by Zofia Alexandrowicz*

The impact of rock climbing on the micro-relief of sandstone surfaces: The case study of the Carpathian tors

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The aim of the article is the proof of the small resistance of Carpathian sandstone tors on the activity of climbers. The threats to rock sites, and the damage caused by climbing, particularly to their natural relief, have only occasionally been recorded and studied. In this paper, the issue was considered regarding protected tors made of the thick-bedded sandstone-conglomerate complexes occurring in the Outer (Flysch) Polish Carpathians. Carpathian tors, particularly those which are small in size with walls that feature diversified morphology, have become particularly frequent sites for bouldering. The assessment of the effects of rock climbing was based on the author's earlier research concerning the preservation and origin of sandstone tors, thermo-humidity regime of their surfaces, as well as the creation and transformation of the weathering crust. Rock climbing activities result not only in the damage and destruction of micro-relief of tors, but they also speed up and disturb the course of natural weathering processes by forcing the exfoliation of the crust and intensifying the granular disintegration of sandstones. Irrespective of the protection status of natural rock forms, various kinds of climbing on them should be considered unethical, in the same way as painting graffiti or drilling to take samples. Within the promoted idea of geoethical education, a wide range of current and forecasted threats to the values of natural geological heritage should be considered.

Introduction

The surfaces of rock formations are exposed by the action of natural processes. They constitute unusually attractive components of landscapes in various climatic zones, lending peculiar beauty to them. They assist both the development of tourism and also various kinds of climbing sports. Usually, such uses are associated with economic benefits but also with threats to the environment and nature. As a consequence of the increasingly visible and documented results of excessive tourist activities, restrictions have been introduced but they do not solve this ever deepening problem (Giuliano, 1994). This particularly affects the most beautiful and accessible mountain regions, covered by protec-

tion under various categories of national and international schemes. In order to counteract the threats, the locations occupied by rare species of epilithic plants, as well as sites where rare animals nest and shelter, are often secured by protective measures. It is only on rare occasions that these measures are designed to prevent the progress in devastation of rock surfaces and their micro-forms caused by the sport of climbing, despite the fact that this types of damage are directly affecting the flora and fauna (Robinson and Williams, 2005; Robinson, 2007; Williams, 2007; Jodłowski, 2011; Alexandrowicz, 2014).

Over the past two decades, climbing has become ever more popular on natural moderately high sandstone rock faces which are considered the most suitable for a form of climbing called bouldering (Jodłowski, 2011). It consists of negotiating the rock wall from its base to the height of several metres without using safety gear but applying adhesion-improving agents, using the natural unevenness of the rock face and sometimes even artificially deepening or carving steps. These damages are being monitored on walls of numerous sandstone tors in the Carpathian Mts. One of the most frequently visited bouldering sites is the Forest of Fontainebleau near Paris, protected within a UNESCO Biosphere Reserve (Čeřovský, 2007; Jodłowski, 2011). The experience gathered there was used to develop the scale of difficulty in this sport, called the Fontainebleau scale – abbreviated as Font.

To date, there has been an insufficient amount of monitoring data that could be used to evaluate the rate and extent of damage to the relief of sandstone tors due to climbing. Photographic documentation which enables comparisons between the past and present state can be particularly useful for this purpose. From this, we can principally learn about the progressing and excessive succession of plants overshadowing the tors, as well as their fragments which fall off, are lost or are damaged by climbers. Known instrumental methods for long-term measurements (e.g., photogrammetry and micro-mapping) of weathered rock surfaces, have not yet been applied in the case of damage from climbing (Williams et al., 2000; Moses et al., 2014).

According to Polish legislation climbing on rocks protected as nature monuments as well as situated in nature reserves and in national parks is not allowed. However this regulation is not obligatory in landscape parks and areas of protected landscape so that a lot of valuable and interesting rocky forms stay still outside protection. For all that in the Flysch Carpathians, climbing activities, particularly bouldering, are pursued in 55 localities with c. 1000 climbing routes (Jodłowski, 2011). These are mostly situated in all nine existing rock reserves, as well as

Figure 1. Distribution of protected sandstone rocky forms in relations to climbing activity (after Alexandrowicz and Poprawa (eds.), 2000, supplemented; Jodłowski, 2011) on the main geological structures of the Polish Outer (Flysch) Carpathians and Central Carpathians (after Żytko et al., 1988–1989): 1 – national parks with rocky forms without climbing, 2 – nature reserves with rocky forms occupied by climbing, 3 – rocky forms as nature monuments occupied by climbing, 4 – rocky forms as nature monuments without climbing, 5 – Magura Unit, 6 – Dukla U., 7 – Silesian U., 8 – Subsilesian U., 9 – Skole U., 10 – Stebnik Stebnik U., 11 – Neogene deposits on flysch, 12 – Tatra Mts, 13 – Podhale Flysch, 14 – Pieniny Klippen Belt, BS – Nature Monument Brodziński Stones.

within 28 of the 40 protected nature monuments of this type (Alexandrowicz, 1978; Alexandrowicz and Poprawa, 2000; Alexandrowicz and Urban, 2005) (Fig. 1). These objects are easily accessible and offer diversified relief. In particular localities, the number of registered climbing routes range from several to twenty or so. In 2011, in some areas of rock reserves, several hundred passages were recorded. Perhaps the data pertaining to these activities (number of passages) is understated compared to the real numbers due to the limited restrictions imposed on climbers and their movements. Sometimes, rocky sites in as many as four national parks in a given area are used.

The long-term observation and multi-directional studies of sandstone tors occurring in the Polish Outer (Flysch) Carpathians provide sufficient data to explain the causes, courses, and outcomes of the destructive effects of climbing on the morphology of tor surfaces. The results, which are interesting from the viewpoint of the presented topics, principally pertain to the recording of threats and the protection status of the tors occurring there, as well as the thermo-humidity regime of rock surfaces, and the origin and transformation of their natural protective weathering crust.

Outline of geological setting and origin of sandstone forms in the Polish Carpathians

The Polish Outer (Flysch) Carpathians are the northernmost part of

the Carpathian Mountains. They consist chiefly of middle mountain ranges (800–1300 m a.s.l.) with its highest summit – Babia Góra (1725 m a.s.l.), intra-mountain basins, and foothills in the northern foreland area. The flysch formations of the Late Jurassic – Early Miocene age, developed as alternating variably-thick beds of sandstones, mudstones and shales, occasionally marls and hornstones, as well as thick-bedded sandstone-conglomerate complexes. Natural rocky forms occur on ridges, in upper parts of mountain slopes, and within the valley-sides. They are built by sandstone-conglomerate formations, classified to various lithostratigraphic units (Alexandrowicz, 1970, 1978). The sequences of these forms occur within nappes thrust over each other horizontally towards the north (Książkiewicz, 1972; Żytko et al., 1989; Oszczytko, 2006) (Fig. 1).

Natural sandstone exposures, particularly within the area of the Carpathian Foothill, show specific lithological, tectonic, and sedimentary features. These are formations of flysch composed mainly of thick-bedded, coarse-grained sandstones and conglomerates with a rare network of joints. They are composed of quartz grains with an admixture of feldspar, glauconite and muscovite. Sandstones are poorly sorted, with irregularly distributed cement, usually argillaceous, argillaceous-ferruginous, and more rarely calcareous-argillaceous, calcareous or matrix comprising fine clastic-clayey sediment. Conglomerates, apart from quartz, contain pebbles of hornstones, granites, metamorphic schists and other exotics of the pre-Carpathian origin. Particular complexes of thick beds are separated by thin-bedded shale-sandstone flysch.

Somewhere within the coarse grained beds, clay balls and ferruginous concretions are found. Rock beds show specific features in the form of various bedding and traces of erosion testifying to the sediments deposition processes in a deep-sea environment. The thick-bedded coarse-grained complexes and differentiated sedimentary structures are characteristic of the fluxoturbidites deposited by submarine sliding as mud/sand/gravel debris flows (Unrug, 1963; Ślaczka and Thompson, 1981; Leszczyński, 1989).

Because of their considerable thickness, the sandstone-conglomerate complexes became exposed in the relief of the Flysch Carpathians during their formation. The segmentation of rock massifs occurred along joints which underwent opening and turned into cracks. Particularly favorable conditions for the development of this process prevailed when long-term permafrost disappeared towards the end of the last glaciation in the Pleistocene (Alexandrowicz, 1977, 1978). At first, the gravitational disintegration of the originally compact rock massif had not been of the sliding type where packets separate from the substrate and move along a slope. The separating of rock forms followed during the gradually subsidence of the massif, divided along broaden joints and open fissures (Dikau et al., 1996).

The relaxation of conglomerate-sandstone complexes affected by retreating permafrost, their flysch clayey-sandy substrate, and the erosive deepening of valleys, markedly favoured the development of mass movements. In the Pleistocene and Holocene, intensively initiated relief-formation processes led to the lowering of the summit surfaces and the withdrawing of slopes (Baumgart-Kotarba, 1974). Within them, relatively more resistant, concretionary, and naturally exposed fragments of rocks were ultimately shaped by the processes of selective weathering into original forms occurring *in situ* chiefly in the Carpathian Foothill, or – relocated by the mass movements of various intensities – on steep slopes of the Outer (Flysch) Carpathians in Beskidy Mts and Bieszczady Mts (e.g., Lach, 1970; Alexandrowicz, 1978; Margielewski, 2006; Alexandrowicz and Margielewski, 2010). At present, despite the continuous transformation of natural outcrops, an evident link can be observed in numerous places between the morphology of walls and open fissures, and the running planes of joints.

Damaging of weathering micro-relief caused by climbing

The elements of relief occurring on exposed surfaces of sandstones are called weathering micro-forms or weathering micro-relief, whereas in the classification proposed by A.V. Turkington and T.R. Paradise (2005) they are included in the group of small-scale forms. Chemical, physical, and biological weathering processes participate in developing these forms. The effects of these processes depend on the lithology, mineralogical composition, as well as on the sedimentary and structural properties of the sandstones. The diversity of micro-forms indicates relationships between different weathering processes of rocks. Similarly developed weathering forms occur in various climatic zones and in a wide spectrum of rock types (e.g., Wilhelmy, 1958; Wiśniewski, 1983; Robinson and Williams, 1994; Adamovič et al., 2000; Mikuláš, 2007a; Goudie and Viles, 2008). It testifies to their polygenic origin. During more than 170 years of observations, fascination, and descriptions of these forms, various names have emerged (e.g., Mustoe, 1982; Turkington and Paradise, 2005; Mikuláš, 2007b; Robinson, 2007).

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Typical relief elements on the surfaces of Carpathian tors are thin ribs of relatively hard, cemented sandstone protruding from the walls, as well as the cavernous structures of different types and origins, referred to by many different names (Świdziński, 1933; Klimaszewski, 1932, 1947; Koszarski, 1962; Alexandrowicz, 1970; 1978, 2008; Kicińska, 2009; Strzeboński, 2009). The mentioned relief of sandstone walls is particularly characteristic for lithologically diversified small rock forms, usually five to eight metres high, rarely exceeding ten metres. Compared to these, the high rock walls, usually connected with landslides, are less modelled and clearly limited by planes of joints.

The principal objective of protecting the micro-relief of sandstone surfaces is to guarantee their natural course of further evolution under the existing climatic conditions. Climbing activities are currently one of the factors making this task more difficult. Examinations of technical (physical) properties of Carpathian sandstones where tors occur, revealed their low cohesiveness and remarkable porosity compared to other types of sandstone in the area (Bromowicz et al., 1976). The sandstones of tors usually show fairly low apparent density not exceeding the value of 2.6 g/cm³. They also have relatively high water absorption with their mean value in the range of 2–8% (Alexandrowicz, 1978). Despite their unfavourable physical properties, they have remained in mountain landscapes as relatively resistant fragments, exposed among different lithological types of thick sandstone complexes.

Thermo-humidity regime of rock surfaces

Depending on the prevailing meteorological (weather) conditions, rock surfaces undergo variable cycles of warming and cooling, as well as humidifying and drying. To date, the specific conditions of micro-climates which occur in the contact zone are only little studied (Turkington and Paradise, 2005). The great majority of such data has been collected in areas where climate shows large amplitudes of daily and seasonal temperatures (Hall, 1997; Lewkowicz, 2001). However, in relation to the growing sport of climbing, particularly in areas with sandstone tors that are especially vulnerable to degradation caused by climbing, these types of measurements are essential indicators of the potential dangers to the micro-relief of rock surfaces. This statement is emphatically supported by the measurements of temperature and humidity taken at 28 points located at different levels of height and exposure, conducted on two selected Carpathian sandstone tors differing in their shape and location with respect to the surrounding elements of land morphology (Alexandrowicz and Brzeźniak, 1989). The published data was obtained in ten cycles of measurements in one-hour (temperature) or two-hour intervals (humidity) throughout 24 hrs or only during the day in the summer from 1982 to 1986, in different weather conditions, as well as in a single cycle during winter (1983). The measurements were taken with the use of Assmann aspiration psychrometers, and purpose-made analogue thermometers with adhesive pads and semiconductor sensors. The weather conditions were also monitored throughout the measurements. Checking measurements led occasionally in later years didn't contribute essential corrections.

The regularities found in the distribution of the measured thermo-humidity parameters made it possible to evaluate their effect on the development of weathering processes in particular height-zones of the tor profile. In the warm seasons of the year, the lower portion of the

tor wall, up to the height of 2 m, has – irrespective of the wall exposure – the lowest temperature over 24 hrs, and the highest humidity, the latter coming chiefly from the capillary drawing of water from the substrate. The amplitudes of temperature and humidity between day and night are relatively the lowest there compared to the whole profile of the tor, and the temperatures in the day during the winter are the highest. In the higher part of the tor profile, there is a clear increase in surface temperature coupled with a simultaneously decreasing humidity, coming chiefly from atmospheric precipitation and the condensation of water vapour. The phenomena of humidifying and drying up the rock surface is repeated a number of times. In the highest part of the tor profile, the highest fluctuations in temperature and humidity occur over 24 hrs. The changeability of weather conditions within the 24-hour period manifests itself in particular portions of the tor profile principally in the diversification of amplitudes of the measured parameters.

Rock thermo-humidity and their implications for weathering

The natural protective layer, irregularly covering the surfaces of Carpathian tors, consists of a hard weathering crust, usually 1–2 cm thick, and – more rarely – several centimetres thick (Alexandrowicz and Pawlikowski, 1982; Rzepa et al., 2011; Alexandrowicz et al., 2012, 2014; Marszałek et al., 2012). It is composed of very thin laminae, macroscopically differing in colour, running either as a continual or broken layer, in parallel to the rock surface. This crust is a transformed zone of sandstone where pores were partly filled up by secondary minerals originating from the chemical decomposition rock and the migration of dissolved components towards the surface. The hardened zone is enriched chiefly with goethite, hematite, and amorphous silica. The iron contents are responsible for the diversified colouration of the weathering crust, and its hardness depends above all on the occurrence of amorphous silica. Also essential is the role played by the outer, black lamina which emerged as a result of air pollution, composed principally of sulphate incrustations and containing organic particles. The transformation of the mineralogical composition of the surface zone of sandstone walls caused by weathering agents proceeds very slowly, compared with the rate of this process in the architectural historic details (Wilczyńska-Michalik, 2004; Marszałek et al., 2014). In natural conditions, it enables the successive regeneration of damaged surfaces by developing a new protective crust. The weathering crust and co-existing weathering micro-forms are at a different stage of development, thus testifying to the continuity and progress of the process of transformation of the rock surface (e.g., Robinson and Williams, 1994; Čílek, 1997; Turkington and Paradise, 2005; Mikuláš, 2007b; Robinson, 2007; Alexandrowicz et al., 2014). The measurements demonstrated that the particular height-zones of the tors showed differences in the thermo-humidity regime of the exposed surfaces (Alexandrowicz and Brzeźniak, 1989). Apart from the lithology and porosity of the sandstone, this regime has a major influence on the diversification of the cementation of tors' surfaces and developing micro-forms within them. In the lower portions of tor walls, the crust is mostly poorly and fragmentarily developed. The humidification prevailing there, either permanent or periodical, favours both the strong effect of frost action and salt weathering. The progress of these processes leads to granular disintegration, and the exfoliation of sandstones, resulting in the rapid destruction of lower parts of tors. It chiefly per-

tains to the wall exposed toward the north and south which are characterized by the largest contrasts in the values of humidity and temperatures measured over 24 hrs. Furthermore, the rock walls maintaining permanent humidity are easily colonized by mosses, and the humic acids produced in their biochemical decomposition largely accelerate the weathering of sandstones. The intensive processes proceeding at the tor bases can lead to creating variably-sized niches, unstable overhangs, and narrowings giving the tors mushroom-like shapes.

Within the higher parts of tor walls, well-developed crusts with diversified weathering forms usually occur. This zone is subject to the frequent moistening and drying of the sandstone. With the passage of time, the cyclically repeated heating of the surface during the day and its cooling at night leads to the exfoliating and dropping of thick weathering crusts developed on poorly cemented sandstone. In the top parts of tors there is a phenomenon of most frequent cycling of rock temperatures through 0 °C which increases the local effectiveness of frost action. Stresses occur in the rock, which contribute to its segmentation along joints, and the horizontal stratification of beds. The environmental conditions on an uneven top surface favour the development of weathering pits having specific seasonal developmental cycles, dependent entirely on atmospheric precipitation and air temperature (Alexandrowicz, 1989).

Destructive effects of rock climbing

Climbing activities pursued on exposed sandstone walls result in accelerating and disturbing the course of natural processes of their weathering. On climbing routes, the morphology of rock walls is successively destroyed as a result of the forced exfoliation of the protective crust as well as of co-occurring weathering micro-forms and – as a consequence – the intensive disintegration of exposed, poorly cemented sandstone. The frequent manner of climbing on marked routes excludes entirely the regeneration of the weathering crust in such places. Its destruction prompts climbers to mark new, more suitable and more attractive routes for climbing.

The bouldering-type of climbing, increasingly often pursued on sandstone tors, is particularly destructive. Chosen of this an example is the Nature Monument “Brodziński Stones” situated in the middle part of Carpathian Foothill (Fig. 1 – BS), particularly the relatively large and effective rocky form called “Ship” (Fig. 2a). Different kinds of the degradation of rock faces can be observed here. In particular, it involves destroying the lower fragments of walls which are subject to particularly adverse micro-climatic conditions in any season of the year. In strongly overhanging places, rock falls are most numerous. The platforms and thresholds occurring at the tor bases which are initial parts of climbing bear the risk of permanent destruction. Bouldering with the aid of magnesia (hydrated magnesium bicarbonate) leaves unaesthetic white stains not washable by rain (Fig. 2b). Many climbing routes are permanently marked with coloured oil paints and engraved inscriptions (Fig. 2c), or – at some places – facilitated by carved thresholds. Various substances facilitating climbing result in the local sealing of the sandstone surface, thus hindering the free vaporization of moisture. In such conditions, the rate of increase of the weathering crust not yet completely destroyed, is markedly slowed down. The occasionally used mechanical removal of stains by scratching, forces their exfoliation, and the exposed sandstone poor in cement undergoes

Figure 2. Trace markers of climbing (bouldering) activity on walls of the rock called “Ship” (Nature Monument Brodziński Stones) in the Polish Carpathian Foothill (Fig. 1 – BS): (a) the rock “Ship” (view from SE), the relief reflects differentiation of lithology and sedimentary structures of the Istebna Sandstone Formation, numerous traces of destruction and exfoliation of weathering crust in the lower part of the tor; (b) damages to weathering crust along the route of bouldering marked by white magnesium on fissured rock corner at risk of fall off; (c) fragment of wall with natural cavities marked by red oil paint on the climbing route.

intensified disintegration. The protective crust is destroyed by climbing on the whole height of the wall when the former uses various permanent installations or impermanent safety points.

Final remarks

In view of the increasing popularity of climbing activities on natural rock walls, and the application of newer and newer possibilities of methods and techniques, the necessity has arisen to regulate them in ways that are individually adapted to particular sites. Regulations and bans on climbing should include not only sites of particular values and those that are legally protected, but also other rocky forms with low resistance to this type of use. Natural outcrops of sandstones showing a diversity of sedimentary structures and forms of weathering exposed on the rock surface by selective weathering are particularly popular sites for bouldering. These structures and forms are both convenient and safe points along the routes for negotiating the height of walls.

Destructive changes in weathering micro-forms on the exposed surfaces, being the consequences of climbing, are found in various regions of the world whenever rock landscapes occur. Unfortunately, they do not encounter strong opposition. At the same time, ever more numerous local climbing clubs are organized which illegally develop their activities that are also, and sometimes exclusively, in areas protected by regional, state, or even international laws. The protection of the

natural character of elements of nature and landscape has, after all, to serve the whole of society, and not to satisfy the individual needs of certain small groups of people.

Climbing activities should first be completely eliminated from areas where rock objects are a primary objective of protection. They should be attributed by regulations, scientific and didactic functions, as well as ensure properly controlled tourism. Any other kind of use of these sites definitely exerts a negative educational effect on visitors, particularly on young people, giving them permission for such improper conduct. Climbing can be exercised with full emotional satisfaction on artificial walls, especially those which are formed to mimic natural rocks. These are safer and more accessible than natural forms sometimes situated (e.g., in the Carpathians) in places that are far from centres of tourism.

Any activity causing the destruction of exceptional rocky outcrops and areas with natural landscapes regardless of their object and the protection status is unethical (Martinez-Frias et al., 2011; Druguet et al., 2013; Matteucci et al., 2014). When harming and destroying the morphology of rock surfaces shaped by natural processes, it becomes one of many signs of vandalism. Such activities show a lack of sensitivity to the surrounding nature and landscape, as well as a lack of awareness of the consequences of such conduct, generally stemming from a lack of knowledge of geological history and processes going on Earth. A widespread education on many thematic levels can successively contribute to positive changes more effectively than difficult-to-enforce bans. Geoethical education, promoted in the sphere of principles of proper conduct, should cover a wide spectrum of present and predicted anthropogenic threats to the values of geological heritage. Current threats to it come not only from activities consisting of drilling holes for taking samples, considered part of “*A Code of Conduct for Rock Coring*” (Robinson, 1989). Equal attention should be paid to the similarly damaging role of unethical rock climbing activities and careless graffiti, which are especially fashionable activities among certain groups of young people. Geoethical education is a constructive foundation for implementing all types of activities aimed at protecting our geological heritage.

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