LANDSLIDES MORPHOGENETIC COMPLEXITY IN THE BUZĂU CARPATHIANS AND SUBCARPATHIANS. IMPLICATIONS FOR HAZARD ASSESSMENT

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Key-words: landslides, Buzău Carpathians and Subcarpathians, typology, susceptibility, hazard.

Abstract. The Vrancea Seismic Region, corresponding to the Curvature sector of the SE (Romanian) Carpathians and Subcarpathians and including their Buzău sub-unit, is a very active geomorphic region, marked by a wide variety of fluvial, slope gravitational and seismic processes. The morpho-litho-structural traits, the active neotectonic movements, the climatic regime and the anthropic activities are the main controlling factors within complex multi-hazard environments. In this context, numerous landslide hazard evaluations have been developed during the past decade, employing the existing landslide inventories to calibrate and validate statistic and probabilistic susceptibility models. Previous results of various landslide hazard assessment initiatives suggested that fine-tuned regional susceptibility models, performing properly from a statistical point of view, could result in differently-distributed susceptibility classes, which increases the uncertainty of results and may decrease their uptake by stakeholders and end-users. It is the purpose of this paper to outline the geomorphic complexity of landslide typology in the study-area, and the induced sources of epistemic uncertainties in hazard assessment. The study discusses the landslide distribution and typologies, as derived from existing landslide inventories (based on field mapping, optical remote sensing imagery, radar interferometry). Furthermore, a wide range of aspects such as slope sensitivity, the geomorphic complexity of landslides, their evolution, frequency-magnitude relationship, triggering thresholds, morphodynamic sectors and connectivity are evaluated from the perspective of potential epistemic uncertainty sources. The study elaborates a series of geomorphic-driven recommendations for enhancing the robust predictability of susceptibility models in support of a more accurate hazard evaluation. By improving the methodological framework for evaluating the past, present and future behaviour of such mass movement processes, geomorphologists should engage relevant stakeholders when developing their hazard assessment approaches to advance and optimize the risk management decision-making process through informed proactive measures for risk prevention and preparedness and effective reactive actions for response and recovery.

1. INTRODUCTION

Mass movements, in general, and landslides, in particular, are some of the most complex slope modelling processes, and the importance of studying them has both fundamental and applied ramifications. The recognition of the role of landslides in slope modelling is unequivocal, even if in the early theories regarding the evolution and modelling of landforms, dominated by the role of fluvial erosion, the place of gravitational slope processes was largely substituted and reduced to local manifestations of (extremely) short intensity. From here to the suggestion that, alongside, for example, a coastal, fluvial or karst geomorphology, *landslide geomorphology* can express its solid individuality and find a legitimate place within the broad geomorphology (Crozier, 2010), is but a small leap. Through the first theories interpreting the evolution of the landforms (Davis, 1899; Penk, 1953; King, 1962), the landslides have been seen as “accidents”, within the long evolution of these surfaces. Later on, their role in both the removal and accumulation of more or less cohesive materials, over extended surfaces and extended periods of time (and even between large-scale triggering events), was reconsidered, showing that such processes impose themselves through imprinting their own specific patterns of slope evolution in mountainous and hilly regions (Skempton, 1953; Hutchinson, 1965;

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Selby, 1974; Carson and Kirkby, 1972; Crozier, 2010; Korup, 2010). Landslides cover a wide variety of processes and resulting landforms, which derive especially from their evolution under different morphoclimatic conditions. Their spatial-temporal distribution covers extremely wide spectrums (i.e., processes whose frequency can follow a monthly-annual pattern, but with a low magnitude; processes that can occur once every ten to hundreds of years, characterized by a higher magnitude). Under such conditions, landslides emerge as a consistent topic of geomorphological, geological, hydrogeological, hydro-meteorological or socio-economic research. There is a wide variety of stakeholders involved in landslide research (e.g., scientists, government or private end-users, financial planners, education providers, NGOs, civil society representatives), and their interest in understanding the future (potential) spatial-temporal occurrence and evolution of such processes has constantly increased. The *Sendai Framework for Disaster Risk Reduction* 2015–2030 (SFDRR) outlined that, in the past decades, there has been strong evidence of a faster exposure of assets and individuals to landslide risk in comparison with the decrease in vulnerability. Such a context was noted mainly at the level of local communities, despite the overall important advance in the landslides hazard research. In geomorphologically-active regions, such as the Vrancea seismic region, the scientifically robust evaluation of landslide hazard is of paramount importance, as the potential damages inflicted by such processes may cause consistent disturbances, not only to the directly and indirectly-exposed elements at risk, but also to medium and long-term investment strategies and adaptation planning. The mountain and hill regions of Buzău County are a national and even European landslide hotspot (Zumpano *et al.*, 2014, Micu 2017, Bălteanu *et al.*, 2020), with a high complexity of predisposing, conditioning and triggering factors for multi-hazard processes like landslides, erosion, rain- and river-induced floods and earthquakes. The effects of a large number of landslides, occurring in various forms and stages of activity, and of the recurrent flash-flood episodes are enhanced by the intensive human activity, e.g., the recent deforestations and inappropriate land management measures. The wide typological variety of landslide forms and processes, alongside their spatial and temporal patterns influence the results of hazard evaluations. Building robust predictive models of landslide susceptibility, with a high predictive performance, largely depends on the quality and relevance of existing landslide inventories. Moreover, the elaboration of hazard scenarios, based on the accurate identification of a certain (often replaced by only a more or less strongly potential) triggering factor, individualized based on an estimated threshold value with a distinct return period, also depend on the adequate classification of processes that the entire evaluation refers to. In the absence of representative and comprehensive multi-temporal landslide inventories, the hazard scenario elaboration process may be subjected to numerous uncertainties, either epistemic or aleatory (i.e., as dealing with one of the most complex natural processes, highly unlikely to be the subject of an easy, straightforward simplification through modelling). A proper understanding of the morphogenetic patterns of landslide occurrence (as either first time failures or subsequent reactivations) is therefore of critical importance, as it provides key elements for the development of reliable predictive susceptibility models and hazard evaluations.

2. STUDY AREA

The study focuses on an area increasingly known as one of Europe’s most important landslide hotspots, namely the Curvature sector of the Romanian Carpathians (South-East European Carpathians), where the Buzău Carpathians and Subcarpathians are situated (Fig. 1). This region offers a large spectrum of favourability factors for the occurrence and development of gravitational slope processes, often combined with sheet and gully erosion. The heterogeneous lithology and structure imprint different physiographic and morphometric traits, which result in different movement parameters. The climate provides propitious conditions for landslide and gully occurrence in both cold and warm seasons, both in the Carpathian and Subcarpathian sectors. According to the Koeppen-Geiger climate classification scheme, the characteristic climate types within the study area are Dfc (snow climate, fully humid with cool summers) in the mountains and Cfb (warm temperate climate with warm summers) in the hill areas.

The inner sector of the studied area is represented by the Buzău Carpathians, mountains built on Cretaceous and Palaeogene flysch deposits (alternation of more – Cretaceous - or less – Palaeogene – cohesive sandstones with conglomerates or schistose clayey and marly intercalations). They are low and medium-altitude mountains, reaching only 1771m in height (Penteleu Peak), with a topography that reflects the more cohesive and harder lithology and the intensely folded structure: steep slopes (20–50^o), deep fragmentation (400–600 m) and good forest coverage. Towards the exterior, the mountains are bordered by a quasi-parallel succession of hills and depression, which form the Buzău Subcarpathians. This hilly and depressionary region (reaching a maximum altitude in Cornet Hill – Manta Peak, 988 m) is built on Mio-Pliocene Molasse formations (marls, clays, sands, salt breccia, gravels, loose sandstones with marly-clay intercalations), and their topography reflects the loose and less cohesive lithology and the intensely folded and faulted structure. Some of the Subcarpathians' morphometric features, such as its 300–500m relative relief, 3–8 km/km^2 river network density, and 15–45^o slopes, highlight the increased potential for the occurrence of mass movements (Micu and Bălteanu, 2013).

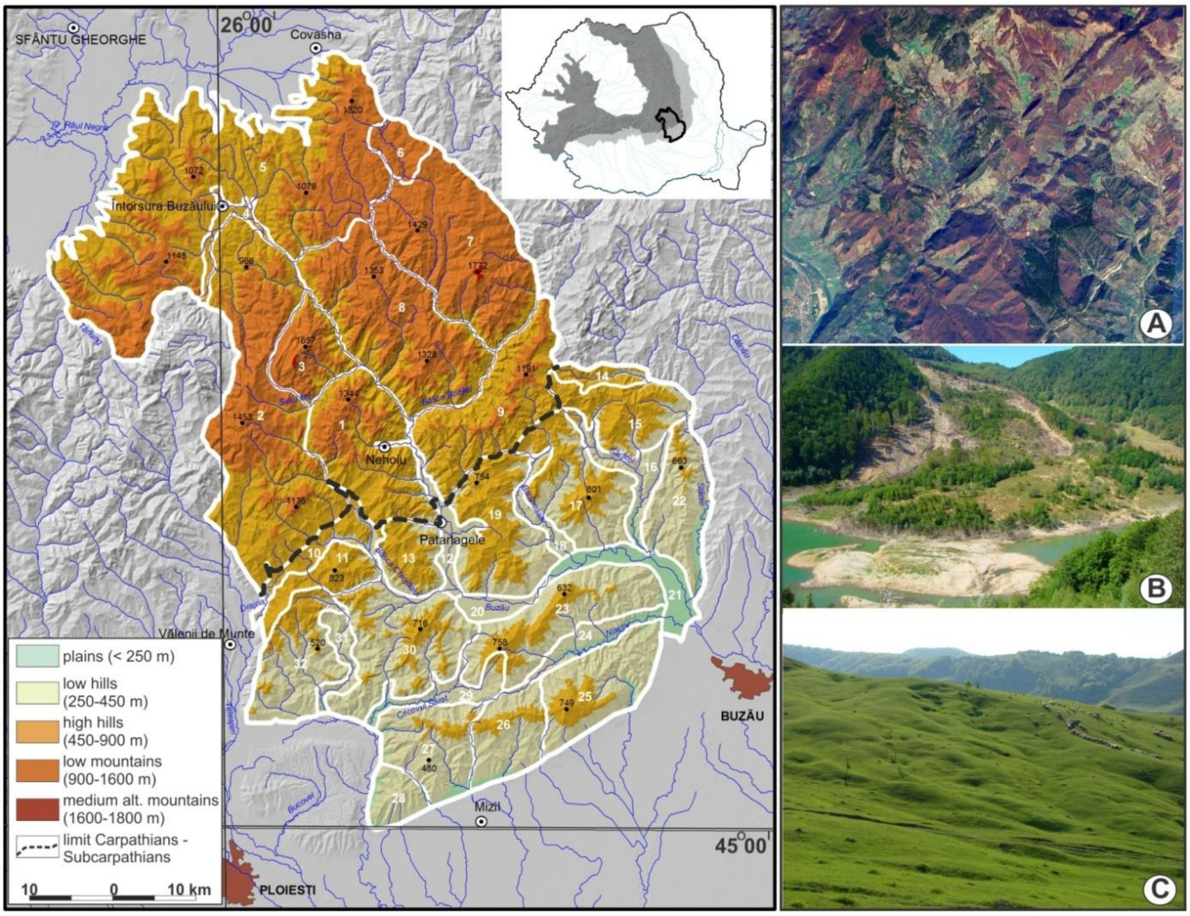

Fig. 1 – The location of the Buzău Carpathians and Subcarpathians (and their subunits: 1. Monteoru Ridge; 2. Tătaru Ridge; 3. Mălâia Ridge; 4. Întorsurii Depr.; 5. Întorsurii Mts.; 6. Comandău Depr.; 7. Penteleu Mts.; 8. Podul Calului Mts.; 9. Ivănețu Ridge; 10. Drajna-Chiojd Depr.; 11. Priporu Hills; 12. Pătârlagele Depr.; 13. Cornet Hill; 14. Lopătari Hills and Depr.; 15. Bocu Hills; 16. Sărățel Depr.; 17. Dâlma/Botanu Hills; 18. Bălăneasa Depr.; 19. Blidișel Hill; 20. Cislău Depr.; 21. Pârscov Depr.; 22. Pâcle Hills; 23. Ciolanu Hill; 24. Nișcov Depr.; 25. Istrița Hill, 26. Dealul Mare Hill; 27. Ciortea Hills; 28. Ceptura Hills; 29. Cricovul Sărat Hills; 30. Salcia Hills; 31. Podeni Depr.; 32. Lazu Hills; after Badea, 2014). Conditioned by the structural and lithological traits (reflecting in the predominant NW–SE orientation of major structures and landforms – A – the active tectonic process taking place in the Curvature sector, responsible also for the increased seismicity), the landslides follow a pattern of high magnitude and low frequency in the Carpathians (B) and low magnitude-high frequency in the Subcarpathians (C).

Against the general background of the uplift of the Curvature Carpathians and Subcarpathians, tendencies of local amplification of these neotectonic movements (anticlinal bending, local subsidence in depression areas) have been recorded, with measured values of 3–4 mm/year (Zugrăvescu *et al.*, 1998). This fact confirms the current trend of relief energy increase due to the lowering of the local erosion bases, a fact that has led to the accentuation of the degree of instability of the slopes and the individualization of an extremely wide range of mass movements, evolving from creep to landslides and flows, often combined with fluvial erosion. The seismicity of the region represents a key factor in conditioning, preparing and even triggering a wide variety of landslides. The Vrancea Seismic Region, marked by its two domains (i.e., Vrancea crustal, with focal depths not exceeding 60–70 km, and Vrancea intermediate, with focal depths clustering below 100–150 km; Radulian *et al.*, 2000), represents the most important source of seismic energy in Romania, causing effects during the high magnitude events triggered in the intermediate field regions extending to Russia, Ukraine, Bulgaria, Serbia and Greece.

The climate of the Curvature Region is temperate-continental. The Curvature sector of the Carpathians plays the role of an orographic barrier for the prevailing westerly airflows, leading to a high frequency of Föehn effects in the Subcarpathian and border plain areas. The complex interactions between the large-scale atmospheric circulation and local topography influence the distribution patterns of the heavy precipitation events (frequency and intensity), and could explain much of the dynamics and magnitude of slope modelling and hydrological processes across the entire Curvature region of Romania, recognized for its intense erosion rates all across Europe (Popa, 2016). The precipitation regime of the study-area is moderate-to-dry in the hill (Subcarpathian) sector and moderate-to-humid in the mountain (Carpathian) sector. The total precipitation in the Curvature region ranges between 600–700 mm in the Subcarpathians, and 800–900 mm in the Carpathians (Clima României, 2008). There is a great concentration of rainfalls over the April–October interval, with a share of about 75% of the total annual amount. The summer droughts are only moderately intense in this region (e.g., 1990, 2007-2008, 2012). The wettest decades over the 1970–2000 period were the 1970s (with great focus on the 1972 and 1975 years) and the 2000s (e.g., 2005, 2010). The very heavy precipitation events (>20–30 mm) span mostly over the May–August period in the Subcarpathians and over the June–August period in the Carpathians, overlapping the convective interval of the year. Although rather rare throughout the 1970–2010 period (under 5% occurrence probability), extreme rainfall episodes resulted in more than 50–60 mm/day and were recorded in both the Carpathian and Subcarpathian sectors of the study region.

The vegetation cover reflects the topographic and climatic conditions, as well as the intense human intervention. The Carpathians comprise large and compact beech (Fagus sp.) and spruce (Picea sp.) forests, generally providing the soil and regolith with a good root cohesion. Especially during more recent times, one of the most active factors involved in preparing and even triggering landslides is anthropic activity. In the Subcarpathians, the long-lasting human habitation transformed the original vegetation into a secondary one by largely replacing forests with pastures, grasslands and orchards. In this sector, anthropic activities contribute to slope instability both directly (e.g., the case of National Road 10, built along the valley of the Buzău River during the 60s–80s, which cut the slope in its middle sector, triggering numerous landslides) as well as indirectly (e.g., the management of the water level in reservoirs, which can prepare the landslide initiation as was the case of the 2006 Groapa Vântului landslide – see Micu and Bălteanu, 2013, or deforestation). Quantifying the human impact on slope equilibrium is still a challenge under the given high complexity of the socio-economic context (closely related to the political one), which render the understanding and discretizing in clear actions rather difficult. Although, at a local level, the effects of anthropogenic activity can be significant indeed, at the general (regional) level its quantification is even more difficult due to the heterogeneous pattern of manifestation of these interventions; however, the changes in land use and cover are impacting the probability of future landslide occurrence, as described by Jurchescu *et al.*, 2020.

In this general framework, landslides are associated with numerous occurrence-prone areas, conditioned mainly by structural and lithological traits. Often, the processes are complexly combined with gully erosion, one leading to the occurrence/development of the other, resulting in complex or compound forms. In the Carpathians, the large, deep-seated landslides (high magnitude, low frequency) characterized by a very rich micromorphology, are allowing gully erosion to install and eventually control, further on, through erosion-transport-accumulation processes, the landslide’s local or even entire morphodynamic behaviour. In the Subcarpathians, an area intensely affected by shallow and medium-seated landslides (of low magnitude and very high frequency), gully erosion can be recognized as induced by landslides, but also (sometimes associated with additional processes like piping) as the causes of slope gravitational processes. In addition, they may occur at the same time (the process’ morphodynamics is controlled by the physical, mechanical or chemical properties of the *in-situ* rocks, regolith or soil, the precipitation regime and the topographically-controlled flowing parameters).

3. DATA AND METHODOLOGY

The favourability of precipitation regime characteristics for the initiation of shallow landslide processes in the Curvature Region of Romania was analysed over the 1970–2010 period, using the daily precipitation data provided by two representative weather stations, in terms of geographical location, data homogeneity and length of record interval, for deriving the main features of the precipitation regime in the two sectors of the Curvature Region: Pătârlagele (Buzău Valley – Pătârlagele Depression; 45°19’N, 26°22’E, 289m a.s.l.) in the Subcarpathian sector, and Lăcăuţi (in the vicinity of Vrancea Mountains, immediately outside the study-area towards the NW; the 45°49’N, 26°23’E, 1,776m a.s.l.), for the high-elevation Carpathian sector. The daily precipitation data was provided by the National Meteorological Administration within the framework of the FP7 CHANGES project.

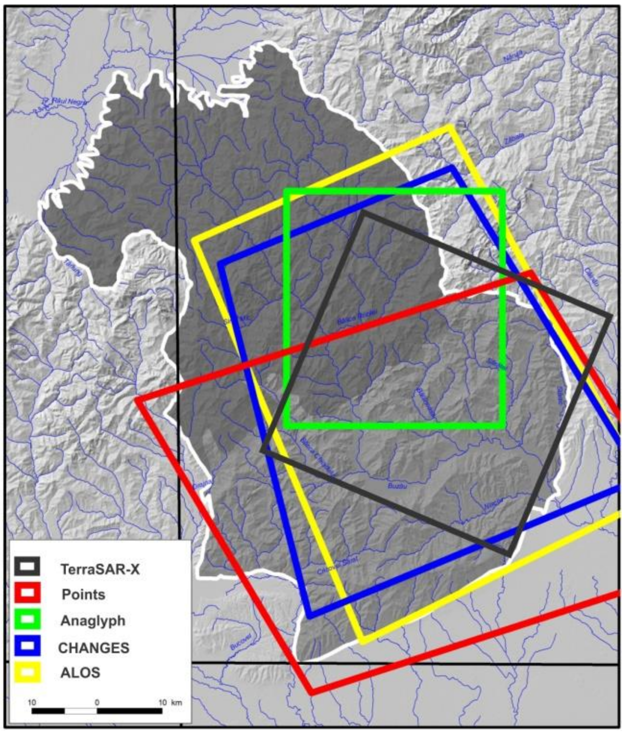

Fig. 2 – The coverage of different landslide inventories used for typological evaluations.

Several landslide inventories (Fig. 2) were used to investigate the correlation between the climatic factor and other predisposing factors (as follows): anaglyph (2014; 1028; obtained through the digital stereographic interpretation of 2005 and 2008 ANCPI aerial photos within the IncREO FP7 and CHANGES FP7 Projects; undifferentiated landslides; polygons, with scarp and body mapped as either distinct or indistinct; 1028 deep-seated landslides; Damen *et al.*, 2014); CHANGES (compiled in 2014 within CHANGES FP7 Project; 1579 undifferentiated shallow slides and flows; points; Zumpano *et al.* 2014); ALOS-PALSAR (compiled in 2014 within CHANGES FP7 Project using ALOS PALSAR 2007–2010 archive imagery and D-InSAR for automatic detection and PS-InSAR for kinematics; 515 alleged landslides, 193 confirmed; Provost *et al.* 2015)*;* TerraSAR-X (compiled in 2014 within the IncREO FP7 Project using TerraSAR-X Nov. 2013 – Jun. 2014 archive imagery; 60 alleged landslides, 12 confirmed; Riedmann *et al.*, 2014)*;* Punctual (2017; 4047 slides, 72 flows; point; Micu *in print*).

4. RESULTS AND DISCUSSIONS

The study area is characterized by an extremely wide variety of landslides, highly different from a morphogenetical, morphological and dynamic point of view (Fig. 3). The litho-structural conditions (predominantly NE–SW-oriented major structures of intensely folded and faulted inner Cretaceous and Palaeogene flysch in the Carpathian Mountains, stretching towards the exterior by the Neogene molasse deposits on which the Subcarpathian hills are modelled) reflect the intense tectonic activity associated with this typical, intra-continental plates collisional area. The (relatively) more cohesive inner flysch formations consist of alternations of thick (more or less) cohesive sandstone with schistose intercalations of marls, clays or bitumen. The molasse formations are built out of a heterogeneous mixture of clays, marls, salt breccia and sands. The relief's morphology reflects the differentiated denudation, with steep slopes, narrow valleys and continuous ridges in the mountains, and large depressions and valleys, rounded summits and slopes almost entirely covered by colluvial deposits in the hill sector. The large landslide typology mainly reflects the complexity of predisposing factors. The inner, mountainous flysch sector is characterized by the existence of large, dormant (partially relict) landslides (rock and debris slides, rock falls or complex landslides). Showing a low frequency-high magnitude pattern, these landslides present many sectors with recent reactivations, situated either at their toe or scarp. The outer, hilly molasse area features very frequent but low-magnitude landslides, in the form of earth slides and flows, rock slides, and rarely in the shape of debris flows/slides. Here, landslides form large complex areas where they associate with (either as conditioning or being induced by) erosion processes, especially in the form of sheet wash, rills and, rarely, gullies.

Slopes below 3° (6%) are particularly characteristic of floodplains, terraces and landslide/alluvial accumulation cones, as well as part of the slopes affected by weak surface erosion processes. Slopes of 3–10° (31%) are characteristic of colluvial slopes, as well as some slope sectors that can be affected mainly by shallow landslides, given a prone lithology. Slopes of 10–15° (29%) frequently coincide with the lower and middle slope sectors, which are intensely shaped by sliding and flowing processes, while slopes of 15–20° (18%) usually correspond to the upper sectors of the slopes, affected in significant proportions by both shallow and deep-seated landslides and erosion. Slopes of 20–30° (11%) have a much wider distribution in the mountain areas and are mostly forested; with the increase in inclination, the place of sliding processes is slowly taken over by erosion forms and rock falls. Surfaces with slopes of 30–40° (4%) include litho-structurally conditioned mountain slopes (mainly cuestas), shaped predominantly by frost weathering or gravity (falls), while surfaces with slopes greater than 40° (only 1% of the studied area) correspond to rock walls modelled on hard rocks or steep river banks; the predominant processes are rock falls, rock slumps and rock topples.

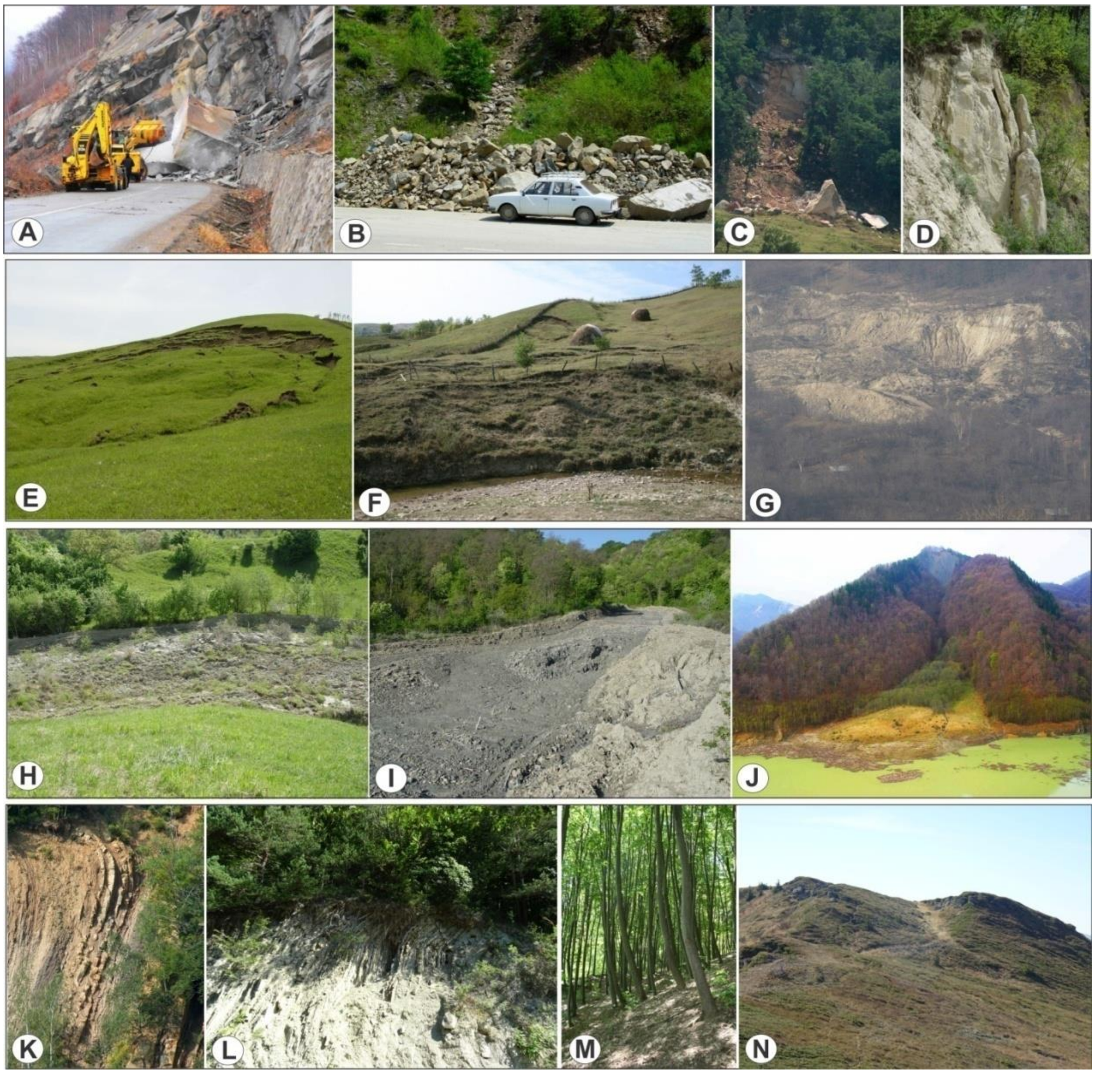

Fig. 3 – Landslide types (according to the Varnes-updated terminology proposed by Hungr *et al.*, 2013) in the study-area: A) rock falls (Podul Calului Mts); B) boulder/debris falls (Podul Calului Mts); C) rock flexural topple (Ivănețu Ridge); D) sand/silt topple (Cornet Hill); E) clay planar slide (Cornet Hill); F) clay rotational slide (Cornet Hill); G) rock rotational slide (Priporu Hills); H-I) earth flow (Cornet Hill); J) debris flow (Siriu Mts.); K-L) rock slope deformations (Ivănețu Ridge); M) soil creep (Cornet Hill); N) mountain slope deformation (Siriu Mts.).

Analysing the distribution of (mainly shallow) earth/debris slides and flows within the four inventories with regional coverage (Table 1), a series of features stands out highlighting the specificity of the processes within the two major units. If the CHANGES and ALOS inventories can be considered representative for the entire study-area, the anaglyph inventory more precisely reflects (using a representative perimeter) the image of landslides in the Carpathian area, while the point inventory does so in the Subcarpathian area. Thus, in both areas, a predominant distribution of processes in the slope inclination classes of 3–30^{o} is noted, with lower values (10–20^{o}) characterizing the Subcarpathian area, while in the Carpathians, deep-seated landslides, conditioned by the specific lithology, need even steeper slopes (30–35^{o}) to be initiated. The distribution of landslides within the inventories confirms the difficulty of RS radar images to capture landslide processes on forested slopes (especially those with northern exposure) and the higher possibility of capturing landslides on slopes with eastern and western exposure, a fact also imposed by the satellite trajectory with the NE-SW litho-structural disposition. The correlation between the landslide location with the corresponding land use/cover, was difficult to establish for the landslides occurring under (or covered by) forests. These events have been identified by employing interferometry techniques or based on the records in the official reports of local authorities. In the areas covered in pastures, hayfields or old, degraded orchards, one has noted a plausible overestimation of the number of landslides due to the easier visual interpretation of available imagery archives. The reduced presence of slides and flows records in built-up areas support the author's personal observation, namely that the traditional construction approaches (including the location) were (and still partially are) taking into account the areas prone to such slope processes, and most cases of damage to the built-up fund may be attributed to the most recent construction, many times organized with less attention to the natural conditions (pre-existing landforms and landscapes). Landslide distribution by lithological formations highlights their maximum concentration on Middle Miocene-Middle Pliocene formations (shale sandstones, clay shales, marly shales, intercalations of gypsum and salt, clays, marls; Helvetian-Dacian) in the Subcarpathians, while in the Carpathian area, the highest concentration is recorded on the lower Oligocene formations (sandstone flysch with shale intercalations – the Fusaru facies, the Kliwa facies), prone to slow-moving landslide processes; besides the long duration of the process (several days to one/two weeks), the magnitude of the latter processes makes them more easily detectable on aerial radar images. However, in the meantime, these landslides are not frequently recorded in official reports because they occur predominantly in uninhabited areas, without causing particular damage to man or personal property. The external Subcarpathian area, built on Upper Pliocene-Quaternary formations, is more prone to rapid movements, such as earth flows (frequently associated with erosion), themselves not particularly successful in remote sensing radar monitoring procedures.

Table 1

Landslide distribution (on different classes of predisposing factors) according to different inventories

Inventory	**Slope** (^{o})							**Aspect**			
	0–3	**3–10**	**10–15**	**15–20**	**20–30**	**30–40**	**40–90**	**N**	**E**	**S**	**V**
CHANGES	1	17	31	28	18	5	<1	14	12	37	36
ALOS	1	19	27	26	19	7	<1	7	13	19	61
Anagliph	1	10	23	28	32	5	<1	10	9	37	44
Punctual	1	35	45	15	4	<1	<1	13	17	33	38

Inventory	**Fragmentation depth** (m/km^2)					**Units**				
	0–50	**50–150**	**150–250**	**250–350**	**350–650**	**Plain**	**Low hills**	**High hills**	**Low mts.**	**Average mts.**
CHANGES	<1	20	18	40	21	4	44	48	4	<1
ALOS	<1	12	20	34	33	3	37	41	19	<1
Anagliph	*	*	5	17	78	*	12	69	18	*
Punctual	<1	21	66	13	<1	<1	40	60	*	*

**non-existent within the inventory extent*

Inventory	**Land use**					
	Built-up	**Forests**	**Pastures, hayfields**	**Orchards, vineyards**	**Arable**	**Bedrock**
CHANGES	6	22	38	17	17	<1
ALOS	1	31	48	12	8	<1
Anagliph	5	59	21	6	8	<1
Punctual	5	14	39	23	19	<1

Table 1 (continued)

Inventory	**Lithology 1** (age)										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
CHANGES	<1	<1	0	1	1	5	13	1	0	29	8
ALOS	0	0	0	9	2	4	23	0	0	25	8
Anagliph	*	*	<1	7	3	18	37	0	1	26	5
Punctual	*	*	*	1	<1	*	4	0	1	32	11

*1 – Lower Cretaceous; 2 – Mid Cretaceous; 3 – Upper Cretaceous; 4 – Low-medium Eocene;5 – Upper Eocene; 6 – Undifferentiated Eocene; 7 – Lower Oligocene; 8 – Upper Oligocene; 9 – Upper Oligocene – Lower Miocene; 10 – Mid Miocene; 11 – Upper Miocene; * Non existing inside the inventory extent*

Inventory	**Lithology 2** (age)									
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
CHANGES	6	14	13	5	2	0	0	0	1	1
ALOS	4	15	7	1	1	0	0	0	2	0
Anagliph	0	1	<1	*	*	*	*	*	*	*
Punctual	22	6	*	19	1	*	0	0	0	3

*12 – Lower Pliocene; 13 – Mid Pliocene; 14 – Upper Pliocene; 15 – Upper Pliocene – Lower Pleistocene; 16 – Lower Pleistocene; 17 – Mid Pleistocene; 18 – Mid-Upper Pleistocene; 19 – Upper Pleistocene; 20 – Lower Holocene; 21 – Upper Holocene; * Non existing inside the inventory extent*

In this context, the landslides in the study area completely reflect, both on a spatial and temporal scale, the geomorphological specificity of each region. To understand the landslide system in the Buzău Carpathians and Subcarpathians, a series of concepts governing its functionality must be followed: complexity, evolution, frequency/magnitude, threshold, sensitivity, morphodynamic sectors and connectivity. To exemplify these concepts, we will use a comparative image (Fig. 4), between a perimeter affected by deep-seated landslides located in the Carpathians (the Buzău Valley in the Păltineni basin sector) and another in the Subcarpathians (the Muscel small catchment in its middle third), characterized by the predominance of shallow translational slides.

Fig. 4 – The Păltineni depressionary basin (left) and Muscel catchment (right) outlining the difference in landslide magnitude between the Carpathian and Subcarpathian sectors of the study area.

The **complexity** of landslides practically represents the materialization of the interaction between the multitude of predisposing factors (lithology, structure, morphometry), preparatory factors (neotectonics, changes in land use) and triggers (precipitation, earthquakes) specific to the two major units (Carpathians and Subcarpathians). The prevalent deep-seated character of landslides in the Carpathians (controlled by a less friable lithology that also imposes a specific structure, where the alternation of cohesive and less cohesive rocks within the flysch deposits imprints the consequent or insequent typology of the landslides) is opposed to that of the Subcarpathian area, where the superficial and medium depth landslides are more spread out. Here, the lithological heterogeneity of the molasses deposits imprints a similarly-increased heterogeneity in the typology of landslides, modelled by frequent transitions from plastic to viscous displacements and back again. The same litho-structural predisposition factors also impose the combination of landslides either among themselves or with erosion processes: if in the Carpathian area, rockfalls and rock avalanches (such as those from Terca, Lopătari-Luncile, Budești, Brăești, Fișici, Scăeni, Colții de Jos etc.) are frequently associated with deep landslides; in the Subcarpathian sector, the combination of shallow earth slides with flows (frequent shifts between Atterberg limits due to the high content of clay minerals), sheet wash, rills or gullies (especially towards the outside, within the predominantly sandy and loessoid Romanian-Quaternary formations) frequently favours the development of large perimeters evolving under the combined forcing of mass movements and erosion.

The **evolution** of landslides in time and space outlines different evolutive typologies in the two sub-regions. The large magnitude of the processes in the Carpathian area allows for greater accuracy in their morphological individualization, the (largely local and very rare total) reactivation processes being usually smaller in coverage and not disturbing the morphological profile imprinted by the primary failure. On the opposite side is the Subcarpathian area, where numerous slopes show a polycyclic evolution through successive generations of new and reactivated processes (partially and even totally), which many times makes the development of (complete or representative) landslides inventorying extremely difficult and subjected to potential mapping errors of first-time failure and subsequent reactivations.

The **frequency-magnitude** relationship is defining for the individualization of two different patterns in the Carpathians and Subcarpathians. The low frequency (return periods of 20–50 years and even more; Micu *et al.*, 2013, Surdeanu *et al.*, 2009) and high magnitudes (often 2–5 million m^3; Micu and Bălteanu, 2009) of landslides in the Carpathians (also as a reflection of the lithology, in particular) correspond to a completely different pattern of landslides in the Subcarpathians; here these processes occur much more frequently, many times throughout a single year (in the spring, when the snow melts or when spring showers are overlapping, or in summer, as a result of heavy convective precipitation condensed over short intervals of time, which cause earth flow pulsations or flash-flood events, actively contributing to slope undercut). This fact comes as an apparent compensation of the comparatively lower magnitude. Establishing a trigger threshold based on certain return periods can be highlighted as an important element in calibrating (and then validating) hazard scenarios to estimate exposure and quantify vulnerability or risk. This task is highly challenging for several reasons: in the Carpathian area, the low frequency of occurrence makes it difficult to create a comprehensive multi-temporal inventory, and the complexity (in most cases) of the process implies (very often) more than one triggering factor; in the Subcarpathian area, the presence of numerous moments of partial or total reactivation of some existing landslides makes it difficult to distinguish between the first initiation and the reactivations, which would allow the quantification of primary or secondary rock physical or mechanical parameters. Nevertheless, this polycyclic evolution doesn't allow for a clear delineation between dormant or just suspended processes.

The identification of a distinct **trigger threshold** for various landslide types has had the most important contribution, along with frequency and magnitude, to the calibration of hazard scenarios and validation of hazard assessments. Thresholds can be seen as responsible for breaking the slope equilibrium (either due to external or internal agents) and inducing a more or less long time of interstadial evolution, thus leading to a nonlinear relationship between the forcing and the morphodynamics of the processes. Despite its theoretical importance, this threshold is, practically, extremely difficult to be estimated and even more so, to be validated as relevant, for the entire Curvature area. The morphometric complexity of the relief of the Curvature region, the seasonal or even diurnal air circulation pattern, as well as the lack of a dense network of observation points hardly allow the individualization of a distinct threshold. This leads either to possible erroneous conclusions (as an example, between 2001–2015, several large-scale pulsations of the Chirlești earth flow could not be quantified from this point of view due to the strictly local behaviour of the summer, convective precipitation which triggered it, so that at the nearest weather station – Pâtârlagele, 6.5 km downstream – we encountered a complete lack of recorded precipitation). The separation of antecedent factors from those of the moment is also a highly challenging process. In the case of earthquakes, determining a triggering threshold has proven an even more difficult endeavour (Micu, *in print*), since, beyond a simple correlation with seismic parameters (epicentral distance, hypocentral distance and depth, magnitude, intensity) and depending on the degree of water saturation of the soil, regolith or rock deposits, elastic movements may combine with and enhance the visco-plastic ones. Nonetheless, local side effects, either topographic (with amplifications of seismic waves in convex areas, and attenuations in concave ones) or lithologic (amplifications within loose cohesive deposits and attenuations in the case of massive, compact ones), if not properly quantified, may challenge the accurate landslide zonation procedures. Investigating the meteorological conditions during some severe floods of the 1970s in Romania, Milea (1976) showed that daily precipitation exceeding 20 mm could trigger flood events in hill and mountain areas under high soil moisture conditions, while those above 30 mm, account for the initiation of flood and erosive events under dry soil conditions. Considering the importance of soil moisture content for shallow landslides and gully formation (Casalí *et al.*, 1999; Castillo *et al.*, 2003; Poesen *et al.*, 2003), the greatest 1-day (R24h) and 3-consecutive days (R72h) amounts were regarded as a proxy indicator for the soil moisture content (Table 2).

Table 2

Main characteristics of the precipitation regime in the study-area: total precipitation amounts (Rtot); average number of wet days (Rwet) and very heavy precipitation days (R20); greatest 1-day precipitation amount (R24h); greatest 3-day precipitation (R72h)

Decades	Rtot (mm)	Rwet / R20 (days)	R24 (mm)/Date of occurrence (RT)	R72h (mm)/Date of occurrence (RT)
Curvature Subcarpathians				
1971–1980	685.1	85.0 / 7.6	177.8/July 2, 1975 (380.2 years)	203.8/July 1975 (284.1 years)
1981–1990	550.3	74.9 / 5.0	67.4/August 6, 1983 (8.6 years)	88.3/May 1988 (7.3 years)
1991–2000	635.9	78.7 / 7.1	60.0/January 21, 1998 (5.6 years)	93.4/January 1998 (9.1 years)
2000–2010	688.5	83.9 / 8.3	69.3/March 23, 2007 (9.5 years)	93.3/September 2006 (9.1 years)
Curvature Carpathians				
1971–1980	954.0	128.4 / 8.7	101.2/July 2, 1975 (44.6 years)	200.7/July 1975 (145.3 years)
1981–1990	574.9	100.8 / 3.1	50.7/June 18, 1989 (2.7 years)	103.9/June 1988 (6.1 years)
1991–2000	635.9	99.0 / 6.8	88.0/June 18, 1999 (20.9 years)	115.7/June 1994 (9.1 years)
2000–2010	715.4	47.6 / 8.3	91.5/July 12, 2005 (25.5 years)	140.8/July 2005 (21.3 years)

The recurrence period (RT) of these indicators was calculated for the two representative stations and for the 1970–2010 period, using the Generalized Extreme Value Distribution. The peak 24-h precipitation value was recorded in July 1975 (the effects of those extreme rainfall events were documented by Bălteanu, 1983), reaching 177.8 mm in the Subcarpathian sector (a return period of 380 years) and 101.2 mm (a return period of 45 years) in the Carpathian one. The frequency of heavy precipitation days (above 10 mm) and very heavy precipitation days (above 20-30 mm) in the region is very low (5.2% and 1.8%, respectively). For comparison, the probability of such events in 2005 (a historical record-year of excessive rainfall across the region and countrywide) increased to 9.3% and 4.1%, respectively. Dragotă (2006) delineated the regions exposed to intense rainfalls in Romania, based on an index defined as the average of the top five maximum rainfall intensities (I5max) over the 1961–1996 period, using the records of 130 weather stations located up to 1,500 m in altitude. The variation range of the index in Romania is between a maximum of more than 6 mm/min (e.g., parts of the Moldavian, Dobroujan, Transylvanian and Getic Plateaus, Western Hills) and a minimum of under 3 mm/min (in high Carpathian areas). Accordingly, the Curvature Subcarpathians are assigned to the regions where the I5max is 4–5 mm/min, while in the mid-elevation areas of the Curvature Carpathians it is 3–4 mm/min. The concentration of snowmelt runoff is also a significant control factor of shallow landslide initiation, particularly in terms of their spatial expansion. The average date of snowmelt is during mid-March in the Subcarpathian sector and late-May in the Carpathians. The potential for shallow landslide initiation and rill/gully formations increases significantly in the late winter to early spring interval (generally from February to April), when snow melting overlaps the fall of liquid precipitation, particularly in the Subcarpathian sector, where the minimum temperature values become exclusively positive starting March. During the snowmelt season, the share of liquid/mixed precipitation in the total annual number of precipitation days is lower than that of solid precipitation (15% compared to 20%). As described by Micu (2008) and Dragotă *et al.*, 2008, by mapping landslide occurrences in small catchments at the Carpathians-Subcarpathians limit (Cornet Hill, Muscel, Viei, Rea basins) during 2005, a year marked by extreme precipitations, several potential shallow landslides triggering thresholds were identified: greatest 1-day precipitation over 25 mm; greatest 1 to 3 consecutive days precipitation between 50 and 100 mm; at least three wet days cumulating 32 to 41 mm (such precipitation amounts could trigger floods/flash-floods in low soil moisture hill and mountain areas according to Stăncescu, 1968); 10 days antecedent precipitation prior to the landslide failure between 36 and 122 cm. For the clear delineation of triggering thresholds with regional relevance, these values should be backed up by similar studies, which are still missing. Moreover, it has been estimated that the preparing/triggering role of the climate factor in the case of deep landslides is even more difficult to evaluate, in the context of the lack of a clear, well-founded case study archive with a representative spatial-temporal coverage. Based on a limited (4) number of events, deemed representative for the study-area, in terms of thickness and size of the affected area, a first estimate was made by Micu (*in print*). In these cases, the length of the rainfall for the analysed antecedent period is considered more important to characterize the quantitative rainfall threshold leading to the occurrence of these complex processes. The frequency of heavy precipitation (*FR10*) and very heavy precipitation (*FR25*) days was decreased, such extreme precipitation days having an occurrence probability below 10% (or under 16 days) over the antecedent precipitation period considered in the analysis, with a total precipitation amount of 120–290 mm; the maximum number of wet spells (the number of episodes of consecutive precipitation days) was 7, with a maximum duration ranging from 4 to 7 days, resulting in a total precipitation value of 26–49 mm; the total precipitation during the antecedent precipitation interval ranges between 250 and 471 mm, distributed as follows: 3–21% of the total precipitation in the first 1 to 7 days of the antecedence period (short-term, before the landslide failure), 10–25% over days 8 through 30 (medium-term) and 70–80% over days 31 through 180 (long-term); the maximum daily precipitation intensity rates (mm/day) of 23–38 mm for up to one month before the landslide failure, with return periods of 21 to 66 years.

Sensitivity is the geomorphic response of the slope system that can be different for the same external forcing. The sensitivity of a slope is higher as the lag time (that is, the time difference between recording the first external impulse and the one in which the system starts to react) and the relaxation time (the time difference between the moment of the first reaction and that of reaching a specific shape) are shorter (Jain *et al.*, 2012). Both at the level of morpho-litho-structural units and the level of the slope sector, different sensitivities can be registered in the context of the same climatic or seismic forcing. In the Subcarpathians, in the case of the predominantly shallow earth slides and flows, sensitivity is higher in comparison to the Carpathians, where the morphodynamic characteristics of the predominantly large, deep-seated rock and debris slides are prolonged sometimes to weeks (as seen in the case of Groapa Vântului complex landslides; Micu and Bălteanu 2013), comprising both lag and relaxation times.

Approaching landslides from the point of view of **morphodynamic sectors** is in direct relation with evolution and frequency/magnitude. Highlighting the distinct or indistinct features of the morphodynamic sectors in the Carpathian area is made difficult by the advanced age of the processes. The detailed assessments to which those large-scale processes must be subjected (where high accuracy field geomorphological maps are supplemented with an external input derived from geophysical surveys) allow for the individualization of primary and secondary sectors, first activations and various episodic or quasi-continuous reactivations, which enable the outlining of a morphogenetic framework where elements such as agents, processes and resulting forms can be understood and quantified. In the Subcarpathian area, the polycyclic evolution of many slopes that follow a redundant pattern of first activation-partial reactivation-total reactivation often makes it difficult to correctly establish, especially within multi-temporal inventories, the depletion and accumulation sectors. The strongest impact of this uncertainty is reflected in the different distribution of susceptibility or hazard classes within a regional study, based on (possible) multi-temporal inventories.

Connectivity is a concept whose quantification has only started to become possible a short time ago and which has experienced sustained growth over the past 5–10 years. Be it functional (through stream-level interactions) or structural (physical connections), it enables an improved understanding of the nonlinear response of the slope-channel coupled with external forcings and allows the quantification of the indirect impact (Jain *et al.*, 2012). The most visible manifestation of this interaction is in the form of landslide dams, and in the Buzău Carpathian and Subcarpathian region, numerous cases of such dams are recorded in literature along the streams of Caşoca, Siriu, Bălăneasa, Bâsca Rozilei (for detailed descriptions see Ielenicz, 1984, Bălteanu, 1983, Cioacă, 1996, Micu and Bălteanu, 2013). These dams usually have a short lifetime, of around weeks or months (in agreement with the result of the synthesis of Costa and Schuster from 1988, which states that 85% of slide dams are destroyed by erosion in their first year of being operative). A useful benchmark for estimating the geomorphic response of connectivity in the study area is provided by Korup's (2005) classification (based on a consistent inventory of such events in the New Zealand Southwestern Alps) of geomorphological impact types and impact surface features.

Thus, according to the category of the slope-channel coupling interface, one may note in the area of the Buzău Carpathians and Subcarpathians the following types (Fig. 5): *area* (when very large volumes of landslide material produce major reorientations of the hydrographic network; less comparable than other mountainous regions of the world, especially due to the relatively low relief energy and slope inclinations, it can be found on a smaller magnitude scale in the case of the deep-seated landslides that have diverted the course of the Bâsca Rozilei river downstream from the village of Varlaam and up to the confluence with the Buzău); *linear* (when more than 50% of the length of the contact follows the direction of the river; the cases are numerous and most of the tributaries of the 1st and 2nd order of the Buzău river in its Subcarpathian sector present such couplings); *point* (below 50% contact; the distribution is similar to the previous case); *indirect* (produces the separation of rivers or reservoirs; such a case may be that of the Groapa Vântului landslide, which interrupted water flow inside the Siriu reservoir for one month) or *nil* (when there is no contact between the landslide deposits – left suspended on the slope for structural, petrographic or varied reasons – and the drainage lines; this situation is widespread throughout the upper catchments of the 1st and 2nd degree tributaries of the Buzău river). The classification of the geomorphological impact is in agreement with the previously mentioned study: *buffered* (when landslides do not make direct physical contact with the drainage system); *riparian* (direct contact of the landslide deposit with the hydrographic network, lateral erosion being dominant and controlling the triggering of landslides and the further drainage of landslide deposits reaching the river banks); *occlusion* (the diversion of the river course by the landslide deposit); *blockage* (appearance of landslide dams); *obliteration* (covering kilometres' worth of sectors, of the alluvial plain with complex deposits).

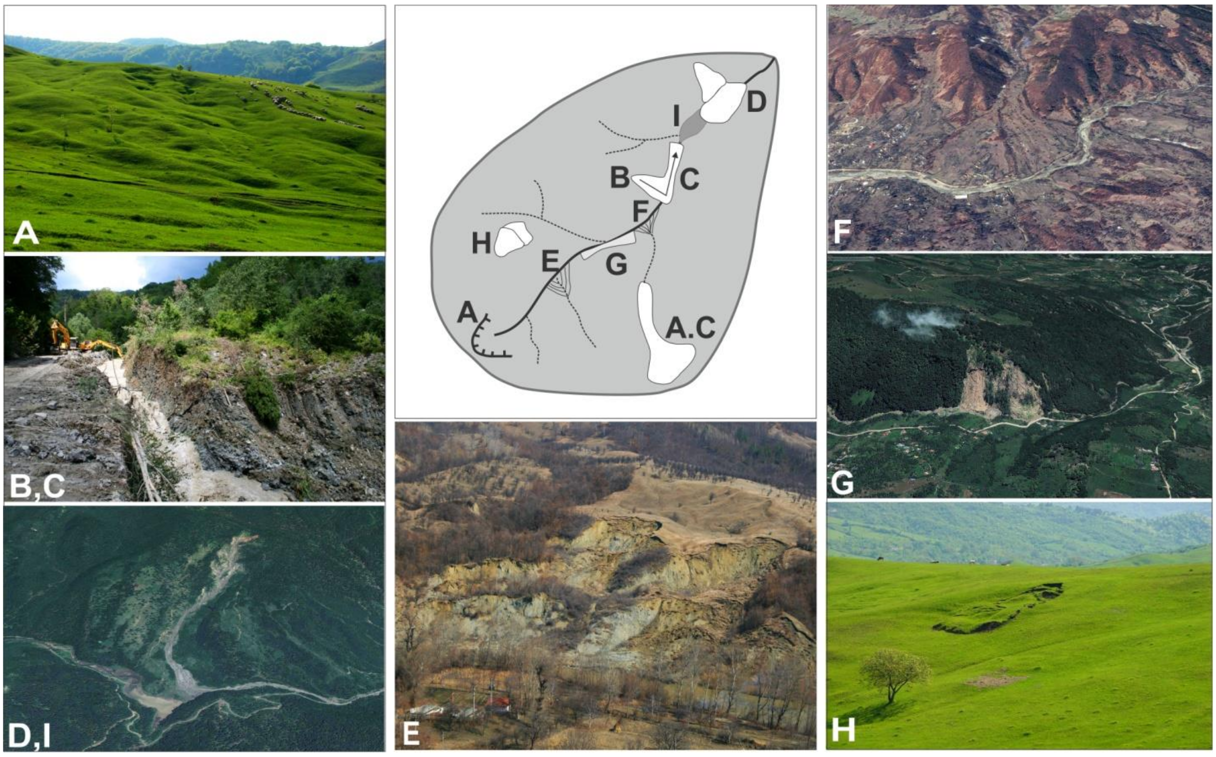

Fig. 5 – A schematic representation of impact types caused by landslides at the slope-channel interface: **A**) shallow earth slides initiation (and headward evolution) in the uppermost catchments (Viei basin, Cornet Hill); **B**, **C**) lateral input from landslide accumulation deposit and sediment loading/material transfer to the river (Viforâta landslide, Penteleu Mts.); **D**, **I**) full river blockage and landslide (permanent or temporary) dam formation (Răoaza debris flow, Vrancea Subcarpathians, immediate vicinity of the study-area); **E**) temporary deposition of the landslide accumulation fan (Păltineni debris flow, Ivănețu Ridge); **F**) long-lasting supply of fine sediments resulting from landslide accumulation fan river undercut (Terca, Ivănețu Ridge); **G**) landslide accumulation blockage by the morphometric buffer of terrace/ floodplain formations (Terca, Ivănețu Ridge); **H**) landslides retained on slopes, with a null/very low contribution to river sedimentation (Muscel catchment, Cornet Hill) (adapted after Korup, 2005).

5. CONCLUSIONS

Landslide susceptibility modelling and hazard evaluations are key geomorphic services meant to build proactive risk mitigation measures. A sound scientifically-based evaluation of the hazard and its level, hazard zonation processes, the assessment of elements at risk, their exposure and vulnerability could contribute to an enhanced preparedness and prevention which could further ensure the proper implementation of effective risk management strategies. All these strategic goals rely on the improved understanding of landslide typology, their past and present-day behaviour, as well as their future likelihood of occurrence. In regions showing such a high susceptibility to various landslide types across small areas, the development of more robust and highly predictive susceptibility models and hazard evaluations should be the subject of a comprehensive sensitivity analysis relying on a reliable landslide typological understanding, which may improve the susceptibility model quality in terms of reliability, the model's robustness to changes in the input data, the error associated with the probabilistic estimates, the goodness of fit and overall predictive performance. The study-area outlines the necessity of using representative inventories for each spatial unit, adapted to the site-specific conditioning and triggering factors. While, a susceptibility analysis at the regional level may prove successful for shallow landslides (earth slides and flows), for deep-seated landslides (debris and rock slides) such an approach may prove difficult because of the morphogenetic complexity of such processes, answering more to local preconditioning features (structure, lithology) and to more complex triggering contexts (frequently associated with superposed factors and longer lag and relaxation times). However, due to their large magnitude (expressed in large surfaces and volumes), deep-seated landslides may represent key issues in modelling landslide susceptibility to shallow processes when their (partial or even total) reactivation potential is fully understood and quantified. In such active areas (in agreement with other reviews or synthesis works; see Reichenbach *et al.*, 2018), a geomorphic-based sensitivity analysis for susceptibility and hazard assessment should address the following: a) the reason (or constraints) why a certain/particular method was chosen with respect to another; b) the type and the choice of variables (how representative they are for each region and for the respective landslides typology, what the reason was when being chosen, which combinations gave the best results and in the opposite case, whether there were any other choices of variables or any other more or less suitable reclassifications); c) variables classification (continuous versus categorical); d) the modelling technique; e) landslide points versus landslide polygons and the procedure of transforming polygons into points (how many points were/should be used for each landslide entirely or for each scarp); f) the number of run models; g) the robustness of the model and the predictive capacity of different results (success and prediction rate curves, ROC, confusion matrix etc.); h) assessing the level of agreement among susceptibility first-to-last classes and the evaluation of middle values in order to know in which classes they would be included; i) final classification (which classifying method – automated or manual – proved to give the best results and for what reason).

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