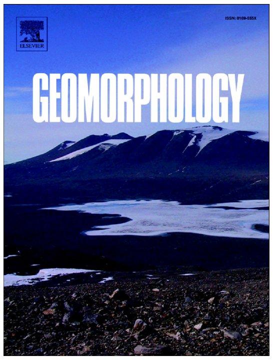

Earthquake-induced landslide hazard assessment in the Vrancea Seismic Region (Eastern Carpathians, Romania): Constraints and perspectives

Mihai Micu, Dana Micu, Hans-Balder Havenith

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Earthquake-induced landslide hazard assessment in the Vrancea Seismic Region (Eastern Carpathians, Romania): constraints and perspectives

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Abstract

In seismically-active regions, earthquake-induced landslides (EqIL) are likely to enhance slope denudation and sediment delivery both over short and longer terms, which might strongly condition landscape evolution in general. In mountain regions marked by a medium to high seismicity, co-seismic slope failures typically present a relatively low frequency but also high magnitude pattern which should be addressed accordingly within landslide hazard assessment, considering the already high frequency of precipitation-triggered landslide events. The Vrancea Seismic Region located in the curvature sector of the Eastern Carpathians (Romania) is the most active intermediate-depth seismic zones (focal depth > 70 km) in Europe. It represents the main seismic energy source throughout Romania with significant transboundary effects recorded as far as Ukraine and Bulgaria. During the last 300 years, the region featured 13 earthquakes with magnitudes (M_w) above 7, out of which seven events had M_w above 7.5 and three between 7.7 and 7.9. Apart from the direct damages, the Vrancea earthquakes are also responsible for causing numerous other geohazards, such as ground fracturing, groundwater level disturbances and deep-seated landslide occurrences (e.g. rock slumps, rock-block slides, rock falls, rock avalanches). The previous large earthquake-induced deep-seated landslides of the Vrancea region were found to affect the entire slope profile. They often formed landslide dams which strongly influenced the river morphology, posing a serious threat to human life and human facilities of the downstream rural communities through the imminent lake outburst floods. Despite the large potential of this research issue, the correlation between the region's seismotectonic context and landslide geomorphic predisposing factors has not been extensively documented and fully understood yet. Presently, the available geohazard inventories provide limited historical information to quantify the triggering role of seismic activity for observed slope failures across the Vrancea region. However, it is acknowledged that the morphology and geology of numerous large, deep-seated and dormant landslides of this region, which may be reactivated in future, with head scarps near mountain tops and located close to faults, in anti-dip slope conditions show significant similarities to the large mass movements with a proven seismic origin (such as in the Tien Shan, Pamir, Longmenshan, etc.). Thus, the relationship between landslide occurrences and the joint action of triggers and preparing factors (seismotectonic or climatic or both) needs to be investigated in more detail and further considered in the regional multi-hazard risk assessments. The purpose of this paper is to outline the current knowledge level of the landslide-earthquake relationship by accounting for the possible effects of the previous major earthquakes in the Vrancea region. The key findings contribute to the gain of the baseline knowledge for an improved assessment framework of multi-hazard (earthquake-landslide) risks, as required by the *Sendai Framework for Disaster Risk Reduction* (SFDRR).

Keywords

Vrancea seismic region (VSR), earthquake-induced landslides, multi-hazard, research perspectives

Authors

Mihai Micu*

Institute of Geography, Romanian Academy, No. 12, Dimitrie Racoviță Str., Bucharest, Romania, email: mikkutu@yahoo.com

Dana Micu

National Meteorological Administration, No. 97, Soseaua București-Ploiești, Bucharest, Romania, email: dana.micu@meteoromania.ro

Hans-Balder Havenith

Georisk and Environment, Department of Geology, University of Liège, Liège, 4000, Belgium, email: hb.havenith@uliege.be

**corresponding author*

1. Introduction

In seismically-active regions, earthquakes are important triggers of landslides conditioning the general landscape evolution, enhancing short-to-long term slope denudation and degradation and driving substantial perturbation of human activity. However, due to the interaction of pre-, co- and post-seismic failure processes, the first and last being influenced by multiple other hydro-meteorological and anthropic factors, earthquake-induced landslides (EqIL) can present a wide spectrum of morphologies and internal structures. This complexity requires the development of extensive multi-hazard scenarios for risk analysis and mitigation (Fell et al., 2008; Van Westen et al., 2008; Del Gaudio and Wasowski, 2011; Wasowski et al., 2011; Havenith et al., 2015; Wang et al., 2016). ‘Pure’ co-seismic slope failures present in general a low frequency - high magnitude pattern which should be addressed in landslide hazard assessments, against the background of the higher frequency of precipitation-triggered landslides. However, the morphogenetic context of initially earthquake-triggered ones that are later reactivated by climatic factors, complicates the determination of future slope and even entire valley shape evolution and related hazards. And, for sure, also the opposite scenario is possible, such as seismic reactivation of slope failures previously triggered by intense rainfall, as described for the 2016 Hurricane Matthew – 2021 Haiti Earthquake event sequence in Haiti by Havenith et al., (2022). There is an increasingly larger number of studies tackling the issue of the seismically induced landslides. Previous earthquake events such as those in Taiwan (Chi Chi 1999, Mw 7.6), India/Pakistan (Kashmir 2005, Mw 7.6), China (Wenchuan 2008, Mw 7.9), Japan (Tohoku 2011, Mw 8.9), Italy (L’Aquila 2009, Mw 6.3; Accumoli-Amatrice 2016, Mw 6.2) or New Zealand (Kaikoura 2016, Mw 7.8), generated a large number of landslides of up to tens of thousands of failures (Gorum et al., 2011; Xu, 2015; Massey et al., 2018). Damage to assets and human lives of these events often resulted from the combined effects of the seismic shaking (direct damage) and slope failures (indirect damage), highlighting the need for well-substantiated multi-hazard risk studies. The GIS-based deterministic approaches like the permanent-displacement analysis (Newmark displacement; ND), stress-deformation analysis, runout numerical modelling or propagation estimation of jointed rock masses are reliable methods to assess the distribution of EqIL hazard classes by integrating seismic shaking parameters, ground geotechnical and geomorphic data (Fell et al., 2008; Wasowski et al., 2011; Wang et al., 2016).

The *Sendai Framework for Disaster Risk Reduction* 2015-2030 (SFDRR) revealed that during the recent decades, there is growing evidence of a faster exposure of assets and individuals to landslide risk in comparison with a decrease in vulnerability; this is registered especially at the level of local communities, despite the significant advancements achieved in the geohazards research. The complex earthquake-landslide relationship is still subject to epistemic uncertainties (as it will be outlined in this paper) related to the accuracy of hazard identification and evaluation approaches and the relevance and effectiveness of risk reduction measures (Van Westen et al., 2008; Del Gaudio and Wasowski 2011; Xu, 2015; Tanyas et al., 2019; Zhang et al., 2020). Documenting and monitoring the EqIL hazard in different seismic hotspot regions on the globe (largely similar to Vrancea) are ongoing: New Zealand operates since 2016 web tools for regional-scale EqIL hazard assessment (forcasting the number, volume and runout distance of landslides generated by different earthquake types/magnitudes; Pradel et al., 2020). Following the 2015 Gorkha earthquake in Nepal, in 2016, multi-temporal interferometry techniques allowed the rapid mapping and updating of the existing landslide inventories, improving the landslide statistic and deterministic hazard assessment (Burrows, 2020). In Japan, numerous EqIL studies have started since 2009-2012, after the *International Symposium on Earthquake-induced landslides* (Kiryu). In Europe, the EqIL hotspot countries such as Turkey, Greece and Italy provided important contributions in the field over the last decade: comprehensive monitoring activity in the Marmara Sea Region, one of the most densely populated parts of Europe and rated at a high seismic risk level (e.g. 1999 Izmit and Duzce earthquakes; Bourdeau et al., 2017).; in Italy, acknowledging that during the last millennium, more than 2,000 landslides were identified (or reconstructed) as being triggered by earthquakes, affecting many densely populated areas (Del

Gaudio and Wasowski, 2011), accelerometer-based monitoring activity started since 2008 in Central Italy, improving the management strategies of landslide risk (Iannuci et al., 2020). Worldwide, presently there is a consistent advance in earthquake-induced landslides (fast) mapping with radar and optical remote sensing (RS) techniques. The processing of RS imagery (*Multi-Temporal Interferometry* and *Persistent Scatterer Interferometry*) is increasingly exploited in landslide detection and hazard monitoring, for improving landslide inventories and susceptibility/hazard assessments (Burrows et al., 2019, 2020).

In Romania, the role of earthquakes as a landslide triggering factor and the extent of associated effects have been little explored, despite the occurrence of several major historical earthquakes in the Vrancea Seismic Region (VSR) that affected Romania. Furthermore, most studies have been focused on the rainfall-induced slope failures in the earthquake-affected region of Vrancea (Fig.1), overlapping the Curvature sector of the Eastern Carpathians (Micu et al., 2017), but those approaching the separation between the two triggers – rainfall and earthquakes – have been rather rare (e.g. Kumar et al., 2021)

Fig.1. The location of the VSR study area in Europe and in Romania

The previous synthesis works targeting the Curvature Carpathian and Subcarpathian sectors, including Bălteanu 1983; Bălteanu et al., 2010; Micu, 2017; Micu et al., 2017; Bălteanu et al., 2020, acknowledge the VSR as the most landslide susceptible region of Romania, through the favourable lithological (e.g. loose flysch and molasse formations), structural (e.g. intensely folded and faulted deposits) and morphometric (e.g. gentle slopes carved in schistose, clayey and marly formations, steep slopes corresponding to thick sandstone packages) land features. In these areas, the preparing factors for landslides occurrence are mostly related to the land use/cover management practices, whereas the triggers are either heavy precipitation or earthquakes. The region is subject to intense neotectonic movements (uplift rates of 3-5 mm/year) which together with the high magnitude intermediate-depth seismicity enhance the overall denudation potential, for which the landslides play by far the most important role. In this region, especially in its mountain sector, the typical morphology of numerous large, deep-seated and dormant landslides (with a high potential of being reactivated in future) shows obvious similarities with the events having a proved seismic trigger. Such landslides are commonly found in the Buzău and Vrancea Mountains, in several catchments such as those of the Bâsca Chiojdului, Buzău, Siriu, Cașoca, Bâsca Rozilei, Slănic, Putna, Năruja and Zăbala rivers, impressing through their surfaces (frequently above 10 hectares) and displaced volumes (above 5-10 m^3) (Ielenicz, 1984; Mreyen et al., 2021).

In terms of historical landslides triggered by earthquakes across the VSR, the available information is by far exceeded by the importance of the topic. The latest studies (Havenith et al., 2016) emphasized the potential of the VSR to trigger widespread landslides (500-1000 cases) during a large (M_w 7-8) earthquake, over an area possibly larger than 150,000 km^2 and at distances of more than 500 km away from the epicentre, due to the typically large depths (>70 km, as described below) of the related earthquake hypocentres. In this context, despite the large fundamental and applied potential of this research issue, the correlation between the region's seismotectonic context and landslide predisposing factors has not yet been entirely understood or widely documented. Presently, there is a lack of information provided by the geohazard inventories in the VSR that does not allow a clear delineation of the seismic triggering role on slope failures in this region. The concern of scientists was mainly focused on the direct effects of earthquakes expressed in structural damages, losses of lives or indirect economic costs. The available information appears to be not sufficient for establishing a clear or direct link between the major recent earthquakes and the occurrence of landslides. However, two major historical earthquakes that affected the region serve as a good opportunity to document the earthquake-landslide triggering relationship, namely the M_w 7.7 November 1940 and the M_w 7.4 March 1977 events. The first one occurred during the autumn-winter of 1940-1941, a period when Romania was confronted with an extremely troubled political framework related to internal conflicts raised by the imminent involvement in the outbreak of WW2; meanwhile, the second registered in a period when Romania was experiencing a communist regime which was not easily accepting that nature can severely harm people, minimising the effects of the earthquake in the official reports (Sandi, 2001).

This paper aims to harmonize the existing information and knowledge about the seismotectonic landslide predisposing and triggers factors in the VSR (Romanian part of the Eastern Carpathians). As the VSR lacks detailed chronological information concerning EqIL hazard, through this study we attempt to partly fill this gap and to provide evidence on the EqIL hazard to enable accurate multi-hazard risk evaluations at a regional scale.

2. Regional settings

2.1. Seismotectonic context

As one of the top seismic hazard hotspots in Europe (Jimenez et al., 2001; Giardini et al., 2013), the VSR experiences numerous earthquakes and related geohazards, including mass movement activity. The region is located at the intersection of the East-European plate (north and north-west) with the Moesian (south) and Intra-Alpine (west) subplates. It represents the most active intermediate-depth earthquake sources of Europe (focal depth > 70 km), with the highest hypocentral depth concentration between 70-180 km and a maximum concentration of the hypocenters to an epicentral area of some 20-30x70-80 km (Radulian et al., 2008; Rogozea et al., 2014). As an intermediate-depth seismic source of high magnitudes, three to five M_w>=6.5 and two to three M_w>=7 earthquakes per century (Bala et al., 2003; Rogozea et al., 2014), the VSR can generate severe effects over a much larger area than crustal earthquakes, being the main seismic energy source throughout Romania. Due to their large focal depths, the VSR events have the potential to generate severe effects almost across entire Romania, even with significant transboundary effects recorded as far as Ukraine/eastern Russia and Bulgaria/Serbia/Greece (Rogozea et al., 2014). The highest observed seismic magnitude corresponds to the 1802 earthquake event (M_w = 7.9), while the maximum admitted magnitude was calculated (compared with the 1802 event) as $M_{max,w}$= 8.07 +/- 0.23 (Kijko and Graham, 1998). Apart from the direct damage, the VSR earthquakes generated numerous associated geohazards such as ground fracturing, groundwater level disturbances and possible shallow/deep-seated landslides (e.g. shallow earth-debris/rock slides, rock slumps, rock-block slides, rock falls, rock avalanches; Bălteanu, 1983). However, the literature of the last 50 years noted that none of the large 'recent' earthquakes (since 1800) had triggered very large mass movements, at least not as large as some ancient landslides (>=10 mio. m^3) with a possible seismic origin that will be described below.

The region develops at the contact between the Carpathian orogen and its foredeep and the pre-alpine East-European (to the north and north-east) plate and Moesian (south) platform. The complexity of the colliding processes lead to the formation of a deep sedimentary basin (reaching its maximum in the Focșani sector, of more than 10 km; Petrescu et al., 2021) located in front of the Carpathian arch, between Peceneaga-Camena and Intramoesian faults. Many of the typical NW-SE crustal tectonic faults are seismogenic (Petrescu et al., 2021, as shown in Fig. 2). The region resulted in a complex intracontinental collisional framework (Fig.2), which forms an intermediate-depth earthquake nest, described as isolated volumes of concentrated subcrustal seismicity, usually at the depths of 60–300 km, that are distinct from aftershock sequences or earthquake swarms due to their persistent seismic activity in time and unusual spatial isolation (Zarifi and Havskov, 2003).

Together with the similar region of Central Asia (Hindu Kush, Afghanistan), the VSR has the particularity of not being located in or related to any classic oceanic subduction systems, being far from the active plate margins (Prieto et al., 2012; Petrescu et al., 2021). The origin of its forming mechanisms is strongly debated, being either related to an oceanic slab beneath the Eastern Carpathians or to the delamination (and not subduction) facilitating the recycling of the lithosphere material in this intracontinental collisional area (further details are provided by e.g. Mațenco et al., 1997; Heidbach et al., 2007; Koulakov et al., 2010; Ferrand and Manea 2021). As a region inflicting numerous earthquake-related damages throughout centuries, the fundamental understanding of its seismicity proved to be vital in acknowledging the existence, in a rather confined area, of two different focal seismic domains, i.e. *Vrancea intermediate-depth* and *Vrancea superficial* (described by Radulian et al., 1999, 2000 or Bala et al., 2015). The seismic activity in the VSR has an important minimum depth of about 40-60 km, which separates the crustal and the subcrustal domain. The shallow seismicity is propagating eastwards to the Curvature sector of the Carpathians, within an area limited by the Peceneaga-Camena fault in the north and the Intramoesic fault in the south. This type of seismicity consists in low and moderated magnitude earthquakes, which sometimes generate earthquake swarms, with magnitude usually below 4 and not exceeding M_w 5.9 (1894 event, as described by Țugui et al., 2009 or by Craiu et al., 2017). This seismicity shows an apparent decoupling with the intermediate-depth one. As directly linked with the overall Vrancea seismicity, the origin of intermediate-depth seismicity is also subject to an ongoing debate.

Fig.2. The intra-collisional position of the VSR and the epicentres of the major (Mw>7.4) earthquakes during the last 300 years, in a geotectonic context (based on Săndulescu, 1994). Morphostructural profiles. 1) Holocene: present-day floodplain alluvia; 2) Lower Pleistocene: gravels, sands and loess-like deposits; 3) Upper Pliocene (Romanian): sands, sand clays, clays; 4) Upper Pliocene (Dacian): marly sandstones, sandy marls; 5) Lower-Medium Pliocene (Meotian – Pontian): sandstones, marls and sand marls; 6) Lower Pliocene (Meotian): sandstones, marls, cynnerite marls; 7) Upper Miocene (Sarmatian): sandstones, marls, shales; 8) Lower-Medium Miocene (Helvetian): sandstones, schists, gypsium; 9) Upper Oligocene-Medium Miocene (Aquitanian–Helvetian): sandstones, schists with salt and gypsium blocks; 10) Lower Miocene (Burdigalian): sandstones, conglomerates, schists; 11) Oligocene: sandstones, clays, marls; 12) Eocene: sandstone and sandstone schists; 13) Cretaceous: conglomerates, marly limestone, curbicortical flysch; 14) fault .

Radulian et al., (2008) described the seismicity at intermediate depth beneath the Vrancea region as extremely spatially concentrated and following specific alignments, with the focal mechanisms showing dominant extension in the vertical direction and dominant compression in the horizontal direction. More recently, Petrescu et al., (2021) described a lithospheric volume which is seismically active, and which can be approximated by a prism vertically oriented between 60 and 170 km depth, with a horizontal cross-section of 30×70 km^2.

The procedures for compiling and updating the earthquake catalogue have changed consistently in Romania over the last 30 years. The early ROMPLUS catalogue, described by Oncescu et al. (1999) covers the 984-1997 time period and is the first complete, homogeneous and easily accessible (permanently updated by the National Institute for Earth Physics) earthquake inventory of Romania. Its 1000 years duration, shorter if compared with the 3000-year-long earthquake records compiled for China (Cheng et al., 2017) still keeps opening the question on the possibility of M_w>=8 events. Later, Radulian et al., (2019) introduced the new catalogue of Romanian Earthquakes Focal Mechanisms (REFMC), which is the most comprehensive catalogue of focal mechanisms for all the earthquakes recorded in Romania until 2000, providing reliable information about 258 crustal events (focal depths below 50 km) and 428 intermediate depths events (focal depths between 50 and 201 km). These two catalogues provide good seismic activity evidence for in-depth investigations of the earthquake-landslide triggering relationship. Accordingly, over the last 300 years, the VSR featured 13 earthquakes with M>7, among which seven events had a magnitude above 7.5 and three between 7.7 and 7.9 (tab.1). Fig.3 shows the clustered spatial position of the M_w>7 earthquakes epicentres triggered by the Vrancea intermediate domain over the 1700-2021 period. The preferential propagation of the seismic waves along a NE-SW orientation and the isoseismal orientation are outlining the Curvature sector of the Carpathians and Subcarpathians, the Moldavian and Getic Plateaus and the Romanian Plain as being the regions most subjected to seismic shaking likely to trigger landslides.

However, the VSR lacks landslide inventories to support such investigations, allowing the correlation of a potential seismic trigger with landslide events; this relationship is poorly exploited since there are no landslide inventories, neither regional nor national which can highlight the potential cause-effect context.

Table 1

The list of earthquakes with M_w>7 during the last 300 years (according to the ROMPLUS catalogue of the National Institute for Earth Physics)

There are numerous seismic hazard and risk assessments (e.g. Wenzel et al., 1999; Lungu et al., 2004; Mărmureanu, 2016; Văcăreanu and Ionescu, 2016, 2018), which provide valuable findings which can be used as proxies for a further evaluation of EqIL hazard. Also, other studies (as not the direct focus of this paper, only the most recent references are included) relying on a statistic, probabilistic or deterministic modelling-based approaches (e.g. Văcăreanu et al, 2016; Pavel et al., 2018a; Cioflan et al., 2022) or focusing on earthquake attenuation/amplification effects (Radulian et al., 2006; Pavel et al., 2018b, 2019), ground motion parameters (Zaicenco et al., 2008; Borcia et al. 2013; Ardeleanu et al., 2020), the impact of seismicity on lifelines (Pavel et al., 2021), building construction codes adapted to Vrancea seismicity (Neagu et al., 2018), disaster management (Georgescu and Pomonis, 2018; Toma-Dănilă et al., 2022), or early warning (Mărmureanu et al., 2011, 2015; Toma-Dănilă et al., 2020) provides a solid scientific knowledge on the VSR seismicity. However, the large body of literature described above, does not provide strong evidence on the correlation between the old landslides the historical earthquakes, mostly due to deficient landslide inventories for this region.

Fig.3 The distribution of the 222 cases of M_w>5 earthquakes epicentres triggered by Vrancea intermediate domain (light blue to red on the depth scale) during the 1700-2021 time period; with

blue lines, the isoseismal of the "etalon" earthquake (M_w 7.1, August 1986) - generalised attenuation curves (source of the data: ROMPLUS catalogue, NIEP: https://web.infp.ro/#/romplus; isoseismal after Enescu and Enescu, 2007, modified by Mărmureanu et al. 2011)

2.2. Geomorphic-geological context

The main structural units of interest (after Săndulescu, 1984) for the studied area in its geomorphological limits are represented by the Outer Dacides, Moldavides and Neogene Molasse depressions and foredeep (see Fig. 2). The Outer Dacides (Middle and Upper Cretaceous) consist mainly of flysch formations with conglomerate intercalations, showing rather similar lithological features (flysch) with the younger Moldavides (Lower Cretaceous-Middle Miocene). The molasse formations of the Carpathian Foredeep that borders them towards the exterior consist of post-nappe rocks accumulated during the Upper Miocene-Lower Pleistocene period.

The regional litho-structural traits (detailed in the geological map presented in Fig. 4) are conditioning two different orogenic sub-units, different also from a geomorphological point of view: the Buzău-Vrancea Carpathians and the Subcarpathians (Sandu and Micu, 2008).

Fig.4 The geological map of the study area (Carpathians and Subcarpathians separated by the black line): 1) alluvial plains deposits (Holocene); 2) loess-like deposits (Upper Pleistocene); 3) terrace deposits (Upper Pleistocene); 4) terrace deposits (Mid Pleistocene); 5) loess-like deposits (undiferentiated Quaternary); 6) sands, pebbles, loess (Romanian-Lower Pleistocene); 7) sandstones, marls, coal intercalations (Meotian-Dacian); 8) sandstones, marls, clayey schists (Sarmatian); 9) marls, sandstones, clayey schists, salt breccias, tuffa (Mid Miocene); 10) sandstones, conglomerates, clays, salt, gypsum (Lower Miocene); 11) sandstone, clays, marls, disodiles, menilites, conglomerates (Oligocene); 12) schistose sandstone limy flysch (Eocene); 13) sandstone flysch with clayey intercalations (Paleocene + Eocene); 14) schistose sandstone and limy flysch (Paleocene); 15) sandstone limy flysch, schistose sandstone flysch (Senonian + Paleocene) 16) massive sandstones with marly intercalations (Upper Cretaceous); 17) black schistose flysch (Lower and Upper Cretaceous);

18) sandstone schistose flysch (Barremian + Aptian); 19) sandstones and marls, masive sandstones (Barremian + Albian); 20) sandstones and conglomerates (Albian) ; 21) massive sandstones flysch (Lower Cretaceous). Maps source: Geological Map of Romania 1:200,000 (Ploiești and Covasna sheets), Institute of Geology, Bucharest (Murgeanu et al., 1968; Dumitrescu et al., 1970).

While the fist sub-unit consists of low and medium-altitude mountains built on the harder flysch formations, reaching altitudes usually below 1,700 m a.s.l. (maximum altitude in Goru Peak, 1,785 m), the second sub-unit corresponds to an association of hills and depressions built on less harder molasse deposits, ranging from 400 to 900 m a.s.l. in altitude (maximum height in Manta Preak, 990 m). This zonation reflects in the landslide typological pattern, high frequency-low magnitude shallow and medium seated earth slides and flows being characteristic of the Subcarpathians, while the Carpathians are featuring an opposite pattern, of predominantly high magnitude-low frequency medium and deep seated rock and debris slides. The Buzău-Vrancea Carpathians are developed on Cretaceous (internally) and Palaeogene (externally) flysch deposits. They consist of different tectonic units (nappes), formed of conglomerates, sandstone, limestone, limy sandstone and marly-limy sandstone, shales, micaceous sandstones, strongly faulted and folded in compressed, longitudinally-fractured synclines and anticlines, with regional structural complications. Across the unit, the tectonic lines and the main NE–SW orientation of structures (steeper NW-facing slopes, predominantly corresponding to harder sandstones, and less steep and prolonged SE-facing slopes, built by softer shales) are imprinting obvious traits in the landforms' morphology (Fig.5).

Fig.5. The predominant and almost continuous NE-SW orientation of the structures is imposing a rather equally-distributed (expressed in percentages) presence of landslide processes on NW (1) and SE (2)-facing slopes, considering a representative study area of 900 km^2 situated at the Buzău Carpathians-Subcarpathians contact (based on the dataset of Damen et al., 2014)

Furthermore, regional lithological differences are conditioning the configuration of the relief and the intensity of present-day modelling processes.

From a tectonic-structural and lithological perspective, the Carpathians were constituted during the time interval between the Cretaceous (Aptian-Albian) and Neogene (Middle-Upper Miocene). The accumulation of sedimentary deposits with different rhythms led to the emersion of the region in the early Miocene. The following orogenic phases (until Pleistocene) determined the significant rise of flysch deposits and locally uneven block rise, consistent with the overall uplift of the entire Eastern Carpathians. This lead to the strong stimulation of the external modelling of the mountains during the Quaternary. The friability and plasticity of the rocks, both those of the internal Cretaceous flysch, marked by thick packages of cohesive and more compact sandstones, alternating with thin layers of schistose marly-clayey deposits, but especially of the outer Paleogene flysch, characterized by less cohesive and compact sandstones, forming thinner packages alternating with thicker schistose intercalations (Fig. 6), favoured a strong denudation, caused equally by erosion and mass movements (Badea, 2008); thus, the existence of large volumes of landslide deposits (inactive, relict or dormant, with reactivation potential) in sub-units like Penteleu, Podul Calului, Siriu, Ivănețu, Lăcăuți, Furu, Zboina Frumoasă or Furu, is explained.

Fig. 6 Typical Palaeogene flysch structures in the study area: alternance of thick/thin sandstone-schistose layers (A, B), intensely folded and faulted (C, D)

In this region, some particular morphologic traits (as detailed below) pinpoint numerous deep-seated landslides as potentially being triggered by earthquakes.

The Buzău-Vrancea Subcarpathians unit, which is the most important one in terms of active landslides, corresponds to the Mio-Pliocene molasse deposits accumulated in the Carpathian foredeep, locally alternating with Palaeogene flysch spurs, NE-SW oriented. Combined with the heterogeneous disposition of loose molasse deposits, the Subcarpathians are highly tectonised (reverse faults, strike-slip faults) and folded (asymmetrical and fractured longitudinally, transversally and diagonally) towards the interior (Mio-Pliocene structures) and marked by structures characterized by slightly faulted (prevailing normal faults), simple, large, symmetrical folds (Pliocene-Quaternary), showing typical homoclines, towards the exterior. The formation of the molasse deposits began during the Miocene sedimentary cycle and continued until the Lower Pleistocene, when a thick package of sandstones, sands, clays, marls, tuff, salt breccia and gypsum accumulated. Regionally, the accumulation of salt and salt breccias along syncline axes increases the complexity of the structures and enhances the slope denudational potential. The deepening of the river network started in the Upper Pleistocene and determined the accentuation of the denudation potential. During the Holocene, the deepening of the valleys was accompanied by intense modelling of the slopes by mass movements and erosion. Against the general background of the rise of the Curvature Carpathians and Subcarpathians, there were trends of local amplification of neotectonic movements (anticline folding, local subsidence in depressionary areas), whose measured values reached 3-4 mm / year (Zugrăvescu et al., 1998). This fact confirms the current trend of increasing the energy of the relief, due to the lowering of local erosion bases, which has led to the accentuation of the slopes' instability degree and to the individualization of an extremely wide range of mass movement processes (mainly landslides), often combined with fluvial erosion. In present times, the Carpathian and the Subcarpathian units are following a phase of adaptation of slope and channel processes to structure, lithology, neotectonics, with an intensity of the geomorphic processes which acts differently within regional catchments and tectonic compartments (Bălteanu, 1983).

3. Earthquake-induced landslides

3.1. Landslides typology

In addition to the direct damages (e.g. Atanasiu, 1961; Bălan et al., 1982; Wenzel et al., 1999; Văcăreanu and Ionescu, 2016), the Vrancea earthquakes are directly responsible for the initiation of many other geohazards: fault ruptures, ground cracks and fractures, disturbance of the groundwater levels (sometimes accompanied by the eruption of mud volcanoes, favoured by the friable deposits) and the initiation (as either first-time failures of reactivations) of mass movements; they occur in the form of shallow or deep-seated landslides, rock falls and topples, rock avalanches and even earth and debris flows (especially under the conditions of local amplification, either topographic or lithological). Fig.7 illustrates the broad range of landslide types, both fast and slow-moving, which have been mapped as co/post-seismic processes, within local and temporally-scattered studies, as described below.

Fig.7 Different types of landslides caused by earthquakes in the VSR: shallow and medium-seated rock/earth slides, triggered during the 1977 earthquake (Photos A, B, by D. Bălteanu; C by N. Mândrescu,) and rock falls (ranging from massive failures D, witnessing large magnitude paleoseismic events, to low magnitude blocks collapses and rolling E, F; photos D, F, by M. Micu; E by D. Bălteanu).

As previously outlined, the correlation between the region's seismotectonic context and landslide-predisposing factors has not yet been entirely understood. However, the morphology of numerous large, deep-seated and dormant landslides, shows an obvious reactivation potential (as revealed during wet years like 2005, 2006, 2010), with head scarps situated in the immediate vicinity (or directly on) of water divides, mountain or hill tops or close to faults (as those marked on the 1:100,000 and 1:200,000 geologic maps produced by the National Geological Committee and the Geological Institute of Romania; https://geoportal.igr.ro/). Such mass movements indeed look similar to those, for which a seismic origin has already been proved, e.g. in the seismically active mountain belts of the Tien Shan, Pamir and Longmenshan (Havenith et al., 2015; Strom and Abdrakhmatov, 2018; Fan et al., 2021, ,) (Fig.8).

Fig.8 High magnitude (usually 2-3 km long) old, dormant landslides (A. Balta - footwall, B. Păltineni - hangingwall, C. Răoaza – along fault) in the Buzău (A, B) and Vrancea (C) Mountains, whose morphology indicate a potential seismic trigger: main scarps close to the watersheds, far away from the river network, anti-dip slopes (A, B), fault line crossing the main scarp area (reverse faults in this case). For morphologic comparison, processes with proven seismic triggers (Havenith et al., 2015): Kaindy rockslide (D) and Seven Lakes long runout landslides (E), Tien Shan Mts. (imagery source: Google Earth).

While in the latter, the above-mentioned literature demonstrated the linkage with active faults, in Vrancea, we can only consider that fault lineaments (especially the NE-SW oriented ones, supposed to be inactive) play a significant role in structural weakening (though this still has to be quantified). The distribution of about 500 landslide scarps situated at the Buzău Carpathians-Subcarpathians contact, as derived from several combined inventories (Micu, 2008; Damen et al, 2014; Zumpano et al., 2014) shows that almost equally, the landslides are distributed on both hanging wall and footwall of the predominantly-present (due to the general tectonic and structural framework) reverse faults (Fig.9). Moreover, as seen in Figure 10, the same distribution concerning potential initiation sectors linked with structural weakening along faults and with river lateral erosion shows more important conditioning of the first one, as 65% of the scarps are situated in the vicinity of (supposed non-active) faults (0-400 m), while only 46 % are situated at less than 400 m away from rivers.

A focused research on direct damages to properties and human losses caused by coseismic and postseismic landslides have been conducted less intensively, as compared with the potential damages that they may inflict. The earthquakes that occurred in the XIXth Century are almost completely lacking a proper explanation of the occurrence of various associated geohazards (excepting the simple descriptions of land deformation – e.g. cracks, bulging, collapses, soil displacements, which may be associated with landslides, without a clear specification of the typologies; ***,1883). Some information available after 1940 and 1977 allows now for a closer correlation between the seismic trigger and the induced geohazards (including the landslides). The findings collected from several previous papers (e.g. Radu and Spânoche, 1977; Bălteanu 1979a, 1979b,; Mândrescu 1981, 1982; Radu and Polonic, 1982; Roman 1991) provide a more clear image, of least at a local or regional scale, on the landslide typologies associated with the triggering earthquakes, which can allow a primary hazard estimation. With very few exceptions (e.g. Bălteanu 1979a, 1979b, 1983), morphometrical parameters (surfaces, volumes) and precise spatial positioning are lacking.

Fig.9 Examples of landslides (dark brown – depletion area, light brown – accumulation area; after Damen et al., 2014) equally distributed along the reverse fault (A), predominantly distributed on the footwall (B) and predominantly distributed on the hangingwall (C), according to the steepness of the slopes in the fault vicinity.

Fig.10 Distribution of 500 landslide scarps according to the faults (grey) and rivers (blue) distance.

From a broader perspective, without the separation of the climatic and seismic triggers, the most widespread landslides type across the VSR are the shallow translational slides (less rotational, occurred mainly as the effect of river undercut). Together with the earth flows, this landslide type shows a very high frequency and low magnitude, affecting, areas of up to 1-5 ha. These slides show polycyclic reactivations over the entire slope profile. Particularly, the Carpathians are the unit affected mainly by deep-seated landslides, in form of translational rock block slides and rock slumps.

These deep-seated landslide processes are characteristic of the outer (Palaeogene) flysch units, built on looser formations (alternation of less cohesive sandstones with schistose marly and clayey intercalations) and show a high magnitude (frequently reaching 1-3 mil. m^3) and low frequency (tens of years). Today such processes are present in form of relict and dormant deposits, are covered almost entirely by old forests and are marked by numerous reactivations, especially due to river undercut, since the large accumulation deposits frequently reached the valley bottom, causing river blockages and landslide dams. The morphology of most of these events indicates a potential seismic implication (Fig.7) and consequently, they can be considered as co- or post-seismic landslide events (Micu, 2017). The old (or relict) landslides with a potential earthquake trigger usually affect the entire slope profile and could form landslide dams, which may strongly influence the river morphology and threat the downstream communities through exposure to lake outbursts.

3.2. Earthquake-induced landslides evaluation: existing data and results

The selection of a relevant case study area for analysing the correlation between the earthquake, as a triggering factor and the resulting landslides is not an easy task. To delineate the potential triggering role played by climatic/hydrometeorological factors (eg. precipitation, lateral erosion during floods), a landslide event with an accurate date of occurrence should be chosen. This depends on the type of process: a deep-seated landslide marks the morphography of the slope for a long time; meanwhile, the landmarks of a shallow one are attenuated by reactivations or even totally removed from the landscape by land improvement works or by incorporating the original affected area into a larger one, associated to a new landslide event.

There are several morphological elements that, once identified, increase the chances that the process will be confirmed to have been triggered by an earthquake:well individualized steep scarps, located near the crests/watersheds (as a potential result of seismic amplifications induced by specific convex topography, see e.g. Bourdeau and Havenith, 2008); the scarp location near a fault; a long distance from watercourses (to minimize the role of lateral erosion and also to consider the groundwater level much lower than that of the inland, upper sector of the slope); the presence of landslides on anti-dip slopes (making a 'simple' trigger process more unlikely, as this more stable structural position requires larger energy input for failure; Lemaire et al., 2020). Furthermore, the individualization of processes beyond the average magnitude scale under present-day climatic conditions could lead to the idea that an additional triggering factor was involved in the landslide failure initiation.

The review of the previous studies underlined that the quantitative assessment of EqIL hazard in the VSR is still subject to several scientific (and technical) challenges, such as:

- complete understanding of the correlation of landslides distribution and fault typology (direct, reverse, strike-slip) and fault compartments (hanging wall, footwall), as due to lithological proneness, landslides seem to characterize equally hanging walls and footwalls (see Fig. 9);

- complete understanding of the EqIL mechanisms (especially for such intermediate focus earthquakes), driven by the complex morphogenesis of the landsliding processes; this makes difficult the landslides typological correlation with seismic shakings; furthermore, as the VSR shows no sings of obvious faults (due to deep hypocenters, thick sedimentary coverage), a rapid and reliable morphogenetic landslide differentiation is still difficult.

- scarce measurements (at least in Romania, such as provided by Mreyen et al., 2021) and limited understanding of seismic site response, including the role of topographic and lithologic amplification/attenuation; across the VSR, similarly to most major seismic regions, there is a scarce amount of continuous data provided by instrumented landslide slopes. Another technical challenge is related to the extraction and interpretation of tectonic lineaments (faults, fractures) using DEM and remote sensing data, due to the inadequate spatial resolution, as the highest spatial resolution of available data in our study area, is 10-12 m (TanDEMX). Crucial studies are lacking in the estimation of topographic effects, which could facilitate the separation between the contribution of other factors such as the stratigraphy, near-surface weathering and the presence of fault zones.

- the generation of comprehensive post-event EqIL inventories (distinction from the rainfall-induced ones); for the last major historical VSR earthquakes (1940, 1977, 1986, 1990) there are few remote sensing resources available for obtaining comprehensive landslide inventories before/after the seismic events. Recently, Havenith et al., (2016) analysed the joint action of factors such as (intensity, faults, topographic energy, climatic background, and lithology) to quantify the effects of a M_w>7 earthquakes in terms of the potential number of EqIL events and the total affected area. The authors showed that such high magnitude seismic events across the VSR are likely to trigger cca.500-700 landslides, with a potential spread of affected area of over 150,000 km^2, along more than 500 km away from the epicentre.

- the generation of reliable EqIL hazard zonation, showing the distribution of hazard classes within different return periods. The few contributions to this topic (Micu et al., 2015; Micu, 2017; Harmouzi et al., 2021), reveal that this approach is still in its early stages in Romania.

The correlation between the existing information with the results of some well-documented case studies, was performed for the estimation of 1) the maximum distance at which landslides can occur; 2) the extension of the area across which landslides may occur; 3) the total number of potential landslides; 4) expected process surfaces and volumes (a synthesis is presented in Table 2).

Table 2 A synthesis correlation among existing information on EqIL, as derived from documented case studies

3.2.1. Maximum epicentral distance of landslide occurrence: this parameter is largely influenced by the focal depth of the Vrancea earthquakes, which makes their effects be felt at a greater distance as compared to those of shallow earthquakes. For comparison, Keefer, (2002) identified four surface earthquakes, which caused different slides and falls at about 40-80 km away from the epicentre; for the Wenchuan earthquake, Gorum et al., (2011) identified landslides at 30 km away from the Longmenshan fault, whereas Owen et al., (2008) reported slides and falls at 20-30 km away the epicentral area of the Kashmir earthquake. Vrancea intermediate earthquakes are known to cause geohazards at much longer distances to the epicentres, as reported by several studies: e.g. Radu and Spânoche, (1977) confirm at least 70 landslide events (without distinguishing among typologies), up to 250-330 km away from the epicentre of the 1940 earthquake; Mândrescu, (1981) mapped landslides (reported separately, as slides and falls) at distances of 100-120 km after the 1977 earthquake; Radu and Polonic, (1982) identified about 100 landslide events (slides and falls) in response to the 1977 earthquake (Fig.11), along a distance of up to 340 km, although no information about magnitude criteria was provided.

Another valuable contribution is given by Angelova, (2003), who evaluated for Bulgaria the data records related to the ground cracks and fissures at Bregare, Cap Emine and Silistra (epicentral distances of 160-290 km), falls (coastal cliffs, caves, steep river banks, limestone ridges) and slides observed at Tyulenovo, Galata and Iskrets (epicentral distances of 270-380 km) and slides occurred at Razgrad, Popovo, Silistra (epicentral distances 210-260 km). All these processes have been attributed to the 1977 earthquake. According to Bruchev et al., (2007), the same seismic event has caused the initiation of several landslide failures along the Bulgarian bank of the Danube (160-250 km) and the northern part of the Bulgarian Black Sea coast (250 km), a region recognized as being prone to landslides such as falls and bank collapses (Berov et al., 2016). Possible long-distance impact of the 1977 and 1986 earthquakes was mentioned for the Polish Western Carpathians (650-700 km) by Wistuba et al., (2018). The landslide distribution maps attributed to the 1940 and 1977 seismic events show that most events (58% in 1940 and 70% in 1977) are concentrated along epicentral distances lower than 100 km (Fig.12).

Fig.11 The distribution of landslides triggered by the 1940 (A) and 1977 (B) earthquakes relative to their epicentres (yellow star) and isoseismals (based on the maps of the 1940 and 1977 macroseismic fields produced by Kronrod et al., 2013; landslide distribution based on Radu and Spânoche, 1977 and Radu and Polonic, 1982)

3.2.2. Extension of the landslide distribution area: this parameter is also directly influenced by the depth of the Vrancea earthquakes. Mândrescu, (1981) described two main areas with landslides caused by the 1977 earthquake: the first, corresponding to the region of the Curvature Paleogene flysch Carpathians and the Neogene molasses Subcarpathians, together with the south part of the Moldavian Plateau, where slides and falls, soil and rock cracks and fissures were identified as prevailing processes at epicentral distances of 50 to 80 km; and the second one, corresponding to the region of the Romanian Plain and the Danube Valley affected by landslides, ground cracks, liquefaction along distances of up to 220-310 km.

Fig.12 The distribution of landslides triggered by the 1940 and 1977 earthquakes in relation to the epicentral distance

Mândrescu, (1981) also depicted the area of maximum concentration of the processes based on the 8 degrees isoseismal, represented as an ellipse of about 120 km elongated in the NE-SW direction (similarly to Radu and Spânoche, 1977, who extend the same isoseismal of the 1940 earthquake up to 230- 280 km). In agreement with the aforementioned information, a more recent evaluation of local effects, based on a detailed compilation of the available macroseismic data for the 1940, 1977, 1986, and 1990 earthquakes (Kronrod et al., 2013), shows that a maximum concentration of landslides resulted from the 1940 earthquake within the 7 degrees isoseismal, while for the 1977 event, the maximum concentration was found within the 8 degrees isoseismal. The correlation between the distribution of 1977 landslides and the PGA values (in %*g*), shows a particular cluster situated in the south-western units of the Getic Piedmont and Romanian Plain, at very far distances of 300-350 km, where PGA values were considerably lower than those observed close to the epicentral area (Fig.13). The information about landslide typologies in these studies is scarce, most mentions being related to numerous “*...river bank collapses ...falls...*”, occurred in loose, Quaternary alluvial deposits, with low strengths and cohesion. As mentioned by Havenith et al., (2016), a very strong (possibly Mw>=8) future Vrancea earthquake is likely to trigger significant ground effects over a wider area, that could exceed 150,000 km^2 and at distances of more than 500 km away from the epicentre.

Fig.13 The distribution of 1977 EqIL events (based on Radu and Polonic 1982) relative to the PGA (red lines; in %*g*) of the same seismic event (according to INFP – ROMPLUS catalogue)

3.2.3. Total potential number of landslides: although this parameter is highly important in geoseismic hazard assessments, it is difficult to be quantified accurately across the VSR, which lacks multitemporal inventories of historical landslides caused by different triggering mechanisms (extreme rainfall events, earthquakes or anthropogenic activities). Radu and Spânoche, (1977) have mapped over 70 co-seismic landslide events triggered by the 1940 earthquake (a number expected to be biased by the previous wet 4-year stretch between 1937-1940, with positive deviations of up to 40% against the average). Bălteanu, (1983) also emphasised the role of antecedent precipitation when investigating and mapping the landslide events in the Buzău River catchment occurred after the 1977 earthquake. Mândrescu, (1981) reported at least 12 co-seismic and 4 post-seismic landslides, triggered by the 1977 earthquake in time intervals from less than 24 hours to 5 weeks post-event, with surfaces of up to 10 ha. The author argued that the small number of landslide events was due to the dry autumn and winter months prior to the earthquake event of 1977 when the negative seasonal deviations (in this case) were up to 40% against the average. Later, Radu and Polonic, (1982) reported for the same quake a higher number of landslide events (about 100). More recently, Havenith et al., (2016) showed that while several tens of thousands of landslides have been triggered by a single high-magnitude earthquake in the South Tien Shan, the number of landslides triggered by a similarly large earthquake is expected to be far less (<1,000) in the VSR due to the much deeper hypocentre of the Vrancea earthquake events.

3.2.4. Potential slope failure surface areas and volumes: all over Romania, only a few contributions are focusing on the estimation of this parameter, mostly conducted at a local scale. Bălteanu (1983) identified dozens of falls in several small basins in the Buzău Subcarpathians, with volumes between 5 and 360 m^3 and slides, with volumes of about 30,000-200,000 m^3, that followed the 1977 earthquake. The more recent works of Kumar et al., (2021) and, Mreyen et al., (2021) provide additional evidence, showing that high-magnitude earthquakes (M_w>7.5) could trigger massive slope failures (rock slides) with 70-90 m thicknesses and volumes reaching or exceeding 30 million m^3 (as the case of Balta rock slide). Taking into account the fact that such massive, deep-seated landslides have a large reactivation potential, especially in the vicinity of the steep and largely extended scarps, as well as in the lower parts of accumulation sectors (toe), where thick landslide deposits are undercut by the lateral erosion of the river network (Fig. 14), such events may be considered important proxies for paleoenvironmental reconstructions.

The aforementioned results made possible, for a representative area at the Buzău Carpathians-Subcarpathians contact, several primary evaluations of the EqIL susceptibility based on Newmark Displacement (Micu et al., 2015; Micu, 2017), which were followed by those of Harmouzi et al., (2021). The comparison with the results of other landslide susceptibility assessments focusing on the VSR, but employing different methods (e.g. *weight of evidence*, Zumpano et al., 2014; *spatial multi-criteria evaluation*, Damen et al., 2014) (Fig. 15) suggests in general a good correspondence between the distributions of landslide susceptibility classes zonation.

Fig.14 Reactivation of 40-60 m thick (earthquake-induced) landslide accumulations deposits due to lateral erosion (A. Păltineni landslide, Buzău River, B. Balta landslide, Bâsca Rozilei River)

Fig.15 Comparison of results of weights of evidence (A; Zumpano et al., 2014) and spatial multi-criteria evaluation (B; Damen et al., 2014) with Newmark Displacement (C; Micu et al., 2015) - based evaluations of landslide susceptibility in the Buzău-Bâsca Rozilei confluence sector (Buzău Carpathians-Subcarpathians contact)

However, some important differentiations are observed in terms of the specific features of EqIL events, namely: i) the predominantly south and south-east-facing slopes, covered by a thick regolith layer, are more prone to high frequency/low magnitude shallow (or rarely medium-seated) landslides (a constant value of 70-80% of the entire number of landslides from various inventories; for detailed analysis, see Micu and Micu, 2022), mainly in form of earth-debris slides/flows, which are prepared and triggered by climatic conditions; ii) the predominantly north and north-west-facing slopes are mainly affected by high magnitude/low frequency, deep-seated landslides (20-30% of the entire number of landslides; Micu and Micu, 2022), mainly in form of rock slides, with scarps' positioning in the vicinity of the watershed, far away from the rivers network and frequently located along geologically-drawn faults, which are likely to have a potential seismic trigger (Fig.16).

Fig.16 Comparison between long runout debris flow (Ruptura landslide) on a south-facing slope and coherent rockside on the north-facing one (Balta landslide) in Bâsca Rozilei catchment. The high-intensity seismic trigger initiated a high-magnitude landslide, still allowing during present days the clear delimitation of the depletion (A) and accumulation (B) morphodynamic sectors regardless of the dense forest cover installed afterwards.

4. Discussions on hazard assessment constrains and research perspectives

Numerous state-of-the-art studies (e.g. Keefer, 2002; Bourdeau and Havenith, 2008; Miles and Keefer, 2009; Del Gaudio and Wasowski, 2011; Jibson, 2011; Wasowski et al.. 2011; Havenith et al.. 2015; Xu, 2015; Wang et al.. 2016; Zhang, 2018), contributed to and advanced the understanding of EqIL, through the development of new investigation techniques, data mining or modelling algorithms for investigating the earthquake-landslide triggering mechanisms in various seismic regions on the globe. However, earthquake-landslide triggered susceptibility assessment is still challenging especially in the data-scarce regions such as the VSR, also showing particular geoseismic features (intermediate-depth focal characteristics) and transboundary effects of its seismic events. Further investigations are needed across the VSR to minimise the losses of EqIL events and the population vulnerability, contributing to i) understanding earthquakes-landslides relationship and involved mechanisms conditioned by the specific intermediate focal seismic activity of the region, ii) detection of seismic site response as derived from in-situ measurements, iii) compile comprehensive EqIL inventories, and iv) elaboration of reliable EqIL hazard zonation maps. All the above-mentioned topics are currently missing in-depth research. Such results will allow the establishment of consistently applied research initiatives, targeting an enhanced population resilience, coping capacity development, and landslide risk mitigation in the context of present-day climate and environmental changes. In this framework, the development of a reliable quantitative assessment approach will enable the achievement of reliable zonation of landslide hazard levels, which will be an excellent decision-support tool for different stakeholders operating at regional (county) and national scales, for risk management (in agreement with the recommendations of Fell et al., 2008; Miles and Keefer, 2009; Wasowski et al., 2011; Zhang 2018). To achieve this, we argue the need for developing highly inter/transdisciplinary approaches, by assimilation the results of the geomorphic (i.e. relief models and morphometry analysis), seismic (i.e. computation of seismic intensities and accelerations, acceleration/attenuation as conditioned by different litho-morphostructural environments), geologic (i.e. bedrock and regolith regional assessments, local rock slope configurations) and geotechnical (i.e. determination of safety factors based on reliable physical rock/soil parameters) analyses, which may complement the local and regional GIS-supported probabilistic and deterministic evaluations of the EqIL hazard.

Despite the recent advances in the EqIL research (Havenith et al., 2016, 2017; Mreyen et al., 2017, 2021; Kumar et al., 2021), there are still some open issues to be further addressed for the VSR namely: i) the relationship between epicentre location (or hypothetical source fault) and the distribution of typologically-different landslides, with focus on the previous major earthquake events (e.g. 1990, 1986, 1977, 1940); ii) the paleoseismic reconstruction based on relict/dormant landslides, implying a systematic dating of landslides; iii) the role of topographic/lithologic site-effects as derived from accelerometric measurements; iv) the development of reliable multi-hazard assessments by integrating EqIL hazard scenario information for identifying effective risk management measures. In this context, correlation analyses between landslide occurrence and combined seismotectonic-climatic factors are strongly recommended. The previous assessment of the precipitation-triggered landslide events that occurred in the Carpathian and Subcarpathian sectors of the VSR (Dragotă, 2008) provided valuable inputs for further correlation analyses with the seismic activity across the region. Using the ROMPLUS earthquake catalogue and selecting the seismic events of $M_w \geq 4$, a threshold value at which landslide failures have been recorded (Micu et al., 2014) one may outline several periods of seismic triggering which have been identified, although under enhanced failure-prone climatic conditions: the summers of 1977-1979, 1986, 2001-2003, the summer-autumns of 2005 and 2006 (Fig.17).

The recent advances in sensor technology and image processing techniques made satellite, airborne and terrestrial remote sensing to become an essential geospatial assessment tool for EqIL studies, successfully complementing the ground-based in situ measurements. These innovative technologies enabled faster assessments of co/postseismic displacements and facilitated a better discrimination between the effects of seismic shaking and strength reduction on displacement by those induced by precipitation/pore water pressure increase, supporting the development of reliable multi-hazard scenarios. Despite the drawbacks determined by the consistent forest coverage and the lack of regional high-resolution (LiDAR) DEMs, the benefits of landslide risk management and mitigation are highly significant due to a more accurate automatic landslide recognition, fast mapping and inventory (Provost et al., 2015; Riedmann et al., 2014).

Quantitative EqIL hazard assessment across the VSR should rely on harmonized landslide inventories at a local and regional scale with a clear delineation between the predisposing factors and seismotectonic triggers. The importance of this approach is mainly *fundamental*, as it provides regional insights into the earthquake-induced landslides triggering framework, improving the understanding of the link between the intermediate-deep focus earthquakes and small/massive slope failures (e.g. as observed in the seismic regions of Central Asia); secondly, this approach is *applied*, allowing better instrumentation and monitoring of slope dynamics, under different conditions of seismic shaking and precipitation recurrences, for an enhanced multi-hazard risk preparedness and prevention framework.

The main emerging priorities for the EqIL hazard assessment across the VSR are i) development of regional inventories of EqIL; ii) field measurement-based documentation of landslide behaviour during seismic shaking; iii) analysis of site-effects (topographic, lithologic) of EqIL events; iv) improving the landslide inventories by coupling climatic and seismic triggering frameworks; v) integrating *in-situ* measurements of climatic and seismic triggers in regional and local hazard assessment. The fulfilment of the aforementioned is expected to pave the way for the achievement of the SFDRR-related key targets in Romania as well as in its neighbouring countries such as: i) to substantiate the connection between landslides and the seismic trigger in the most important intermediate-deep focal earthquake province of Europe; ii) to provide stakeholders with robust predictions of earthquake-induced landslides hazard zonation maps; and iii) to improve the future development of multi-hazard scenarios for risk mitigation.

Fig. 17 The M_w>4 earthquakes overlay on precipitation (herein expressed by the Angot pluvial index - Dragotă, 2008; Micu et al. 2014, computed over 1961-2007, for two representative weather stations of the Curvature Carpathians and Subcarpathians with long record time series) (left) and the spatial distribution of the mentioned earthquakes epicentres.

Conclusions

Like in other similar seismically active mountain regions of the World, the evaluation of EqIL hazards is of great importance for the VSR: in this case, focus is on the understanding of the role of deep focal earthquakes in landslide initiation across very extended areas. Additionally, it also requires the application of multi-hazard scenarios modelling in risk management and consequences mitigation, combining both seismic and climatic effects. This is in agreement with the study of Nadim et al., 2006, who showed in a world-scale study that most landslide hotspots are located in seismically active mountain ranges. This was also confirmed after their publication, when the Wenchuan, Tohoku, L'Aquila, Accumoli-Amatrice or Kaikoura earthquakes triggered widespread landslide phenomena, and caused enormous economic losses, injuries and loss of human lives (Xu 2015; Zhang, 2018), pointing out the necessity for well-substantiated multi-hazard risk studies. The Haiti 2021 earthquake-triggered landslides further highlighted the importance of the aforementioned joint effect of seismic and climatic events on landslide triggering and distribution (see Havenith et al., 2022).

As shown in this work, a major constraint in the EqIL hazard assessment is related to the link between the seismotectonic context (preparing and triggering factors) and landslide predisposing factors, which is not fully understood and does not yet allow us to forecast EqIL occurrences or their characteristics with high confidence. As outlined by our review, further EqIL research initiatives are needed to overcome the existing lack of consistent information in the geohazard inventories covering the VSR, to facilitate the location of earthquake-triggered landslides and to provide new insight into post-seismic landslide evolution processes. During the last 5 years, local geomorphic, geophysical and seismic measurement studies (Balta, Păltineni, Varlaam and Lacul Vulturilor landslides) combined with numerical models (see example by Mreyen et al., 2021, an approach which could be followed elsewhere, in regions of similar seismicity) found a precise local linkage between the high-magnitude earthquakes and large, medium to deep-seated rock slides, but without enough representativity to allow for a regional assessment (preliminary results have been presented e.g. by Damen et al., 2014 and Harmouzi et al., 2021). In the meantime, the importance of these studies in developing proper regional-to-national multi-hazard risk reduction strategies has been outlined in the national priority project RO-RISK and in the SFDRR Country Report 5.1 Conditionality Romania, 2016 (https://www.igsu.ro/Resources/COJ/RapoarteStudii/ Raport_Final_de_tara%20pt %20Condit%20ex-ante%202016.pdf)

An improved EqIL hazard assessment framework for the VSR is also important for an increased understanding of landslide risk for governmental authorities, to develop proactive/prevention measures (County Councils) and to design risk response frameworks (Prefectures, County Inspectorates for Emergency Situations). A knowledge transfer and capacity building via co-design (which is currently missing) is needed to make judicious landslide inventories, documenting the location, date of occurrence, the extent at the local scale and associated damages attributed to these processes, classified according to a well-understood typology. A correlation of such studies in the VSR with others, from similar seismic regions (like Hindu Kush in Central Asia, for example) would allow a better understanding of the extent of the area potentially affected by such processes and their magnitude, substantiating (overlapping or cascading) multi-hazard evaluations.

Concluding, this overview covering the relevant aspects of earthquake-induced landslides in the VSR not only highlights the fundamental importance and applied possibilities, but the wider, globally relevant implications of the presented work. The innovative potential of studies of those phenomena may significantly influence the scientific, social, economic and cultural environments not only in Romania, but also worldwide. The scientific environment may be enriched through the development of deterministic evaluation of earthquake-landslides relationships in Romania and the surrounding countries, and by fostering precise, continuously improved multi-hazard assessments via the integration of seismic and climatic triggers. By supporting quantitative evaluations for a better assessment of multi-hazard exposure/vulnerability (in agreement with SFDRR guidelines), risk reduction through better development of non-structural plans (multi-hazard maps) and consequences mitigation through a better focus of structural preparedness measures may influence the socio-economic environment. Meanwhile, the cultural environment will be enriched through knowledge and innovation to build a culture of resilience and risk.

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References

Angelova, D., 2003. Influence of the Vrancea earthquake from 04 03 1997 on terrains with established paleoseismic events in Bulgaria (preliminary data). p. 303-313 in: Lungu, D., Wenzel, F., Mouroux, P., Tojo, I. (Eds.) Proceedings of the International Conference on Earthquake Loss Estimation and Risk reduction, Oct. 24-26 2002, Bucharest, Romania, pp. 303-309.

Ardeleanu, L., Neagoe, C., Ionescu, C., 2020. Empirical relationships between macroseimic intensity and instrumental ground motion parameters for the intermediate-depth earthquakes of Vrancea region, Romania. Natural Hazards. 103. https://doi.org/10.1007/s11069-020-04070-0.

Atanasiu, I., 1961. Cutremurele de pământ din România. Edit. Academiei RPR, 198 p.

Badea, L., 2008. Unitățile de relief ale României – Dealurile pericarpatice. Edit. Edit. Ars Docendi,143 p.

Bala, A., Radulian, M., Popescu, E., 2003. Earthquakes distribution and their focal mechanism in correlation with the active tectonic zones of Romania. Journal of Geodynamics. 36, 129–145.

Bala, A., Radulian, M., Popescu, E., 2003. Earthquakes distribution and their focal mechanism in correlation with the active tectonic zones of Romania. Journal of Geodynamics. 36, 129–145.

Bala, A., Raileanu, V., Dinu, C., Diaconescu, M. 2015. Crustal seismicity and active fault systems in Romania. Romanian Reports in Physics 67-3, 1176-1191.

Bălan, S., Cristescu, V., Cornea, I., 1982. Cutremurul de pământ din România de la 4 martie 1977. Edit. Academiei, 516 p.

Bălteanu, D., 1979a. Procese de modelare a versanţilor declanşate de cutremurul din 4 martie 1977 în Carpaţii şi Subcarpaţii Buzăului. SCGGG-Geogr. XXVI.

Bălteanu, D., 1979b. Slope-Modelling Processes Triggered by the March 4, 1977 Earthquake in the Buzau Carpathians and Subcarpathians. SCGGG-Geogr. XXVI.

Bălteanu, D., 1983. Experimentul de teren în geomorfologie, Edit. Academiei, Bucureşti.

Bălteanu, D., Chendeș, V., Sima, M., Enciu, P., 2010. A country-wide spatial assessment of landslide susceptibility in Romania. Geomorphology 124 (3–4), 102–112. https://doi.org/10.1016/j.geomorph.2010.03.005.

Bălteanu, D., Micu, M., Jurchescu, M., Malet, J.P., Sima, M., Kucsicsa, G., Dumitrică, C., Petrea, D., Mărgărint, M.C., Bilaşco, S., Dobrescu, C.F., Călăraşu, E.A., Olinic, E., Boți, I., Senzaconi, F.,

2020. National-scale landslide susceptibility map of Romania in a European methodological framework, Geomorphology 371, 107432. https://doi.org/10.1016/j.geomorph.2020.107432.

Berov, B., Ivanov, P., Dobrev, N., Krastanov, M., 2016. Addition to the method of Mora &Vahrson for landslide susceptibility along the Bulgarian Black Sea coast. in Aversa et al. (Eds) Landslides and engineered slopes. Exprience, theory and practice, Asociazione Geotecnica Italiana, Rome, ISBN 978-1-138-02988-0.

Borcia, I.S., Craifaleanu, I.G., Tanase, F.N., Praun, I.C., Dragomir, C.S., Georgescu, E.S., 2013. The SP Vrancea NT database. Example of use for a comparative analysis of records obtained in Russe (Bulgaria) and Giurgiu (Romania), Proceedings of the 13th SGEM GeoConference, Albena, Bulgaria, Vol.2, pp. 927-934.

Bourdeau, C., Havenith, H.B., 2008. Site effects modeling applied to the slope affected by the Suusamyr earthquake (Kyrguzstan, 1992). Engineering Geology, 97, 126-145.

Bourdeau, C., Lenti, L., Martino, S., Oguz, O., Yalcinkaya, E., Bigarrè, P., Coccia, S., 2017. Comprehensive analysis of the local seismic response in the complex Büyükçekmece landslide area (Turkey) by engineering-geological and numerical modelling, Engineering Geology, Volume 218, 90-106. https://.org/10.1016/j.enggeo.2017.01.005.

Bruchev, I., Dobrev, N., Frangov, G., Ivanov, P., Varbanov, R., Berov, B., Nankin, R., Krastanov, M., 2007. The landslides in Bulgaria – factors and distribution. Geologica Balcanica, 36 (3-4), 3-12.

Burrows, K., Walters, R.J., Milledge, D., Spaans, K., Densmore, A.L., 2019. A New Method for Large-Scale Landslide Classification from Satellite Radar. Remote Sensing, 11 (3). https://doi.org/10.3390/rs11030237.

Burrows, K.A., 2020. Rapid Detection of Earthquake-triggered Landslides from Satellite Radar, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/13772.

Burrows, K., Walters, R.J., Milledge, D., Alexander, L., Densmore, A.L., 2020. A systematic exploration of satellite radar coherence methods for rapid landslide detection. Nat. Hazards Earth Syst. Sci.. 20, 3197–3214. https://doi.org/10.5194/nhess-20-3197-2020.

Cheng, J., Rong, Y., Magistrale, H., Chen, G., Xu, X., 2017. A M_w-based historical earthquake catalog for mainland China. Bulletin of the Seismological Society of America, 107 (5), 2490-2500.

Cioflan, C.O., Manea, E.F., Apostol, B.F., 2022. Insights from neo-deterministic seismic hazard analyses in Romania. in Panza, G.F., Kossobokov, V.G., Laor, E., De Vivo, B. (Eds.) Earthquakes and Sustainable Infrastructure, Elsevier, pp. 415-432, ISBN 9780128235034.

Craiu, A., Craiu, M., Diaconescu, M., Marmureanu, A., 2017. 2013 seismic swarm recorded in Galati area, Romania: focal mechanism solutions. Acta Geod Geophys (2017) 52:53–67. https://doi.org/10.1007/s40328-016-0161-9.

Damen, M., Micu, M., Zumpano, V., Van Westen, C.J., Sijmons, K., Balteanu, D., 2014. Landslide mapping and interpretation: implications for landslide susceptibility analysis in discontinuous data environment. Proceedings of the International Conference Analysis and Management of Changing Risks for Natural Hazards,pp. 177-186.

Del Gaudio, V., Wasovski, J., 2011. Advances and problems in understanding the seismic response of potentially unstable slopes. Engineering Geology. 122, 73-83.

Dragotă, C., Micu, M., Micu, D., 2008. The relevance of pluvial regime for landslides genesis and evolution. Case-study: Muscel Basin (Buzău Subcarpathians), Romania. in Present Environment and Sustainable Development, 242-257, Edit. Univ. Al.I. Cuza, Iaşi.

Dumitrescu, I., Săndulescu M., Bandrabur T., (1970), Geological Map of Romania 1:200,000, Sheet 29 - Covasna, Institute of Geology, Bucharest.

Enescu, D., Enescu, B.D., 2007. A procedure for assessing seismic hazard generated by Vrancea earthquakes and its application. III. A method for developing isoseismal and isoacceleration maps. Applications. Romanian Reports in Physics 59 (1), 121–145.

Fan, X., Dufresne, A., Whiteley, J., Yunus, A.P., Siva, S.S., Okeke, C., Pánek, T., Hermanns, R., Ming, P., Strom, A., Havenith, H.B., Dunning, S., Wang, G., Tacconi, S.C. 2021. Recent technological and methodological advances for the investigation of landslide dams. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2021.103646.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., 2008. Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. Eng. Geol.102(3–4):99–111.

Ferrand, T.P., Manea, E.F., 2021. Dehydration-induced earthquakes identified in a subducted oceanic slab beneath Vrancea, Romania. Sci Rep 11, 10315. https://doi.org/10.1038/s41598-021-89601-w.

Georgescu, E.S., Pomonis, A., 2018. New Archival Evidence on the 1977 Vrancea, Romania Earthquake and Its Impact on Disaster Management and Seismic Risk. in: Vacareanu, R., Ionescu C. (Eds) Seismic Hazard and Risk Assessment. Springer Natural Hazards. Springer, Cham. https://doi.org/10.1007/978-3-319-74724-8_19.

Giardini, D., Woessner, J., Danciu, L., Cotton, F., Crowley, H., Grünthal, G., Pinho, R., Valensise, G., and the SHARE consortium. 2013. Seismic Hazard Harmonization in Europe (SHARE): Online Data Resource. https://doi.org/10.12686/SED-00000001-SHARE.

Gorum, T., X. Fan, C.J. van Westen, R. Huang, Q. Xu, C. Tang, and G. Wang. (2011). Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan earthquake. Geomorphology 133: 152–167.

Harmouzi, H., Schlögel, R., Jurchescu, M., Havenith, H.B., 2021. Landslide Susceptibility Mapping in the Vrancea-Buzău Seismic Region, Southeast Romania. Geosciences; 11(12):495. https://doi.org/10.3390/geosciences11120495.

Havenith, H.B., Strom, A., Torgoev, I., Torgoev, A., Lamair, L., Ischuk, A., Abdrakhmatov, K., 2015. Tien Shan geohazards database: Earthquakes and landslides. Geomorphology 249, 16-31.

Havenith, H.B., Torgoev, A., Braun, A., Schlögel, R., Micu, M. 2016. A new classification of earthquake-induced event sizes based on seismotectonic, topographic, climatic and geologic factors. Geoenvironmental Disasters, 3, pp.1-24.. https://doi.org/10.1186/s40677-016-0041-1.

Havenith HB., Mreyen AS., Torgoev A., Micu M. 2017. Numerical Models of Unstable Slopes in Seismic Areas– Based on 3D Geomodels. in: Mikoš M., Casagli N., Yin Y., Sassa K. (Eds) Advancing Culture of Living with Landslides. WLF 2017, pp.47-57. Springer, Cham.

Havenith, H.B., Guerrier, K., Schlögel, R., Braun, A., Ulysse, S., Mreyen, A.S., Victor, K.H., Saint-Fleur, N., Cauchie, L., Boisson, D., Prépetit, C., 2022. Earthquake-induced landslides in Haiti: analysis of seismotectonic and possible climatic influences, Nat. Hazards Earth Syst. Sci., 22, 3361–3384. https://doi.org/10.5194/nhess-22-3361-2022.

Heidbach, O., Ledermann, P., Kurfeß, D., Peters, G., Buchmann, T., Matenco, L., Negut, M., Sperner, B., Müller, B., Nuckelt, A., Schmitt. G., 2007. Attached or not attached: slab dynamics beneath

Vrancea, Romania, Proceedings of the International Symposium on Strong Vrancea Earthquakes and Risk Mitigation Oct. 4-6, 2007, Bucharest, Romania.

Iannucci, R., Lenti, L., Martino, S., 2020. Seismic monitoring system for landslide hazard assessment and risk management at the drainage plant of the Peschiera Springs (Central Italy). Engineering geology, 277, 105787. https://doi.org/10.1016/j.enggeo.2020.105787.

Ielenicz, M., 1984. Munţii Ciucaş-Buzău. Studiu geomorphologic. Edit. Academiei RSR, Bucureşti, 148 p.

Jibson, R., 2011. Methods for assessing the stability of slopes during earthquakes - a retrospective. Engineering Geology 122, 45-30.

Jimenez, M.J., Giardini, D., Grunthal, G., SESAME Working Group, 2001. Unified seismic hazard modeling throughout the Mediterranean region. Boll. Geog. Teor. Appl. 42, 3–18.

Keefer, D.K. 2002. Investigating landslides caused by earthquakes – a historical review. Surveys in Geophysics 23(6), 473–510.

Kijko, A., Graham, G., 1998. Parametric-historic procedure for probabilistic seismic hazard analysis. Part I: Estimation of maximum regional magnitude mmax., Pure Appl. Geophys. 152, 413–442.

Koulakov, I., Zaharia, B., Enescu, B., Radulian, M., Popa, M., Parolai, S., Zschau, J., 2010. Delamination or slab detachment beneath Vrancea? New arguments from local earthquake tomography. Geochemistry Geophysics Geosystems, 11, 3-24.

Kronrod, T., Radulian, M., Panza, G., Popa, M., Paskaleva, I., Radovanovich, S., Gribovszki, K., Sandu, I., Pekevski, L., 2013. Integrated transnational macroseismic data set for the strongest earthquakes of Vrancea (Romania), Tectonophysics, Volume 590, 1-23. https://doi.org/10.1016/j.tecto.2013.01.019.

Kumar, V., Cauchie, L., Mreyen, A.S., Micu, M., Havenith, H.B., 2021. Evaluating landslide response in a seismic and rainfall regime: a case study from the SE Carpathians, Romania. Nat. Hazards Earth Syst. Sci., 21, 3767–3788. https://doi.org/10.5194/nhess-21-3767-2021.

Lemaire, E., Mreyen, A.S., Dufresne, A., Havenith, H.B. 2020. Analysis of the Influence of Structural Geology on the Massive Seismic Slope Failure Potential Supported by Numerical Modelling. Geosciences, 10, 323.

Lungu, D., Wenzel, F., Mouroux, P., Tojo, I., 2004. Earthquake loss estimation and risk reduction. Proceedings of the International Conference Oct. 24-26, 2002, Bucharest, Romania, Independent Film, 2 vol, 366/421 p.

Mândrescu, N. 1981. The Romanian earthquake of March 4, 1977: aspects of soil behavior, Rev. Roum. Geol. Geophys. et Geogr. – Geophysique, 25, 35-56.

Mândrescu, N., 1982. The Romanian earthquake of March 4, 1977: damage distribution. Rev. Roum. Geophysique, 26, Edit. Acad. Rom.

Mărmureanu, G., Cioflan, C.O., Mărmureanu, A., 2011. Intensity seismic hazard map of Romania by probabilistic and (neo)deterministic approaches. Romanian Reports in Physics 63 (1), 226–239.

Mărmureanu, A., Craiu, M., Craiu, A., Nagoe, C., Radulescu, S., Ionescu, C. 2015. Vrancea earthquake early warning system: first tests to add location capabilities. Acta Geod Geophys 50, 121–130. https://doi.org/10.1007/s40328-014-0081-5.

Mărmureanu, Gh. 2016. Certitudini – incertitudini în evaluarea hazardului şi a riscului seismic vrâncean. 330 p. București. Editura Academiei Române.

Massey, C., Townsend, D., Rathje, E., Allstadt, K.E., Lukovic, B., Kaneko, Y., Bradley, B., Wartman, J., Jibson, R.W., Petley, D.N., Horspool, N., Hamling, I., Carey, J., Cox, S., Davidson, J., Dellow, S., Godt, J.W., Holden, C., Jones, K., Kaiser A., Little, M., Lyndsell, B., McColl, S., Morgenstern, R., Rengers, F.K., Rhoades, D., Rosser B., Strong, D., Singeisen, C., Villeneuve, M., 2018. Landslides Triggered by the 14 November 2016 MwMw 7.8 Kaikōura Earthquake, New Zealand. Bulletin of the Seismological Society of America; 108 (3B), 1630–1648. https://doi.org/10.1785/0120170305.

Maţenco, L., Zoetemeijer, R., Cloetingh, S., Dinu C., 1997. Lateral variations in mechanical properties of the Romanian external Carpathians: Inferences of flexure and gravity modeling, Tectonophysics, 282, 147 – 166, https://doi.org/10.1016/S0040-1951(97)00217-5.

Micu, M. 2008. Landslide hazard assessment in the Buzău-Teleajen Rivers Subcarpathians, Manuscript PhD Thesis, Institute of Geography, Bucharest, 220 p.

Micu, M., Jurchescu, M., Micu, D., Zarea, R., Zumpano, V., Bălteanu, D., 2014. A morphogenetic insight into a multi-hazard analysis: Bâsca Mare landslide dam, Landslides. https://doi.org/10.1007/s10346-014-0519-4.

Micu, M., Balteanu, D., Ionescu, C., Havenith, H.B., Radulian, M., van Westen, C., Damen, M., Jurchescu, M., 2015. A preliminary regional assessment of earthquake-induced landslide susceptibility for Vrancea Seismic Region, Geophysical Research Abstracts Vol. 17, EGU2015-12524.

Micu, M., 2017. Landslide types and spatial pattern in the Subcarpathian area. in: M.Radoane, A.Vespremeanu-Stroe (Eds.) Landform dynamics and evolution in Romania, Springer, pp 305-325.

Micu, M., Jurchescu, M., Șandric, I., Mărgărint, C., Zenaida, C., Dana, M., Ciurean, R., Ilinca, V., Vasile, M., 2017. Mass Movements. in: M.Radoane, A.Vespremeanu-Stroe (Eds.) Landform dynamics and evolution in Romania, Springer, pp. 765-820.

Micu, M., Micu, D., 2022. Landslides morphogenetic complexity in the Buzău Carpathians and Subcarpathians. Implication for hazard assessment, Romanian Journal of Geography, Vol. 66 (2), 137-152.

Miles, S.B., Keefer, D.K., 2009. Evaluation of CAMEL - Comprehensive Areal Model of Earthquake-Induced Landslides. Engineering Geology 104, 1-15.

Mreyen, A.S., Micu, M., Onaca, A., Cerfontaine, P., Havenith, H.B. 2017. Integrated Geological-Geophysical Models of Unstable Slopes in Seismic Areas. In: Mikos, M., Tiwari, B., Yin, Y., Sassa, K. (Eds.) Advancing Culture of Living with Landslides. WLF 2017. Springer, Cham.

Mreyen, A.S., Cauchie, L., Micu, M., Onaca, A., Havenith, H.B., 2021. Multiple geophysical investigations to characterize massive slope failure deposits: application to the Balta rockslide, Carpathians. Geopysical Journal International. https://doi.org/10.1093/gji/ggab028.

Murgeanu, G., Motaş, I., Bandrabur T., Săndulescu M. (1968). Geological Map of Romania 1:200,000, Sheet 36 – Ploieşti, Institute of Geology, Bucharest.

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., Jaedicke, C., 2006. Global landslide and avalanche hotspots. Landslides 3, 159–173. https://doi.org/10.1007/s10346-006-0036-1.

Neagu, C., Arion, C., Aldea, A., Calarasu, E. A., Văcăreanu, R., Pavel, F., 2018. Ground Types for Seismic Design in Romania. In: Văcăreanu, R., Ionescu, C. (Eds.) Seismic Hazard and Risk Assessment. Updated Overview with Emphasis on Romania, Springer Natural Hazards Book Series, p. 157-172, eBook ISBN 978-3-319-74724-8, Hardcover ISBN 978-3-319-74723-1. https://doi.org/10.1007/978-3-319-74724-8.

Oncescu, M.C., Marza, V.I., Rizescu, M., Popa, M., 1999. The Romanian earthquake catalog between 1984– 1997. in: Wenzel, F. et al. (Eds.) Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation. Kluwer, Dordrecht, pp 43–47.

Owen, L.A., Kamp, U., Khattak, G.A., Harp, E.L., Keefer, D.K., Bauer, M.A., 2008. Landslides Triggered by the 8 October 2005 Kashmir Earthquake. Geomorphology, 94(12):19. https://doi.org/10.1016/j.geomorph.2007.04.007.

Pavel, F., Popa, V., Văcăreanu, R., 2018a. Impact of Long-Period Ground Motions on Structural Design: A Case Study for Bucharest, Romania. Springer Briefs in Geotechnical and Earthquake Engineering, Springer, 87p., ISBN 978-3-319- 73402-6. https://doi.org/10.1007/978-3-319-73402-6.

Pavel, F., Văcăreanu, R., 2018b. Investigation on regional attenuation of Vrancea (Romania) intermediate-depth earthquakes. Earthquake Engineering and Engineering Vibration, 17(3): 501–509. https://doi.org/10.1007/s11803-018-0458-5.

Pavel, F., Văcăreanu, R., Pitiliakis, K., 2019. Intensity-dependent site amplification factors for Vrancea intermediate depth earthquakes. Bulletin of Earthquake Engineering, 17(5): 2363–2380. https://doi.org/10.1007/s10518-019-00563.

Pavel, F., Văcăreanu, R., Arion, C., Aldea, A., Scupin, A. 2021. Seismic risk assessment of lifelines in Bucharest. International Journal of Disaster Risk Reduction, Volume 66, 102629, ISSN 2212-4209. https://doi.org/10.1016/j.ijdrr.2021.102629.

Petrescu, L., Borleanu, F., Radulian, M., Ismail-Zadeh, A., Maţenco, L., 2021. Tectonic regimes and stress patterns in the Vrancea Seismic Zone: Insights into intermediate-depth earthquake nests in locked collisional settings. Tectonophysics, Volume 799. https://doi.org/10.1016/j.tecto.2020.228688.

Pradel, G.J., Lukovic, B., Dellow, G.D., 2020. Earthquake-induced landslide forecast and hazard assessment, Hawke's Bay Region. Lower Hutt (NZ): GNS Science. 25 p. Consultancy Report 2020/46.

Prieto, G.A., Beroza, G.C., Barrett, S.A., Lopez, G.A., Florez, M., 2012. Earthquake nests as natural laboratories for the study of intermediate-depth earthquake mechanics, Tectonophysics, 570, 42–56. https://doi.org/10.1016/j.tecto.2012.07.019.

Provost, F., Malet, J.P., Doubre, C., Puissant, A., Micu, M., 2015. DInSAR and PSI methods for the recognition of landslides: an experience in the Romanian Subcarpathians. Geophysical Research Abstracts, Vol. 17, 7469.

Radu, C., Polonic, G., 1982. Seismicitatea teritoriului României cu referire specială la regiunea Vrancea – fenomene speciale asociate. in Bălan, Cristescu, Cornea (1982) Cutremurul de pământ din România de la 4 martie 1977, Edit. Academiei Române, p. 115-123.

Radu, C., Spânoche, E. 1977. On geological Phenomena associated with the 10 November 1940 earthquake. Rev. Roum. Geol. Geophys. et Geogr. – Geophysique, 21, p. 159-165.

Radulian, M, Mandrescu, N., Popescu, E., Utale, A., Panza, G.F., 1999. Seismic activity and stress field in Romania. Rom. Journ. Phys., 44, 1051–1069.

Radulian, M., Mândrescu, N., Panza, G., Popescu, E., Utale, A., 2000. Characterization of Seismogenic Zones of Romania. Pure appl. geophys. 157, 57–77. https://doi.org/10.1007/PL00001100.

Radulian, M., Panza, G.F., Popa, M., Grecu, B., 2006. Seismic wave attenuation for Vrancea events revisited. Journal of Earthquake Engineering, Vol. 10, No.3. https://doi.org/10.1142/S1363246906002694.

Radulian, M., Popa, M., Cărbunar, O., Rogozea, M., 2008. Seismicity patterns in Vrancea and predictive features. Acta Geod.Geoph.Hung., Vol. 43(2-3), 163-173.

Radulian, M., Bălă, A., Ardeleanu, L., Toma-Dănilă, D., Petrescu, L., Popescu, E., 2019. Revised catalogue of earthquake mechanisms for the events occurred in Romania until the end of twentieth century: REFMC. Acta Geod Geophys 54, 3–18. https://doi.org/10.1007/s40328-018-0243-y.

Riedmann, M., Bindrich, M., Damen, M., Van Westen, C.J., Micu, M., 2014. Generating a landslide inventory map using stereo photo interpretation and radar interferometry techniques, a case study from the Buzau area, Romania, Proceedings of the International Conference Analysis and Management of Changing Risks for Natural Hazards, pp.571-577.

Rogozea, M., Mărmureanu, G., Radulian, M., Toma, D. 2014. Reevaluation of the macroseimic effects of the 23 january 1838 Vrancea earthquake. Romanian Reports in Physics, Vol. 66, No. 2, 520–538.

Roman, F., 1991. Noi aspect geohidromorfologice în sectorul superior al Văii Zăbala, Lucrările Seminarului Geografic Dimitrie Cantemir, Nr.2, Iaşi, 81-91.

Sandi, H., 2001. Obstacles to earthquake risk reduction encountered in Romania. In: Lungu, D., Saito, T. (2001) Earthquake Hazard and Countermeasures for Existing Fragile Buildings, Contributions from the JICA International Seminar, Bucharest, Romania, Nov. 23-24, 2000; Independent Film, ISBN 973-85112-2-4, Bucharest, 261-267.

Sandu, M., Micu, M., 2008. Morphostructure and Morphology in the Bend Carpathians and Subcarpathians. Trotuş – Teleajen Sector. Revue Roumaine de Geographie, Tomes 49-52, 2005-2008.

Săndulescu, M., 1984. Geotectonica Romaniei. Ed. Tehnica, 336 p. Bucureşti.

Strom, A., Abdrakhmatov, K. 2018. Seismically Induced Rockslides. In Strom, A., Abdrakhmatov, K. (Eds.) Rockslides and Rock Avalanches of Central Asia: Distribution, Impacts and Hazard Assessment, pp. 381-399. https://doi.org/10.1016/C2014-0-02190-9.

Tanyas, H., Rossi, M., Alvioli, M., van Westen, C.J., Marchesini, I., 2019. A global slope unit-based method for the near real-time prediction of earthquake-induced landslides. Geomorphology, Volume 327, 126-146. https://doi.org/10.1016/j.geomorph.2018.10.022.

Toma-Dănilă, D., Armaş, I., Ţigănescu, A., 2020. Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania. Natural Hazards and Earth System Sciences. https://doi.org/10.5194/nhess-20-1421-2020

Toma-Dănilă, D., Ţigănescu, A., D'Ayala, D., Armaş, I., Sun, L., 2022. Time-Dependent Framework for Analyzing Emergency Intervention Travel Times and Risk Implications due to Earthquakes. Bucharest Case Study. Front. Earth Sci. 10:834052. doi: 10.3389/feart.2022.834052

Ţugui, A., Craiu M., Rogozea, M., Popa, M., Radulian, M., 2009. Seismotectonics of Vrancea (Romania) zone: the case of crustal seismicity in the foredeep area. Romanian Reports in Physics, Vol. 61, No.2, 325-334.

Văcăreanu, R., Aldea, A., Lungu, D., Pavel, F., Neagu, C., Arion, C., Demetriu, S., Iancovici, M., 2016. Probabilistic Seismic Hazard Assessment for Romania. In: D'Amico, S. (Eds.) Earthquakes and Their Impact on Society, Springer Natural Hazards Book Series, p. 137-169, ISBN: 978-3-319-21752-9 (Print) 978-3-319-21753-6 (Online). https://doi.org/10.1007/978-3-319-21753-6.

Văcăreanu, R., Ionescu, C., (Eds.) 2016. The 1940 Vrancea Earthquake. Issues, Insights and Lessons Learnt. Proceedings of the Symposium Commemorating 75 Years from November 10, 1940 Vrancea Earthquake, Springer Natural Hazards Book Series, 521 p., Hardcover ISBN 978-3-319-29843-6. https://doi.org/10.1007/978-3-319- 29844-3.

Văcăreanu, R., Ionescu, C., (Eds.) 2018. Seismic Hazard and Risk Assessment. Updated Overview with Emphasis on Romania, Springer Natural Hazards Book Series, 544 p., Hardcover ISBN 978-3-319-74723-1. https://doi.org/10.1007/978-3-319-74724-8.

Van Westen, C.J., Castellanos, E., Kuriakose, S.L., 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview. Eng. Geol 102 (3–4):112–131.

Wang, Y., , Song, C., Lin, Q., Li, J. 2016. Occurrence probability assessment of earthquake-triggered landslides with Newmark displacement values and logistic regression: The Wenchuan earthquake, China. Geomorphology 258, 108–119.

Wasowski, J., Keefer, D.K., Lee, C.T., 2011. Towards the next generation of research on earthquake-induced landslides: current issues and future challenges. Engineering Geology, 122, 1-8.

Wenzel, F., Lungu, D., Novak, O., 1999. Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation; Contributions from the First International Workshop on Vrancea Earthquakes, Bucharest, Romania, November 1–4, 1997; Kluwer Academic Publishers, ISBN978-94-011-4748-4. https://doi.org/10.1007/978-94-011-4748-4, 375 p.

Wistuba, M., Malik, I., Krzemień, K., Gorczyca, E., Sobucki, M., Wrońska-Wałach, D., Gawior, D. (2018) Can low-magnitude earthquakes act as a triggering factor for landslide activity? Examples from the Western Carpathian Mts, Poland. Catena, Volume 171, 359-375, https://doi.org/10.1016/ j.catena.2018.07.028.

Xu, C., 2015. Preparation of earthquake-triggered landslide inventory maps using remote sensing and GIS technologies: principles and case studies. Geoscience Frontiers 6, 825-836.

Zaicenco, A., Craifaleanu, I., Paskaleva, I., 2008. Harmonization of Seismic Hazard in Vrancea Zone with Special Emphasis on Seismic Risk Reduction, 347 p, Springer, Dordrecht. https://.org/10.1007/978-1-4020-9242-8.

Zarifi, Z., Havskov, J., 2003. Characteristics of dense nests of deep and intermediate-depth seismicity. Adv. Geophys., 46, 238–278.

Zhang, Y., 2018. Earthquake-Induced Landslides: Initiation and run-out analysis by considering vertical seismic loading, tension failure and the trampoline effect, Springer Natural Hazards. https://doi.org/10.1007/978-981-10-2935-6.

Zhang, S., Li, C., Zhang, L., Peng, M., Zhan, L., Xu, Q., 2020. Quantification of human vulnerability to earthquake-induced landslides using Bayesian network. Engineering Geology, Volume 265. https://doi.org/10.1016/j.enggeo.2019.105436.

Zugrăvescu, D., Polonic, G., Horomnea, M., Dragomir, V., 1998. Recent vertical movements on the Romanian territory, major tectonic compartments and their relative dynamics. Rev. Roum. Géophys., seria Geofizică, 42.

Zumpano, V., Hussin, H., Reichenbach, P., Bãlteanu, D., Micu, M., Sterlacchini, S., 2014. A landslide susceptibility analysis for Buzãu County. Romania. Revue Roumaine de Geographie/Romanian Journal of Geography, Vol. 58 (1).

*** Raportul Domnului Dr. Gustav Schuller, asupra cutremurului de pamânt întâmplat în Ţara Românească, în anul 1838, Bulletin de la Société Géologique de Roumanie, 1883.

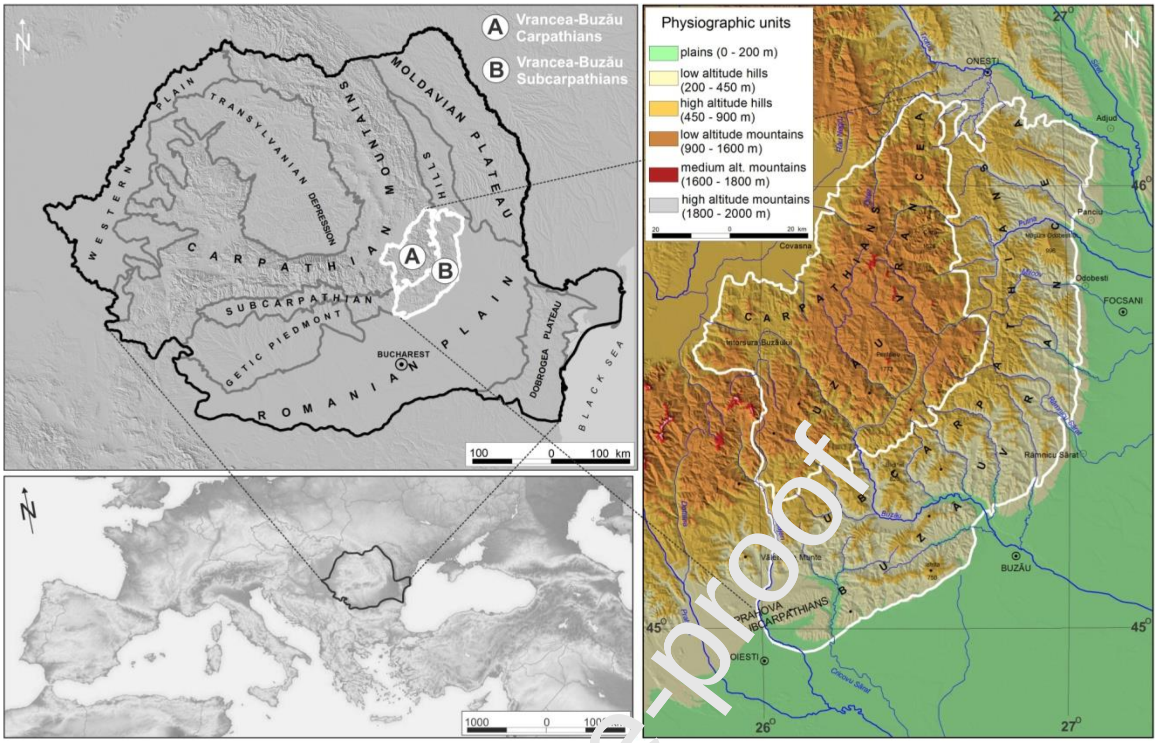


Fig.1. The location of the VSR study area in Europe and in Romania

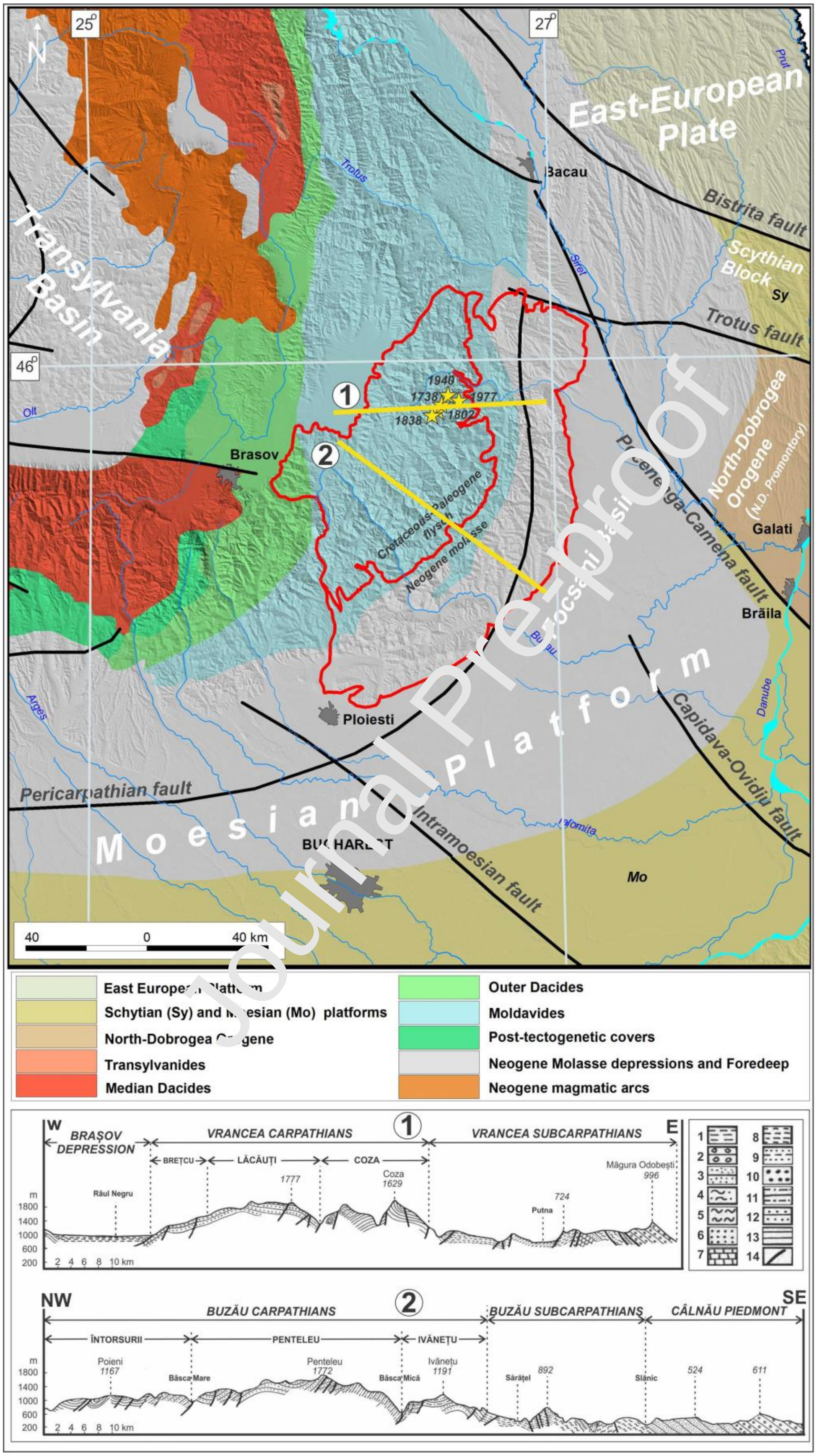

25°
27°
46°
N
East-European Plate
Prut
Bacau
Trotus
Bistrita fault
Scythian Block
Sy
Siret
Trotus fault
Transylvania Basin
Olt
1940
1738
1977
1838
1802
1
2
Brasov
Cretaceous-Paleogene flysch
Neogene molasse
Focsani Basin
Peceneaga-Camena fault
North-Dobrogea Orogene (N.D. Promontory)
Galati
Brăila
Buzău
Danube
Capidava-Ovidiu fault
Argeș
Ploiesti
Pericarpathian fault
Moesian Platform
Ialomita
Intramoesian fault
BUCHAREST
Mo
40
0
40 km
East European Platform
Schytian (Sy) and Moesian (Mo) platforms
North-Dobrogea Orogene
Transylvanides
Median Dacides
Outer Dacides
Moldavides
Post-tectogenetic covers
Neogene Molasse depressions and Foredeep
Neogene magmatic arcs
W
E
BRAȘOV DEPRESSION
VRANCEA CARPATHIANS
VRANCEA SUBCARPATHIANS
BREȚCU
LĂCĂUȚI
COZA
Râul Negru
1777
Coza 1629
Putna
724
Măgura Odobești 996
m
1800
1400
1000
600
200
2 4 6 8 10 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
NW
SE
BUZĂU CARPATHIANS
BUZĂU SUBCARPATHIANS
CÂLNĂU PIEDMONT
ÎNTORSURII
PENTELEU
IVĂNEȚU
Poieni 1167
Bâsca Mare
Penteleu 1772
Bâsca Mică
Ivănețu 1191
Sărățel
892
Slănic
524
611

Fig.2. The intra-collisional position of the VSR and the epicentres of the major (Mw>7.4) earthquakes during the last 300 years, in a geotectonic context (based on Săndulescu, 1984). Morphostructural profiles. 1) Holocene: present-day floodplain alluvia; 2) Lower Pleistocene: gravels, sands and loess-like deposits; 3) Upper Pliocene (Romanian): sands, sand clays, clays; 4) Upper Pliocene (Dacian): marly sandstones, sandy marls; 5) Lower-Medium Pliocene (Meotian – Pontian): sandstones, marls and sand marls; 6) Lower Pliocene (Meotian): sandstones, marls, cynnerite marls; 7) Upper Miocene (Sarmatian): sandstones, marls, shales; 8) Lower-Medium Miocene (Helvetian): sandstones, schists, gypsium; 9) Upper Oligocene-Medium Miocene (Aquitanian–Helvetian): sandstones, schists with salt and gypsium blocks; 10) Lower Miocene (Burdigalian): sandstones, conglomerates, schists; 11) Oligocene: sandstones, clays, marls; 12) Eocene: sandstone and sandstone schists; 13) Cretaceous: conglomerates, marly limestone, curbicortical flysch; 14) fault .

Table 1 The list of earthquakes with M_w>7 during the last 300 years

(according to the ROMPLUS catalogue of the National Institute for Earth Physics)

Year	**Estimated M_w**	**Estimated depth (km)**
1701	7.1	150
1738	7.7	130
1740	7.3	150
1790	7.1	150
1802	7.9	150
1829	7.3	150
1838	7.5	150
1893	7.1	100
1894	7.1	130
1908	7.1	125
1940	7.7	150
1977	7.4	94
1986	7.1	131

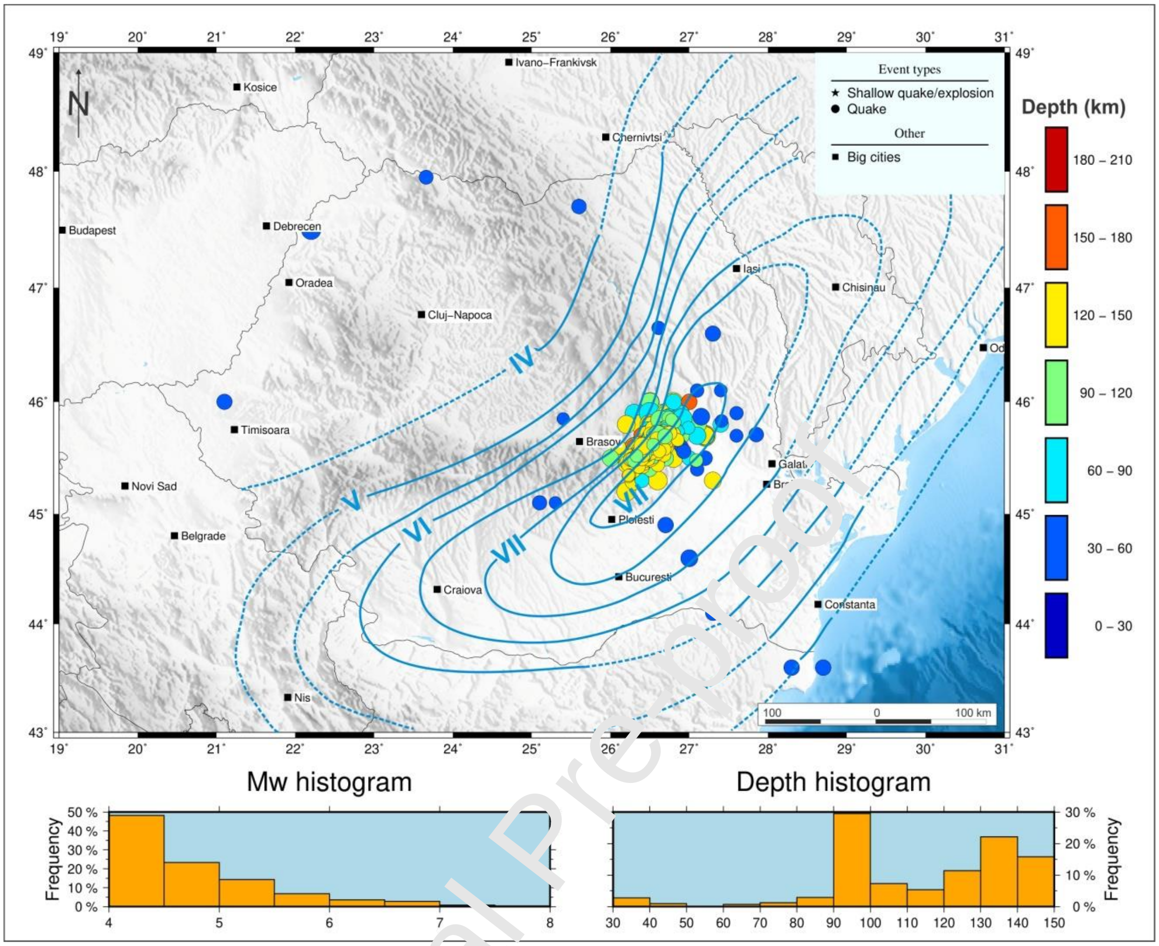


Fig.3 The distribution of the 222 cases of M_w>5 earthquakes epicentres triggered by Vrancea intermediate domain (light blue to red on the depth scale) during the 1700-2021 time period; with blue lines, the isoseismal of the “etalon” earthquake (M_w 7.1, August 1986) - generalised attenuation curves (source of the data: ROMPLUS catalogue, NIEP: https://web.infp.ro/#/romplus; isoseismal after Enescu and Enescu, 2007, modified by Mărmureanu et al. 2011)

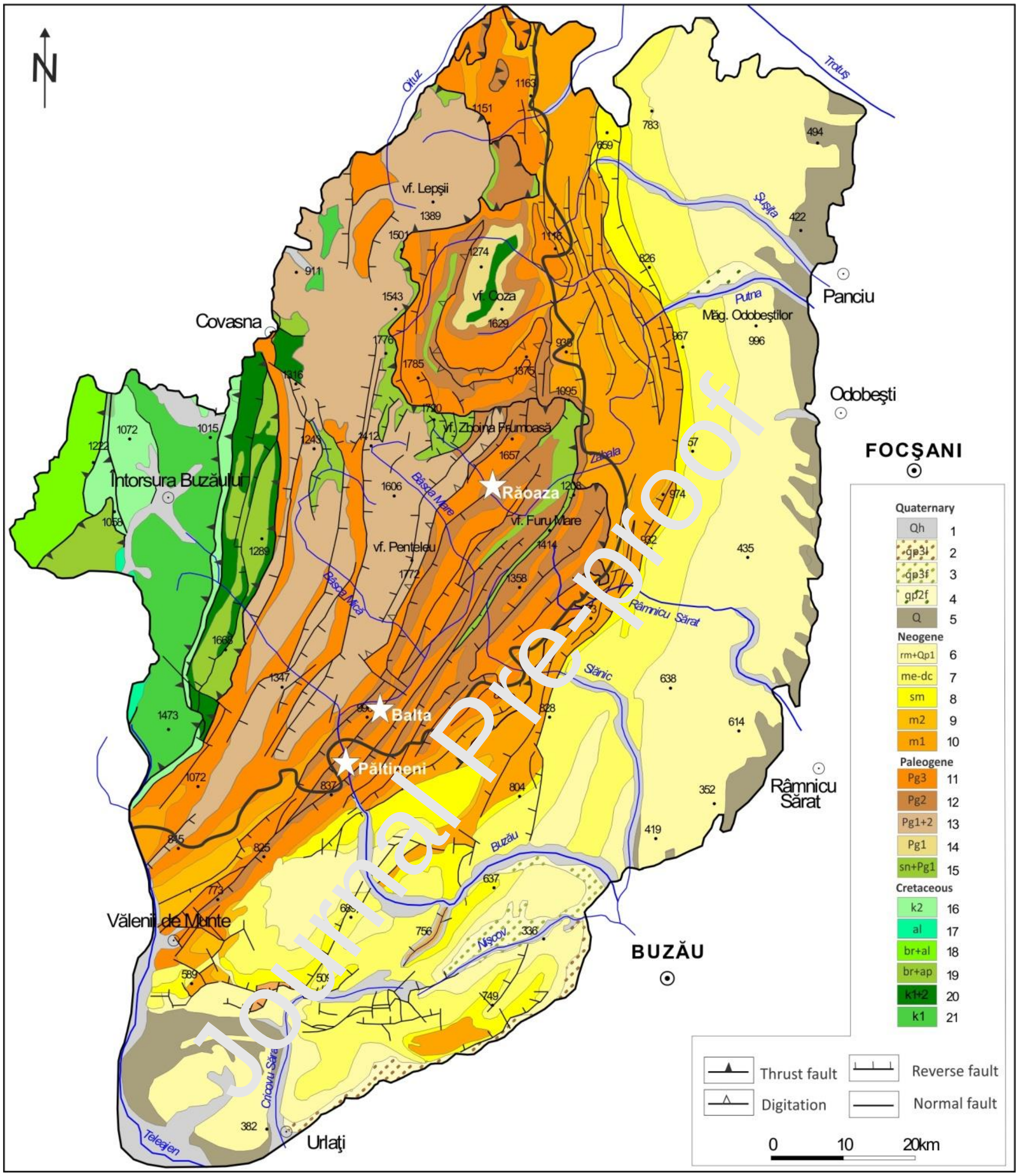


Fig.4 The geological map of the study area (Carpathians and Subcarpathians separated by the black line): 1) alluvial plains deposits (Holocene); 2) loess-like deposits (Upper Pleistocene); 3) terrace deposits (Upper Pleistocene); 4) terrace deposits (Mid Pleistocene); 5) loess-like deposits (undiferentiated Quaternary); 6) sands, pebbles, loess (Romanian-Lower Pleistocene); 7) sandstones, marls, coal intercalations (Meotian-Dacian); 8) sandstones, marls, clayey schists (Sarmatian); 9) marls, sandstones, clayey schists, salt breccias, tuffa (Mid Miocene); 10) sandstones, conglomerates, clays, salt, gypsum (Lower Miocene); 11) sandstone,

clays, marls, disodiles, menilites, conglomerates (Oligocene); 12) schistose sandstone limy flysch (Eocene); 13) sandstone flysch with clayey intercalations (Paleocene + Eocene); 14) schistose sandstone and limy flysch (Paleocene); 15) sandstone limy flysch, schistose sandstone flysch (Senonian + Paleocene) 16) massive sandstones with marly intercalations (Upper Cretaceous); 17) black schistose flysch (Lower and Upper Cretaceous); 18) sandstone schistose flysch (Barremian + Aptian); 19) sandstones and marls, masive sandstones (Barremian + Albian); 20) sandstones and conglomerates (Albian) ; 21) massive sandstones flysch (Lower Cretaceous). Maps source: Geological Map of Romania 1:200,000 (Ploiești and Covasna sheets), Institute of Geology, Bucharest (Murgeanu et al., 1968; Dumitrescu et al., 1970).

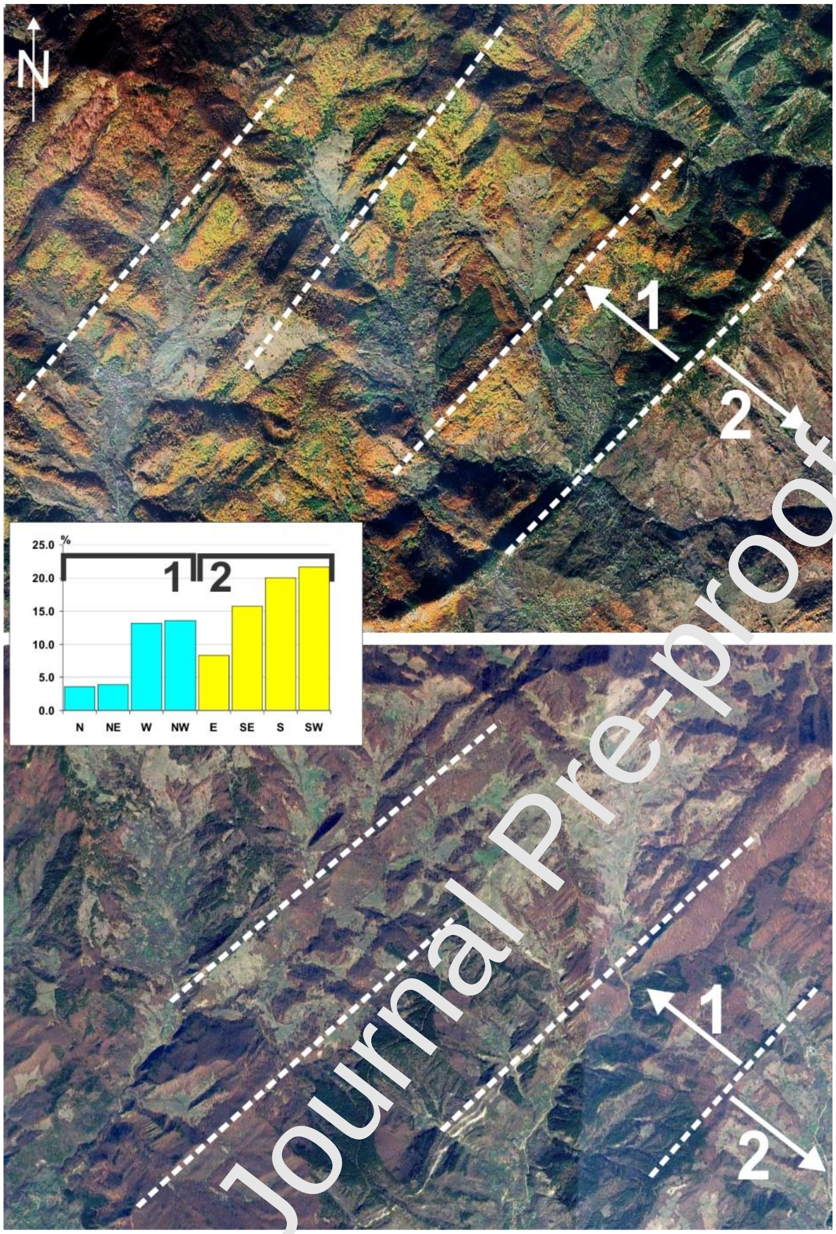


Fig.5. The predominant and almost continuous NE-SW orientation of the structures is imposing a rather equally-distributed (expressed in percentages) presence of landslide processes on NW (1) and SE (2)-facing slopes, considering a representative study area of 900 km^2 situated at the Buzău Carpathians-Subcarpathians contact (based on the dataset of Damen et al., 2014)

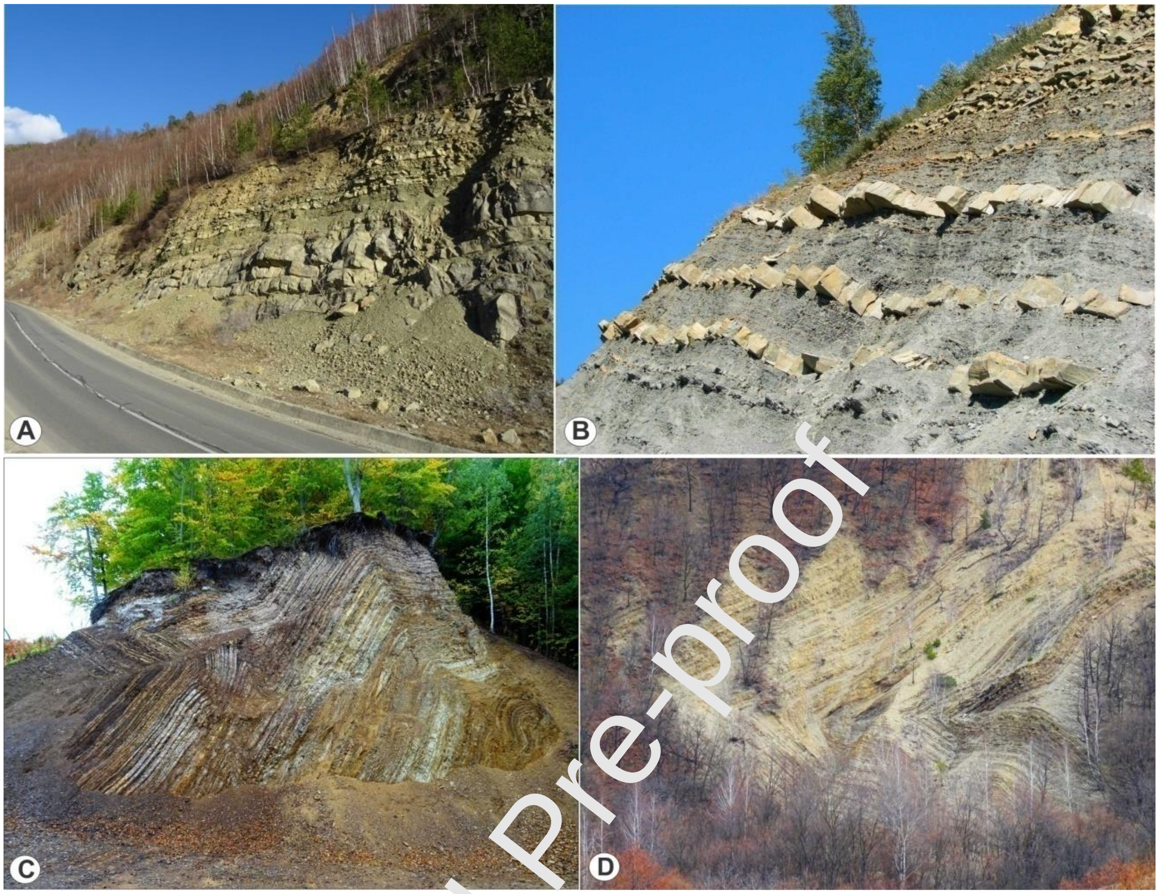


Fig. 6 Typical Palaeogene flysch structures in the study area: alternance of thick/thin sandstone-schistose layers (A, B), intensely folded and faulted (C, D)

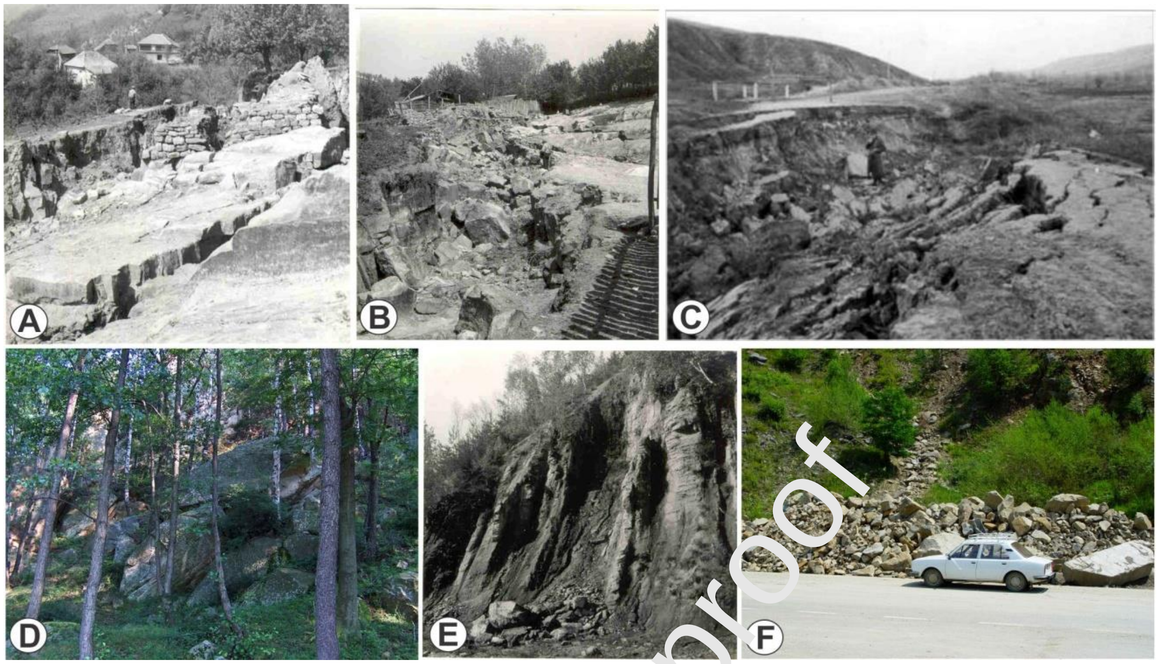


Fig.7 Different types of landslides caused by earthquakes in the VSR: shallow and medium-seated rock/earth slides, triggered during the 1977 earthquake (photos A, B, by D. Bălteanu; C by N. Mândrescu,) and rock falls (ranging from massive failures D, witnessing large magnitude paleoseismic events, to low magnitude blocks collapses and rolling E, F: photos D, F, by M. Micu; E by D. Bălteanu).

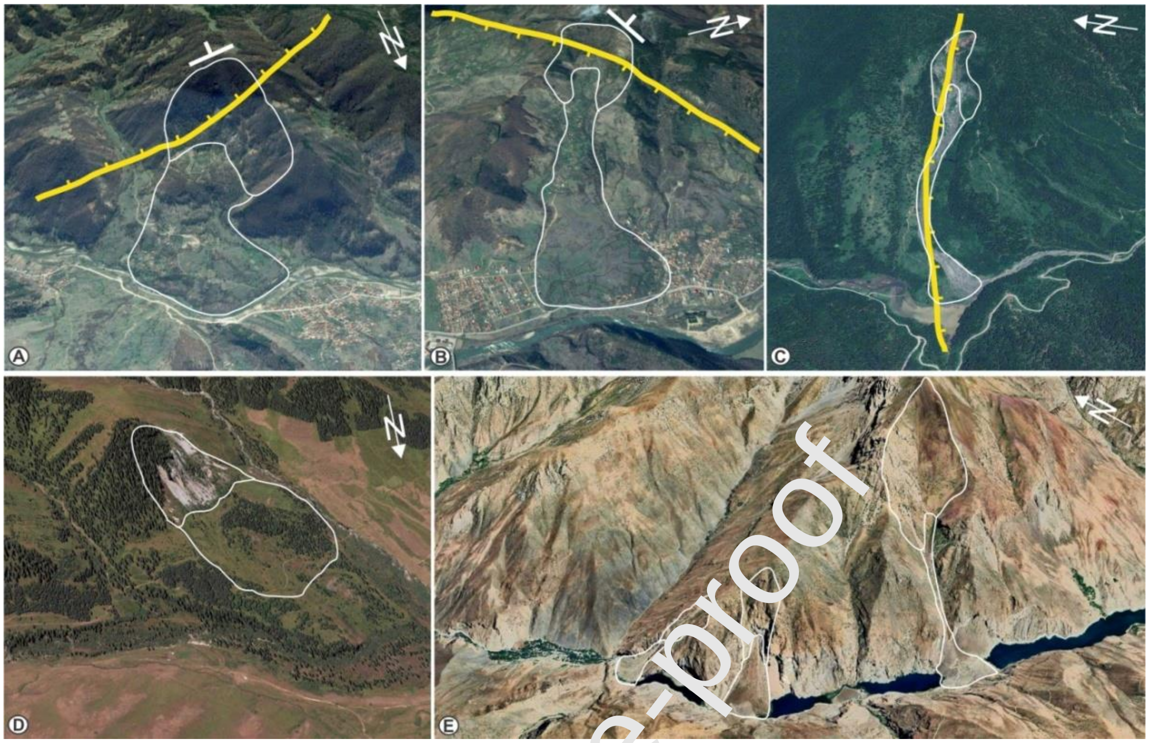


Fig.8 High magnitude (usually 2-3 km long) old dormant landslides (A. Balta - footwall, B. Păltineni - hangingwall, C. Răoaza – along fault) in the Buzău (A, B) and Vrancea (C) Mountains, whose morphology indicate a potential seismic trigger: main scarps close to the watersheds, far away from the river network, anti-dip slopes (A, B), fault line crossing the main scarp area (reverse faults in this case). For morphologic comparison, processes with proven seismic triggers (Havenith et al., 2015): Kaindy rockslide (D) and Seven Lakes long runout landslide (E), Tien Shan Mts. (imagery source: Google Earth).

Fig.9 Examples of landslides (dark brown – depletion area, light brown – accumulation area; after Damen et al., 2014) equally distributed along the reverse fault (A), predominantly distributed on the footwall (B) and predominantly distributed on the hangingwall (C), according to the steepness of the slopes in the fault vicinity.

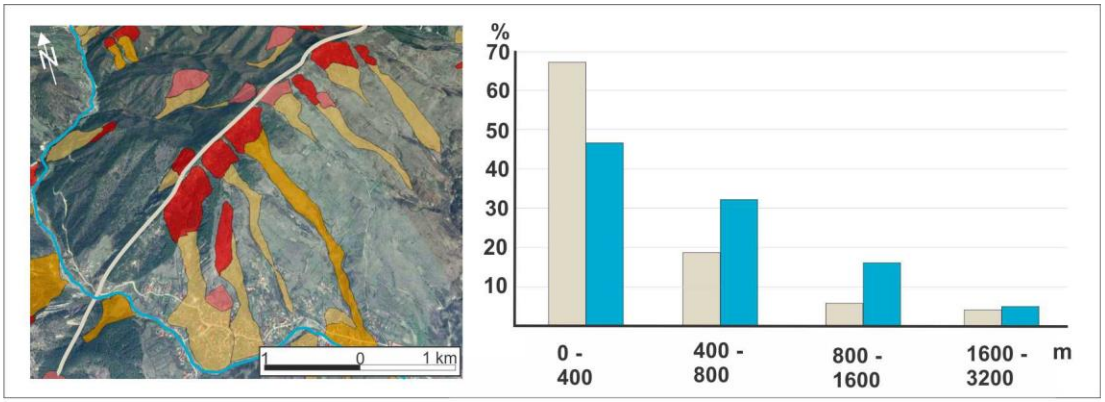


Fig.10 Distribution of 500 landslide scarps according to the faults (grey) and rivers (blue) distance.

Table 2 A synthesis correlation among existing information on EqIL, as derived from documented case studies

	Earthquake year	**Magnitude (M_w)**	**Landslide type**	**Landslide number**	**Landslide individual surfaces/vol.**	**Landslide cumulated surfaces/vol.**	**Place of occurrence**	**Reference**
Maximum epicentral distance of landslide occurrence	1940	7.7	No typological classification	Over 70	Not specified	Not specified	Up to 250-330 km	Radu and Spânoche, (1977)
	1977	7.4	Slides and falls; no material specified	Not specified	Not specified	Not specified	Up to 100-120 km	Mândrescu, (1981)
	1977	7.4	Associated phenomena (ground cracks and fissures)	Not specified	Not specified	Not specified	Up to 160-290 km	Angelova, (2003)
	1977	7.4	Rock Falls	Not specified	Not specified	Not specified	Up to 270-380 km	Angelova, (2003)
Extension of the landslide distribution area	1977	7.4	Soil/earth slides and falls	Not specified	Not specified	Not specified	50 to 80 km	Mândrescu, (1981)
	1977	7.4	Associated phenomena (ground cracks, liquefaction)	Not specified	Not specified	Not specified	Up to 220-310	Mândrescu, (1981)
	future	>8	No typological classification	<1000 (predicted)	Not specified	Not specified	>500 km	Havenith et al., (2016)
Total potential number of landslides	1940	7.7	No typological classification	Over 70 (wet conditions)	Not specified	Not specified	Up to 250-330 km	Radu and Spânoche, (1977)
	1977	7.4	Slides and falls; no material specified	At least 12 co-seismic and 4 post-seismic (dry conditions)	Not specified	Not specified	Up to 100-120 km	Mândrescu, (1981)
	1977	7.4	No	Above 100	Not specified	Not specified	Up to 300 km	Radu and

			typological classification					Polonic, (1982b)
Potential slope failure surface areas and volumes	1977	7.4	Earth/debris/ slides and rock falls	Tens-dozens	1-5 m^3(falls), 1000-3000 m^2(slides)	5-360 m^3 (falls), 30000-200000 m^2 (slides)	Under 50 km	Bălteanu, (1983)
	presumed	>7.5	Rock slides	Not specified	Not specified	>30 mio.	Not specified	Kumar et al.,(2021), Mreyen et al., (2021)

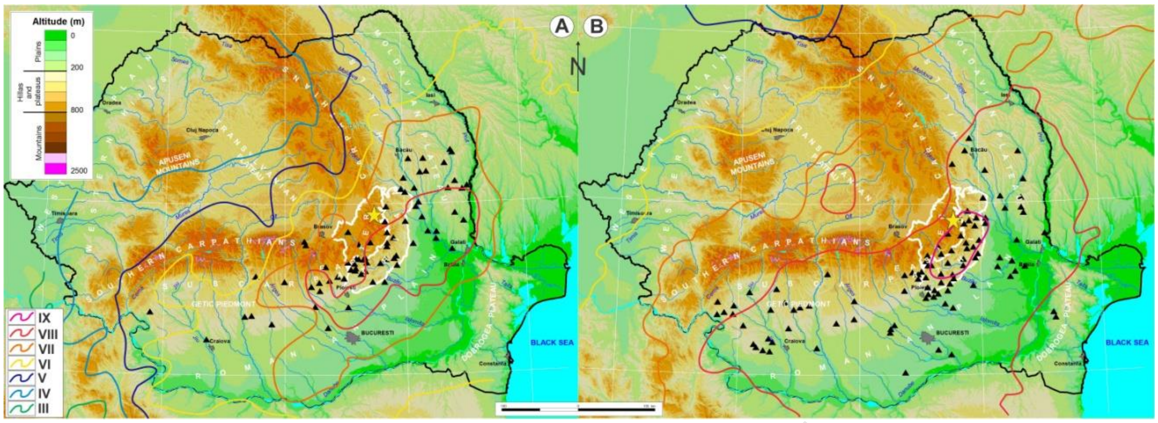


Fig.11 The distribution of landslides triggered by the 1940 (A) and 1977 (B) earthquakes relative to their epicentres (yellow star) and isoseismals (based on the maps of the 1940 and 1977 macroseismic fields produced by Kronrod et al., 2013; landslide distribution based on Radu and Spânoche, 1977 and Radu and Polonic, 1982)

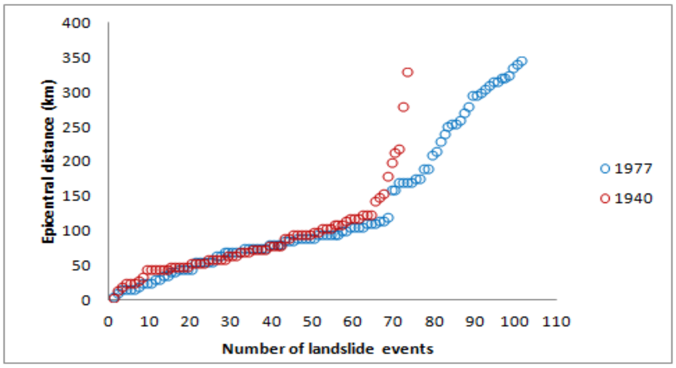


Fig.12 The distribution of landslides triggered by the 1940 and 1977 earthquakes in relation to the epicentral distance

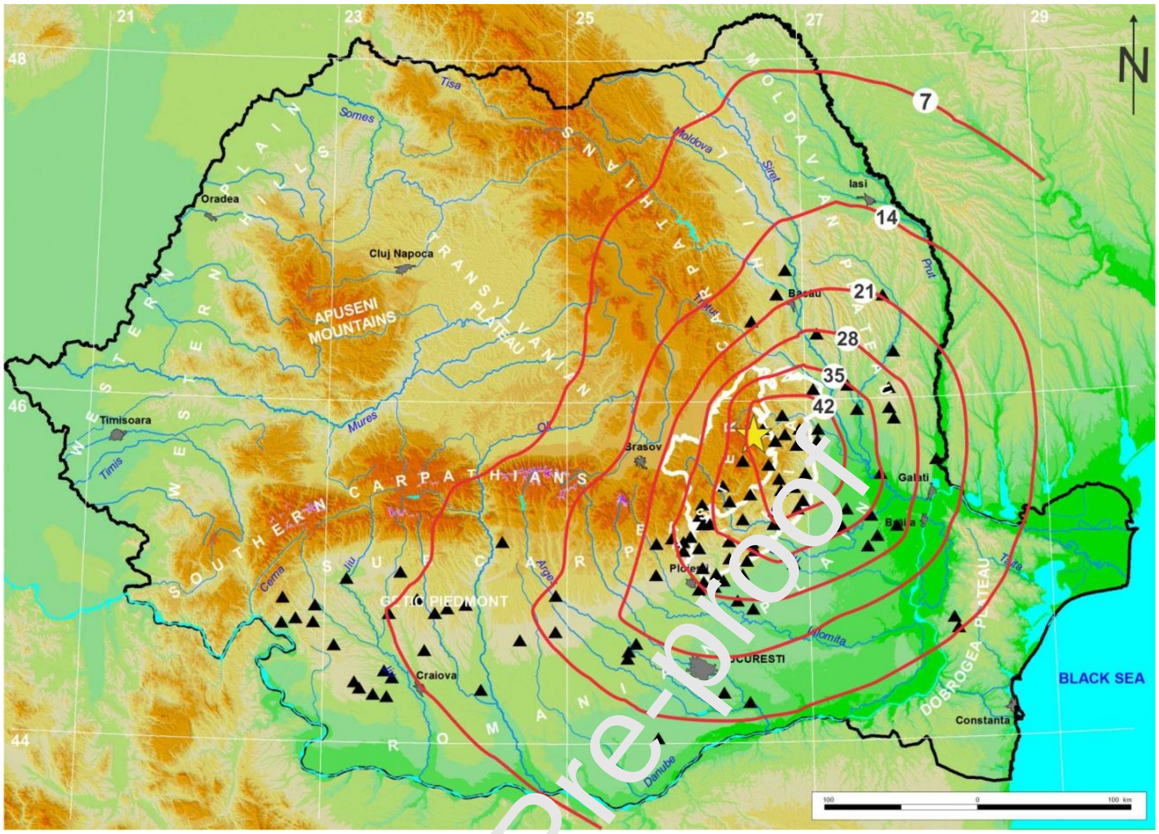


Fig.13 The distribution of 1977 EqIL events (based on Radu and Polonic 1982) relative to the PGA (red lines; in %*g*) of the same seismic event (according to INFP – ROMPLUS catalogue)

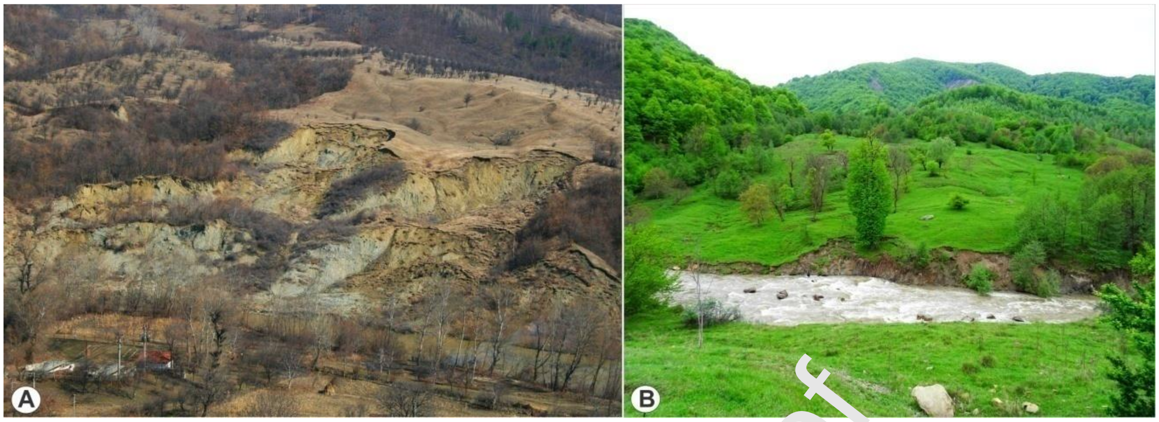


Fig.14 Reactivation of 40-60 m thick (earthquake-induced) landslide accumulations deposits due to lateral erosion (A. Păltineni landslide, Buzău River, B. Balta landslide, Bâsca Rozilei River)

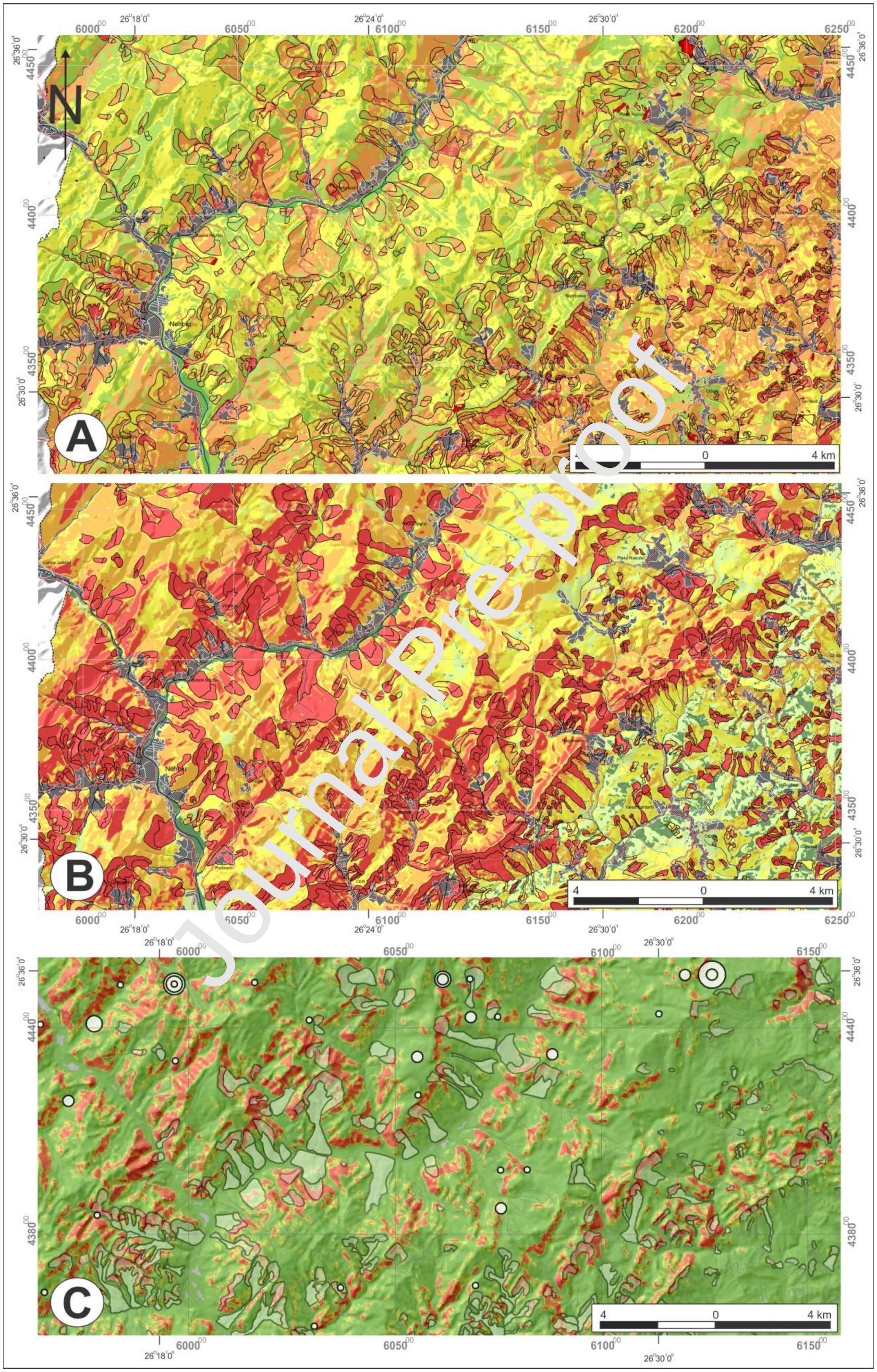

A
B
C
N
4 0 4 km
6000
6050
6100
6150
6200
6250
4450
4400
4350
4440
4380
26°18'0"
26°24'0"
26°30'0"
26°36'0"
Nehoiu

Fig.15 Comparison of results of weights of evidence (A; Zumpano et al., 2014) and spatial multi-criteria evaluation (B; Damen et al., 2014) with Newmark Displacement (C; Micu et al., 2015) - based evaluations of landslide susceptibility in the Buzău-Bâsca Rozilei confluence sector (Buzău Carpathians-Subcarpathians contact)

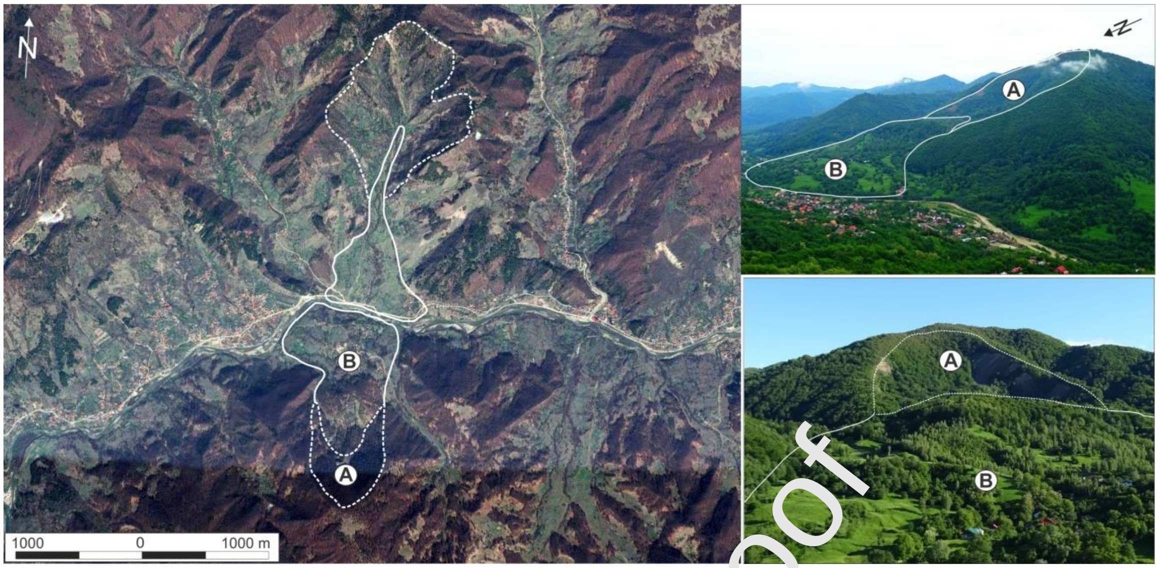


Fig.16 Comparison between long runout debris flow (Ruptura landslide) on a south-facing slope and coherent rockside on the north-facing one (Balta landslide) in Râsca Rozilei catchment. The high-intensity seismic trigger initiated a high-magnitude landslide, still allowing during present days the clear delimitation of the depletion (A) and accumulation (B) morphodynamic sectors regardless of the dense forest cover installed afterwards.

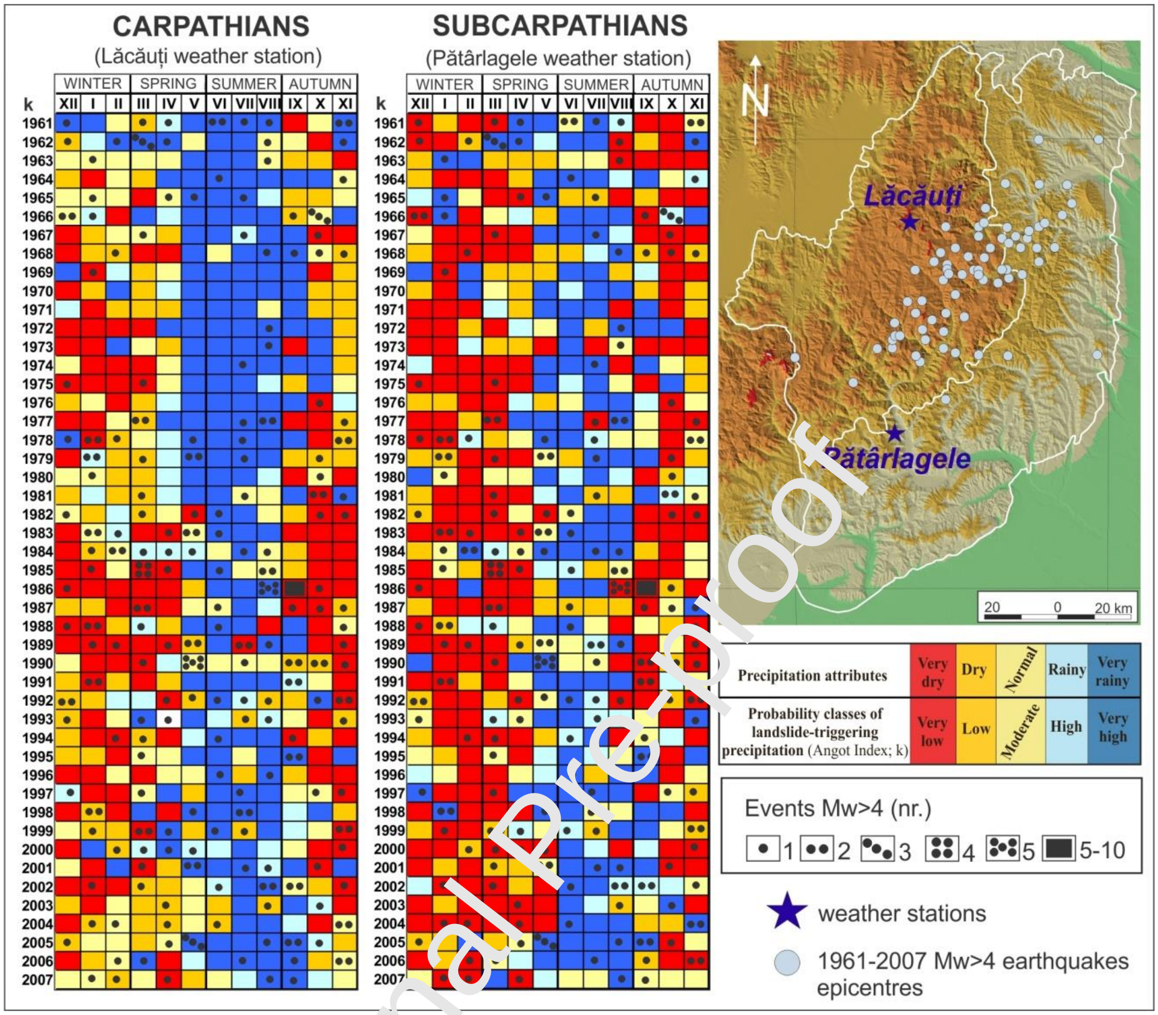
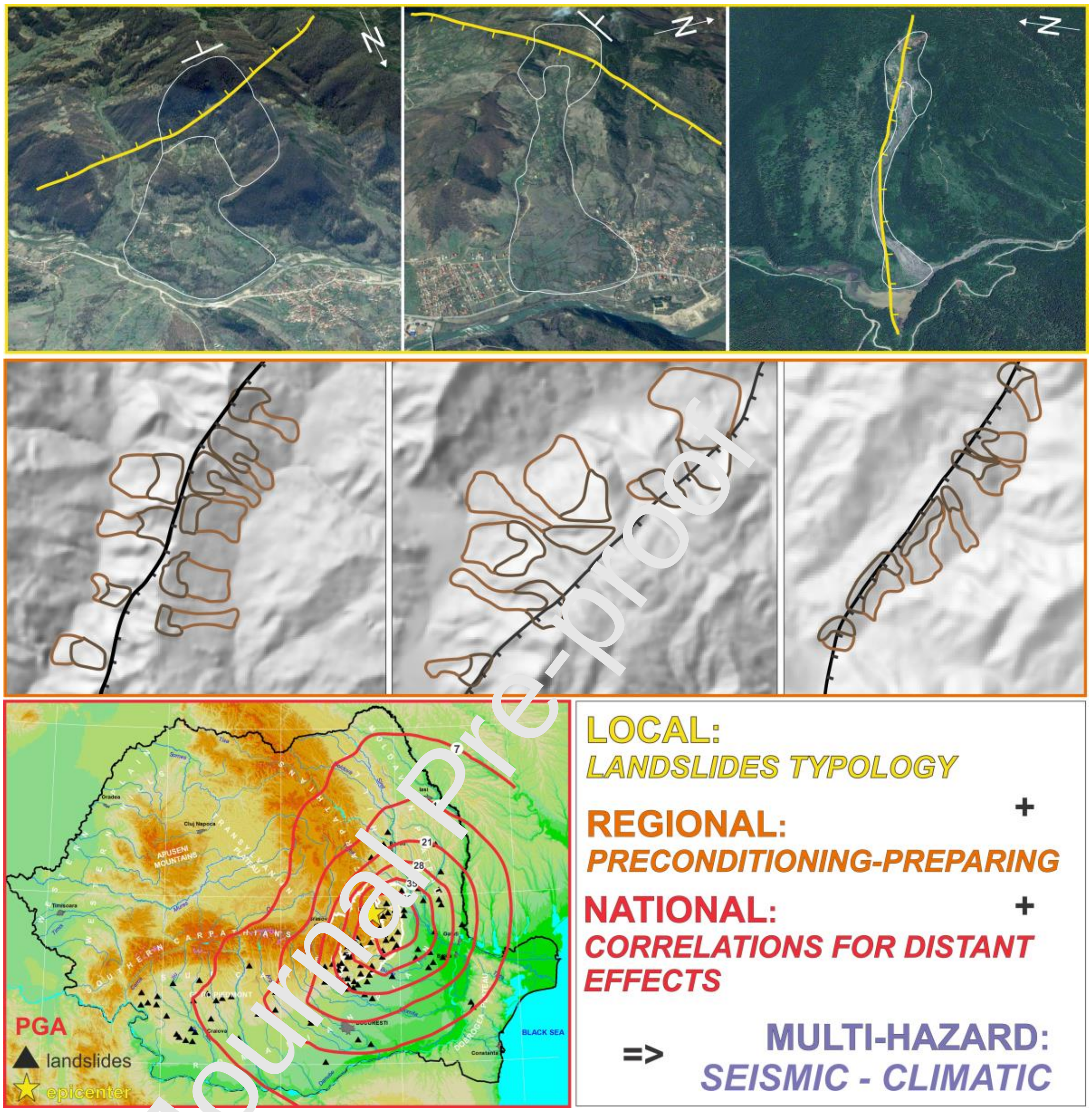


Fig. 17 The M_w>4 earthquakes overlay on precipitation (herein expressed by the Angot pluvial index - Dragotă, 2008; Micu et al., 2014, computed over 1961-2007, for two representative weather stations of the Curvature Carpathians and Subcarpathians with long record time series) (left) and the spatial distribution of the mentioned earthquakes epicentres.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



Graphical abstract

Highlights

- Vrancea earthquakes are responsible for causing landslides
- Vrancea seismotectonic-landslide context is not fully understood yet
- Numerous landslides show a typical seismically-induced morphology
- Deep-focal earthquakes are conditioning complex and distant landslides
- The research improves multi-hazard (earthquake-landslide) risk assessment