ACTIVE MORPHOTECTONIC EVIDENCE IN THE TIRANA AREA (NW ALBANIA)

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Introduction. Albania lies in the centre of the active Peri-Adriatic thrust and fold belt, roughly trending NW-SE from the Dinarides (north) to the Hellenides (south), cut by major NE-SW- fault zones (Fig. 1a). Compressional seismic events with magnitudes > 7 (e.g., 1979 Montenegro earthquake) affect the external, coastal areas, while normal faulting dominates the inner areas. The recent Mw 6.4 Durrës earthquake on 26-11-2019 caused heavy damage and killed 51 people (IGEWE 2019, Vittori et al. 2021), rivitalizing the open question of seismic hazard in NW Albania. In fact, the historical seismic catalogue shows an intense seismicity with many Mw > 6 only during the last two centuries, likely providing an incomplete picture of the actual seismic potential. Several important faults, mainly thrusts and transfer faults, are already known (Aliaj et al. 2010 with references), but their true seismogenic potential and capability are still poorly accounted for. The goal of the ongoing work is to point out the capable faults and folds in the Tirana and Durres Basins by their morphotectonic evidence and seismicity, to contribute to a more geologically-sound assessment of the seismic hazard in this highly developed region. A better knowledge of the seismogenic structures is also relevant for the seismic and tsunami hazard of the Adriatic-Ionian facing countries, including Italy.

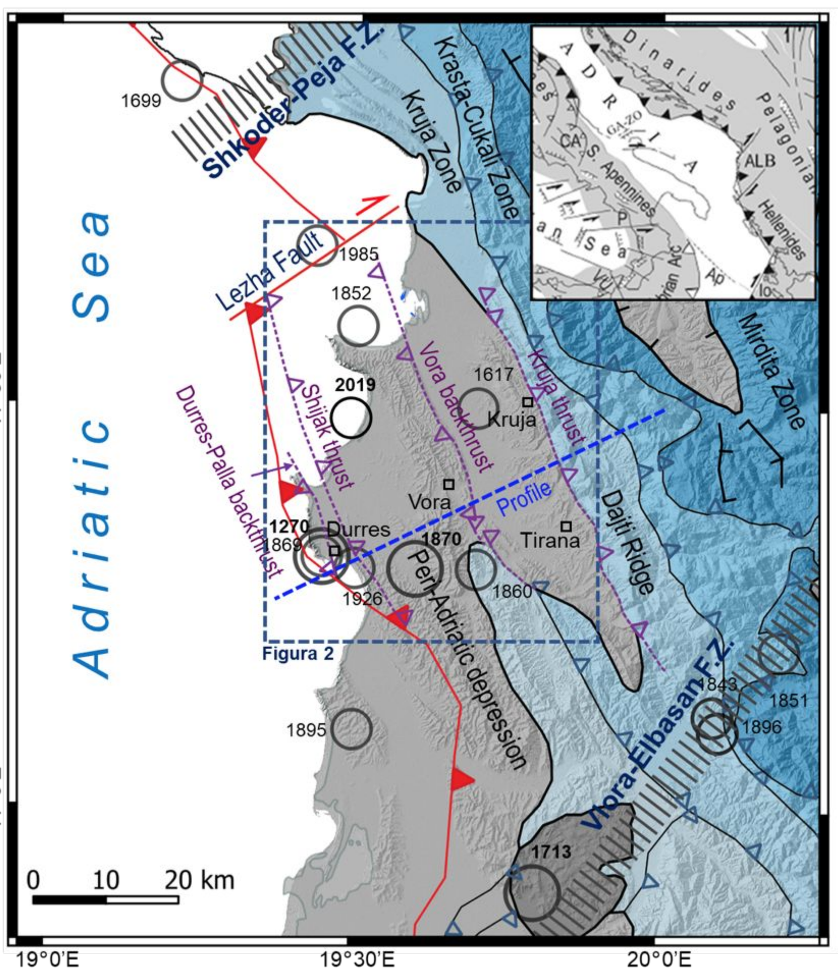


Fig. 1a. Simplified Geological map of NW Albania (Vittori et al. 2021) and major historical earthquakes.

Geological and tectonic setting of western Albania. The Albanides developed since the Upper Jurassic following the subduction of the Adria microplate under the Eurasian Plate and the subsequent collisional and post-collisional process started in the Early Miocene (Handy et al. 2019 with references). The study area corresponds to the NW sector of the Western Albanides tectonic domain, where three main tectonic units crop out bounded by regional thrusts: from E to W, Krasta-Cukali, Kruja and Ionian zones (Fig.1a,b,c). The peri-Adriatic depression developed as a foredeep on the front of the external Albanides thrust belt. In this sector, the active SW shortening is probably related to a slab take-off process (Biermanns et al. 2018 with references). The continuity of the Albanides along strike is interrupted by three main transversal, roughly NE-SW striking, lineaments whose role is debated: the Shkodër-Peja, Lezha and Vlora-Elbasan fault zones. Seismological, GPS and field data suggest a normal faulting along the Shkodër-Peja since the Neogene and an earlier right-lateral kinematics (Jouanne et al. 2012). The Lezha fault zone (Aliaj et al. 2000) separates Plio-Quaternary thrust and fold belts of different axial orientation: about NW-SE in the north (Dinarides trend) and about NNW-SSE to the south. Across the fault zone also a rapid change of the GPS velocity field occurs (Jouanne et al. 2012). To the south, the SW-NE-trending Vlora-Elbasan lineament (VEL) (e.g., Roure et al. 2004) roughly marks the boundary between the Ionian and the Adriatic sectors of the External Albanides.

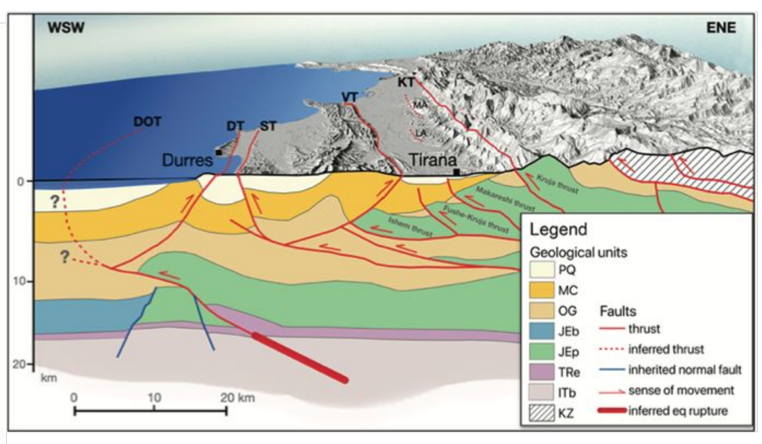


Fig. 1b. 3D tectonic section across western Albania.

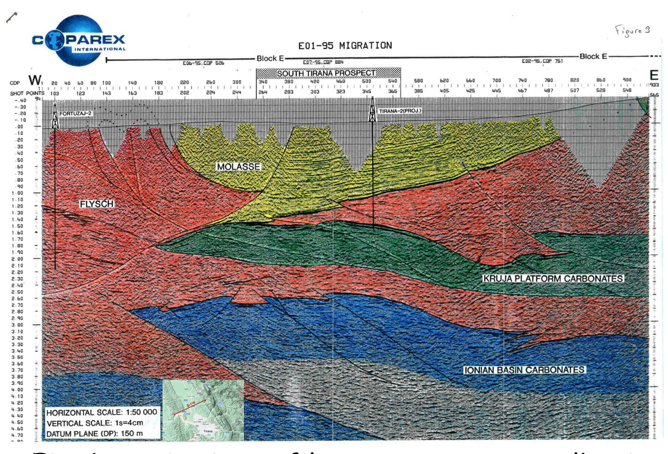


Fig. 1c. Seismic profile across western Albania

Major seismic events. Albania is affected by diffuse seismicity, both historical (Aliaj et al. 2010, Guidoboni et al. 2019) and instrumental (Ormeni et al. 2022; Fig. 2). In the study area 12 events of M>6 are known since Roman times, of which 7 in the last two centuries. The 1270 earthquake is the first sufficiently documented event. It caused damages and many victims in Dyrrachium (IX-X MCS, Me 6.2, Guidoboni et al. 2019) (Fig. 1d). Supposedly, the source fault was very close to the city, since violent vertical movements were reported. A poorly known event, Me 6.2, hit Kruja in 1617. After, several earthquakes with M>6 took place between Durres and Tirana in the XIX century, the strongest in 1870 (M 6.7). Two strong seismic events followed with epicenter near Durres: 1926 (IX MSK, Mw 6.1) and 2019 (VIII-IX EMS, Mw 6.4) (IGEWE, 2019; Ganas et al. 2020; Vittori et al. 2021). During this last event, due to the rather deep hypocentre (≥ 20 km), no coseismic surface faulting occurred and tectonic uplift/subsidence and westward movement were the only primary effects (Vittori et al. 2021; Fig. 3). The field surveys (Lekkas et al. 2019, Vittori et al. 2021) pointed out widespread secondary effects: mostly, ground fissures, liquefaction and lateral spreading. The focal mechanisms confirm the prevalent compressive tectonics (Ormeni et al. 2022; Fig. 2).

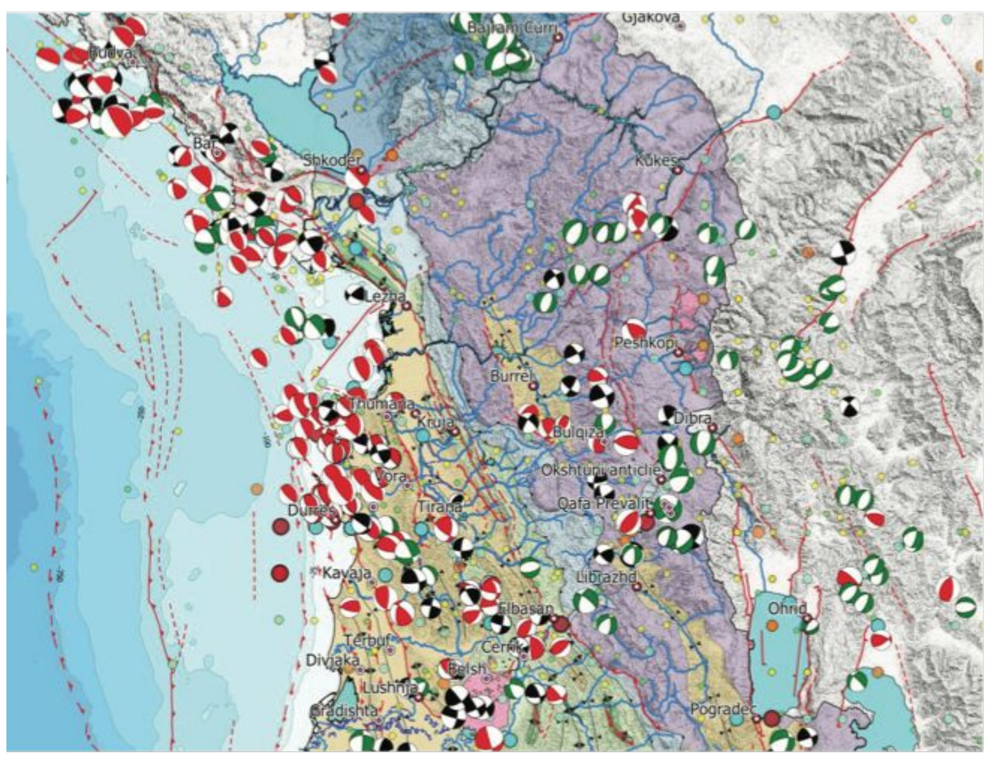
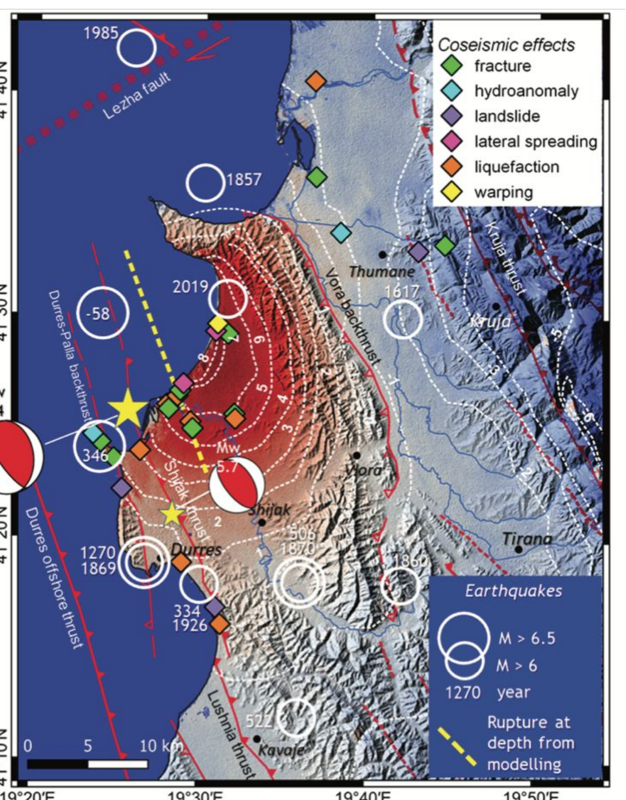


Fig. 2. Focal mechanisms distribution in NW Albania, according to IGEWE data

Fig. 3. Effects of the November 26, 2019, earthquake.The epicentres according to IGEWE of the main shock and the strongest aftershock are shown, together with their focal mechanisms (RCMT catalogue, Pondrelli 2002). White circles: historical earthquakes. Yellow dashed line: top of rupture from modelling (14 km deep, 20 km long). Coseismic deformation according to InSAR (toward Line Of Sight), red to blue, also represented as dashed white isolines (cm). From Vittori et al., 2021



Morphotectonics. The landscape from the Kruja thrust front to the coastline is characterized by folding with narrow anticlines and large synclines, resulting in alternating NW-SE-elongated lowlands and ridges, the latter often bordered by active thrust faults on their western side and/or backthrusts on their eastern flank. The parallel organization of tectonic plains and ridges highly affects the hydrographic network (Fig. 3A). The Tirana-Thumana synform, filled by Late Miocene-Pliocene molasses covered by Quaternary fluvial deposits, is a wide NW-SE depression controlled by the combined activity of the external structures of the Kruja thrust front to the east and the facing Vora backthrust.

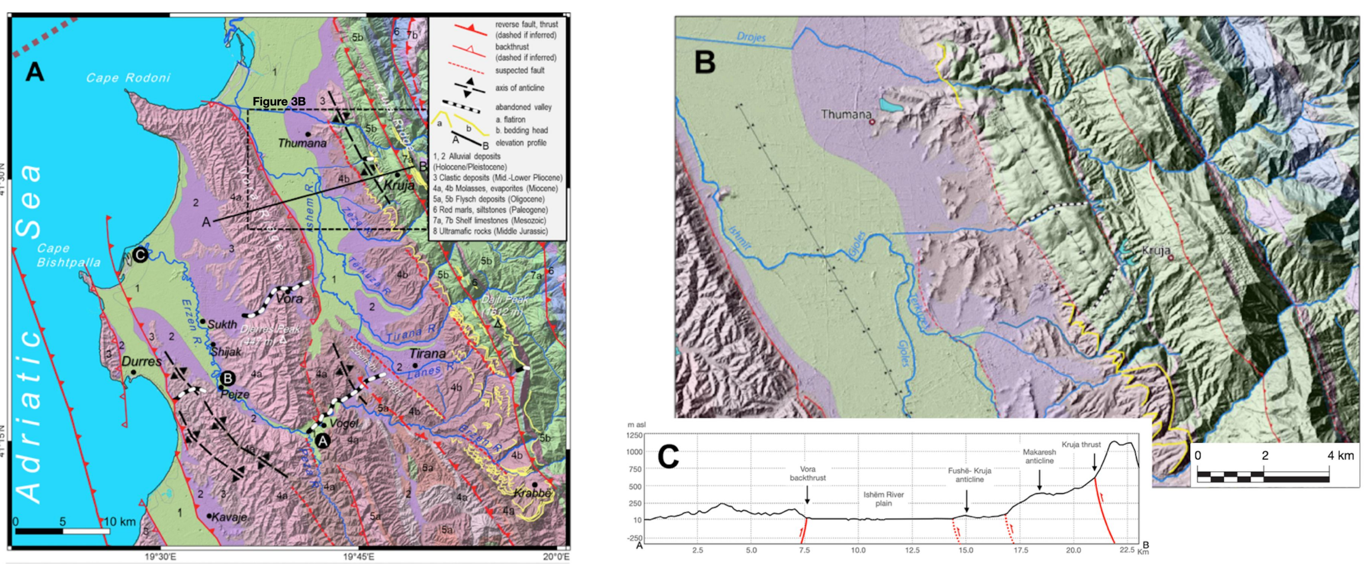


Fig. 3. A) Morphological evidence of active tectonics in NW Albania. Red lines: thrusts (empty teeth: backthrusts). Stratigraphy from (https://geoportal.asig.gov.al/en/data). B) Copernicus 10 m DTM detailing the morphotectonic features of the anticlines in front of Kruja thrust. C) Topographic profile across the Tirana Basin.

The **Kruja thrust front** is composed by an outcropping internal roof thrust and a basal thrust envelopping a stack of thrusts buried under the Tirana wedge-top basin deposits, deformed at surface by the NW-SE oriented Ma- karesh, Fushë-Kruja and Ishëm anticlines. The main thrust (Dajti-Kruja) bounds with a NW-trending rectilinear front the Dajti mountain ridge for ca. 50 km (Fig. 3, 4a). The very steep and straight scarp just above the tectonic contact of the Mesozoic limestones with the underlying Oligocene flysch de- posits is suggestive of neotectonic activity, but the slope deposits were not seen affected. In the frontal zone, Quaternary slope breccias were found in tectonic contact with the limestones through a SW dipping normal fault (Fig. 4b) NW of Kruja, without a clear scarp at surface, likely representing secondary phenomena within the thrust mechanisms. Conversely, the morphological connection between the emergence of the thrust and the top surface of old Quaternary breccias, now largely eroded, under the old castle, may suggest sealing (Fig. 4c). Overall, the data collected so far are insufficient to conclusively deny the current activity of the thrust, constraining it to the younger structures west of it. At the foot of the Dajti-Kruja main thrust, an Early Oligocene-Late Miocene succession of mainly clay and sandstone deposits crops out, with a prominent bedding steeply dipping SW. The tectonic uplift and the differential rate of the erosional processes have generated impressive flatirons at the base of the ridge just NE of Tirana (Fig. 3). West of Kruja, the shortening associated to the first buried thrust has originated the NW-SE trending **Makaresh anticline**, whose growth is shown by disruption of the hydrographic network, including small endorheic basins on its eastern flank. West of it, another smaller anti- cline is the surficial expression of the Fushë-Kruja thrust (Velaj 2011). Its recent growth has originated a kind of hummocky morphology, possibly suggestive of a slowing down of the folding process here.
The course of the Ishëm River is determined by Holocene activity of the main tectonic structures. Notably, its right-side tributaries show a bend from ca. E-W to SE-NW due to the barrier effect created by the uplift of the Vora ridge and the concurrent subsidence of its footwall in the Tirana syncline (Fig. 3). The western side of the Ishëm river plain is bordered by the NW-SE striking Vora ridge, whose uplift results from the NE-vergent Vora backthrust and the activity of the buried Kruja and ionian thrust systems (Fig. 5).

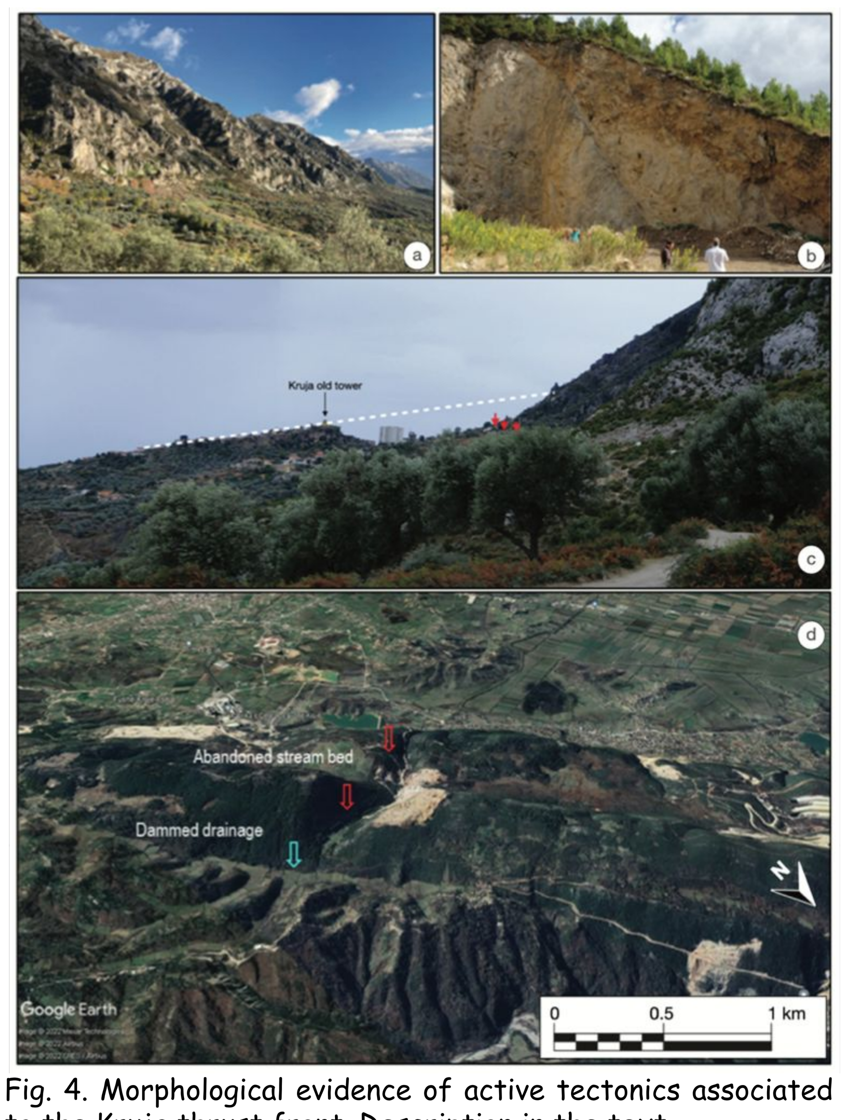


Fig. 4. Morphological evidence of active tectonics associated to the Kruja thrust front. Description in the text

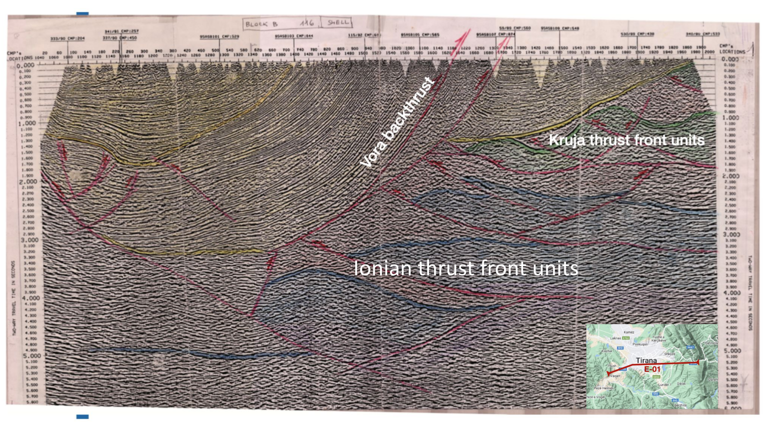


Fig. 5. Seismic profile across the Vora ridge and the Tirana Plain. The Vora backthrust and the Kruja and Ionian thrust fronts are marked

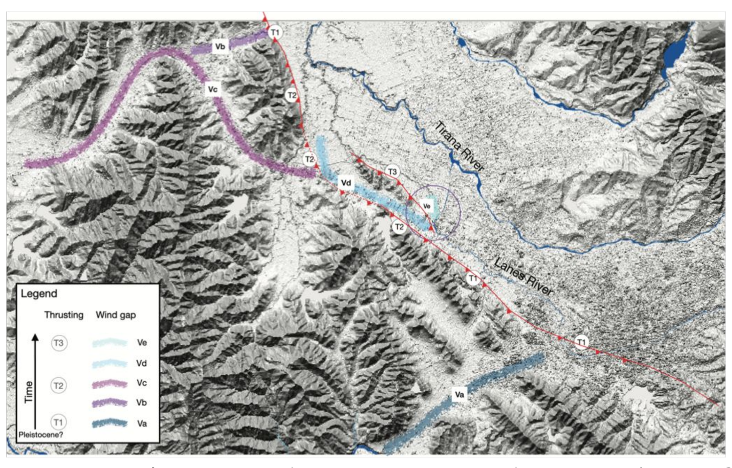


Fig. 6. The progressive growing of the Vora ridge/backthrust is responsible for the migration toward NE of the Tirana and Lanes rivers. Main phases of uplift and related diversions can be identified.

The **Vora backthrust** runs for about 25 km with a rather continuous, rectilinear and steep scarp, despite the soft clastic lithologies (Fig. 3). The ridge top represents the uplifted and tilted paleosurface of the hangingwall of the thrust separating the Tirana-Thumana syncline from the coastal Shijak syncline. Quaternary and ongoing rise of the ridge is documented by the abandoned valley that today hosts the SH2 highway from Tirana to Durrës. Excavated in the Pleistocene first by the Terkuza River and later by the Tirana River, that joined the Erzen River near Sukth (Fig. 3), this valley was left almost dry by the flow diversion towards the Ishëm River. The valley from Yzberisht to SW of Vogel, across the Yzberisht ridge, is another major abandoned valley (windgap) used before by the Tirana and Lana Rivers to flow SW into what is now the lower Erzen River. Thus, both Vora and Yzberisht valleys once provided direct outflow to the sea for the rivers from the Dajti ridge. The still active high rate of tectonic uplift is possibly confirmed by reverse faulting/folding downthrowing recent alluvial deposits with a step of 8-9 meters in the SW outskirts of Tirana. In the sector south of the Tirana plain, there is morphotectonics evidence of the migration toward NE of the river courses emphasizing the direct relationship with the growing of the Vora ridge (Fig. 6). Another evidence of the Vora backthrust activity is the westward diversion of the N-S Peza River (A in Fig. 3) carved into the uplifting front of the thrust. In addition, the rise of the Shijak thrust pushes the flow of the Erzen River along the eastern flank of the Shijak syncline, with a rather sharp deviation at Pejze (B in Fig. 3). Nearby, a narrow incision without active drainage is carved across the whole small anticline growing on the hangingwall of the Shijak thrust. Moreover, the growth of the anticline dams the Erzen River forcing its deviation from NE-SW to NW-SE downstream of the confluence of the Peza river (near A in Fig. 3). In addition, a splay of the Shijak thrust could cause the uplift of a few aligned hills that control the northeastern migration of the Erzen River avoiding the predictable capture by the near Juba River (C in Fig. 3A).

Discussion and conclusions.
The morphotectonic evidence clearly shows that the growing of the fault and fold systems control the landscape evolution between the Kruja thrust front and the coastline. Very steep and rectilinear fault scarps are associated with the major NW-SE striking thrusts and backthrusts run- ning with lengths reaching 50 km along the Kruja mountain front and the edges of the Durrës and Vora Hills. Fluvial diversions, dammed drainages and wind gaps are clear evidence of the ongoing compressional regime. Shortening and uplift result from the activity of major deep-seated and seismogenic thrust structures that induce the passive movement of the folds and thrusts observed at surface.
The obtained results contribute to a better understanding and characterization of the inland many potential seismogenic sources in the region. So far, with the exclusion of the last Durres event likely caused by the Durrës Offshore Thrust (Vittori et al. 2021), none of the known major seis- mic events has been attributed with certainty to a specific fault source.
A major effort, based also on paleoseismological studies, is required to significantly improve the current seismic hazard estimates, which must include also the hazardous effects of coseismic phenomena, such as surface faulting, landsliding, liquefaction.

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SCIENTIFIC COOPERATION AGREEMENT CNR (ITALY) - MOES (ALBANIA) 2021-2022

Project coord. L. Piccardi, I. Hoxha

"Earthquakes, Active tectonics and seismogenic sources in Albania"

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