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Impact of mass movements on geo- and biodiversity in the Polish Outer (Flysch) Carpathians

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ABSTRACT

Complex research was simultaneously done on the geological, geomorphological, and biocenotic features of landslide areas in the Polish Outer (Flysch) Carpathians. The research allowed us to define the relations between the diversity of the landslide-originating landforms and the biotopes occurring within them. High geodiversity (diversity of landforms, soil, and water) of landslide areas allows for a mosaic network of extremely diversified natural habitats. All of these natural habitats together, are characterized by a specific biodiversity. Dependence between geo- and biodiversity in landslide areas is connected with a specific co-evolution which is related to the adaptation of the ecosystems to landforms. Comprehensive research of this relation to landslide areas would promote the necessity to protect the landslide areas. Unfortunately, such research done in the Carpathians is still sporadic. The comprehensively documented landslide areas are especially valuable elements of the nature protection network within the Carpathian Euro-region. If made reasonably accessible, they may be used for didactic purposes and in geotourism.

1. Introduction

In the Polish Flysch (Outer) Carpathians, mass movements are common phenomena. They have played an essential role in the natural environment. They have also caused great economic damage. Therefore, those processes, generated by natural factors or stimulated by human activity, are considered to be disadvantageous for human economic activities (e.g. Ziętara, 1968; Bober, 1984; Mrozek et al., 2000; Bajgier-Kowalska and Ziętara, 2002; Poprawa and Rączkowski, 2003). Landslides have a varied morphology and a mosaic arrangement of natural habitats occurring within them. These habitats are adapted to the diversified landforms. Such an arrangement of habitats imparts a character to the landscape of these areas that differs from the surrounding landscape. These differences are true both on the local and the regional scale. The landslide areas are characterized by a specific geo- and biodiversity. Research about the diversity in this context has hardly ever been done. If some investigations are launched, then they refer, in general, to some selected aspects of transforming the natural environment (Cendrero and Dramis, 1996; Borgatti and Soldati, 2005; Geertsema and Pojar, 2007; Corenblit et al., 2008; Hradecký et al., 2008).

Research into landslide areas in the Carpathians allowed us to determine the complex impact of mass movements on the mountainous environment. Determination of the relationship between geodiversity (landforms, soil, and water) and biodiversity (mosaic of plant and animal associations) was particularly important on the landslide areas (Alexandrowicz and Margielewski, 1995, 2000; Alexandrowicz et al., 2003). Distinctive landslide forms in the Carpathians are a common occurrence. The biocenoses appearing within the landslides, however, are rarely considered (by foresters, biologists, etc.) to be associated with, and conditioned by, individual and diversified landforms occurring within the landslides.

2. Study area

2.1. Geological and geomorphological settings

The Polish Carpathians are divided into the Inner Carpathians (Central Carpathians) and the Outer Carpathians (Flysch Carpathians) (Fig. 1). The Outer (Flysch) Carpathians are built of very thick flysch deposits of the Upper Jurassic–Lower Miocene age. The Outer (Flysch) Carpathians are made up of deep-sea sediments consisting of alternating layers of sandstones, conglomerates, mudstones, claystones, and partly marls. The rock formations strongly folded and dislocated, form the great facies-tectonic units thrust from south to north, one over the other. These units are distinguished as nappes: Magura, Fore-Magura or Dukla, Silesian, Sub-Silesian and Skole. The Carpathian Foredeep filled with Miocene sediments has developed at the front of them (Fig. 1; Żytko et al., 1989). Densely jointed and porous sandstones usually underlain (or overlain) by shales are rich water collectors which influence hydrological conditions of the region. On the bedrock of flysch formations, mainly acid, loamy brown soils developed. These soil types are cambisols, as well as some

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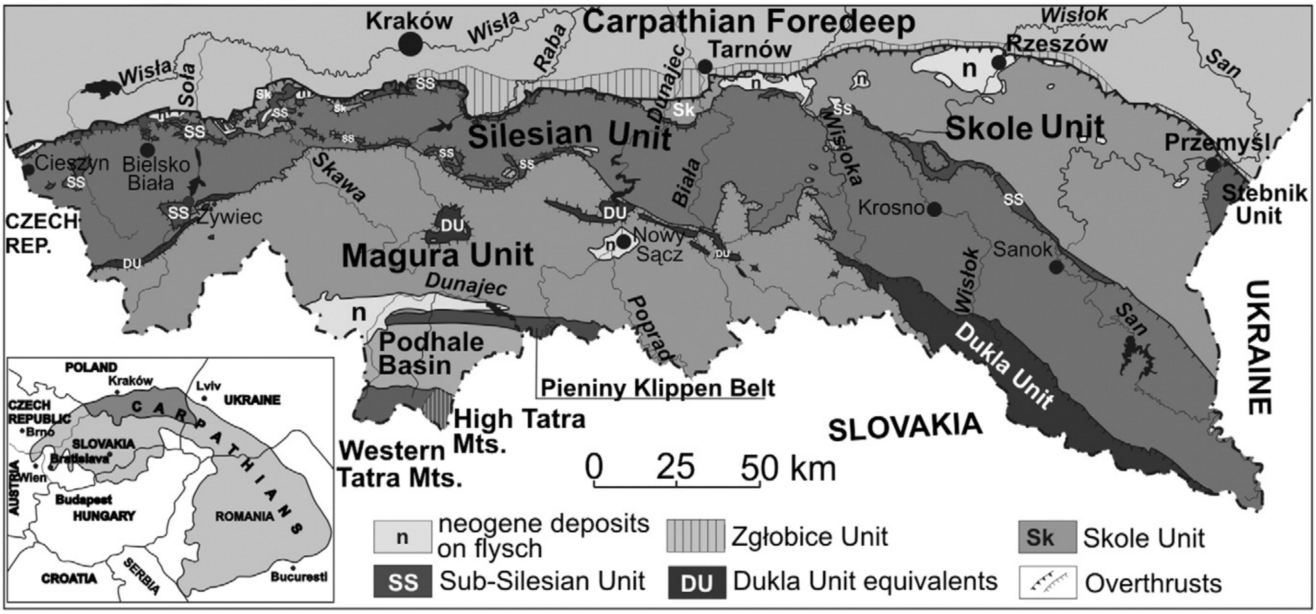


Fig. 1. Geological map of Polish Outer Carpathians (after Żytko et al., 1989).

lithosols and regosols (Warszyńska, 1995). Wide river valleys and intermountain basins are covered with fluvisols.

The relief of the Polish Outer Carpathians explicitly reflects differences in the resistance and tectonic structures of the rocks (Starkel, 1969). The following types of relief can be distinguished: from the north to the south of the Outer Carpathians—the foothill relief (altitudes do not exceed 600 m a.s.l.), the bottom valley and mountain depression relief, the low mountain relief (600–800 m a.s.l.), the middle-high mountain relief with steep slopes (800–1300 m a.s.l.) and the alpine relief in the highest massifs which attain 1725 m a.s.l.

In the Polish Outer Carpathians, lithologically diversified flysch rocks strongly jointed and faulted, create advantageous conditions for mass movements to develop. Besides, human activity plays a part in the hydrogeological condition of the region (dam lakes, river regulation, etc.). Human activity is also responsible for accelerating mass movements by stimulating the instability of the slopes with buildings, roads etc.

2.2. Climate and vegetation

The Carpathian climate is diversified. The western part is somewhat under the influence of more oceanic air masses. The eastern part is more often affected by continental air masses. The mean annual precipitation amounts to ca. 700 mm for the Carpathian foothills, to 1000–1300 mm in the higher parts of the mountain (Warszyńska, 1995).

Predominating plant communities in the Polish Carpathians are arranged in vertical belts, thus, they refer to the altitude variation in the mountains (Warszyńska, 1995). The following belts of vegetation occur in the Flysch Carpathians:

–Foothill belt (up to 600 m a.s.l.), with multispecies deciduous forest of *Querco-Fagetea* class as dominating plant community, oak-hornbeam forests (*Tilio-Carpinetum*), and riparian forests (*Alnetum incanae, Caltho-Alnetum, Carici remotae-Fraxinetum, Ficario-Ulmetum, Fraxino-Alnetum*) in the river valleys;
–Lower mountain forest belt (up to 1150 m a.s.l.), represented by a Carpathian *Dentario glandulosae-Fagetum* beech forest of the *Querco-Fagetea* class, a fir and spruce coniferous forest (*Abieti-Piceetum*) as well as a mixed spruce and fir coniferous forest (*Galio-Piceetum*);
–Upper mountain forest belt (up to 1400 m a.s.l.) with acidophyllic spruce forest – *Plagiothecio-Piceetum*;
–Dwarf pine zone, above the timberline (up to 1650 m a.s.l.), only in Mt. Babia Góra and Mt. Pilsko massifs situated in the western part of the Carpathians; and
–Alpine meadow zone, only in Mt. Babia Góra (1725 m a.s.l.).

A characteristic mark of the Polish Carpathian fauna is the occurrence of numerous alpine and boreal–alpine species. The vertebrates are represented by the majority of species which are also found living in all the other mountain regions of Europe (Warszyńska, 1995). Among the invertebrates, endemic species reside abundantly. The zoocenoses are arranged in zones roughly corresponding with plant and climatic mountain belts.

3. Materials and methods

To characterize mass movement landforms and relief elements related to them, a nomenclature according to the International Geotechnical Societes' UNESCO Working Party on World Landslide Inventory (WP/WLI, 1990, 1993; Dikau et al., 1996) was applied. The nomenclature was supplemented with regional classifications, which include specific determinants conditioning the development of landslides in the flysch massifs of the Carpathians (Starkel, 1960; Ziętara, 1969, 1988; Bober, 1984; Kotarba, 1986; Wójcik, 1997; Zabuski et al., 1999; Margielewski, 2006a).

Descriptions of the typical features of the biodiversity of the landslide areas are based partly on the authors' own studies, and partly on numerous papers related to this study. Phyto-sociological maps were the main material analysed. Profiles and registers of flora and fauna species were also analysed (e.g. Lisowski and Kornaś, 1966; Staszkiewicz, 1972, 2000; Alexandrowicz and Denisiuk, 1991; Głowaciński, 1991, 2001; Denisiuk, 1993; Warszyńska, 1995). The compiled and analysed materials depicting the current state of nature and landscape in the landslide areas created a significant basis for determining a characteristic correlation between the patterns of geodiversity and biodiversity habitats of the studied sites. The authors have already once attempted to accomplish such a comprehensive analysis using the example of the habitat types of the Polish Network

NATURA 2000 and the endangered plant species in the Carpathian landslide areas (Alexandrowicz et al., 2003).

4. Patterns of geodiversity of landslide areas

Many authors define the term "geodiversity" in a similar way (Eberhard, 1997; Gray, 2004; Kozłowski et al., 2004, Dingwall et al., 2005). From a general perspective, it can be said that geodiversity is the natural diversity of geological (rocks, minerals, and fossils), geomorphological (landforms and processes) and soil features including their assemblages, relationships, properties, interpretations and systems.

The mass movements generate a total transformation of the natural environment in the area of their occurrence. On slope surfaces damaged and transformed by mass movements, diversified morphology is formed with concave and convex landforms, often with bedrock expositions. Moreover, a new system of water circulation and specific pedogenetical conditions are formed. As the effect of gravitational transformations of the substratum, a mosaic of diversified, natural small-sized habitats develop.

4.1. Relief of landslide areas

The relief of landslide areas transformed by mass movements is generally more diversified compared to the surroundings of the landslide, and, thus, well identifiable. The diversity scale of individual landslides depends first and foremost, on the depth of sliding plane and the dynamics of gravitational transformation of rock masses and on the geological and geomorphological conditions of mountain areas (see Fig. 2; Alexandrowicz and Margielewski, 1995, 2000; Geertsema and Pojar, 2007). A considerable impact on the type of behaviour and distinctiveness of landforms is also caused by the age of landslide formation or their rejuvenation, and, sometimes, economic utilization of its surface.

Within the landslides, the following types of landforms usually occur: scarps (main and minor scarps), rock trenches, landslide body, colluvial tongues/ramparts, block fields and debris (Fig. 2). Within the landslide depressions, there are also water basins.

4.1.1. Scarps

The steep main (head) scarp situated in the highest part of a landslide and minor scarps is characteristic landforms of landslide zones (Figs. 3 and 4). Rock walls up to 50 m high often form a frame of the head scarp (Fig. 3). The way rock walls run depends on the predominating directions of joints. Wall shape can be rectilinear (according to the direction of one joint set; Fig. 3A,B), wavy (along unloading joints; Figs. 3C and 4A), wedge-like (following two crossing joint sets), or pile-like (found only in thin-bedded flysch; Fig. 4C; Alexandrowicz, 1978b; Margielewski, 2006a). Rock walls which are exposed due to the gravitational process are shaped by erosion and weathering in the course of time (Figs. 3D and 4A).

High rock walls framing the scarps of landslides constitute natural, geological exposures that are often difficult to access (Fig. 4A–D; Alexandrowicz, 1978b; Margielewski, 2006a). In such rock walls, the sequences of lithologically various rocks (deposits) and sedimentary structures characteristic for the Carpathian flysch are outcropped (Fig. 4A,B). These exposures are also instructive for identifying tectonic elements of rock massifs including joint systems, the faults and tectonic mirrors and tectoglyphs connected with them (Margielewski, 2006a). In the process of long-lasting selective weathering, the diversity of lithological or sedimentary features of rocks exposed within the landslide scarps is emphasized. Affected by the weathering factors, the rock walls that were previously formed as even, joint planes are remodeled and covered with weathering-generated microrelief (Fig. 4A,D; Alexandrowicz, 1978b).

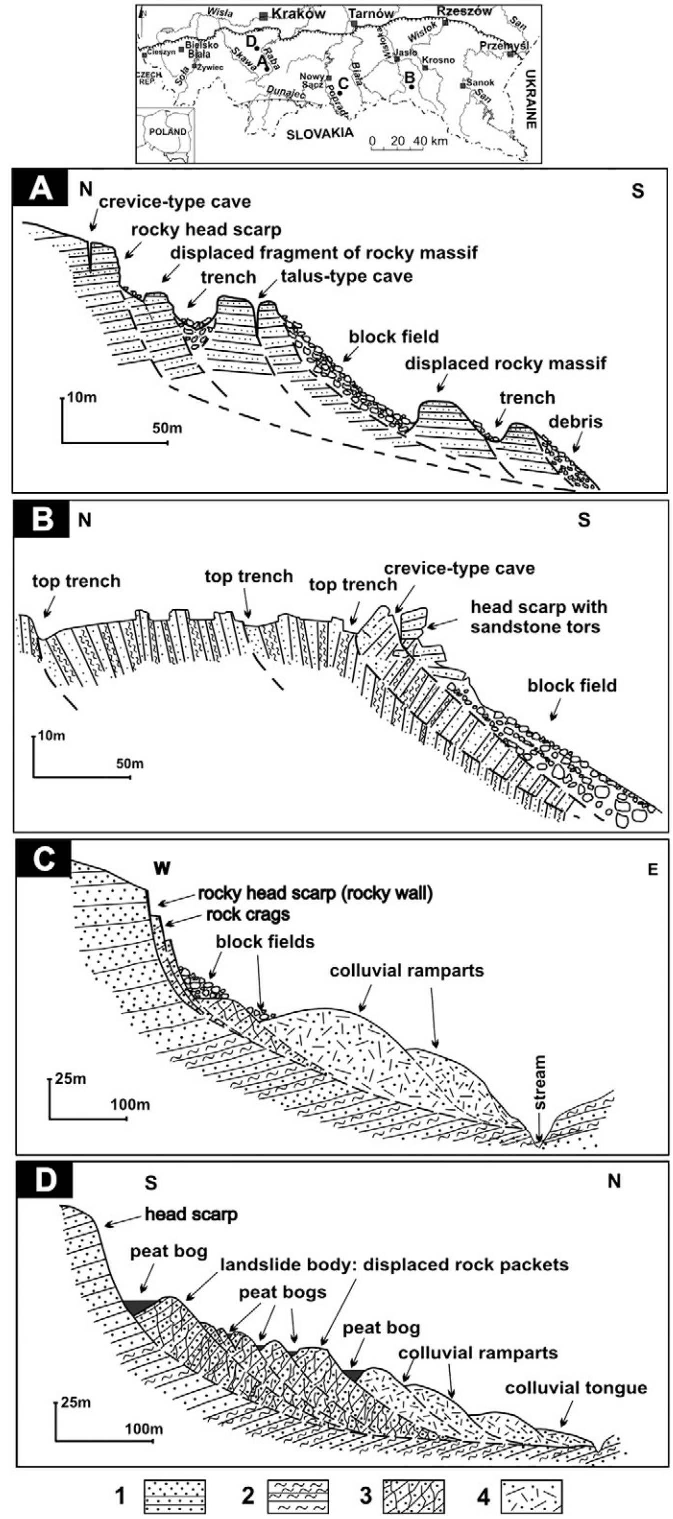


Fig. 2. Examples of various types of Carpathian landslide relief, with distribution of landforms presented in cross-sections: A – landslide with the rocky head scarp and landslide body with trenches and debris (Luboń Wielki Nature Reserve, Beskid Wyspowy Mts.; after Alexandrowicz and Alexandrowicz, 1988); B – landslide with top trenches, rock crags and block fields (Kornuty Nature Reserve, Beskid Niski Mts.; after Alexandrowicz and Alexandrowicz, 1988); C – landslide with rocky head scarp and colluvial ramparts (Barnowiec Nature Reserve, Beskid Sądecki Mts.; after Margielewski, 1998); and D – landslide with steep soil head scarp, landslide body and colluvial tongue with peat bogs (Klaklowo Landslide, Beskid Średni Mts.; after Margielewski, 2001). Legend symbols: 1 – sandstones, 2 – shales, 3 – landslide body, and 4 – mixed colluvial material.

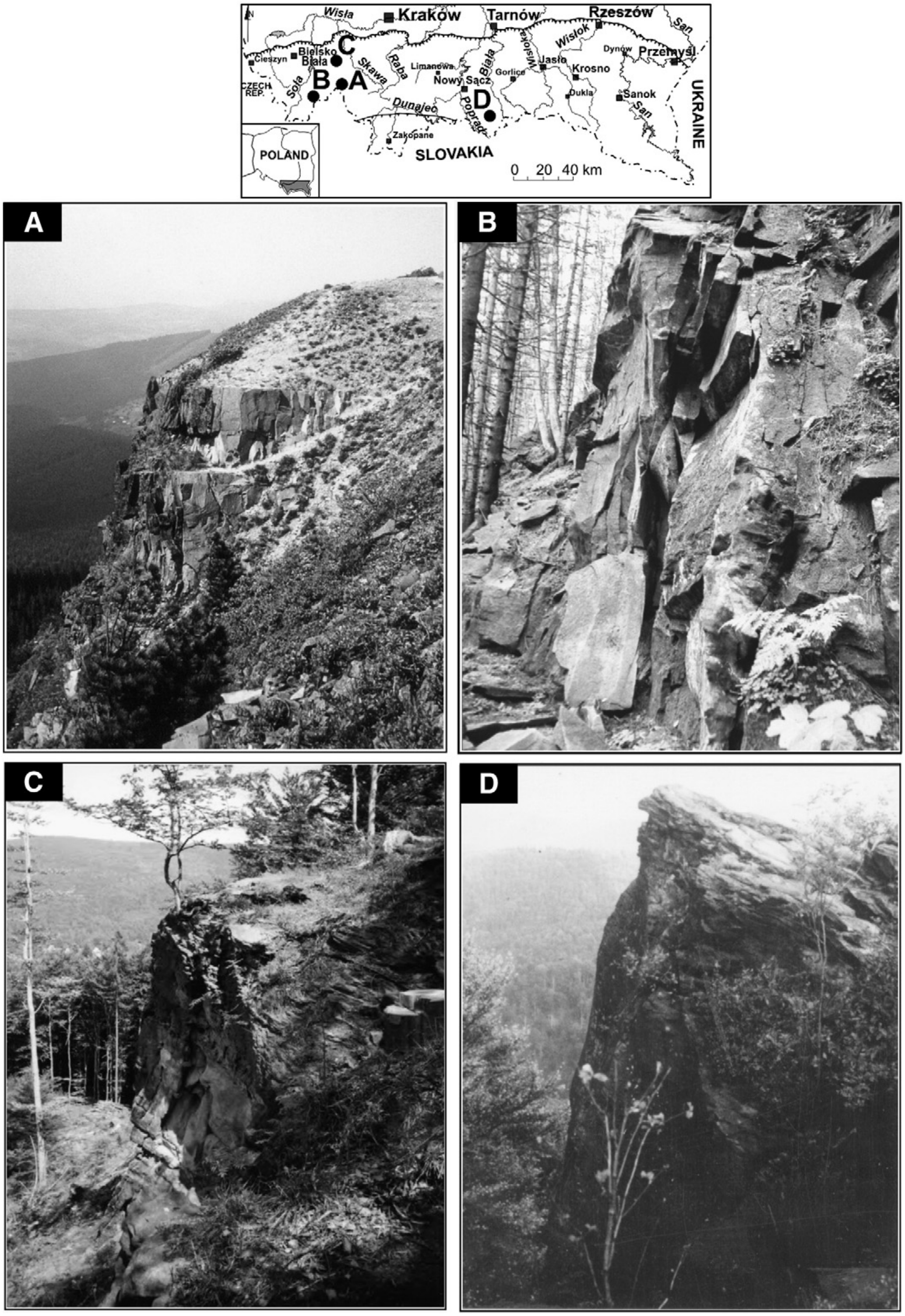


Fig. 3. Head scarps of large landslides, as landscape elements: A – on Mt. Sokolica (Babia Góra Massif); B – over the Cebulowy Potok valley head, Pilsko Massif; C – Zakocierz Crag (Beskid Mały Mts.) (Photo Z. Alexandrowicz); and D – Diabelskie Ściany (Beskid Sądecki Mts.) (Photo W. Margielewski).

Mass movements, acting from two sides of narrow mountain ridges, can produce spur rock forms bordered by joint planes. Mass movements can also contribute to the intensification of other denudation processes (including, among others, weathering) responsible for shaping freestanding rock formations such as: pinnacles, table-, and mushroom-rocks (Fig. 5A,B). Sometimes rock arches form owing to the collapse of the lower part of a rock massif and subsequent gravitational displacement of crushed material. Rock arches, however, appear only as exceptions in the areas affected by mass movements (Fig. 5C).

4.1.2. Rock trenches

Relaxation of rock masses caused by mass movements leads to the formation of extension cracks above the edges of the head and the

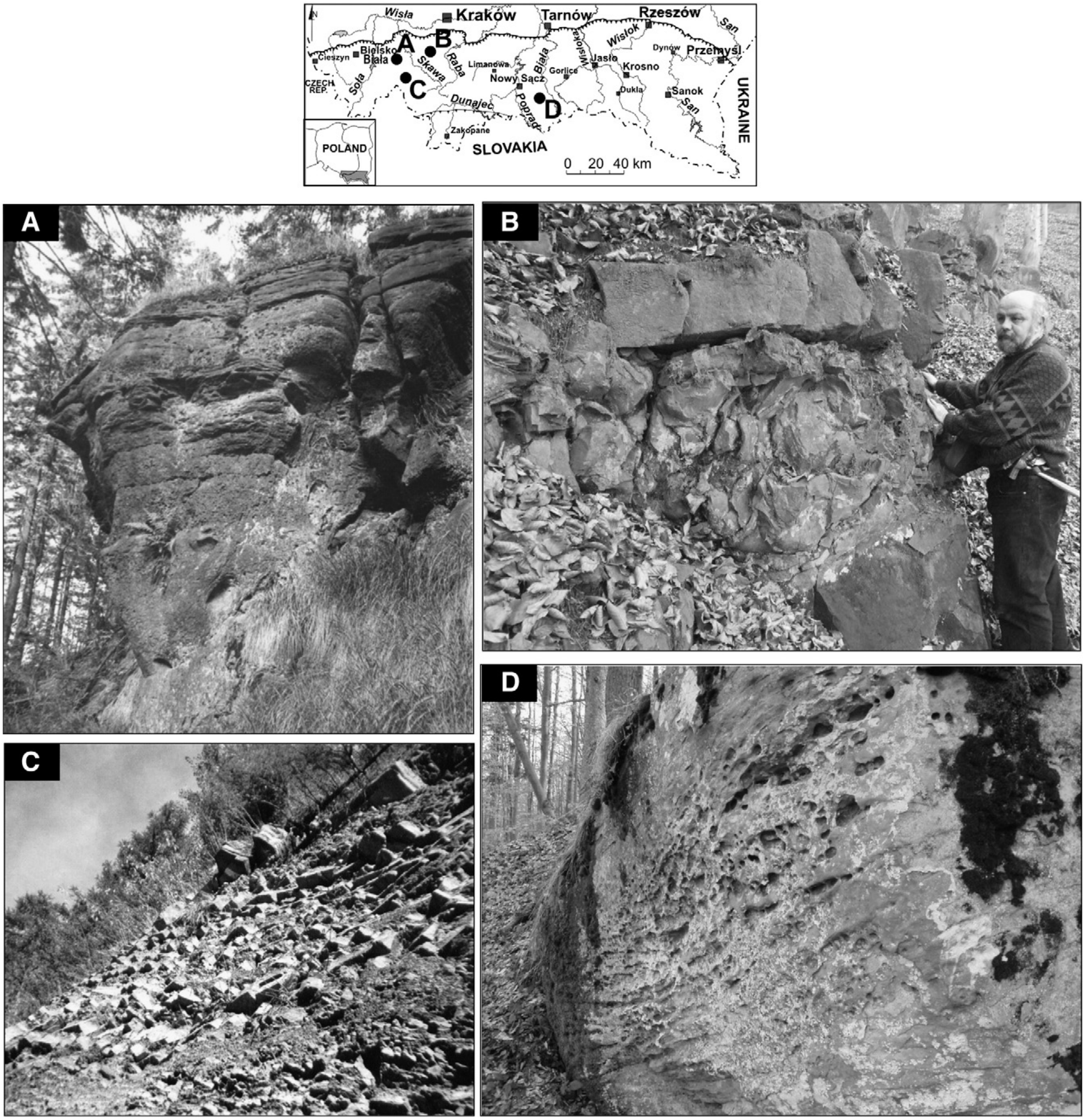


Fig. 4. Sedimentary, tectonic and weathering structures outcropped on landslide head scarps: A – head scarp on Mt. Madohora (Beskid Mały Mts.) – fluxoturbidites within thick bedded sandstones (Photo Z. Alexandrowicz); B – submarine landslide deposits on Mt. Parszywka (Beskid Średni Mts.); C – typical flysch: thin and thick bedded sandstones with shales, cut by crossing joint sets - hieroglyphic beds, Zawoja Wilczna (Babia Góra massif); and D – weathering structures: tafone covering rock wall in the Barnowiec landslide (Beskid Sądecki Mts.). Photos by W. Margielewski.

secondary scarps of landslide (Figs. 2A-B and 6A). The widely opened cracks, form trenches or even deep gorges with vertical walls parallel to the joint sets (Fig. 6A; Alexandrowicz, 1978a; Alexandrowicz and Alexandrowicz, 1988; Margielewski, 2006a). Such cracks can also develop within (and along) the mountain ridges, as ridge-top trenches (Fig. 2A,B). Double ridges are then formed.

Cracks occurring above the landslide scarps are often covered with a rock head. Such a formation can shape caves of the crevice type (Fig. 6B; Vitek, 1983; Margielewski and Urban, 2003). The formation of such cracks (caves) also precedes the development of landslides. Therefore, these cracks (caves) represent the initial stage of slope destruction indicating a predisposition toward mass movements (Margielewski and Urban, 2003). Crevice type caves can be formed also along the sliding surface during the landslide formation as a result of a phenomenon called fissure macrodilatancy (Fig. 6C) (Margielewski et al., 2007). Speleothems (including stalactites) and underground streams and pools (small lakes) (Fig. 6C) are unique phenomena in these caves (Margielewski and Urban, 2005; Margielewski et al., 2007; Urban et al., 2007).

4.1.3. Landslide body and colluvium

The gravitationally dislocated rock material represents characteristic morphological formations (landforms). In the upper parts of landslide, it is the main landslide body, defined as the part of the

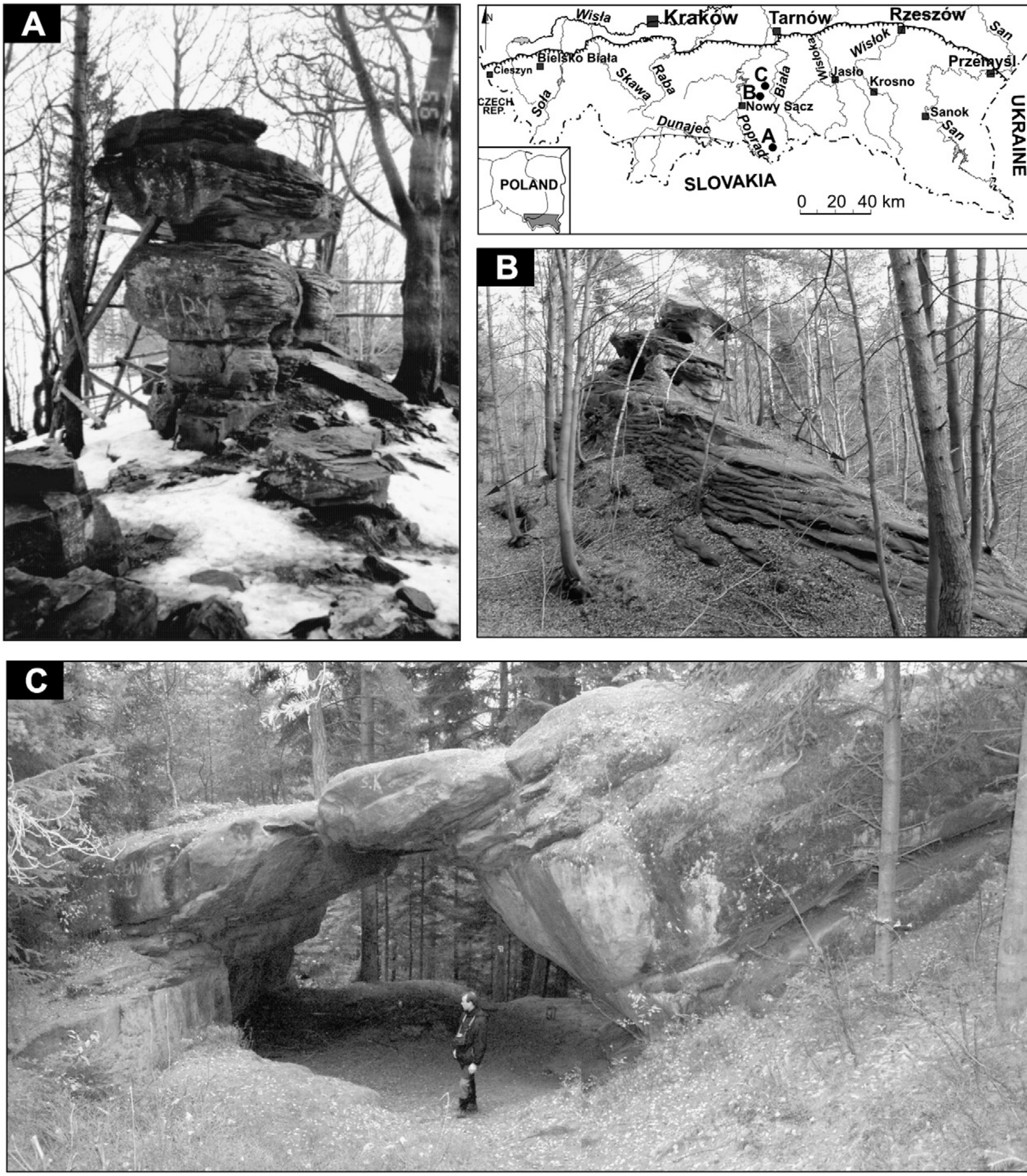


Fig. 5. Rock crags formed by mass movements: A – mushroom, Devil's Rock on Mt. Jaworzyna Krynicka (Beskid Sądecki Mts.); B – rock form in "Diable Skały na Bukowcu" Nature Reserve; and C – Diable Boisko Arch, Pleśna, Ciężkowice Foothill. Photos by W. Margielewski.

displaced material of the landslide that overlies the surface of the rupture (Dikau et al., 1996). In the lower parts of landslide, there are usually landslide tongues formed of mixed colluvial material (Fig. 2C,D).

Large rock blocks and rock packages, composing the landslide body, are separated by rock debris or cracks and voids. These latter form trenches or caves of the talus type (Fig. 2A; Vitek, 1983). Individual fragments of the displaced rocky massifs are usually chaotically arranged, owing to their considerable fragmentation and gravitational displacements. They also lean differently and form characteristic sets of rock forms. These extraordinary configurations resemble "rock cities". Sometimes, parts of rock packages of a landslide's main body are strongly disintegrated. They form unique block or debris fields that become displaced across a slope (Figs. 2A and 7A). Those block and debris fields are also formed at the foot of rocky walls of landslides as a result of rockfalls occurring within the head or minor scarps.

In the lower parts of a landslide, there are colluvial ramparts and colluvial tongues. These forms are generally characterized by diversified morphology depending on the nature of displacements, the thickness of colluvial material accumulated, as well as its fragmentation and permeability (Figs. 2C and 7B). Colluvial ramparts can form numerous

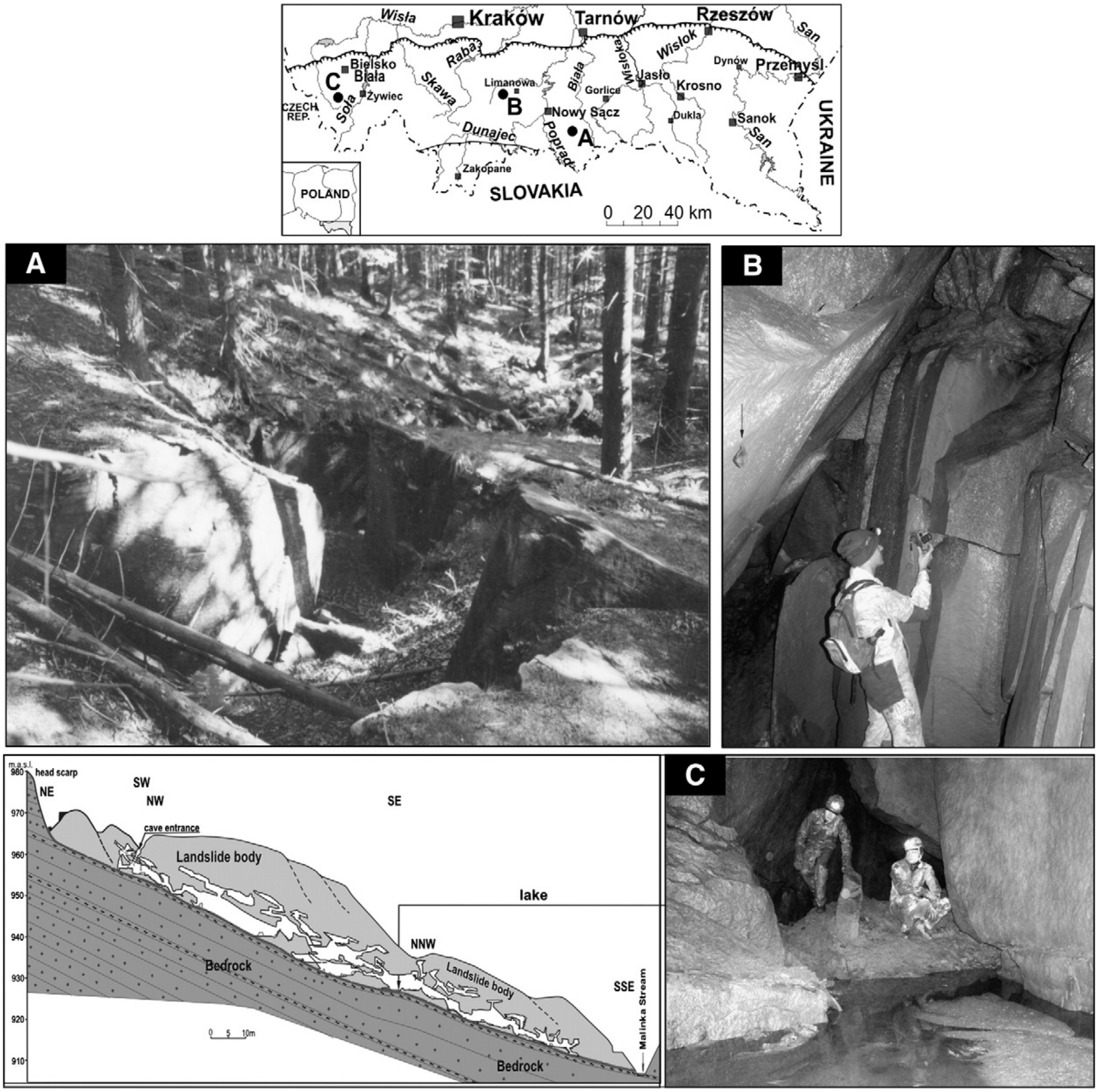


Fig. 6. Trenches and caves formed by mass movements: A – trench above the head scarp of the Wierch nad Kamieniem landslide (Beskid Sądecki Mts.); B – crevice type cave Jaskinia Zbójecka na Łopieniu: arrow points to the hanging bat (Beskid Wyspowy Mts.); and C – Jaskinia Miecharska cave (a chamber with a small lake, Beskid Śląski Mts.) and cross section (after Margielewski et al., 2007). Photo A by W. Margielewski; Photos B and C by J. Urban.

steps and flats among which depressions occur. These depressions are often undrained and can be periodically or even permanently filled with water (Fig. 7C).

4.2. Water phenomena

Water-bearing horizons cross and cause mass movements to produce essential changes in hydrological conditions in the areas affected by mass movements. Therefore, in the foot of rocky walls framing landslide niches, there are frequent fracture springs and water seepages that drain the higher rock sets. Springs within the landslide areas in the Carpathians are often classified as a separate "landslide type of springs" (Koniar-Shaeferowa, 1972; Dynowska, 1986). The springs recharge the surface and intra-colluvial water network. A local, specific hydrological system is then built. As a consequence, landslide slopes are strongly saturated with water, which is evidenced by abundant springs, water courses, wet depressions, small ponds or even landslide lakes. These water phenomena are situated at the foot of head and minor scarps (Fig. 7C), inside the colluvium (Fig. 7B), and sometimes in the ridge trenches as well as peat bogs. These peat bogs are the effects of water basins overgrown with plants. All this establishes a specific type of water regime depending on the disturbance degree of the original, natural hydrogeological conditions.

Owing to abundant and easy accessible water resources the landslide areas have been sites of frequent human colonisation since prehistoric time (Margielewski, 2006b). People have settled in the upper parts of the mountains and have used water in their homesteads for economic purposes.

The landslide lakes differ in their surface area (from 20 m² to several thousand m²) and depth (between 0.5 and 8.0 m). They are gradually filled with organic deposits and became peat bogs, usually of a fen type. The following kinds of peat predominate: woody peat, sedge peat, and sedge-moss fen peat. The organic material accumulated in the peat bogs is intercalated with clayey-clastic material carried into the basins by water ephemeral or perenial water flows which form illuvial or minerogenic horizons (Margielewski, 2006b).

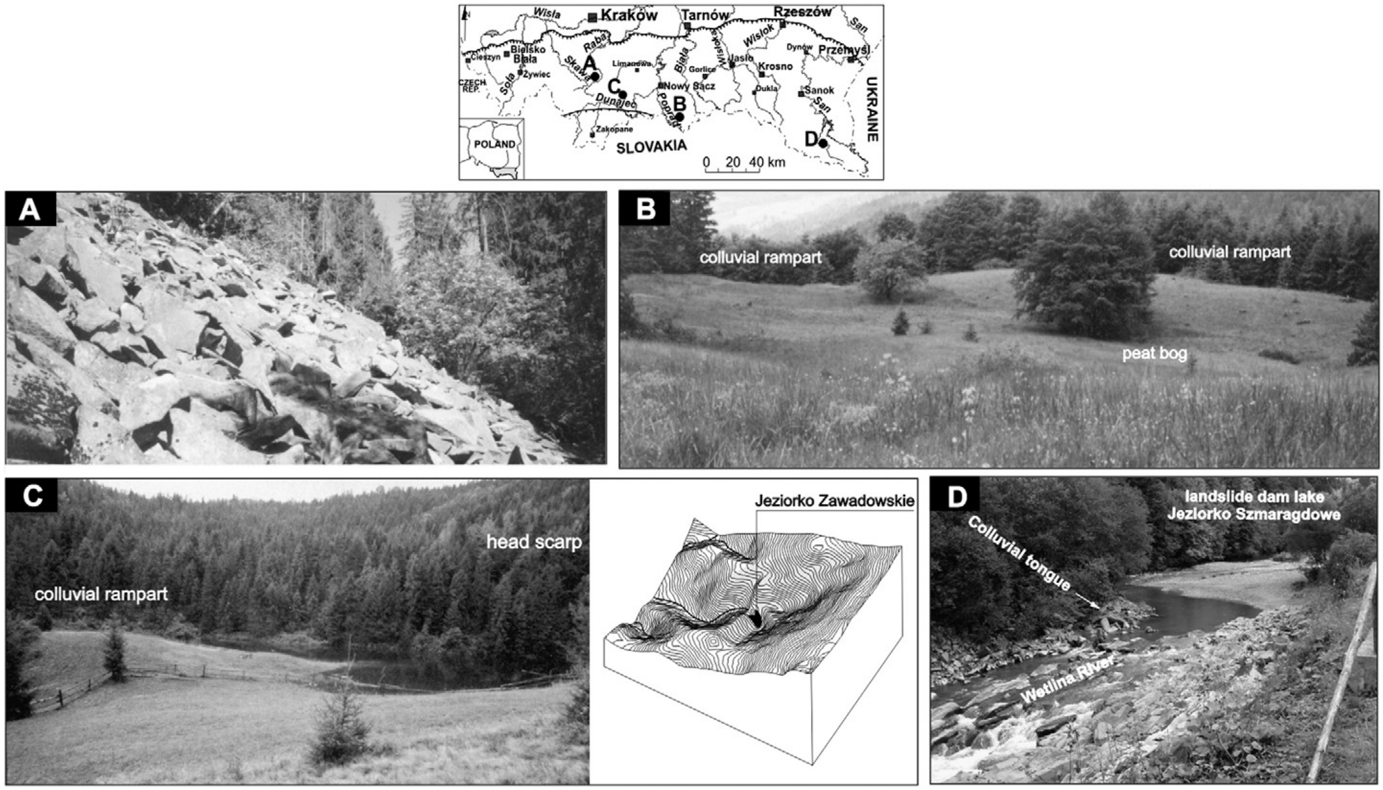


Fig. 7. Landforms connected with landslide main body and colluvium (toe): A – block field in Luboń Wielki landslide (Beskid Wyspowy Mts.); B – colluvial ramparts enclosing peat bogs in the Wierchomla landslide (Beskid Sądecki Mts); C – Jeziorko Zawadowskie lake, filling the depression at the foot of landslide head scarp, with position of lake on orthogonal projection of hypsometry (in “z” value) of landslide zone (Gorce Mts.); and D – landslide dam lake, Jeziorko Szmaragdowe formed on Wetlina river in 1980, gradually filled up by river gravel (Bieszczady Mts.). Photos by W. Margielewski.

It is also possible to find peat bogs completely covered with 2 m of mineral deposits. These deposits even form water confining horizons. The nature and succession of sediments in peat bogs are sensitive indicators of climatic and paleoenvironmental changes during the late Glacial and Holocene (e.g. Margielewski, 2001, 2006b). The peat bogs discussed are similar to a complex type of classification (Kaule and Gottlich, 1976; Ringler, 1978). However, there is justification for classifying landslide peat bogs as a separate type and class of peat bogs. They deserve a specific classification as a result of their distinctive geomorphological conditions, the nature of their sedimentation, as well as from the considerable amount of minerogenic material in peat (Margielewski, 2006b).

Other open water basins related with landslides are formed when landslides descend into a river valley and dam the flow. They are called landslide dam lakes (e.g. Schuster, 1986; Nicoletti and Parise, 2002; Korup, 2005). A rampart of piled up colluvial material dams the water flow. In time, this bank can be cut and then the drainage of the dam lake takes place. Drainage is followed by the removal of deposits accumulated therein. However, under favourable conditions, the lake and its deposits can last for a long period of time. In the Polish Carpathians, several sites of landslide dam lakes were found and dated (using radiocarbon) at various phases of the Holocene (Alexandrowicz, 1996). Two dam lakes have recently formed in the Bieszczady Mts. (eastern part of the Outer Carpathians). One of the dam lakes is Jeziora Duszatyńskie, formed in 1907 on Mt. Chryszczata. The other recently formed dam lake is Jeziorko Szmaragdowe, formed in 1980 on the Wetlina River (Fig. 7D; Margielewski, 1991).

5. Landscape generated by mass movements

Extensive landslide zones, which are often composed of numerous landslide formations and/or generations, are clearly marked in the landscape of the Carpathians owing to specific transformations of broad parts of mounatin slopes and ridges (Figs. 2 and 8A–D), and, sometimes, of the whole mountain ranges and large fragments of river valleys (Fig. 8E,F). The effects of mass movement impacts, which are particularly noticeable in the landscape, occur in the upper parts of ridges formed of sequences of thick-bedded sandstones, underlain with thin-bedded flysch or with shale series. Depending on the geological structures which control the nature of rock massif destruction (cutting, sliding and accumulation), the shapes of landslide slope profiles are concave (Fig. 8A), convex (Fig. 8B), or concave–convex (Fig. 8C) (Starkel, 1960; Baumgart-Kotarba, 1974; Kotarba, 1986; Alexandrowicz and Margielewski, 2000). Large-scale gravitational displacements within the mountain ridges sometimes caused ridge trenches and characteristic double ridges formation (Figs. 2B and 8D) (Alexandrowicz and Alexandrowicz, 1988; Margielewski, 2006a). Some mountain ranges in the Polish Carpathians are entirely modified and shaped by mass movements. The specific landscape elements of landslide slopes are morphological edges formed as cuestas and/or rock cliffs. These rock formations are often set along the fault or overthrust zones, broken ranges, or, isolated hills. In the case of the Beskid Niski Mts., a special landslide type shaping landforms and relief was even defined (Starkel, 1960; Kotarba, 1986). Another range, the Beskid Wyspowy Mts. is distinguished by clear-cut features of this type of landscape, i.e. individual mountain massifs (which do not form a range) are bordered on several sides by landslide slopes (Fig. 8F). Also, two the highest mountain massifs in the Polish Flysch Carpathians (in the borderland between Poland and Slovakia), Mt. Babia Góra (1725 m a.s.l.) and Mt. Pilsko (1557 m a.s.l.), are particularly distinguished by their landslide landscape. Current research proved that the relief of these two massifs, previously described as glacial (developed during the last glacial period), represents typical landslide formations (Ziętara and Ziętara, 1958; Alexandrowicz, 1978a; Łajczak, 1992;

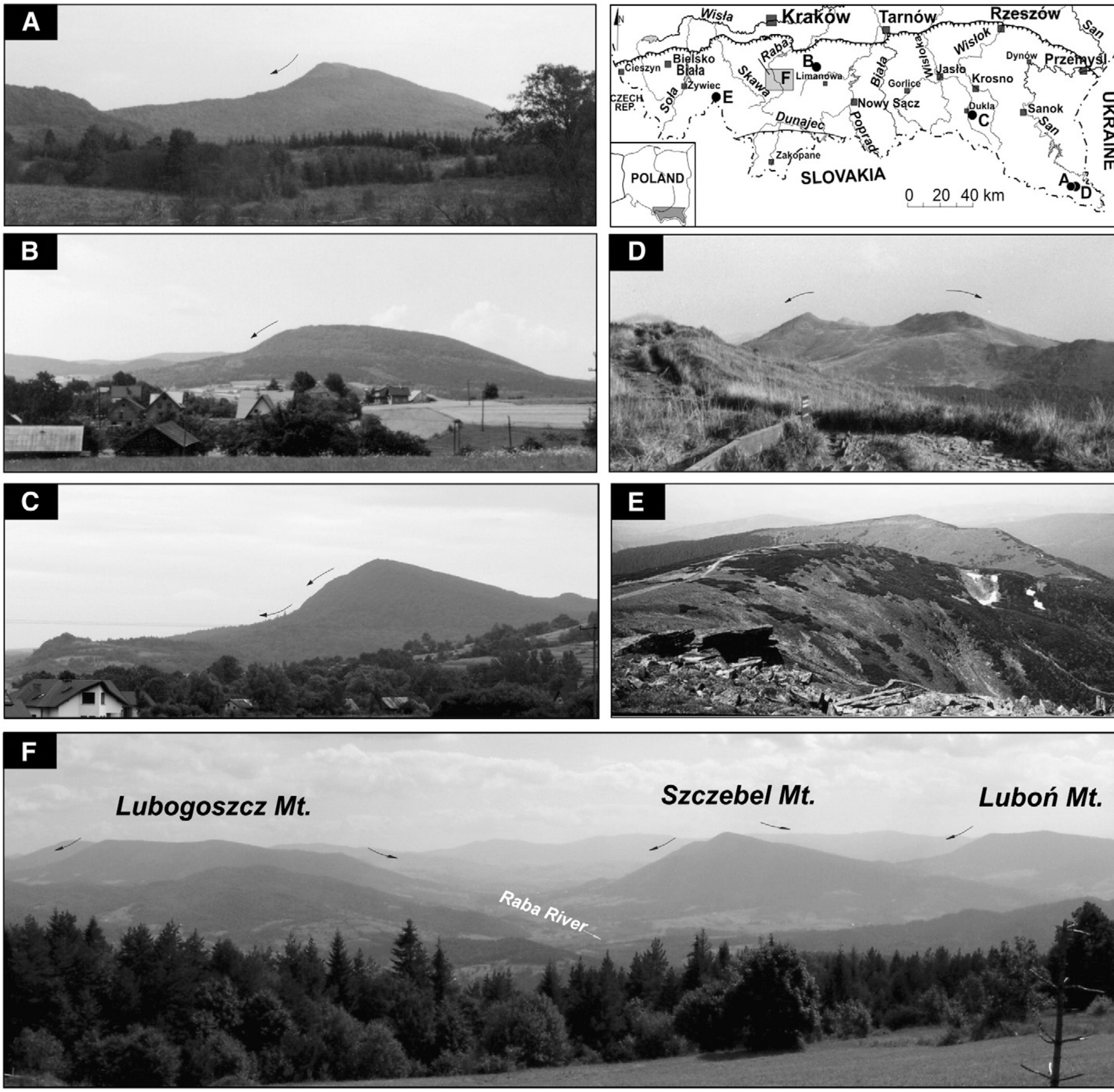


Fig. 8. Large-scale landslide landforms affecting mountainous landscape: A – concave slope: Mt. Hnatowe Berdo (Bieszczady Mts.); B – convex slope: Mt. Kostrza (Beskid Wyspowy Mts.); C – concave-convex slope: Mt. Cergowa (Beskid Niski Mts.); D – top trench (double ridge): Mt. Połonina Wetlińska (Bieszczady Mts.); E – landslide relief of Mt. Babia Góra (Babia Góra National Park); and F – landslide relief of Beskid Wyspowy Mts. Arrows show characteristic slope shape affected by mass movements. Photos A–D and F by W. Margielewski; Photo E by Z. Alexandrowicz.

Wójcik, 1994). Their slopes are shaped by deep-seated landslides with high, amphitheatre-like rock scarps, trenches, and block fields significantly influencing the mountain landscape (Fig. 8E).

6. Biodiversity patterns and their connection with landslide relief

Biological diversity (or biodiversity) is defined, according to the "Convention on Biological Diversity" (accepted during the Conference on Environment and Development – "Earth Summit", in Rio de Janeiro, 1992) as the variability among living organisms in every ecosystem, including terrestrial, marine, and other aquatic ones and variability within ecological complexes of which organisms are part. This includes diversity within species (genetic), between species and of ecosystems. A simplified version of this definition reads that biodiversity is the variability of life at any and all levels of life organization (Lovejoy, 1994, 1997). There are known various quantification methods of biodiversity; for example, in the segments being analysed or compared, one of the biodiversity indicators is the number of species or the number of ecosystems (e.g. Lovejoy, 1994, 1997; Grime, 1997; Pullin, 2002; Stallins, 2006; Renschler et al., 2007).

Regarding the geological structure, relief (e.g. rock formations), hydrogeological and edaphic conditions, diverse forest, meadow, water,

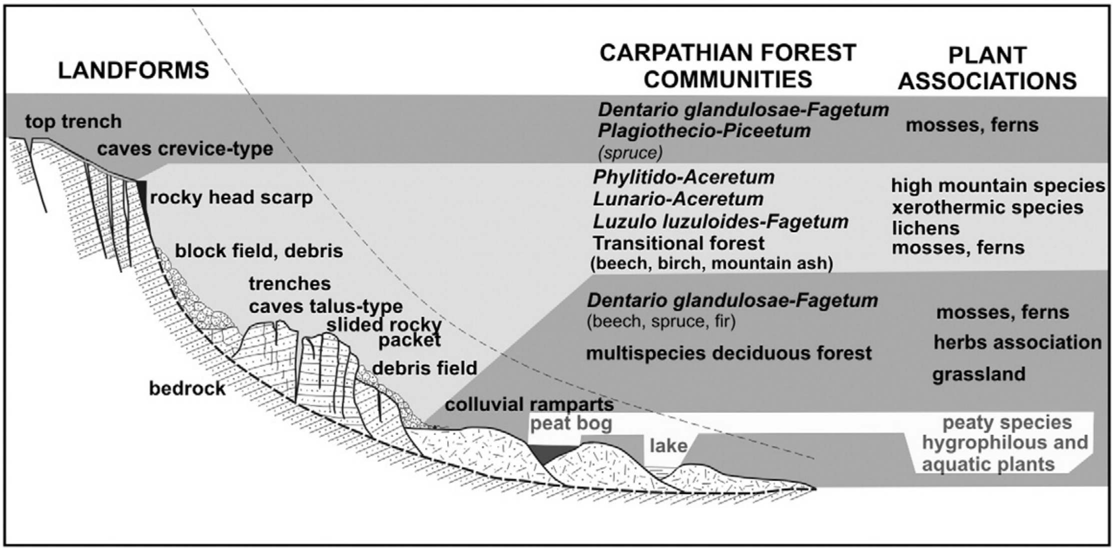


Fig. 9. Conceptual model of landslide, with distribution of landforms and plant communities (partly after Alexandrowicz et al., 2003).

bog, and peat communities exist side by side. These communities make up a diversified network adjusted to individual landforms and habitat conditions (Fig. 9; see: Tilman, 1985; Parker and Bendix, 1996; Naylor et al., 2002; Alexandrowicz et al., 2003; Geertsema and Pojar, 2007; Hradecký et al., 2008). A correlation that has come into being between the landslide forms and ecosystems (biocenoses) can be regarded as a typical example of co-evolution (Dawkins, 2004; Corenblit et al., 2008).

The significant impact of mass movements on the biodiversity development is evidenced by the fact that as many as 16 habitat types have been classified within the Carpathian landslides. Among these 16 types, 4 have been given priority rank. All of them meet the requirements of the European Ecological Network NATURA 2000, which is one of the most fundamental programmes for nature conservation in Europe (Alexandrowicz et al., 2003).

6.1. Forest associations

Considerable areas of the Polish Carpathians (ca. 70% of the area) are covered by forests showing diverse composition. The character of forest communities is now natural or semi-natural in places where people have utilized them for traditional economic activities (Sprugel, 1991).

The development of mass movements caused local damage to forest cover. Thus, the regeneration of degraded areas and establishing biotopes adapted to the existing, freshly changed environmental conditions (among others to the bedrock and relief) has progressed successively in different parts of the Carpathians.

The acidophylic spruce forests (*Plagiothecio-Piceetum*) appear typical for the upper parts (ridges, slopes) of the Carpathians. This type of plant community commonly covers landforms generated by gravitational movements. Transformations of the mountain landforms and relief by mass movements, reach as far as above the upper timberline forest (Babia Góra Mts. - see Fig. 8E).

The Carpathian community of *Dentario glandulosae-Fagetum* beech forest (*Querco-Fagetea class*) appears typical for the lower forest parts (slopes and valleys) of the Carpathians. It covers habitats on the slope which have varying expositions, inclination, humidity, and soil fertility. In the same mountain communities mixed spruce and fir coniferous forests (*Abieti-Piceetum* and *Galio-Piceetum*) also occur. The areas, where those forest communities initially grew, and which are included in the zone strongly impacted by mass movements totally degrading the substratum, are gradually overrun by less demanding communities: woods of acidous *Luzulo luzuloides-Fagetum* beech or by transitional communities with birch and mountain ash trees (Figs. 9 and 10A). Those communities occupy poor habitats with shallow, stony soils (lithosols) showing various degrees of degradation. The succession of the more demanding communities of the Carpathian *Dentario glandulosae-Fagetum* beech forests, progresses at the beginning, from the landslide surroundings towards the lower parts of colluvia that are healed first and quickest. Next, as the substratum stabilizes and the soil and water conditions regenerate in the areas originally damaged by mass movements, the succession proceeds towards the higher lying parts of landslide (Fig. 9).

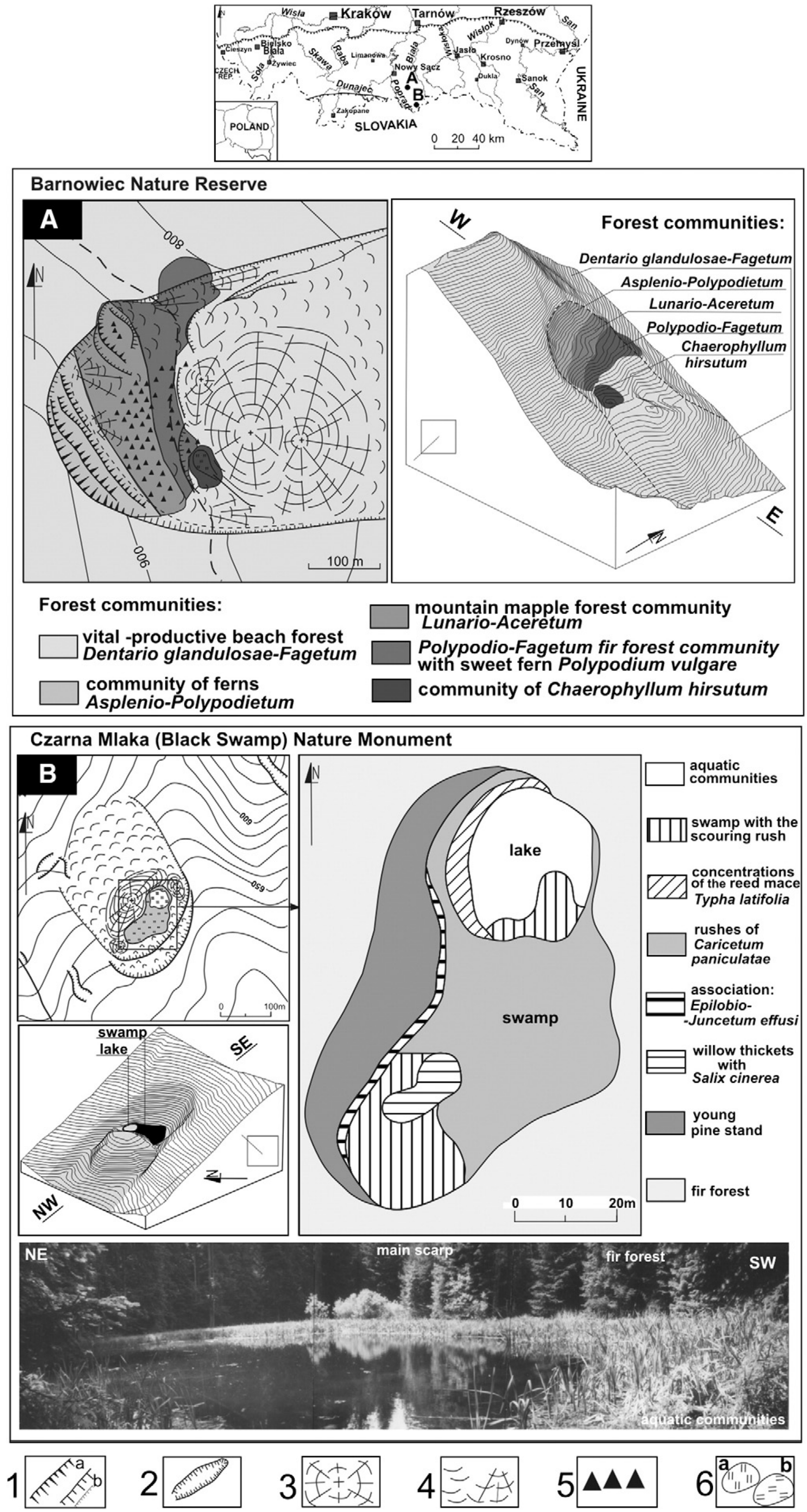
Unique forest communities occur in places within the old, stabilized landslides. At the foot of rock walls and in the areas with boulders and block fields, small patches of *Phyllitido aceretum* or *Lunario-Aceretum* are found (Staszkiewicz, 1972; 2000; Michalik and Mazur, 1991; Denisiuk, 1993). Within the landslide areas located in the lower parts of slopes, remains of linden forests survived but they are an exception. Now these remains constitute thermophilous relics that grew in the Carpathians in the period of optimum climatic conditions during the Atlantic phase of the Holocene (ca. 8.0–5.0 ka BP; Fabijanowski, 1961).

The landslide areas are difficult to access and thus, protected from felling. Therefore, they are typical solitaries of fragments of the Carpathian Virgin Forest with their undergrowths rich in many species of fungi. When taking into account the entire Carpathian Mountains, these impressive tree stands, standing usually at high altitudes, deserve special attention because of their exceptional nature-linked values. They can still be protected from felling and other human impact, by establishing legal protection.

Slow, secondary gravitational movements of the bedrock generate characteristic deformations of trees growing on the landslide areas. Tree trunks are tilted, curved and tangled giving rise to the name “drunk forest”. Tree bark is damaged, as are tree root systems (Alestalo, 1971; Shroder, 1978, 1980; Krąpiec and Margielewski, 2000). The gravitational displacement of bedrock and the unstable hydrogeological conditions in the landslide areas, cause tree damage and the tree stands are then weaken. Those tree stands become a place where pests invade and spread into the neighbouring healthy forest.

6.2. Plant associations

High diversity of plant species in the Outer Carpathians is conditioned by many factors, such as character of bedrock, altitude, topography (e.g. slope angle and aspect), and microclimate, among


Wisła
Kraków
Tarnów
Rzeszów
San
Wisłok
Przemyśl
Dynów
Bielsko Biała
Cieszyn
Żywiec
Soła
Skawa
Raba
Limanowa
Biała
Nowy Sącz
Jasło
Krosno
Dukla
Sanok
CZECH REP.
Dunajec
Poprad
A
B
Zakopane
SLOVAKIA
UKRAINE
POLAND
0 20 40 km
Barnowiec Nature Reserve
A
800
900
N
100 m
W
E
N
Forest communities:
Dentario glandulosae-Fagetum
Asplenio-Polypodietum
Lunario-Aceretum
Polypodio-Fagetum
Chaerophyllum hirsutum
Forest communities:
vital -productive beach forest Dentario glandulosae-Fagetum
community of ferns Asplenio-Polypodietum
mountain mapple forest community Lunario-Aceretum
Polypodio-Fagetum fir forest community with sweet fern Polypodium vulgare
community of Chaerophyllum hirsutum
Czarna Mlaka (Black Swamp) Nature Monument
B
N
600
650
0 100m
swamp
lake
SE
NW
N
lake
swamp
0 10 20m
aquatic communities
swamp with the scouring rush
concentrations of the reed mace Typha latifolia
rushes of Caricetum paniculatae
association: Epilobio- -Juncetum effusi
willow thickets with Salix cinerea
young pine stand
fir forest
NE
main scarp
fir forest
SW
aquatic communities
1
a
b
2
3
4
5
6
a
b

which environments of landslide areas are very specific. There are many relic and endemic species, often endangered and at risk of becoming extinct (Mirek and Piękoś-Mirkowa, 2008). The total quantity of those species, as well as of other rarely occurring and thus protected species in Poland, is most probably high. These are species that found convenient ecological niches in the areas transformed by gravitational movements. It is impossible to assess the number of these species in the present stage of the research. So far, among the endangered species included in the Polish Plant Red Data Book, 22 taxa were identified, which occur in the landslide areas representing the habitat types of the European Ecological Network NATURA 2000 (Kaźmierczakowa and Zarzycki, 2001; Alexandrowicz et al., 2003).

The plant associations occurring in the landslide areas have extremely different ecological requirements resulting from different habitats. The composition of micro- and macroelements in soils available to plants varies. The diverse environments can be both dry and wet, and can contain water (Fig. 9).

The exposed sandstone walls in the scarps of landslides usually have a generally poor and low diversified flora from the communities classified as *Asplenietea rupestris*. In the sun-lit places, there are rock vegetation and xerothermic plants (*Saxifraga paniculata, Clematis alpine, Campanula rotundifolia, Valeriana tripteris, Polygonatum verticillatum*). In the cracks and on the shaded walls, moss species and ferns appear (i.e. *Asplenium septentrionale, A. viridae, A. trichomanes, Athyrium filix-femina, Phegopteris polypodioides and Phyllitis scolopendrium*) (Lisowski and Kornaś, 1966; Dubiel, 1977; Granoszewski, 1987; Potoczek, 2009). Rock walls, and locally, rock boulders and blocks are covered with lichens (e.g. *Rhisocarpon geographicum*, *Rhisocarpon alpicola*). The study of lichens helps to determine the time that rocks surfaced and were exposed (Bajgier-Kowalska, 2008).

Contrary to dry habitats on rocks, wet areas of landslides are represented by very diverse plant taxa, despite the poorly developed soils. These plants grow on meadows, peat bogs, bog-springs, and in the vicinity of springs and watercourses. These diverse plant taxa constitute the most abundant associations rich in various species. Among them appear the herb communities. The herbs are particularly picturesque against the landscape background growing in mid-forest bog-springs, on the edges of springs, streams/brooks, and small ponds. These are the richest in species associations in the landslide areas, which usually has more than 100 taxa (Michalik, 1992). There are also numerous well developed, multi-species moss patches. Landslide peat bogs form another characteristic biotope which gets covered successively with specific peat growth-generating plants, e.g. *Carex, Bryales, Sphagnum, Eriophorum,* and *Equisetum* (Denisiuk et al., 1977; Margielewski, 2006b). There is an occurrence of hygrophilous species in water sites of various types, both ephemeral and permanent, or on their fringes. In many cases these hygrophilous species contribute to the increase in biodiversity of the areas discussed.

The old, stabilized landslides in the upper forest zone and above the timberline forest boundary are characterized by the occurrence of high mountain species of the vascular plant flora. Some of the vascular plants e.g. *Sweertia perennis subsp. alpestris and Allium sibiricum* are very rare in the Polish Carpathians (Michalik, 1992). Those high-lying areas are covered by a dwarf pine zone.

6.3. Animal associations

There are landslide areas located far away from places inhabited by people and characterized by the occurrence of forest solitaries that are difficult to reach. These areas have rich undergrowth and water abundance, and constitute particularly convenient living conditions for wild animals (Alexandrowicz et al., 2003; Geertsema and Pojar, 2007). In these isolated areas numerous species find shelter and a place to reproduce including those at the risk of extinction introduced in the Polish Animal Red Data Book (Głowaciński, 2001), as well as those protected by law. Often, the landslide areas are sanctuaries for big mammals such as the brown bear (*Ursus arctos*), Eurasian lynx (*Lynx lynx*), wild cat (*Felix sylvestris*), and wolf (*Canis lupus*). Furthermore, within the miscellaneous landforms and plants of landslide areas, rare birds find favourable conditions to nest. This is especially true of eagles (*Aquila pomarina*, *Aquila chrysateos*) and owls (*Bubo bubo*, *Strip uralensis*, and *Aegolius funerus*) as well as many other species (e.g. *Accipiter nissus*, *Buteo buteo*, *Lyrurus terix*, and *Tetrastes bonasia*) (Głowaciński, 1991). Small landslide lakes represent nesting places for water birds or places to rest during their seasonal migrations. Various amphibian species (e.g. newts) and insect species, especially dragonflies (*Odonata*) occupy landslide lakes and peat bogs (Czekaj, 1993). Wide block fields and tectonic trenches provide refuge for various species of animals, as e.g. deer and reptile species, especially snakes (*Coronella austriaca*, *Lacerta*). In numerous caves, the majority of Polish bats (*Chiroptera*), classified as endangered and thus, legally protected, hibernate and procreate (Fig. 6B; e.g. Mysłajek et al., 2007). Unique streams and small lakes in caves contain a unique aquatic fauna (Fig. 6C) (Dumnicka, 2009). In some shallower parts of caves, animals find shelter in winter because the air temperature is higher than outside.

6.4. The co-evolution between landforms and biocenoses in the selected landslides

From among several tens studied landslides, two examples have been selected for they have relatively complete data referring to the present state of natural environment preservation (Fig. 10A,B). These examples represent typical, but different landslides. They show a cohesion (or compactness, termed co-evolution) among their landforms, edaphic and water features, and the peculiar biotopes adapted to those specific conditions. The below depicted landslides show a wide-scale geodiversity standing for the standard framework conservation of geosites protected and those on the agenda to be protected (Alexandrowicz et al., 1996).

6.4.1. Case study: Barnowiec Nature Reserve

The Barnowiec Nature Reserve in the Beskid Sądecki Mts. is situated within the valley head of the Barnowiec stream (Fig. 10A). It is typical example of a transformation of forest plant communities stimulated by mass movements. The Barnowiec forest, being the remains of the Carpathian Virgin Forest has an abundance of old trees and unique plant communities. It has been protected since 1905 (in 1924 it was granted the formal status of natural forest reserve) and currently covers 21.6 ha. The detailed study proved that unique, for the size of the Carpathians, protected forest communities cover the area of the rotational landslide. This landslide comprises the rocky head scarp 50 m high, the block fields at its foot and the extensive colluvial ramparts in the lower part of this landform (Margielewski, 1998). Characteristic distribution of these morphological elements and hydrological and edaphic conditions connected with them, caused the specific adjustment of plant associations to the habitats developed in the particular landslide elements. As a consequence, the peripheral zone of the landslide is covered by the vital-productive beech forest (*Dentario glandulosae- Fagetum*), typical for the stabilized

Fig. 10. Distribution of plant associations affected by landslide: A – forest communities occurring in the Barnowiec landslide (Barnowiec Nature Reserve, Beskid Sądecki Mts.) (landslide map and 3D diagram after Margielewski, 1998; forest communities: after Staszkiewicz, 2000); and B – distribution of swamp–hygrophilous plant associations, occurring at the Czarna Młaka site (Nature Monument, Cergov Mts.) (location of Czarna Młaka on landslide map after Gurbała, 1998; plant distribution after Denisiuk et al., 1977), and 3D diagram. Photo: view of lake occurring at the Czarna Młaka Swamp, taken by W. Margielewski. Legend symbols: 1 – rocky (a) and creeped (b) scarps; 2 – trench; 3 – landslide body and rampart; 4 – colluvial tongue, creeping; 5 – rock block; and 6 – swamp (a) and lake (b).

mountain areas (Staszkiewicz, 1972, 2000). The steep rocky walls of the head scarp are overgrown by ferns of the *Asplenio-Polypodietum* (=*Hypno-Polypodietum*) community. The block fields situated at the foot of the head scarp are occupied by a unique forest community (*Lunario-Aceretum*) with mountain mapple (*Acer pseudoplatanus*). The lower fragments of these block fields are covered by beech-fir forest with adder's fern (sweet fern) (*Polypodium vulgare*). This unique forest community *Polypodio-Fagetum* in the block fields is a new forest community in Poland, described for the first time on this site (Fig. 10A; Staszkiewicz, 2000). It proves the significant influence of mass movements on the development of new and/or unique plant associations. The lower part of the landslide (landslide tongue) is forested by tree association with spruce. The inner-forest swamps are occupied by the community of *Chaerophyllum hirsutum* (*Chaerophylletum hirsuti*). Differentiated wood associations attract rare birds, e.g., red crossbill (*Loxia curvirostra*), spotted nutcracker (*Nucifraga caryocatactes*), and song trush (*Turdus philomelos*) (Staszkiewicz, 2000). Such birds are the next elements of biodiversity produced indirectly by mass movements.

6.4.2. Case study: Czarna Młaka (Black Swamp) Natural Monument

Landslide with Czarna Młaka (Black Swamp) formed in the slope of the Hajnica Hill of the Cergov Mts. It fills the elongated depression at the foot of main scarp of the length ca. 85 m and maximum width 30 m, dammed by the extensive colluvial rampart (Fig. 10B) (Denisiuk et al., 1977; Gurbała, 1998). The major part of the depression has a maximum depth of 3.7 m, and is now filled with fen peat bog (Gurbała, 1998). A lake is in the northern part of the depression (peat bog). The lake has gradually shrunk and become shallower due to plant overgrowth. Within the lake aquatic plants occur. The area in close proximity to the lake is covered by swamp with scouring rush (*Equisetum limosum*), which was also found in the southern part of the swamp. The margins of the lake are full of reed mace *Typha latifolia* (Fig. 10B). The major part of the peat bog and the surroundings of the lake are covered by rush association *Caricetum paniculatae*. *Epilobio-Juncetum effusi* association occurs in a narrow strip surrounding the peat bog. In places the peat bog is occupied by willow thickets with *Salix cinerea*. The wetland plant associations are surrounded by fir forest with the predomination of a vital-productive beech community *Dentario glandulosae-Fagetum* (Fig. 10B) (Denisiuk et al., 1977).

The unique water basin, with the peat bog covered by rare plant communities and fragments of forest (area ca. 0.3 ha) was granted legal protection as a nature monument in 1978 (Alexandrowicz, 1989). It should be noted that this relatively large, high, mountain lake is located on a seasonal bird migration path. It serves as the resting place for numerous taxa of water birds.

7. Nature conservation in the landslide areas

As a motivator for obtaining legal nature protection of landslide areas, the aspect of the cohesion between geo- and biodiversity deserves special attention (Alexandrowicz et al., 2003; Margielewski and Alexandrowicz, 2004). Comprehensive research of the geo- and biodiversity relationship at landslide sites would help promote the necessity to protect the sites. Unfortunately, such research is still sporadic in different mountain areas. Right now, the main motivations for legal protection of such sites are either forest associations or unusual landscape elements. For this reason individual landforms or sets of landforms which are genetically connected with mass movements are under legal protection only in eight geological nature reserves. There are 40 nature monuments with selected elements of landslides (caves, crags, rock walls, and lakes) which are protected (Alexandrowicz and Poprawa, 2000).

The areas characterized by the best developed landslide relief, including their typical single forms, were recommended for the European Network of Geosites (Margielewski and Alexandrowicz, 2004; Alexandrowicz, 2006). The Polish part of the Carpathian Euro-region is represented, at the beginning, by nine geosites of this class. Due to unique plant associations (or bat community protection), some of the landslide areas are included in the protected NATURA 2000 areas. The small number of protected landslide areas and their elements show that conservation of landslides is still not adequate in the Polish Carpathians.

8. Conclusions

Mass movements in the Polish Carpathians strongly influenced the mountainous landscape on both regional and local scales. The landscape is rich in unique morphological forms typical for landslides. Specific feature of the landslide areas include a high diversity of landforms and relief, as well as edaphic and hydrogeological conditions that are marked by the mosaic occurrence of varying natural micro-habitants. Specific plant associations (including forest communities) overgrowing the mosaic of habitats within the landslide areas create the unique biotopes, controlled by mass movements. Dependence between geo- and biodiversity, precisely marked in landslide areas, is connected with specific co-evolution, i.e. adaptation of ecosystems to landforms. Specific individual elements of the landslides contribute to the variety of the local landscape.

The Carpathian landslide areas, well identified in the range of geo- and biodiversity should be objects of detailed biotic investigations especially of individual landforms. On the other hand, research into landslide topography should also include the peculiar character of biotopes occurring within them. This is the only way to achieve the complete interpretation of correlations between geo- and biodiversity. This would be interpretations of areas of individual landslides characterized by a diversified relief. Research on those areas which are legally protected, recommended for protection, or planned for didactic-tourism purposes is especially needed.

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