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Differential evolution of rockwall and talus cones in abandoned basalt quarries and its implications for restoration management: case study from the Radobyl Hill, N Czech Republic

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Differential evolution of rockwall and talus cones in abandoned basalt quarries and its implications for restoration management: case study from the Radobyl Hill, N Czech Republic

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The reclamation and restoration of quarries have been well studied in the past decades. Most studies focused on the bio-treatment and restoration of land post-quarrying activities. The present article reports the results of a pilot study on the geomorphic dynamics of an abandoned basalt quarry at the Ceske Stredohori Mountains in Northern Czech Republic. The authors applied geodetic and geomorphologic field techniques together with computer simulations (i) to identify geomorphic processes at the study site and (ii) to assess interrelations and relative rates of impact of the various processes. The results indicated that there were significant differences in rockwall and talus cone dynamics within the study site. The surface dynamics involved (i) a rockfall-dominated mode and (ii) a combination of rockfall and debris-dominated modes. The relative importance of these modes was primarily influenced by the inclination of joints and fissures, rockwall height and profile geometry, which resulted in variable micro-topography of talus cones, and in differential growth of talus cones since the abandonment of the quarry. This article reveals that the difference in the type and rate of geomorphic processes influenced the habitat diversity and should be considered in restoration design.

Keywords: basalt quarry; rockwall; talus cone; rockfall; debris flow; restoration

1. Introduction

The extraction of raw materials represents one of the major human impacts on landscape [1]. The impacts include direct effects (pollutants, destruction of habitats and others) and indirect effects (visual impediments, heavier traffic flow and others). These effects are generally perceived as environmental threats [2]. During the past decades, serious attention has been devoted to the reclamation and restoration of mines and quarries. There is particular emphasis on environmental and ecological aspects of open-cast mining [3–5] with associated decontamination following chemical extraction of minerals. Environmental restoration studies have primarily

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addressed problems associated with limestone quarrying [6–8], gravel pits [9] and construction materials (e.g. volcanic rock) quarrying. Most quarrying studies have focused on ecological and biological aspects of post-quarrying dynamics and the restoration process, with the most important issues being spontaneous re-vegetation [10,11] and potential human-assisted colonisation of habitats [12–15].

Geomorphologic studies of quarries are less frequent than ecological and botanical studies. Dávid [16] in 2008 presented a general introduction to anthropogenic landforms in quarries. Several authors have discussed anthropogenic modifications of landforms for stability and for enhancing the local geo-diversity [17,18]. Walton and Allington [19] presented one of the most inspiring studies by emphasising the necessity of a geomorphologic approach to designing landform replication strategies to increase geo-diversity in areas under natural conservation. Other authors have discussed risk processes in quarries, such as mass movements and erosion [20,21].

Traditionally, the foundation of effective restoration management of quarries consisted of field surveys of the consequences of quarrying activity (e.g., soil and groundwater quality) and long-term monitoring of abandoned quarry sites [22]. Nevertheless, the quarries used for the extraction of construction materials frequently do not suffer from toxicity problems, but rather from fundamental changes in the original topography. These changes imply the presence of high surface dynamics. Therefore, effective restoration remains far from convincing in the absence of detailed field information on variability, types and magnitudes of geomorphic processes in abandoned quarries.

Many abandoned quarries may also represent unique localities [23], which could become alternatives to natural sites that have become rare. Examples of such sites include rock-exposed plains, rockwalls and talus slope deposits. In this context, it is very beneficial to use the natural processes of succession to support quarry restoration. Natural succession processes imply self-sustainability; they make it possible to decrease the level of inputs subsequently required to maintain the sites [24]. The use of natural processes in efforts to restore quarries [cf. [25–27]] also assumes the availability of information about the character of rock disintegration, rockfall rates, rockwall and talus cone dynamics relative to rates that are typical for natural sites.

This article reports the results of a pilot study on the geomorphic dynamics of abandoned basalt quarries in the Ceske Stredohori Middle Mts. (Northern Czech Republic). The neo-volcanic mountain range of the Ceske Stredohori Mts. has a unique natural value in the European context. At the same time, however, it has been a centre of basalt quarrying in the Czech Republic since at least the nineteenth century. Much attention has been paid to vegetation succession in these abandoned basalt quarries. The emphasis of these efforts has usually been the conditions of the quarry floor. The specifics and differences in geomorphic evolution of the rockwalls and talus cones at individual sites have previously been neglected. This study focuses on the specification of geomorphic processes affecting the post-quarrying development of Radobyl Hill, which represents an appropriate model system for our research. The main objectives of this study were to identify the fundamental geomorphic processes occurring during quarry development, their interrelations and their relative rates. The characteristics of these processes and the resulting landforms are discussed in relation to the habitat diversity of the quarry with potential applications to the restoration of other localities.

2. Study site

Radobyl Hill (399 m a.s.l.; 50° 31′ 47″ N, 14° 5′ 31″ E) is located in Northern Czech Republic, 5 km from the town of Litomerice (Figure 1). Radobyl Hill is a part of the Ceske Stredohori Mts., a 60-km long, SW–NE trending neo-volcanic range [28]. The hill itself is composed of basalt exposed by a long period of quarrying. There are no sufficient existing reports on the quarrying activities at the site within the archive of the Czech Geological Survey or Regional historical archives. Therefore, it was necessary to refer to indirect information. In 1784, Born [29] mentioned an unspecified quarry that was located at the footslope of Radobyl Hill. However, the first maps showing the quarry were from the III Military survey (1877–1880). The locality was studied in detail by Hibsch (published in 1937, [30]), who described three stages, the lowest of which was the smallest at that time. This fact shows that the quarry was operating during the years represented by the publication date of the study. The quarry was no longer in operation after World War II and was established as a natural reserve in 1963. The previous quarrying of the three stages has exposed high rockwalls that display the unique structure of basalt. The importance of this volcanic outcrop is illustrated by the fact that Radobyl Hill represents one of the comparative examples cited in the document that nominated the Giant's Causeway for inclusion on the UNESCO natural heritage list [31]. Apart from its geologic significance, the abandoned quarry is important because the characteristics of the ecosystem allow several species to occur at the site [32]. For this ecological reason, the site is protected under NATURA 2000. This research was conducted at the lowest stage, Stage A. This area is formed by a 50-m high rockwall partly overlaid by eight talus cones including the flat quarry floor.

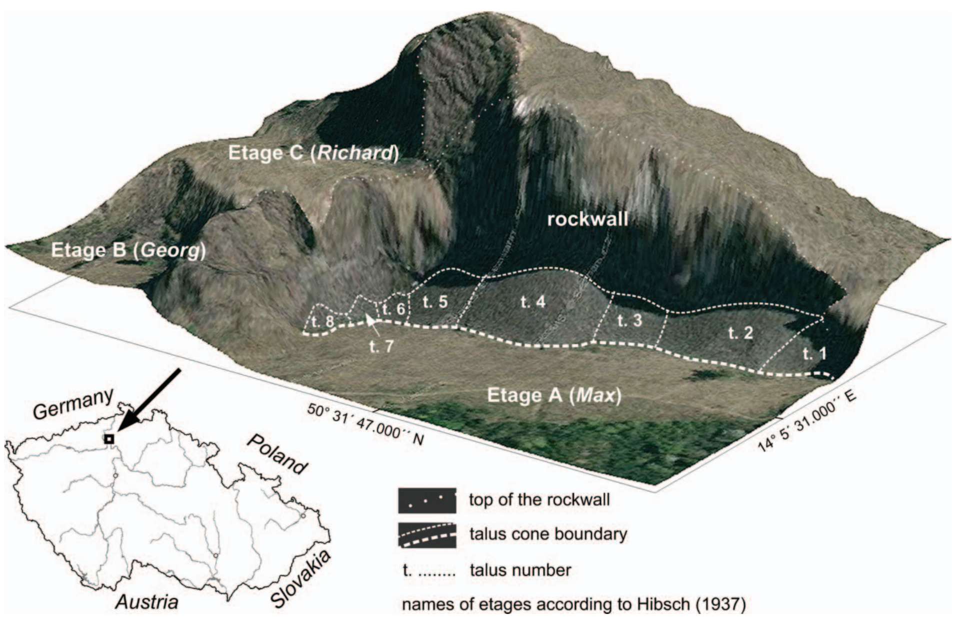

Figure 1. Location of the study site, geomorphologic position of talus cones and rockwall.

3. Methods

3.1. Geomorphologic mapping

The study area, Stage A, was measured using the total station device Trimble 5603 DR200+. This device allows the automatic measurement of a selected area in the prism-less distance measurement mode [33]. The position of the observation standpoints was referenced to the national coordinate system in situ using a Trimble R8 global positioning system (GPS) receiver and the real-time kinematic (RTK) method. The data were used to derive a high-precision digital elevation model (DEM) of the area. The model served as a source base for geomorphologic mapping of elementary landforms as well as for deriving the geometrical properties of the relief for use in geomorphologic analyses and rockfall simulations.

3.2. Sedimentology and lithology

The analyses carried out in this article can be divided into four main groups. We first measured the basic geomorphometric parameters of the rockwall and of eight talus cones located beneath the rockwall. These parameters included the height of the rockwall and the length, width and average slope inclination of each talus cone. Sedimentologic measurements were performed on each talus cone. The clast size was sampled at regular distances along the vertical profile of the talus cone. The lengths of clasts were evaluated along three axes to determine the size of the clasts and their shape according to Sneed and Folk [34], using the Tri-plot Excel Spreadsheet [35].

The lithological controls and the relative age for rockwall disintegration were analysed on the rockwall sites above each of the eight talus cones. We measured the average orientation and inclination of the joints dividing individual basalt columns. The columns were originally formed during the lava cooling as contraction discontinuities, and they predispose the basaltic bedrock to further disintegration [36]. The relative age of the rockwall was determined using the Schmidt hammer (NR type) test. This method has frequently been used to detect the susceptibility of bedrock to disintegration and for the relative dating of different landforms built by solid bedrock. A methodological review of Schmidt hammer tests has been presented by Goudie [37]. We collected data from 30 hits on polished rockwall surfaces at each of the eight sites. Five extreme values from each site were excluded from statistical processing. Boxplots were constructed to show the statistical distribution of the data.

The simulation of rockfall trajectories was performed for three representative rockwall profiles above the talus slopes numbered 3, 4 and 5 (Figure 2) by using the Colorado Rockfall Simulation Program [38]. The profiles were derived from geodetic measurements. The input parameters were chosen according to field observations (surface roughness, size and shape of clasts) and empirical values (rock density and tangential and normal coefficients).

4. Results

4.1. Properties of the talus cones

The geomorphologic characteristics of the talus cones and the rockwall are listed in Table 1 and represented graphically in Figure 2. The talus cones displayed significant differences in their geomorphometric and sedimentologic properties. The length and width of the talus varied between 7 and 33.5 m and 6 and 41.5 m, respectively. The corresponding length–width ratios show that the shapes of talus cones differed. The

Table 1. Basic geomorphologic characteristic of talus cones.

	Length (m)	Width (m)	Length–width ratio	Max. slope (°)	Rockwall height* (m)	Column orientation (°)	Column inclination (°)
1	15.0	9.5	1.58	28	4	348.8	8.4
2	25.0	41.0	0.61	36	12	226.8	45.0
3	22.0	10.0	2.20	36	17	340.8	4.8
4	33.5	41.5	0.81	37	36 (50)	341.2	37.0
5	32.5	24.5	1.33	35	46 (55)	340.0	40.0
6	18.0	6.0	3.00	26	28 (40)	276.8	67.0
7	13.5	17.0	0.79	35	23	276.4	70.0
8	7.0	8.5	0.82	32	24	246.4	55.0

Note: *The number indicates the height of the portion of the rockwall having a continuous slope inclination. The number in parentheses indicates the approximate rockwall height, including the rugged surface at its top segment, as set in the rockfall simulations.

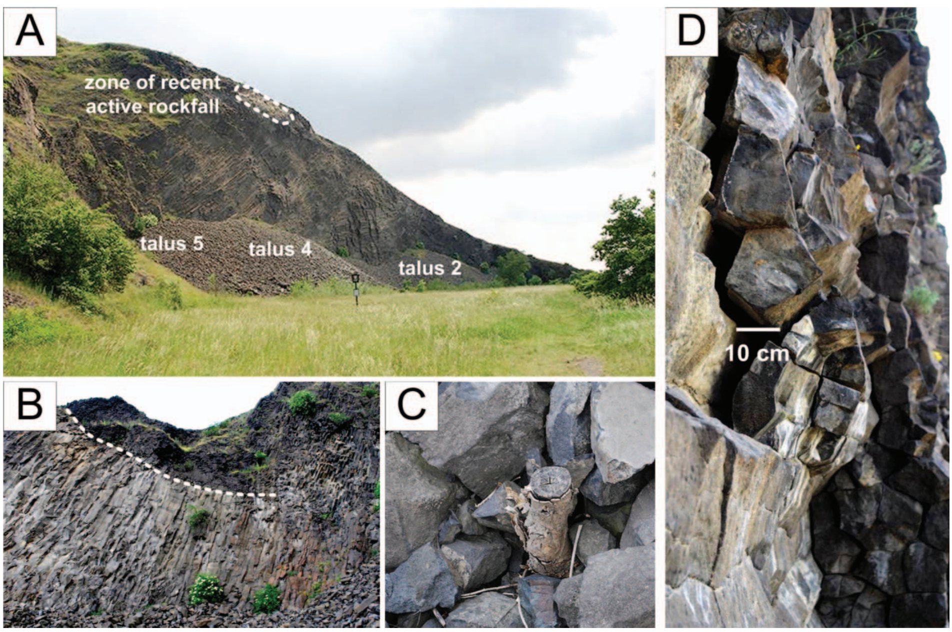

Figure 2. Schematic sketch of the quarry stage studied, showing the average inclination of the basalt columns, their outcrops, the median values of the Schmidt hammer test and the character (fabric) of the deposits forming talus cones.

height of the rockwall above talus cones varied and reflected the original convex shape of the structure (Figures 1 and 3A) exposed by selective erosion of the surroundings. The clast shape on the talus cones is shown in Figure 4. The clasts on talus cones below the high rockwall segments (2, 3, 4 and 5), which run relatively parallel to the basalt columns, displayed higher percentages of elongated and bladed shapes. The middle and lower segments of these talus cone profiles were overlaid with accumulations of imbricated columns of more than 1 m in length. The upper segments of these talus cones were frequently formed by debris-like material with

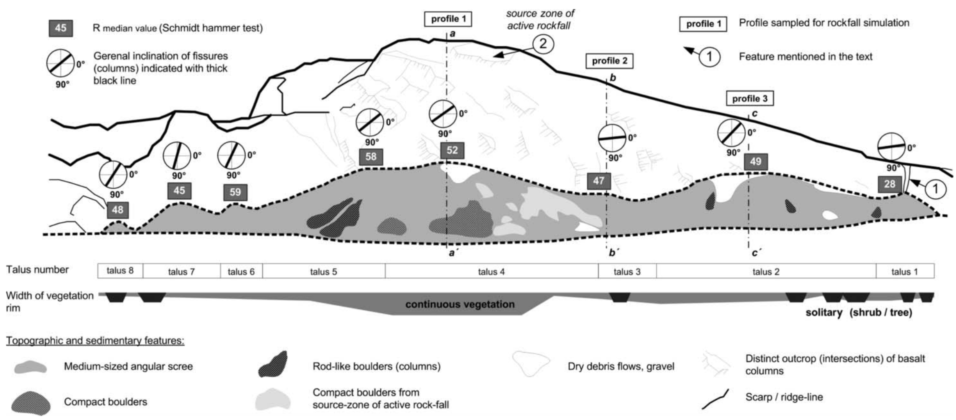

Figure 3. (A) Overall view of the abandoned quarry (Stage A), (B) rockwall segment displaying the boundary between a system of parallel fissures and poorly structured basaltic rock, (C) a tree stump within talus, a result of environmental management of the site, (D) fissures in the surface of the basalt rockwall.

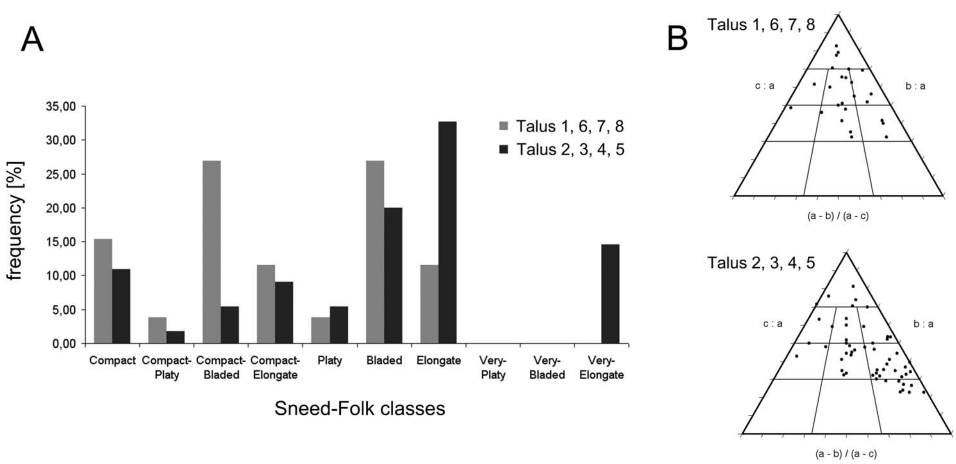

Figure 4. Shape properties of the clasts at the talus cones (according to Sneed and Folk classes [34]).

finer clayey deposits and coarse gravel. The presence of debris material is conditioned by specific combinations of rockfall, mineral weathering on discontinuities between basalt columns and outwash of sediments from the top of the hill.

The lateral talus cones (1, 6, 7, and 8) are located below the rockwall segments intersecting the basalt columns. In contrast with the clasts on the central talus cones, the clasts on the lateral talus cones were less frequently elongated and more often compact and compact bladed. The most lateral talus cones (1 and 8) also showed higher homogeneity in clast size and shape distribution along the vertical profile in comparison with the central talus cones. At all of the talus cones, but with different intensities, gravitational sorting has caused large clasts to penetrate the vegetation rim beneath the foot of the talus cone. The presence of several tree and shrub stumps in the lower parts of the talus cones indicated a gradual increase of the talus cones.

4.2. Lithological controls on rockwall disintegration

The standard orientation of the basalt columns on most outcrops is homogeneously parallel. However, the specifics of the local environment during the eruption, as well as petrographic diversity (see Figure 3B), may cause significant variations. These variations ranged from the absence of columns (lava flows extending into water) to curve-like and fan-like deformations of the column orientation. The uniform orientation of the basalt columns on the rockwall indicates that the rock had a common source zone. In contrast, the inclination of the basalt columns was more diverse, ranging from a subhorizontal (8.4°, talus cone 1) to subvertical (70°, talus cone 7) course. The presence of fissures between basalt columns is one of the major preconditions for rockwall disintegration. Most fissures were filled with mineral cementation bonds. The extent of these fissures was generally from 1 mm to a few centimetres. Some segments of the rockwall, however, were characterised by fissures whose extents could be as much as several centimetres (Figure 3D).

The Schmidt hammer test indicates the intact strength of the rock. This characteristic is considered to be an indirect representation of the relative age of the surface. Lower values of the test indicate a longer period of weathering and vice versa. The lowest and most variable values were obtained for the rockwall segment above talus cone 1 (Figure 5). Other segments of the rockwall had more homogeneous values. The maximum values were found at the segments above talus cones 5 and 6 (median R values were 58 and 59, respectively).

4.3. Simulation of rockfall trajectories

Rockfall trajectories were analysed by simulating the falls of 1000 clasts from the top of the rockwall. The results of the simulation indicated that the falling clasts could follow two movement regimes (Figure 6). The first movement regime involved bouncing and resulted from geometric discontinuities of the rockwall. Two types of rockfall trajectories occurred on the highest rockwall above talus cone 4. The first type of trajectory followed the rockwall, whereas the second reached the lowest parts of the talus cone. The second type of movement regime was characterised by bouncing and rolling of fallen clasts down the slope of the talus cone. This regime was present in all simulated profiles, but it was most prominent in profiles 2 (talus

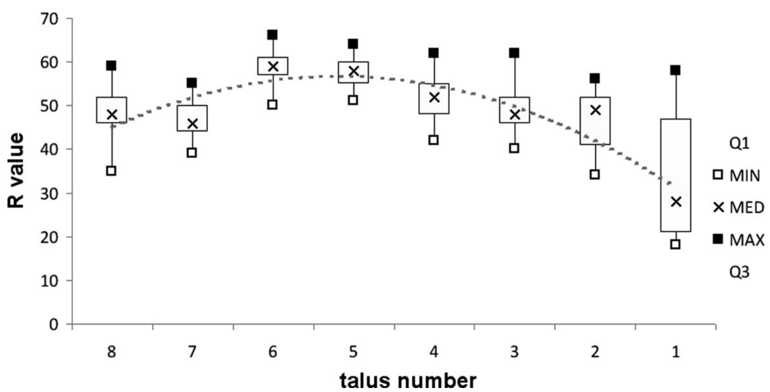

Figure 5. Results of Schmidt hammer tests conducted at the rockwall above the talus cones.

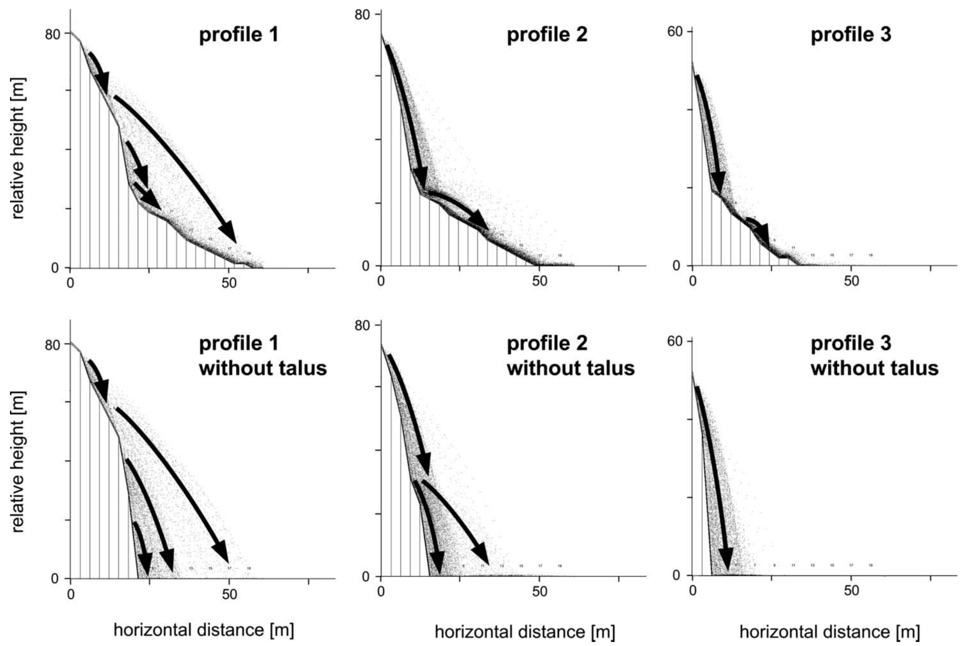

Figure 6. Simulation of rockfall trajectories for rockwall profiles with taluses 4 (profile 1), 3 (profile 2) and 2 (profile 3) and for hypothetical rockwall profiles without taluses.

cone 3) and 3 (talus cone 2). In this regime, the falling clast induced rolling and sliding of temporarily stabilised clasts.

The average velocity of the rockfall clasts (Figure 7) was highest during the fall and after the first bounce in the upper part of the talus cones. The maximum bounce height of the rockfall clasts at all profiles was reached immediately, at the transition of the rockwall segments and the talus slope. Both the average velocity and the bounce height remained high above the talus cones at profiles 1 and 2. These high values were caused by a combination of direct rockfall and rolling at profile 1 and by intense rolling at profile 2. The simulation of rockfall trajectories at hypothetical rockwall profiles without talus cones shows that the growth of the talus cones would occur in two different modes. It is necessary to emphasise that these modes must be viewed as potential modes, because the primary development of talus cones was human-induced and occurred during the quarrying period. Profile 3 displays continual talus growth. This growth starts immediately below the rockwall. The talus cones at the other two profiles would be formed by the second mode of growth, namely combined growth in their upper and middle-to-lower segments.

5. Discussion and conclusions

5.1. Interrelation of the geomorphic and lithological properties

Geomorphologic assessments of talus slope geometry and of the lithological controls governing their evolution have revealed different degrees of relationship among these factors. The variation among these relations points to the specifics of the geomorphic regimes affecting human-induced talus cones in abandoned quarries, in contrast to the regimes affecting natural talus slopes. On natural talus slopes, the length of the

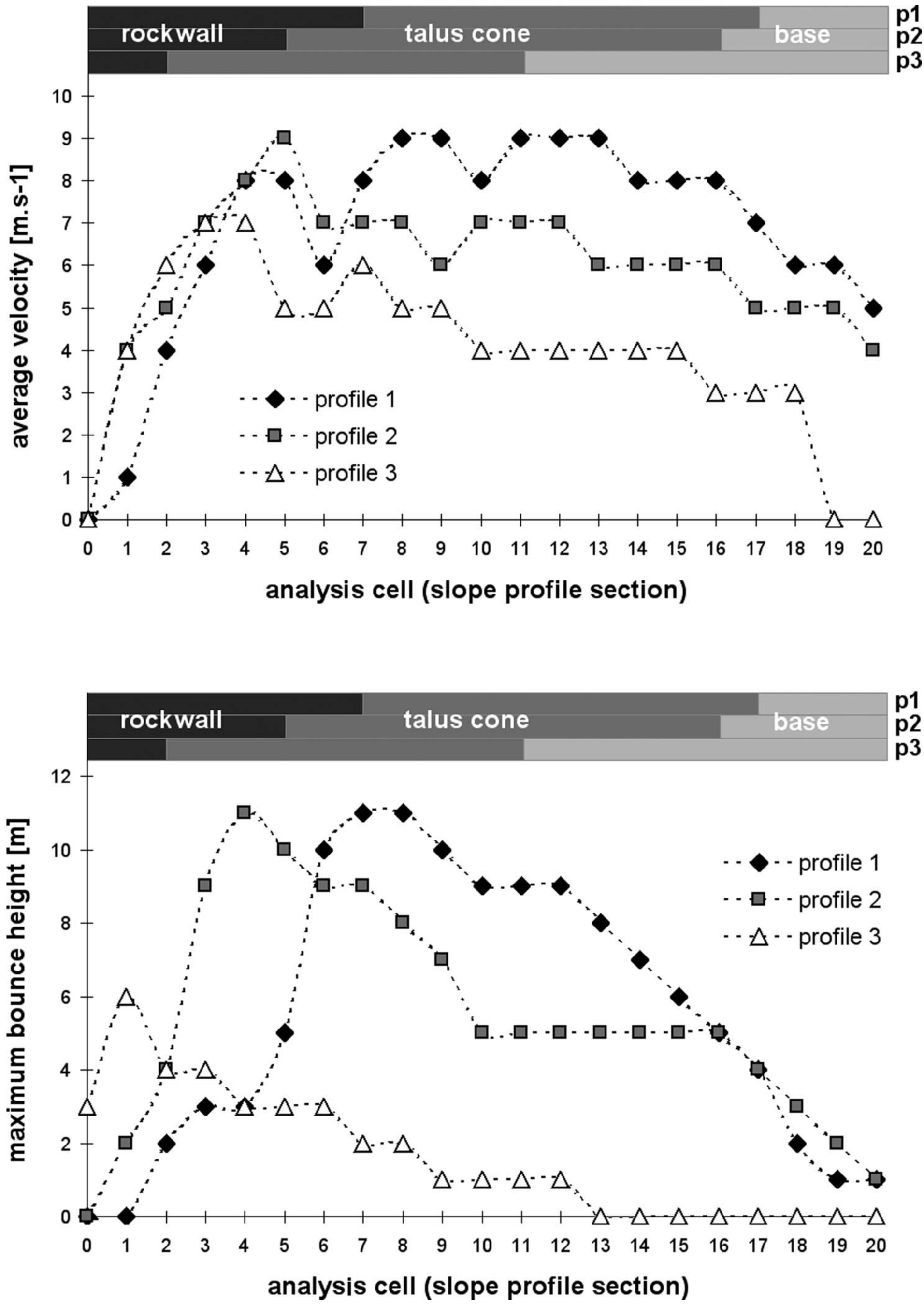

Figure 7. Average velocity and maximum bounce height in the rockfall simulation at profiles 1, 2 and 3 (see Figure 6 for rockfall trajectories). Note the division of topographic segments for each profile above the graphs.

talus cone is considered to depend in part on the height of the rockwall [e.g. 39–42]. The height of the rockwall indicates the extent of the rock surface being disintegrated, which influences the velocity of rockfalls. Such relationships correspond to the weathering-controlled slope development model proposed by Selby [43]. However, the talus cones studied showed weak relationships among these parameters (Figure 8A). The explanation for this result is the different and combined modes of particle movement along the talus cones studied. The rockfall-dominated cones typically exhibit predominant vertical movement, and particles are affected by gravitational sorting along the cone. In contrast, debris-dominated cones frequently exhibit long tailing concavities and show limited particle sorting [44]. Geomorphometric and sedimentologic analyses at the talus cones studied indicate that both of these regimes were present at certain talus cones, whereas other cones developed under only one of these regimes. The talus cones below the highest rockwall segments are typically characterised by combined dynamics. These dynamic processes include both rockfalls and dry debris flows and they also involve the sliding of rockfall clasts to form local imbrications and stratifications [cf. [45]]. In general, the particles were sorted along the talus cones, but significant heterogeneities in clast size were found in individual slope segments. In the upper parts of talus cones, finer unsorted material overlaid the coarse deposits. This finding can be explained by temporal changes in sedimentary regimes. In contrast, individual accumulations of imbricated large basalt columns in the middle and lower parts of the cones indicate random rockfalls and subsequent sliding. The combination of rockfall and debris-dominated dynamics influences the geometry of talus cones. Only the smallest talus cones were characterised by straight profiles. The largest central talus cones exhibited several discontinuities in slope profile and formed terminal tailings. These heterogeneities are evident in the relationship between slope inclination and talus length shown in Figure 8B. The presence of horizontal particle movement on the talus cones studied also limited the gradual decrease of concavity, a result also reported from natural sites by *Statham* [44,46].

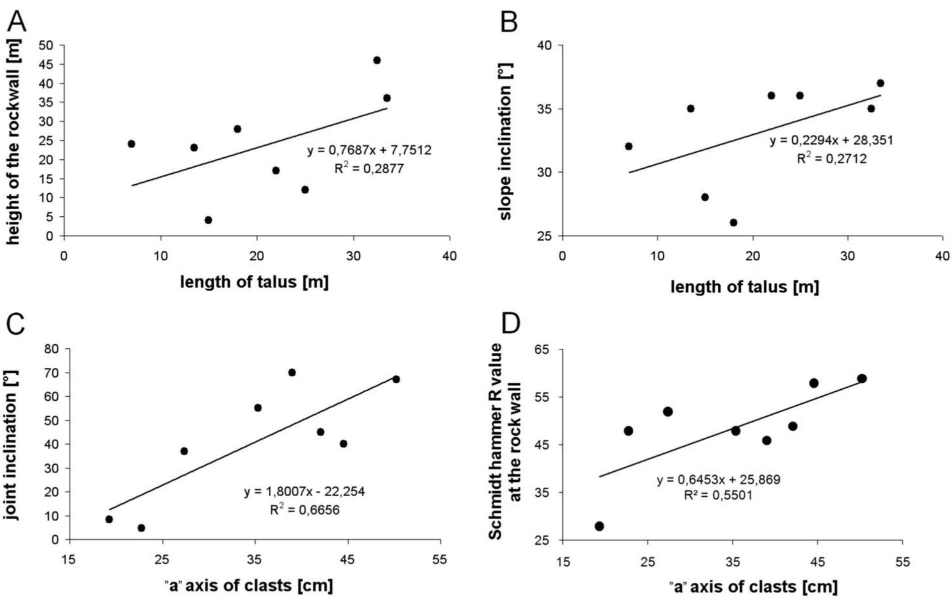

Figure 8. Correlations between geomorphic, lithological and sedimentologic parameters of the rockwall and talus cones.

Significant values were obtained for the relationship between joint inclination and the length of the ‘a’ axis of the clasts (Figure 8C). Significant values were also obtained for the relationship between the Schmidt hammer test values for the intact strength of the rockwall and the length of the ‘a’ axis of the clasts (Figure 8D). The first relationship emphasises that the inclination of the basalt columns is important for determining the effects of weathering. Subvertical columns are more susceptible to the penetration of water into the joints. This factor, together with joint spacing [47] intensifies the weathering effect of freeze-thaw cycles. These processes result in rockfall and in the toppling of whole segments of rockwall. Following these events, large clasts accumulate on the talus cone. The correlation between the results of the Schmidt hammer tests (*R* value) and the average size of the ‘a’ axis of clasts provides valuable information, but it is also open to discussion. Higher values of intact strength should indicate a younger surface, i.e. a higher degree of dynamics for the surface. The correlation shown in Figure 8D suggests high *R* values, which is an indication a surface affected by recently occurring rockfall. Events of this type are documented by the accumulations of basalt columns found below the rockwall segments. Surfaces affected by cumulative rockfall are also visible in Figure 9 as bright patches. However, despite the validity of these findings, the high variability of

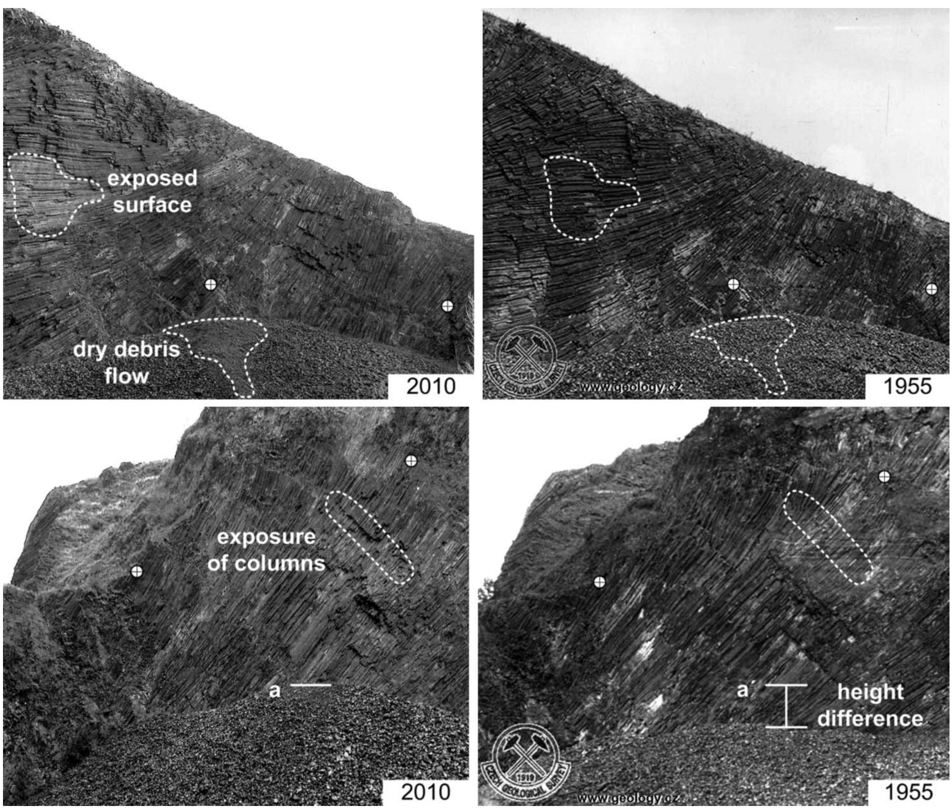

Figure 9. Oblique photographs of talus cones 2 (upper photos) and 4 (lower photos) from the years 2010 and 1955, showing the changes in talus height and in the rockwall surface. The white circles with crosses indicate passpoints. The dashed lines mark major changes in surface microtopography Photo: 2010, author; 1955, B. Cerveny, Archive of Czech Geological Survey.

R values on some rockwall segments does not permit us to determine the exact role of surface dynamics or the differences caused by lithological variances at a microscale and by topoclimatic diversity of rockwall weathering at the study site.

5.2. *Types of geomorphic processes and their relative rates*

The basic geomorphologic processes identified at the study site include rockfall, rolling, flows of dry debris and sliding. The spatio-temporal distribution of these processes is variable, however. We must first consider the historical situation that furnished the basis for the post-mining development of the rockwall and talus cones. During this 'base time', the primary talus cones were formed by human-induced rockfalls produced by controlled detonations. Subsequently, the talus cones developed under different regimes according to the prevailing lithological and topographic conditions.

For the purpose of comparison, Figure 9 shows two pairs of photographs that illustrate the differing development of cones 2 and 4, the two largest talus cones. The photos were taken at two different times: in 1955, representing a year near our 'base time' and in 2010, during the current research. These photos enable us to assess the relative rate of talus development as well as the relative role of different geomorphic processes. The photos show that the geomorphic development of talus cone 2 reflected a combined regime of dry debris flows and rockfall. There was no discovered difference in talus height, but the talus tailings indicate an increase in talus length. These facts aid in the interpretation of the growth of the talus cone. In view of the results of the rockfall simulation at profile 3 (Figure 6), the limited growth of talus height indicates the prevailing role of random rockfall events and of dry debris flows and sliding of clasts along the talus cone. In contrast, talus cone 4 was characterised by a smaller extent of debris flows and by the presence of coarser particles even in its upper section. The growth in talus height indicated by the comparative views in the photographs (see letters 'a' and 'a′' in Figure 9) amounts to a difference in talus height of approximately 0.5 m. This difference can be attributed to rockfall occurring in the lowest part of the rockwall above the talus cone.

Despite the indications of talus growth as revealed by the comparative photographs, the estimation of total talus growth is problematic for the following reasons. First, the variability in talus cone geomorphometry has to be recognised. The recent modelling studies of rockwall retreat and talus growth are based on the presumption of parallel retreat and growth of rockwall and talus cones, approximated as straight surfaces [48]. The base surface is then approximated as linear [49] or parabolic [50]. In abandoned quarries, however, the base surface is formed by the horizontal floor of the quarry stage and undergoes a transition to the subvertical and the vertical surface of the rockwall. Furthermore, the combination of geomorphic regimes creates more-or-less significant deviations from the assumed straight surface of the rockwall and the talus cone. These deviations are also apparent in natural talus cones [44]. The rockwall retreat rates at natural localities range from millimetre to centimetre per 100 years [42,51], and [52]. However, these rates are higher for basaltic rockwalls. The lithological structure of the basalt rockwall at the study site also exhibits high susceptibility to disintegration and rockfall. These properties have resulted in rockfall events that have caused a patchy rockwall retreat of as much as several centimetres since the time of quarry abandonment.

5.3. Implications for quarry restoration and conservation management

In restoration studies, rockwalls and talus cones in basalt quarries are usually considered as relatively homogeneous topographic segments and the restoration efforts and studies both focus on quarry floors [10]. The problems affecting both spontaneous and controlled revegetation of rockwalls are primarily caused by rockwall dynamics [15,21] and by the shade provided by trees at the foot of talus cones [6]. Both of these causes are preconditioned by quarry topography and by rates of rock disintegration along the rockwall. Differences in the rate of weathering and geomorphic processes are therefore responsible for the variability of landforms and, subsequently, the diversity of habitats. Several studies have shown the importance of environmental diversity for species richness at a regional scale [53,54]. The importance of environmental diversity on a local scale for natural talus cones has been demonstrated in the literature [55,56]. Other authors have emphasised the importance of ecological and concurrent conditions [57,58].

Rockwall and talus cones have ecological significance for xerothermic stenoecious species and for species (both sciophytes and xerophytes) related to air circulation patterns in the stony debris of talus cones. Revegetation and environmental management of talus cones must recognise the differential geomorphic dynamics and conditions that characterise these habitats. These considerations are especially important at sites whose restoration involves a combination of natural succession and controlled (designed) measures.

Several issues that emerged from this study should be considered in future research on the restoration management of abandoned quarries. These issues revolve around the development of relationships between geomorphic events and potential habitats, as listed below:

(1) Rockfall-dominated talus cones: the effects of the low stability of the rockwall face on revegetation efforts; the well-developed air circulation present at the talus cone; the surface dynamics favours stenoecious species and by-species with lower competitiveness (in contrast, more competitive species usually dominate in stable environments); and disturbance by rockfalls and processes involving rolling and bouncing.

(2) Talus cones with combined rockfall and debris flow dynamics: the effects of the low stability of the rockwall face on revegetation efforts; the less well-developed air circulation; the suitability of coarse-clast segments for stenoecious species and for species with lower competitiveness; the debris and clayey material suitable for invasive plants and shrubs that compete with stenoecious species; and the horizontal particle movements that may cause burial of plants.

(3) Relatively stable talus cones formed by coarse clasts: the well-developed air circulation at the talus cone; the presence of species with high competitiveness; and the limited suitability of these habitats for plants due to the presence of openwork structure.

(4) Relatively stable talus cones formed by coarse clasts and debris: the presence of debris and clayey material suitable for invasive plants and shrubs that compete with stenoecious species; and the rapid development of plant populations and less well-developed air circulation.

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References

[1] A. Krivtsov. Geoenvironmental problems of mineral resources development, in *Geology and Ecosystems*, I.S. Zekster, ed., Springer-Verlag, New York, 2006, pp. 77–90.

[2] T. Milgrom, Environmental aspects of rehabilitating abandoned quarries: Israel as a case study, Landscape Urban Plann. 87 (2008), pp. 172–179.

[3] P. Sklenička, I. Přikryl, I. Svoboda, and T. Lhota, *Non-productive principles of landscape rehabilitation after long-term open-cast mining in Northwest Bohemia*, J. S. Afr. Inst. Min. Metall. 104 (2004), pp. 83–88.

[4] J. Vráblíková, Reclamation after open-cast coal mining: case study from Northern Bohemia (in Czech), Životné Prostredie 44 (2010), pp. 24–29.

[5] O. Mudrák, J. Frouz, and V. Velichová, *Understory vegetation in reclaimed and unreclaimed post-mining forest stands*, Ecol. Eng. 36 (2010), pp. 783–790.

[6] K.A. Ursic, N.C. Kenkel, and D.W. Larson, *Revegetation dynamics of cliff faces in abandoned limestone quarries*, J. Appl. Ecol. 34 (1997), pp. 289–303.

[7] C.P. Wheater, W.R. Cullen, and J.R. Bell, *Spider communities as tools in monitoring reclaimed limestone quarry landforms*, Landscape Ecol. 15 (2000), pp. 401–406.

[8] S. Tomlinsonand, U. Matthes, P.J. Richardson, and D.W. Larson, *The ecological equivalence of quarry floors to alvars*, Appl. Veg. Sci. 11 (2008), pp. 73–82.

[9] J. Andrews and D. Kinsman, *Gravel Pit Restoration for Wildlife*, Royal Society for the Protection of Birds, Sandy, 1990.

[10] J. Novák and K. Prach, Vegetation succession in basalt quarries: pattern over a landscape scale, Appl. Veg. Sci. 6 (2003), pp. 111–116.

[11] J. Novák and M. Konvička, *Proximity of valuable habitats affects succession patterns in abandoned quarries*, Ecol. Eng. 26 (2006), pp. 113–122.

[12] N.J. Coppin and A.D. Bradshaw, *Quarry Reclamation – the Establishment of Vegetation in Quarries and Open-Pit Non-Metal Mines*. Mining Journal Books, London, 1982.

[13] B.N.K. Davis, *Plant succession in chalk and ragstone quarries in south east England*. Proc. Croydon Nat. Hist. Sci. Soc. 17 (1983), pp. 153–172.

[14] W.R. Cullen, C.P. Weater, and P.J. Dunleavy, *Establishment of species-rich vegetation on reclaimed limestone quarry faces in Derbyshire, UK*, Biol. Conserv. 84 (1998), pp. 25–33.

[15] Z.Q. Wang, L.H. Wu, and T.T. Liu, *Revegetation of steep rocky slopes: planting climbing vegetation species in artificially drilled holes*, Ecol. Eng. 35 (2009), pp. 1079–1084.

[16] L. Dávid, *Quarrying: an anthropogenic geomorphological approach*, Acta Montan. Slovaca 13 (2008), pp. 66–74.

[17] H.J. Schor and D.J. Gray, *Landforming*, John Wiley & Sons, New York, 2007.

[18] V. Pinto, X. Font, M. Salgot, J.C. Tapias, and T. Maná, *Using 3-D structures and their virtual representation as a tool for restoring opencast mines and quarries*, Eng. Geol. 63 (2002), pp. 121–129.

[19] G. Walton and R. Allington, *Landform replication in quarrying*, Trans. Inst. Min Metall. A 103 (1994), pp. A55–A66.

[20] M.Y. Koca and C. Kıncal, *Abandoned stone quarries in and around the Izmir city centre and their geo-environmental impacts Turkey*, Eng. Geol. 75 (2004), pp. 49–67.

[21] J.F. Martin-Duque, M.A. Sanz, J.M. Bodoque, A. Lucia, and C. Martin-Moreno, *Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes*, Earth Surf. Proc. Land 35 (2010), pp. 531–548.

[22] G. Bonifazi, L. Cutaia, P. Massacci, and I. Roselli, *Monitoring of abandoned quarries by remote sensing and in situ surveying*, Ecol. Model. 170 (2003), pp. 213–218.

[23] B.N.K. Davis (ed.), *Ecology of Quarries*, Institute of Terrestrial Ecology, Cambridge, UK, 1982.

[24] A.D. Bradshaw, *Restoration of mined lands – using natural processes*, Ecol. Eng. 8 (1997), pp. 255–269.
[25] M.H.R. Browning, *Abandoned pits and quarry sites: living experiments in Reclamation and restoration of settled landscapes*, Proceedings of the 23rd Annual Meeting, Canadian Land Reclamation Association in association with the Society for Ecological Restoration Ontario Chapter, Markham, Ontario, CA, 1998.
[26] A.D. Bradshaw, *The use of natural processes in reclamation – advantages*, Landscape Urban Plann. 51 (2000), pp. 89–100.
[27] A.D. Bradshaw and R.F. Hüttl, *Future mine site restoration involves a broader approach*, Ecol. Eng. 17 (2001), pp. 87–90.
[28] V. Cajz, *Proposal of lithostratigraphy for the České středohoří Mts. volcanic*, Bull. Czech Geol. Survey 75 (2000), pp. 7–16.
[29] I. Born, *Abhandlungen einer Privatgesellschaft in Böhmen*, Sechster Band, Verlag der Xerlischen Buchhandlung, Prag, 1784.
[30] J.E. Hibsch, *Die Radebeule bei Leitmeritz. Firgenwald*, Vierteljahrschrift für Geologie und Erdkunde der Sudetenländer 10 (1937), pp. 97–107.
[31] UNESCO, *Nomination to the World heritage list – Giantś Causeway*, ICOMOS UNESCO, Paris, 1985.
[32] V. Holubec, *Monitoring of selected threatened species in Bohemia*, Czech J. Genet. Plant Breed. 46 (2010), pp. 21–26.
[33] R. Höglund and P. Large, *Direct Reflex EDM Technology for the Surveyor and Civil Engineer*, Trimble Survey White Paper, Sunnyvale, CA, 2006.
[34] E.D. Sneed and R.L. Folk, *Pebbles in the lower Colorado River, Texas. A study of particle morphogenesis*, J. Geol. 66 (1958), pp. 114–150.
[35] D.J. Graham and M.G. Midgley, *Graphical representation of particle shape using triangular diagrams: an Excel spreadsheet method*, Earth Surf. Proc. Landforms 25 (2000), pp. 1473–1477.
[36] C. Ollier, *Volcanoes*. Blackwell, New York, 1988.
[37] A.S. Goudie, *The Schmidt Hammer in geomorphological research*, Prog. Phys. Geogr. 30 (2006), pp. 703–718.
[38] Ch. L. Jones, J.D. Higgins, and R.D. Andrew, *Colorado Rockfall Simulation Program, version 4.0*. Colorado Geological Survey, Denver, 2000.
[39] E.K. Gerber and A.E. Scheidegger, *On the dynamics of scree slope*, Rock Mech. 6 (1974), pp. 25–38.
[40] F.L. Pérez, *Talus fabric, clast morphology, and botanical indicators of slope processes on the Chaos Crags (California Cascades), U.S.A*, Géographie Physique et Quaternaire 52 (1998), pp. 47–68.
[41] B. Hétu and J.T. Gray, *Effect of environmental change on scree slope development throughout the postglacial period in the Chic-Choc Mountains in the northern Gaspe Peninsula, Quebeck*, Geomorphology 32 (2000), pp. 335–355.
[42] M.A. Curry and Ch.J. Morris, *Late glacial and Holocene talus slope development and rockwall retreat on Mynydd Du, UK*, Geomorphology 58 (2004), pp. 85–106.
[43] M.J. Selby, *Controls on the stability and inclinations of hillslopes formed on hard rock*, Earth Surf. Proc. Landforms 7 (1982), pp. 449–467.
[44] I. Statham, *Scree slope development under conditions of surface particle movement*, Trans. Inst. Br. Geogr. 59 (1973), pp. 41–53.
[45] B. Hétu, H. Vansteijn, and P. Bertran, *Role of dry grain flows in the formation of a certain type of stratified scree*, Permafrost Periglac. Proc. 6 (1995), pp. 173–194.
[46] I. Statham, *A scree slope rockfall model*, Earth Surf. Proc. 1 (1976), pp. 43–62.
[47] N. Matsuoka and A. Sakai, *Rockfall activity from an alpine cliff during thawing periods*, Geomorphology 28 (1999), pp. 309–328.
[48] J.R. Moore, J.W. Sanders, W.E. Dietrich, and S.D. Glaser, *Influence of rock mass strength on the erosion rate of alpine cliffs*, Earth Surf. Proc. Landforms 34 (2009), pp. 1339–1352.
[49] G.A. Olyphant, *Analysis of the factors controlling cliff burial by talus within Blanca Massif, Southern Colorado, USA*, Arct. Alp. Res. 15 (1983), pp. 65–75.
[50] J.M. Harbor, B. Hallet, and C.F. Raymond, *A numerical model of landform development by glacial erosion*. Nature 333 (1988), pp. 347–349.

[51] I. Saunders and A. Young, *Rates of surface processes on slopes, slope retreat and denudation*, Earth Surf. Proc. Landforms 8 (1983), pp. 473–501.

[52] S. Hinchlife and C.K. Ballantyne, *Talus accumulation and rockwall retreat, Trotternish, isle of Sky, Scotland*, Scot. Geogr. J. 115 (1999), pp. 53–70.

[53] J.T. Lundholm, *Plant species diversity and environmental heterogeneity: spatial scale and competing hypotheses*, J. Veg. Sci. 20 (2009), pp. 377–391.

[54] R.H. MacArthur, *Geographical ecology: patterns in the distribution of species*. Princeton University of Press, Princeton, 1972.

[55] K. Kubát (ed.), *Stony Debris Ecosystems*. Acta Universitatis Purkinianae, 52, Studia Biologica IV, UJEP, Ustí nad Labem, 2000.

[56] B.M. Möseler and R. Molenda (eds.), *Lebensraum Blockhalde. Zur İkologie periglazialer Blockhalden im Ausseralpinen Mitteleuropa*. Decheniana – Beheifte des Naturhistorischen Vereins der Rheinlande und Westfalens e. V., 37, Bonn, 1999.

[57] A. Shmida and S. Ellner, *Coexistence of plant species with similar niches*, Vegetation 58 (1984), pp. 29–55.

[58] D. Tilman, *Competition and biodiversity in spatially structured habitats*, Ecology 72 (1994), pp. 2–16.