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## GEOEDUCATIONAL TOOL FOR GEOTOURISM NEEDS – A FILM ILLUSTRATING THE ORIGIN OF SANDSTONE-CONGLOMERATIC DEPOSITS OF THE CARPATHIAN ROCKY FORMS

The relic landforms of the Carpathians, developed in the form of amalgamated massive sandstones and conglomerates, represent the so-called Carpathian flysch. Considering that, in research on deep-water clastic sediments there is a paradigm of turbiditic genesis of massive flysch-type deposits and there are also views on a possible non-turbiditic origin of such siliciclastic lithofacies, researches have been undertaken to clarify their actual process-based genesis. Conducted flume experimental modelling has made it possible to document the transport-depositional mechanism responsible for the formation of massive sandy-gravelly sediments and the development of their accumulation system tract. The creation of an interactive geo-educational tool as a film with geointerpretation has enabled a comprehensive clarification of the controversial sedimentological interpretations of such developed rocky forms deposits. Observations of linearly supplied mass sediment gravity flows generated under laboratory conditions, which resemble subaqueous sandy-gravelly ‘avalanches’, suggest that tor deposits originate from laminar (non-turbulent) debris flows taking the form of tongues forming clastic covers in an apron system. The massive products of gravity-driven redeposition processes of sandy-gravelly material should be termed sandstone-conglomeratic debrites, i.e., non-cohesive debrites (rather than turbidites or fluxoturbidites).

### NARZĘDZIE GEOEDUKACYJNE NA POTRZEBY GEOTURYSTYKI – FILM OBRAZUJĄCY POCHODZENIE PIASKOWCOWO-ZLEPIĘNCOWYCH UTWORÓW KARPACKICH FORM SKAŁKOWYCH

Biorąc pod uwagę, że w badaniach nad głębokowodnymi osadami klastycznymi funkcjonuje paradygmat o turbidytowej genezie masywnych utworów typu fliszowego oraz obecne są poglądy o możliwym innym niż turbidytowe pochodzeniu takich litofacji silikoklastycznych, podjęto prace mające na celu wyjaśnienie ich faktycznej genezy procesowej. Przeprowadzone eksperymentalne modelowania korytowe pozwoliły na udokumentowanie mechanizmu transportowo-depozycyjnego odpowiedzialnego za powstanie masywnych osadów piaskowo-żwirowych. Stworzenie interaktywnego narzędzia geoedukacyjnego w formie filmu z geointerpretacją umożliwiło kompleksowe wyjaśnienie kontrowersyjnych interpretacji sedimentologicznych. Obserwacje generowanych w warunkach laboratoryjnych liniowo zasilanych, masowych spływów grawitacyjnych osadu o charakterze subakwalnych „lawin” piaskowo-żwirowych sugerują, że utwory skałkowe powstawały z laminarnych (nieturbulentnych) spływów rumoszowych przybierających formę jeziorów formujących pokrywy klastyczne w systemie fartuchowym. Masywne produkty procesów grawitacyjnej redepozycji materiału piaskowo-żwirowego powinny być zatem określane mianem debrytów piaskowcowo-zlepięncowych, tzn. debrytów niekohezyjnych (a nie turbidytów czy fluksoturbidytów).

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## 1. INTRODUCTION

Based on the experience of previous turbidity flows modelling and their satisfactory results [1–3], an attempt was made to experimentally reproduce another type of sediment gravity flow – sandy-gravelly debris flow [4, 5]. A characteristic feature of such flow products – sandy-gravelly debrites – is primarily the massive structure (i.e., in the form of randomly dispersed grains in a background of detrital matrix) [4–32]. Such developed debritic deposits commonly form the sandstone-to-conglomeratic residual rocky forms of the Outer Carpathians [32–37].

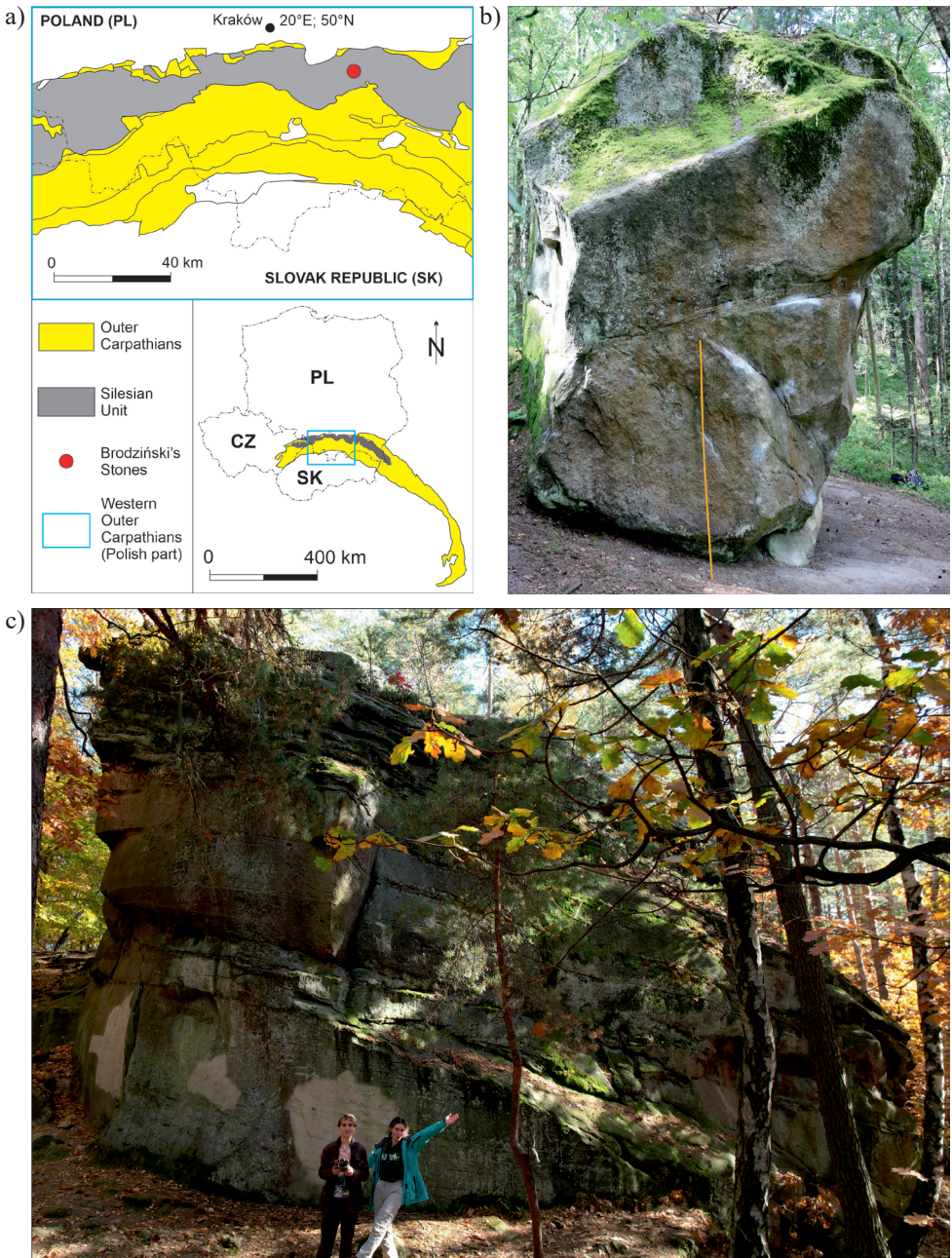
The aim of the project was therefore to design an interactive (stopping, rewinding, looping and repeating) film-based geoelectronic tool with geointerpretative content [1–5], considering the genesis of such developed deposits.

The motivation for conducting new modelling of selected sedimentary processes, which intended to document and explain the formation of sediments with a structure comparable to the aforementioned sandstone-to-conglomeratic deposits, was the geotourist interest in the Carpathian tors (Fig. 1) and the possibility of using this fact to popularise knowledge in the field of broadly understood Earth Sciences and implement geoelectronic in this area [e.g., 32–43]. An additional motivational aspect was also the prevailing interpretative discrepancies, manifested in the form of parallel published views on the different origins of rocky forms deposits representing a variety of coarse-clastic, thick-bedded, and amalgamated flysch [4–32].

Already in the pioneering sedimentological investigations [6–13] – sediment gravity flows with different mechanisms of supporting grains in transportational moving, associated not only with turbulence *sensu stricto* (the state of turbulent motion), were described and interpreted differently.

Therefore, for the purposes of geotourism promotion and geoelectronic dissemination [1–5, 32–43], as well as to clarify genetic doubts, particularly related to the paradigm of turbiditic genesis of the aforementioned massive sandstone-to-conglomeratic deep-water deposits (i.e., developing beyond the edge of the contractural ‘shelf’ – in the slope, its base, and proximal basin plain zone) [6–8, 10, 15–17, 44], which has prevailed for over half a century in research on deep-sea siliciclastics – experimental laboratory works were undertaken to visually determine the actual mechanism of the gravitational transport-depositional process responsible for the formation of sediments corresponding to the flysch deposits of the Carpathian relic rocky forms.

The geoelectronic tool presented in this article was the subject of a conference presentation during a session ‘Geology and Geotourism’ at the 65th Barbórkowa Konferencja Studentycznych Kół Naukowych AGH [4, 5]. Additionally, this article discusses the sedimentological aspect of processes and their deposits (sedimentary products) in the context of the design and production of a film-based geoelectronic tool.



**Fig. 1.** Residual rocky forms built of sandstone-conglomeratic flysch deposits (Istebna Fm.): a) location and geological setting of the study area (Brodziński's Stones) (source: [29] and references cited there in (fig. 1, p. 160), modified); b) Gnome (Gnom) (the yellow gauge is 2 meters) (GPS: 49,847918°N; 20,481422°E); c) Big Stone (Wielki Kamień) [5], (GPS: 49,848223°N; 20,479146°E) (phot. Z. Ziarek, 2024)

## 2. METHODS

The methodics for designing the geoeducational tool in the form of film was based on field-work conducted in a selected area where representative Carpathian sandstone-conglomeratic residual rocky forms occur (GPS coordinates were collected) (Fig. 1) [32, 33, 36]. In order to compare the development of the rocky forms deposits to the experimental sediments, for the geoeducational film tool needs, it was necessary to carry out detailed lithological-sedimentological observations of the first mentioned ones. In the selected area of the Wiśnicz Foothill (Lipnica Górna, Paprotna hill) 10 rocky outcrops were identified, their photographic documentation was made, and one tor (representative in terms of characteristic textural- and structural features development) was additionally logged.

After familiarising with the textural-structural characteristics of the deposits forming the residual rocky forms, the planning of a scenario for laboratory flume modelling was initiated. Modelling the sedimentary process, intended to reflect the genesis of the studied rocky forms deposits, required the creation of an experimental 'proving ground'. An appropriate mini-sedimentological laboratory was designed [4, 5].

The new project of the geoeducational tool (film illustrating sandy-gravelly debris flows) for geotourism was based on the idea of geoeducation, which involves the popularisation of geological knowledge through the exploration of inanimate nature objects and/or the processes responsible for their genesis, considered touristically attractive [1–5, 32–43].

The proposed tool, by visualising the process and its product, was designed to explain the nature of the physical sedimentary process responsible for the formation of massive sandy-gravelly sediments, which are analogues for the massive sandstone-conglomeratic deposits of residual rocky forms representing as an example of one of the types of flysch that build the Outer Carpathians (the so-called Flysch Carpathians) [9, 11, 14, 17, 20, 27–29, 32–37, 40–43, 45–48].

### 2.1. STAGES OF DESIGNING GEOEDUCATIONAL TOOL

The film-based geoeducational tool was intended to illustrate and explain to the audience the sedimentary environment, in which massive, amalgamated sandstone-conglomeratic flysch deposits were created, the gravitational processes involved, the type of granular material, and the depositional system tract in which they were formed. Accordingly, the entire project work was divided into sequentially implemented stages:

1. Establishing the subject of geoeducation, geoeducational objectives, presentation methods, and target audience characteristics.
2. Selection of thematic issues and physical features of the objects/material elements to be presented and explained.
3. Conceptual stage – a review of knowledge in the field of deep-water (outside from the shelf) siliciclastic sedimentology and geoeducational methods.
4. Laboratory stage – design of sedimentological modelling, testing of the analogue model, and making adjustments.
5. Production stage – recording films from three perspectives, developing geointerpretation (text, graphics, individual film fragments and freeze frames), and final montage of the tool.

Finally, the designed and produced multimedia film-text geoeducational tool represents a comprehensive geotourism product.

## 2.2. SEDIMENTOLOGICAL METHODS

The sedimentological research was based on the concept of process sedimentology [1–5, 21–25, 29, 37], where the approach – ‘from detail to general’ – includes the necessary conditions such as:

- 1) detailed factual description (lithological-sedimentological characteristics) of products – sandstone-to-conglomeratic deposits of the Carpathian residual rocky forms,
- 2) interpretation of products towards determining their genesis – environment, sedimentary processes, transport-depositional mechanisms,
- 3) creation of a general model of accumulation system tract, not contradicting field observations of product characteristics.

The final model is intended to illustrate, in a simplified and clear manner, the prevailing environmental conditions and ongoing geological processes within it, and to show their result in the form of sedimentary products. Therefore, during modelling, consistency with reality must be maintained, to such a degree of approximation that the analysed process and its product (rock deposits) are as naturalistic as possible – could occur under natural conditions.

## 3. CARPATHIAN FLYSCH GENESIS AS A SUBJECT OF GEOEDUCATION IN GEOTOURISM

The development of geotourism, understood as thematic tourism based on the tourist’s interest in the surrounding landscape, its structure, and genesis – creates a need to provide knowledge about the processes and their mechanisms that led to the formation of the geotourism objects and attractions seen today. Geosites that are visually appealing and located in areas accessible to tourist traffic, such as in the Flysch Carpathians (Fig. 2), are particularly predestined to such development.

Tourist access to Carpathian flysch geosites, such as the Lhota beds inactive quarry in Kozy (Fig. 2a) or the Istebna sandstone-conglomeratic residual rocky forms in Lipnica Górna (Fig. 2b), arouses curiosity and questions among visitors about the reasons for their different external appearance and lithological-sedimentological development. Based on scientific research on Carpathian flysch deposits conducted over many years, extensive knowledge about the environments and mechanisms of the processes responsible for shaping the products observed today (Carpathian sandstone-to-conglomeratic residual rocky forms), is available. In order to design a geoeducational film tool, it was necessary to refer to the development of Carpathian relic forms deposits and interpret their genesis.

Sedimentation in the Outer Carpathian sub-basins (a marginal fragment of the Tethys Ocean) occurred during simultaneous changes in the geotectonic regime, under different geometric and bathymetric conditions, with the involvement of varying sedimentary processes, and at different distances from alimentary zones (source areas). Consequently, texturally and mineralogically diverse terrigenous clastic material was delivered to the sedimentary basins, sometimes with a significant proportion of exotics (macroscopically recognisable outsized clasts of crystalline rocks and older sedimentary rocks) [9, 11, 14, 17, 20, 27–29, 32–37, 40–43, 45–48].

Therefore, flysch can be considered from different points of view:

- lithologic – series of sedimentary rocks consisting mainly of interbedded siliciclastics of varying fractions (psammitic, psammitic, aleuritic, and/or pelitic), developed as alternating sandstones and shales (mudstones and/or claystones) or amalgamated coarse-clastic deposits (conglomerates and sandstones with transitional members, i.e., sandy conglomerates and conglomeratic sandstones), locally with gravelly mudstone interbeds (sometimes with clasts of exotic rocks – exotics), and to a lesser extent as separate series of marls or cherts;
- genetic – a set of deep-sea (from the edge of the contractual ‘shelf’ towards the open sea) deposits, formed from terrigenous material, created with the dominant participation of sediment gravity events (i.a., slumping, sliding, debris flows or turbidity flows) and reworking by tractional bottom currents of previously deposited material;
- geotectonic – thick (measured in hundreds to several thousand meters) series of sedimentary rocks formed in the pre- or early orogenic stage of the development of sedimentary basins (closure of basins, source area uplift and denudation).

The geoeucational tool illustrates the genesis of one type of flysch, specifically the environmental conditions of its formation, transport-depositional mechanisms, final sedimentary products, and system their accumulation.



**Fig. 2.** Outcrops representing two contrastingly developed types of Carpathian flysch: a) rhythmic interbeddings of sandstone and mudstone layers (Lhoty Fm.), inactive quarry in Kozy near Bielsko-Biala city; b) amalgamated sandstone-conglomeratic deposits without mudstone interbeds separating them (Istebna Fm., Brodziński's Stones in Lipnica Górna near Wiśnicz city) (phot. Z. Ziarek)

#### 4. SUBAQUEOUS SEDIMENT GRAVITY FLOWS

Subaqueous sediment gravity flows are processes of transport and deposition of an incoherent (fragmented) mixture consisting of grain material and interstitial (intergranular/pore) fluids (liquids and gases) of varying volumetric concentration, taking place under the influence of gravity (comp.: [12–31, 35–37, 44–51]). Examples of such gravity-driven flows, including: 1) so-called – turbidity currents (regarded here as only low-concentrated turbulent suspensions – turbidity flows, generating a product in the form of normally-graded turbidites with flute casts at their bed base), as well as 2) debris flows (non-cohesive- or cohesive laminar flows with their products – massive debrites) (see Figs. 3–5) – experimentally modelled by authors for the purposes of this research.

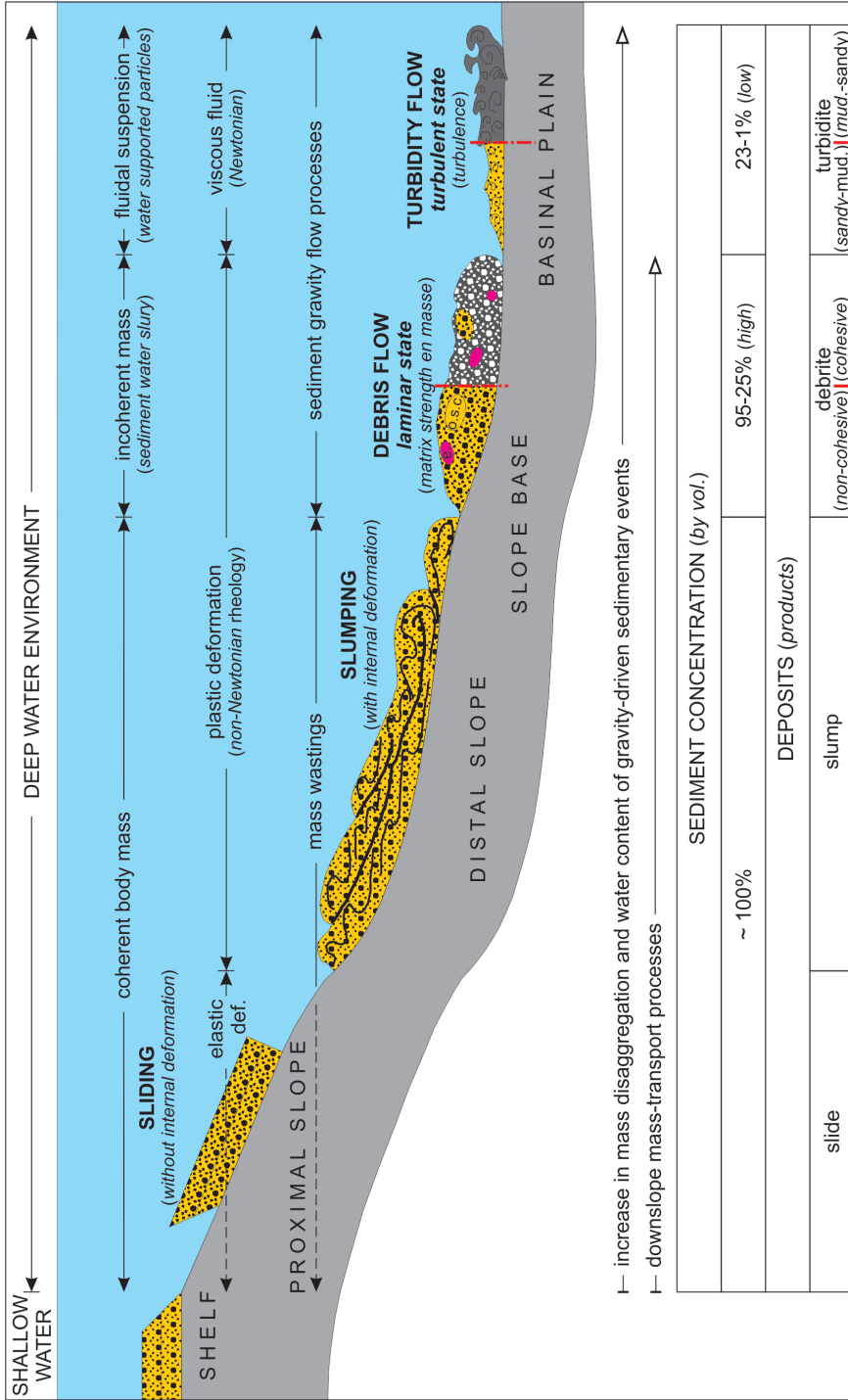
Turbidity flow (*sensu* turbulent turbidity current) (Figs. 3–6) is one of the sediment gravity flow processes in which, during transport, turbulent mixing of grain material (usually mud and sand in varying proportions) with the surrounding water occurs, creating a suspension (the critical supporting mechanism is turbulence). This water-gas-grain mixture can generate and maintain a relatively stable turbulent state at a volumetric concentration not exceeding 23% [24], as, in a flow with a higher concentration (by volume), turbulence is quickly dampened or does not occur at all (cannot be initiated).

The turbulent suspension, moving gravitationally down the slope and bottom of the sedimentary basin, gradually loses its initial energy and velocity, transitioning from an erosional phase (flute casts formed by swirls) to a settling phase (normal grain-size grading formed by gradual gravitational segregation). The product of such a low-concentrated gravity turbidity flow is a turbidite with normal grain-size grading, often with flute casts (swirl scour marks) present on the bed base surface, indicating turbulent flow with eddies above the non-consolidated cohesive muddy bottom [1–3, 18–26, 29–31, 44–54].

Upon deposition of most of the transported grain material and complete cessation of the turbidity flow (i.e., after the turbulence has definitely stopped), the finest aleuritic-pelitic clastic material remains in suspension, gradually settling from a hemipelagic cloud, forming a mud layer (muddy hemipelagite).

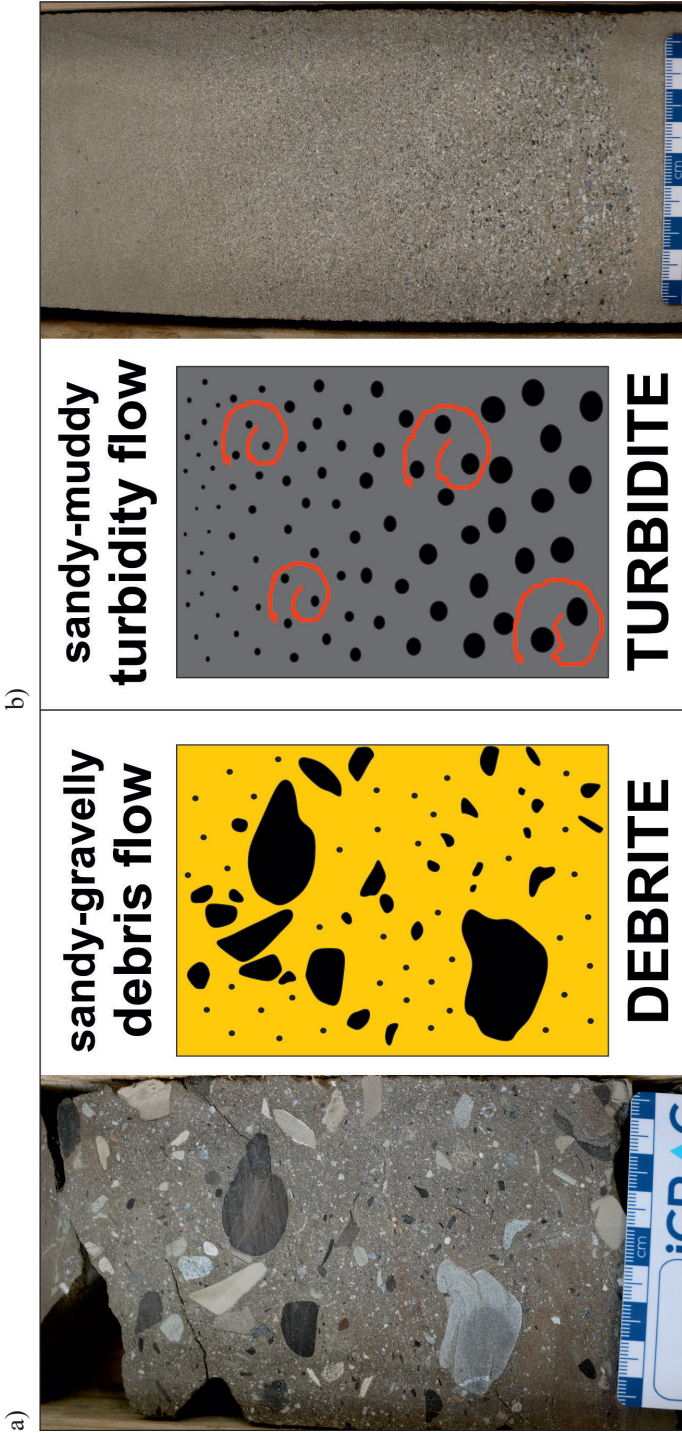
Thus understood turbiditic sediments, together with hemipelagic mudstones (hemipelagites), and possibly with pelagic pelitic layers (pelagites), were deposited mainly in the distal zone of the sedimentary basin (at the base of the slope and on the basin plain), often in the form of depositional lobes and their margins, forming, together with a central channel (constituting a point source of supply), transitioning into branching distributary channels – a deep-sea fan system tract (Fig. 6) [1–3, 20–26, 29–31, 44–47, 49, 50].

Sandy-gravelly (non-cohesive) deep-water debris flow is one type of sediment gravity flow process (e.g., Fig. 3) [6–31]. In such debris flow, redeposited incoherent (granular) material, along with water contained in the intergranular (pore) spaces (at a volumetric concentration above 25% [24]), is transported down the basin slope in a laminar state (in contrast to the low-concentrated turbulent suspensions of turbidity flows) (Figs. 3–5, 7) [24, 29]. In this composition of non-Newtonian gravity flow, transport occurs *en masse*.

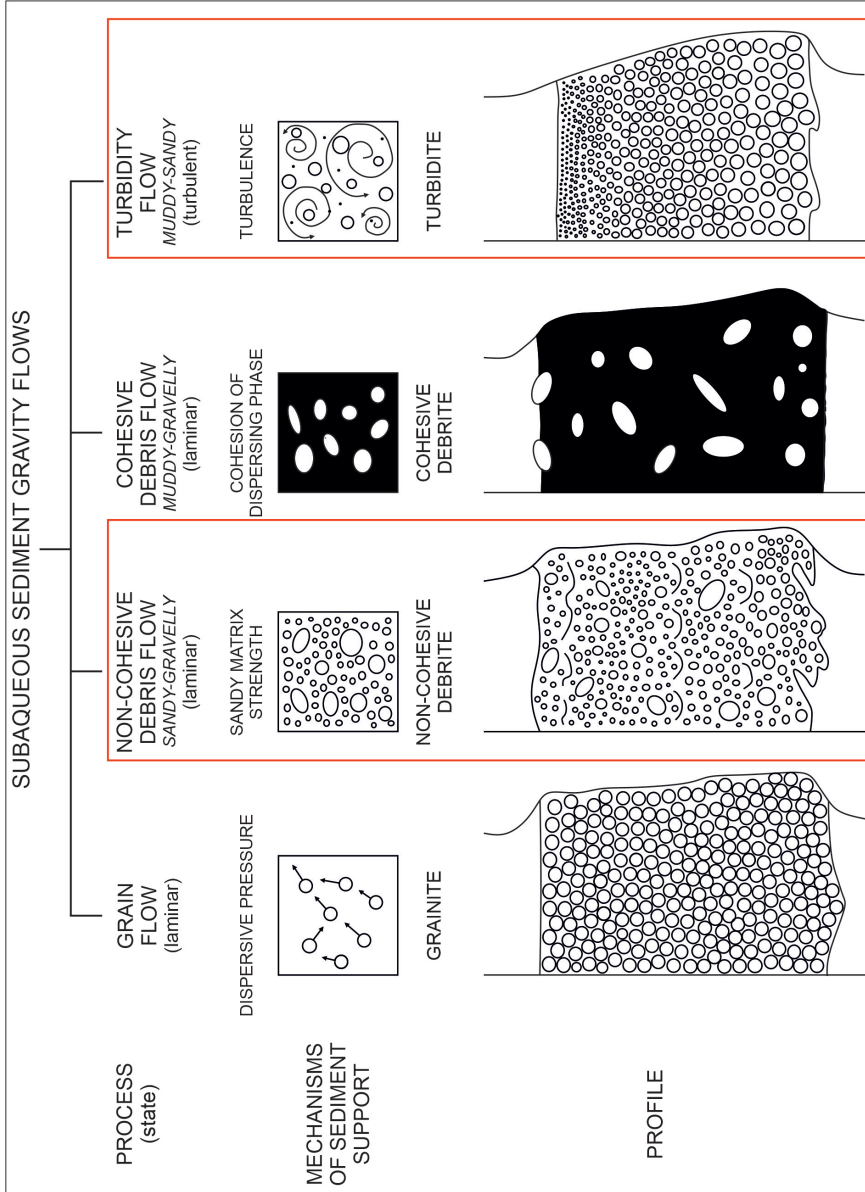


**Fig. 3.** Deep-water gravity-driven sedimentary gravity events: mass wastings and sediment gravity flows. Explanations: o.s.c. – outsized clasts, e. – ‘exotic’ clasts, i.e., exotics (fragments of older rocks incorporated in flow, i.a.: limestones, gneisses and/or granulites – as individual clasts or components of pre-flysch conglomerates), def. – deformation

Source: [24], modified

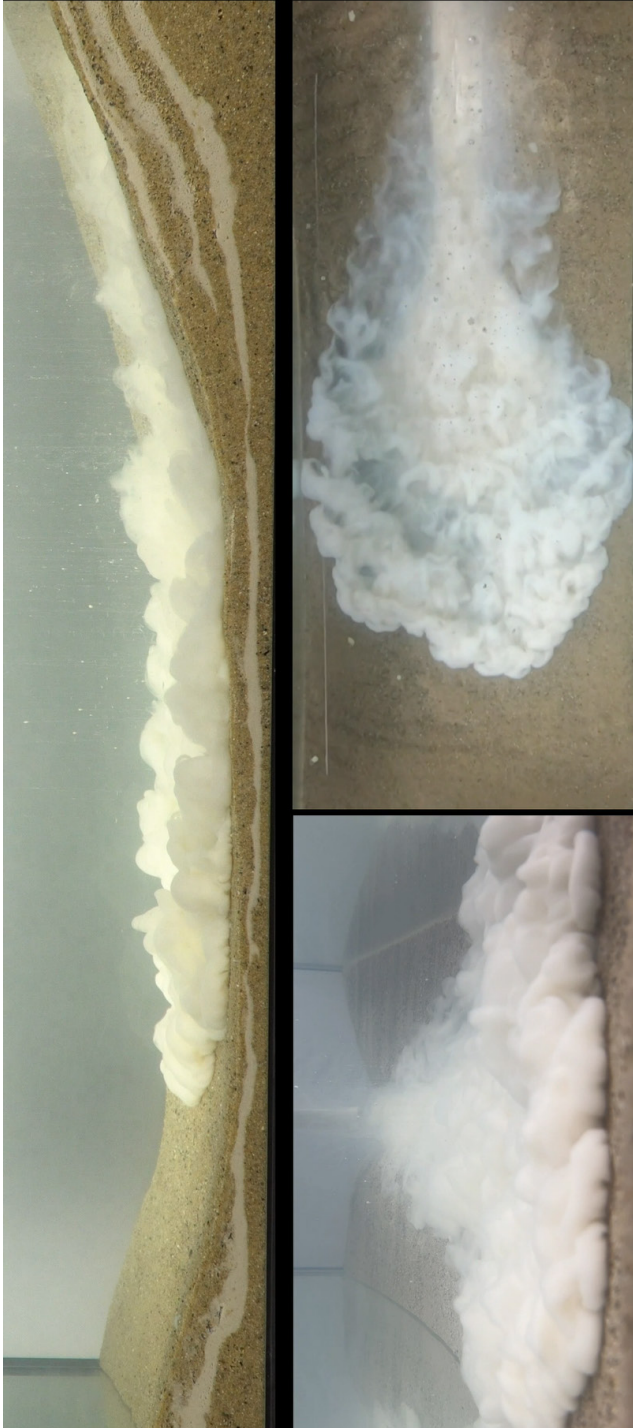


**Fig. 4.** Products of subaqueous sediment gravity flows:  
 a) non-cohesive massive debris;  
 b) normally-graded turbidite (turbulence process marked by red lines)  
 (phot. Z. Ziarek)  
 Source: [24], changed



**Fig. 5.** Types of subaqueous sediment gravity flows, critical mechanisms supporting the transport of sediment particles / grains, and diagnostic products. The processes, mechanisms and products discussed are marked in red

Source: [51], changed



**Fig. 6.** Modelling low-concentrated, turbulent sediment gravity-driven flow (turbidity flow), spreading in the form of point-sourced fan-shaped deep-water system tract [1–3] (phot. K. Kulik)



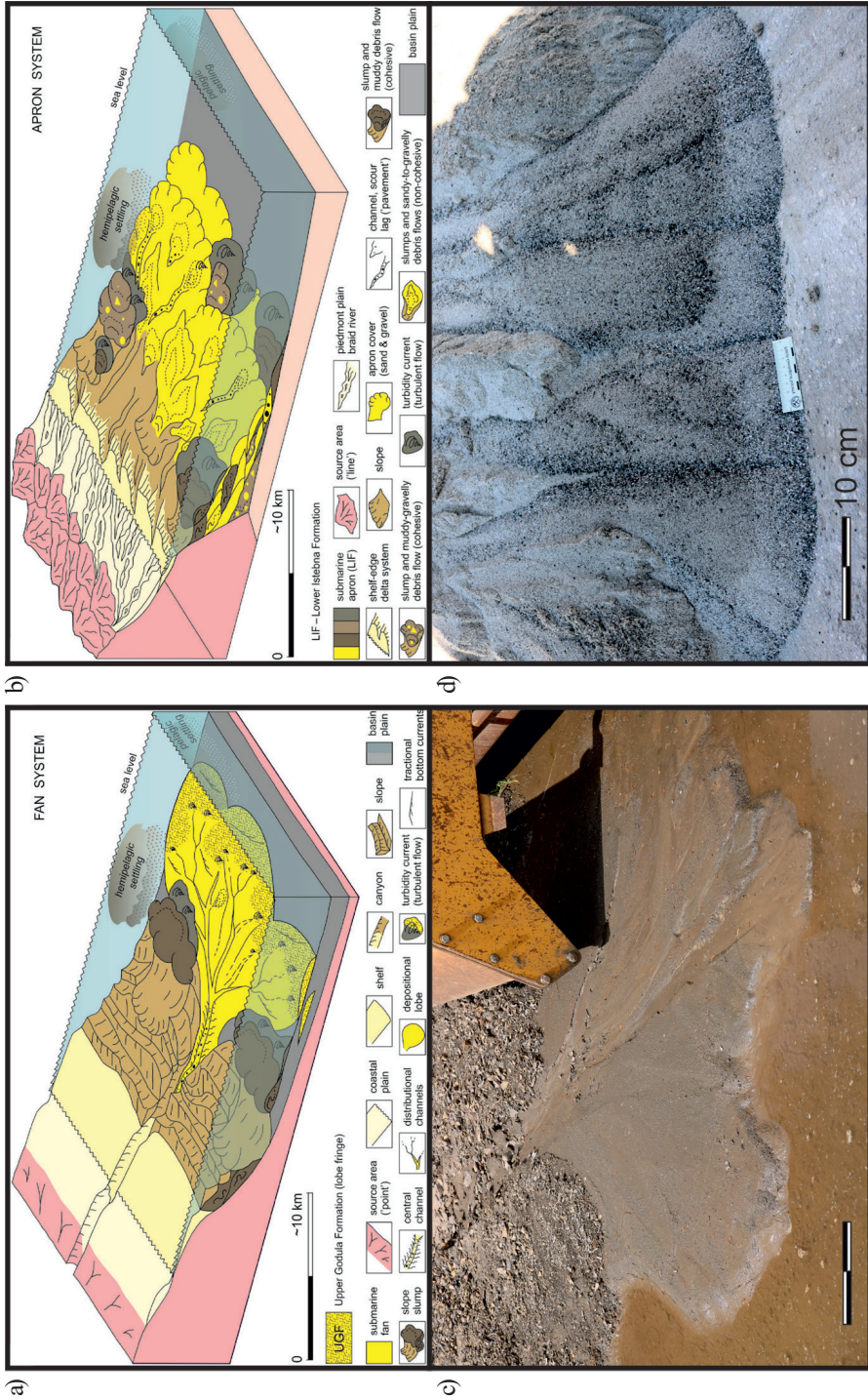
**Fig. 7.** Modelled mass sandy-gravelly sediment gravity flows (non-cohesive debris flows) and their products – massive sandy-gravelly deposits (non-cohesive debris) (phot. Z. Ziarek)

Under conditions of high volumetric concentration of such a non-cohesive mass flow, the mechanism that sustains the movement and the randomly scattered gravel grains in the support, including outsized clasts (constituting the dispersed phase), in suspension is mainly the strength of the sandy matrix, which acts as the dispersing phase. A highly concentrated and high-energy mixture of sandy-gravelly sediment and water, possessing effective erosional force (incorporation of older sediments), moves gravitationally down the slope of the sedimentary basin, then undergoes rapid deceleration and mass deposition, resembling an avalanche and ‘freeze’ of its colluvium. The products of a sandy-to-gravelly debris flows (mass, laminar, non-cohesive debris flows) are a sandstone-to-conglomeratic debrites. Deposits characterised by such a course of the sedimentary processes have a massive structure (lack of gradual gravitational segregation of high-concentrated clastic material sustained by matrix strength during transport and rapid mass deposition). It is that type of coarse-clastic, massive, irregularly bedded, and amalgamated sandstone-conglomeratic flysch deposits (non-cohesive debrites) [4, 5, 23–25, 27–29, 32] that constitutes the primary building material of residual rocky forms, which have enjoyed constant and even growing geotouristic interest in recent years [32, 35–37].

In addition to the varieties of sediment gravity flows products described above, massive gravelly-mudstone debrites (cohesive debrites – products of muddy-gravelly debris flows) [12, 13, 20, 23, 24, 26, 28–31, 46–48, 50, 51] (Figs. 3, 5) also locally occur among Carpathian flysch deposits, but due to their relatively low resistance to denudation factors (e.g., weathering and erosion), they are not rock-forming (they do not persist in the form of residual rocky forms).

In natural conditions, massive sandy-to-gravelly debritic deposits (sandy-, sandy-gravelly-, gravelly-sandy-, and gravelly debrites) were mainly deposited in the deep-water zone of the sedimentary basin (beyond the edge of the ‘shelf’ area), encompassing the basin slope and its base. There, they formed individual clastic tongues, which underwent lateral and vertical amalgamation (‘gluing’ together), forming cover lithosomes resembling ‘aprons’. Overlapping and coalescing piedmont apron covers formed a line-supplied apron depositional system tract of flysch deposition (Fig. 7) [4, 5, 20, 27–29, 32, 35–37, 50].

In addition to the Carpathian non-cohesive debrites – massive sandstones-to-conglomerates (i.e., debritic: sandstones, gravelly sandstones, sandy conglomerates, and conglomerates, respectively) and cohesive debrites – massive conglomeratic mudstones), there are also deep-water flysch turbidites (*sensu* mudstone-to-sandstone deposits with normal grading), the typical transport-depositional system of which is a deep-water fan (Fig. 8a) (e.g., [29]). To demonstrate the difference in their sedimentological nature (genesis and development contrast), illustrative comparisons can be used. For example, the model of a point-sourced deep-water fan system tract (Fig. 8a) could be roughly compared to a mini alluvial fan formed during rainfall (Fig. 8c). Similarly, the model of a line-supplied deep-water apron system tract (Fig. 8b) is comparable to a sandy-gravelly embankment from a construction site (warehouse) (Fig. 8d). A debris flow, on the other hand, can metaphorically be compared to public transport, where the means of transport is filled to the brim with squeezed passengers, and a turbidity flow to individual (private) transport, e.g., a personal car with comfortably traveling passengers at a distance from each other (Fig. 9) (comp. [24], fig. 2.30, p. 47).



**Fig. 8.** Comparison of transport-depositional system tract models: a) point-sourced fan system; b) line-sourced apron system; c) naturalistic model of 'fan system'; d) naturalistic model of 'apron system'

Source: [29] (a, b), phot. Z. Ziarek (c, d)

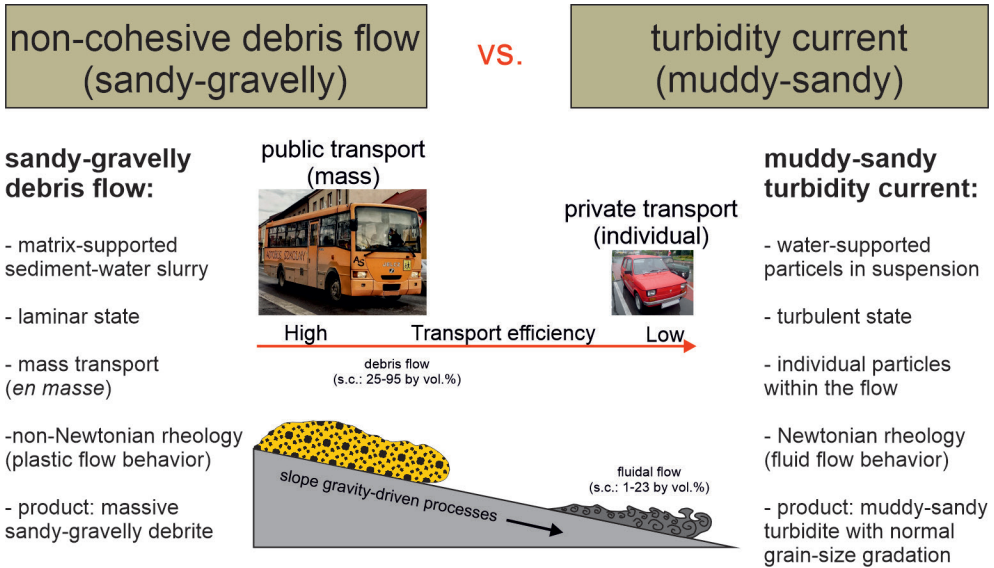


Fig. 9. Figurative comparison of debris flow and turbidity flow

Source: [24], changed

## 5. SANDY-GRAVELLY DEBRIS FLOW LABORATORY MODELLING

In order to create a geoeducational film illustrating and explaining the genesis of the flysch deposits building Carpathian residual rocky forms, an appropriate ‘proving ground’ (mini sedimentological laboratory with experimental flume) was designed and constructed. The subject of analogue sedimentological modelling (flume experiments) was experimentally generated mass sediment gravity flows in the form of laminar sandy-gravelly (non-cohesive) debris flows, as well as their products developed as massive sandy-gravelly deposits. These were intended to approximately correspond to identical sedimentary processes occurring in nature (i.e., in the flysch basin) and their product (after diagenesis) – massive amalgamated sandstone-conglomeratic debrites. Such developed sedimentary products represent one of the varieties of Carpathian flysch deposits (Figs. 1, 2b) [9, 11, 14, 17, 20, 27–29, 32–37, 40–43, 45–48].

Experimental reconstruction of the environmental conditions under which the process of mass gravitational redeposition of sandy-gravelly material occurred – required the preparation of appropriate equipment, materials, and multiple tests to ensure the clarity, legibility, and repeatability of the experiment with a consistent end result. Ultimately, it was possible to replicate/visualise the following elements and processes:

- sedimentary basin reservoir – aquarium with dimensions: 100 cm × 40 cm × 40 cm;
- source area, continental slope, and its base – morphology formed manually from sandy-gravelly material;
- process of triggering mass redeposition and controlling sediment gravity flows – process mechanism triggered by gradual filling of the aquarium with water, simulating marine transgression.

## 6. GEOEDUCATIONAL TOOL – PROJECT, GEOINTERPRETATION AND PRODUCTION

The design of the geoeducational tool was based on specific guidelines. The tool is intended for public access, is to present a strictly defined geoeducational topic, the scope of presented knowledge is to be comprehensive and clear, and its presentation method is to be understandable and adapted to the knowledge level of a student at least at the secondary school level. To achieve the intended goal, both at the tool design and production stages, research problems were identified (Tab. 1), for which solutions were developed and implemented at various stages of the project.

**Table 1.** Theoretical and technical problems, defined, and then solved during the project implementation

Theoretical problems	Technical problems
<ul style="list-style-type: none"> <li>– Which issues should be presented and explained?</li> <li>– What should be the order of presented issues?</li> <li>– What scope and level of substantive geointerpretation should be used?</li> <li>– What form should geointerpretation explanations take (e.g., text, additional graphics, and animation)?</li> <li>– Should freeze frames with additional explanation be included?</li> </ul>	<ul style="list-style-type: none"> <li>– What camera shots should be used?</li> <li>– What tools should be used for film processing and editing?</li> <li>– How to arrange shots in a group frame?</li> <li>– In which part of the map should a place be designed for the geointerpretation package?</li> <li>– What segments should the film material be divided into?</li> <li>– How to choose time intervals to properly present individual processes and their products?</li> <li>– What video format should be used?</li> </ul>

During the conceptual work stage, the objectives of the created geoeducational tool were defined, which then served as guidelines for the design and construction of the experimental site (mini sedimentological laboratory) for modelling non-cohesive (sandy-gravelly) debris flows. The task was set to present, using a properly constructed experimental site and conducted sedimentological experiments:

- present a model of the submarine environment (slope, its base, and the sedimentary basin plain) in which one of flysch rocks categories – massive sandstone-to-conglomeratic deposits – was hypothetically formed;
- show the gravitational mass redeposition (collapse) of rock debris from the source area (zone above the slope);
- illustrate the linear (non-point) method of delivering grain material from the source area;
- present the laminar (non-turbulent) state of sandy-gravelly material transport and the rapid (non-gradual) accumulation of rock debris mass;
- visualise the deposition of massive sandy-gravelly deposits (non-cohesive debrites in the form of coalescing debris tongues forming grain apron covers);
- demonstrate the formation of an apron (not fan shaped geometry) depositional system;

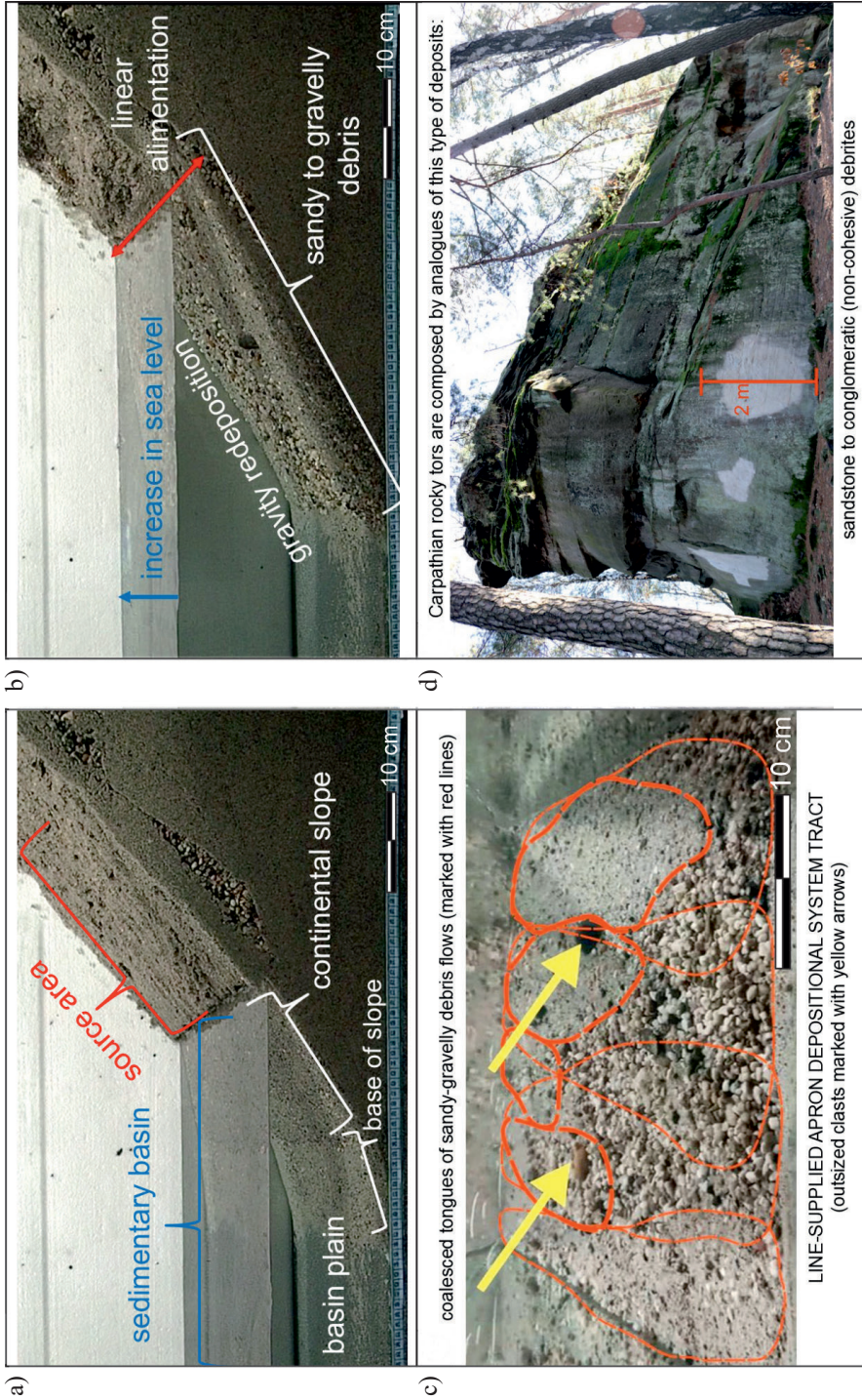
- develop geointerpretative material dedicated to the audience (e.g., geotourists);
- visualise sedimentary processes and their products for the purposes of geoeducation and popularisation in the field of Earth Sciences;
- participate in the promotion of geotourism.

During the digital processing stage creating film-based geoeeducational tool (video material), visual effects were enhanced: footage from three shots was edited into a chronologically consistent visualisation of the laminar debris flow process, a portion of the screen was designated for explanatory captions, and freeze-frames were incorporated. The geointerpretative package, adequate to the observed sequence of events and adapted to the knowledge level of the defined audience, includes two categories – elements of environmental description and stages of sandy-gravelly debris flow genesis (Tab. 2) (Fig. 10).

**Table 2.** Geointerpretation of modelled: environment settings, processes, sedimentary products, and system tract – with assignment to individual still frames of film material

Elements of environmental description	Stages of the origin of sandy-gravelly debris flow
<ul style="list-style-type: none"> <li>– Source area – the area from which the sedimentary basin receives the sedimentary material (sediment).</li> <li>– Linear (non-point) supply of sediment to the depositional system – delivery of the material mobilised <i>en masse</i> in different parts and time ('chaotically').</li> <li>– Debris – a loose accumulation of detrital material.</li> <li>– Sandy-gravelly debris flow – the process of gravity-driven transport of rock debris.</li> <li>– Non-cohesive debris flow – flow of non-cohesive sandy-gravelly material.</li> <li>– Apron depositional system tract – a depositional system in the form of clastic debris covers.</li> </ul>	<ul style="list-style-type: none"> <li>– Eustatic transgression – the sea encroaches on the land due to global rising sea level.</li> <li>– Collapse in the source area caused by transgression – destruction of the coastal zone and delivery of rock debris to the continental slope.</li> <li>– Activation of a debris flow – gravity destabilises the debris material deposited on the slope, and rock debris is transported by gravity.</li> <li>– Amalgamation – the tongues of successive debris flows merge with each other to form covers.</li> <li>– Redeposition of incoherent debris – movement of un lithified (loose) sediment.</li> <li>– Generation of sandy-gravelly debrites – a product of non-cohesive debris flows.</li> <li>– Coalescence (overlapping) of debris covers – formation of an apron depositional system tract.</li> </ul>

Film illustrating sandy-gravelly debris flows serves as an interactive geoeeducational tool enabling independent use by geotourists. It allows for adjusting the pace of assimilating geointerpretative content by pausing and rewinding at any moment, looping it, and repeating the issues presented in individual film fragments and freeze frames by the viewer. The geointerpretative package includes not only descriptive elements but also graphical elements, facilitating the observation and understanding of environmental elements and the stages of debritic-type flysch genesis. The tool is publicly available as a film on the YouTube platform ([https://youtu.be/VKzgJUgh6\\_s](https://youtu.be/VKzgJUgh6_s)), and a similar geoeeducational tool, based on previous modelling of turbidity flows [1–3], is exhibited in the Tatra Archives of Planet Earth (pol. Tatrzańskie Archiwum Planety Ziemia). The film geoeeducational tool can be used by any viewer, especially geotourists and/or tourists interested in the genesis of the Carpathian flysch variety that builds residual rocky forms.



**Fig. 10.** Geointerpretation of visualised modelling steps: (a–c) environment, process, massive product of coarse-grained sedimentation (non-cohesive debrisite), and system tract; d) natural equivalent (phot. Z. Ziarek)

## 7. DISCUSSION

### 7.1. GEOEDUCATIONAL TOOL AS A BRIDGE BETWEEN SCIENTIFIC RESEARCH AND POPULARISATION OF KNOWLEDGE

The geoeducational tool aligns with the idea of a geotourism product [55, 56], and should therefore possess the following characteristics:

- focus on geological diversity and heritage,
- fulfillment of the educational function in the field of Earth Sciences (geoeducation),
- dissemination of knowledge to a broader audience that is not composed of specialists (science popularisation),
- engaging users in the process of learning, absorbing, and understanding newly introduced content,
- providing experiences, emotions, and new encounters connected with cognitive aspects (geological, geomorphological knowledge, etc.),
- dissemination and promotion of activities for the development of geotourism.

The finally produced geoeducational tool addresses strictly defined issues of sandy-gravelly debritic sedimentation, thereby undertaking the challenge of popularising Earth Sciences. The provision of the geointerpretative layer takes place both at the level of graphic visualisations and textual content, and the selection of the substantive level of transmission promotes knowledge dissemination among users outside the scientific branch. Geoeducation is conducted in the context of learning and understanding the sedimentary processes responsible for the formation of specific products – today present on the Earth's surface in the form of Carpathian sandstone-conglomeratic rocks, which are undoubtedly geotourism attractions.

The montage techniques applied in the tool, such as framing images from different angles, several-second freeze frames, or interweaving the film with graphic models, maintain user attention, make tracking the ongoing process more attractive, allow for a more thorough analysis of its significant stages, and confront the image of the forming product – sandy-gravelly debrite – with a graphical model of the apron depositional system tract.

The authors' ownership of intellectual property rights to the final product – the geoeducational tool – enabled the tool to be made available in the public space (YouTube). Open access to the tool creates the possibility of familiarising a wide audience with it.

The process of designing and producing the geoeducational tool in the form of film was based on clearly defined educational goals, a specific scope of geological knowledge (genesis of flysch deposits), the assumptions of process sedimentology, the use of simple laboratory methods, the application of geointerpretation methods, and the engagement of simple digital tools. The experience gained during the project implementation and reflection on the developed end result allowed for the definition of criteria characterising a correctly constructed and properly functioning this geoeducational tool (Tab. 3).

**Table 3.** The criteria for a properly designed and executed film-based geoeducational tool

No.	Criterion	Importance for geoeducation
1.	Completeness	providing a complete sediment gravity flow process and its deposit development – provides a basis for understanding the: environmental nature, physical processes, sedimentary products, and depositional system
2.	Readability / Clarity	easy to observe and clearly visible throughout the entire event/process mechanism facilitates understanding of the educational message
3.	Naturalism	imitation and imitating reality make the demonstrated process, generated product and visualised content credible
4.	Realism	the factual consistency of the laboratory (experimental) model with field observations lends credence to the inferred genesis
5.	Repeatability	obtaining an identical result under the same conditions and with the same parameters of the system during subsequent trials makes the observed process or the postulated genesis of the product credible
6.	Spectacularity	creating a visual impression on the recipient and the associated positive emotions, solidifies the observations in memory
7.	Interactivity	the possibility of user intervention in the tool's operation (e.g. independent start-up, changing the operating speed, modifying the ongoing process according to understandable parameters), embedding the educational message in memory

## 7.2. PROCESS SEDIMENTOLOGY AND THE PARADIGM OF THE GENESIS OF SOME FLYSCH ROCKS

Studies of the subject literature have shown that the same sediment gravity flow processes and their deposits are described and interpreted in very differently manner [6–29]. Establishing the actual state is crucial for explaining the genesis of the rocky form deposits, and therefore also for the proposed geointerpretation applied in the geoeducational film tool.

For example, the so-called Bouma Sequence presented below (described by Bouma [10]), consisting of a strictly defined succession of lithological-sedimentological members (Ta–Te), i.e., an idealistic turbiditic model intended to represent the sedimentary product of a single turbidity current, has different explanations (Fig. 11) [15, 24, 29].

Further differentiation of turbidites, in the context of turbulent suspensions of turbidity currents, was made by Sanders [54]. Another classification of sediment gravity flows based on rheology was the work of Middleton and Hampton [12, 13]. However, in studies on deep-sea siliciclastic deposits, some researchers, such as Mutti *et al.* [44], postulate that the products of all sediment gravity flows should be classified collectively as turbidites (Fig. 12).

primary sedimentary structures	Bouma (1962) [10]	Lowe (1982) [15]	Shanmugam (2021) [24]	authors
laminated to massive (homogeneous)	Te	pelagic and hemipelagic	pelagic and hemipelagic	pelagic and hemipelagic
upper flat-parallel lamination	Td	low-density turbidity current	bottom-current reworking	tractional bottom-current reworking
wave-parallel, cross-ripple, and/or convolute lamination	Tc			
lower flat-parallel lamination	Tb			
massive (1) or normal graded (2)	Ta	high-density turbidity current	sandy debris flow	sandy debris flow if massive (1) or sandy turbidity flow if normally graded (2)

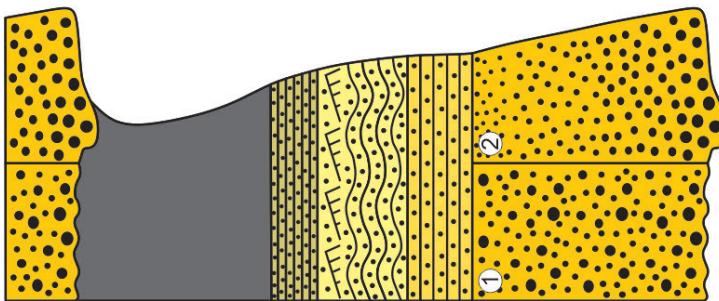
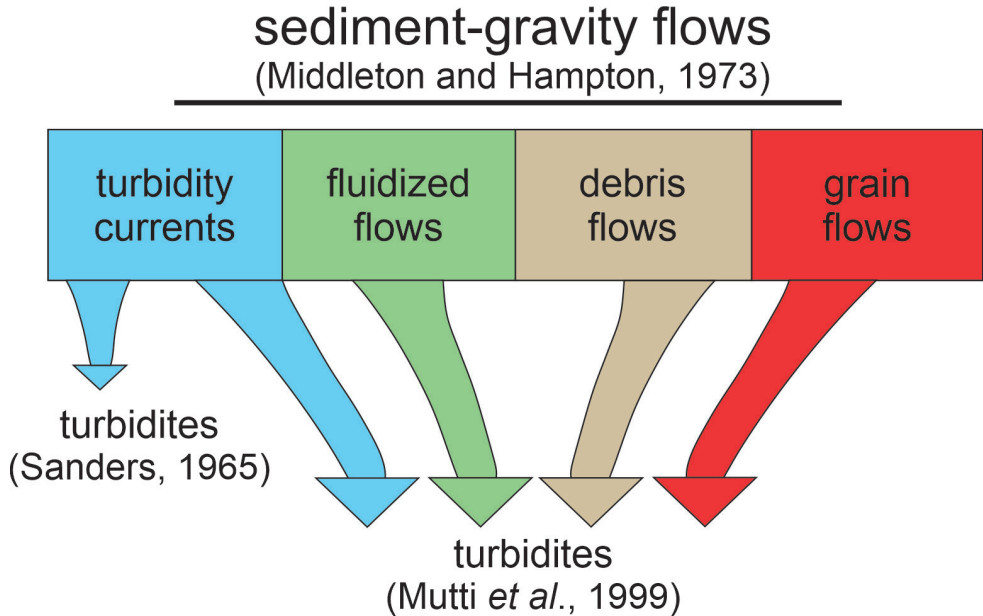


Fig. 11. Different interpretations of the deep-sea depositional sequence model

Source: [24], changed



**Fig. 12.** Different interpretations of sediment gravity flow products

Source: [24], partially changed

Returning to history, Kuenen [6–8] and Kuenen and Migliorini [52], in addition to the so-called low-density turbidites (i.e., products of low-concentrated, turbulent sediment gravity-driven flows – normally graded turbidity flow deposits; within the meaning of this work), also described mass gravity events *sensu* Strzeboński [29], whose movement occurred in a plastic/laminar state (the main sustaining mechanism was not turbulence) – as so-called high-density turbidity currents (to distinguish them from ‘normal’ turbulent low-density turbidity currents). The concept of so-called high-density turbidity currents (i.e., sediment gravity flows with a high volumetric concentration) was subsequently developed by Lowe [15] (Figs. 3–5, 11).

In turn, Kuenen [8] and Dżułyński *et al.* [9], based on observations of flyschoidal deposits outcrops in the form of amalgamated beds consisting of two members with contrasting textural-structural features, proposed the term ‘fluxo-turbidites’ (‘fluxoturbidites’) for them. In the authors’ intent [8, 9], the lower part (i.e., ‘fluxo-’ member) was intended to correspond to a high-density turbidite, and the upper part (‘-turbidity’ member) represented low-density turbidite (‘normal’ turbidite, i.e., the normally graded product of a low-density turbidity current). The idea of fluxoturbidites was later analysed by Ślącza and Thompson [14] and modified by Leszczyński [17]. In response to the ‘fluxoturbiditic’ considerations and controversies associated with them, Prof. Kenneth J. Hsü [18, 19] recalled a historical conversation with Prof. Stanisław Dżułyński, who stated that ‘fluxoturbidites’ are products of ‘sand avalanches’ – below a record of a scientific exchange of views, published in *Physics of Sedimentology*, 2004 (source: [19], p. 82).

I always had difficulty understanding this term. Why fluxo? Why turbidite? What is the difference between a fluxo- and an ordinary turbidite. It seems that this is another case when a geologist wanted to hide his ignorance behind an exotic name.

The term first appeared in an article published by Stan Dzulynski, a noted Polish sedimentologist, and his colleagues. When I visited Cracow in 1976, I asked Dzulynski to show me a fluxoturbidite. He took me to the foothills of the Polish Carpathians to face the prototype of fluxoturbidite. It was a sandstone bed some 5 m thick, intercalated in a deep marine sedimentary sequence. Other sandstone beds of the sequence show graded bedding and other structures typical of deposition by turbidity currents; they are turbidites. The “fluxoturbidite” is relatively well sorted and show none of the turbidite features. There are faint laminations here and there, suggestive of resedimentation of a previously deposited sand.

I asked Dzulynski what was the mechanism of deposition of a “fluxoturbidite”. He answered:

“The sand came down a steep submarine slope like snow avalanches in your mountains.”

“Then why do you not call them sand avalanches?”

“Yes, we did, but then Kuenen came. He was an international expert, and we were just provincials. We wrote an article of our Polish work with joint authorship. Kuenen insisted that the term “sand avalanche deposit” is too long a name, with too many genetic connotations. Fluxoturbidite is shorter, and can always be considered a descriptive name if our interpretation is wrong.”

This is unfortunate, of course, because the expression “sand avalanche” tells everyone clearly the interpretation of the authors on the basis of their evidence; fluxoturbidite is just another new fancy word beloved by fuzzy thinkers in their pretence to be technical.

This directly implies that the mechanism of formation of both high-density turbidites (equivalent to the ‘fluxo-’ member) and the later introduced ‘fluxoturbidites’ (their massively developed sandstone, conglomeratic, or gravelly mudstone members) is not turbulence, but mass, laminar gravitational transport and deposition, in which granular material is mainly sustained by the force of the detrital matrix [21–25, 27–29]. This genesis is also evidenced by observations and results of conducted experimental modelling (comp. also: [27], p. 205; [37], p. 7).

An identical view was maintained by Unrug [11], also writing about sediment gravity flows of the ‘sand flows’ type, in reference to massive sandstone-conglomeratic flysch deposits of the Istebna Formation. In this context, massively developed deep-water siliciclastic and calcareiclastic deposits *sensu* Strzeboński [28] should be called debrites, i.e., products of debris flows – cohesive (in the case of gravelly-mudstone debrites) and non-cohesive (sandstone-to-conglomeratic debrites, respectively) (see also: [21–25, 27–29]), which is postulated through the presented film-based geoeducational tool.

A characteristic feature of the structure of Carpathian residual rocky forms is precisely the presence of their deposits in the form of massive sandstone-conglomeratic lithofacies (rocks resistant to denudation factors – outcrops of inclined layers along which strike a plateau ridge was formed), occurring without regular interbeddings of mudstone/claystone shales (which is one of the basic conditions for the formation and preservation of these relic flysch tors) [32–37]. In connection with such lithological-sedimentological development, amalgamation, i.e., the phenomenon of combining individual beds into a composite bed *sensu*

Strzeboński [29], has become a common feature. Many such amalgamated composite beds form, on a larger scale, sometimes tens of meters of texturally-structurally ‘chaotical’ debrite complexes [27–29].

During the rapid deceleration of a non-cohesive debris flow and mass deposition of sandy-gravelly material (terminal phase of gravitational redeposition of a single episode), in the surface part of the apron tongue zone ending – a very short-lived (rapidly suppressed in less than 1 second) initiation of a turbulent state was observed. Turbulence involved a small (up to a few % of the flow volume) amount of the finest clasts – very fine-grained sand with an admixture of silt (without pelitic particles which were not in the sandy-gravelly flow material). The generated turbulent sandy turbidity flow, induced in this situation, clearly separated (detached) and deposited a normally-graded sandy turbidite with, beyond the front of the previously deposited massive sandy-gravelly debrite ([27] p. 205; [37], p. 7).

In connection with such genesis and development of the structural features of such type deposits – massive sandstone-to-conglomeratic flysch, during field outcrop logging, special attention should be paid to finding sedimentary erosion-depositional boundaries. If caution is not exercised (cursory logging), an amalgamated composite bed composed of individual beds with a massive structure can be mistakenly described as a single bed with normal grading (with the interpretive implication of a ‘turbidite’), when in reality, they are amalgamated massively developed debritic beds (Fig. 13).

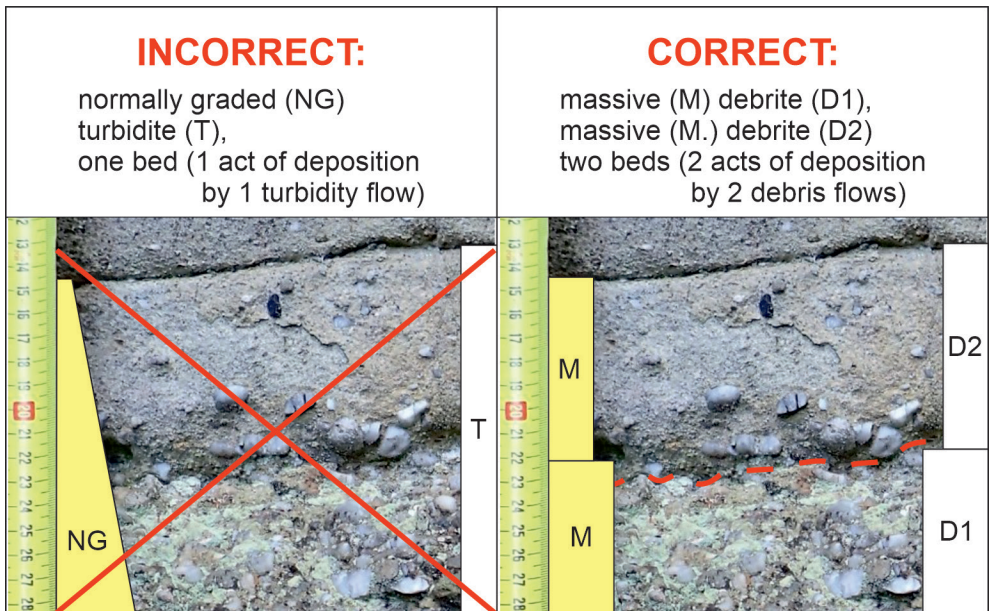


Fig. 13. Amalgamated beds within the Istebna Fm.

Source: [37], fig. 6H, p. 11, changed

## 8. CONCLUSIONS

The geoeducational tool, inspired by the geotouristic attractiveness of Carpathian sandstone-to-conglomeratic residual rocky forms, allowed for a discussion with the paradigm of turbiditic genesis one of the flysch-type deposits building the aforementioned relic flysch tors. Factual field studies, empirical laboratory simulations, and geointerpretative digital work allowed for the following conclusions:

1. Visualising the genesis of sandstone-conglomeratic debrites of the Carpathian flysch, based on the assumptions of process sedimentology ('from detail to general'), required conducting sedimentological modelling (flume experiments) generating sandy-gravelly (non-cohesive) debris flows.
2. Factual observations collected during field studies and repeatedly conducted experimental flume modelling allowed for documenting the genesis of sandy-gravelly deposits with a massive (disorganised) structure.
3. The documented physical sedimentary process responsible for the formation of experimental sandy-gravelly sediments with a massive structure (non-cohesive debrites) is a type of mass sediment gravity flow in which the clasts of a randomly scattered granular framework are supported by the detrital matrix strength and are transported in a laminar state – i.e., by sandy-gravelly (non-cohesive) debris flow.
4. Physical sedimentological modelling, conducted in the direction of searching for a process analogy for the genesis of massively developed sandstone-conglomeratic flysch deposits (non-cohesive debrites) building residual rocky forms of the Outer Carpathians (so-called Flysch Carpathians), can provide a basis for creating a geoeducational tool in the form of a film presenting and explaining their sedimentological nature.
5. Designing a geoeducational tool requires a significantly higher level of substantive preparation than the content later presented and explained to the audience.
6. Ensuring substantive correctness and high (visual) quality of the tool's components requires numerous repetitions and modifications based on the trial-and-error method, ultimately allowing for the achievement of the expected effect. This is very time-consuming, labor- and material-intensive.
7. The scope of geointerpretation of presented processes should be adapted to the audience defined at the beginning of the work.
8. The level of attractiveness can be increased by: adding a soundtrack, content read by a voice-over, different language versions, interactivity, etc.
9. The finished product can arouse the interest of geoeducation centers, museums, and can be exhibited at exhibitions related to Earth Sciences.
10. A film illustrating sandy-gravelly debris flows fits into the definition of a geoeducational tool as a geotourism product.
11. Experimental non-cohesive debrites (massive sandy-gravelly sediments) documented in the film are analogues for sandstone-conglomeratic debrites that constitute the building material for Carpathian residual rocky forms.

12. Such developed flysch lithofacies represent a sediment gravity flow developing in the form of a non-turbulent (laminar) debris flow resembling a subaqueous sandy-gravelly slope ‘avalanche’. The product of such a mass laminar gravity-driven flow should therefore be called a non-cohesive debrite or sandy-gravelly debrite and in relation to ancient (flysch) deposits – sandstone-to-conglomeratic debrite (debritic sandstone-to-conglomerates).
13. The authors are aware that the interpretation of results of fieldwork on selected Carpathian flysch objects (single geosites of massive sandstone-conglomerate debrites that build representative rocky forms and comparative outcrops of sandstone-mudstone flysch turbidites), as well as the geointerpretation of repeatable laboratory experiment results (experimental products), are approximate. Therefore, they cannot be directly applied into processes and their products occurring on the natural environment scale (source area, sedimentary basin, transport-depositional system tract). However, the clear similarity in the lithological-sedimentological characteristics of analogue flume experiment products to the observed factual textural-structural features in the rock record justifies undertaking this discussion and formulating the presented conclusions. It also encourages further studies in the experimental- and field sedimentology on a broader scale (areal and quantitative). Thus, despite the understandable methodological limitation (laboratory scale of modelling, limited number of analysed rocky forms), the proposed geointerpretation of laboratory modelling products can be successfully implemented in geoeducation for the popularisation of Earth Sciences and the promotion of geotourism.

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## STRESZCZENIE

Bazując na doświadczeniu wcześniej przeprowadzonych modelowań turbiditytowych spływów grawitacyjnych (*sensu* prądów zawieszinowych) oraz satysfakcjonujących wynikach geoedukacyjnych ich wizualnej prezentacji (dokumentacja powstawania turbulentnych suspensji, ich transportu i sedymentacji oraz formowania systemu depozycyjnego) [1–3], podjęto próbę eksperymentalnego odtworzenia innego rodzaju spływu grawitacyjnego osadu – piaskowo-żwirowego spływu rumoszewego [4, 5]. Charakterystyczną cechą produktów drugiego rodzaju spływu – debrytów piaskowcowych do zlepieńcowych – jest przede wszystkim ich masywna struktura (tj. bezładne rozproszenie klastów szkieletu ziarnowego w detrytycznym matriks) [4–32]. Tak wykształcone utwory debrytowe powszechnie budują karpackie ostańcowe formy skałkowe [32–37], które z powodzeniem można wykorzystać w popularyzowaniu nauk przyrodniczych o Ziemi, prowadząc geoedukację [32–43].

Dodatkową motywacją podjętych badań były również istniejące w sedymentologii rozbieżności interpretacyjne dotyczące pochodzenia masywnych utworów reprezentujących odmianę gruboklastycznego, gruboławicowego i amalgamowanego fliszu (Fig. 1, 2, 14) [4–32]. Upowszechniony w sedymentologicznych badaniach nad utworami grawitacyjnych spływów osadu paradygmat, wskazujący na turbiditytową genezę wyżej wzmiankowanych masywnie wykształconych litofacji silikoklastycznych budujących przedmiotowe skałki, a także publikacje prezentujące poglądy na temat możliwości innego niż turbiditytowe pochodzenia takich masywnych silikoklastyków fliszowych, zachęciły autorów do przeprowadzenia laboratoryjnego modelowania korytowego umożliwiającego udokumentowanie fizycznego procesu sedymentacyjnego, odpowiedzialnego za powstawanie masywnych piaskowo-żwirowych osadów i uformowanie charakterystycznego dla nich typu systemu transportowo-depozycyjnego.

Tworzenie narzędzia geoedukacyjnego obejmowało: (a) etap projektowy – ustalenie przedmiotu, celu, metod i odbiorcy oraz wybór zagadnień i elementów, które będą prezentowane; (b) etap merytoryczny – przegląd wiedzy z zakresu sedymentologii głębokowodnych (pozaszelfowych) utworów silikoklastycznych i metod geoedukacyjnych; (c) etap laboratoryjny – zaprojektowanie modelowania sedymentologicznego, testowanie modelu analogowego, wprowadzanie poprawek; (d) etap produkcji – nagranie filmów z trzech ujęć, opracowanie treści geointerpretacyjnych i końcowy montaż narzędzia.

Eksperymentalne badania sedymentologiczne oparto na założeniach sedymentologii procesowej [1–5, 21–25, 29, 37], której metodyka postępowania prowadzona jest w wariacie „od szczegółu do ogółu”, czyli od opisowej charakterystyki wykształcenia produktu (cechy teksturalno-strukturalne skały) do krytycznego procesu odpowiedzialnego za jego powstanie. Wynikiem badań projektowych i laboratoryjnych eksperymentów było stworzenie interaktywnego narzędzia geoedukacyjnego (filmu wraz z geointerpretacją), które umożliwiło kompleksowe wyjaśnienie kontrowersyjnej interpretacji (różne poglądy genetyczne) natury sedymentologicznej gruboklastycznych masywnie rozwiniętych utworów. Projekt narzędzia filmowego na potrzeby geoturystyki oparto na idei geoedukacji, czyli popularyzacji wiedzy geologicznej poprzez poznawanie obiektów przyrody nieożywionej i/lub procesów odpowiedzialnych za ich genezę, uznawanych za turystycznie atrakcyjne [1–5, 32–43]. Takie narzędzie geoedukacyjne spełnia funkcję produktu geoturystycznego [55, 56].

Piaskowcowe do zlepieńcowych utwory debrytowe reprezentują jedną z odmian fliszu karpackiego (Fig. 2) [9, 11, 14, 17, 20, 27–29, 32–37, 40–43, 45–48]. Sedymentacja fliszowa w subbasenach zewnętrzno-karpackich (marginalnym fragmencie oceanu Tetyda) przebiegała w czasie w zmieniających się warunkach geotektonicznych i środowiskowych oraz z udziałem różnych procesów sedymentacyjnych, a także w różnej odległości od obszarów alimentacyjnych (źródłowych), z których dostarczany był zróżnicowany materiał terygeniczny, w tym niekiedy w postaci egzotyków (rozpoznawalnych makroskopowo ponadwymiarowych klastów skał krystalicznych i starszych skał osadowych) [9, 11, 14, 17, 20, 27–29, 32–37, 40–43, 45–48, 52–54]. Za transport i depozycję materiału osadów fliszowych w głównej mierze odpowiedzialne były subakwalne spływy (Fig. 3), czyli procesy transportu i depozycji niekoherentnej (rozdrobnionej) mieszaniny materiału klastycznego i płynów (cieczy i gazów) interstycjalnych (międzyziarnowych / porowych) o różnej koncentracji objętościowej, odbywające się pod wpływem grawitacji (spływy grawitacyjne osadu) [por. 12–31, 35–37, 44–51]. Ich przykładami są m.in. turbulenty spływy zawieszinowe, generujące produkt w postaci uziarnionych frakcjonalnie normalnie turbidytów, a także laminarne spływy rumoszowe wraz z ich produktem – masywnie wykształconymi debrytami (Fig. 3–7).

Piaskowo-żwirowy (niekohezyjny) głębokowodny spływ rumoszowy to jeden z typów procesów spływów grawitacyjnych osadu, w którym redeponowany materiał ziarnowy wraz z wodą zawartą w przestrzeni porowej (przy koncentracji objętościowej powyżej 25% [24]) transportowany jest *en masse* w dół skłonu basenowego w stanie laminarnym (w przeciwieństwie do turbulentnych zawieszin spływów turbidytowych) (Fig. 3–5, 7). W warunkach wysokiej koncentracji objętościowej masowego spływu niekohezyjnego (piaskowo-żwirowego) mechanizmem podtrzymującym przemieszczanie i utrzymywanie w zawieszeniu klastów żwirowych, w tym ponadwymiarowych (stanowiących fazę rozproszoną), jest głównie siła matryks piaskowego odgrywającego rolę fazy rozpraszającej. Wysokoskoncentrowana i wysokoenergetyczna mieszanina piaskowo-żwirowego osadu i wody, mająca efektywną siłę erozyjną (inkorporacja starszych osadów), przemieszczająca się grawitacyjnie po skłonie basenu sedymentacyjnego, a następnie ulegająca gwałtownemu wyhamowaniu i masowej depozycji, przypomina lawinę i jej „zamrożone” koluwium. Produktem spływu grawitacyjnego piaskowo-żwirowego rumoszu (masowego, niekohezyjnego spływu rumoszowego) jest debryt piaskowcowo-zlepieńcowy. Utwory tego typu charakteryzują się, w związku z takim przebiegiem rozwoju procesu sedymentacyjnego, strukturą masywną (brak możliwości stopniowej segregacji grawitacyjnej skoncentrowanego materiału okruchowego podtrzymywanego siłą matryks w trakcie transportu i gwałtownej masowej depozycji). To właśnie tego typu gruboklastyczne, masywne, nieregularnie uławiczone i amalgamowane piaskowcowo-zlepieńcowe utwory fliszowe (debryty niekohezyjne) [4, 5, 23–25, 27–29, 32] stanowią podstawowy materiał budulcowy ostańcowych form skałkowych, cieszących się w ostatnich latach nieustającym, a nawet rosnącym zainteresowaniem geoturystycznym [32, 35–37]. Oprócz scharakteryzowanych powyżej odmian produktów spływów grawitacyjnych osadu, wśród karpackich utworów fliszowych występują także masywne debryty mułowcowo-żwirowe (debryty kohezyjne – utwory mułowo-żwirowych spływów rumoszowych) [12, 13, 20, 23, 24, 26, 28–31, 46–48, 50, 51] (Fig. 3, 5), jednak ze względu na ich stosunkowo niską odporność na czynniki denudacji spowodowaną dużą zawartością spoiwa mułowego (mniej odpornego na wietrzenie i erozję) nie są one skałkotwórcze.

W warunkach naturalnych masywne piaszkowe do żwirowych osady debrytowe deponowane były głównie w głębokowodnej strefie basenu sedymentacyjnego (*sensu* poza krawędzią szelfu, gdzie mogły się rozwinąć ruchy masowe i spływy grawitacyjne), obejmującej skłon i jego podnóże. Tworzyły tam one indywidualne jezory klastyczne, które ulegały lateralnej i wertykalnej amalgamacji („sklejaniu” się), czyli litosomy pokrywowe przypominające „fartuszki”. Nakładające się i ulegające koalescencji (łączeniu się) piedmontowe pokrywy fartuchowe formowały liniowo zasilany fartuchowy system depozycji fliszowej (Fig. 7) [4, 5, 20, 27–29, 32, 35–37, 50].

W przeciwieństwie do karpackich debrytów uformowanych w systemie skłonowych pokryw fartuchowych głębokowodne turbidyty fliszowe stanowią podstawowy budulec transportowo-depozycyjnego systemu głębokomorskiego stożka (Fig. 8) (por. [29]). W celu wykazania odmienności ich natury sedymentologicznej można posłużyć się obrazowymi porównaniami. Przykładowo model punktowo zasilanego systemu stożka głębokomorskiego (Fig. 8a) można by w dużym przybliżeniu porównać wizualnie do ministożka napływowego uformowanego w czasie opadów deszczu (Fig. 8c). Podobnie model liniowo zasilanego systemu fartucha głębokomorskiego (Fig. 8b) jest morfologicznie porównywalny do piaskowo-żwirowego nasypu z placu budowy (Fig. 8d). Z kolei spływ rumoszowy można porównać do komunikacji zbiorowej (np. autobusu), w której pasażerowie podczas podróży są ściśnięci (ściśnięci) w wyniku przepełnienia środka transportu, a spływ turbidytowy do transportu indywidualnego (np. samochodu osobowego), zapewniającego pasażerom komfortową (swobodną) podróż w warunkach wzajemnego oddalenia (Fig. 9) (por. [24], fig. 2.30, s. 47).

Projekt narzędzia geoedukacyjnego został oparty na konkretnych wytycznych: narzędzie przeznaczone jest do udostępnienia publicznego, ma prezentować ściśle określony temat geoedukacyjny, zakres prezentowanej wiedzy ma być wyczerpujący i klarowny, zaś sposób jej prezentacji ma być zrozumiały i dostosowany do poziomu wiedzy ucznia szkoły średniej lub wyższej. Do osiągnięcia zamierzonego celu, zarówno na etapie projektowania narzędzia, jak i jego produkcji, zidentyfikowano problemy badawcze (Tab. 1), dla których rozwiązania zostały wypracowane i wdrożone na różnych etapach realizacji projektu. Na etapie obróbki cyfrowej narzędzia geoedukacyjnego (materiał filmowy) zadbano o wzmocnienie efektów wizualnych: obraz z trzech ujęć zmontowano w spójną chronologicznie wizualizację procesu laminarnego spływu rumoszowego, fragment ekranu wydzielono na plansze z treściami objaśniającymi oraz wprowadzono stopklatki z niezbędnymi dodatkowymi wyjaśnieniami kolejno pojawiających się zdarzeń. Geointerpretacja obserwowanych zjawisk, dostosowana do poziomu wiedzy zdefiniowanego odbiorcy, obejmuje dwie kategorie – elementy opisu środowiska oraz etapy genezy spływu rumoszowego (Tab. 2) (Fig. 10). Tak zaprojektowane filmowe narzędzie spełnia funkcję geoedukacyjną dzięki prezentacji odbiorcy sekwencji określonych treści, a możliwość zatrzymania lub przewinięcia filmu w dowolnym momencie ułatwia przyswojenie i utrwalenie wiedzy. Narzędzie udostępniane jest publicznie jako film na platformie YouTube ([https://youtu.be/VKzgJUgh6\\_s](https://youtu.be/VKzgJUgh6_s)). Obserwacje generowanych w warunkach laboratoryjnych masowych spływów grawitacyjnych osadu o charakterze liniowo zasilanych subakwalnych „lawin” piaskowo-żwirowych wykazały, że przedmiotowe utwory (masywne piaskowo-żwirowe debryty) powstają z laminarnych spływów rumoszowych przybierających formę jezorów formujących pokrywy klastyczne w systemie fartuchowym, a nie ze spływów turbidytowych (*sensu* turbulentnych suspensji prądów zawieszinowych) rozprzestrzeniających

się wachlarzowo i akumulowanych w formie lobów w systemie punktowo zasilanego podmorskiego stożka. W tej sytuacji masywnie wykształcone produkty procesów laminarnej redepozycji grawitacyjnej rumoszu piaskowo-żwirowego powinny być określane mianem debrytów (debrytów niekohezyjnych), a nie turbidytów (Fig. 11, 12) czy fluksoturbidytów (Fig. 13).

Autorzy zdają sobie sprawę, że interpretacja wyników badań terenowych wybranych obiektów fliszu karpackiego (pojedyncze geostanowiska masywnych piaskowcowo-zlepieńcowych debrytów budujących reprezentatywne formy skałkowe i porównawcze odsłonięcia piaskowcowo-mułowcowych turbidytów fliszowych) oraz geointerpretacja powtarzalnych rezultatów doświadczeń laboratoryjnych (produkty eksperymentalne) mają charakter przybliżony. W związku z tym nie mogą być one wprost przekładane na procesy i ich produkty występujące w skali środowiska przyrodniczego (naturalny obszar źródłowy, basen sedimentacyjny, system transportowo-depozycyjny). Jednakże wyraźne podobieństwo cech wykształcenia litologiczno-sedymologicznego produktów analogowych eksperymentów korytowych do obserwowanych faktograficznych cech teksturalno-strukturalnych zapisu skalnego uprawnia do podjęcia przedmiotowej dyskusji i sformułowania przedstawionych wniosków. Zachęca także do prowadzenia dalszych studiów w ramach sedimentologii eksperymentalnej oraz terenowej w szerszym zakresie (obszarowym i ilościowym). Zatem mimo zrozumiałego ograniczenia metodycznego (skala laboratoryjna modelowań, ograniczona liczba analizowanych obiektów skałkowych) proponowana geointerpretacja produktów modelowań laboratoryjnych może być z powodzeniem wykorzystana w geoedukacji realizowanej na potrzeby popularyzacji nauk o Ziemi oraz promocji geoturystyki.