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ORIGINAL STUDY

Earthquake-triggered mass movements in Albania

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Abstract
Albania is located in the Alpine fold belt extending to the central part of the Dinarides–Hellenides arc in a zone characterized by intense tectonic-seismic activity that has a considerable influence in shaping the geo-environment of the area. Historically, strong earthquakes occurred in this region and triggered lots of mass movements causing considerable damages such as life loss, destruction of properties and disruption of the geo-environment. This paper introduces several earthquake-triggered mass movement events in Albania that occurred during 1850–2019. It was achieved through collection and analysis of data from historical studies and authors' field investigations. The results show that soil type, slope inclination and seismic activity have a direct influence in the occurrence of these movements consistent with similar parameters occurred worldwide. Earthquake's magnitude and degree of mass movement is well correlated. Mass movements such as lateral earth spread, rock fall, debris slides, sand boils, sand fluidization, cracks and settlement were triggered by earthquakes with a magnitude of 6.0 or higher. On the other hand, lateral rock spread needs a higher seismic magnitude to occur.

Keywords Mass movement · Earthquake · Lateral earth spread · Rockfall · Lateral rock spread · Debris slides · Sand boils · Settlement · Hill slope · Active tectonic and seismic zones · Soil and rock geotechnical properties

1 Introduction

Albania is located in the Alpine fold belt at the central part of the Dinarides–Hellenides arc. This zone is characterized by intense seismic activity which had a considerable influence on shaping the geo-environment. Seventy-six percent (76.6%) of the Albanian territory consists of mountains and hills composed of weak, medium, and hard rocks that

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are covered by unconsolidated deposits and soils deeply affected by geological processes such as tectonic activity, weathering, erosion, and mass movement phenomena. In the last decades, numerous mass movements mainly caused by rainfall and man-made works and, in some cases, triggered by the instability of slopes caused by earthquakes have been observed in Albania (Perrey 1853; Mihailoviç 1927,1951; Boué 1851; Shehu and Dhima 1983; Koçiaj 2000; Ambraseys 2009; Shehu and Dhima 1983; Dibra 1983; Sulstarova 1999; Aliaj et al. 2010; Muceku and Korini 2014; Muceku et al. 2016). In addition to the mass movement triggering, other geological factors such as lithology, geomorphology, weathered crust, and tectonic activity have affected the geotechnical conditions of soils and rocks. During 1998–2019, several geological engineering and geotechnical studies were carried out aiming at the assessment of the geological hazard, identification of unstable areas and mapping of many mass movements in all the Albanian territory (Muceku and Lamaj 2009; Muceku et al. 2019). This paper briefly describes the characteristics and distribution of mass movements that were triggered by the earthquakes around Albania. Several factors such as lithology, geomorphology, seismological and tectonic activity, geo-engineering conditions of soils and rocks are analyzed and their impact on causing the mass movements is assessed.

The identification of earthquake-triggered mass movements was scarce and not well-documented because most of the studies evaluate the seismic hazard and risks rather than the effects of the past earthquakes on the environment (Sulstarova 1999; Sulstarova and Aliaj 2001; Aliaj et al. 2010; Muço 2013). Therefore, the mass movements evaluation, mapping and analysis was accomplished through an integrated methodology based on the combination of archival data and field and laboratory work consisting of a three-step approach: (1) *data collection*; a desk study of previous research; (2) performing laboratory and field work; and (3) *analysis of the data* obtained from previous studies and field- and laboratory work.

In the first phase, it was conducted an extensive literature review on previous geological, tectonic, seismic, and morphologic works in Albania (Perrey 1853; Mihailoviç 1927; Mihailoviç 1951; Boué 1951; Krutja et al. 1991; Dibra 1983; Koçiaj 2000; Aliaj et al. 2004; Aliaj et al. 2010; Aliaj 2012; Ambraseys 2009; Muço 2013; Muço 1996; Duni and Kuka 2008a, b; Duni et al. 2010; Duni 2010; Papazachos et al. 2001; Sulstarova 1999; Sulstarova and Aliaj 2001; Sulstarova and Koçiaj 2001). Besides geological, tectonic, and seismic data, the review provides insights on the environmental impact of earthquakes, such as the loss of human lives, damage of residential buildings and the occurrence of natural phenomena such as mass movements.

The second phase of the current work involves geotechnical and geo-engineering investigations and mapping, completed through 2000–2020, for the regional planning and development of the urban areas, touristic villages, highways, hydroelectric power plants etc., from which important geological, geomorphologic, hydrogeological, and geotechnical data are derived (Muceku and Lamaj 2009; Muceku et al. 2019).

During the field work, special attention was paid to the areas where the earthquakes (M > 6.0 Richter) have caused geological phenomena. As there was little information regarding the mass movements caused by earthquakes, besides literature review, the residents of the affected areas were interviewed.

The third phase of this study consists of the processing and analysis of the seismic and engineering geological data gathered during the first phase. Firstly, the geotechnical characteristics of mountain and hill slopes, as well as flat areas prone to sand liquefaction, were evaluated. After that, historical data of earthquake-induced mass movements was analyzed with regard to the present geotechnical conditions. Among other mass movements, some of them were identified and mapped to have been induced by earthquakes (Muceku and Lamaj 2009; Muceku et al. 2019).

The mass movements caused by earthquakes in Albania are classified as *lateral earth spread, rock falls, lateral rock spread* and *debris slides* (Cruden and Varnes 1996), *sand boils, cracks,* and *settlement* (Fairless and Berrill 1984), as well as *sand liquefaction-fluidization* (Kagawa et al. 2015).

Finally, based on geotechnical studies conducted in the last three decades in Albania, it was observed that the types of mass movements are strongly related to the area's morphological features, the lithological variety, and the geotechnical conditions of the ground (soils and rocks), as well as earthquake magnitude and hypocentral distance from the epicenter.Regional setting.

Recent studies conducted in Albania have shown that apart from earthquake magnitude and rainfall, other factors such as geology, geomorphology, neotectonics have an important role in the triggering of the mass movements (Muceku et al. 2019,2016; Muceku and Korini 2014; Muceku and Lamaj 2009).

1.1 Geology and geomorphological characteristics

Albanian geology is part of the Alpine Mediterranean tectonic system and belongs to the Dinaride-Hellenide branch (Aliaj 2012; Xhomo et al. 2002). The geological structures strike NW–SE, showing asymmetric folds. Albanian geology is divided into two major units, the Internal and External Albanides (Fig. 1) (Aliaj 2012; Xhomo et al. 2002,1999). Their lithological characteristics can be summarized as follows:

1. *The Internal Albanides* are located in northern and eastern part of Albania and include the Gashi, Korab and Mirditë geotectonic zones (Fig. 1). The geological formations of these zones date from the Ordovician–Silurian (O-S), Upper Cretaceous (Cr_2) and Pliocene–Quaternary. They are made up of three main formations such as metamorphic, magmatic and sedimentary rocks, represented by schist, a mixture of limestone and dacite-andesite, conglomerate, quartzite, sandstone and metamorphic formations combined with the basalts and the black clay and siliceous shales, ultrabasic, gabbro-plagiogranites up to volcanogenic-sedimentary-basalts rocks (Fig. 2).
2. *The External Albanides* are located in the north, center, south and west of Albania and include the geotectonic zones of Albanian Alps, Krastë-Cukali, Krujë, Ionian and Sazan islands (Fig. 1). They show a continuous sediment deposition ranging from Triassic (T) to Miocene (N_1) up to Quaternary. These tectonic zones are mainly composed of limestones and evaporitic deposits, as well as terrigenous formations that are represented of flysch rocks, marl, and conglomerates (Fig. 2).

The *Periadriatic Depression* (B_1) and the *Intramontane Depression* (B_2) (Fig. 1) are also included in the geotectonic zones (Aliaj 2012 and Xhomo et. al 2002) (Fig. 1). The Periadriatic Depression extends from Ulcinj to Vlorë along the coastal western lowland and it is situated on older formations of the Krujë and Ionian zones built by molasse deposits (Middle-Upper Miocene-N_1^2-N_1^3 and Pliocene N_2), consisting of intercalation of the thick layers of sandstones and siltstones-claystones (Fig. 2). In the northern and southeastern part of Albania, two post-orogenic sedimentary basins are found, the Burrel Depression (B2) (N) and Korçë Depression (B2) (S) divided by a transgressive boundary over Mirdita

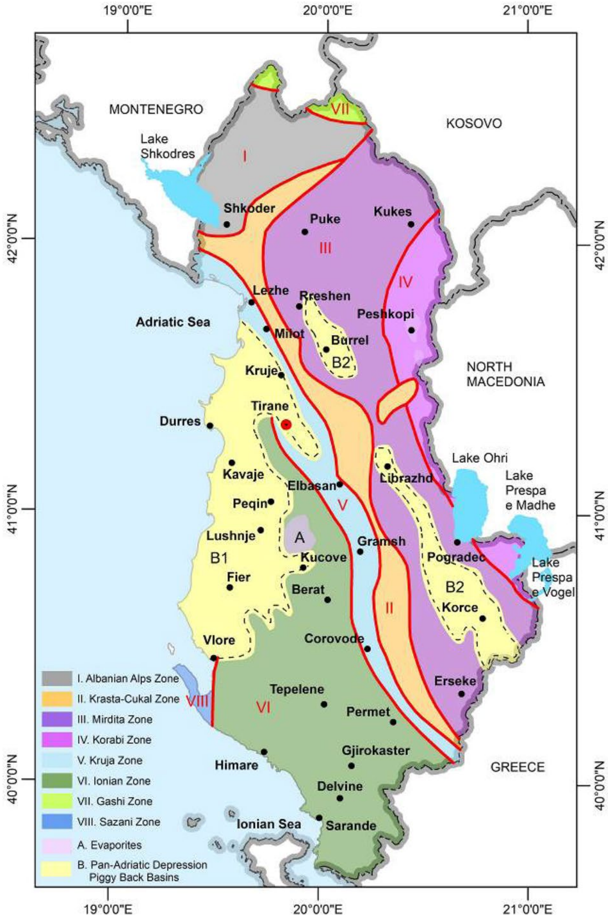


Fig. 1 Geotectonic map of Albania (Xhomo et. al. 1999)

zone and partially on Krastë-Cukali zone (Figs. 1, 2). The Intramontane Depression (B_2) includes Eocene (Pg_2) premolasse deposits, Oligocene (Pg_3) and Miocene (N_1) molasse (Fig. 2), which are transgressively situated on magmatic and Mesozoic deposits of Mirditë and partially on the Krastë-Cukali zones (Figs. 1, 2). It is composed of a combination of thin layers of siltstones-claystones with sandstones. In addition, these formations are overlain by Quaternary sediments located on middle-bottom of hillslopes (diluvium), along of Adriatic-Ionian flat area (coast and beach deposits) and river valleys (alluvial).

The geomorphology of Albania is strongly related to the geology. It represents a hilly-mountains relief, where the area of 200–600 m altitude composes 25.1%, area of 600–1000 m above sea level (a.s.l.) 23% and the area of 1000–2000 m a.s.l., 27% of the Albanian territory.

The geomorphology is strongly related to geology, tectonic evolution and geological processes like mass movements, erosion and rock weathering. Geomorphologically speaking, Albania is classified into three hilly-mountainous morphological units such as the *Albanian Alps*, *the Central and Southern Mountain Region* and a flat morphological unit such as the *Western Lowlands* (Krutja et al. 1991) (Fig. 3). In the mountainous region there are many groups of peaks that exceed 2000 m above sea level (highest peak: Korabi with

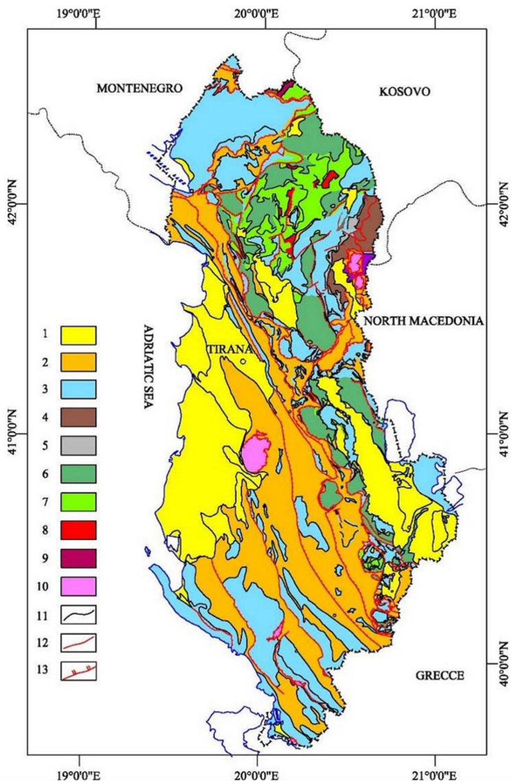
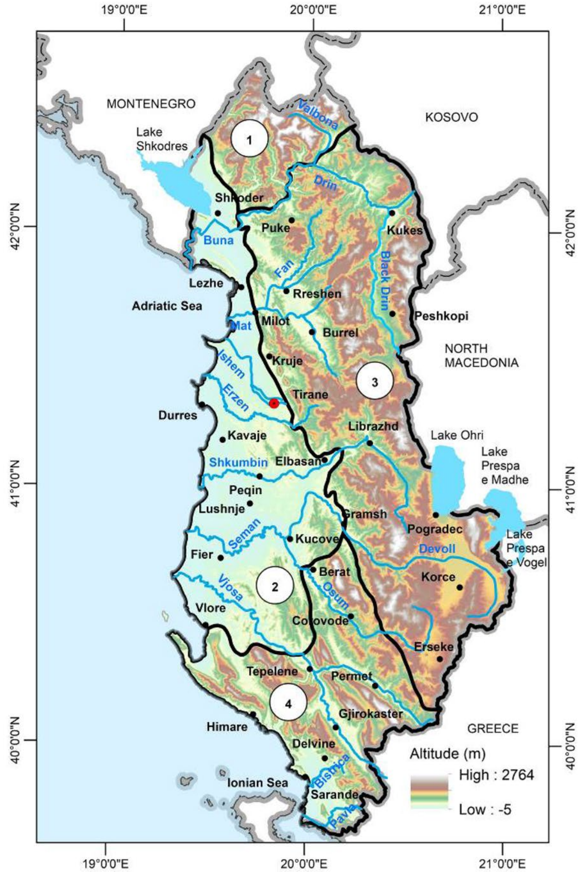


Fig. 2 Geological Map of Albania (Xhomo et al. 2002). 1—Molasse, 2—flysch, 3—limestone, 4—shale, 5—schist, 6—intrusive rocks, 7—volcanic rocks, 8—plagiogranite, 9—granite, 10—gypsum, 11—lithologic boundary, 12—tectonic fault, 13—thrust fault

2751 m) in a pyramidal shape that are separated by narrow and deep gorges due to karstic activity. Moreover, the hilly mountains are affected by tectonic, mass movements, erosion, and rock weathering activities, where many streams and rivers flow in narrow and wide valleys (Buna, Drin, Mat, Ishëm, Erzen, Shkumbin, Seman, Vjosa and Bistrica rivers), as well as depressions and holes, formed and oriented from east to west.

Most of these valleys lie along tectonic zones (Figs. 3, 5) that have been eroded over time. This phenomenon can be easily found in the Drini River valley from the border line of North Macedonia to the city of Kukës where there are seen tectonic faults to the east of a narrow syncline lying between Mirditë and Korab, as well as near Shkodër along the important Shkodër-Pejë tectonic fault. Another type of formation of river valleys is the contact zone between weak and strong rocks. It can be observed in Vjosa River valley along the border line with Greece until Kelcyrë, which is then crossed by the tectonic fault of carbonate structure of Trebeshinë area (Figs. 3, 5).

The Western Lowland represents a flat morphological unit extending along the Adriatic coast from Shkodër to Vlorë. To the west, it is generally flat with a height 2–5 m up to 15–25 m a.s.l.; to the east, there are many hills consisting of molassic formations



1 - Albanian Alps, 2 - western lowland, 3 - central mountain region, 4. southern mountain region.

Fig. 3 Albanian morphological map (Krutja et al. 1991). 1—Albanian Alps, 2—western lowland, 3—central mountain region, 4—southern mountain region

and stretch parallel to each other in the form of chains, oriented NW–SE with altitude that varies from 150–200 m up to 450–565 m a.s.l. The geomorphological feature of the studied area is closely associated with the mass movements and their distribution. The presence of unstable soil deposits and intensive fractured-weathered rocks situated along of the hilly mountain slopes and river valleys, and characterized by low geotechnical properties, contributes to the mass movements triggering. The occurrence of the mass movement coincides mainly with the lithological type and landform characteristics. Thus, from the recent works (Muceku and Lamaj 2009; Muceku et al. 2019) it was observed that rockfalls and debris slides were concentrated in high relief and steep slopes built by fractured-weathered limestones and magmatic rocks. The lateral earth spread was more prone to the river valleys and hilly areas with gentle to moderate slopes that are built by the diluvial deposits situated on molasse and flysch rocks. Whereas, the sand boils, cracks and settlement were prone of the floodplain composed by alluvial deposits, which are represented by very loose to loose and saturated sands.

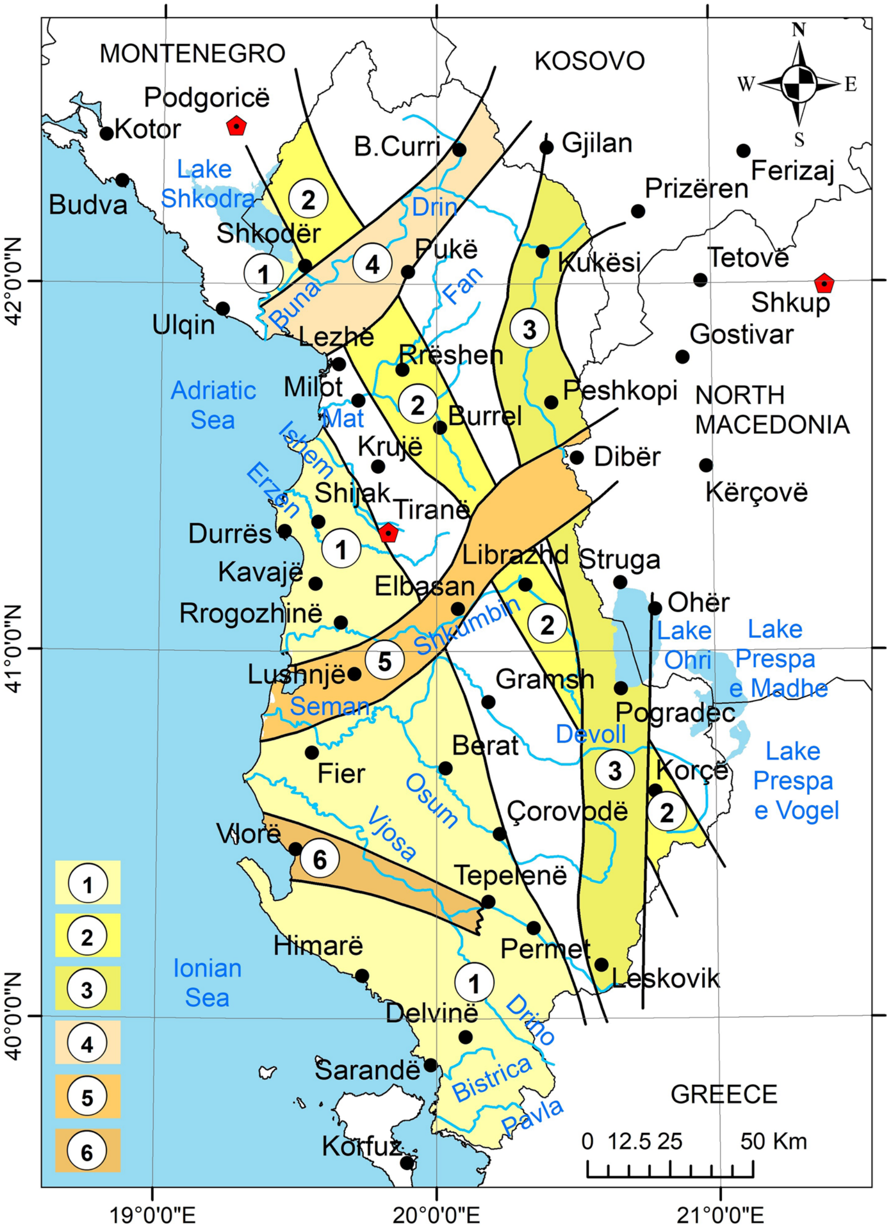
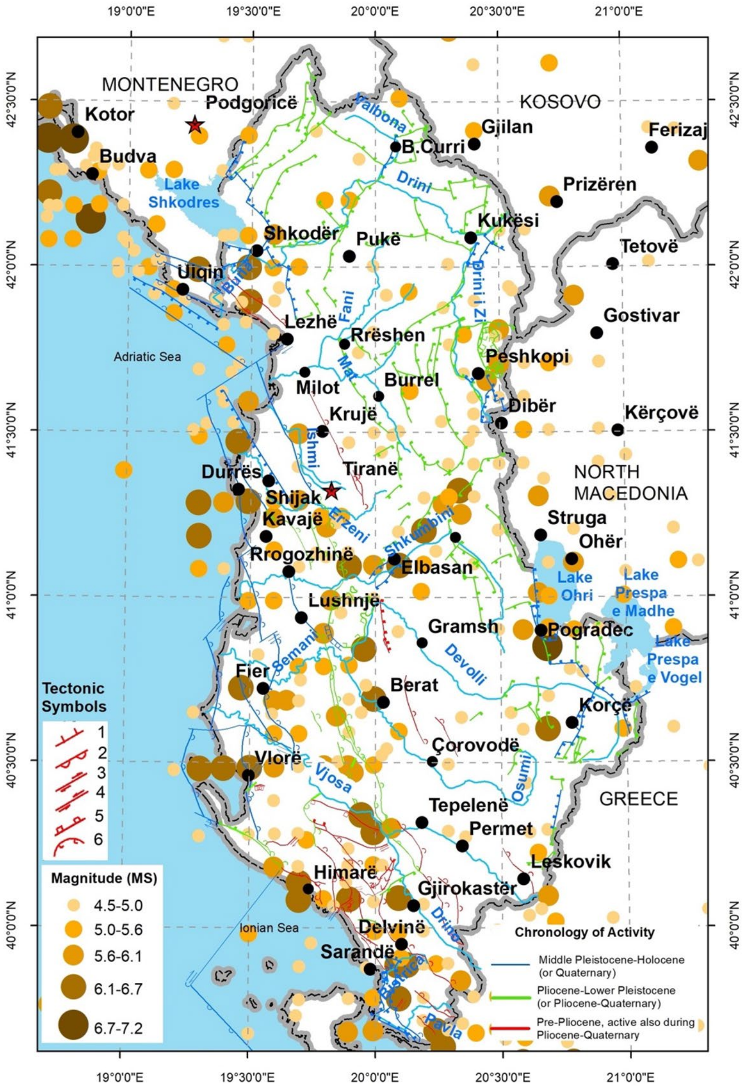


Fig. 4 The main active fault zones in Albania (Aliaj et al. 2010). 1. Ionian-Adriatic thrust fault zone, 2. Shkodra-Mati-Librazhdi graben fault zone, 3. Peshkopi-Korça graben fault zone, 4. Shkodra-Tropoja normal fault zone, 5. Elbasani-Dibra normal fault zone, 6. Vlorë–Tepelenë normal faulting zone

1.2 Neotectonics and seismicity

The Albanian territory is subdivided in two tectonic regions, the inner and outer one. In the inner region, post-Pliocene normal faults are predominant, mainly of the horst-graben type,



1. Normal fault, 2. reverse fault and thrust, 3. dextral strike-slip, 4. sinistral strike-slip, 5. flexure, 6. active evaporite diapir dome.

Fig. 5 Seismotectonic map of Albania at scale 1:500,000 (Aliaj et al. 2000). 1. Normal fault, 2. reverse fault and thrust, 3. dextral strike-slip, 4. sinistral strike-slip, 5. flexure, 6. active evaporite diapir dome

whereas in the outer region mainly pre-Pliocene to Holocene thrust faulting took place, which, in some sectors, is interrupted by several transversally oriented, oblique faults (Aliaj 2012). The Periadriatic Foredeep sub-zone is located in the outer region, which accommodates an Upper Pleistocene-Holocene neotectonic structure (Figs. 4, 5). This fault system has played a determinant role throughout the neotectonic development of Albanides.

Based on previous studies, three longitudinal extended active fault zones and two transversally extended active fault zones with different seismotectonic characteristics, are identified (Aliaj et al. 2010, 2012) (Fig. 5). This zonation is also supported by the spatial characteristics of the distributed intense seismic activity, closely related to these active fault zones.

During the last century, Albania has been characterized mainly by an intense micro-seismicity ($M < 5.0$), by many medium-sized earthquakes ($5.0 \le M \le 6.0$), few strong earthquakes ($M > 6.0$), and rarely very strong ones ($M > 7.0$), (Figs. 4, 5) (Aliaj et al. 2010). The outer domain is the most seismic active region and is characterized by significant E–W post-Pliocene shortening across the external Albanides, due to an important pre-Pliocene ongoing compression stress regime accommodated by thrusts and a back-thrust fault system, as the consequence of the continental collision. A common result from the

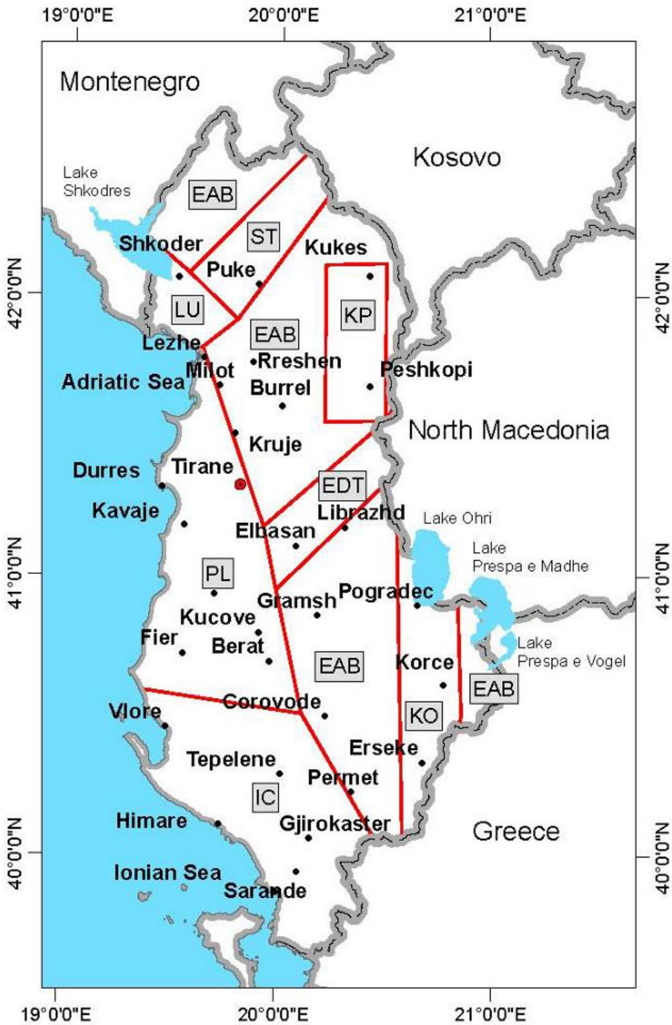


Fig. 6 The main active seismic zones in Albania (Aliaj 2004)

hypocenter's mechanism solutions (FMS), carried out for the Albanian earthquakes, is the predominance of a compression stress regime in the coastal region of the country and of an extensional regime in the interior (Aliaj et al. 2010). The complicated tectonic pattern has been confirmed by GPS measurements too (Jouanne et al. 2012). Based on these observations, the external Albanides have been deformed with rates 3.0–5.0 (±0.3) mm/year, while the inner ones have undergone a moderate E–W extension. A clockwise rotation across Ohrid, and an extension N160° south of Korçë grabens, occour in the inner domain indicating south-westward velocities of 2.0mm/year, for points located NE and SE of the transversal Vlorë–Lushnje–Elbasan–Debar VLED (Jouanne et al. 2012). These results are in good accordance with the hypocenter's mechanism solutions of moderate and strong earthquakes in Albania.

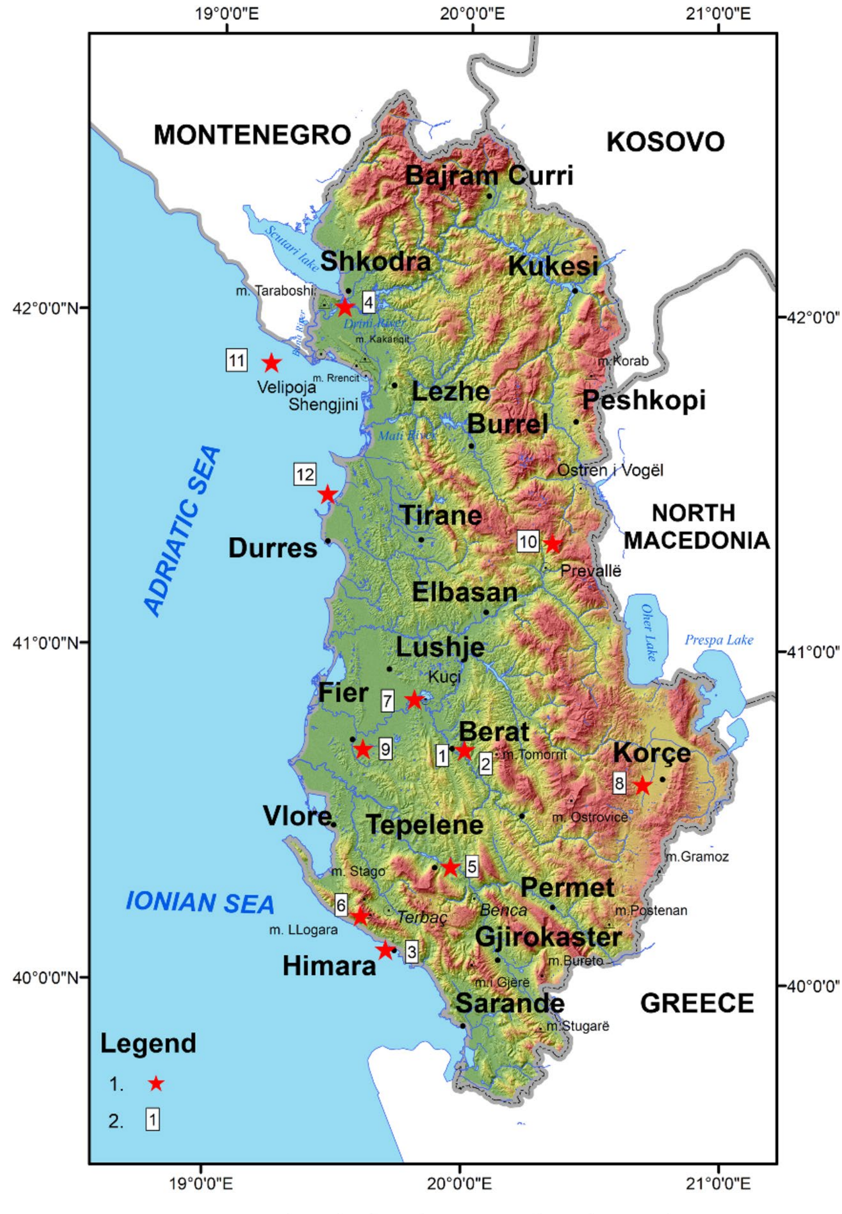
Based on the seismotectonic criteria as well as on the spatial and temporal distribution of earthquake epicenters (Muço 2013), Albania was classified in eight main active seismogenic zones (Fig. 6):

- *Lezhë-Ulqin (LU)*—a coastal zone of pre-Pliocene characterized by earthquakes with $M_{max} = 7.2$,

  - *Periadriatic Lowland (PL)*—represented by the coastal zone of post-Pliocene, defined as zone with $M_{max} = 7.0$ earthquake,
  - *Ionian Coast (IC)*—pre-Pliocene coastal zone, characterized by earthquake with maximum magnitude $M_{max} = 7.0$,
  - *Kukës-Peshkopi (KP)*—Pliocene–Quaternary inner zone, with earthquakes with maximum magnitude $M_{max} = 6.8$,
  - *Ohrid-Korçë (KO)*—Pliocene–Quaternary, inner zone with earthquakes with maximum magnitude $M_{max} = 6.9$,
  - *Shkodër-Tropojë (ST)*—transversely oriented normal fault zone, characterized by $M_{max} = 6.9$ earthquakes,

Table 1 Strong earthquakes that have triggered the mass movements (Papazachos et al. 2001; Sulstarova and Aliaj 2001; Sulstarova and Koçiaj 1975; Koçi et al. 2019; Papadopoulos et al. 2020)

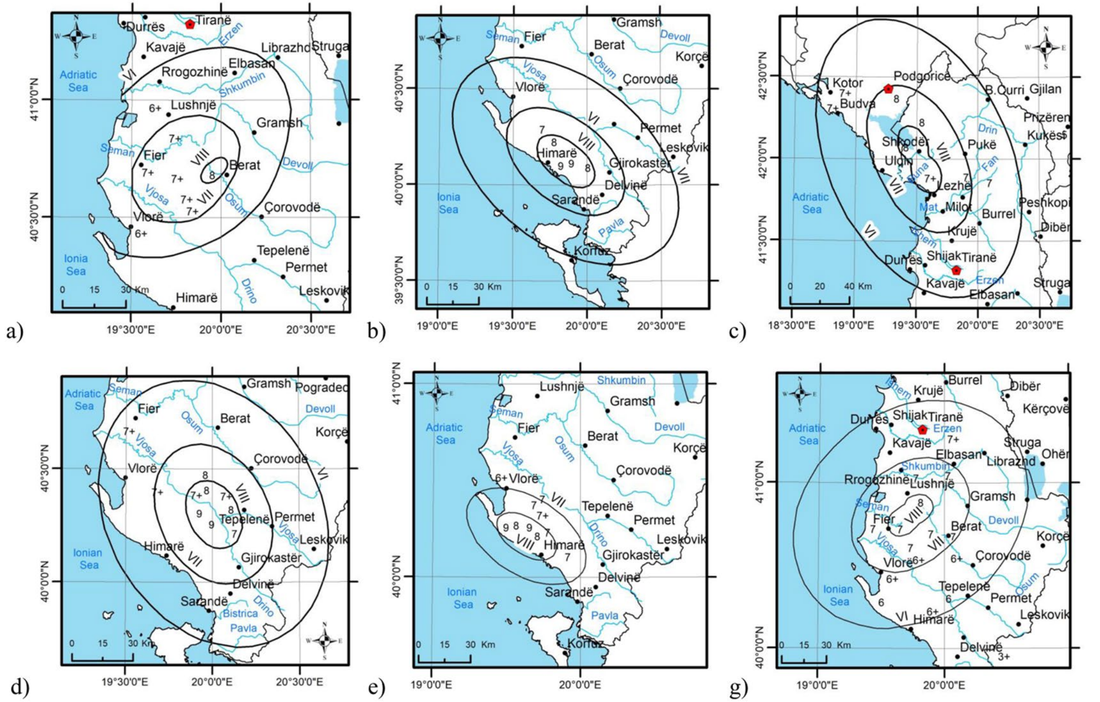
Nr	Date	Time (local)	Lat (N°)	Lon (E°)	Hypocentral depth (km)	M	Location	Seismogenic zone
1	17.10.1851	01:30	40.70	20.00	33	6.6	Berat	Periadriatic Lowland
2	29.12.1851	10:30	40.70	20.00	13	6.0	Berat	Periadriatic Lowland
3	14.06.1893	-	40.10	19.70	6.6	6.6	Himarë	Ionian Coast
4	01.06.1905	04:42	42.02	19.50	15.6	6.6	Shkodër	Lezhë-Ulqin
5	26.11.1920	08:51	40.35	19.95	6.1	6.4	Tepelenë	Ionian Coast
6	21.11.1930	02:00	40.20	19.60	5.2	6.3	Vlorë	Ionian Coast
7	01.09.1959	11:37	40.85	19.80	16.9	6.4	Lushnje	Periadriatic Lowland
8	26.05.1960	05:10	40.60	20.70	7.6	6.5	Korçë	Ohrid-Korçë
9	18.03.1962	15:30	40.70	19.60	14.4	6.0	Fier	Periadriatic Lowland
10	30.11.1967	07:23	41.32	20.34	7.9	6.6	Dibër	Kukës-Peshkopi
11	15.04.1979	06:19	41.85	19.21	16.8	6.9	Montenegro	Lezhë-Ulqin
12	26.11.2019	03:54:12	41.46	19.44	22	6.4	Durrës	Periadriatic Lowland



1. Earthquake location; 2. earthquake number.

Fig. 7 Epicenters of strong earthquakes, which have triggered mass movements. 1. Earthquake location; 2. earthquake number

- *Elbasan-Dibër-Tetovë (EDT)*—transversely normal fault zone, with $M_{max} = 6.8$ earthquakes,
- *Eastern Albanian Backzone (EAB)*—an inner zone, east of the coastal zones. It is characterized by earthquake with $M_{max} = 5.5$.



a) Earthquake of December 29, 1851, Berat; b) earthquake of 1893, Himare; c) earthquake of 1905, Shkoder; d) earthquake 1920, Tepelenë; e) earthquake of 1930, Vlorë; g) earthquake 1959, Lushnja.

Fig. 8. (**A**) 1. Isoseismal maps (Papazachos et al. 2001; Sulstarova and Aliaj 2001; Sulstarova and Koçiaj 1975). (**a**) Earthquake of December 29, 1851, Berat; (**b**) earthquake of 1893, Himare; (**c**) earthquake of 1905, Shkoder; (**d**) earthquake 1920, Tepelenë; (**e**) earthquake of 1930, Vlorë; (**g**) earthquake 1959, (**B**) Lushnja; (**h**) Earthquake 1960, Korça; (**i**) earthquake of 1962, Fier; (**j**) earthquake of 1967 Dibra; (**k**) earthquake of 1979, Montenegro; (**m**) earthquake of 2019, Durres (Papazachos et al. 2001; Koçi et al. 2019)

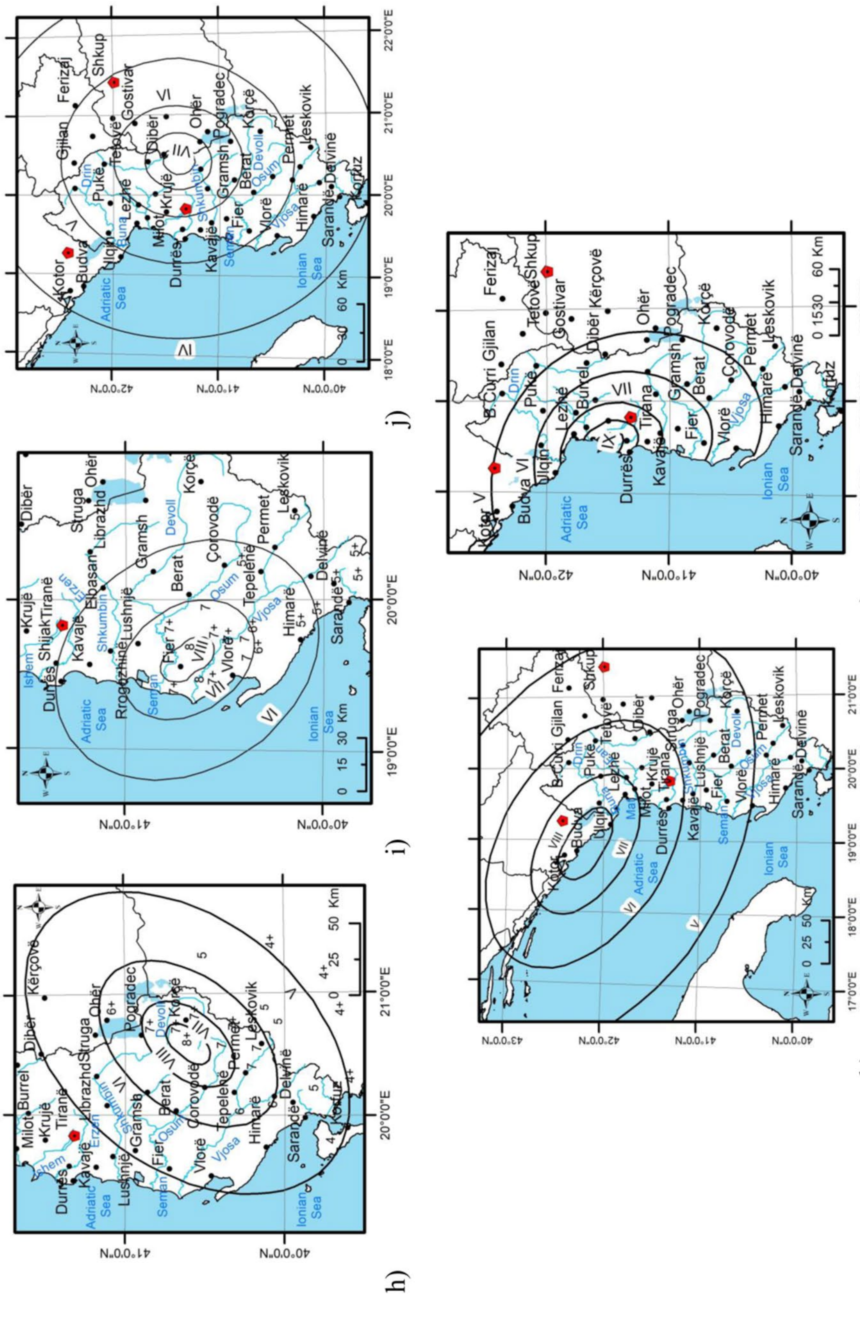


Fig. 8. (continued)

2 Mass movements caused by earthquakes in Albania

2.1 Earthquake database

Albania is extremely affected by mass movements, which are mainly related to meteorological factors and human activity. Only in some cases, they are related to co-seismic effects of earthquakes, strongly controlled by local geotechnical conditions of the affected rocks and soil sites, such as fracture scale, slope inclination, etc. (Chen et al. 2014; Muceku et al. 2016; Muceku and Korini 2014). These site factors combined with earthquake source parameters, seismic energy released and the slant distance between the affected sites and the hypocenters, are obviously effective on triggering co-seismic mass movements for strong shocks ($M \geq 6.0$). There are many cases to support such a relation, for mass movements evidenced during strong earthquakes in Albania (Table 1, Fig. 7). As most of these strong earthquakes are of a more historical than instrumental evidence, the detailed treatment of the above-mentioned factors aims to shed light on this relation.

In Figs. 8, the isoseismal maps of strong earthquakes are shown (Papazachos et al. 2001). They provide a good overview of the affected area, which is also comprised of different soil and rock conditions. The extension of the major axes of the isoseismals reveals information on the causative seismic fault patch orientation. The typology of earthquakes and the characteristics of seismic sources play, in general, a major role in the earthquake-mass movement relations. Moreover, the seismic source parameters, hypocenteral depth and earthquake magnitude observed for strong earthquakes in Albania, are considered as crucial parameters in the landscape modeling and the seismic impact on the geo-environment. Instrumental observations of seismicity demonstrate that the seismic hypocenters are mainly shallow and related to the neotectonic structure activity.

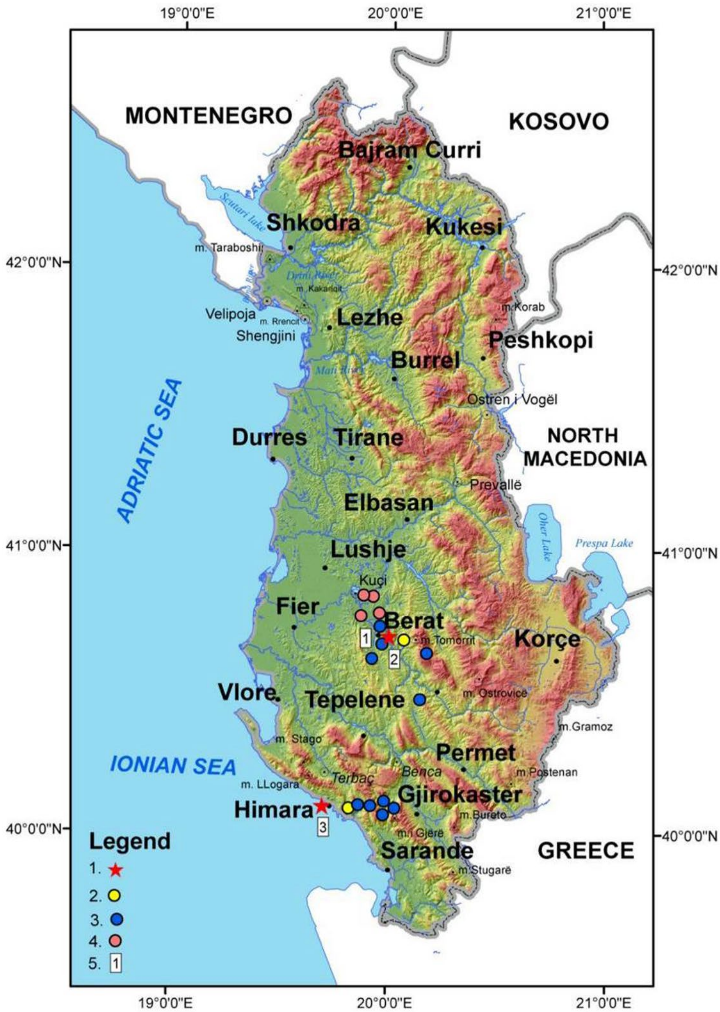
During the last century, many mass movements, settlement, and sand liquefactions have occurred as co-seismic processes. Based on the historical and instrumental data availability and the rate of geotechnical recognition of the earthquake induced mass movement information for the Albanian territory, mass movements are chronologically classified into four groups:

1. Mass movements that occurred during 1850–1900,
2. Mass movements that occurred during 1901–1950,
3. Mass movements that occurred during 1951–2000,
4. Mass movements that occurred after year 2000.

Earthquake-induced mass movements are classified as: *lateral earth spread*, *rockfalls*, *debris slides*, *sand boils*, *sand fluidization*, *cracks and settlement* (Cruden and Varnes 1996; Fairless and Berril 1984).

2.2 Mass movements in 1850–1900

In this section are described the mass movements triggered by Berat and Himarë earthquakes. These events happened more than 125 years ago, therefore the mass movements are treated based on historical information and previous works.



1. Earthquake location; 2. lateral earth spread; 3. rockfall; 4. sand liquefaction; 5. earthquake number.

Fig. 9 Location of earthquake-induced mass movements during 1850–1900. 1. Earthquake location; 2. lateral earth spread; 3. rockfall; 4. sand liquefaction; 5. earthquake number

2.2.1 Earthquake of October 17, 1851

Perrey (1853), Mihailoviç (1927), Boué (1951), Sulstarova and Koçiaj (1975), Sulstarova (1999), and Ambraseys (2009) reported that on October 17, 1851, a strong earthquake with a magnitude M = 6.6 hit of Berat city (Fig. 7), causing severe damage to the geo-environment and human life. Reports of that time estimated the destruction of more than 300 residential buildings, two mosques and one church. This event occurred in the seismogenic zone of Periadriatic Lowland. The ground in and around of Berat urban area was affected by cracks, earth lateral spreading, sand liquefaction and rock falls (Fig. 9). The sand

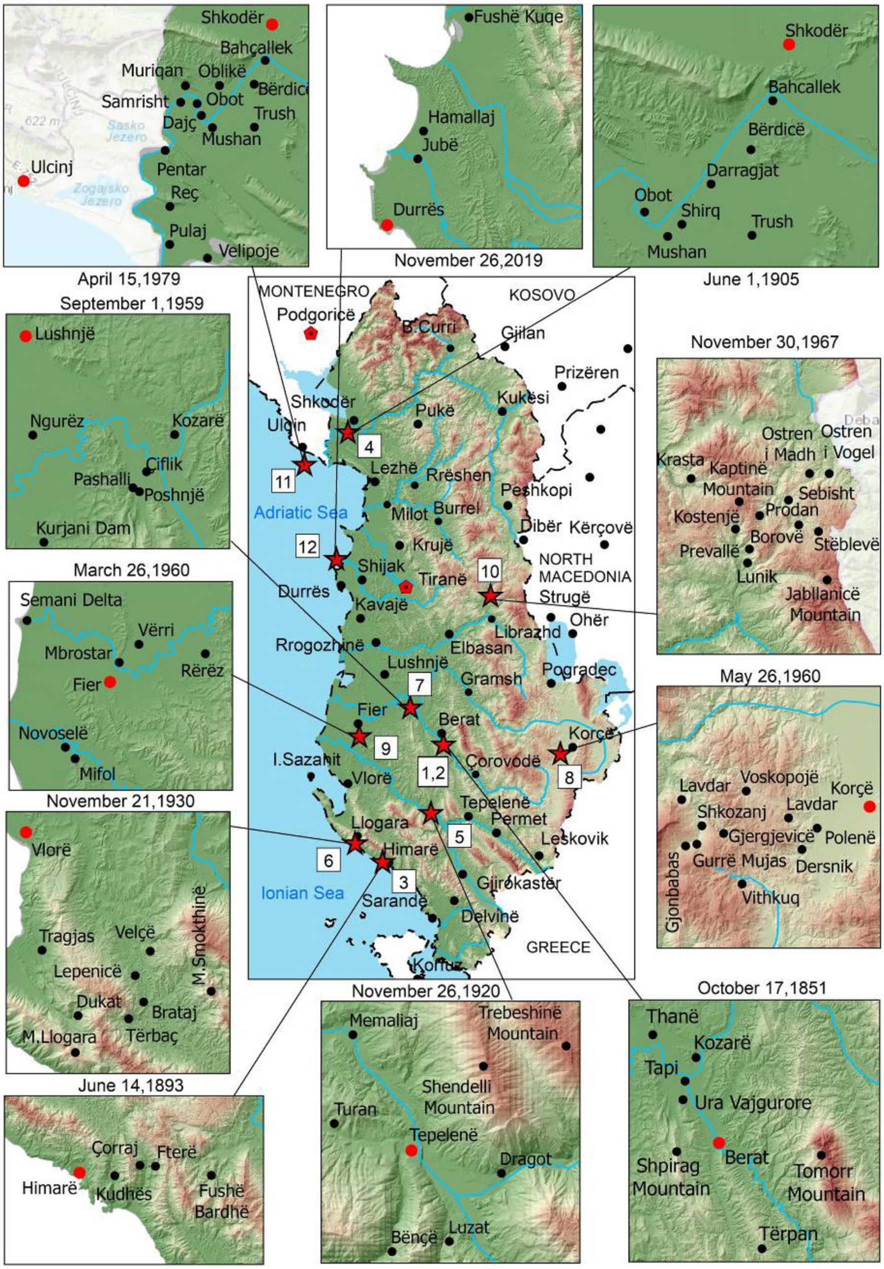


Fig. 10 Location of the occurrence of earthquake-induced mass movements in Albania

liquefaction occurred along the Osumi river deposits in several areas, in the villages of Ura Vajgurore-Tapi, Kozarë, Arrë and from the village of Thanë to the Kuqi bridge (Fig. 10). They were in the form of sand boils and cracks followed by emissions of sulfur gas, causing difficulties in breathing for the inhabitants. On the other hand, in the upper part of

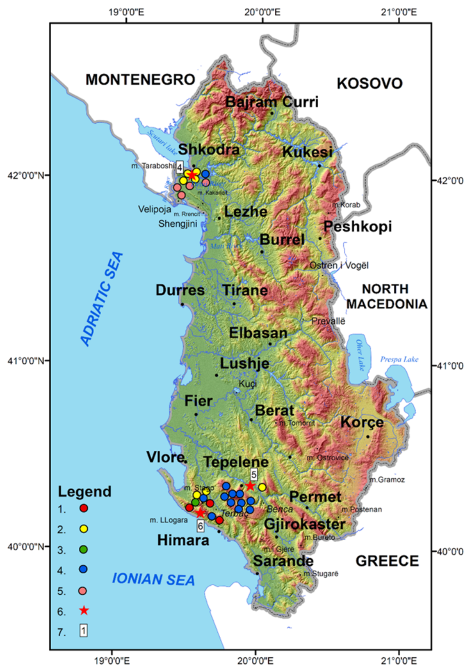
Berat castle and Goricë hills limestone blocks and cobbles fell down the slopes destroying many houses along the way. Rock falls occurred over Tërpan (S), Shpirag (W) and Tomorr (E) Mountains, too (Fig. 10).

2.2.2 Earthquake of December 29, 1851

Perrey (1853), Mihailoviç (1927, 1951), Sulstarova and Koçiaj (1975) and Ambraseys (2009) showed that on 29 December 1851, another earthquake with magnitude M = 6.0, hit the city of Berat (Figs. 7, 8a). Following the October 17 earthquake of the same year, this one affected an area 18 km away from Berat, damaged many houses and killed many residents. Based on historical information and interviews conducted with the residents of this area, rock falls were seen from Tërpani (S), Shpiragu (W) and Tomorri (E) Mountains (Figs. 9, 10).

2.2.3 Earthquake of June 14, 1893

On June 14, 1893, an earthquake with a magnitude M = 6.6 and hypocentral depth of 6.6 km occurred in the seismogenic zone of Ionian Coast, with the epicenter at Himarë region (Aliaj 2010,2012). As a result, Kudhës village (Himarë) was completely destroyed



1. Debris slide; 2. lateral earth spread; 3. lateral rock spread; 4. rockfall; 5. sands liquefaction; 6. earthquake location; 7. earthquake number.

Fig. 11 Locations of earthquake-induced mass movements during 1901–1950. 1. Debris slide; 2. lateral earth spread; 3. lateral rock spread; 4. rockfall; 5. sands liquefaction; 6. earthquake location; 7. earthquake number and most of the residential buildings in Kuç village (Vlorë) were damaged. From this event, the mountain slope areas from Himarë to Fushë Bardha villages (Gjirokastër region) at 5 localities (Himarë, Kudhës, Çorraj, Fterë and Fushë Bardh villages) were affected by numerous rockfalls (Figs. 8b, 9, 10). Moreover, due to this event, the hill slope in Kudhës village was cracked and moved in form of lateral earth spread.

2.3 Mass movements in 1901–1950

During 1901–1950, three earthquake-induced mass movements were recorded in Albania (Fig. 11). It should be noted that nowadays most of the mass movements caused by earthquakes are difficult to detect, as they have lost the geomorphic characteristics such as "landslides features" from further geological and natural events. Reactivations of landslides, erosional action and revegetation have modified the features of these mass movement caused by the earthquake (Muceku and Lamaj 2009; Muceku et al. 2019).

In this section, landslides caused by earthquakes are analyzed based on previous studies (Muço 1996; Koçiaj 2000; Aliaj et al. 2010; Aliaj 2012) and engineering geological investigations (Muceku and Lamaj 2009; Muceku et al. 2019).

2.3.1 Earthquake of June 1, 1905

On June 1, 1905, the region of Shkodër was hit by an earthquake with a magnitude M = 6.6 and hypocentral depth of 15.6 km in the seismogenic zone of Lezhë-Ulqin (Figs. 7, 8c). More than 1500 houses were completely destroyed, and many other buildings were heavily damaged. About 200 lives were lost and more than 500 people were injured (Aliaj 2012). The walls of the castle of Shkodër partially collapsed and stones fell over buildings at Alajbeg and Tabake neighborhoods located at the foothill of the castle.

As a result of this event, many areas were affected by landslides and sand liquefaction (settlement). In both riverbanks of Buna at Bahçallëk, Obot and Shirq villages, lateral earth spread and considerable damage to agriculture was observed (Koçiaj 2000; Aliaj et al. 2010) (Figs. 10, 11). Thus, the bank's soils (pastures and agriculture areas) reached to the stream and were eroded by the water flow (Muceku and Lamaj 2009; Muceku et al. 2019). At the terraces of Drini and Buna Rivers at Bahçallëk, Berdicë, Darragjat, Mushan and Trush villages sand liquefaction as settlements, sands boils and wide cracking were also observed.

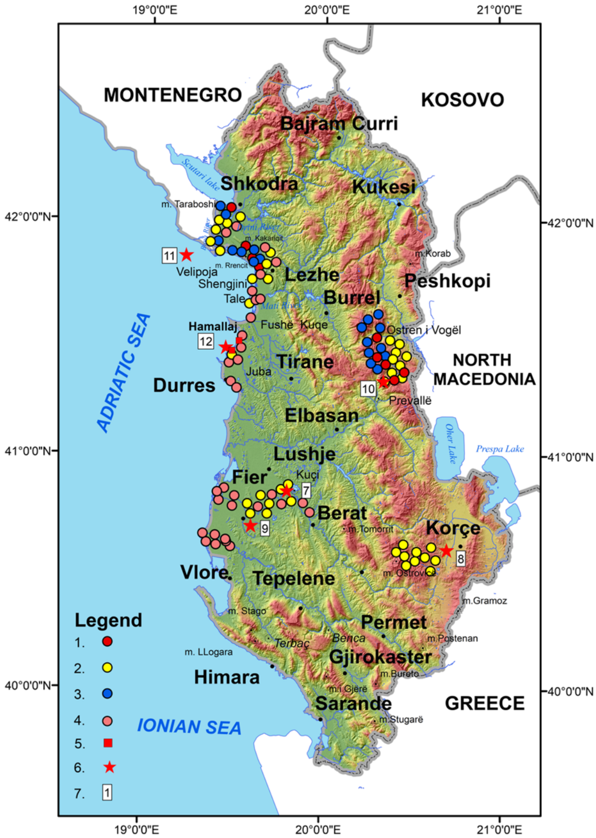
2.3.2 Earthquake of November 26, 1920

On November 26, 1920, an earthquake of magnitude M = 6.4 and hypocentral depth of 6.1 km occurred in the seismogenic zone of Ionian Coast, with epicenter in Tepelenë (Figs. 7, 8d). It caused the destruction of most of the houses in the city and at the villages of Bënçë, Turan, Dhëmblan, Memaliaj, Kashis, Salari, Dragot, Luzat (Fig. 10). From this event 36 people died and 102 were injured (Aliaj et al. 2010).

In Tepelenë, at the northern part of castle, a lateral earth spread was activated, demolishing its walls, whereas, to the west, a massive debris slide occurred on Tresenikë mountain slopes at Bënçë village, blocking the traffic corridors and communication lines of this village (Fig. 11). Additionally, around this area there were recorded 23 rockfalls at 14 locations; large blocks fell down the mountains of Bençë, Tresenikë, Këndrenicë, Dhëmblan, Kudhës, Tartanë, Shendelli, Golik and Trebeshinë over national traffic routes connecting the cities of Tepelenë with Vlorë, Gjirokastër, Përmet, and their respective villages (Koçiaj 2000) (Fig. 10).

2.3.3 Earthquake of November 21, 1930

On November 21, 1930, an earthquake with a magnitude M = 6.3 and hypocentral depth of 5.2 km hit the Llogara Mountain (Vlorë region) (Figs. 7, 8e). This event caused the complete destruction of Dukat, Tërbaç and Palasë villages, and partial destruction of Dhërmi, Smokthinë, Velçë, Brataj, Vranisht, Lepenicë and Tragjas villages. More than 30 lives were lost and over 100 injured (Aliaj et al. 2010). In two places of Stago Mountain slopes, Tërbaç and Brataj villages, several lateral earth spreads occurred (Figs. 10, 11)



1. debris slide; 2. lateral earth spread; 3. rockfall; 4. sands liquefaction; 5. ground crack, 6. earthquake location; 7. earthquake number.

Fig. 12 Locations of earthquake-induced mass movements after 1950. 1. debris slide; 2. lateral earth spread; 3. rockfall; 4. sands liquefaction; 5. ground crack, 6. earthquake location; 7. earthquake number

(Muço 1996; Koçiaj 2000). At Brataj village, a considerable part of the forest and agricultural land was washed out. Both slide areas (ground crack spreading) were 70–100 m long, 100–150 m wide and 2–4 m deep (Muceku and Lamaj 2009; Muceku et al. 2019). About six rockfalls and three debris slides occurred in two locations (Terbaç village and Çika Mountain). A large landslide of massive limestone blocks and loam fell and rolled along of mountain slope, damaging a large forest area (Koçiaj 2000). Furthermore, a lateral rock spread occurred on limestones on the western slope of Çika Mountain at Llogara Pass, which resulted in triggering a 1.0 km long and 1–1.5 m wide failure (Figs. 10, 11) (Aliaj et al. 2010). From all these events, road network and communication lines were heavily damaged.

2.4 Mass movements in 1951–2000

During 1951–2000, many earthquake-induced mass movements (Fig. 12) occurred in Albania. Some of the landslides are eroded and covered with vegetation (shrubs and plants) and were found during field work (Muceku et al. 2009; Muceku et al. 2019). These ground failures were identified by the "*geomorphic features*" such as: "*arcuate scarp and hummocky topography in main track*" for lateral earth spread and "*arcuate head scarp, planar failure and soils and rocks mass deposition*" for rock falls and debris slides. The main earthquakes that triggered mass movements during this period are described below.

2.4.1 Earthquake of September 1, 1959

On September 1, 1959, an earthquake of magnitude M = 6.4 and hypocentral depth of 16.9 km (Arapaj village) hit the region of Lushnje (Figs. 7, 8 g) causing severe damage to residential buildings and geo-environment. More than 250 houses were damaged, from which 100 were completely destroyed (Aliaj et al. 2010). In several localities along Osum and Seman riverbanks and over the hill slopes, sand liquefaction and landslides occurred (Fig. 12). The liquefaction (ground settlement and sand boils) was generated across of the first terrace of Osum and Seman rivers in several locations at Ngurëz e Vogël and Arapaj villages (Lushnje region); Kurjan dam, Strumë and Çukas villages (Fier region); Kozarë villages (Kuçovë region); Çiflik-Poshnje and Pashalli villages (Berat region) (Fig. 10). At the same time, many lateral earth spreads occurred on the hill slopes near the villages of Stromë, Poshnje and Kurjan. This earthquake also caused environmental damage, such as sliding of the riverbanks and hills slopes accompanied by the destruction of tree plantations and loss of agricultural land.

2.4.2 Earthquake of May 26, 1960

A strong earthquake (M = 6.5 and hypocentral depth of 7.6 km) occurred on May 26, 1960 in southeast of Albania, in Korçë region (Figs. 7, 8 h). Aliaj et al. (2010) reports that this earthquake caused severe damage to the city of Korçë and to several villages located nearby (to the east and southeast) (Lavdar, Vithkuq, Voskopojë, Polenë, Lavdar, Dersnik, Gjergjevicë, Skozanji, Gjonshtiras, Gurrë Mujas and Gjon Babas). Seven people died and 127 were injured. Over 400 houses were completely destroyed, and 1900 others damaged. This event triggered 13 lateral earths spreads in Gjergjevicë, Skozanji, Gjonshtiras, Gurrë Mujas and Gjon Babas villages (Figs. 10, 12). The earth spreads were shallow, relatively small and situated on weak rocks as sandstones and claystone-siltstone-sandstone combinations. These slides have damaged a considerable area of pastures, forests, and agricultural goods. Additionally, the earthquake caused rockfalls over the road Vithkuq—Shtyllas, blocking it for several hundred meters (Muceku and Lamaj 2009; Muceku et al. 2019; Koçiaj 2000).

2.4.3 Earthquake of March 18, 1962

On 18 March 1962, the Fier district was hit by an earthquake of a magnitude M = 6.0 and hypocentral depth of 14.4 km (Figs. 7, 8i), that caused severe damage to the city and villages nearby. About 2100 houses were damaged and more than 680 were completely destroyed, 5 people died, and many others were injured (Aliaj et al. 2010). This event triggered more than 9 landslides over the hill slopes around Mbrostar, Vërri and Rërës villages (Figs. 10, 12). The landslides induced over hillslopes of the Rërës village occurred in the diluvial soils that are situated on molasse rocks. The landslides were the lateral earth spread type, relatively small (20–80 m wide and 5–10 m long) and shallow (1–4 m deep). On the other hand, the landslides that occurred along of the Seman River valley were situated on alluvial terraces composed by silty and clayey sands. These landslides were from the lateral earth spread type, shallow in depth and small in size. Moreover, from this event, sand liquefaction was observed at river terraces of Gjanicë (Rërës village, Fieri), Vjosë (Novoselë and Mifol villages) and Seman delta areas (Adriatic coast) (Fig. 10).

2.4.4 Earthquake of November 30, 1967

The earthquake of November 30, 1967, with M = 6.6 and hypocenteral depth of 7.9 km, occurred in Dibër region (Figs. 7, 8j) and caused severe damage in 13 localities. About 540 houses were destroyed, 5800 buildings (houses, schools) were damaged, 12 people died, and 177 others were injured (Aliaj et al. 2010). This event also triggered many lateral earth spreads 10–15 m to 30–50 m long (Fig. 12).

The landslides occurred on hills slopes extend along of the active fault from Prevallë village up to Trebisht-Ostren i Vogël villages. This part is one of the most active tectonic areas in Albania where the limestone rocks of Middle Triassic–Middle Jurassic through active tectonic fault overthrust on flysch rocks (claystone-sandstone combinations) of Eocene age. As a result of this earthquake, this fault was reactivated and a massive 1.2–1.5 km long and 0.5–1 m wide fracture was opened. It was immediately followed by several landslides (Figs. 9, 12) (Aliaj et al. 2010; Koçiaj 2000; Muço 1996). Many lateral earth spreads 10–15 m to 30–50 m occurred across the stream valleys in Sebisht, Zabzun, Borovë, Prodan and Ostren i Madh villages causing the damage of a lot of buildings and many hectares of tree plants and agricultural areas (Muceku and Lamaj 2009; Muceku et al. 2019). Moreover, about 31 rockfalls and debris slides occurred in five localities that extend from Prevallë village (south) up to Trebisht -Ostren i Vogël village (north) and from Steblevë village (east) up to Krasta village (west) (Figs. 10, 12). The materials, which fell down from the mountain slopes (Lunik, Kostenjë, Polen, Kaptinë, Ramingore and Jabllanica Mountains) and stream valleys consist of broken boulders and cobbles (Muceku and Lamaj 2009; Muceku et al. 2019).

2.4.5 Earthquake of April 15, 1979

On April 15, 1979, the region of Shkodër was struck by a strong earthquake (M = 6.9 and hypocentral depth of 16.8 km) with an epicenter in Ulcinj region, Montenegro (Figs. 7, 8 k). This event occurred in the seismogenic zone of Lezhë-Ulqin and was by far the most devasting earthquake in Albania. More than 17,000 residential and social-cultural buildings were destroyed (Aliaj et al. 2010) and sand liquefaction and mass movements (lateral earth spreads, rock falls and debris slides) distributed along of the riverbanks and terraces of Buna and Drini Rivers (Lezha), as well as Tarabosh, Kakarriq and Rrenc Mountain slopes were triggered. The first terrace of Drini and Buna rivers from Bahçallëk Square to Shirq-Trush-Dajç-Reç villages and Adriatic coastal area (Velipojë village) were affected by sand liquefaction, inducing many extensive cracking, settlement, lateral earth spread and sand boils (Fig. 12). The cracks formed in these areas extend parallel to the Buna and Drini Rivers with width and length range from 10–15 cm up to 35–40 cm and 15–20 m to 35–40 m, respectively (Muceku and Lamaj, 2009; Muceku et al. 2019). The mass movements generally were represented by shallow lateral 10–20 m up to 50–70 m long earth spreads located at Bahçallëk, Bërdicë, Obot, Shirq, Mushan, Dajç, Samrisht, Belaj, Pentarë, Muriqan, Pulaj, Ceraj-Velipojë, Oblik and Barbullush (Figs. 10, 12).

Lateral earth spreads, sand boils, settlement and ground cracking were also observed along Drini riverbanks in the city of Lezhë, as well as at the delta in Fishtë e Poshtme village. The slide's body moved to the riverbed (Shehu and Dhima 1983). Due to this earthquake, some small and shallow lateral earth spread (7–10 m to 15 m wide and 5–10 m long) occurred in hills slopes of Oblika village (Shehu and Dhima 1983; Muceku and Lamaj, 2009; Muceku et al. 2019). Additionally, the mountain slopes of Tarabosh, Renc and Kakarriq (Figs. 10, 12) were destabilized and moved down as rock falls and debris slides from cities of Shkodër to Lezhë. These landslides were composed of mixtures of rubbles, broken stones, cobbles, and limestone blocks (Muceku and Lamaj 2009; Muceku et al. 2019).

2.5 Mass movements after 2000s

After 2000s, there was only a strong earthquake recorded with a magnitude larger than 6.0. It occurred on November 26, 2019, in the region of Durrës.

2.6 1.1.1. Earthquake of November 26, 2019

On November 26, 2019, a strong earthquake with a magnitude of M = 6.4 and hypocentral depth of 22 km (Papadopoulos et al. 2020) struck the western part of Albania, with the epicenter in the west of the Hamallaj village, 15 km north of the city of Durrës (Figs. 7, 8 m). The faulting was of reverse type dipping to the east (strike = 155°, dip = 72° and rake = 85°). This event caused 51 casualties, and more than a thousand were injured. Most of the damages occurred in Durrës and its surrounding villages. There were also many damages in the city of Shijak, Thumanë, Vorë and Tiranë. Over 1,000 buildings within the Durrës district and hundreds more in the towns nearby were severely damaged. This earthquake also caused sands liquefaction, ground cracking, lateral earth spread and differential settlements (Fig. 12).

In this section are presented the results of the geotechnical investigations carried out over the last three months in the coastal area where the earthquake had the greatest devastating impact. Four locations that were the most affected by seismic event were mapped (Figs. 10, 12). They were spread out along the coastal plan to the east of the earthquake epicenter and along of the tectonic line from Durres beach (south) up to Fushë Kuqe village (north) like a 43 km long and 2.7–3.5 km wide belt. The earthquake ground effect areas were observed in Jubë, Hamallaj and Fushë Kuqe villages, as well as along the Durrës coastline (Figs. 10, 12).

Site of durres coastline Along the coastline in the sand beach about 1.5 km south of the Durrës seaport, in a 500 m long and 100 m wide rectangular area, sand liquefaction-fluidization (Kagawa et al. 2015) occurred. It was followed by ground subsidence from which three five-story hotels were demolished (Fig. 12).

Site of Juba village The best case of the mapped sands liquefaction occurrence was found in the Juba village. It is located about 11 km northeast of Durrës and 5–7 km east of the earthquake epicenter. From the geotechnical investigations, it was observed that soil liquefaction occurred in two sites, one within the Juba village, and the other to west, closed to the Erzeni river delta (Figs. 10, 12). The Juba village is built upon the alluvial plain terrace. The affected area by liquefaction is in a 620–650 m long and 100–150 m wide rectangular area, extending from northeast (riverbank of Erzeni) to southwest along the village. The soil liquefaction is represented by sand boils, which take part among of the residential buildings (flower garden and agricultural areas) of the village and below their foundations. During the earthquake, silt, fine sand and water were ejected 3.5–4 m over the land surface. The other surveyed site is about 2.7 km west of the village of Jube, located along the Erzeni river delta, on its south side. Geologically and geomorphologically, this area represents back swamps and lowlands and is generally composed by intercalation of soft silt and clay layers with very loose and water-saturated sand layers. Liquefaction in this site took place with cracks, lateral earth spreads and sand boils. The cracks were developed near and parallel to the river. They were 160–170 m long, 0.2–0.5 m to 1–1.2 m wide and 2.5–3 m deep. Whereas, to the south, close to cracks, many outcrops of sand boils were observed on the alluvial deposits. The affected area has a rectangular shape, is105 m long and 50 m wide and extends parallel to the Erzeni River.

Site of Hamallaj village Numerous sand boils, ground cracks and settlements were mapped west and north of Hamallaj village. They were distributed on rectangle zone to the east and parallel of beach sands from San Pietro beach (north) up to Hamallaj village (south), extending about over a 3.5 km long and 200–300 m wide (Figs. 10, 12). The sand boils range from 2–5 m up to some tens meters in length, extending into sectors and zones varying from several up to many hundreds square meters. In the central part of this area, land subsidence with diameter of 50 m occurred. Cracks strike 342–345° and are 50 m long, 0.3–0.5 m wide and more than 10 m deep. In several parts the main road of the village and a bridge were damaged by cracking and subsidence. Differential settlement caused by sands liquefaction damaged four residential buildings (wall cracks) in the village of Hamallaj.

Site of Fushë Kuqe village In this area, the sand liquefaction affected a rectangular, 700 m long and 200 m wide area southwest and north of the Fushë Kuqe village (Figs. 10, 12), stretching in a west direction over the Adriatic flat plain, and on terraces of the Mat River.

The upper part of the lithological profile (0–30 m) of the liquefaction area on the Adriatic flat plain) is generally composed by combination of soft silts, organic soils, and loose sand layers with shallow ground water level (0.5–1 m deep). It extends to the east of Adriatic coastline along the flat plain in the form of a 4.5–5 km long and 1.5 km wide belt. In this region, due to liquefaction, many sand boils occurred.

The other area affected by liquefaction lies to the north of the Fushë Kuqe village along of the Mat River terrace, extending from east to west and is 1.4 km long and 250–500 m wide. Lithologically, this area is built on soft silt and clay soils intercalated by saturated loose sand layers. As a result of the earthquake, the liquefied soil ejected from the ground between the residential buildings across the courtyards and Mat River terrace. The occurrence of lateral earth spreads perpendicular and parallel to the Mati riverbank caused several hundred square meters of pastureland to slide towards the river. The differential settlement caused by sand liquefaction damaged seven residential homes (1–3 story buildings).

3 Results and discussions

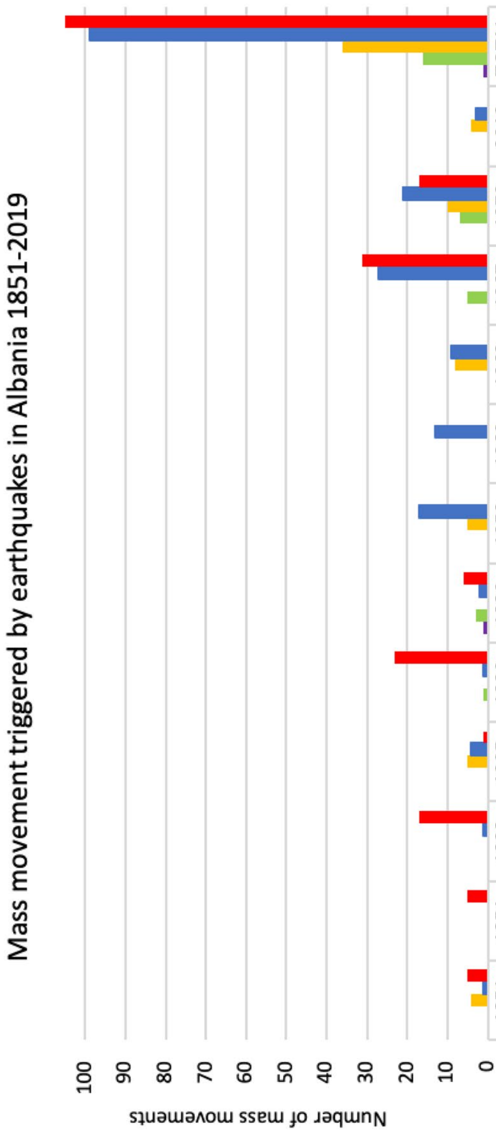
In Albania, the mass movements triggered by earthquakes are closely associated with the magnitude (M), hypocentral depth, distance from the epicenter, areas' morphology (slope inclination), lithological types and the geotechnical conditions of the ground (soils and rocks). From the results of this analysis, it was observed that in the terrains with similar morphological characteristics the same types of mass movements have occurred.

Thus, from all the analyzed earthquakes that have occurred in Lezhë-Ulqin and Peri-adriatic Lowland seismic zones, lateral earth spreads and sand liquefaction features have occurred in the areas with weak geotechnical properties. Lateral earth spreads were observed along t riverbanks and on hills slopes made of "CL" and "ML" soils with stiff consistency (ASTM 2011).

After the Durrës earthquake, lateral earth spreads extended over an area with a radius 7–8 km, after the Berat, Lushnje and Fier earthquakes over a radius of 9–10 km and after Ulcinj earthquake within a radius of 36–37 km from the epicenter. Sand liquefaction was observed in saturated and loose sands "SM" & "SC" (ASTM 2011). The distribution of this phenomenon showed that sand liquefaction was observed in a radius of 25–27 km after the Durrës earthquake, 18–22 km after the Berat, Lushnje and Fier earthquakes and around 40 km from the epicenter after the Ulcinj earthquake. In the mountainous terrains, due to the slope inclination, debris slides and rockfalls occurred in "GP" soils (ASTM 2011) and fractured and blocks of limestones.

From the gathered geological-engineering and seismological data, debris slide lay on a distance up to 10 km after the Vlorë earthquake, 15–16 km after the Dibër earthquake and 20 km from the epicenter after the Montenegro earthquake. Historical data, previous studies, as well as the engineering geological mapping conducted over the past two decades, indicate that the mass movements and sand liquefaction structures are induced by earthquakes with a magnitude $M \geq 6.0$ and shallow hypocenter depth (5.2–33 km). It is found that about 221 landslides have occurred, and 36 locations were affected by sand liquefaction. In Albania, based on mass movement evaluation and classification as of Cruden and Varnes (1996) and Fairless and Berrill (1984), 99 of landslides are lateral earth spreads, 105 are rockfalls, 16 are debris slides, one is lateral rock spread and in 36 localities sand liquefaction, cracks and settlement were observed. The graph in Fig. 13 summarizes all the mass movements triggered by earthquakes during 1851–2019 in Albania.

According to Cruden and Varnes (1996), Fairless and Berrill (1984) and Kagawa et al. 2015, the mass movements triggered by earthquakes are respectively classified in: *lateral earth spreads*, *rock falls*, *lateral rocks spreads*, *debris slides*, *sand boils, sand fluidization, cracks* and *settlements*. They are summarized in the sections below.



	1851	1851	1893	1905	1920	1930	1959	1960	1962	1967	1979	2019	TOTAL
Lateral rock spread	0	0	0	0	0	1	0	0	0	0	0	0	1
Debris Slide	0	0	0	0	1	3	0	0	0	5	7	0	16
Ground subsidence & sand boils	4	0	0	5	0	0	5	0	8	0	10	4	36
Lateral earth spread	1	0	1	4	1	2	17	13	9	27	21	3	99
Rock fall	5	5	17	1	23	6	0	0	0	31	17	0	105

Fig. 13 Mass movements occurred from earthquakes during 1851—2019 in Albania

Fig. 14 Examples of lateral earth spread: **a** along Buna river bank, 1979; **b** along Erzeni river bank, 2019

3.1 Lateral earth spreads

From the investigations, it was found that about 61 earthquake-induced lateral earth spreads have occurred on hillslope areas and 38 along the river valleys in Albania during 1851–2019. From the geotechnical investigations, it was concluded that the lateral earth spreads induced from earthquakes on hillslopes are generally shallow and of small size, with dimensions of 7–10 m to 15–25 m in length and 15–20 m to 30–40 m in width. On the other hand, the sliding plane depth varies from 1–2 m to 3.5–5 m (Muceku and Lamaj 2009; Muceku et al. 2019). The lateral earth spreads on hillslopes, which occurred from the earthquakes of Berat 1851, Himarë 1893, Tepelenë 1920, Vlorë 1930, Lushnje 1959, Korçë 1960, Fier 1962, Dibër 1967 and Montenegro 1979 are commonly composed by diluvial soils composed of inorganic silts and clays of low- to medium-plasticity and fine sands with a stiff consistency and medium water contents (ML and CL). These mass movements are found on the hill's slopes built by flysch and molasse rocks with an inclination angle ranging from 30°–35° to 50°–55°.

Moreover, the earthquakes of Shkodër 1905, Lushnjë 1959, Fier 1962, Montenegro 1979 and Durrës 2019 have triggered lateral earth spreads on the river valleys and terraces of Buna, Drini (Lezhë), Vjosa, Semani, Erzen and Mat Rivers (Figs. 10, 14). Generally, these mass movements formed parallel to the riverbed ranging between 15–25 m and 50–75 m with sliding planes varying from 1–2 m to 2.5–5 m depth. The slide bodies consist of proluvial soils of inorganic clays of low to medium plasticity "CL" and inorganic silts and very fine sands "ML" with stiff consistency (ASTM 2011). The lateral earth spreads were distributed and concentrated in the riverbanks, which have the inclination angle 55–75°. It is important to note that most of the lateral earth spreads described in this paper, over the years occurring during the wet season, were also associated with shallow landslides, such as landslides and land flows, as well as with erosion and vegetation.

Fig. 15 Evidence of rockfall in Dibër county after the 1967 earthquake

3.2 Rockfalls

From the geotechnical investigations, it was observed that most of the rocks in the upper part of lithological profile are intensively fractured by joints, separated by bedding planes, and divided in blocks with variable sizes ranging from 0.2–1 m^3 to 1.5–2.5 m^3 by weathering processes, discontinuities and tectonic activity (Muceku and Lamaj 2009; Muceku et al. 2019). During seismic events from 1851 to 1979, 105 rockfall locations on mountains slopes with a slope angles of 70° (or higher) were identified and documented (Fig. 15). They occurred in fractured massive limestone cobbles and boulders in the seismogenic zones of the Periadriatic Lowland, Lezhë-Ulqin, Ionian Coast and Kukës-Peshkopi. The rock falls resulted in two casualties, in damage of many residential buildings, blocked communication networks and occupation of the agricultural land of several villages that are treated in this paper.

3.3 Debris slides

The debris slides are mainly caused by rainstorms, but in some cases, they are triggered by shallow and strong earthquakes ($M \geq 6.3$). As was reported by several authors (Koçiaj 2000; Sulstarova 1999), the debris slides were triggered by earthquakes of Tepelenë in 1920 ($M = 6.4$), Vlorë in 1930 ($M = 6.3$), Dibër in 1967 ($M = 6.6$) and Montenegro in 1979 ($M = 6.9$). From the geotechnical investigations, more than 16 debris slides were identified that had occurred on limestones and slopes composed of magmatic rocks with slope inclination angle of 35°–45° up to 60° in the seismogenic zones of the Lezhëa-Ulqin, Ionian Coast and Kukës-Peshkopi. They are 10–50 m long, 15–30 m wide and 0.5–1 m thick. The debris slides material consists of a coarse and angular gravel-cobble mixture with little

Fig. 16 Example of a sand boil along Buna River at Dajç village, 1979

Fig. 17 Example of a sand boil after the November 26, 2019, earthquake

Fig. 18 Tilting of the building due to liquefaction and ground subsidence

fines “GP” (ASTM 2011) that have been and is in loose density (Muceku and Lamaj 2009; Muceku et al. 2019).

3.4 Lateral rock spread

Evidence of a lateral rock spread have been found in the seismogenic zone of the Ionian Coast, in the western side of Çika Mountain on limestone formations, in the district of Vlorë (Figs. 10, 11), from the November 21, 1930, earthquake. A deep failure of an about 1.0 km long, 0.8–1.2 m thick rock mass was also accompanied with the 0.2–0.5 m downward dislocation of the western side along the mountain slope (Aliaj et al. 2010).

3.5 Ground settlement and sand boils

From the investigations, it was observed that 36 localities in Albania were subjected by sand liquefaction as ground settlement, cracks, sand fluidization and sand boils. The liquefaction analysis revealed that 60% of liquefaction occurred in the seismogenic zones of the Periadriatic Lowland and 40% in the Lezhë-Ulqin. The earthquakes during 1851–2019 triggered ground settlement, ground cracks, sand fluidization and sand boils (Figs. 10, 16, 17, 18) along the terraces of Drini and Buna Rivers at Bahçallëk, Berdicë, Darragjat, Mushan and Trushi villages, in the terraces of Osumi and Semani Rivers, close to Ngurëz e Vogël and Arapaj villages (Lushnje region), at the Kurjan dam, in Strumë and Çukas villages, (Fier region), Kozarë villages (Kuçovë region); Çiflik-Poshnje and Pashalli villages (Berat region), in the riverbank of Gjanica (Rërës village, Fier) and Vjosa (Novoselë and Mifol villages) and Seman delta area (along the Adriatic coast), Trush-Dajç-Reç villages and Adriatic coastal area (Velipojë village), in the riverbank of Erzeni (Jubë and Hamallaj villages, Durrës) and Mati Rivers (Fushë Kuqe village), as well as along the Durrës beach (Fig. 10).

Generally, the head of the sand boils were 0.1–0.3 m and ground settlement depth vary from 0.2–0.3 to 0.5–0.8 m. From the geotechnical analyses performed in these areas, it was observed that sand liquefaction occurred in saturated fine- to medium-sized silty sands “SM” & clayey sands “SC” (ASTM 2011), which are characterized by a loose density. These soils consist of 89–96% of fine (0.06–0.6 mm) to medium (0.6–1.0 mm) sands. Usually, the liquefied soils in the investigated areas were observed in sands layers, extending from 3.5–5 m to 12–15 m depth along the river terrace and coastal plain.

4 Conclusions

In this paper are presented the earthquake-triggered mass movements that have occurred from 1850 to 2019 in Albania. Historically, strong earthquakes that have hit this region have triggered lots of mass movements causing considerable damages such as life loss, destruction of properties and disruption of the geo-environment. Identification of earthquake-triggered mass movement is scarce and not well-documented, especially for the seismic events that have occurred in the past. Even though the dataset is not comprehensive, historical and field investigation data collection and analysis provide some useful information that could be used in the future works. The results show that the mass movements triggered by earthquakes are closely related to the magnitude (M), hypocentral depth, distance from the epicenter, areas' morphology (slope inclination), lithological types and the geotechnical conditions of the ground (soils and rocks). Mass movements such as lateral earth spread, rocks fall, debris slides, sand boils, sand fluidization, cracks and settlement were triggered by earthquakes with a magnitude of 6.0 or higher. On the other hand, lateral rock spread requires a higher seismic magnitude to occur. Based on the data presented, the following conclusions can be drawn:

- The historical data, field work, and engineering geological mapping have indicated that 221 landslides have occurred (99 lateral earth spreads; 105 rockfalls; 16 debris slides and 1 lateral rock spread), and 36 locations were affected by sand liquefaction (sand boils, cracks, and settlement) in Albania.
- From the presented investigations, it was found that about 61 earthquake-induced lateral earth spreads have occurred in hillslopes areas and 38 along the river valleys in Albania during 1851–2019. The lateral earth spread induced from earthquakes on hillslopes are generally shallow and small-sized with dimensions of 7–10 m to 15–25 m in length and 15–20 m to 30–40 m in width. It is commonly composed by diluvial soils composed of inorganic silts and clays of low to medium plasticity and fine sands with stiff consistency and medium water content (ML and CL). These mass movements were found on the hillslopes of flysch and molasse rocks with an inclination angle ranging from 30°–35° to 50°–55°. The lateral earth spreads induced by earthquakes on the river valleys and terraces occurred parallel to the riverbed ranging between 15–25 m and 50–75 m with sliding planes varying from 1–2 m to 2.5–5 m depth. The slide bodies consist of proluvial soils of inorganic clays of low to medium plasticity "CL" and inorganic silts and very fine sands "ML" with stiff consistency. Most lateral earth spreads triggered by earthquakes, over the years during the wet season, were associated with shallow landslides, such as landslides and land flow, as well as with erosional features and vegetation.
- During seismic events of 1851 – 1979, 105 rockfalls locations on mountains slopes of 70° (or higher) were identified and documented. They occurred in fractured limestone cobbles and boulders. The rock falls materials consist of limestones of various sizes from 0.2–1 m^3 to 1.5–2.5 m^3.
- 16 debris slides were identified. They occurred on limestones and magmatic slopes with inclination angle of 35°–45° up to 60°, and are 10–50 m long, 15–30 m wide and 0.5–1 m thick. The debris slide material consists of a coarse angular gravel-cobble mixture with little fines "GP" (ASTM 2011) that have been and are in a loose density.
- 36 locations were subjected of the sand liquefaction phenomena such as ground settlements, cracks, sand fluidization structures and sand boils. The liquefaction analysis revealed that 60% of liquefaction occurred in the seismogenic zones of the Periadriatic Lowland and 40% in the Lezhë-Ulqin area. The earthquake during the 1851–2019 period triggered ground settlements, ground cracks, sand fluidization and sand boils. The ground settlement depth varies from 0.2–0.3 to 0.5–0.8 m, whereas the head of the sand boils were 0.1–0.3 m. The sand liquefaction occurred in saturated fine- to medium-sized silty sands "SM" & clayey sands "SC", which are characterized by a loose density. These soils consist of 89–96% of fine (0.06–0.6 mm) to medium (0.6–1.0 mm) sands. Usually, the liquefied soils in the investigated areas were observed in sands layers, extending from 3.5–5 m to 12–15 m depth along the river terraces and coastal plain.
- One lateral rock spread was discovered in the seismogenic zone of the Ionian Coast, in the western side of Çika Mountain (Vlorë district) on limestone rock formations, which is represented by a deep failure of about 1.0 km long, 0.8–1.2 m wide.

- The dominant type of mass movement caused by earthquakes in the Albanian area is rockfall, which constitutes 48% of landslides followed by lateral earth spreads that represent 45% of landslides.

Based on the collection of historical and field investigation data, during the seismic events of 1851–2019 in Albania, 61 mass movements were identified and documented that occurred in the seismogenic zone of the Periadriatic Lowland, 64 mass movements in the seismogenic zone of the Lezhë-Ulqin, 55 mass movements in the seismogenic zone of the Ionian Coast, 13 mass movement in the seismogenic zone of the Ohrid-Korçë and 63 mass movement occurred in the seismogenic zone of the Kukës-Peshkopi.

In conclusion, the mass movements triggered by earthquakes were found to be closely associated with (1) lithological types of soils and rocks; (2) geotechnical conditions of soils and rocks; (3) morphology-slope inclination; (4) earthquake epicenter depth; and (5) earthquake magnitude. Thus, earthquake's high magnitude and shallow hypocentral depth, as well as areas with poor to very poor geotechnical characteristics generate higher damaging effect on the geo-environment than other parameters.

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