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Residual rocky forms in the landscape of the Outer Carpathians (Silesian Beskid Mts, Poland) – geotourist and sedimentological case study

Ostańcowe formy skałkowe w krajobrazie Karpat zewnętrznych (Beskid Śląski, Polska) – geoturystyczne i sedymentologiczne studium przypadku

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Abstract: *This study investigated residual landforms developed within of the flysch bedrock in the Outer Western Carpathians as sandstone-to-conglomeratic tors. The studied relic rocky forms are locally exposed on the valley slopes in the top and plateau parts of the Silesian Beskid Mts. The cognitive values of such relic landforms, especially in the context of their morphogenetic traits and shaping of their macro- and microrelief, are well known and described. In contrast to epigenetic processes, the sedimentological aspect of the origin of such siliciclastic rocky deposits is still subject to different approaches in terms of terminology and interpretation. Thus, the aim of this study is to describe the conditions of environmental settings and character of the sediment transport and deposition processes from gravity flows, and to present a depositional system model for such a variety of flysch deposits. This study also attempts to present geotourist and geoeducational attractiveness of the tors against the background of regional geodiversity, geoheritage, and geoprotection. The results yielded a synthetic morpho-litho-sedimentological and geotouristic specification of the rocky forms analysed. The residual rocky landforms are polygenic geomorphological elements developed as a consequence of multistage and different scale of morph-forming activity operating on the basis of litho-sedimentological and tectonic assumptions under the influence of denudation processes.*

Keywords: *relict landform, sandstone-conglomerate tor, rocky geosite, geoeducation, geotourism, geodiversity, geoheritage, geoconservation, Carpathian flysch*

Treść: *Przedmiotem artykułu są ostańcowe formy terenu rozwinięte na bazie fliszowego podłoża skalnego w zachodnich Karpatach zewnętrznych jako skałki od piaskowcowych do zlepieńcowych. Omówione ostańcowe formy skałkowe lokalnie eksponowane są na stokach dolinnych w przyszczytowych i wierzchowinowych partiach Beskidu Śląskiego. Walory poznawcze, jakie ze sobą niosą, w szczególności w kontekście morfogenetycznym oraz kształtowania ich makro- i mikroreliefu, są dobrze poznane i opisane. W przeciwieństwie do procesów epigenetycznych aspekt sedymentologiczny pochodzenia takich silikoklastycznych utworów skałkowych jest natomiast nadal przedmiotem dociekań zarówno w kwestii terminologicznej, jak i interpretacyjnej. Celem badawczym artykułu jest zatem próba przybliżenia warunków środowiskowych ustawień, natury procesów transportu i depozycji osadów ze spływów grawitacyjnych oraz modelu systemu depozycyjnego takiej odmiany utworów fliszowych. Zamierzeniem autora było także przedstawienie geoturystycznej i geoedukacyjnej atrakcyjności skałek na tle regionalnej georóżnorodności, geodziedzictwa i ich geoochrony. W rezultacie przedstawiono w ujęciu syntetycznym specyfikację morfologiczną, litologiczną, sedymentologiczną i geoturystyczną badanych form skałkowych. Ostańcowe skałkowe formy terenu stanowią poligeniczne elementy geomorfologiczne rozwinięte w następstwie wieloetapowej i różnoskalowej działalności rzeźbotwórczej zachodzącej w utworach o określonych uwarunkowaniach litologiczno-sedymentologicznych i tektonicznych za pośrednictwem procesów denudacji.*

Słowa kluczowe: *ostańcowa forma terenu, piaskowcowo-zlepieńcowa skałka, geostanowisko skałkowe, geoedukacja, geoturystyka, georóżnorodność, geodziedzictwo, geoochrona, flisz karpacki*

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Introduction

Sandstone-to-conglomeratic tors, as attractive natural geosites rich in various qualities, are perfectly in line with the development of geotourism and the promotion of geoeducation (e.g., Słomka & Kicińska-Świderska, 2004; Alexandrowicz, 2008; Strzeboński, 2009; Słomka, 2013; Starzec *et al*., 2017, 2018; Welc & Miśkiewicz, 2019, 2020; Migoń & Pijet-Migoń, 2020; Alexandrowicz & Alexandrowicz, 2022). Such landscape components highlight the geological and morphological heterogeneity of abiotic nature and thus illustrate the exceptional value of the Carpathian geoheritage and the need for its conservation (e.g., Alexandrowicz *et al*., 2000). One such type of residual landforms is the tors in the Silesian Beskid Mts (Beskid Śląski) (e.g., Alexandrowicz, 1978; Słomka, 2013; Chybiorz & Kowalska, 2017; Starzec *et al*., 2017, 2018; Chybiorz *et al*., 2020; Sikora, 2022) that are built up of the lower part of the Istebna Formation deposits (*sensu* Strzeboński *et al*., 2017). Geologically, the denudational outliers developed on the Upper Cretaceous flysch bedrock within the Silesian Unit, which is part of the orogenic fold-thrust belt (continental accretionary prism) of the Outer Western Carpathians (Figs 1, 2) (cf. Golonka *et al*., 2000; Jankowski, 2015).

The origin of variously shaped relic landforms has been relatively well understood and described over decades of research (e.g., Alexandrowicz, 1978; Migoń *et al*., 2017; Michniewicz, 2019; Migoń & Pijet-Migoń, 2020; Duszyński & Migoń, 2022). Therefore, the subjects, such as geoeducational potential, geotourism development, and legal protection of rocky geosites in the Carpathians do not raise any doubts.

An interesting aspect of multifaceted studies on residual forms of rock formations – from the perspective of the ‘source’ (primary origin) of deposits that serve as their building materials – is process sedimentology (Shanmugam, 2000, 2021). In this aspect, a particularly interesting area of debate is the genesis of physical sedimentary processes responsible for the formation of rocky deposits. In particular, the sandstone-conglomerate flysch-type deposits are the subject of various sedimentogenic interpretations (see Strzeboński, 2015, 2022). In this domain, the main subject of discussion is the differing approach to the process nature of sediment gravity flows (*sensu* Middleton & Hampton, 1973, 1976) and their products, in addition to the terminology associated with them (e.g., Dżułyński & Ślączka, 1958; Bouma, 1962; Unrug, 1963; Lowe, 1982; Nemec & Steel, 1984; Postma *et al*., 1988; Leszczyński, 1989; Shanmugam, 1996, 2000, 2021, 2022; Gani, 2004; Talling *et al*., 2012; Leszczyński & Nemec, 2015).

Although genetic interpretations constitute an important element of scientific studies on this topic – owing to the possible changes in views (over time and with scientific progress) – they are of lesser importance to this study as compared to the factual materials provided (i.e., unburdened from the genetic implications at the stage of field sampling), which are generally not subject to such changes.

In the context of scientific focus, the main objectives of this study covered two aspects. First, this study is concerned with the presentation of rocky forms from the perspective of flysch geodiversity, emphasis on and preservation of regional geoheritage, popularisation of broadly understood geotourism, and promotion of geoeducation. Second, this study focused on the approximation of the nature of ancient sediment gravity-driven processes (genetic implications) through the lithological-sedimentological descriptive characteristics of rocky deposits (the practical portion), as well as the adjustment of deposit-process sets to the potentially corresponding models of system architecture forms (theoretical portion).

Therefore, in this study, it was assumed that: 1. the characteristics of the tors in the example of outcrops within the lower part of the Istebna Formation in the Silesian Beskid Mts contribute to the further popularisation and development of geotourism, as well as the promotion of a geoeducational approach to visiting this type of residual rocky landform; 2. documenting a set of empirical data concerning textural-structural features of the siliciclastic deposits that serve as the building blocks of tors will allow the interpretation/reinterpretation of sedimentary processes responsible for their formation and to present a depositional model.

The utilitarian results of the combined geotourist-sedimentologic case study of the relic Carpathian flysch landforms can be successfully approximated in a broader scientific and geoeducational aspect to similar rock formations and tors within a supra-regional scope. Therefore, the innovative approach initiated in this study should also significantly affect future research in the form of a renaissance of interest in the subject matter, continuation of the development of studies on many important levels (practical, theoretical, and experimental), in addition to numerous substantive discussions.

Administrative and geographic – geological settings

The rocky objects studied (geosites I–IV) (Fig. 1) are located in the commune of Wisła, which is part of Cieszyn County in the Silesian Voivodeship (Słomka, 2013). All selected geosites are legally protected and have been established as monuments of inanimate nature (Alexandrowicz *et al*., 2000). The abiotic objects are open to the public and have been given this status in order to protect the valuable landscape and natural values they present against anthropogenic destruction. The rocky forms in question belong to the Silesian Beskid Mts, along the westernmost range of the Western Beskids in Poland, which is part of the Outer Western Carpathians (Fig. 1) (Żytko *et al*., 1989; Kondracki, 2009; Richling *et al*., 2021).

Sediments accumulated in the Carpathian Basin, including those within the Silesian Sub-Basin, were involved in the Neogene geotectonic reorganisation (orogenic processes) of the Alpine Tethys (cf. Golonka *et al.*, 2000, 2008; Poprawa *et al.*, 2002; Jankowski, 2015; Szczuka *et al.*, 2022). Therefore, as a result of the Alpine orogeny, the flysch series underwent the following: folding, detaching from the parent basin substrate, overlapping in the form of regionally sized tectonic units (so-called nappes), and together were tectonically and gravitationally transported to the foreland, thus forming a continental accretionary prism of the Carpathian orogen.

The deposits building the rocky landforms in question represent one of the main lithostratigraphic subdivisions in the Silesian Unit of the Outer Carpathians (Figs 1, 2) (Burtanówna *et al.*, 1937; Unrug, 1963; Żytko *et al.*, 1989). In the Silesian Succession, the tor deposits occupy a position within the lower part of the Istebna Formation, which reaches its fullest development (up to 1500 m in thickness) in the Silesian Beskid Mts (Fig. 2). Based on previous micropaleontological studies (e.g., Burtanówna *et al.*, 1937), the age of the geosite deposits studied was estimated as Late Cretaceous (approx. 83–73 Ma) (Fig. 2).

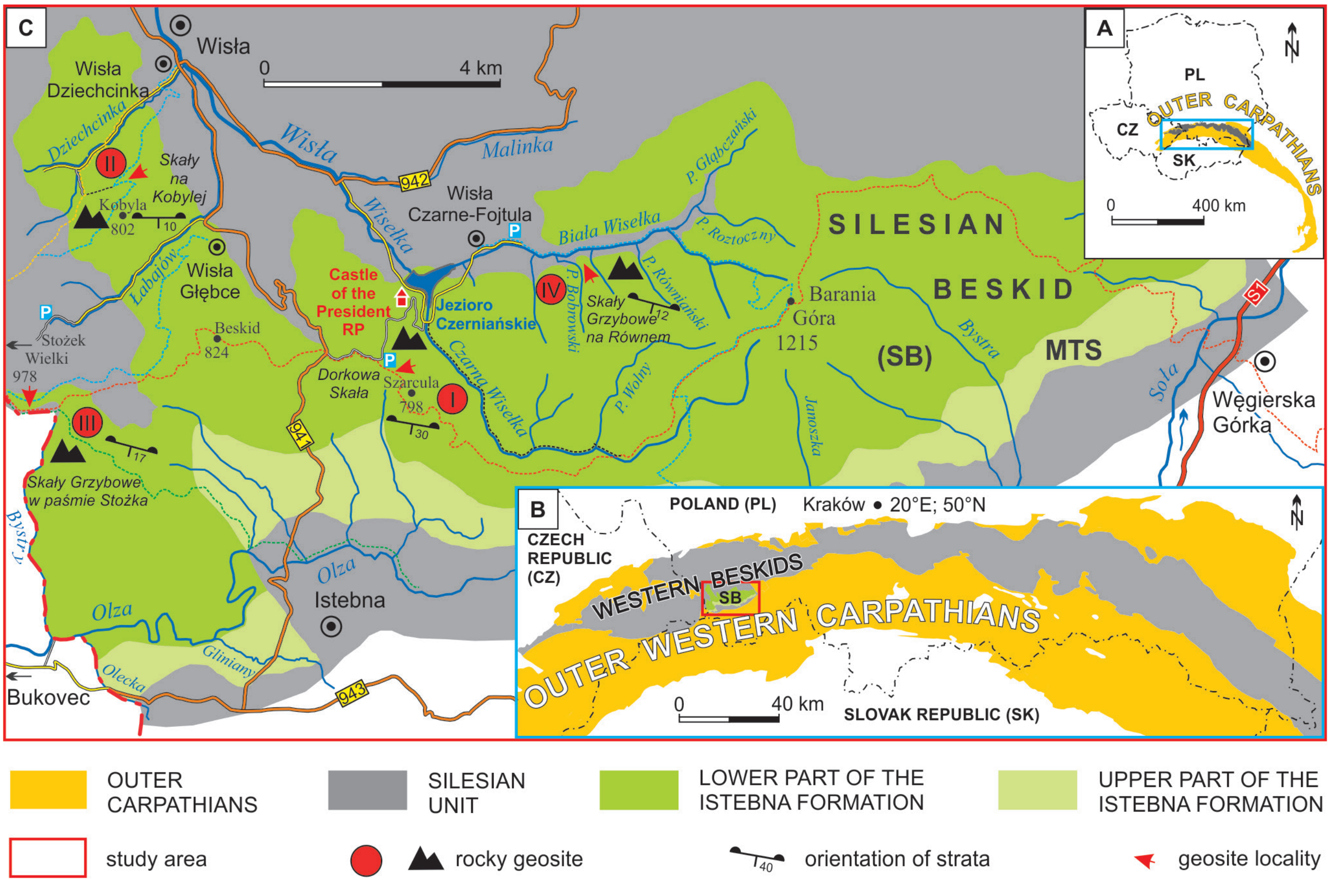

Fig. 1. Study area location maps: A – position of the Outer Carpathians (yellow belt) and the Silesian Unit (grey nappe) relative to the contour map of: Poland (PL), Czech Republic (CZ), and Slovak Republic (SK); B – location of the studied area (SB in red rectangle) on the background of the Silesian Unit in the Outer Western Carpathians; C – geological sketch map showing the occurrence of the Istebna Formation (IF) (lower part of the IF – dark green, and upper part of the IF – light green) in the territory of the Silesian Beskid Mts (SB) with an indication (red arrows) of the positions of rocky geosites (I–IV). Simplified and partly modified from: Burtan *et al.*, 1956; Burtan, 1972; Żytko *et al.*, 1989; Golonka *et al.*, 2000; Lexa et al., 2000; Strzeboński, 2015

Materials, methods, and outline of the concepts

Based on the earlier identification of geotourist objects in the form of residual sandstone-to-conglomeratic landform (i.e., tors built up of sandstones, gravelly sandstones, sandy conglomerates, and conglomerates) outcropping in the Silesian Beskid Mts (cf. Alexandrowicz, 1978; Słomka, 2013; Chybiorz *et al.*, 2020), a reconnaissance was carried out within the lower part of the Istebna Formation deposits.

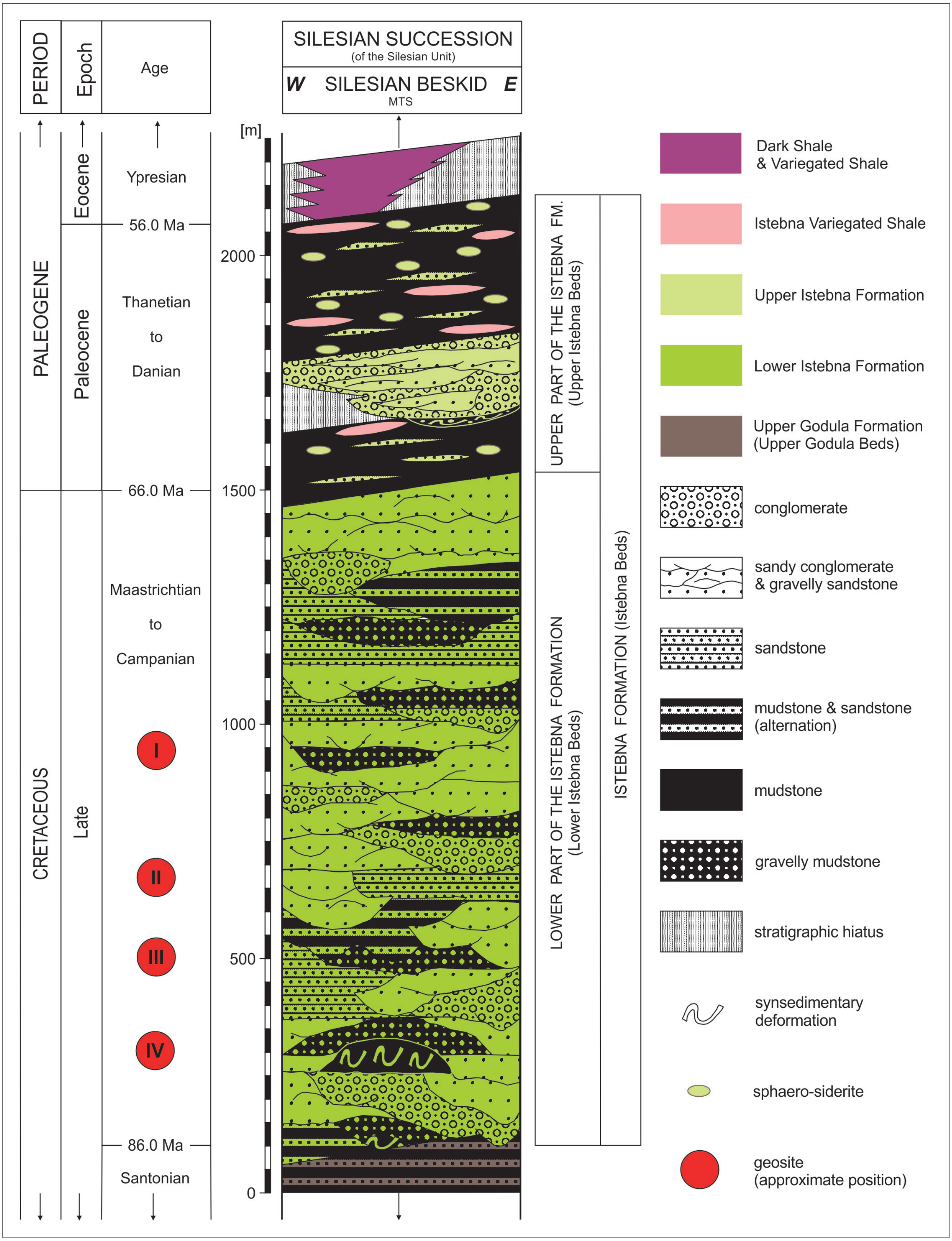

Fig. 2. Integrated lithostratigraphic column for the fragment of the Cretaceous–Paleogene part of the Silesian Succession in the Silesian Beskid Mts and accompanying explanations, with the approximate location of the sample geosite sections (I–IV) (after: Burtanówna *et al*., 1937; Cohen *et al*., 2013; Strzeboński, 2015; compiled and partly changed). For map location, see Figure 1

Among the numerous exposures of the coarse-grained siliciclastic deposits in the area studied (see also Strzeboński, 2015), four rocky geosites (Figs 1, 2) were selected for further detailed ('bed-by-bed') examination (Fig. 3) as characteristic and valuable examples of Carpathian relic rocky landform development (Figs 4–6). GPS coordinates of the geosites were taken from www.geoportal.gov.pl website (accessed: September 9th, 2022).

Tectonic observations within rock outliers were limited to measurements (Freiberger geological stratum compass) of bed orientation (dip direction/dip angle) and directions of tectonic crack planes (tectonic joints) (see Strzeboński, 2009). Geomorphological characterisation of the outcrop sections was carried out in terms of identifying and measuring the type of rocky forms as well as recognising the epigenetic macrorelief morphology of their outer surfaces. The geotourist aspect of the surroundings of the tors studied was characterised based on the author's own field observations.

The siliciclastic rocks were also characterised based on the assumptions of the facial sedimentological analysis (e.g., Słomka, 1995; Strzeboński, 2015; Strzeboński *et al*., 2017, p. 563) in combination with the research procedure of process sedimentology (see Shanmugam, 2000, 2021; Strzeboński, 2022). Given the research context presented, an attempt was made to link the features of lithological-sedimentological development of flysch deposits that serve as building layers of rocky forms with the geological processes potentially involved in their formation (the concept of process geology deduction). For this purpose, a set of critical determinants that characterise physical sedimentary processes (in this case, sediment gravity flows) was taken into consideration (cf. Dott, 1963; Sanders, 1965; Middleton & Hampton, 1973, 1976; Shanmugam, 1996, 2000, 2021, 2022; Talling *et al*., 2012; Strzeboński, 2022). From the perspective of the assumptions of fluid mechanics (e.g., Mezger, 2014), it is possible to develop a spectrum of specific sediment gravity-powered flows within broadly understood suspensions (multiphase water-gas-clastic systems). During the development of gravitational redeposition of non-coherent masses composed of clastic materials (grains), the basic factors determining the suspension centers and the associated development of characteristic sedimentary processes include the following: (i) primarily, the volumetric concentration of a qualitatively defined grain-fluid mixture (high *vs* low); (ii) further consequences in the form of rheological properties (e.g., non-Newtonian-like debris flows *vs* Newtonian-like turbidity currents); (iii) consequently, mechanical states of suspension behaviour (e.g., essentially laminar, i.e., debris flows *vs* turbulent, i.e., turbidity currents *sensu stricto*); and (iv) as a result sediment support mechanisms (e.g., matrix strength and/or dispersive pressure in case of debris flows *vs* turbulence in turbidity currents). These particular process determinants result in a specific way of transport and, above all, deposition of clastic material, diagnostic of a given sedimentary process, and *vice versa* (e.g., mass and frictional freezing in sandy-gravelly debris flows *vs* gradual and gravitational settling 'grain-by-grain' in muddy-sandy turbidity currents). Ultimately, this combination of factors has a direct impact on the sedimentary features of the resulting deposits. For example, massive sandstone-to-conglomeratic debrites are depositional products of sandy-to-gravelly debris flows (Strzeboński, 2015, 2022) (cf. also sandy debris flows *sensu* Shanmugam, 1996 or non-cohesive debris flows *sensu* Nemec & Steel, 1984; Gani, 2004; and Talling *et al*., 2012) *vs* normal single gradation (from bottom to top) within the simple bed (non-composite/non-amalgamated) with flute casts at the bed base, e.g., normally graded sandstone-to-mudstone turbidites as products of sandy-to-muddy turbidity currents, respectively.

Therefore, the sedimentological studies consisted of the following: (i) making direct observations in the sections of field exposures in the scope of different-scale development of textural-structural features of the deposits studied; (ii) collecting empirical data in qualitative, quantitative, semi-quantitative and vector forms; (iii) drawing up descriptive characteristics of the formation studied; (iv) statistical analysis of the obtained data for determining the thickness shares of particular lithological types of deposits (lithotypes), frequency of their occurrence, and average values of their thickness as well as ranges of variability; (v) comparisons of the factographic rock record with model features ascribed to particular sedimentary processes; (vi) comparisons of the observed characteristics with the results of the author's own modelling of the development of clastic gravity redeposition; and (vii) referring the results obtained to the types of well-defined models of depositional systems of clastic accumulation (e.g., Reading & Richards, 1994).

In order to achieve the research goal and verify the thesis assumed (regarding the sedimentological aspect) – in addition to theoretical considerations (determinants of sedimentary processes) – observations of empirically generated sediment-gravity flows were conducted under field conditions. The artificial release of sediment gravity flows (i.e., experimental) consisted of mechanically pushing clastic material into the lake waters (Jezioro Rożnowskie – Rożnowskie Lake). Portions of the material were released from the shoreline, from which they then propagated naturally by gravity along the slope, spreading and depositing in the depths of the lake (see also observations of underwater sandy flow modelling; Strzeboński, 2015, p. 205).

Approximately 10 L of edge/marginal clastic materials, only visually assessed for the overall grain composition (e.g., poorly sorted sands, sands with gravel-size clasts, or sandy-gravelly material rich in mud), were placed in operation at one time. The triggered clastic material was observed in terms of the development of runoff behaviour and the deposition effects, giving a visual feature of their nature.

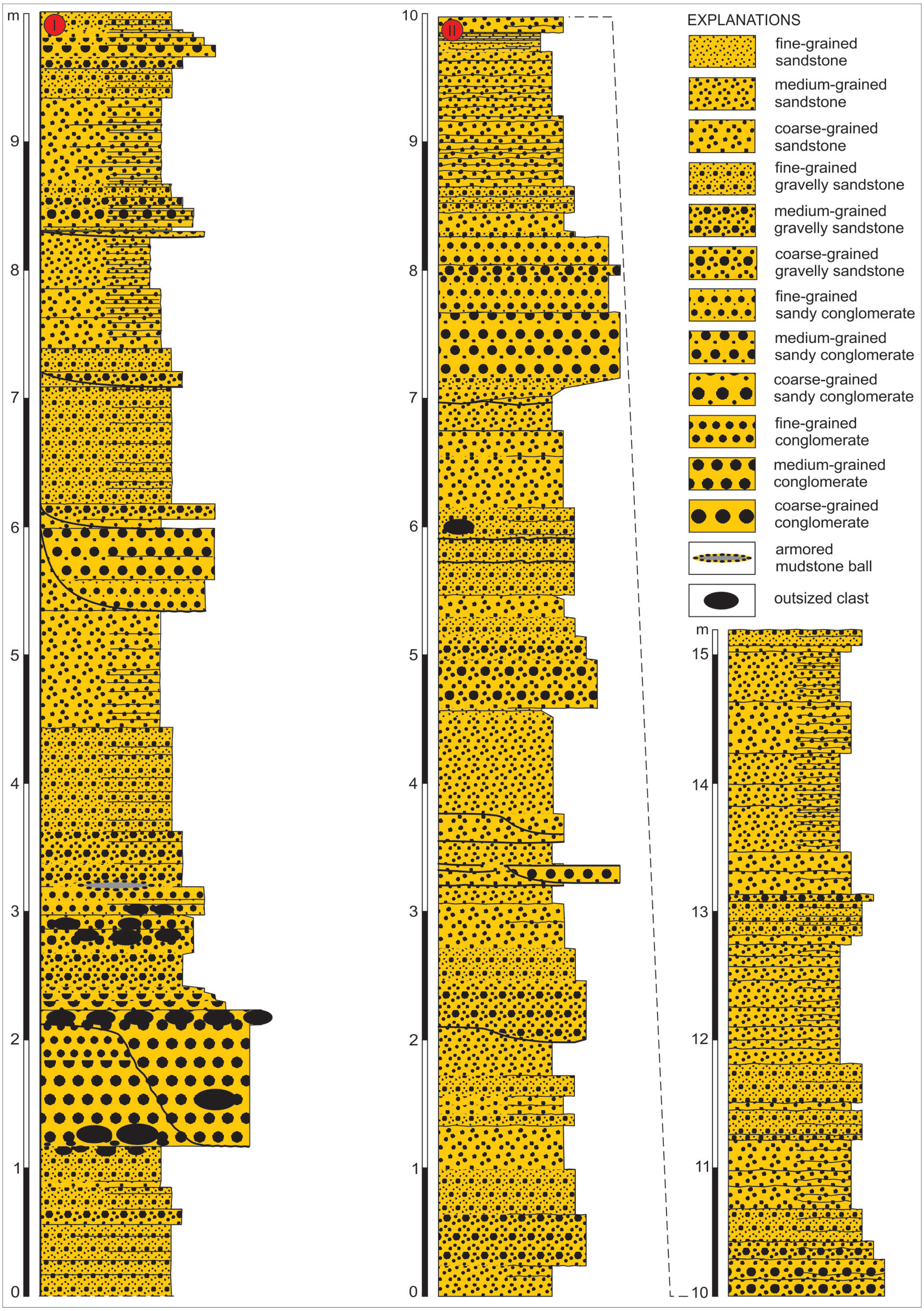

Fig. 3. Schematic lithological-sedimentological logs showing an example of the rocky form deposits in the form of the coarse-grained flysch-type siliciclastics which are representative of the lower part of the Istebna Formation in the Silesian Beskid Mts, with an explanatory key attached. For the overall position and lithostratigraphy of the profiles, see Figures 1 and 2

Fig. 4. Outcrop details of the studied rocky forms and panoramic view of the surroundings: A – general view on the Dorkowa Skała; B–D – enlarged views (from E to W, respectively) of the summit rock pulpit (for scale: 33 cm-long geological hammer in the white circle); E – panorama of the Silesian Beskid Mts, observed towards the N from the viewpoint below of the rocky form (visible are the Jezioro Czerniańskie and, on the left, among trees, the residence of the president of Poland); F – the Jezioro Czerniańskie from the side of the mouth of the Biała Wisełka (view towards the SW of the Castle of the President RP; cf. also Fig. 1). Photos P. Strzeboński unless otherwise noted

Fig. 5. Examples of flysch deposits in the lower part of the Istebna Formation and panorama of the area: A – the Skały na Kobylej; B – angular outlines of summit rock wall caused by joint planes; C – close-up view of irregular bedding; the sandstone-conglomeratic deposits of varying thickness occurring without mudstone intercalations; D – weathering zone (rusty-coloured) inside of the lower part of the Istebna Formation deposit; E – example of the use of the siliciclastic rocks of the Istebna Formation as a building material (one of the stone block of a cottage house has an inscription with the year: 1928); in the background there is a historic (1932) railway viaduct in Łabajów; F – panorama of the Vistula valley from the 'little bench of lovers' at the top of the rocky form Kobyla; G – the Skały Grzybowe w paśmie Stożka. Epigenetic structures (voids) are marked with white arrows; H – profile view of the mushroom type rocky forms (Fig. 5G)

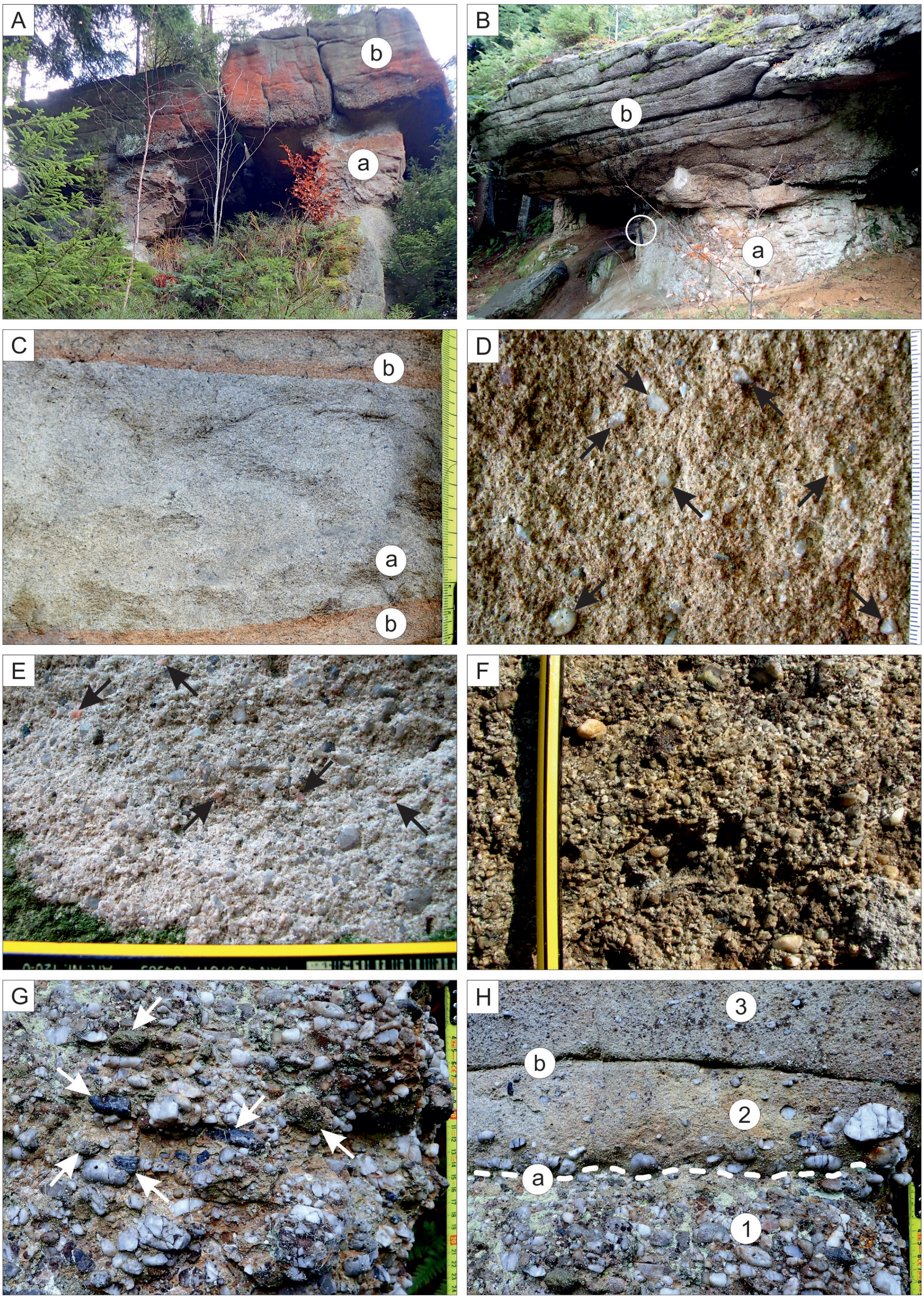

Fig. 6. Close-up textural-structural details of the rocky forms deposits: A – the Skały Grzybowe na Równem: a – 'stem', b – 'cap', view from the Dolina Białej Wisełki (cf. Fig. 1); B – the mushroom tors (pedestal rock) exposed from the side of the Potok Bobrowski (a – 'stem', b – 'cap') (cf. Fig. 1); C – coarse-grained sandstone typical of the siliciclastic rocks of the Istebna Formation: a – light grey colours (primary/diagenetic feature), b – rusty colours (secondary/epigenetic weathering); D – gravelly sandstone with massive structure (random fabric) visible as the lack of vertical sorting of different size grains; floating quartz granules (2–4 mm gravel) are indicated by the black arrows; E – massive (chaotic mix of a wide range of grain sizes in mass) arkosic (admixture of potassium feldspar grains indicated by black arrows) gravelly sandstone (unsorted and vertically unordered psamitic-psephitic grain material); F – sandy conglomerate with randomly scattered grains in gravel and sand size (overall pencil dimensions: 162.5 × 6.25 mm); G – massive conglomerate with sandy matrix- and clast supported fabric (examples of exotic rock clasts are marked with white arrows); H – flysch beds of three depositional events (layers number: 1, 2, and 3): a – amalgamation surface (1 + 2 = amalgamated/composite bed), b – bedding plane as interbed surface (3 = lower fragment of 22 cm-thick simple bed)

Although these field 'experiments' were performed without any specialist equipment, they visually allowed for a better general understanding of (i) the transport-deposit nature of analogous ancient sedimentary processes, (ii) the texture-structure development of their depositional products, and (iii) the forms of clastic accumulation systems, thereby constituting a potential corroboration for the actual theoretical assumptions, model reconstructions, and sedimentological interpretations considered in this study. As a result, the proposed genetic interpretation of sandstone-conglomerate development of rocky forms from the Silesian Beskid Mts may potentially be of use for consideration of similarly developed flysch siliciclastics from different Carpathian regions.

Results

Topographic location of the rocky landforms

The geosites distinguished in this study were as follows:

- Geosite I – the Dorkowa Skała (Dorkowa Rock) is a geotourist object (tor) located on the NE slope (about 800 m a.s.l.) of Szarcula peak, adjacent to the red tourist trail passing along the Kubalonka-Beskidek ridge through Stecówka to Barania Góra peak (Ram Mountain, 1215 m a.s.l.; Compass, 2020). The rocky landform described is located approximately 350 m SE from the car park on the Szarcula Pass and approximately 1 km SE from the Kubalonka Pass near Istebna–Wisła national road 941 (GPS: 49°36′04.30″N 18°55′06.47″E) (Fig. 1).
- Geosite II – the Skały na Kobylej (Rocks on the Kobyla), also known as the Krzakoska Skała (e.g., Compass, 2020) (colloquially called Krzokowa Skała, Krzokowska Skała or the Kobyla Skała (Kobyla Rock) are located in Wisła-Dziechcinka settlement. Its tors are located on the N side of the top of the Kobyla Góra (Kobyla Mountain, 802 m a.s.l.), also named Kobyła, adjacent to the blue tourist trail leading to Stożek Wielki peak (Big Cone) (978 m a.s.l.) (cf. Compass, 2020). An alternative route to the rock exposure is the yellow Adam Sabela trail, leading from the historic railway viaduct in Wisła-Dziechcinka, along the valley of the charming Dziechcinka stream, to the 'Na Chałupianki' housing estate (accessible by car), from where a steep, forested path leads directly to the site (GPS: 49°37′47.86″N 18°51′21.60″E) (Fig. 1).
- Geosite III – the Skały Grzybowe w paśmie Stożka (Mushroom Rocks in the Stożek Range), also known as Kiczory are located in the Wisła-Łabajów settlement. This group of tors is situated in the pass between Kyrkawica (973 m a.s.l.) and Kiczory (989 m a.s.l.) peaks, approximately 1.5 km SE from the Stożek Wielki peak (978 m a.s.l.) (Compass, 2020). The state border between Poland and the Czech Republic runs along the ridge of the pass (GPS: 49°35′42.15″N 18°49′55.48″E) (Fig. 1).
- Geosite IV – the Skały Grzybowe na Równem (Mushroom Rocks at the Równe) are located approximately 1 km from the car park in the Wisła-Czarne settlement. Outlier exposures continue along the southern slopes of the Dolina Białej Wisełki (White Little Vistula Valley) for approximately 500 m. Along the ridge and its slopes, which are delimited by the valleys of two forked streams – the Biała Wisełka and Potok Bobrowski (at the altitude of approx. 700 m a.s.l.; Compass, 2020) – a number of rocky denudational landforms have been exposed. Lots of other sandstone-to-conglomeratic tors nearby, in the form of 'pulpits' and rock thresholds, are also interesting and valuable in terms of cognition but they are located directly above the steep slope and several meters high rock wall of the Dolina Białej Wisełki, therefore visiting them can be dangerous (GPS: 49°37′07.82″N 18°57′27.50″E) (Fig. 1).

Morphological characteristics of rocky landforms

The following geosites were distinguished:

- The Dorkowa Skała (geosite I) is a bedrock exposure in the form of a rock pulpit (pol. *ambona*) (Fig. 4A) that developed along the ridge below the local summit (denudational outlier). The rocky landform is approximately 40 m long, 10 m high, and 3 m wide. The dip direction of the beds and their dip angle are 200° to 230° and 25° to 30°, respectively. As a result, the face of the rock pulpit is exposed from the N to NE. The geometric outline of the exposure clearly duplicates the well-marked planes of the joint system. The joint systems limiting the tor from the side of the exposed outcrop front (in the form of the rock threshold) also create smaller projections resembling 'watchtowers' (Fig. 4B–D).
- The Skały na Kobylej (geosite II) (Fig. 5A) form a rock wall (cliff) at the top of local hill (relief of the landform) which has been partly modified by anthropogenic activity (exploitation). The rocky form is approximately 75 m long, with a height of up to 15 m, and a few metres wide (at the top; Fig. 5F). The face of topographical relief (rock cliff) is generally exposed in the N direction forming a local cuesta. This arrangement, with the opposite direction of bed inclination (i.e. in the general S direction), favoured the local cuesta creation. The exposed front wall has a varied morphological outline. Along the front line, numerous bends and rock protrusions occur. Their shapes, which resemble turrets in defensive walls, reflect very clearly marked systematically intersecting planes of the joints (Fig. 5B).
- The Skały Grzybowe w paśmie Stożka (geosite III) (Fig. 5G, H) are a group of a denudational outliers that developed along the hill plateau axis. The natural rocky forms of the topography relief are shaped in the following forms: a ridge knickpoint with a rock platform (12 m long, 2.5 m wide, and up to 1.5 m high); a rock form resembling a table top (4 m long, up to 2 m wide, and 1.5–3 m high); and mushroom-shaped rocks (8 m long, up to 3 m wide, and 3–7 m high).

The tor, due to its separation by a joint, can also be treated as two separate rocky forms with a common stem placed on a platform base. Following the crest of the plateau towards the Kiczora summit, several outcrops of conglomeratic- and sandstone bedrock appear from under rock debris cover.

- The Skały Grzybowe na Równem (geosite IV) (Fig. 6A–B) are natural, mushroom-type rocky forms developed along the local ridge axis with heights of up to several metres. The other objects included in the group are: a perch, multiple pulpits, and a slope wall. The geometry of the crags reflects a system of intersecting joint planes.

Moreover, the common features of the rocky forms discussed (geosites I–IV; see Fig. 1) include the epigenetic (secondarily developed) structures observed on the wall surfaces (e.g., Alexandrowicz, 1978; Kicińska, 2009) (see also Strzeboński, 2009). On some surfaces of rock walls there are a number of different-scale (several to a dozen or so cm), more or less regular depressions (cavities) in the form of variously shaped caverns (e.g., Figs 4A–D, 5G, H and 6A, B) (cf. also Migoń *et al*., 2017; Migoń & Pijet-Migoń, 2020).

Cyclically developing weathering-erosion-cementation structures in the form of voids, the shapes of which resemble elements of building architecture (e.g. arcades), are the so-called arcade structures. Other isolated oval niches in the form of larger or smaller single bowls can be called bowl structures. Yet another type of surface depressions in the form of multiple contiguous, shallow, often flat-bottomed skeletal voids delimited by thin walls, resembling organic tissue or intercellular space, are the so-called cellular structures.

The characteristic features of the described rocky forms also include the epigenetic yellowish-rusty colouration present in the surface zone of sandstone-conglomerate deposits (Figs 5D, 6C) (cf. Alexandrowicz *et al*., 2014). Additionally, concentrations of iron compounds (also appearing secondarily) can be observed on weathered rock surfaces, for example in the form of impregnation, pseudo concretions, and limonite covers (i.e., limonitic crust).

Frequent elements of the surroundings of the rocky forms are debris covers. They formed on the slope below tors base and have the form of rock tallus. Such colluvial covers composed of sandstone-to-conglomeratic rock fragments, including blocks with diameters of up to several dozen cm (cf. Chybiorz *et al*., 2020; Sikora, 2022).

Interpretation of morphogenesis

Various rocky forms in the landscape of the Silesian Beskid Mts, constituting elements of the residual relief of the Outer Carpathians, are undoubtedly an example of a complex genesis and multi-stage origin. A number of interacting and interdependent factors and processes that developed in different proportions and with varying intensity at successive morphogenic stages had to be involved in the formation of residual rocky forms built of the sandstone-to-conglomeratic-type of flysch deposits.

The possibility of creating, modelling, and relative preservation over time of a variety of such tors was conditioned by precisely-defined qualitative and quantitative determinants (cf. Alexandrowicz, 1978; Strzeboński, 2009; Słomka, 2013; Migoń *et al*., 2017; Michniewicz, 2019; Migoń & Pijet-Migoń, 2020; Alexandrowicz & Alexandrowicz, 2022; Duszyński & Migoń, 2022). The basic factors determining the morphogenetic development of rocky forms included: (i) original textural and structural features, i.e. the variability of the lithological and sedimentological development of the beds affecting the differentiation of the susceptibility of individual rocky sections to weathering and erosion factors. The massive sandstone-conglomerate deposits, occurring in outlier forms essentially devoid of mudstone and claystone interbeds (intercalations) (e.g., Fig. 5C), are of particular rocky-forming importance; (ii) the closeness of joints (largely dependent on the lithotype and variable thickness of the beds) influencing, among others, the formation of angular outlines of tors (e.g., Fig. 5B), the formation of crevices, and the development of surface mass movements; (iii) the location of the rock outcrops in relation to the morphological surface, including plateau ridge, slope, or valley slope, in relation to the parameters of the elements of the layer deposition (horizontal position *vs* inclined, i.e. subsequent or obsequent); (iv) climate changes, including thermo-hygric and hydrological conditions (temperature-humidity-water relations) in relation to the nature and intensity of denudation processes (weathering, erosion and large-scale gravitational and hydraulic transport); and (v) selective epigenetic processes (dissolution of matrix components, exfoliation, suffosion, swelling clay minerals, and precipitation of mineral compounds from the solution) shaping the surface relief of rocks in small-scale (e.g. arcade structures, cellular structures, limonitic crusts, etc.).

The inclination of the rock layers is related to the orogenic processes, during which the flysch basin sediments were subject to deformations and tectonic-gravitational transport towards the foreland platform. As a result of tectonic detachment of sediments from the basin basement, their progressive folding and overlapping in the form of the so-called nappes (tectonic units), thereby forming the orogenic fold-thrust belt of the Carpathians (cf. Golonka *et al*., 2008; Jankowski, 2015).

The geometrical form of the outlines of such rocky relicts has been shaped based on the aforementioned system of systematically intersecting joint planes (fracture system). The genesis of the systematic fractures is related to the tectonic stress (tectonic joint) caused by the above-mentioned processes of Alpine orogenesis. The fracturing is also associated with the earlier (post-sedimentation) stage of sand and gravel sediment diagenesis (diagenetic joints).

The characteristic yellowish colour of rocks on weathered surfaces is related to the epigenetic oxidation and hydration of iron compounds originally contained in the binder of the detrital matrix. The infiltrating waters activate the dissolved iron compounds that migrate through the interconnected pore spaces, joints, and interbedding surfaces. In this way, iron structures (limonite impregnations and crusts) have developed at the sites of the descending flow/outflow of meteoric waters. Ferrous cementation is also an element of a secondary chemical binder (cement type) that strengthens the walls of newly developing epigenetic voids (e.g., in a cellular or arcade structure), thus slowing down the progress of their further destruction.

The effects of the currently developing selective weathering, erosion and cementation processes shape the specific surface relief of tors. The epigenetic structures of the rocky forms also often develop on the border of layers differentiated in terms of of textural and structural features, thus emphasising litho-sedimentological variability of the siliciclastic deposits.

The presence of rock debris (rock blocks sometimes exceeding 1 m^3) near the foot of rocky forms (tallus) stems from the superior relation of the landform to the morphology of rocky outliers and development of their deposits. Additionally, the coincidence of the following processes is important: the aforementioned joints, physical weathering (e.g., frost weathering/block and granular disintegration), biogenic weathering (e.g., vegetation entering rocks, which further enhances chemical decomposition and mechanical decay/root expansion), and processes of gravitational transport (i.e., mass wastings) such as rockfalls and rolling or slow creep.

Litho-sedimentological characteristics of rocky forms deposits

All the rocky forms presented are built of clastic rocks, i.e. sandstones to conglomerates (Figs 4A–D, 5 and 6). The sandstone-to-conglomeratic deposits have a light grey colour both on a fresh fracture and on a dry surface (Fig. 6C/a). On the surfaces of such deposits, in weathered zones with a thickness of several to several dozen centimetres, the colour changes to various shades of yellow, and sometimes orange, or even locally rusty (a characteristic feature of coarse-grained lithotypes of the Istebna Formation) (Figs 5D, 6C/b).

The main mineral component of such deposits are different genetic varieties of detritic quartz (mainly vein quartz). This quartz occurs in the form of sand-size grains and fine to medium-grained gravels (2–32 mm) with milky and light grey translucent colour (Fig. 6D). The siliciclastics usually have a macroscopically recognisable admixture of crumbs of pinkish (whitish weathering) alkali feldspars (Fig. 6E). An important, macroscopically visible component of such arkosic deposits is also muscovite in the form of tiny (usually fractions of a millimetre) silvery shimmering brocade-like plaques. The primary binder of these deposits is typically a detrital matrix. The layers of considerable hardness additionally have a chemogenic silica cement increasing resistance to weathering factors. As a whole, the detrital material is characterised by having relatively high mineralogical maturity but poor to moderate textural maturity (low to medium degree of sorting and roundness of the components) (Fig. 6D–H).

The rocky deposits are bedded (Fig. 5A–C). Usually, however, the recognition of the boundaries between simple beds (single sedimentation episodes) of medium- and coarse-grained siliciclastics is particularly difficult. This is due to the commonly occurring amalgamation, i.e. the joining of sandstone and/or conglomerate layers without mudstone and/or claystone intercalations (Fig. 6H/a). As a result, multiple sets of amalgamated simple beds form a multilayer clastic body with a complex internal structure (i.e., composite bed; Fig. 6H/1+2). The poorly discernible boundaries of the layers are often revealed by the developing interaction of weathering and erosion, which together accentuate the original surfaces of their separation. The bedding is also highly irregular. This is marked in the rocky profile by both the random decreasing or increasing thickness of successive layers/grain fraction sizes in an upward direction (no ordered depositional sequences) and lateral changes of bed thickness. A frequent phenomenon is the pinching-out of beds (sedimentary and/or erosional in origin), sometimes at a distance of only a few metres. Clastic bodies with a lenticular shape in cross-section, often in the form of interbeds coarser grained than the detritic surroundings, are also not uncommon.

Primary sedimentary structures can also be observed in the cross sections of beds. Simple beds (non-amalgamated) of sandstones and conglomerates generally show a random distribution of components (massive development) (Fig. 6C–H). Normally graded structure in terms of both matrix and grain skeleton (fabric) is rare in this type of deposits. Locally, normal grading may be marked in the highest part of some composite beds, directly above the dominant part with massive structure. The profile also shows cut-and-fill structures (erosional-depositional marks) (Fig. 3) in the form of relatively shallow (up to several dozen cm) wash-outs and slightly deeper (usually cutting through several beds) erosional chutes (ephemeral channels), usually filled with a material coarser than that of the surrounding area. Locally, on the border of sandstone and conglomeratic layers, there are also, the so-called armorerd mudstone balls in the form of flattened mudstone clasts (originally, before compation, spherical) with quartz gravels on their surface (Fig. 3).

A characteristic component of some flysch deposits, in particular of certain sandy and muddy conglomerates, are clasts of exotic rocks, i.e. of ‘exotic’ provenance, representing the parent rocks that comprise the source areas feeding the flysch series in the past (Fig. 6G) (cf. Burtanówna *et al.*, 1937). These so-called exotics occur in the Istebna Formation predominantly in the form of megascopically recognisable fragments of crystalline rocks (e.g., Unrug, 1963; see also Strzeboński, 2005, 2015; Starzec *et al.*, 2017, 2018; Gawęda *et al.*, 2019; Strzeboński, 2022; Szczuka *et al.*, 2022). In the region studied, the exotic clasts are mainly metamorphic rocks (mostly gneisses, granulites), to a lesser extent igneous rocks (primarily granitoids), and relatively rarely sedimentary rocks (e.g., hornstones or exceptionally limestones).

The remaining features of the rocky form deposits are as follows:

- The Dorkowa Skała predominantly (over 90% thickness share) (th. sh. – in brief) consists of thin- and medium-bedded deposits (from 3–10 and 10–30 cm, respectively), represented mainly by sandstones (>75% th. sh.). The rest are conglomerates (Fig. 3/I);
- The Skały na Kobylej are mainly composed of thin- and medium beds (74% th. sh., 3–30 cm), as well as thick layers (30–100 cm, 24% th. sh.). Gravelly sandstones (i.e., detritic rocks with a predominance of sandy fraction grains over the rarer clasts in gravel size scattered within the bed) and sandstones are obviously dominant (over 90% th. sh.). The remaining part consists of fine- to medium-grained matrix-supported sandstone conglomerates, i.e. clastics with psephitic grain framework (fraction clasts above 2 mm) and a rich psammitic matrix (sandy binder) (Fig. 3/II).
- The Skały Grzybowe w paśmie Stożka have mainly (85% th. sh.) medium to thick (10–100 cm) beds. The dominant deposits are sandy conglomerates (in total 82% th. sh.). The remaining siliciclastics are medium- and coarse-grained gravelly sandstones and sandstones (see also Słomka, 2013, p. 538–541).
- The Skały Grzybowe na Równem are developed as lithotypic associations of sandstones-to-conglomerates, i.e. sandstones, gravelly sandstones, sandy conglomerates, and conglomerates (for details see Słomka, 2013, p. 534–537).

Interpretation of sedimentogenesis

The nature and type of mineralogical components that comprise the rocky form deposits, i.e. psephitic to psammitic grains of detritic quartz, feldspar, and muscovite, primarily prove their terrigenous provenance. Such features of the clastic sedimentary rocks, together with their significant thickness (Fig. 2), also indicate the relatively high rate of denudation of the source area subject to heavy uplift and emersion. In particular, the arcosic character (admixture of alkaline feldspar) of siliciclastic sandstones and conglomerates suggests a type of landform originally rich in crystalline rocks of gneiss- and granitoid-types, as well as a relatively quick burial of such materials in the basin. In addition, the general textural immaturity of the grain components (poor rounding and low degree of sorting), further suggests their short-distance and short-lived transport (slope/base of slope sedimentation zone), as well as a sudden and rapid accumulation of large portions of mass-supplied material.

The origin of this type of material indirectly allows for the local presence of the aforementioned exotics in flysch deposits. Exotic clasts, in the form of metamorphic, igneous, and sedimentary rocks, originally derived from inter-basin terrestrial areas uplifted and emersed in the course of geotectonic reorganisation (orogenic half-graben–half-ridge system) (cf. Dadlez & Jaroszewski, 1994). Such ridges (cordilleras *sensu* Ksiazkiewicz, 1956), including the Silesian Sub-Ridge (alimentary area, e.g. for the Istebna Formation deposits in the Western Beskids) were mainly the basic source areas of the clastic material that was delivered to the Carpathian Basin (incl. the Silesian Sub-Basin) (Unrug, 1963, 1968; Golonka *et al*., 2000, 2008; Strzeboński & Uchman, 2015; Gawęda *et al*., 2019; Szczuka *et al*., 2022). Some of the exotics present in the flysch formations may also have come from the reworking of older parental clastic series (e.g., exotic conglomerates) building up fragments of the source area (Strzeboński, 2022). Clasts of exotic rocks also came from older flysch basinal series in which exotics were placed, undergoing uplift and destruction (as a result of tectonic uplift and relative regression) again providing building material for younger formations (Matyszkiewicz & Słomka, 1994, 2004), such as flysch recycling and exotic clasts from a secondary source/on a secondary place (Strzeboński *et al*., 2017).

The sandstone-to-conglomeratic deposits of rocky forms represent a type of proximal flysch created through sedimentary gravity events. Their genesis is related to the multiple collapses of the marginal part of the sublittoral zone (the 'shelf' edge) (cf. Porębski & Steel, 2006) overloaded with coarse-grained detritic sediments and their further redeposition down the slope of the sedimentary basin. In the initial stage of the development of gravity-induced processes, the mass movements were triggered mainly in the form of sandy-to-gravelly slumps. During the downslope transfer of clastic masses, they evolved mainly towards non-coherent (fragmented) sediment gravity flows in the form of sandy-to-gravelly debris flows (sand flow *sensu* Dżułyński & Ślączka, 1958, p. 218 or sandy debris flow *sensu* Shanmugam, 1996) (see also Strzeboński, 2015, 2022; Strzeboński *et al*., 2017; cf. Łapcik, 2018, p. 80). The depositional system for sandstone-to-conglomeratic debrites formed in such a way was a linearly fed, essentially non-chanellised (only with locally developing ephemeral chutes) submarine apron rich in sandy-gravelly debritic components (Fig. 7) (cf. Reading & Richards, 1994; Słomka, 1995).

The massive structure of such deposits (debritic flysch) is related to the above-mentioned multiple mass resedimentationn of the clastic material (mixing different-source and mixed-grain debris). The massive development, especially in combination with outsized clasts (including exotics) supported by matrix, apart from mass transport, also indicates that mass deposition of debris took place relatively rapidly as a result of the sudden frictional freezing (similar to grain flows *sensu* Lowe, 1982). This process resulted in there being no possibility of gradual, grain-by-grain gravitational segregation and settling of the sediment in the form of normally graded structure. Therefore, the phenomenon of clearly marked normal grading indicating progressive sorting and sedimentation of the clastic material through gravity from the turbulent suspension of turbidity current (normally graded turbiditic deposit), is relatively rarely observed among the deposits of rocky forms in question. Such characteristic features of the textural-structural development of the examined deposits confirm that they mainly are products of gravity-driven, high-concentrated, non-turbulent, matrix supported, cohesionless sandy-to-gravelly debris flows (Strzeboński, 2022).

The characteristic yellowish-to-rusty colour observed on the surface and in the weathered subsurface zone of the sandstone-to-conglomeratic rocky forms deposits is related to the chemical weathering of their primary components containing iron compounds (e.g., biotite). The iron-bearing components present mainly in the matrix, in the hypergenic zone, undergo epigenetic oxidation, hydration, activation in the presence of meteoric waters and secondary concentration, and cementation in the form of limonite impregnations or crusts.

Diagnosis of the accompanying geotourist attractions

- The Dorkowa Skała One of the accompanying, popular tourist attractions is the Castle of the President of the Republic of Poland in Wisła (Figs 1, 4E). The historic residence (‘palace’) in the modernist style (1929–1931) is located on the picturesque Jezioro Czerniańskie (Czerniańskie Lake) (Figs 1, 4F). Streams that flow into the Czerniańskie reservoir include the Biała Wisełka and Czarna Wisełka (Fig. 1). The Wisełka (Little Vistula) flows below the dam and together with the Malinka stream gives rise to the longest river in Poland, the Vistula (Wisła). It is also worth visiting the spa town itself, Wisła, and the Adam Małysz ski-jumping hill in Wisła-Malinka. The Church of Our Lady of Fatima in Stecówka is also frequented by many visitors, especially by pilgrims. From the geotourist point of view, the hike up the aforementioned valleys of the Biała Wisełka and/or the Czarna Wisełka to the peak of Barania Góra (1215 m above sea level) is interesting due to numerous geosites along the way. The trip to this peak, the second highest peak of the Silesian Beskid Mts, and the opportunity to admire the picturesque Beskid panorama is very attractive (Fig. 4E).
- The Skały na Kobylej. The blue and yellow trails are full of sightseeing attractions, leading along the Czantoria range to Stożek Wielki (978 m a.s.l.) (Fig. 1). At the top of the Kobyla one, you can also admire the beautiful view of Wisła (the Polish name of the river – Wisła – comes from the name of Wisła town). Next to the shelter, there is a very well-known (especially among winter sports enthusiasts), all-year-round chairlift station. The picturesque streams Dziechcinka and Łabajów with crystal clear water are situated at the foot of the hill of Kobyla Skała, bringing a long-awaited coolness, especially in the summer heat. Moreover, this geotourist site is accompanied by nearby attractions in the form of the aforementioned town Wisła and the ski-jump hill.
- The Skały Grzybowe w paśmie Stożka. This geotourist site is frequently visited by tourists on the nearby popular hiking trails connecting the towns of Jablunkov, Jaworzynka, Istebna, and Wisła. This geosite is accompanied by tourist attractions in the form of the aforementioned Stożek Wielki, which is an excellent vantage point, the PTTK shelter, and the chairlift. It is also worth visiting the aforementioned presidential ‘Castle’ with the accompanying buildings and the crest of the dam of the Jezioro Czerniańskie reservoir.
- The Skały Grzybowe na Równem. These rocky forms are accompanied by numerous geotourist attractions located in the Dolina Białej Wisełki (Fig. 1). They include, among others, cascading waterfalls formed on outcrops of the Godula and Istebna Formations with plunge pools developed below the rock thresholds (knickpoints). The undoubted attraction are the largest knickpoints, the so-called Rodło Cascades (see Strzeboński & Słomka, 2007). Parallel to the trails to Barania Góra (the valleys of the Biała Wisełka and Czarna Wisełka), there are educational nature paths marked with information boards. They present in detail the main elements of animate nature, thus they do not constitute a sufficient geodidactic aid.

Discussion

Geoeducation and geotourism process

The rocky forms accessible for visiting and accompanied with geoeducational information in the form of stationary boards and/or mobile references to websites (e.g., *via* QR codes) have unquestionable value of multi-level attractiveness. Rocky objects of this type are rich not only in aesthetic value, but also, and perhaps above all, in geomorphologic, litho-sedimentologic, and tectonic features. Such elements, from a geotourist point of view, constitute an excellent training ground for acquiring knowledge in the field of broadly understood Earth sciences. In such cases, visits to even individual geosites spontaneously contribute to the increased interest in geoeducation. Popularisation of geotourism in the context of the above-mentioned conditions leads to the promotion of the region, furthermore resulting in tangible socio-cultural and economic benefits. In favourable circumstances, once launched, local geoeducational and geotourist activities may create a supra-regional system of feedback loops, resulting in a specific tourist drive, that is, a ‘perpetual motion machine’ for the tourism industry and *vice versa*. Unfortunately, one downside of such a development is he lack of balance between the supply and geotourism-related demand. As a result, excessive promotion of geotourist attractions may lead to tourist overcrowding in the region and degradation of the natural environment. Therefore, it seems that the right course of action aimed at the development of geoeducation and geotourism is the sustainable promotion of geosites and their simultaneous geoprotection without trying to achieve economic gains ‘at all costs’. This kind of behaviour is a condition for preserving geodiversity and geoheritage for future generations.

Process geomorphology

Based on the concept of the formation and development of residual rocky landforms/formations and the author’s observations, it can be generally stated that the common denominator of the genesis of the sandstone-to-conglomeratic rocky forms (apart from the primary lithological-sedimentological and diagenetic factors) are primarily the effects of denudation processes developing on the basis of the tectonic conditions of the outer Carpathian flysch deposits and actively shaped topography (as part of feedback). Therefore, the involvement of different types and shares of weathering, erosion and transport (gravitational and hydraulic) of the weathered materials in the coincidence with the assumptions of the joint system (systematic cracks) and deposition of beds, and later also the location relative to the morphology of the area, led to the possibility of development and further transformation of the relict landforms. The joint involvement/coexistence of the above factors contributes mainly to the position settings of the rocky forms (e.g., plateau ridge, valley slope), the development of the geometry of such forms (in the three-dimensional system), including the formation of the characteristic shape of their outline, as well as the development of morphological features on the surface of rock walls (epigenetic weathering-erosion-cementation macro- and microrelief).

Currently exposed sandstone-to-conglomeratic tors in the Silesian Beskid Mts usually occur as single or grouped, autochthonous elements of positive land relief. These types of morphologically convex objects were shaped without losing contact with the parent flysch bedrock. There is no doubt, however, that such natural outliers as local exposures of a specifically developed flysch have been distinguished within the much more widely spread and similarly developed Carpathian deposits. That is, in the geological past, before denudation processes, the assistance by specific climate conditions (e.g., hygric-thermal and hydrological processes) or sometimes of anthropogenic activities led to the formation and present exposure of the tors (as denudational outliers); there was generally a laterally continuous relatively homogeneous rock cover between them.

Process sedimentology

A characteristic structural feature of sandstone-to-conglomeratic rocky forms, observed in the stratigraphic sequence (usually in a vertical arrangement, i.e. horizontal or more often slightly inclined), is their bedding. Such stratification, in the case of coarse-clastic flysch deposits, however, is usually relatively irregular and not clearly marked. The irregularity is manifested laterally by the variable thickness of the individual beds (reduction in simple layer thicknesses/undulations), as well as by their lack of continuity (simple bed pinch-outs). On the other hand, discrete bedding occurs especially in the case of repeated individual acts of sedimentation of sand and/or gravel material, between which there was no accumulation of fine-clastic sediment (e.g., mud). Then, due to the lack of mud supply or its permanent preservation in the form of a layer (due to submarine erosion of previously deposited mud/mudstone), coarse-grained layers were joined, i.e. their amalgamation occurred. Such a set of amalgamated simple beds, in the case of already lithified deposits (solid rock layers after diagenesis), in the form of sandstones and/or conglomerates only, then forms ‘one’ composite bed (often many metres thick). A clear (well-defined) boundary between such composite beds is generally only possible to define after the appearance and preservation of the separating mud material (present in their ‘bases and tops’, i.e. at the beginning and end of the composite beds).

Due to the common phenomenon of the amalgamation of simple beds of sandstones, gravelly sandstones, sandy conglomerates, and/or conglomerates, their sedimentation boundaries (beginning and end of an individual deposition acts) are almost undetectable. The weathering and erosion processes that developed more intensively on the natural inter-bed surfaces are helpful in identifying the amalgamation of such layers. They make the sedimentation and/or sedimentation-erosion boundaries more visible. Proper recognition of simple beds within the composite bed is the basis for the correct description of sedimentary structures, and thus for the correct inference about the origin of the processes responsible for their formation. This poor readability of the boundary surfaces of coarse-grained amalgamated simple beds (sometimes treated collectively in different sets as ‘one’ bed) is also the reason for various interpretations and drawing false conclusions about the origin of this type of deposits.

Such repeated sandstone-to-conglomeratic composite beds form even thicker (tens of metres), relatively homogeneous complexes (complex series) which together form clastic apron covers (Fig. 7). Clastic lithosomes of this type also coalesced further, merging on an even larger scale, ultimately forming a linearly developed flysch depositional system in the form of deep-water apron system (Strzeboński, 2022) rich in sand and gravel material on the basin slope and at its base (Fig. 7) (cf. Reading & Richards, 1994; Słomka, 1995).

A special case of rocky deposits are simple beds of non-clayey sandstones with developed single normal grading from bottom to top. These actual normally graded sandstones, found locally in rocky forms between massive sandstone--conglomerate beds (deposits of sand-gravel debris flows), are an example of sandstone turbidites. Such ‘clean’ turbiditic sandstone indicate the following: the triggering of a relatively short-term turbulent suspension (due to the substantial lack of clay particles which effectively support the turbulention mechanism), gravitational sorting of the clastic material (in terms of grain size and density), and its gradual settling from a turbidity current.

The presence of grains (clasts) larger than the average size can be observed locally at the bed bases in the axial parts of wash-outs and erosional channels fillings (‘similar’ to the lag in the axis of some riverbed). Coarser clasts may also form lag on the bed surface (detrital residuum after washing/removal of finer material) as a result of reworked sediment *via* bottom currents involving the traction process. Gravitational rolling of the gravels down to depressions is also taken into account.

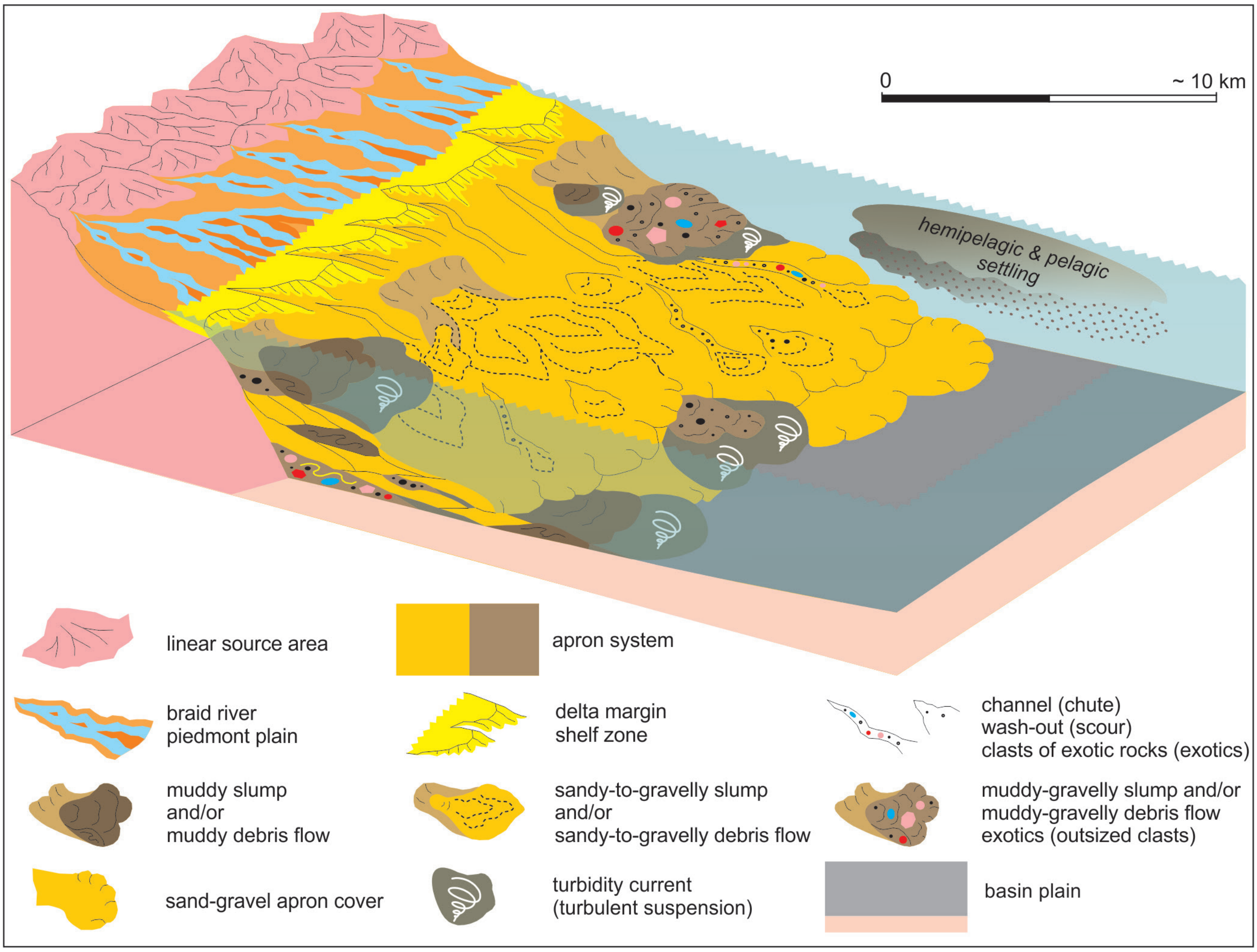

Fig. 7. General model of deep-water depositional system in the form of a linearly supplied submarine apron dominated by sandy-gravelly and muddy-gravelly debris flows (after Reading & Richards, 1994; Strzeboński, 2009, 2022; partly modified)

Such discontinuous laterally (lenticular) accumulation of coarser-grained (from the surroundings) clastic material together with the overlying finer-grained detritic mass does not constitute jointly normal grading *sensu stricto* in this context (i.e., they only resemble simple bed of 'normally graded turbidite'). However, the most common case is the apparent pseudonormal grading observed in amalgamated complexes composed of massive sandstone-to-conglomeratic deposits. This situation occurs particularly in case of very thick composite beds composed of the lower massive conglomerate and the upper massive sandstone. With such a random combination of the effects of different depositional events/episodes – *de facto* two simple beds, sometimes it may be preceded by partial erosion or a shorter or longer period without deposition. In this case, a massive deposit in the form of conglomerate or sandy conglomerate bed overlain directly (without mudstone) with massive gravelly sandstone or massive sandstone, amalgamated together, creates the impression of a 'single normally graded bed'. Accurate observation and the method of multiple sampling and comparison of the grain size samples and sedimentary structures along their profile (rather than only the traditional comparison of the sample fraction from the 'bottom' and 'top' of such a composite bed), confirm the false gradation. This procedure also helped capture the amalgamation boundary/surface, and not to mention the importance of such a distinction for interpretation, i.e., two debrites *vs* pseudo normally graded 'one turbidite'.

The wider context of the relationship can be described as follows: (i) approximately latitudinal occurrence of the lower part of the Istebna Formation deposits, along with (ii) their laterally continuous distribution, (iii) their similar style of litho-sedimentological development also outside the Silesian Beskid Mts (cf. Unrug, 1963; see also Strzeboński & Uchman, 2015; Strzeboński *et al.*, 2017), and (iv) the measured sedimentary paleotransport generally from the S and SSW directions (especially in conglomeratic channels fillings less prone to progradational twisting), does not allow for the interpretation of such features as filling of the central channel of a point-fed submarine fan (*sensu* Reading & Richards, 1994).

Although deposits developed in such a way may appear in an almost identical form (textural and structural) in the central channel of the fan system, such a model does not allow for the presence of a number of directly adjacent main channels of this type. Such a condition would have to be met for the effect of regional lateral continuity of sandstone-to-conglomeratic massive deposits. In addition, the lack of the development of depositional lobes (necessary elements of building deep-marine fans) formed at the mouth of the channels (see Strzeboński, 2022), indicates even more strongly the impossibility of using the submarine fan as interpretation of depositional system model in this case.

Based on the entire development of the siliciclastics studied (e.g., Fig. 3), the author postulates the previously mentioned model of the linearly- and mass supplied with sandy-gravelly flysch material, i.e. in the form of aprondepositional system (Fig. 7). The basic foundational unit of such a deep-water system are irregular and massive clastic bodies (single 'tongues' of rock debris). These sedimentation units developed during multiple gravity redeposition of sandy-gravelly material that was mass-transported and mass-deposited (freezing en-masse) *via* non-cohesive debris flows (cf. Nemec & Steel, 1984; Shanmugam, 1996, 2021; Gani, 2004; Talling *et al*., 2012; Strzeboński, 2015, 2022). As indicated above, debris tongues in the form of single, irregular beds were amalgamated, forming apron covers. In the edge zone of the shelf (*sensu* Porębski & Steel, 2006) and proximal slope, within such clastic covers, ephemeral erosional chutes, which could resemble fan channels, were also locally formed. However, at the outlet (mouth) of such channels there were formed not turbiditic, regularly layered depositional lobes, consisting of alternated deposits as follows: sandstones (with normal grading and flute casts, i.e. turbidites) and mudstones (normally grained hemipelagites), but with lobelike lithosomes, consisting of massive, irregularly bedded and amalgamated coarse-clastic bodies (debrites). Additionally, the scale of the lithosomes (at least an order of magnitude smaller) completely differed from the typical geometry of lobes belonging *sensu stricto* to the above-mentioned submarine fans. Consequently, in the sedimentological investigation of rocky forms deposits and their interpretation in single exposures (in particular the systemic accumulation model), apart from the 'point' interpretation (meaning limited to a local, currently isolated exposure of a single rocky form, e.g. tor, or a group of such forms in one place, or even a quarry), the broader context of the formational development of such deposits and their range according to lateral field analysis, along with the clastic material paleotransport distribution patterns, should also be taken into account.

Conclusions

One of the geotourist attractions of the Outer Carpathians are sandstone-to-conglomeratic rocky forms. The tors built of these siliciclastic rocks, separated within a specifically developed Carpathian bedrock, are occasionally exposed in the slopes of valleys and the ridges of plateaus within the Beskids Mts and the Carpathian Foothills. These types of flysch residual landforms are not only distinguished by their scenic and natural attractiveness, but also have significant didactic and scientific value. For example, relic rocky forms together with their building materials are one of the valuable sources of knowledge about the processes that have been dynamically shaping the Earth's surface, both in the past and today. The geological and geomorphological history recorded in such tors and the possibility of an excellent insight into their spatial (three-dimensional) image including their lithological-sedimentological development (rock textures and structures) confirm their significance in research. Various rocky forms developed selectively in the Silesian Beskid Mts, in particular in the Upper Cretaceous flysch (Fig. 2) represented by outcrops of the lower part of the Istebna Formation sandstones and conglomerates. The flysch tors investigated are clearly of a polygenic origin. After the complex sedimentation-tectonic (basin-orogenic) stage of the evolution of their deposits, the most important for the formation of rocky forms was the shaping of the bedrock through the processes of multi-scale weathering, erosion and transport of weathering waste (denudation process). Denudation in turn, had to develop in a selective manner in time and space with a specific intensity in relation to the specific meteorological and hydrological conditions occurring in the Beskids Mts.

In particular, the possibility of developing and modelling these rocky forms was conditioned from the following aspects, among others: (i) sedimentologically – e.g. by the type of lithology, thickness, and bedding, as well as sedimentary structures and diagenetic fractures; (ii) tectonically – according to the joint assumptions, dip direction, and dip angle of layers; (iii) climatically – based on the predominant type of weathering, type of erosion and hydraulic transport of the weathered material (including the development of the river network); (iv) gemorphologically – according to the location of the rocky forms in relation to the landform elements; and (v) gravitationally – by surface mass wasting processes, e.g. in the form of, for instance, creeps, landslides, and/or rock falls.

Sandstones and conglomerates also perfectly highlight the geodiversity of flysch development, thus allowing the tors to be studied and entered on the list of the Carpathian geoheritage. Therefore, these rocky objects, when made accessible and properly maintained, can be broadly recommended as attractive tourist geosites. Properly prepared, such geotourist attractions can successfully encourage interest in the science behind the abiotic processes that shape the Earth's surface (dynamic geology/geomorphology). This, in turn, will allow for the popularisation of geoeducation and increase the interest in geotourism, consequently contributing to the promotion and development of the region.

Sedimentologically, the features of the textural and structural development of sandstone-to-conglomeratic deposits characteristic of this lithotype varieties of the Carpathian flysch, within which the rocky forms were formed are also a very important paleorecord of environmental conditions, sedimentary processes, and depositional systems. Among the particularly diagnostic features of the rocky deposit association, allowing to unambiguously define and delineate its genesis, is the psammitic-psephitic textural development, which is mainly associated with a massive type of sedimentary structure, irregular bedding, widespread amalgamation, and parallel-oriented (not radially oriented) records of paleotransport directions.

A set of such characteristics representing the flysch siliciclastics studied implies the following: (i) the formation of clastic components of the psammitic and psephitic fractions under conditions of strong tectonic involvement of the land source area (intensification of the compressional regime in the region); (ii) the intensification of the development of weathering, erosion, and transport factors in the alimentation area as a result of its intensive uplift and emersion (elevation); (iii) the production of a significant amount of coarse-grained terrigenous material, being the result of the interaction of the above tectonic and denudational processes; (iv) the overloading, overburdening, and loss of stability of slopes in the ‘shelf’ edge zone, being the consequence of the supply of very large amounts of clastic material in sand and gravel size from the source area to the sublittoral (shallow water/coastal) zone; (v) the triggering, type, and course of sedimentary events in the form of submarine slumps and specific sediment gravity flows, supported by relative (tectonically forced) regression of basin waters; (vi) the dominance of cohesionless debris flows that massively and non-turbulently transported as laminar plug and en-masse deposited by frictional freezing of non-sorted sandy-gravelly material; (vii) the repeated gravitational resedimentation of such clastic masses ultimately deposited under deep water environmental conditions in slope and base of slope settings; and (viii) the way of delivery and type of material jointly shaping the form of the flysch depositional system, i.e., linear supply (approximately perpendicular to the oblique to the main axis of the western part of the Silesian Sub-Basin) with components rich in sand and gravel fractions which uniquely define the deep-sea apron system.

Sandstones and conglomerates representing the above features, with as emphasised, a characteristic lack of mudstone shale intercalations (leading to the amalgamation of coarse-grained beds), in coincidence with tectonic conditions and with appropriate morphological exposure are especially predestined to create rocky forms due to their lower susceptibility to destructive denudational factors.

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