SURFACE EFFECTS AND ACTIVE GEOTECTONIC REGIME OF THE NOVEMBER 26, 2019, DURRËS EARTHQUAKE

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ABSTRACT

On November 26, 2019, a strong earthquake of M_w 6.4 occurred in central Albania. The epicenter is located about 7 km north of Durrës (epicentre EMSC: 41.38°N, 19.47°E; IGEWE source: 41.46°N, 19.44°E). The fault plane solutions show that the causative fault is reverse, striking NNW-SSE and delineates a low angle thrust. The aftershock sequence supports this trend, while the mainshock displacement has been modeled at *ca.* 1.6 m (

Fig. 1a). The most affected areas were Durrës city and Thumanë town, while damages were also reported in Laç and Fushë-Krujë areas, as well as in Kamëz and Tirana city.

In this paper the surface effects of the earthquake are presented and the the geotectonic structure of Albania territory in Durrës broader area examined. Emphasis is given to the active or capable faults of the region, especially on the accretionary wedge which consists of Oligocene-Miocene sediments affected by the Durrës offshore thrust and its accompanying backthrusts. They are part of the compressional fold-and-thrust belt that was developed due to the Adria-Albanides collision, the activity of which is well documented by the seismic activity characterizing the area. The occurrence of a deeper structure is proposed, causing a tectonostratigraphic duplication, within which the last seismic event occurred. Widespread damage was observed in buildings throughout the meisoseismal area. The most severe cases were the collapse of hotels and residential buildings in Durrës and Thumanë, which unfortunately led to human loss. Some of the damages were observed in the immediate vicinity of surface effects (mainly liquefaction), indicating a possible association with poor inherent or co-seismic ground conditions.
Keywords: Durrës detachment, seismotectonics, fold-and-thrust systems, liquefaction, lateral spreading

Surface effects

The present paper aims to briefly describe the surface effects of this earthquake and discuss their possible association with the active structures of the meisoseismal and broader areas. Surface effects are mainly distributed in three areas of particularly poor geotechnical properties (

Fig. 1b):

1. Area 1: Durrës Beach.
2. Area 2: Rrushkull area.
3. Area 3: FushëKuqe area.

The following paragraphs summarize in brief the ground effects in each area.

Durrësi beach

The most severe damages around Durrës were observed in the area bordering the beach, SE of the city. Three hotels collapsed (Miramare Hotel, Vila Verde and Lubjana Hotel), and several more buildings were damaged beyond repair. At least one of the cases (Miramare Hotel), the collapse is associated with liquefaction, as is evident from the ejected sand. In this case, damages may be associated with poor geotechnical conditions, as the buildings are built on coastal sand deposits with a very shallow water table. The varied response to the earthquake (i.e. destroyed buildings next to intact ones) is an indication of differentiated build quality, which may also have played a significant role in the distribution of damages.

Rrushkull area

This is a flat area that is controlled by the interaction of the meandering river and the coast. Satellite images show a clear interplay between the river and the coast development. The flat morphology has led to the deposition of loose fine to medium grained alluvial sediments. In these sediments widespread liquefaction was observed, together with lateral spreading along the riverbanks.

This is the area where maximal displacements on the ground were modeled (

Fig. 1a) according to Papadopoulos *et al*., (2020). Liquefaction was frequently observed along cracks, while in other cases the source of the liquefied sand was not possible to be identified. In any case, the sand was of the same properties, (i.e. grain size, color, etc.), which is consistent with previous geotechnical investigation which had indicated the presence of layers of the fine light gray sand throughout the broader area.

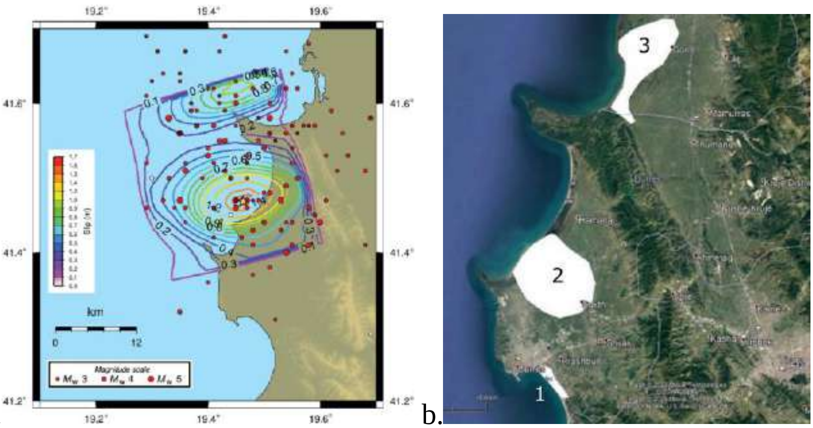
a.  b.

Fig. 1. a. Epicenter location and displacement model of the earthquake sequence (modified from Papadopoulos et al. (2020). b. Generalized location map of the areas in which liquefaction was observed: 1. Durrësi beach, 2: Rrushkull area, 3: Fushë Kuqe area.

Of particular importance in this area are the lateral spreading effects that were observed along the riverbanks. The location of the main ones is shown in

Fig. 2a. They are mostly parallel to the riverbanks and are attributed to local failures due to the shaking during the earthquake. The most prominent of those crack sets is observed at the area close to the estuary (

Fig. 2b), where a complex set of cracks accompanied by liquefied ejecta has been formed (

Fig. 3a).

The cracks had a general trend parallel / subparallel to the riverbank (NE-SW), while the longest (northern branch) show a rather uniform displacement vector towards the NW. A small vertical displacement of up to 15 cm is also evident in some cases along the crack (

Fig. 3b). Similar, smaller-scale, cracks with ejecta were observed in other areas of the flatlands as well.

a. b.

Fig. 2. a. Location of lateral spreading cracks (yellow lines) along the banks of the river south of Rrushkull.Their location is marked with red circles. b. Detail of the mapped lateral spreading near the river estuary in area 2. Liquefaction was widespread along the southern branches of the fracture system.

Fushë Kuqe area

This area has many common geological-geotechnical characteristics with the Rrushkull one. A shallow water table is developed in alluvial deposits, with the main difference being the existence of gravels that can be seen in a gravel pit next to the river north of Gurëz village. In this area, liquefaction was observed in the fields (e.g.

Fig. 3c), as well as around boreholes (

Fig. 4a). Solely in one particular case, liquefaction caused the ejection of not only sand, but gravel as well (

Fig. 4b).

a. b. c.

Fig. 3. a. Part of the southern branches of the lateral spreading near the river estuary. b. Vertical displacement of up to 15 cm was evident in certain places along the crack. c. Detail of sand ejecta along a crack in the area.

Along the coast of Patok Lagoon some limited surface cracks and lateral spreading were also observed, but they are interpreted as secondary features due to poor geotechnical conditions with no direct association with primary earthquake effects. According to some reports from local fishermen, some liquefaction phenomena were also observed at the beach west of Adriatik village; however, these reports were not evidenced, due to very difficult approach to the location, as well as due to time constraints.

The spatial distribution of historical liquefaction occurrences in south Balkans, including Albania, is included in the DALO database, where the empirical relationships between Magnitude (M_s)and maximum epicentral distance (R_e) are also presented (Papathanassiou *et al.*, 2005; Papathanassiou and Pavlides, 2011). The 2019 earthquake liquefied areas are included.

a. b. c.

Fig. 4. a. Liquefied sand in Gurëz area. b. According to reports, liquefaction at this site started with gravels that were ejected first, followed by sand. The sampling site is also visible. c. Typical occurrence of a sand boil.

Active geotectonic regime

The region is characterized by compressional tectonics, as it represents the outermost continental thrust belt of the Albanides. The main indication of compression in the area, apart from focal mechanisms, is an array of NW-SE-trending parallel fold axes perpendicular to the inferred active maximum stress axis (σ_1),

Fig. 5a. Crustal deformation is characterized by NNE-SSW to E-W oriented contraction (

Fig. 5b). Thrusting, which also contributes to the area shortening, is represented by typical thrust faults, mostly blind, that occupy the core of the mapped anticlines. Given also that the November 2019 hypocenter was relatively deep, the tectonic structure of the area is consistent with the observed ground effects that are, in their entirety, secondary ones. Primary effects (i.e. fault ruptures) were not observed in the affected area.

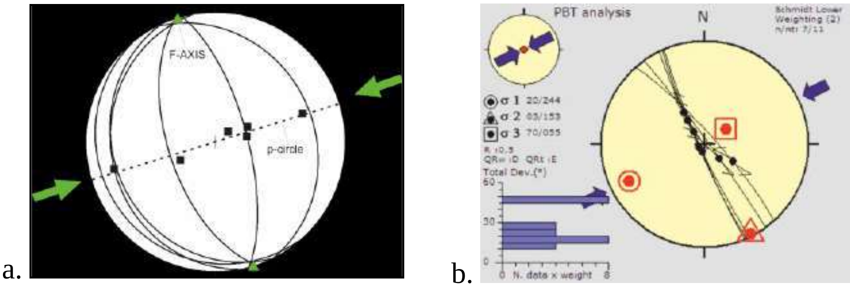


Fig. 5. a. The inferred compressional stress direction in the study areas, using the bedding planes as indicators of folding. b. Kinematic analysis of fault data collected in the broader area. The stress direction, as derived from the calculated $\sigma_1$axis, coincides with the active one in the area, hence the reverse faults associated with the folding are characterized as possibly active. Both diagrams are a result of data collected in the field.

Seismotectonics

The Southern Balkans are characterized by intense seismic activity due to the rapidly deforming broader Eastern Mediterranean area and its complex neotectonic structure. Although the Albanian region has a long record of historical seismicity, available knowledge about co-seismic surface ruptures in the region is limited. The Greek Database of Seismogenic Sources – GreDaSS (Caputo *et al*., 2012; Sboras *et al*., 2009) geographically covers the broader Aegean Region including Greece and its neighboring countries, such as Albania. From a long list of published papers and catalogues describing ground co-seismic deformation cases, only few pre-instrumental earthquakes can be directly correlated to a particular fault and even fewer ones contain reliable information about the surface rupture length, the maximum displacement, and the average displacement(Wells and Coppersmith, 1994; Pavlides and Caputo, 2004;). A fundamental problem in all statistical analyses and empirical relationships is the accuracy of the primary data. Fault-associated ground deformation is usually investigated and described by different authors who are not necessarily scientists, especially for old historical events.

Located in a region of high seismic activity, Albania is placed among the most frequently struck countries by damaging earthquakes, along with Turkey, Greece, and Italy (Mihailović, 1951; Sulstarova and Kociu, 1975; Kárník, 1979; Koçiaj and Sulstarova, 1980; Sulstarova, 1986; Papazachos and Papazachou, 2003; Ambraseys, 2009). During the last fifty years alone, Albania was struck many times by destructive earthquakes: 16 events of M=5.5 (I_o=VII), 3 events of M=6.0-6.5 (I_o=VIII), and 2 events of M=6.5-7.0 (I_o=IX). The strongest events occurred on April 15, 1979 (M=6.8) in the broader Montenegro-Shkodra area, on June 1, 1905 (M=6.6, I_o=IX), on

November 30, 1967 (M=6.6, Io=IX) in Diber (Sulstarova and Koçiaj, 1980), and on January 9, 1988 (M=5.4, I_o=VII) in Tirana (Koçiaj and Pitarka, 1989). Strong and destructive historical earthquakes among others are the Butrint AD 368 (Pavlides *et al*., 2001), the 1267 and especially the July 14thDurrës earthquakes (Aliaj *et al*., 2010; Ambraseys, 2009), as well the AD 522 devastating earthquake of Durrës, following the AD 518 extremely destructive Skopje earthquake (Ambraseys, 2009).

Active faults

The active faults of Albania can be classified into three very broad groups, based on their geodynamic characteristics and seismic potential (

Fig. 6a):

1. Eastern Albania mainland faults: these faults are predominantly normal dip-slip to oblique-slip, with length typically ranging from a few to a couple of tens of km. They generate shallow earthquakes with hypocentral depths of no more than 10-15 km (seismogenic layer thickness)
2. Western Albania mainland faults: they consist of mainly reverse faults (thrusts, overthrusts and back-thrusts) and strike slip faults as well.
3. Albanian coastal and offshore faults: according to focal mechanisms, as well as seismic profiles that have been performed along the coastal area, these faults can be of any kind. Depending on kinematics, their length varies from a few to several tens of km.

The active fault zones of Albania have been enumerated and their individual characteristics have been identified (

Fig. 6b). Based on their approximate quantitative characteristics, a number of properties associated with SHA were estimated, including theirearthquake potential, maximum expected displacement, slip rate, recurrence interval, etc.

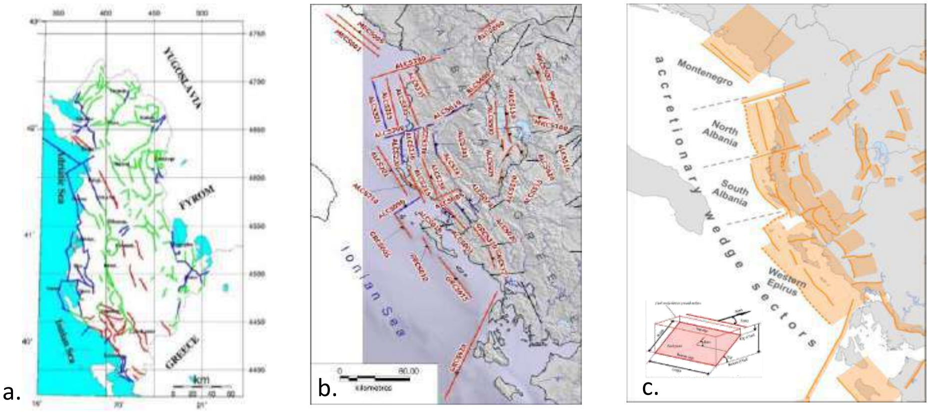


Fig. 6. a. Simplified neotectonic map of Albania (Aliaj et al., 2004). b. Schematic map of the main active fault zones of Albania and the surrounding areas (TAP pipeline design study) c.Schematic projections of the main active fault zones (seismogenic sources) in Albania(modified from GreDaSS, gredass.unife.it). The orogenic thrust system of the accretionary wedge is divided into four sectors. Inset shows the way that the quantitative properties of the fault zones are extrapolated.

The accretionary wedge of Albania

The accretionary wedge represents the most external sector of the Albanian orogene and is formed from sediments that are accreted onto the obducting tectonic plate along the plate boundary. The western sector of the Albanian territory and its nearby offshore area are characterized by a convergent regime, where Adria-Albanides continental plates collision takes place. The occurrence of major faults is well constrained due to the seismic reflection profiles performed for hydrocarbon explorations, while their recent seismogenic activity is documented both historically and instrumentally. The Albanian accretionary wedge is in continuity with the southern one of the Hellenides and the northern one of the Dinarides. It is displaced by major transfer zones which play a crucial role in fault zone segmentation, by reducing the length of thrust systems. Four principal sectors along the accretionary wedge have been recognized separated by such transfer zones; from North to South, these are: Montenegro, North Albania, South Albania and Western Epirus, Greece(

Fig. 6c).

The active Durrës detachment system

Durrës Detachment represents the frontal tectonic structure of the central sector of the Albanides accretionary wedge (Fig.7). It separates the orogenic belt developed in the hanging wall block from the underthrusting units of the Adria plate and is associated with the Albanian Foredeep. This basal detachment is typically low angle, and it is possibly mechanically connected with several thrusts and backthrusts affecting the coastal sector of Albania, like the Durrës Offshore Thrust and the Durrës Backthrust. In instrumental times, seismicity is relatively low in magnitude and diffused, thus not permitting to recognize with enough confidence the causative faults. All regional focal mechanisms though, show almost pure reverse faulting. However, some focal mechanisms obtained from moderate magnitude earthquakes ($5 < M < 6$; Albanian territory), document seismogenic depths of 15-18 km, therefore suggesting the occurrence of a deeper major low-angle east-dipping shear zone (Louvari *et al*., 2001).

Seismic profiles crossing this offshore area do not have enough details to constrain the geometry of the fault. The problem is on the fact that in the shallowest sector (thin-skin tectonics), Durrës Detachment runs parallel to layering and probably along the stratigraphic-mechanical discontinuity separating the Albanian Foredeep deposits from the carbonate platform units of the underthrusting Adria plate. The overall dimensions of this tectonic structure are certainly important; however, considering all uncertainties and the lack of a clear signature in seismic profiles (at least at shallow depths), Durrës Detachment is probably highly segmented. In any case, the uppermost tip of the fault does not reach the sea bottom (i.e. minimum depth of some kms). A further argument for suggesting the occurrence of Durrës Detachment offshore the Albania coast, is the comparison with both the northern and southern sectors of the Albanian accretionary wedge. Indeed, north of the Shkodra Transfer Fault the basal detachment is clearly active (Montenegro Detachment), while south of the so-called Fieri-Elbasan-Dibra shear zone the Karaburuni-Sazani Island Detachment has a clear evidence of recent activity. Focal mechanisms in the broader Durrës area are documenting horizontal E-W-trending P-axes (i.e. compression).

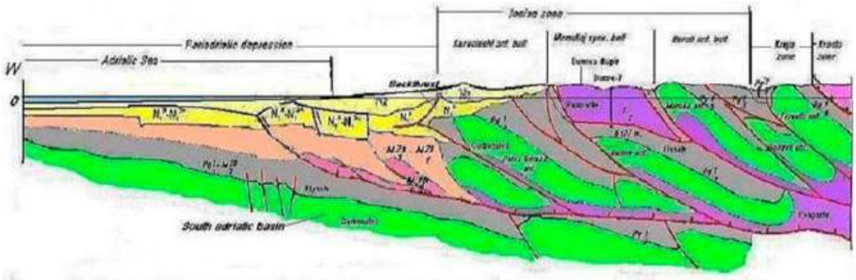


Fig.7. Interpreted seismic profile across the external Albanides (Velaj, 2011).

According to the interpretation of seismic profile by (Velaj, 2011), the most external fault of the accretionary wedge is the Durrës Offshore Thrust. It is characterized by a ramp-flat geometry, generally east-dipping and associated with some secondary structures synthetic splay faults developed in its hanging wall block. The fault does not seem to affect the whole Neogene sedimentary succession. It represents a major structure; however, it is clearly blind (i.e. maximum depth of some km) and any seismogenic reactivation will not directly cut the sea floor. The ramp-flat geometry and the occurrence of several secondary structures likely induce a segmented behavior of this composite seismogenic source. In map view it strikes 300-350º and dip angle 20 to 25º.

Durrës Backthrust is also part of the overall system and is clearly detected in several regional seismic and geological profiles (Velaj, 2011).The fault is also particularly evident in other interpreted profiles (Aliaj, 2006; Skrami, 2001). Based on the interpretation of the seismic profile in (Skrami, 2001), the unconformity between the Quaternary deposits and the Pliocene molassic sediments is formed due to the recent and ongoing activity of the backthrust (Durrës Backthrust- ALCS325 in

Fig. 6b). Thrust faults belonging to this system and associated with the November 26, 2019 epicenter are about 75 km long with slip rates of ~1 mm/yr (Stein and Sevilgen, 2020). It is similar to the Vlore backthrust (ALCS5220 in

Fig. 6b), which has been interpreted as an active backthrust, associated to the low-angle frontal thrust of the Albanides over the Apulian platform. Various seismic profiles of the broader area however, as well as the local stress field, suggest that this is a W-dipping reverse active structure.

Geodynamic model of the area–Conclusions

Based on published seismic interpretations, local geology, and comparative assessment of similar structures in NW Greece, we suggest that the geodynamic model of the area is controlled by a stacking of several (at least two) repetitions of carbonates, which have been accumulated during the Adria obduction (Fig. 8). As a basal weakness zone, it is suggested that it could be consisted of evaporites, which are very often acting as a mechanically weak zone that facilitates large-scale horizontal displacements. In this case, a shortening of at least 70% must be assumed, which is consistent with similar observations in the southern part of this fold and thrust belt (i.e. Epirus, Greece).

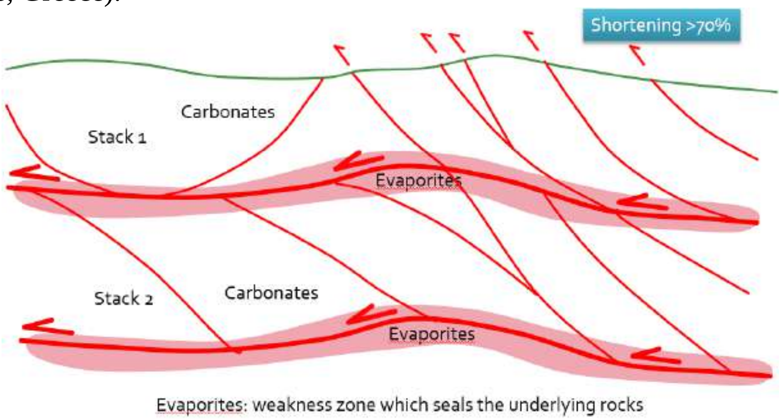


Fig. 8. Indicative sketch of a thin-skinned geodynamic model, that could explain the large hypocentral depth of the November 29, 2019 earthquake.

The 2019 earthquake was a deep-seated event that was likely produced by the reactivation of the backthrust of the basal thrust in the fold-and-thrust belt. It is a blind structure, as suggested by onshore and offshore seismic sections, as well as by field observations. This deep epicentral rupture mitigated the surface effects, causing mainly liquefaction and in certain cases secondary ruptures due to lateral spreading. The pattern of the surface effect distribution however, is consistent with the assumed strike of the causative fault, despite them being rather scattered.The proposed geodynamic model is compatible with both the seismotectonic and the geological data. The properties of this earthquake are also in accordance with theinferred deep structures and the active stress field, as is shown by structural analysis on surface structures, showing thus that there is no differentiation in the stress direction in deeper parts of the crust. Finally, the comparison of the current event structural setting with similar structures along the western Albanian –

NW Greece fold-and-thrust belt shows that the role of backthrusts may be underrated in terms of seismic potential and current activity.

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