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CONTRASTING STYLES OF SILICICLASTIC FLYSCH SEDIMENTATION IN THE UPPER CRETACEOUS OF THE SILESIAN UNIT, OUTER WESTERN CARPATHIANS: SEDIMENTOLOGY AND GENETIC IMPLICATIONS

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Abstract: This study reports on a new set of sedimentological data and related interpretations of the Santonian–Campanian siliciclastic deposits in the Western Flysch Carpathians based on natural outcrops in the uppermost Godula Formation and lowermost Istebna Formation. The rationale was to confront the characteristics of this flysch succession with current controversies and state of knowledge on deep-water clastic sedimentation. The sedimentological analysis of the field data allowed for multi-scale synthetic classifications of the depositional components in the investigated flysch. The hierarchical and practical nature of the suggested classification schemes allows for their application to similar deposits in other regions. The siliciclastic deposits are products of gravity-driven terrigenous sediment redeposition via submarine slumps, debris flows, and turbidity currents. Sediment reworking by tractional bottom currents is considered as an accompanying factor. Point-sourced turbiditic fan lobe fringes from the submarine piedmont ramp and linearly supplied debritic covers along the slope apron are proposed as dominant. The innovative linking between the textural-structural descriptive features of the deposits and the critical determinants of specific sediment gravity-flow processes and architectural elements of the deep-water clastic depositional systems is a significant contribution to this research field.

Key words: Carpathian flysch, debrites, deep-sea deposits, depositional system, gravitational resedimentation, Silesian Basin, tractionites, turbidites, Late Cretaceous.

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INTRODUCTION

The Godula and Istebna formations, representing the upper Cretaceous flysch deposits of the Silesian Unit in the Outer Carpathians (Fig. 1), are a valuable source of knowledge on deep-water sediment transport and deposition owing to their highly diversified lithological and sedimentological development (e.g., Burtanówna *et al*., 1937; Unrug, 1963; Eliáš, 1970; Menčík *et al*., 1983; Słomka, 1995). This study focuses on the contrasting development of the uppermost Godula Formation and the overlying lowermost Istebna Formation (Figs 2, 3), which includes differences in the sedimentary facies and their vertical and lateral distributions, as well as the bedding style and depositional architecture. The wide spectrum of characteristics suggests several different genetic groups of deposits and environmental conditions; hence offering a convenient basis for confronting outcrop observations with the evolving modern concepts of deep-water sedimentation and related controversies in the literature.

The diversified development of the sedimentary succession poses a considerable interpretational challenge. Although such flysch deposits are commonly acknowledged as representing sediment gravity flows (*sensu* Middleton and Hampton, 1973, 1976), their diversification implies a range of specific transportational-depositional processes and environmental-system conditions, which is an area of current debate in the sedimentological literature (e.g., Mutti *et al*., 2009, 2010; Shanmugam, 2010, 2018, 2020; Mulder, 2011; Talling *et al*., 2012).

The aim of this study is to classify the siliciclastic flysch deposits – on the descriptive basis of their beds'

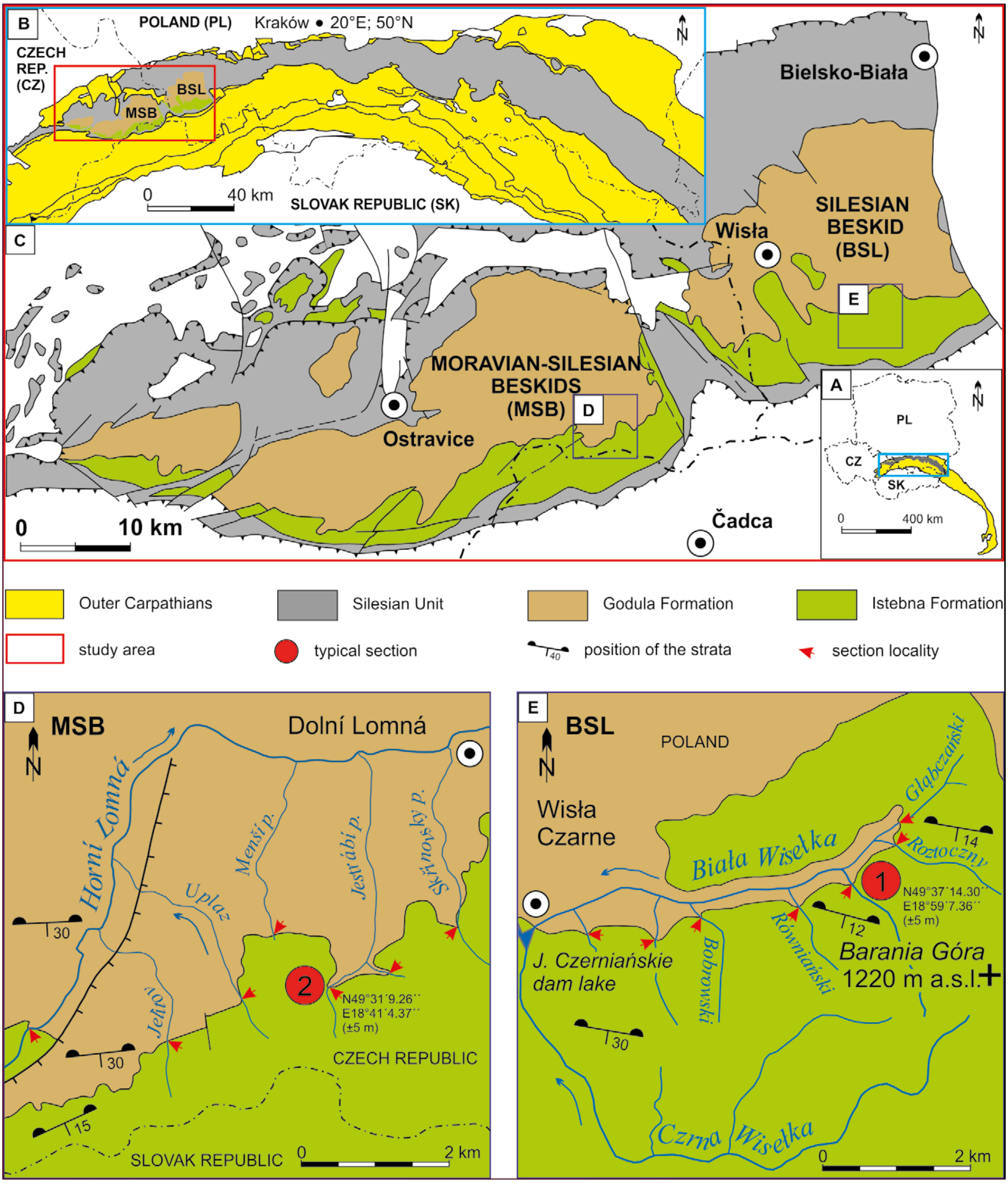


Fig. 1. Study area location maps. **A.** Position of the Outer Carpathian belt (yellow) and the Silesian Unit (grey within the blue rectangle) relative to the territories of Poland (PL), Czech Republic (CZ), and Slovak Republic (SK). **B.** Location of the Moravian-Silesian Beskids (MSB) and Silesian Beskid (BSL) areas with the Silesian Unit nappe (green/brown in the red rectangle) in the Western Outer Carpathians. **C.** Areal extent of the Godula and Istebna formations within the Silesian Unit nappe (grey), with the location of detailed maps (blue squares D and E). **D.** Detailed geological sketch map of the study area in the Moravian-Silesian Beskids, showing the localisation of the Jestrábí type section of the Godula Fm/Istebna Fm boundary. **E.** Detailed geological sketch map of the study area in the Silesian Beskid, showing localisation of the Biała Wisełka type section of the Godula Fm/Istebna Fm boundary. Simplified and partly modified maps based on Burtan (1972), Menčík and Tyráček (1985), Żytko *et al*. (1989), Golonka *et al*. (2000) and Lexa *et al*. (2000).

internal features, geometry, and stacking architecture – into multi-scale genetic categories reflecting the mode of sediment transport, deposition, and environment physiography. The analysis was performed based on the ongoing dispute over the processes and products of deep-water clastic sedimentation.

GEOLOGICAL SETTING

The upper Cretaceous siliciclastic flysch of the Silesian Unit in the Outer Western Carpathians (part of the eastern European Alpides *sensu* Golonka and Picha, 2005; Figs 1, 2) indicates the occurrence of radical changes in the environmental conditions and depositional system during Santonian–Campanian sedimentation. The variability in the siliciclastic basin-fill succession in this region is likely an indirect reflection of diastrophic activity (e.g., Nemčok *et al.*, 2001) and eustatic trends (e.g., Haq *et al.*, 1988) that occurred in the province of the Alpine Tethys during the Late Cretaceous (cf. Górny *et al.*, 2022). The coexisting changes in the geotectonic regime and global sea level likely translated into the local development of both the source areas and basinal zones (e.g., Golonka *et al.*, 2000; cf. also Mastalerz *et al.*, 2006). In the study region, the diastrophically driven reorganisation was responsible for elevating or submerging the source zone (the Silesian Cordillera *sensu* Książkiewicz, 1956), as well as for changes in the geometry, bathymetry and rate of subsidence in the Silesian Basin (e.g., Poprawa *et al.*, 2002), which entailed regressive or transgressive

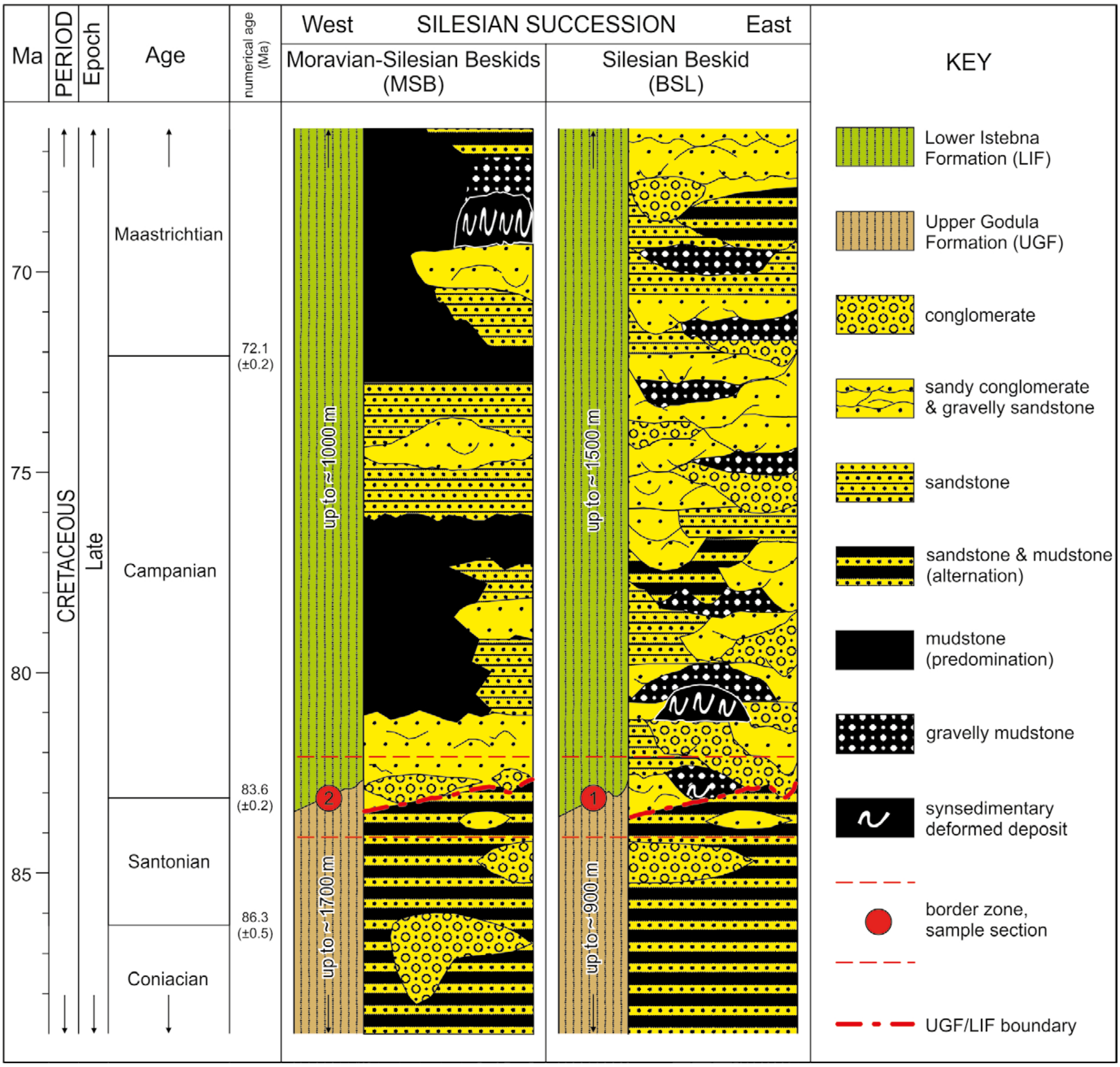


Fig. 2. Synthetic lithostratigraphy of the upper Cretaceous part of the Silesian Series in the Moravian-Silesian Beskids and Silesian Beskid regions, with an indication of the stratigraphic position of the sample sections. For section location, see Figure 1D, E. Compiled and slightly modified from Burtanówna *et al.* (1937), Bieda *et al.* (1963), Słomka (1995), Picha *et al.* (2005), Cohen *et al.* (2013), and Strzeboński and Uchman (2015).

effects and changes in the shoreline position. Tectonically and/or eustatically exposed older intra-basinal flysch deposits tended to be reworked (flysch recycling) and have provided clastic material for younger flysch formations (e.g., see Matyszkiewicz and Słomka, 1994, 2004). The combination of tectonic and eustatic changes in the basinal sea level, together with variable climatic conditions and probable local earthquakes, may have created a temporal preference for specific sedimentary processes. This hypothesis underlies the cause of the varied 'patterns' of flysch development in the Carpathian deep-water sedimentary successions (Figs 3, 4), with contrasting types of siliciclastic deposits (Figs 5, 6). The variable patterns of flysch sedimentation further include the development of specific architectural lithosomes, such as channels, levees, crevasse splays, terminal lobes, and apron covers, as well as possible influences on them from non-turbulent tractional bottom currents (e.g., Pickering *et al*., 1986; Shanmugam *et al*., 1993; Shanmugam, 2021a, b). As a result, some deep-water depositional systems in their outcrops show orderly vertical facies trends (repetitions and sequences) indicative of specific architectural elements (Figs 5, 7A). Such systems are considered to be slope, base-of-slope, and basin floor coalesced turbiditic fans (i.e., piedmont ramp; cf. Słomka, 1995; Janocko *et al*., 2013; Łapcik, 2019). Another form of deep-water accumulation are depositional complexes containing different facies (Figs 6, 7B) while lacking any orderly vertical and lateral organisation ('chaotic complexes' *sensu* Jankowski, 2007). Such disorderly complexes consist of thicker, coarser-grained, and predominantly massive deposits with irregular bedding and common amalgamation are considered to be slope and base-of-slope debritic apron covers (apron systems; cf. Reading and Richards, 1994).

The orderly flysch successions in the Outer Carpathians, as exemplified by the upper Godula Formation in the Silesian Unit, typically consist of alternating sandstone (S) and mudstone (M) sheets that form couplets with either thicker sandstone (couplet labelled SM) or thicker mudstone (couplet labelled MS; Figs 5, 7A, C; see also Eliáš, 1970; Menčík *et al*., 1983; Słomka, 1995). The rhythmic alternation of lithological SM and MS couplets was historically first reported from the Polish Outer Carpathians as a flysch prototype model (Dżułyński *et al*., 1959; Dżułyński and Smith, 1964; Dżułyński and Walton, 1965). Based on similar deposits in the French Alps, the first detailed flysch facies model was proposed (Bouma, 1962), which came to be known as the 'turbiditic' Bouma Sequence.

The disorderly ('chaotic') flysch successions in the Outer Carpathians, as exemplified by the lower Istebna Formation in the Silesian Unit (Figs 3, 4; see Burtanówna *et al*., 1937; Unrug, 1963), markedly differ from the orderly classical flysch. These are coarse-grained sandstone to conglomeratic deposits (S, SG, CS, and C; Fig 8A–F), mainly massive, irregularly thick-bedded, and commonly amalgamated. Mudstone (shale) intercalations are rare, whereas local interbeds of gravelly mudstone are characteristic for the lower Istebna Formation (labelled MG; Figs 6, 8G, 9C, D; cf. pebbly mudstone *sensu* Crowell, 1957). This type of bimodal deposit is particularly characteristic of the 'chaotic' flysch successions (Figs 7B, 8, 9).

SEDIMENTOLOGICAL BACKGROUND

This section briefly links the topic of this study with the current state of knowledge and ongoing literature discussions on sediment gravity-flow processes, outlining the sedimentary criteria used herein for the classification of the studied siliciclastic flysch deposits.

Sediment gravity-flow processes

From a fluid mechanics perspective (Mezger, 2014), a whole range of sediment-gravity flow varieties may occur as broadly understood multi-phase 'suspensions' of water-gas-sediment mixtures (cf. Schatzmann *et al*., 2003, 2009). Sediment-gravity flows range rheologically from fluidal, whether Newtonian (viscous) or non-Newtonian (pseudoplastic and dilatant), to plastic and plastic-viscous, i.e., whether Bingham (Bingham plastic) or non-Bingham (Bingham pseudoplastic), and may be cohesive or non-cohesive (Lowe, 1982; Nemec and Steel, 1984; Shanmugam, 1996, 2006; Gani, 2004). Subaqueous plastic-, pseudoplastic-, and dilatant mass gravity flows (e.g., cohesive and cohesionless debris flows) are non-turbulent ('laminar'), whereas viscous fluidal gravity flows are generally turbulent (low-density turbidity currents *sensu* Kuenen and Migliorini, 1950; cf. also Hampton, 1972). Their grain-size composition ranges from mud to gravel and their run-out distance depends on the flow type, i.e., determined by their volumetric concentration, rheological properties, mechanical states, support mechanisms, total volume, and substrate gradient. Cohesive plastic and pseudoplastic flows tend to be shear-thinning during downslope mass-gravity redeposition and longer running, whereas non-cohesive dilatant flows tend to be shear-thickening and have a shorter runout (Mezger, 2014; see also Fisher, 1983; Shanmugam, 1996, 2018; Felix *et al*., 2009). Some flows may have one rheological and mechanical mode of behaviour or evolve from one mode to another with distance, whereas others may have combined two-storey modes (cf. Postma *et al*., 1988; Shanmugam, 2000) or represent the overlapping and mixing of different independent flows ('hybrid flows' *sensu* Shanmugam, 2021a, b). In certain environmental settings, a specific range of such processes may dominate and be characteristic (cf. Dott, 1963; Sanders, 1965; Middleton and Hampton, 1973, 1976; Pickering *et al*., 1986; Shanmugam, 1996, 2021a, b; Talling *et al*., 2012). Therefore, it is crucial for a given deep-water sedimentary succession to recognise its depositional modes from the descriptive diagnostic features of its deposits (Figs 3–9), as a contrasting style of deposition invariably implies a major change in environmental conditions.

The distinction of most modes of gravity-flow sediment deposition may be simple, based on sedimentological criteria; however, some modes may be difficult to identify, especially where deep-water sediment-gravity flows have an interplay with other marine bottom currents (Shanmugam *et al*., 1993; Shanmugam, 2021a, b). For example, the planar-stratified and ripple cross-laminated deposits associated with turbidity currents may be difficult to distinguish from those of influenced by other tractional bottom currents.

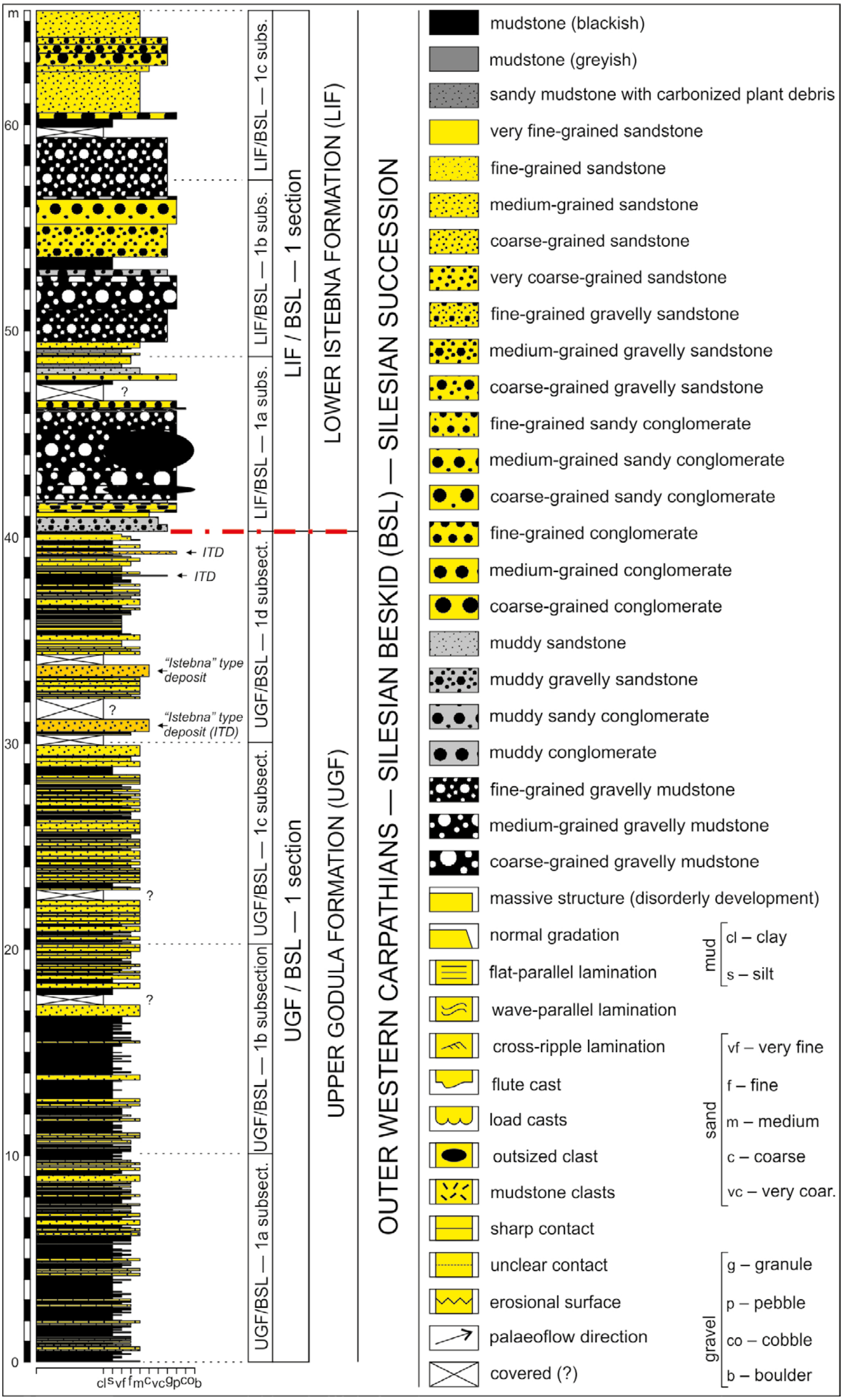


Fig. 3. Sedimentological log showing the contrasting lithotype composition of the upper Godula Formation and the overlying lower Istebna Formation in the Silesian Beskid (Fig. 1E).

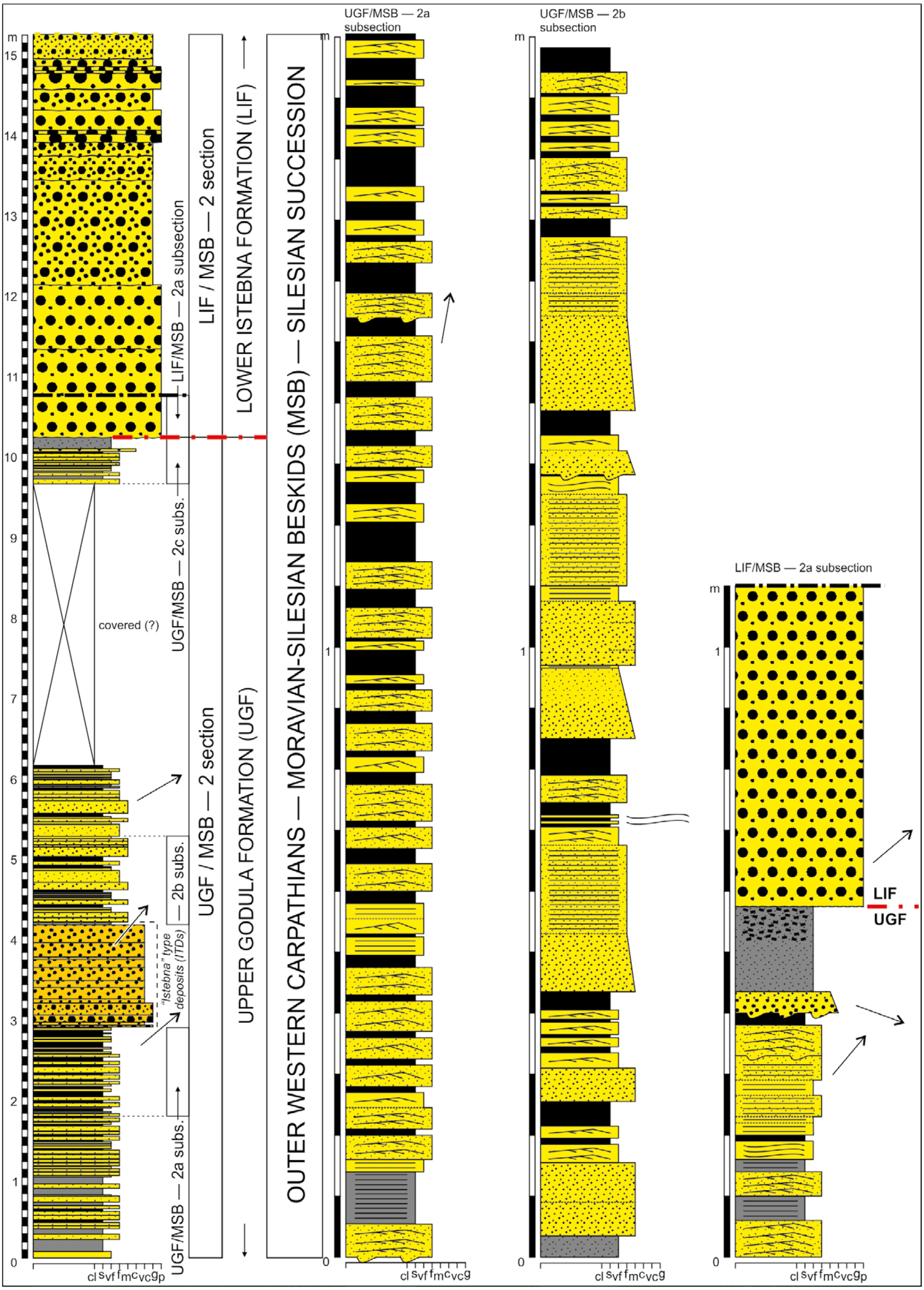


Fig. 4. Sedimentological log showing the contrasting lithotype composition of the upper Godula Formation and the overlying lower Istebna Formation in the Moravian-Silesian Beskids (Fig. 1D). For lithotype explanations, see legend in Figure 3.

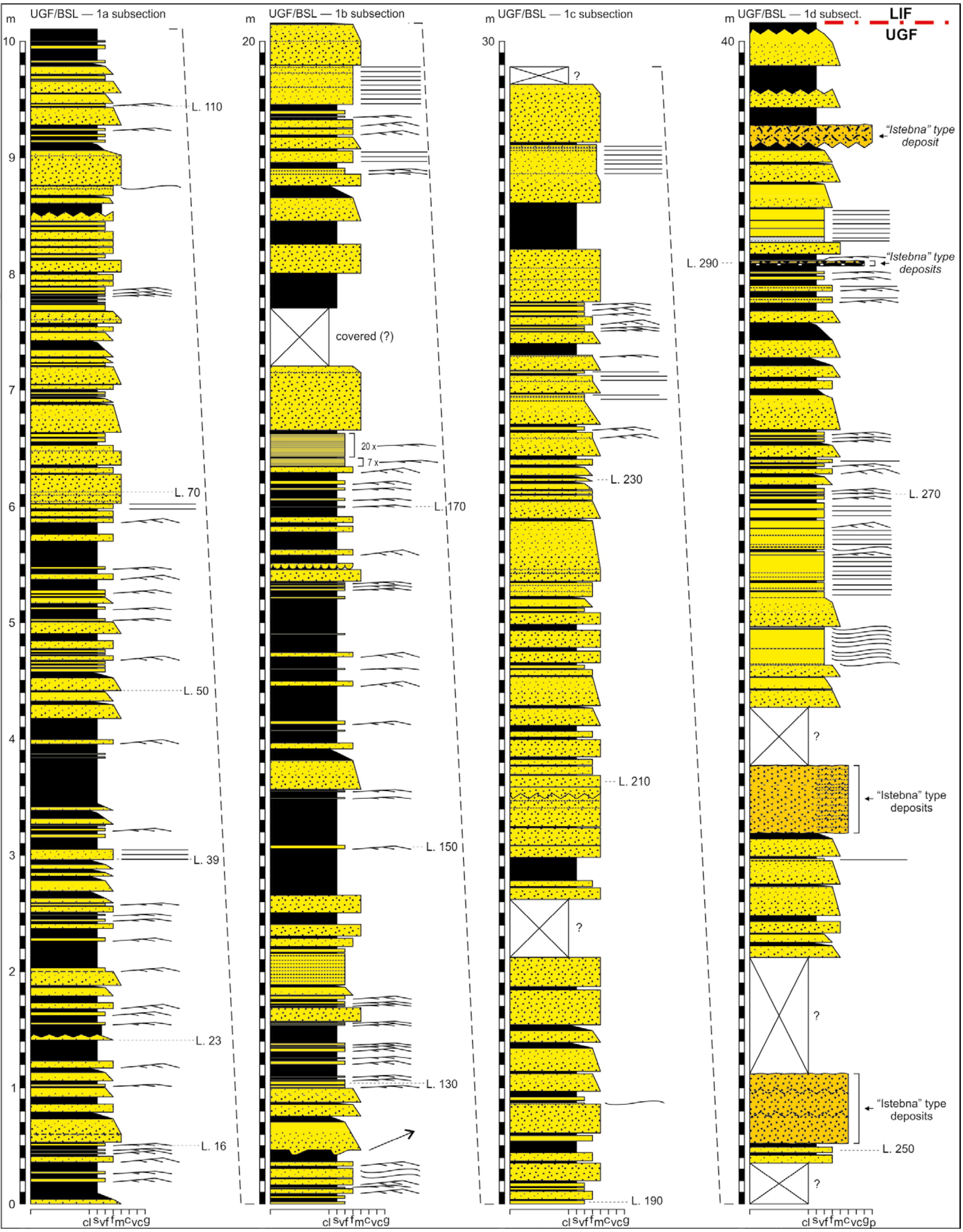


Fig. 5. Sedimentological log of the upper Godula Formation from the Biała Wisełka section in the Silesian Beskid (Fig. 1E). Note that the proportion of the sandstones generally increases upward at the expense of mudstones, heralding the forced-regressive systems tract of the lower Istebna Formation. For lithotype explanations, see legend in Figure 3.

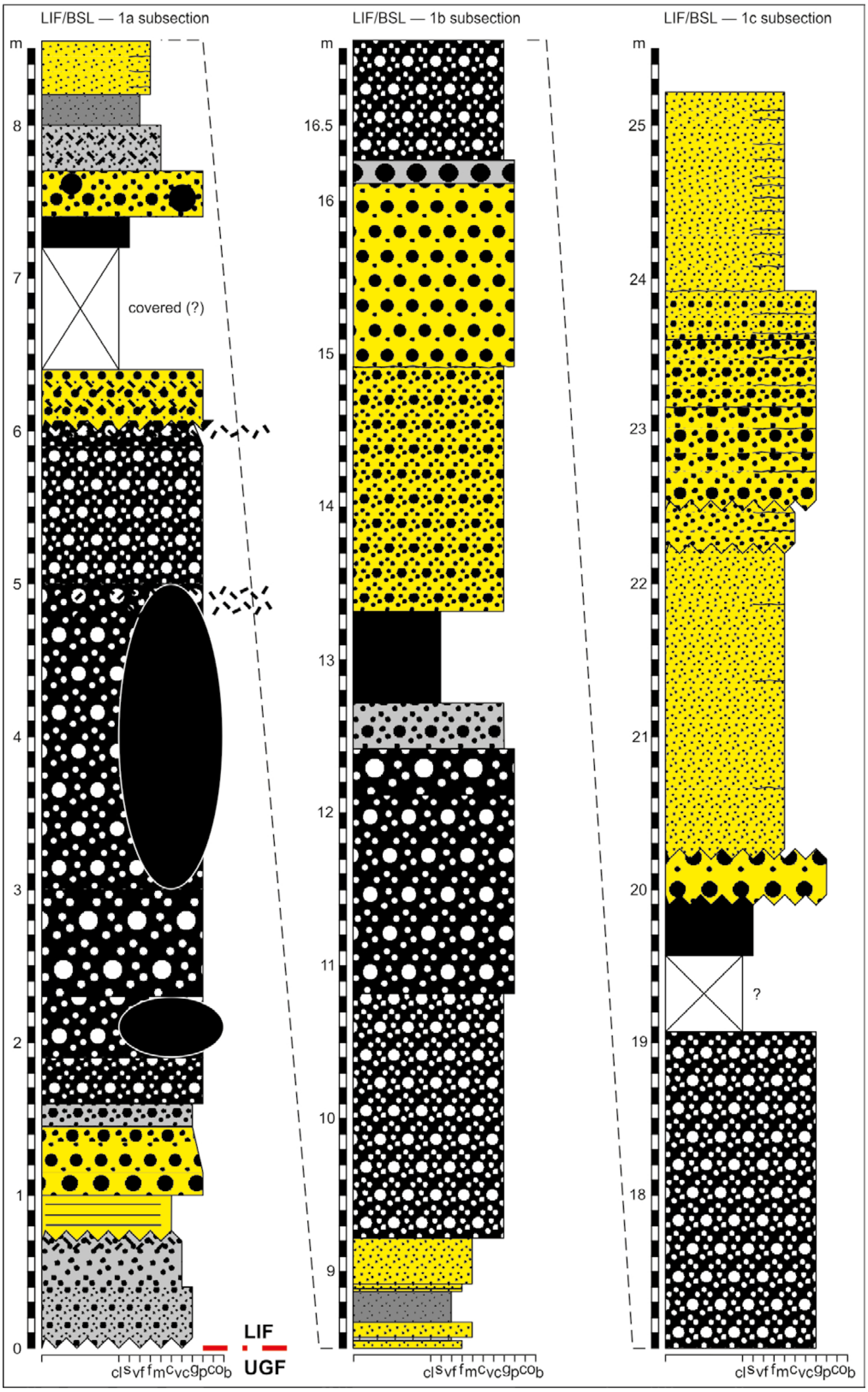
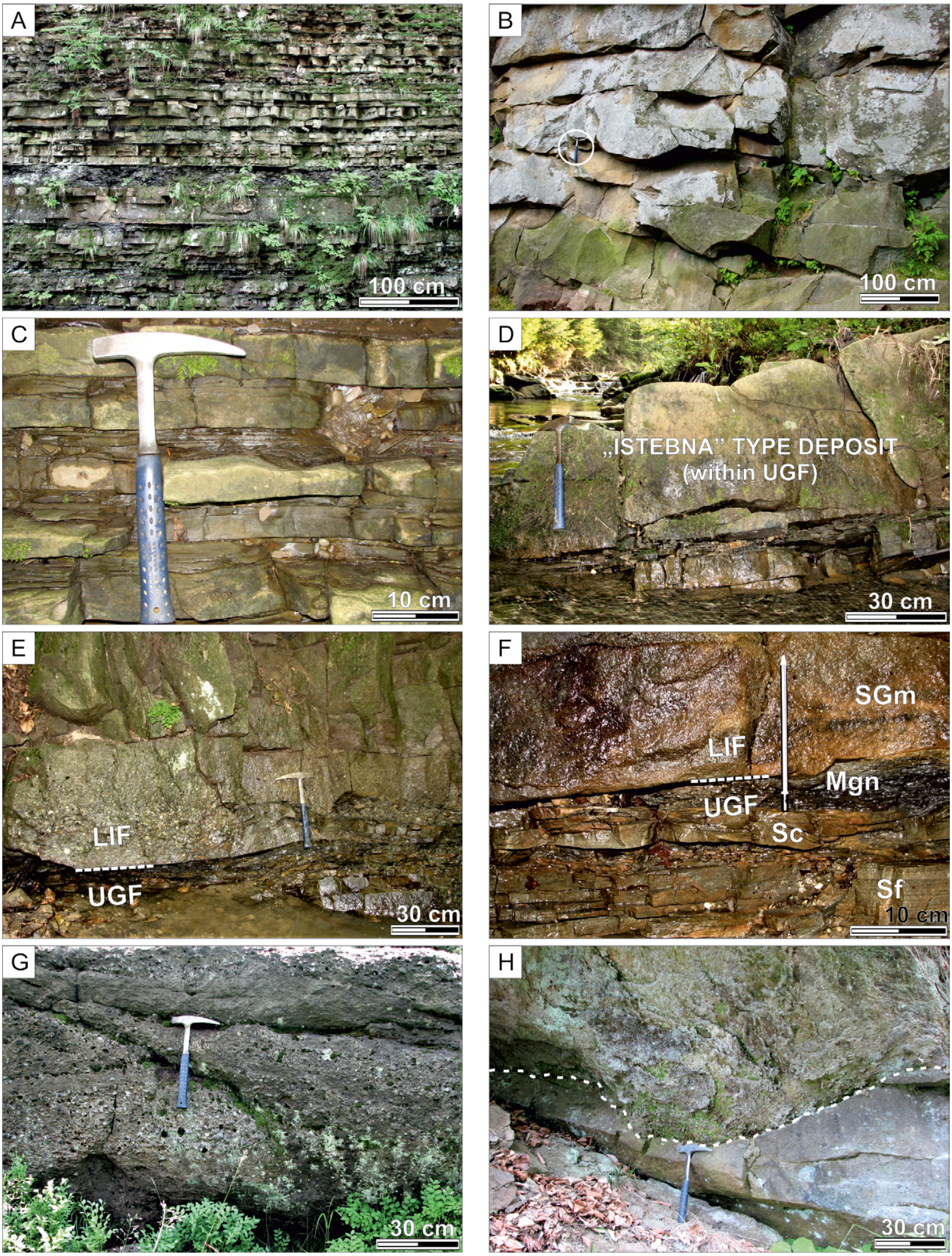


Fig. 6. Sedimentological log of the lower Istebna Formation from the Biała Wisełka section in the Silesian Beskid (Fig. 1E). For lithotype explanations, see legend in Figure 3. For an illustration of lithotype outcrop details, see Figures 8 and 9.

Fig. 7. Outcrop details of the studied flysch succession. For scale, the geological hammer is 33 cm long and the pencil is 16.25 cm long. **A.** Evenly thin- to medium bedded tabular flysch deposits of the upper Godula Formation composed of the alternating SM and MS lithotype couplets, interpreted as turbidites and hemipelagites, with possible tractionites of other deep-sea tractional bottom currents; from the Biała Wisełka Valley in the Silesian Beskid. **B.** Unevenly bedded amalgamated massive sandstone to conglomeratic deposits of the lower Istebna Formation; from the Rocks on the Kobyla in the Silesian Beskid, interpreted as non-cohesive debrites. **C.** Close-up detail of the SM and MS lithotype couplets, upper Godula Formation. **D.** Thick coarse-grained massive sandstone interbed in the uppermost Godula Formation, prompting the forced-regressive deposition of the Istebna Formation. **E.** Example of the boundary between the upper Godula



Formation (UGF) and lower Istebna Formation (LIF) in the Silesian Beskid region. **F.** Example of the boundary between the UGF and LIF in the Moravian-Silesian Beskids region. Sub-lithotypes: S_f – flat parallel laminated sandstone, S_c – ripple cross-laminated sandstone, M_{gn} – normal graded mudstone, and SG_m – massive gravelly sandstones. **G.** Uneven irregular bedding of coarse-grained amalgamated debrites in the LIF, Silesian Beskid. **H.** Very thick bed of a massive sandy conglomerate (sub-lithotype CS_m) interpreted as a debritic genotype dCS, with a basal scour overlying medium-bedded, coarse-grained massive sandstones (S_m; genotype dS) in the LIF, Moravian-Silesian Beskid.

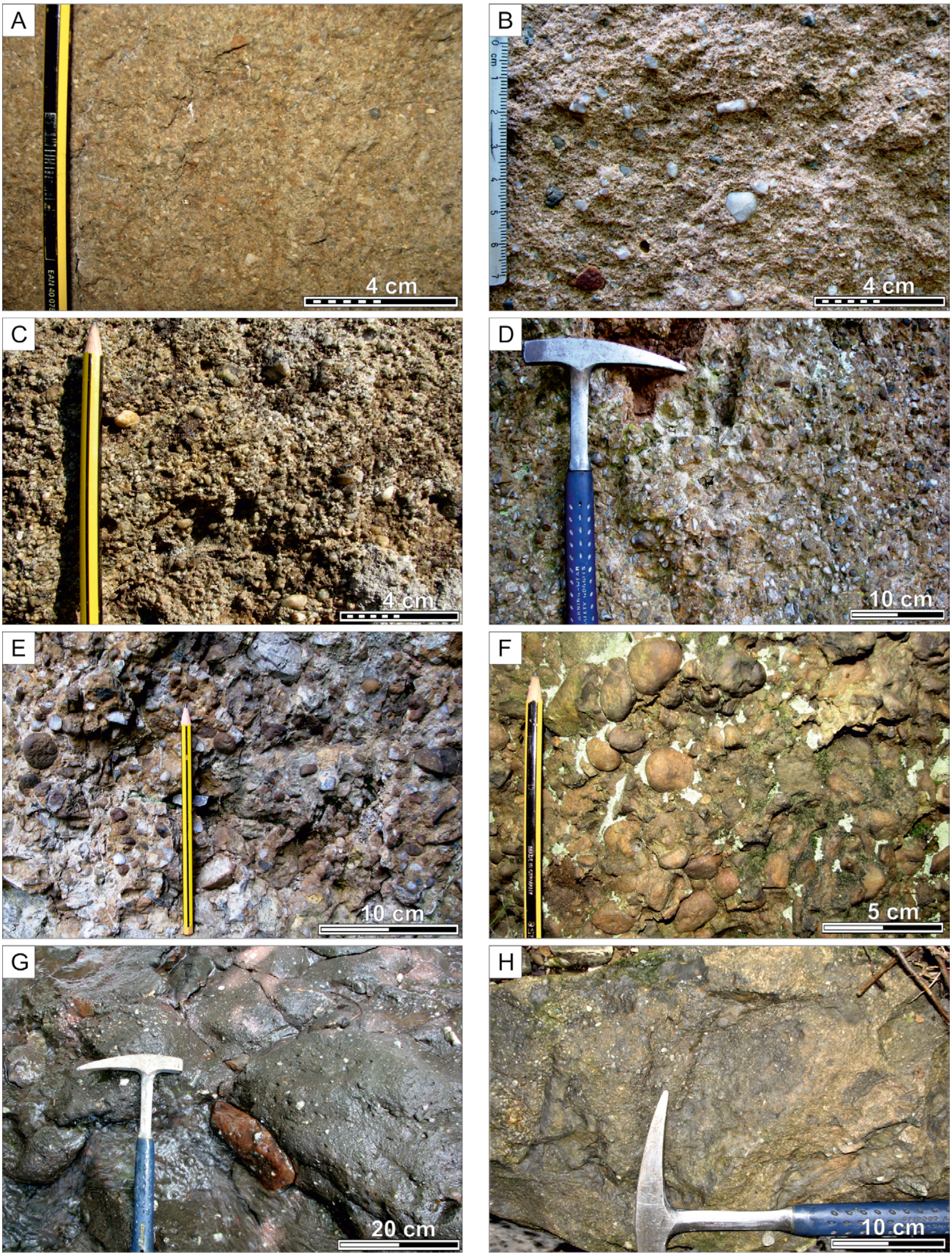


Fig. 8. Close-up textural-structural details of the flysch debrites in the lower Istebna Formation (scale and areas as in Figure 7). **A.** Very coarse-grained massive sandstone (sub-lithotype S_m), interpreted as debritic genotype dS (i.e., deposit of sandy debris flow *sensu* Shanmugam, 1996; non-cohesive debris flow *sensu* Nemec and Steel, 1984; Gani, 2004). **B.** Massive gravelly sandstone (SG_m), interpreted as debritic genotype dSG. **C.** Massive, sandy granule conglomerate (CS_m) interpreted as debritic genotype dCS. **D.** Massive, sandy granule

The depositional facies context and transport directions are generally used, although these criteria are less reliable.

Textural and structural characteristics

Macroscopic observations allowed the identification of the diverse types of litho-sedimentological development in the studied siliciclastic deposits. The diversity of these flysch deposits is further presented in terms of a descriptive and genetic classification scheme based on diagnostic textural and structural criteria.

The aim of this approach is to enable a relatively clear distinction among particular types of deposits in the field and facilitate their macroscopic categorisation and interpretation while using the letter code for further analysis, especially for the digital processing of large and diversified datasets.

The most important diagnostic textural and structural features included in the descriptive characterisation of deposits were the range of grain-size distributions (grain framework *vs*. detrital matrix, grain sorting and roundness) and the type of internal sedimentary structure (bed divisions) and its upward changes. Based on the objective descriptive categorisation of the deposits, it was then possible to interpret their modes of origin in terms of potential physical sedimentation processes.

Genetic characteristics of flysch deposits

The distinction of sediment gravity-flow processes in sedimentology refers to flow rheological and mechanical behaviour but is generally based on the descriptive macroscopic features of the deposits (cf. Dott, 1963; Sanders, 1965; Middleton and Hampton, 1976; Lowe, 1982; Nemec and Steel, 1984; Schatzmann *et al.*, 2003, 2009; Shanmugam, 2006, 2021a; Mezger, 2014). The first-order distinction is between viscous (fluidal), dilatant, and plastic-viscous (pseudoplastic) to plastic flows. Deposits of fluidal flows can be recognised based on flow turbulence (normal grading) and related tractional transport (stratification, lamination, and 'rolling' clast fabric). Tractional deposits represent low-density (low viscosity) flows with a Newtonian fluid rheological behaviour. Normally graded (non-stratified and non-laminated) turbiditic deposits represent higher-density (higher viscosity) flows while retaining Newtonian behaviour (full turbulence) and rapid non-tractional dumping owing to gradual gravity settling of sediment from turbulent suspension. The two modes of deposition (i.e., non-tractional and tractional) can combine in a given flow, with the latter mode usually followed by the former, as dumping reduces the excess sediment load while there is a significant decrease in the density and viscosity (volumetric concentration) of the flow.

Deposits of plastic, pseudoplastic (shear-thinning), or dilatant (shear-thickening) flows are recognised by their lack of turbulence (high-concentrated flows), i.e., by the presence of massive (non-stratified/laminated) structure and the absence of normal grading. Such deposits are the products of debris flows, which may be cohesive or non-cohesive (*sensu* Gani, 2004), depending on the clay content and degree of dilution by interstitial water (i.e., muddy gravelly debris flows or gravelly to sandy debris flows, respectively). Deposits of cohesive debris flows show either no grain-size grading or a crude coarse-tail inverse grading limited to the coarsest clasts, resulting from flow basal shearing with the upper part of the flow acting as a non-shearing or insignificantly shearing 'rigid plug'. Their texture is typically muddy matrix-supported, and the clast fabric is disorderly. Deposits of non-cohesive debris flows typically have a clast- to matrix-supported texture and tend to be massive or inversely graded. Depending upon the regime of clast interaction (Drake, 1990), the clast fabric may be disorderly (frictional regime) or flow-aligned and possibly imbricated (collisional regime).

Based on such macroscopic criteria, sub-lithotypes of deposits have been distinguished and linked with their potential deposition process, thereby leading to the distinction of genetic sub-lithotypes. The terms lithotype and sub-lithotype in this study correspond to the previously used terms of lithofacies and sub-lithofacies, respectively (Ghibaudo, 1992; Słomka, 1995).

MATERIALS AND METHODS

The field material for this study was obtained from the upper Cretaceous (Santonian–Campanian) siliciclastic flysch of the upper Godula and lower Istebna formations in the Moravian-Silesian and Silesian Beskid areas (MSB, *Cz. Moravskoslezské Beskydy* and BSL, *Pol.* Beskid Śląski, respectively; Fig. 1). Outcrop sections of the succession studied have a total true thickness of > 950 m. The selected 16 sections (Fig. 1) satisfied the criterion of vertical stratigraphic continuity (Fig. 2) and allowed for a detailed, bed-by-bed examination of the deposits (Figs 4–6).

Field investigation was carried out with the standard method of sedimentological facies analysis (e.g., Pickering *et al.*, 1986; Słomka, 1995; for details see also Strzeboński *et al.*, 2017, p. 563). By linking the descriptive litho-sedimentological observations with potential physical depositional processes, this methodological approach can be regarded as process sedimentology (Shanmugam, 2006).

Palaeotransport directions were approximated from field measurements of the directional sedimentary structures (e.g., Figs 4, 5; see also Słomka 1995) measured with a Freiberger geological compass. The directional indices in the upper Godula Formation (e.g., Figs 3, 7A) were predominantly

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conglomerate (CS_m) interpreted as debritic genotype dCS. **E.** Massive, sandy matrix-supported conglomerate (C_m) interpreted as debritic genotype dC. **F.** Massive conglomerate (C_m), partly clast-supported, interpreted as debritic genotype dC. **G.** Massive gravelly mudstone (MG_m) interpreted as debritic genotype dMG; pebbly mudstone *sensu* Crowell (1957). **H.** Massive muddy (mud-rich) sandy conglomerate (MCS_m) interpreted as debritic genotype dMCS; deposit of cohesive debris flow *sensu* Nemec and Steel (1984) and Gani (2004).

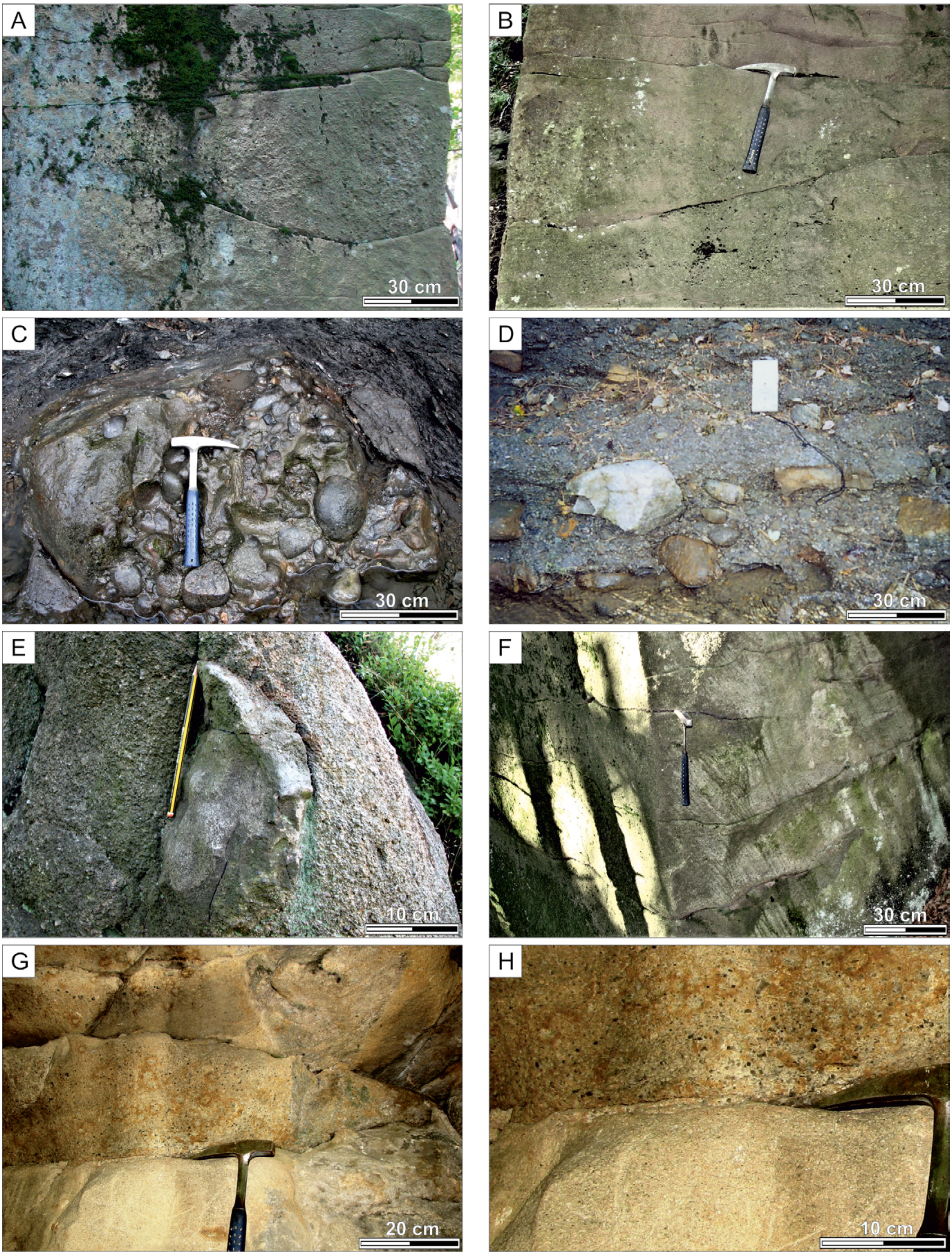

Fig. 9. Examples of flysch deposits in the lower Istebna Formation highlighting their contrast with the flysch of the upper Godula Formation (cf. Fig. 7A). **A**, **B.** Uneven irregular bedding of amalgamated debrites, with shallow scours and compensational stacking of deposits. **C.** 'Exotic boulder' of clast- to matrix-supported massive conglomerate composed of metamorphic and igneous pebbles, as a resedimented outsized clast (olistolith), in a massive mudstone (see pebbly mudstone *sensu* Crowell, 1957), illustrating the multi-generational

flute marks (turbulence indicators) at the bottom of sandstones (Figs 4, 5). Palaeocurrent indices in the lower Istebna Formation (e.g., Figs 3, 7B), owing to the general lack of flute marks, were the axes of erosional-depositional features, such as cut-and-fill and pinch-out structures (Figs 7H, 9A, B), as well as clast lineation and imbrication fabric (e.g., Fig. 8F).

The field data were acquired using the standard method of lithostratigraphic logging and are presented herein in a graphic form as schematic litho-sedimentological logs (Figs 3–6). The Biała Wisełka outcrop section (Figs 1E, 2, 3) is suggested as a reference profile and type locality, showing the diversified development of the flysch succession deposits (Figs 5, 6).

RESULTS

This section is a synthetic descriptive review of the lithotypes and sub-lithotypes distinguished within the studied flysch succession. The litho-sedimentological classification scheme is exhaustive with respect to the studied deposits but is hierarchical and open to possible extension with other lithotypes and/or sub-lithotypes in future research or in other regions.

Lithotypes

The clastic lithotype is a lithological body characterised by specific textural features. It may occur as a simple bed (solitary mono-structural bed), representing a single depositional event/act, or as a division of a composite bed (amalgamated multi-structural bed), representing multi-depositional event(s). Lithotypes were identified macroscopically (Tables 1, 2; Fig. 3) and given an informative letter code. The main lithotypes distinguished on a textural basis in this study were as follows:

- conglomerates (lithotype C) – composed of a psefitic fraction (grain size > 2 mm; frequently poorly sorted in the range of 4–32 mm), which volumetrically dominates over the sandy matrix in both matrix- and clast-supported fabric (Fig. 8E, F);
- sandy conglomerates (CS) – with a matrix-supported texture dominated by mainly granule gravel (grain size 2–4 mm) dispersed in a sandy non-cohesive matrix (Figs 6, 8C–D, 9E);
- gravelly sandstones (SG) – volumetrically dominated by sand, with dispersed gravel clasts (Fig. 8B; Fig. 9H, upper layer);
- sandstones (S) – deposits composed solely of a psammitic fraction (Fig. 5, yellow units; Fig. 8A; Fig. 9H, lower layer);
- gravelly mudstones (MG) – composed of aleuritic-pelitic sediment forming the dispersing phase (cohesive muddy matrix) for a dispersed phase of randomly scattered gravel clasts, ranging from granules to boulders (Fig. 6, black and white patterns; Figs 8G, 9D);
- mudstones (M) – solitary accumulations of mud with sharp bottom and top boundaries, found as distinct beds separating other lithotypes (Fig. 5, the upper three units in black in the topmost part of subsection 1d; Fig. 6, deposits in pure black).

In addition, two lithotypes of heterolithic deposits were distinguished, composed of an alternation of very thin to medium sandstone and mudstone layers:

- sandstone-dominated heterolithic beds (SM) – with sandstone layers thicker than gradationally superimposed mudstone layers, S > M (Tables 1, 2; Figs 4, 5, 7A, C);
- mudstone-dominated heterolithic beds (MS) – with mudstone layers thicker than sandstone layers, M > S (Tables 1, 2; Figs 4, 5, 7A).

Structural aspects of lithotypes

As a second-order classification criterion, the internal primary structural characteristics of the lithotype beds were used. A ‘depositional interval’ was defined as a sediment accumulation characterised by one type of sedimentary structure. Mono-structural beds (simple beds) consist of one structural interval, while two or more vertical intervals form a multi-structural beds (composite beds). The depositional intervals are thus conceptually similar to the divisions of a ‘Bouma sequence’ (Bouma, 1962), but without any pre-prescribed vertical sequence as well as attachment to the process genesis.

Based on direct macroscopic field observations, the following main types of structural intervals were distinguished, with a lower-case letter code used as subscripts for the lithotype symbols (see previous section):

- massive interval (m) – a deposit lacking both stratification/lamination and vertical grain-size grading (Fig. 6, black- and black-white patterns; Figs 7F, SG_m, 8, 9C–H). Such interval are particularly common within the deposits of the lower Istebna Formation (Figs 3, 7B);
- normal-graded interval (gn) – a non-stratified/laminated deposit with normal grading of its bulk grain-size distribution (Figs 4, 5, see normally graded sandstone beds; Fig. 7F, M_{gn}). Normal grading is common in the deposits of the upper Godula Formation (Figs 3, 7A);
- laminated interval, with such varieties of deposits as: f – flat parallel laminated; w – wavy parallel laminated; c – ripple cross-laminated (Figs 4, 5, laminated sandstone beds; Fig. 7F, S_f, S_c). Laminated intervals dominate in the deposits of the upper Godula Formation (Figs 3, 7A).

No depositional intervals with large (dune)-scale cross-stratification were found in the studied flysch succession.

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nature of Carpathian exotics. **D.** Outsized gravel clasts floating in a gravelly mudstone debrite (open geological compass 7 × 14 cm for scale). **E.** Outsized sandstone intraclast floating in a massive sandy conglomerate debrite, illustrating system erosion and resedimentation during forced regression. **F.** Packet of irregularly bedded amalgamated massive gravelly sandstones as a typical example of the debritic cover of the slope resedimentation apron. **G.** Uneven bedding of massive debrites, illustrating the chaotic pattern of resedimentation in the forced-regressive slope apron. **H.** Sharp contact (at the hammerhead level) of a sandy debrite and subsequent gravelly sandstone debrite deposited in the slope-resedimentation flysch apron.

Table 1

Relative proportion of the main flysch lithotypes in the upper Godula Formation (UGF) in the Moravian-Silesian Beskids (MSB) and Silesian Beskid (BSL) regions, with a data emphasis on the Biała Wisełka section (see Figs 1, 5).

UGF	Thickness share [%]		Frequency share [%]		Thickness range [cm]		Average thickness [cm]	
Lithotypes	MSB	BSL	MSB	BSL	MSB	BSL	MSB	BSL
M	2.3	3.0	3.3	2.6	3.5–10	1–40	6.7	14.1
MS	23.9	24.8	28.9	26.9	1–23	2–55	8.0	11.0
SM	45.4	55.7	56.1	60.8	1.5–38.5	1.5–45	7.8	11.1
SG	8.6	< 0.1	1.7	0.3	5–87	2–2	21.7	2.0
S	19.8	16.3	10.0	9.1	0.5–40	2–60	6.9	21.5
MG	0.0	< 0.1	0.0	0.3	0.0	2–2	0.0	2.0

Table 2

Relative proportion of the main flysch lithotypes in the lower Istebna Formation (LIF) in the Moravian-Silesian Beskids (MSB) and Silesian Beskid (BSL) regions, with a data emphasis on the Biała Wisełka section (see Figs 1, 3, 6).

LIF	Thickness share [%]		Frequency share [%]		Thickness range [cm]		Average thickness [cm]	
Lithotypes	MSB	BSL	MSB	BSL	MSB	BSL	MSB	BSL
M	0.0	6.6	0.0	6.9	0	20–60	0.0	32.0
C	1.5	0.6	7.2	1.4	5–30	15	16.0	15.0
CS	14.4	9.3	36.3	8.3	3–110	7–120	29.9	37.5
SG	15.2	17.5	31.9	22.2	10–130	4–160	35.8	26.4
S	20.4	22.4	17.4	47.3	3–500	2–70	88.2	15.9
MG	48.5	43.6	7.2	13.9	50–1750	10–285	502.0	104.5

As shown, for example, by the Biała Wisełka outcrop section (Figs 3, 5), sandstone intervals with normal grading have a relatively high thickness share (nearly 50%) in lithotype SM, whereas their share in lithotypes MS and S does not exceed 20%. In the heterolithic MS beds, sandstone intervals with ripple cross-lamination have the largest thickness share (40.5%) and highest frequency (nearly 55.0%), although they have the lowest mean thickness (2.1 cm). Massive intervals are significant in all lithotypes, especially in the S solitary beds (nearly 70% thickness), where they reach the highest individual (nearly 60 cm) and mean thickness (over 30 cm).

The field data indicate that the upper Godula Formation has a stable proportion of lithotype depositional intervals in the area of the Moravian-Silesian Beskids (Fig. 4). In contrast, the beginning of the lower Istebna Formation in both the Moravian-Silesian Beskids and Silesian Beskid is dominated by massive sandstone to conglomeratic deposits (S–C lithotype association), with local occurrences of MG interbeds, mostly with massive intervals (Figs 4, 6, 7B, 8).

Sub-lithotypes

The descriptive classification of the flysch deposits was completed by linking their main textural categories (upper-case letter code) with primary structural features (lower-case subscript letter code), which resulted in the distinction of sub-lithotypes. They occur as single-interval solitary beds or as divisions of composite multi-interval beds. The dominant sub-lithotypes were as follows:
- massive conglomerates (C_m) – lithotype C without stratification and vertical grain-size grading (Fig. 8E, F);
- massive sandy conglomerates (CS_m) – lithotype CS with similar structural features as above (Figs 8C, D, 9E);
- massive gravelly sandstones (SG_m) – lithotype SG with similar structural features as above (Fig. 8B and Fig. 9H, upper layer);
- massive sandstones (S_m) – lithotype S with similar structural features as above (Fig. 8A and Fig. 9H, lower layer);
- massive gravelly mudstones (MG_m) – lithotype MG with similar structural features as above (Fig. 6, see black and white patterns; Figs 8G, 9D);

- massive mudstones (M_m) – lithotype M with similar structural features as above (Fig. 6, see black pattern);
- normal-graded sandstones (S_{gn}) – lithotype S showing normal grain-size grading (Fig. 5);
- normal-graded mudstones (M_{gn}) – lithotype M showing normal grading (Fig. 7F).
- laminated sandstones – lithotype S with flat parallel lamination (S_f), wavy parallel lamination (S_w), or ripple cross-lamination (S_c) (Figs 4, 5, 7F).

The sandy sub-lithotypes in the sandstone–mudstone couplets (MS and SM) in heterolithic beds showed the following range of upward sequences (Table 3).

The sequence, i.e., II, XIV, and XVII (Table 3), as well as S_{m-gn-c} M (XX), $S_{m-gn-f1-c}$ M (XXI), $S_{m-gn-c-f2}$ M (XXII), and $S_{m-gn-f1-c-f2}$ M (XXIII), theoretically expected, was not found in this study (the latter, i.e., XX–XXIII are not included in Table 3).

These sequences are hardly comparable to the Bouma classic 'turbidite sequence' (see also discussion by Shanmugam, 2021a, b) and appear to be partially compatible with recent experimental studies on turbidity current energy auto-fluctuations by Ge *et al.* (2017, 2022).

GENETIC INTERPRETATION

In this section, the genetic interpretation of the sub-lithotypes is summarised, based on existing literature on deep-water sedimentation processes and depositional systems (Fig. 10). The sub-lithotypes distinguished in this study were interpreted as follows:

- C_m sub-lithotype – deposits of gravelly debris flows (conglomeratic debrites), debritic genotype dC (Fig. 8E, F), where their lack of grading indicates flow internal low-rate 'frictional' shear regime *sensu* Drake (1990);
- CS_m sub-lithotype – deposits of gravelly-sandy debris flows (sandy conglomeratic debrites), dCS (Figs 6, 8C–D, 9E); their lack of grading indicates a flow 'frictional' shear regime (*sensu* Drake, 1990), where the sand matrix reduces gravel friction but does not permit direct gravel clast interaction;
- SG_m sub-lithotype – deposits of sandy-gravelly debris flows (gravelly sandstone debrites), dSG (Fig. 8B; Fig. 9H, upper layer); the lack of grading indicates a low-rate 'frictional' shear regime (*sensu* Drake, 1990),

Table 3

Variety and relative contribution of lithotypes S-M in the upper Godula Formation (UGF) in the Moravian-Silesian Beskids (MSB) and Silesian Beskid (BSL) regions of the study area, with an emphasis on data from the Biała Wisełka section (see also Figs 2, 4, 5). Symbols M > S and S > M refer to the couplet's relative thickness proportion of sandstone and mudstone.

UGF / Variety of lithotype S-M couplets	M > S couplets in MSB region		M > S couplets in BSL region		S > M couplets in MSB region		S > M couplets in BSL region	
	Thickness [%]	Frequency [%]	Thickness [%]	Frequency [%]	Thickness [%]	Frequency [%]	Thickness [%]	Frequency [%]
$S_{gn-f1-c-f2}$ **M** (I)	0.0	0.0	0.0	0.0	2.9	1.0	0.0	0.0
$S_{gn-c-f2}$ **M** (II)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$S_{gn-f1-c}$ **M** (III)	0.0	0.0	0.0	0.0	12.0	5.0	0.0	0.0
S_{gn-c} **M** (IV)	0.0	0.0	3.8	1.1	3.9	3.0	2.1	1.1
S_{gn-f} **M** (V)	0.0	0.0	0.0	0.0	4.1	3.0	5.2	2.7
S_{gn} **M** (VI)	0.0	0.0	16.0	10.1	11.8	6.1	33.9	27.5
$S_{f1-c-f2}$ **M** (VII)	4.9	2.0	0.0	0.0	1.4	1.0	0.0	0.0
S_{f1-c} **M** (VIII)	2.2	2.0	0.0	0.0	21.9	18.2	2.5	1.1
S_f **M** (IX)	1.9	6.1	1.9	1.1	6.7	7.1	3.2	4.9
S_{c-f2} **M** (X)	1.7	2.0	2.0	2.2	0.7	1.0	0.0	0.0
S_c **M** (XI)	87.4	83.8	41.4	50.7	26.2	46.6	8.0	20.3
S_m **M** (XII)	1.9	4.1	34.9	34.8	2.2	4.0	31.1	37.0
S_{m-c} **M** (XIII)	0.0	0.0	0.0	0.0	4.2	3.0	0.9	0.5
S_{m-c-f2} **M** (XIV)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S_{m-f} **M** (XV)	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.1
S_{m-f1-c} **M** (XVI)	0.0	0.0	0.0	0.0	2.0	1.0	0.0	0.0
$S_{m-f1-c-f2}$ **M** (XVII)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S_{m-gn} **M** (XVIII)	0.0	0.0	0.0	0.0	0.0	0.0	9.0	3.3
S_{m-gn-f} **M** (XIX)	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.5

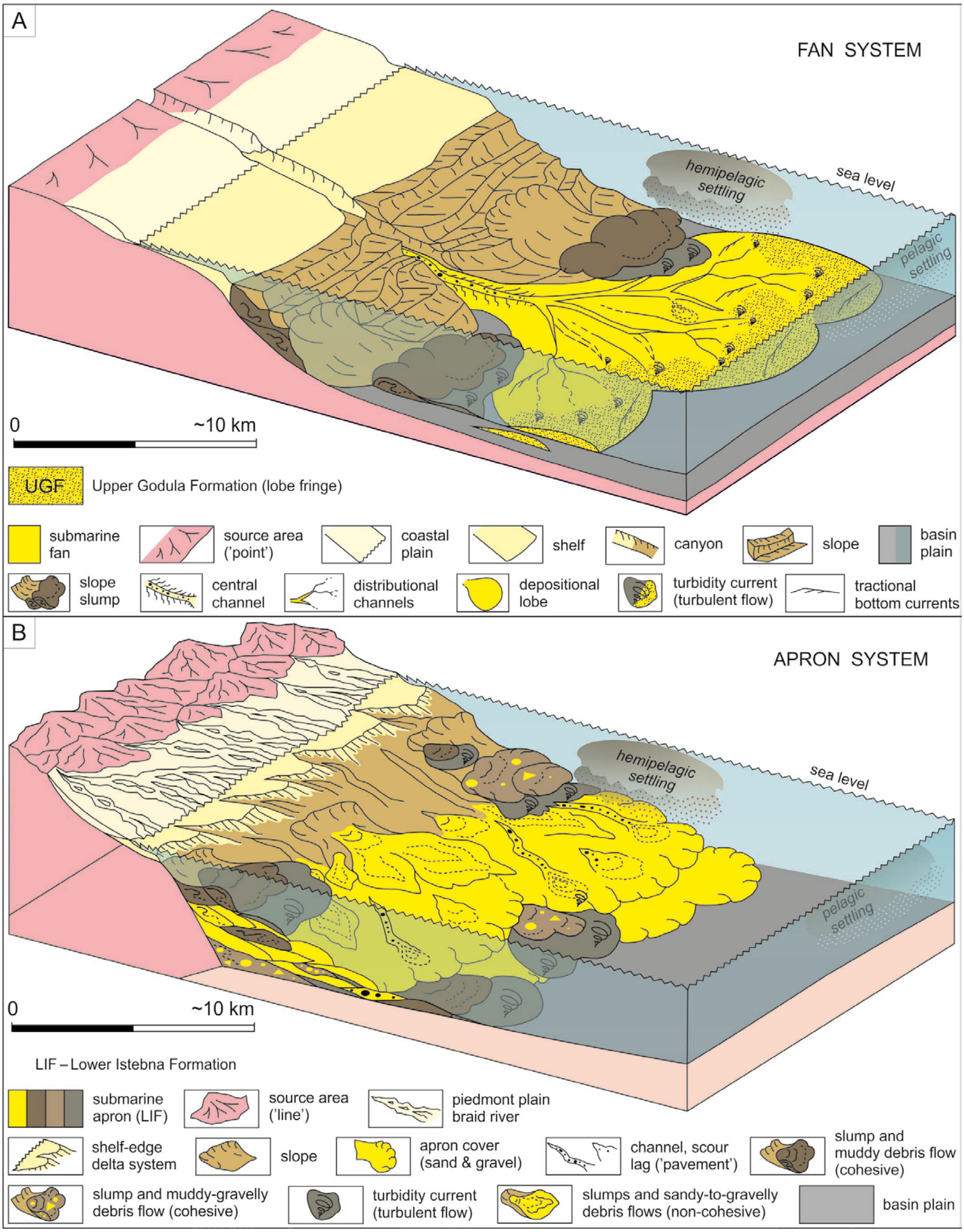

Fig. 10. Schematic sedimentation model for the evolving depositional systems tract of the studied flysch succession (diagrams redrawn and modified from Reading and Richards, 1994). **A.** Point-sourced normal-regressive submarine fan systems tract of the upper Godula Formation, dominated by MS and SM lithotypes (see Figs 5, 7A). **B.** Line-supplied slope resedimentation apron in the forced-regressive systems tract of the lower Istebna Formation, dominated by lithotypes S-C and MG (see details in Figs 6, 7G–H, 8, 9).

with the shear rate just sufficient to mobilise the gravel-hosting sand matrix.

- S_m sub-lithotype – deposits of sandy debris flows (sandstone debrites), dS (Fig. 8A; Fig. 9H, lower layer); their lack of grading indicates a low-rate ‘frictional’ shear regime (*sensu* Drake, 1990), with the shear rate just sufficient to mobilise sand material.

Debritic genotypes (dC, dCS, dSG, and dS) are attributed to the mass gravitational resedimentation of non-cohesive clastic sediments on the depositional system slope (cf. sandy debris flows *sensu* Shanmugam, 2006).

- MG_m sub-lithotype – deposits of muddy-gravelly debris flows (gravelly mudstone debrites), dMG (Fig. 6, black and white patterns; Figs 8G, 9D); diamictites attributed to the mass gravitational resedimentation of deep-water slope mud destabilised by an overload of sinking gravel usually with an admixture of sand (cf. Crowell, 1957; for debris-fall process, see Nemec, 1990).
- M_m sub-lithotype – deposits of muddy debris flows (mudstone debrites), dM (Fig. 6, black pattern); attributed to the mass gravitational resedimentation of deep-water slope mud.

These massive debritic deposits dominate the lower Istebna Formation.

- S_{gn} sub-lithotype – sandy deposits of turbidity currents (sandstone turbidites), turbiditic genotype tS (Fig. 5), attributed to a non-tractional gradual gravity settling or rapid dumping with the sorting of suspended sand by the turbulent current (cf. Lowe, 1988); these turbiditic sandstones with normal gradation are characteristic of the upper Godula Formation (Fig. 7A).
- M_{gn} sub-lithotype – muddy deposits of turbidity current tails (mudstone turbidites), tM (Figs 5, 7F); these normally graded turbiditic mudstones abound as interlayers in the upper Godula Formation (Fig. 7A).
- S_f, S_w, and S_c sub-lithotypes – tractional sandy deposits (sandstone tractionites), henceforth relabelled genetically as tractionitic genotype tS_f, tS_w and tS_c, respectively (Figs 4, 5, 7F); these laminated tractionitic sandstone layers occur mainly in the upper Godula Formation (Figs 3, 7A, C; cf. Unrug, 1977).

COMPARATIVE SEDIMENTOLOGICAL CHARACTERISTICS

The lithotypic analysis, based on the textural and structural features of the siliciclastic flysch deposits, revealed a striking contrast between the upper Godula Formation (Figs 3–5, 7A) and overlying lower Istebna Formation (Figs 3, 4, 6, 7B) while providing insight into their representative characteristics (Tables 1–3) and allowing for a regional comparison between the Moravian-Silesian Beskids and Silesian Beskid (Fig. 1C–E) within the Silesian Unit of the Outer Western Carpathians (Figs 1B, 2).

Notably, the similarity of the field sections showed the formation boundary (Fig. 2) in the two areas (Fig. 1C–E), with similarly contrasting lithological and sedimentological aspects of the two stratigraphic parts in the siliciclastic flysch succession (Figs 3, 4). The upper part of the Godula Formation in both Beskidian regions is generally developed as an MS–SM series (Figs 3–5), whereas the lower part of the overlying Istebna Formation is dominated by the S–C lithotype association with subordinate MG interbeds (Figs 3, 4, 6). The details of this contrast are summarised in Tables 1–3 and shown in the outcrop graphical logs (Figs 3–6). The difference between the two formations includes the thickness and regularity/irregularity of the bedding (Figs 4–7A, B).

This marked litho-stratigraphic contrast and its regional similarity indicate a profound trans-regional change in the basinal mode of the siliciclastic flysch sedimentation, including the sediment sourcing style and depositional processes (Figs 3, 4, 7A–F, 10). The two formations represent two genetically different types of flysch deposits. Most striking is the predominance of thin, tabular, fine-grained, and normally graded turbidites and laminated ‘tractionites’ (*sensu* Unrug, 1977) in the lower flysch succession and the predominance of a range of thick, irregular, coarse-grained, and massive debrites (debris flow deposits; see Górny *et al.*, 2022) in the upper flysch succession, which implies a major change in the basin depositional systems tract. The lower flysch suggests an alternation of lobe-fringe sediments along a base-of-slope (submarine piedmont) ramp, fed by shelf point sources (Fig. 10A; Reading and Richards, 1994) and possibly affected by basin-axis tractional bottom currents, which likely recorded a basin-fill highstand systems tract (*sensu* Catuneanu, 2006). The upper flysch suggests a coalescence of abruptly encroaching, linearly resedimented slope sediments from an apron (Fig. 10B; Reading and Richards, 1994), likely signifying the intensification of the source area uplift (Unrug, 1963) and a falling-stage or forced-regressive systems tract (*sensu* Catuneanu, 2006).

DISCUSSION

Relation to the context of previous investigations

The interpretational notion adopted for lithotypes in this study invokes the possibility of the coexistence of various physical processes within a single sedimentary gravity event, broadly consistent with the original pioneering concepts of flysch sedimentation by Kuenen (1950, 1951, 1958), Kuenen and Migliorini (1950), Dżułyński *et al.* (1959), and Dżułyński and Smith (1964). These concepts postulated that flysch sedimentation involves a range of transport-deposit processes – later labelled as slides/slumps, debris flows (cohesive) and turbidity currents by Middleton and Hampton (1973) and sandy debris flows (non-cohesive) by Shanmugam (1996) – which can occur concomitantly via downslope rheological transformation and/or mass movement layering as evolving storeys. Initially (Kuenen, 1950, 1951; Kuenen and Migliorini, 1950), a set of mass sedimentation processes (i.e., slides/slumps and laminar debris flows) was defined by a single collective term, ’high-density turbidity current,’ such that it could be distinguished from (in contrast to) the typical turbidity current (i.e., turbulent flow) with a ‘low density.’ This concept places emphasis on the vertical changes in the sediment concentration, different rheological properties, and mechanical behaviour in the stratified gravity event. On this basis, fully turbulent flows together with tractional deposition have been labelled as 'low-density' turbidity currents while sediment gravity flows involving non-turbulent and non-tractional mass sediment dumping or freezing are denoted as 'high-density' turbidity currents (cf. Lowe, 1982).

The concept of high-density turbidity currents was heralded by the early notion of 'fluxoturbidites' (Kuenen, 1958; Dżułyński *et al.*, 1959). However, Kuenen's (1958, p. 332) statement, "These beds I imagine have slid down comparatively steep slopes without developing fully into turbidity currents", indicates that the 'high-density' component of a 'fluxoturbidite' could be a remnant of a parental slide or slump, rather than an excessively concentrated basal division spawned by turbulent flow (cf. Bouma, 1962; Lowe, 1982, 1988). Likewise, Dżułyński and Ślączka (1958, p. 213) suggested that "in some cases watery slides were responsible for [the] deposition" of 'fluxoturbidites', using such alternative genetic terms as 'sand flow' or 'flow of sand', and 'incoherent slurry slump'. In the context of the 'fluxoturbiditic' concept, Unrug (1963, p. 64) wrote, "clastic material which was not transported in suspension by turbidity currents [turbulent flows], but rather by watery slides of sand and gravel, [resulted in] an intermediate type of mass movement ['fluxoturbidite'] between true slumps and turbidity currents" (i.e., sandy to gravelly debris flows), adding that such mass-flow processes were triggered by the rapid uplift and denudational stripping of the source area. The notion of such intermediate/transitional deposits, referred to as fluxoturbidites, was elaborated by Ślączka and Thompson (1981) and Leszczyński (1989).

In their pioneering study, Dżułyński *et al.* (1959, p. 1114) pointed to composite sediment gravity flow deposits, with the lower part non-tractional (normal-graded or massive) and the upper part as fully tractional (planar stratified and ripple cross- laminated). The latter was followed by Bouma (1962), with the proposal of the turbidite vertical facies model with non-tractional basal division 'a' ('Ta' normally graded or 'Ta' massive) and tractional divisions 'b' and 'c'. In these interpretative concepts, the non-tractional basal phase of the gravity flow would only spawn via the parental turbidity current. Meanwhile, Postma *et al.* (1988) demonstrated a similarly bipartite gravity event with the basal laminar phase of the mass-flow (parental inertia debris flow), generating an overriding, faster moving, and fully turbulent phase (i.e., a turbidity current spawned by the debris flow). Cohesive debris flows (i.e., rich in muddy matrix), during gravitational redeposition and transformation, commonly generate turbulent suspensions propagating downslope as turbidity currents (cf. Middleton and Hampton, 1973, 1976). In the ancient sedimentary record, it is often difficult to distinguish between a turbiditic depositional relic from a parental slumps or debris flow and a turbidite from a current self-generated turbulent flow (see also Shanmugam, 2021b, figs 28,31, 32); this contentious issue requires further sedimentological research.

The genetic spectrum of lithotypes in this study appears to comprise all of these sediment-transport varieties, from the fine/medium-grained, normally graded, and regularly (tabular) bedded classic 'distal' turbidites of the upper Godula Formation to the coarse-grained, unevenly bedded, and massive 'proximal' debrites (cohesionless and cohesive type) of the lower Istebna Formation. The interpreted pattern of depositional mechanisms for the individual lithotypes is consistent with the modern concepts of sediment transport mechanics (Mezger, 2014), which extend beyond Kuenen's (1950, 1951) original concept. Flysch lithotypes involve depositional phases ranging from a fully turbulent flow, through tractional flow to a non-tractional and non-turbulent flow referred to as 'laminar' and 'mass' flow. These physical flow varieties can coexist, in space and time in a given sediment transport event. The laminar phase is either a remnant of the parental slump/debris flow or spawns at the bottom via excess mass sediment settling from a passing turbidity current. Mass laminar-flow phases in this study are represented by the deposits of gravelly to sandy debris flows – conglomeratic to sandstone debrites (dC, dCS, dSG, and dS; cf. sandy debris flow deposits *sensu* Shanmugam, 1996) and gravelly mudstone debrites (dMG; cf. pebbly mudstones *sensu* Crowell, 1957).

Although the original attribution of 'fluxoturbidites' to laminar mass gravity flows 'intermediate' between a slide/slump and fully turbulent turbidity current is rheologically and mechanically unclear and is no longer applicable today (cf. Hsü, 2004; Shanmugam, 2006; see also Strzeboński, 2015), this study does not deny that this early 'fluxoturbiditic' concept remains a source of inspiration for the physical interpretation of such massive flysch deposits.

Lowe (1979, 1982) failed to recognise that the early term 'fluxoturbiditic flow' was a precursor of his own term, i.e., 'high-density turbidity current' (see Leszczyński, 1989; Leszczyński and Nemec, 2015), but his sedimentological analysis of field cases is a useful preliminary guide for understanding complex deposits, such as composite (stratified) flows. However, the recognition of a coarse-grained debrites at the base of some turbidites – whether an inertial remnant of a parental debris flow (Postma *et al.*, 1988) or an autogenic mobile non-turbulent basal layer (Lowe, 1982) – and the recognition of a 'linked' mudflow division in the capping of some turbidites (Haughton *et al.*, 2003) have led to another poorly defined term: 'hybrid flow' (*sensu* Haughton *et al.*, 2009), which is not consistent with the etymology of the term 'hybrid' *sensu stricto* (Shanmugam 2021b, fig. 29, p. 22). This category of stratified underwater sedimentary gravity-events, with diversified rheological and mechanical modes of deposition, requires further scrutiny and a more specific sedimentological classification. This study thus attempted to classify the record of flysch depositional events on an individual descriptive basis with a single genetic interpretation of their depositional modes.

Interpretational approach

The textural and structural differences shown by the depositional intervals of the individual flysch beds reflect changes in the physical process of sedimentation. Based on this assumption, the heterogeneity of the studied deposits (Tables 1–3, Figs 3–7A, B) suggests the involvement of more than one mode of sediment transport and deposition. The observed varieties of flysch beds can thus be considered distinct genetic types of deposits distinguished on the descriptive basis of their textural and structural development. They may range mainly from classic 'Bouma-type turbidites', with possible influences from tractional bottom currents (Figs 5, 7A) to various debrites (Figs 6, 8, 9), as well as to possible combined-flow deposits attributed to coexisting debris flows and turbidity currents (composite bed – massive base and normally graded top). As shown by this study, the relative proportion of these deposits may vary from one flysch formation to another as the depositional systems tract evolves in space and time (Fig. 10). This study postulates that the S–C association of non-tractional massive sub-lithotypes (mC, mCS, mSG and mS; Figs 8A–F), instead of being labelled as 'fluxoturbidites' or 'high-density turbidites', should rather be considered conglomeratic to sandstone debrites (dC, dCS, dSG, and dS), whereas massive gravelly mudstones (MGm) should be considered gravelly mudstone debrites (dMG; Figs 8G, 9C, D; see also Shanmugam, 1996; Strzeboński *et al.*, 2017; Łapcik, 2018, 2019).

The 'turbiditic' Bouma sequence (i.e., 'Tabcde' divisions), reflects a changing mode of sediment transport and deposition (Bouma, 1962). There are tractional divisions 'Tb' and 'Tc', differ in their depositional flow regimes (Allen, 1985), underlain by non-tractional division 'Ta' and overlain by 'Te' increasingly dominated by hemipelagic mud fallout. The classic Bouma sequence would then appear to be an amalgam of products of different transportational and depositional processes. This rock record fails to validate the idealised Bouma model (Ge *et al.*, 2017, fig. 17; Shanmugam, 2021b; Ge *et al.*, 2022, fig. 6). Therefore, Shanmugam *et al.* (1993) and Shanmugam (2021b) postulated that the deposition of Bouma's 'turbidite' may, in reality, be a combination of: mass deposition from high-concentrated sandy debris flow (massive 'Ta'), gravity gradual settling from a turbulent turbidity current (normally graded 'Ta'), accompanied by traction processes (*sensu* Allen, 1985; tractionites *sensu* Unrug, 1977, i.e., 'Tbcd') and/or influences of other deep-sea tractional bottom currents, which may act independently or combine to form new bottom flows reworking through previously accumulated sediments, i.e., a 'hybrid flow' (Shanmugam, 2021b). Conversely, Ge *et al.* (2022) demonstrated the discrepancies between the idealised Bouma sequence; the rock record can also result from, in some cases, autogenic energy fluctuations in the 'low density' turbidity current itself. The issue of these discrepancies thus remains open to future sedimentological research while the Bouma sequence is not a universal guide for the interpretation of flysch deposits.

CONCLUSIONS

In this study, the Santonian–Campanian siliciclastic flysch succession of the upper Godula and lower Istebna formations (Silesian Unit), in the regions of the Moravian-Silesian Beskids and Silesian Beskid, Western Outer Carpathians, was examined in detail based on the macroscopic textural and primary structural characteristics of the deposits. The individual flysch beds were hierarchically classified, in descriptive terms, into a range of lithotypes, sub-lithotypes and associations, concurrently interpreted in genetic terms with reference primarily to their deposition mechanisms, but also taking into account likely transport modes and supports. Turbulent flows, tractional bottom flows, and debris flows were recognised as the main depositional processes, with a turbidite- and tractionite-dominated lithotype association in the upper Godula Formation and a debrite-dominated association in the lower Istebna Formation, respectively.

The first association was interpreted as fringe deposits of coalescing base-of-slope turbiditic fan lobes fed by shelf point sources (piedmont clastic ramp) at the sea-level highstand within a highstand systems tract. The second subsequent association was interpreted as slope resedimentation deposits of a debritic apron covers (piedmont apron system) fed linearly at the sea-level fall within a forced-regressive systems tract. This change in the lithotype associations was recognised as a trans-regional regression, although it remains unclear as to whether it was forced by eustasy or the Carpathian orogen tectonics or both, with an emphasis on the latter.

The discussion focused on the genetic categorisation of massive flysch deposits, also referred to as 'fluxoturbidites' or 'high-density turbidites', suggesting them as debrites (debris flow deposits), as they do not fit the notion of deposition from a turbulent flow, i.e., low-concentrated turbidity current (normally graded structure).

The discrepancies between the Bouma 'turbidite sequence' and the actual rock record were also addressed, with an inconclusive opinion that they may be due to a combination of: sandy debris flows, turbiditic currents, and the action of other deep-marine tractional bottom currents or, their simultaneous influence (i.e., hybrid flows), as well as to autogenic energy fluctuations in the turbidity current itself.

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REFERENCES

Allen, J. R., L., 1985. *Principles of Physical Sedimentology*. George Allen & Unwin, London, 272 pp.

Bieda, F., Geroch, S., Koszarski, L., Książkiewicz, M. & Żytko, K., 1963. Stratigraphie des Karpates externes polonaises. *Institut Geologique Biulletin*, 181: 5–174. [In French.]

Bouma, A. H., 1962. *Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies Interpretation*. Elsevier, Amsterdam, 168 pp.

Burtan, J., 1972. *Szczegółowa mapa geologiczna Polski, 1:50000, arkusz Wisła (1028)*. Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Burtanówna, J., Konior, K. & Książkiewicz, M., 1937. *Carte géologique des Karpates de Silésie*. Wydawnictwa Śląskie Polskiej Akademii Umiejętności, Kraków, 104 pp. [In Polish, with French summary.]

Catuneanu, O., 2006. *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam, 375 pp.

Cohen, K. M., Finney, S. & Gibbard, P. L., 2013. *International Chronostratigraphic Chart*. International Committee on Stratigraphy, http://www.stratigraphy.org/ICSchart/ChronostratChart2013-01.pdf [Accessed 15.01.2014].

Crowell, J. C., 1957. Origin of pebbly mudstones. *Geological Society of America Bulletin*, 68: 993–1010.

Dott, R. H., Jr., 1963. Dynamics of subaqueous gravity depositional processes. *AAPG Bulletin,* 47: 104–128.

Drake, T. G., 1990. Structural features in granular flows. *Journal of Geophysical Research*, B95: 8681–8696.

Dżułyński, S. & Ślączka, A., 1958. Directional structures and sedimentation of the Krosno beds (Carpathian flysch). *Rocznik Polskiego Towarzystwa Geologicznego,* 28: 205–260.

Dżułyński, S., Książkiewicz, M. & Kuenen, Ph. H., 1959. Turbidites in flysch of the Polish Carpathian Mountains. *Bulletin of the Geological Society of America*, 70: 1089–1118.

Dżułyński, S. & Smith, A. J., 1964. Flysch facies. *Rocznik Polskiego Towarzystwa Geologicznego,* 34: 245–266.

Dżułyński, S. & Walton, E. K., 1965. *Sedimentary Features of Flysch and Graywackes*. Developments in Sedimentology, 7, 274 pp.

Eliáš, M., 1970. Lithology and sedimentology of the Silesian Unit in the Moravo-Silesian Beskydy Mts. *Sborník Geologických Věd, Geologie*, 8: 7–99. [In Czech, with English summary.]

Felix, M., Leszczyński, S., Ślączka, A., Uchman, A., Amy, L. & Peakall, J., 2009. Field expressions of the transformation of debris flows into turbidity currents, with examples from the Polish Carpathians and the French Maritime Alps. *Marine and Petroleum Geology,* 26: 2011–2020.

Fisher, R. V., 1983. Flow transformations in sediment gravity flows. *Geology*, 11: 273–274.

Gani, M. R., 2004. From turbid to lucid: a straightforward approach to sediment gravity flows and their deposits. *Sedimentary Record*, 3: 4–8.

Ge, Z., Nemec, W., Gawthorpe, R. L. & Hansen, E. W., M., 2017. Response of unconfined turbidity current to normal-fault topography. *Sedimentology*, 64: 932–959.

Ge, Z., Nemec, W., Vellinga, A. J. & Gawthorpe, R. L., 2022. How is a turbidite actually deposited? *Science Advances,* 8, doi: 10.1126/sciadv.abl9124.

Ghibaudo, G., 1992. Subaqueous sediment gravity flow deposits: practical criteria for their field description and classification. *Sedimentology*, 39: 423–454.

Golonka, J., Oszczypko, N. & Ślączka, A., 2000. Late Carboniferous–Neogene geodynamic evolution and paleogeography of the circum-Carpathian region and adjacent areas. *Annales Societatis Geologorum Poloniae*, 70: 107–136.

Golonka, J. & Picha, F. J., 2005. Introduction. In: Golonka, J. & Picha, F. J. (eds), *The Carpathians and their Foreland: Geology and Hydrocarbon Resources*, *AAPG Memoir*, 84: 1–9.

Górny, Z., Bąk, M., Bąk, K. & Strzeboński, P., 2022. Planktonic biota constituents responses to global sea-level changes recorded in the uppermost Albian to middle Cenomanian deep-water facies of the Outer Carpathians. *Minerals*, 12, 152: 1–26.

Hampton, M. A., 1972. The role of subaqueous debris flows in generating turbidity currents. *Journal of Sedimentary Petrology,* 42: 775–793.

Haq, B. U., Hardenbol, J. & Vail, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. S. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C. (eds), *Sea-Level Changes: An Integrated Approach*. *SEPM Special Publication*, 42: 71–108.

Haughton, P. D., Barker, S. P. & McCaffrey, W. D., 2003. ‘Linked’ debrites in sand-rich turbidite systems – origin and significance. *Sedimentology*, 50: 459–482.

Haughton, P. D., Davis, Ch., McCaffrey, W. & Barker, S., 2009. Hybrid sediment gravity flow deposits – classification, origin and significance. *Marine and Petroleum Geology*, 26: 1900–1918.

Hsü, K. J., 2004. *Physics of Sedimentology, Textbook and Reference (2nd ed.)*. Springer-Verlag, Berlin, 240 pp.

Jankowski, L., 2007. Chaotic complexes in Gorlice region (Polish Outer Carpathians). *Biuletyn Państwowego Instytutu Geologicznego*, 426: 27–52. [In Polish, with English summary.]

Janocko, M., Nemec, W., Henriksen, S. & Warchoł, M., 2013. The diversity of deep-water sinuous channel belts and slope valley-fill complexes. *Marine and Petroleum Geology*, 41: 7–34.

Książkiewicz, M., 1956. Geology of the Northern Carpathians. *Geologische Rundschau*, 45: 369–411.

Kuenen, P. H., 1950 [for 1948]. Turbidity currents of high density. In: Harland, W. B. & Jones, O. T. (eds), *The Geology of Sea and Ocean Floors: Part 8, Proceedings of Section G, Report of the Eighteenth Session*. *International Geological Congress.* London. pp. 44–52.

Kuenen, P. H., 1951. Properties of turbidity currents of high density. In: Hough, J. L. (ed.), *Turbidity currents and the transportation of coarse sediments to deep water*. *SEPM*, *Special Publication*, 2: 14–33.

Kuenen, P. H., 1958. Problems concerning source and transportation of flysch sediments. *Geologie en Mijnbouw*, 20: 329–339.

Kuenen, P. H. & Migliorini, C. I., 1950. Turbidity currents as a case of graded bedding. *The Journal of Geology*, 58: 91–127.

Leszczyński, S., 1989. Characteristics and origin of fluxoturbidites from the Carpathian Flysch (Cretaceous–Palaeogene), South Poland. *Annales Societatis Geologorum Poloniae*, 59: 351–390.

Leszczyński, S. & Nemec, W., 2015. Field-trip topic 1: How do the classic ‘fluxoturbidites’ compare with the latest turbiditic models? In: Leszczyński, S., Dziadzio, P. S. & Nemec, W., *Some current sedimentological controversies in the Polish Carpathian flysch*. *Guidebook for Field Trips Accompanying the 31st IAS Meeting of Sedimentology*. Polish Geological Society, Kraków, pp. 247–287.

Lexa, J., Bezák, V., Elečko, M., Mello, J., Polák, M., Potfaj, M. & Vozár, J. (eds), 2000. *Geological Map of Western Carpathians and Adjacent Areas, 1:500000*. Ministry of Environment of the Slovak Republic and Geological Survey of Slovak Republic, Bratislava.

Lowe, D. R., 1979. Sediment gravity flows: their classification and some problems of application to natural flows and deposits. In: Doyle, N. J. & Pilkey, O. H. (eds), *Geology of Continental Slopes*. *SEPM Special Publication,* 27: 75–82.

Lowe, D. R., 1982. Sediment gravity flows: 2. Depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology*, 52: 279–298.

Lowe, D. R., 1988. Suspended-load fallout rate as an independent variable in the analysis of current structures. *Sedimentology*, 35: 765–776.

Łapcik, P., 2018. Sedimentary processes and architecture of Upper Cretaceous deep-sea channel deposits: a case from the Skole Nappe, Polish Outer Carpathians. *Geologica Carpathica*, 69: 71–88.

Łapcik, P., 2019. Facies anatomy of a progradational submarine channelized lobe complex: semi-quantitative analysis of the Ropianka Formation (Campanian–Paleocene) in Hucisko Jawornickie section, Skole Nappe, Polish Carpathians. *Acta Geologica Polonica*, 69: 111–141.

Mastalerz, K., Wysocka, A., Krzywiec, P., Kasiński, J., Aleksandrowski, P., Papiernik, B., Ryzner-Siupik, B. & Siupik, J., 2006. Sukcesja osadowa miocenu w rejonie zrębu Ryszkowej Woli (obszar Sieniawa–Rudka), zapadlisko przedkarpackie: wyniki facjalnej i stratygraficznej interpretacji danych wiertniczych oraz sejsmiki 3D. *Przegląd Geologiczny*, 54: 333–342. [In Polish, with English summary.]

Matyszkiewicz, J. & Słomka, T., 1994. Organodetrital conglomerates with ooids in the Cieszyn Limestone (Tithonian–Berriasian) of the Polish Flysch Carpathians and their palaeogeographic significance. *Annales Societatis Geologorum Poloniae*, 63: 211–248.

Matyszkiewicz, J. & Słomka, T., 2004. Reef-microencrusters association *Lithocodium aggregatum-Bacinella irregularis* from the Cieszyn Limestone (Tithonian–Berriasian) of the Outer Western Carpathians (Poland). *Geologica Carpathica*, 55, 449–456.

Menčík, E., Adamová, M., Dvořák, J., Dudek, A., Jetel, J., Jurková, A., Hanzlíková, E., Houša, V., Peslová, H., Rybářová, L., Šmíd, B., Šebesta, J., Tyráček, J. & Vašíček, Z., 1983. *Geology of the Moravskoslezské Beskydy Mts. and the Podbeskydská pahorkatina Upland*. Ústřední Ústav Geologicky, ČSAV, Praha, 304 pp. [In Czech, with English summary.]

Menčík, E. & Tyráček, J. (eds), 1985. *Synoptic Geological Map of the Beskydy Mts. and the Podbeskydská Pahorkatina Upland*, 1:100000. Czech Geological Office, Geological Survey, Prague.

Mezger, T. G., 2014. *The Rheology Handbook: For Users of Rotational and Oscillatory Rheometers (4th ed.)*. Vincentz Network, Hannover, 432 pp.

Middleton, G. V. & Hampton, M. A., 1973. Part I. Sediment gravity flows: Mechanics of flow and deposition. In: Middleton, G. V. & Bouma, A. H. (eds), *Turbidites and Deep-Water Sedimentation.* SEPM, Pacific Section, Short Course No. 1, Lecture Notes, pp. 1–38.

Middleton, G. V. & Hampton, M. A., 1976. Subaqueous sediment transport and deposition by sediment gravity flows. In: Stanley, D. J. & Swift, D. J. P. (eds), *Marine Sediment Transport and Environmental Management*. Wiley, New York, 197–218.

Mulder, T., 2011. Gravity processes and deposits on continental slope, rise and abyssal plains. In: Hüneke, H. & Mulder, T. (eds), *Deep-Sea Sediments*. Developments in Sedimentology, 63: 25–148.

Mutti, E., Bernoulli, D., Ricci Lucchi, F. & Tineterri, R., 2009. Turbidites and turbidity currents from Alpine 'flysch' to the exploration of continental margins. *Sedimentology*, 56: 267–318.

Mutti, E., Bernoulli, D., Ricci Lucchi, F. & Tinterri, R., 2010. Reply to the Discussion by Ganapathy Shanmugam on "Turbidities and turbidity currents from Alpine 'flysch' to the exploration of continental margins." *Sedimentology*, 57: 933–934.

Nemčok, M., Nemčok, J., Wojtaszek, M., Ludhova, L., Oszczypko, N., Sercombe, W. J., Cieszkowski, M., Paul, Z., Coward, M. P. & Ślączka, A., 2001. Reconstruction of Cretaceous rifts incorporated in the Outer West Carpathian wedge by balancing. *Marine and Petroleum Geology*, 18: 39–64.

Nemec, W., 1990. Aspects of sediment movement on steep delta slopes. In: Colella, A. & Prior, D. B. (eds), *Coarse-Grained Deltas*. *IAS Special Publication,* 10: 29–73.

Nemec, W. & Steel, R. J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. In: Koster E. H. & Steel R. J. (eds), *Sedimentology of Gravels and Conglomerates*. *CSPG Memoir*, 10: 1–31.

Picha, F. J., Stráník, Z. & Krejčí, S., 2005. Geology and hydrocarbon resources of the Outer Western Carpathians and their foreland, Czech Republic. In: Golonka, J. & Picha, F. J. (eds), *The Carpathians and Their Foreland: Geology and Hydrocarbon Resources*. *AAPG Memoir*, 84: 49–175.

Pickering, K., Stow, D., Watson, M. & Hiscott, R., 1986. Deep-water facies, processes and models: a review and classification scheme for modern and ancient sediments. *Earth-Science Reviews*, 23: 75–174.

Poprawa, P., Malata, T. & Oszczypko, N., 2002. Tectonic evolution of the Polish part of Outer Carpathian's sedimentary basins constraints from subsidence analysis. *Przegląd Geologiczny*, 50: 1092–1108. [In Polish, with English summary.]

Postma, G., Nemec, W. & Kleinspehn, K. L., 1988. Large floating clasts in turbidites: a mechanism for their emplacement. *Sedimentary Geology*, 58: 47–61.

Reading, H. G. & Richards, M., 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. *AAPG Bulletin*, 78: 792–822.

Sanders, J. E., 1965. Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms. In: Middleton, G. V. (ed.), *Primary sedimentary structures and their hydrodynamic interpretation*. *SEPM, Special Publication*, 12: 192–219.

Schatzmann, M., Fischer, P. & Bezzola, G. R., 2003. Rheological behaviour of fine and large particle suspensions. *Journal of Hydraulic Engineering*, 129: 796–803.

Schatzmann, M., Bezzola, G. R., Minor, H. E., Windhab, E. J. & Fischer, P., 2009. Rheometry for large-particulated fluids: analysis of the ball measuring system and comparison to debris flow rheometry. *Rheologica Acta*, 48: 715–733.

Shanmugam, G., Spalding, T. D. & Rofheart, D. H., 1993. Process sedimentology and reservoir quality of deep-marine bottom-current reworked sands (sandy contourites): an example from the Gulf of Mexico. AAPG Bulletin, 77: 1241–1259.

Shanmugam, G., 1996. High-density turbidity currents: Are they sandy debris flows? Perspectives. *Journal of Sedimentary Research*, 66: 2–10.

Shanmugam, G., 2000. 50 years of the turbidite paradigm (1950s–1990s): deep-water processes and facies models – a critical perspective. *Marine and Petroleum Geology*, 17: 285–342.

Shanmugam, G., 2006. *Deep-water Processes and Facies Models: Implications for Sandstone Petroleum Reservoirs. Handbook of Petroleum Exploration and Production 5*. Elsevier, Amsterdam, 476 pp.

Shanmugam, G., 2010. Discussion: 'Turbidites and turbidity currents from Alpine flysch to the exploration of continental margins.' *Sedimentology*, 56: 267–318.

Shanmugam, G., 2018. *Slides, Slumps, Debris Flows, Turbidity Currents, and Bottom Currents: Implications: Reference Module in Earth Systems and Environmental Sciences*. Elsevier, 120 pp. https://doi.org/10.1016/B978-0-12-409548-9.04380-3 [Accessed 10.02.2019].

Shanmugam, G., 2020. Gravity flows: Types, definitions, origins, identification markers, and problems. *Journal Indian Association of Sedimentologists*, 37: 61–90.

Shanmugam, G., 2021a. *Mass Transport, Gravity Flows, and Bottom Currents: Downslope and Alongslope Processes and Deposits*. Amsterdam, Elsevier, 608 pp.

Shanmugam, G., 2021b. The turbidite-contourite-tidalite-baroclinite-hybridite problem: orthodoxy vs. empirical evidence behind the "Bouma Sequence". *Journal of Palaeogeography*, 10: 1–32.

Słomka, T., 1995. *Deep-marine siliciclastic sedimentation of the Godula Beds, Carpathians*. Prace Geologiczne, 139: 1–132. [In Polish, with English summary.]

Strzeboński, P., 2015. Late Cretaceous–Early Paleogene sandy-to-gravelly debris flows and their sediments in the Silesian Basin of the Alpine Tethys (Western Outer Carpathians, Istebna Formation). *Geological Quarterly*, 59: 195–214.

Strzeboński, P. & Uchman, A., 2015. The trace fossil Gyrophyllites in deep-sea siliciclastic deposits of the Istebna Formation (Upper Cretaceous–Palaeocene) of the Carpathians: an example of biologically controlled distribution. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 426: 260–274.

Strzeboński, P., Kowal-Kasprzyk, J. & Olszewska, B., 2017. Exotic clasts, debris flow deposits and their significance for reconstruction of the Istebna Formation (Late Cretaceous-Paleocene, Silesian Basin, Outer Carpathians). *Geologica Carpathica*, 68: 562–582.

Ślączka, A. & Thompson III, S., 1981. A revision of the fluxoturbidite concept based on type examples in the Polish Carpathian Flysch. *Annales Societatis Geologorum Poloniae*, 51: 3–44.

Talling, P. J., Masson, D. G., Sumner, E. J. & Malgesini, G., 2012. Subaqueous sediment density flows: Depositional processes and deposit types. *Sedimentology*. 59: 1937–2003.

Unrug, R., 1963. Istebna Beds - a fluxoturbidity formation in the Carpathian Flysch. *Rocznik Polskiego Towarzystwa Geologicznego,* 33: 49–92.

Unrug, R., 1977. Ancient deep-sea traction currents deposits in the Lgota beds (Albian) of the Carpathian Flysch. *Rocznik Polskiego Towarzystwa Geologicznego*, 47: 355–370.

Żytko, K., Gucik, S., Ryłko, W., Oszczypko, N., Zając, R., Garlicka, I., Nemčok, J., Eliáš, M., Menčík, E., Dvořák, J., Stráník, Z., Rakus, M. & Matějovská, O., 1989. Geological map of the Western Outer Carpathians and their foreland without Quaternary formations, 1:500000. In: Poprawa, D. & Nemčok, J. (eds), *Geological Atlas of the Western Outer Carpathians and their Foreland*. Państwowy Instytut Geologiczny, Warszawa.