. 1).

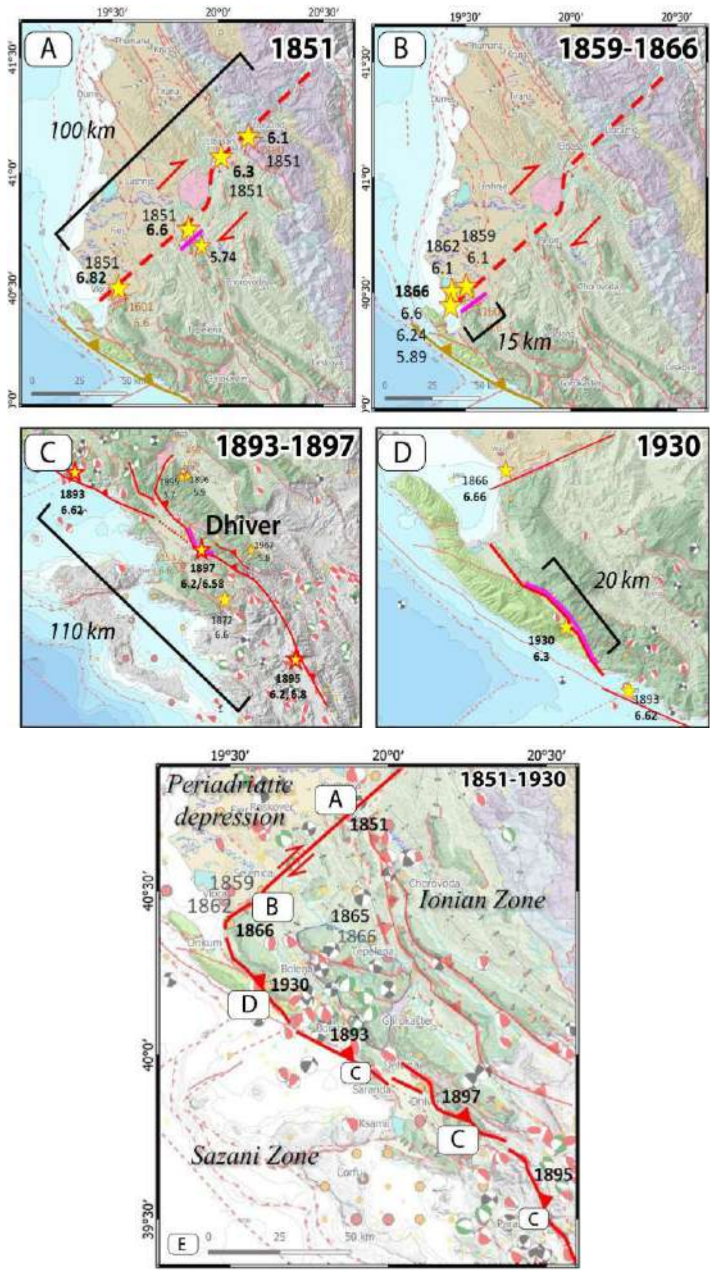

Fig. 4: Relevant earthquakes along the VEL and southern front of the Ionian zone: (**a)** 1851, (**b**) 1866, (**c**) 1893-1897, (**d**) 1930. In purple the relative co-seismic surface ruptures. (**e**) Summary diagram of the 1851-1930 seismic cycle, allowing the thrusting of the Ionian Zone over the Sazani Zone (Adria).

3.1.1. Dhiver earthquake, 1897

The Dhiver earthquake of 17 January 1897 (Mw 6.2-6.58) is examined in detail as a representative case study, as the coseismic ruptures associated with the event are not only well documented in contemporary sources but are also preserved in the collective memory of the local population.

Agamennone (1897), the primary contemporary source, compiled information obtained from local eyewitness accounts (Albini and Stucchi, 1997). Although Agamennone reports the date as 15 January, the event is consistently listed as January 17 in subsequent catalogues.

The earthquake was strongly felt in Saranda and Delvina and the near-complete destruction of the mountain village of Dhiver (Fig. 5). Severe damage was also reported in localities located within approximately 15 km of the epicentral area, including Koukouratés or Kullurice, Cerkovice and Navarice (Albini and Stucchi, 1997) (Fig. 5B). Despite the detailed historical documentation, there remain contrasting interpretations regarding both the epicentral location and the magnitude of the event. Sulstarova *et al*. (1972) initially placed the epicenter at Dhiver, whereas Sulstarova and Kociaj (1975) later relocated it closer to Delvina. In the European Pre-instrumental Earthquake Catalogue EPICA (Rovida *et al*. 2022), the epicentre is positioned near the Greek border, approximately 15 km south of Dhiver. Based on the spatial distribution of damage and documented coseismic effects, we consider the most plausible location to be at or near Dhiver, along the same frontal thrust system activated during the 1893 and the 1897 earthquakes (Fig. 4C). The magnitude is estimated at 6.58 in the EPICA catalogue and at 6.2 in Papazachos *et al*. (2010); the latter estimate appears more consistent with the spatial distribution and intensity of observed effects. Given the limited extent of both the epicentral and damage areas, the earthquake was likely characterized by a relatively shallow focal depth.

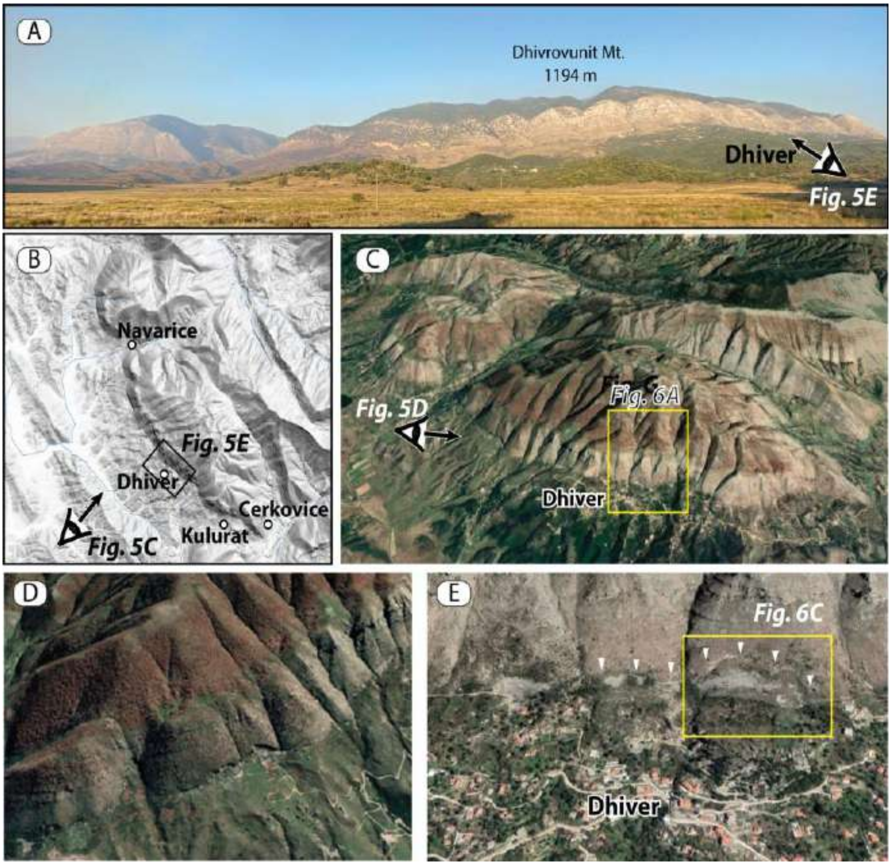

Fig. 5: (**a**) Panorama on the Dhiveri thrust front toward the southwest. (**b**) DEM of Dhiveri thrust area. (**c**) Perspective view toward NE of the fault generated mountain front. (**d**) Thrust front and fault scarp between Dhiveri and Navarica. (**e**) Seismic rupture of the 1897 earthquake at the base of the faceted slope (white triangles).

Coseismic ground ruptures were described in a contemporary local newspaper (*Le Moniteur Oriental*; Agamennone, 1897):

" … *La montagne de Divri a été fendue en plusieurs endroits et des crevasses sortaient des flammes et de la fumée*" ["The mountain of Divri was split in several places, and flames and smoke were coming out of crevasses"].

Sulstarova *et al.* (1972) further note:

"*This village* [Dhiver] *was completely destroyed. There were cracks in the ground up to 15 cm wide, in root (limestone) rocks.*

> […] *many aftershocks, which lasted for 7-8 months. In the vicinity of the epicentral area (Dhiver mountain), tremors were felt every 10-30 minutes during the first month.*"

During a field survey conducted on October 4, 2021, we interviewed a local resident, Mr. Spyros Saqellaris (born in Dhiver in 1947), who spontaneously provided the following oral testimony. According to his grandfather, the earthquake of 1897 produced three distinct ground steps at Dhiver extending from the base of the mountain slope down to the square of the present-day village. At that time, the settlement also occupied the area at the foot of the slope [the ruins of several houses can still be seen]. The highest rupture can still be seen at the foot of the mountain [Mr. Saqellaris identified these traces with the rock "scarplet" that we had observed at the base of the triangular facets], the lowest rupture passed through the square of the present-day village. The houses at the foot of the slope were abandoned on that occasion, and the people moved to the present-day village.

The details reported in this oral account are consistent with our geomorphological observations and structural interpretations, thereby supporting the attribution and dating of the surface rupture to the 1897 event (Figs 5 and 6). Owing to the clarity of the description and the precision of the locations indicated, this testimony constitutes a reliable account of significant seismological value and shows how oral tradition can preserve detailed memories of major seismic events across generations.

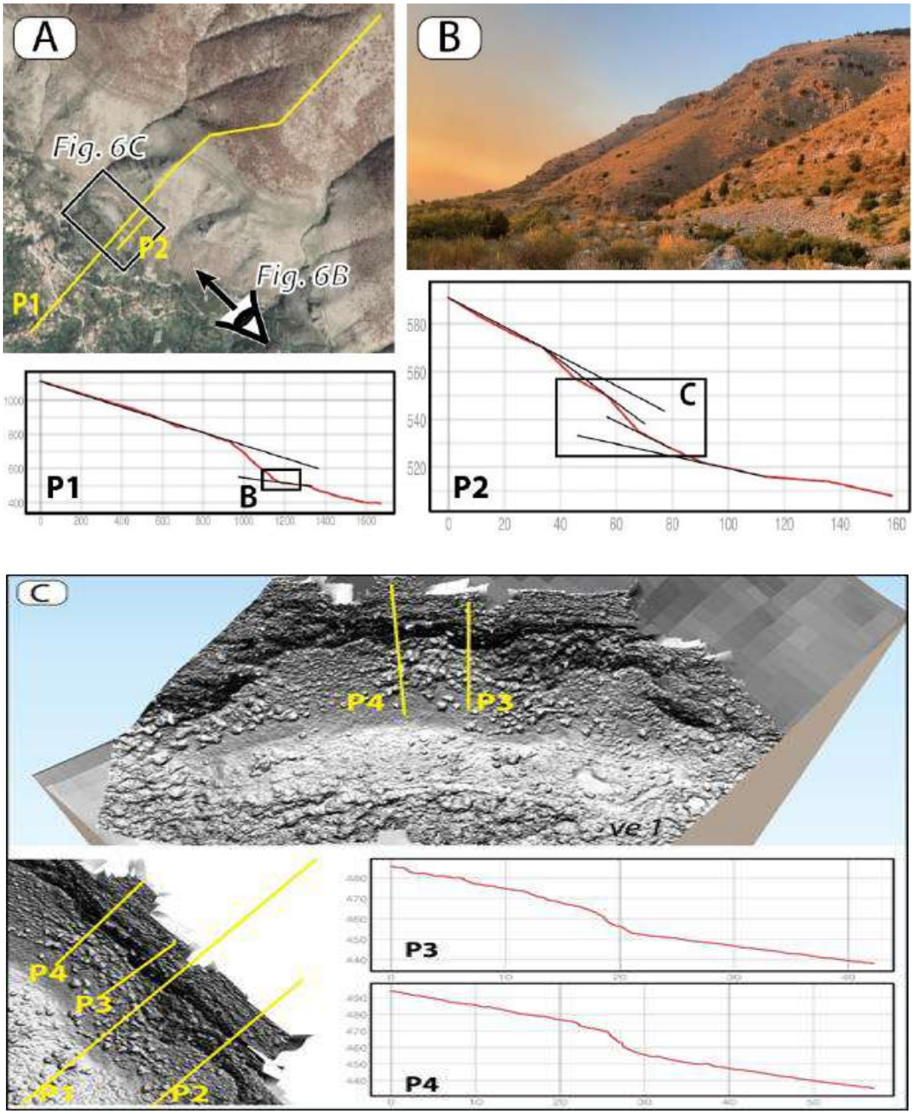

Fig. 6: (**a**) Mountain front profile, vertical height of the faceted spurs. (**b**) Vertical offset of the long-term cumulative scarp at the base of faceted spurs. (**c**) Topographic profiles across the scarp of the seismic rupture of the 1897 earthquake, DTM from drone photogrammetry. Fault plane, oriented N150, dipping 70° toward the southeast.

The concave geometry of the fault plane (Figs 5E and 6C) indicates a significant contribution of gravitational processes to the evolution of the thrust front. At the surface, we observe coseismic normal faulting, despite the broader structural and morphotectonic evidence indicating an active thrust front. This apparent inconsistency can be explained by the effect of thrust-front collapse (Pace *et al*. 2017, and the references therein), a process documented at several locations in Albania, including the Bureto thrust front (Fig. 7).

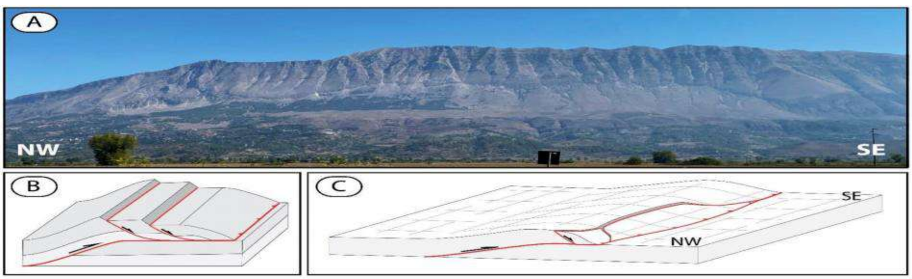

Fig. 7: (**a**) Gjirokastra valley, western slope of Mt. Bureto thrust ridge (1763 m). The fault trace is clearly visible. This fold and thrust ridge, extending until Berat, is a major structure, the first one to the northeast of the southern frontal thrust system (Fig. 4E). (**b**) Theoretical schematization of the thrust front collapse as it may have happened at Dhiveri (redrawn after Pace *et al*. 2017). (**c**) Sketch of the same mechanism along the Mt. Bureto thrust ridge of Fig. 7A.

3.2. Eastern province: the Peshkopia-Bilishti strike-slip system (1894-1942)

The tectonic extension observed in the eastern seismotectonic province is unlikely to reflect a regional extensional regime. Instead, it is interpreted as the result of localized deformation associated with pull-apart structures developed along the Peshkopia-Bilishti strike-slip fault system (Fig. 8A). This configuration is evident north of Peshkopia, where the fault bends to an approximately N-S orientation, and is particularly well expressed in the Ohrid Lake graben, which developed as a pull-apart basin along the right-lateral structure.

A destructive seismic sequence affected this fault system over a five-year period, with major earthquakes occurring on 28 September, 1896, (Mw 6.2) and 18 February, 1911, (Mw6.6-6.80), in the Ohrid pull-apart graben system (Hoffman *et al*. 2010; 2012; D'Agostino *et al*. 2022). A longer seismic sequence spanning the period 1894-1942 may reflect the progressive activation of the entire strike-slip system.

The effects of the right-lateral displacement along the transcurrent fault system are expressed by the offset of geomorphological and tectonic features. These include the dextral offset of Mt. Deja-Mt. Kreshta massif, west of Peshkopia, which is consistent with the stress field inferred from earthquake focal mechanisms in the area (Fig. 8B). The outlet of the smaller of Prespa Lakes also shows right-lateral offset (Fig. 8C), and a comparable horizontal displacement is observed at the western termination of the Inoi fault near Lake Kastoria (Fig. 8D). In several locations, the fault plane is exposed at the surface (Fig. 9), where slickensides further confirm the right-lateral component of slip inferred from the morphotectonic analysis.

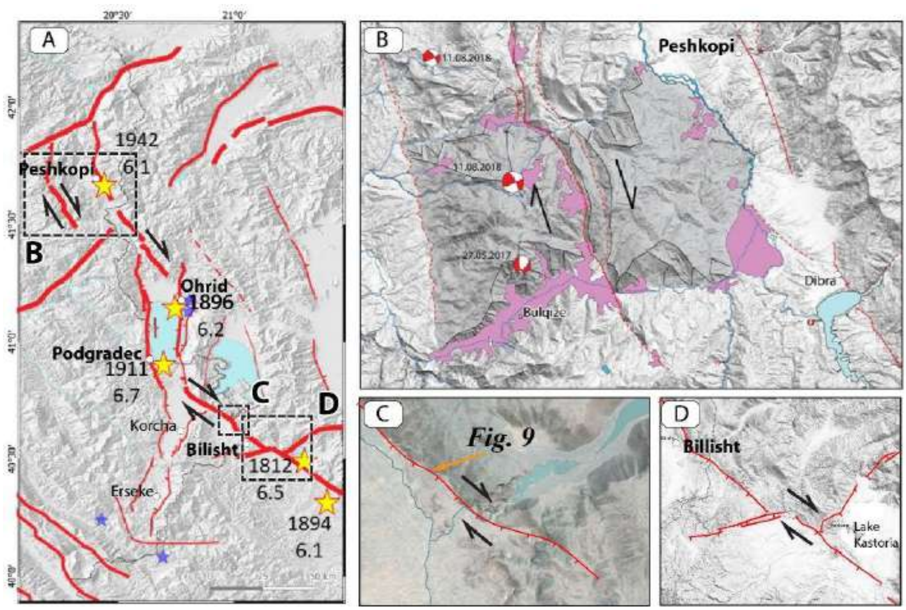

Fig. 8: Eastern province. (**a**) Erkese-Korçë-Ohrid graben and Peshkopia-Bilishti strike-slip system. Blue stars indicate hydrothermal springs. (**b**) Mt. Dejes-Mt. Kreshtes massif is right-laterally dislocated, coherent with focal mechanisms of local earthquakes. (**c**) Abandoned outlet of the Prespa Lake, right-laterally offset by the fault. (**d**) Inoi fault displaced by strike-slip.

Fig. 9: Bilishti fault. (**a**) View toward the NW. (**b**) Fault plane. (**c**) Slickensided fault plane.

4. CONCLUSIONS

The present study adopts an integrated tectonic approach applied to selected seismically active, fault-related zones. This approach combines the analysis of historical and instrumental seismicity with documentation of earthquake effects derived from contemporary reports and eyewitness accounts, together with structural and morphotectonic analyses conducted using remote sensing data and targeted field surveys at key sites. Preliminary interpretations of fault kinematics and geometry are evaluated in relation to the regional stress field and the spatial distribution of historical earthquake effects. In several areas, available geochronological data and coseismic indicators support the occurrence of recent surface faulting. Where possible, correlations are proposed between individual fault segments and specific seismic events documented in the historical catalogue.

The overarching goal is to propose a methodology that can be progressively extended to the national scale, and refined at the level of individual fault systems. Although the examples presented here are spatially limited, they demonstrate the potential of active fault mapping as a fundamental tool for constraining seismic source models. They also highlight the importance of a multidisciplinary framework integrating geology, paleoseismology, historical seismology, and geodesy.

This contribution is intended to support a shared framework for seismotectonic mapping in Albania. By illustrating how individual fault zones can be systematically analysed and linked to seismic observations, this study provides a reference for ongoing efforts to improve the national-scale characterization of seismic sources, an essential requirement for robust seismic hazard assessment, risk mitigation and land-use planning. The preliminary nature of the case studies reflects both the richness of the available datasets and the remaining gaps in knowledge that must be addressed through future targeted investigations.

The identification and characterization of seismic sources, particular those affecting major urban centres, represent a critical priority for Albania. Cities such as Vlora are exposed to high seismic hazard, and rapid urban expansion over the past century has significantly increased the associated risk. Comprehensive mapping of active faults, improved understanding of the architecture and interconnections of fault systems, paleoseismological characterization of major structures, and continued refinement of historical and instrumental seismic catalogues, are all essential steps toward a more complete understanding of earthquake behaviour in Albania.

Advances in these areas are crucial for the development of effective seismic risk mitigation strategies, ultimately reducing the potential impact of earthquakes on communities, infrastructure, and the environment in one of the most seismically active regions of the Mediterranean.

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