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Review article

Facies analysis of gravity flow deposits of an ancient foreland basin (Magura Nappe, Western Carpathians)

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Abstract: Sedimentary logging at outcrops remains a basic method of sediment description in the field. The area of sedimentological study in this work was the Slovak western part of the Magura Nappe, which is the largest tectonic unit of the Outer Western Carpathians. Sediments were deposited by gravity flows in the predominantly deep-sea environment of the foreland Magura Basin. The stratigraphic extent of the studied deposits is Late Cretaceous (Cenomanian) to Oligocene/early Miocene. Up to 113 sedimentological logs have been documented in detail with a total thickness of 2022 m. Simplified logging and interpretation of the depositional environment was additionally developed for 15 of the most interesting logs. Sedimentation by debris-flows, turbidity currents, slides, and slumps in the environment of the distributary channel, levee, inter-channel, and basin plain was also interpreted. An important element of the study was the inclusion of paleocurrent directions in the analysis of logs. The purpose of the study was to record the most important outcrops in the region and thus preserve them and make them accessible to the greater public, as well as supplement the characteristics of lithostratigraphic units and knowledge on the sedimentary evolution of the Magura Basin.

Keywords: outcrop documentation, gravity flow, turbidity currents, debris-flows

Introduction

The following work is the result of more than 20 years of detailed geological research and mapping of an area of almost 2000 km^2 in the Magura Nappe. The purpose of the study was to record the most important outcrops in the region and thus preserve them and make them accessible to the greater public, including the interpretation of the depositional environment so as to supplement the characteristics of lithostratigraphic units and knowledge of the Magura Basin fill. Today, most of the studied outcrops no longer exist or they are significantly altered, overgrown with vegetation, or difficult to access.

The area of sedimentological study includes the Slovak western part of the Magura Nappe, which is the largest tectonic unit of the Outer Western Carpathians (Figs. 1, 2). The Magura Nappe extends across the territories of Austria, the Czech Republic, Slovakia, Poland, and Ukraine. It consists almost exclusively of a several thousand-metre-thick sequence of "flysch" character sedimentary facies with alternating sandstone and claystone beds in different proportions and thicknesses. Conglomerates are rather rare (Hók et al. 2019). Although the area of the Magura Nappe is significantly overgrown with vegetation and the rare and short-living outcrops cover colluvial and alluvial deposits, the region offers valuable opportunities to study a typical ancient and mostly deep-marine foreland basin system.

The works of Kuenen & Migliorini (1950), Bouma (1962), Mutti & Ricci Lucchi (1972), Lowe (1982), Pickering et al. (1986), Ghibaudo (1992), Mutti (1992), Mutti et al. (2003), Talling et al. (2012), Tinterri et al. (2020), and many others have been regarded as significant breakthroughs in the field of documentation and interpretation of sedimentary structures and sedimentological logs of gravity flow deposits. In Slovakia (or Czechoslovakia), they were, for example, the works of Pesl (1964, 1968), Marschalko & Potfaj (1982), Potfaj et al. (1991) and Teťák (2010), while in neighbouring Poland they were e.g., Dzulynski et al. (1959) and Wójcik et al. (2018). The exposures in the Magura Nappe have been described in a similar way by Marschalko & Potfaj (1982), Potfaj et al. (1991), Starek & Pivko (2001), Leszczyński & Malata (2002), Pivko (2002), Starek & Šimo (2015), Dirnerová & Farkašovský (2018), Łapcik (2019), and Maceček (2021). Despite the rich tradition of sedimentary studies in the Magura Nappe, there is still a lack of systematic processing and publication of high-quality lithological logs.

The objectives of the article are: (1) logging of the most important outcrops; (2) GPS location of the outcrops; (3) detail logging of all observed sedimentary structures; (4) making logs available for further processing; (5) interpretation of the most interesting logs.

Geological setting

The Western Carpathians are part of a mountain range that includes the Alps, Balkans, Dinarides, and other mountain

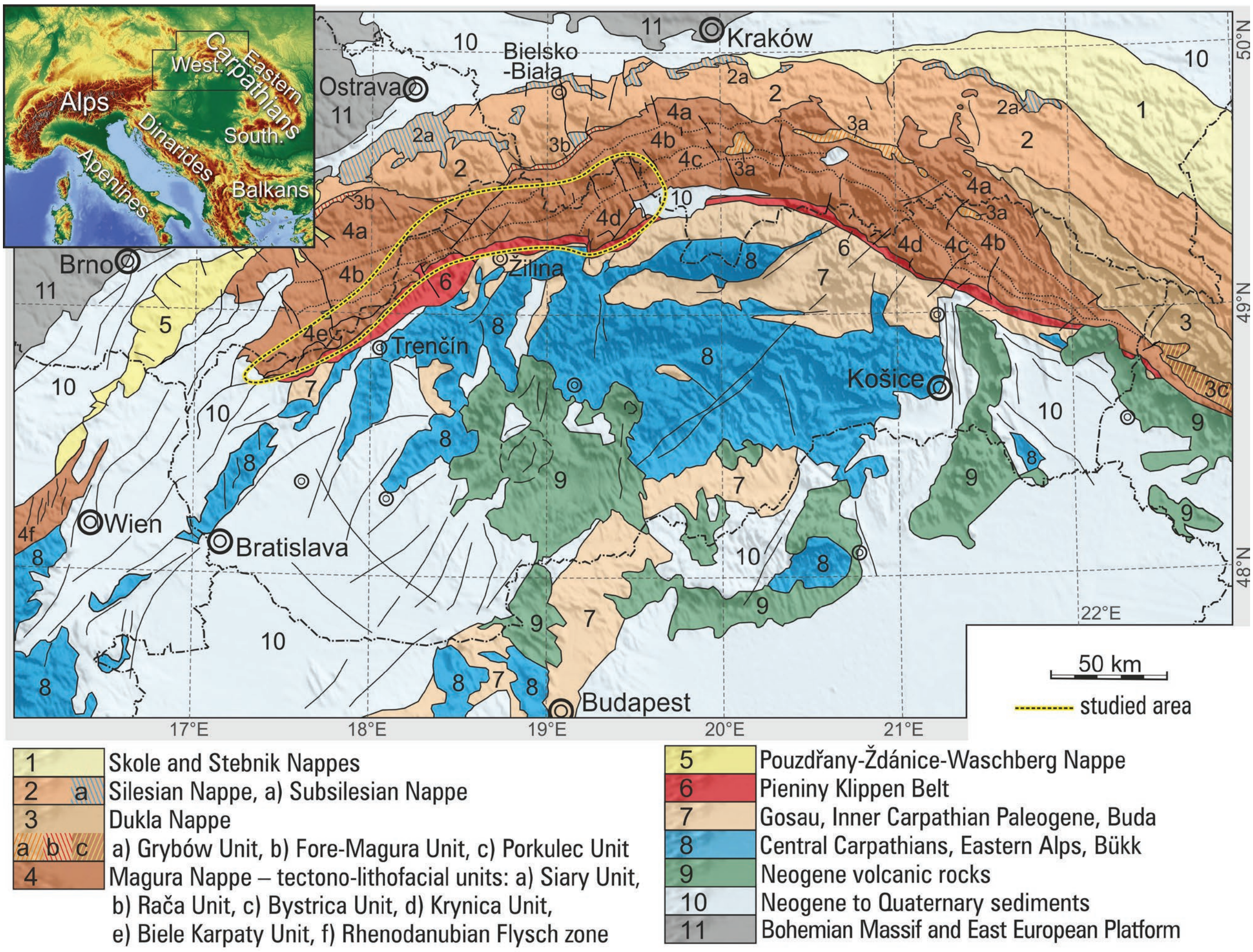

Fig. 1. The schematic geological map of the Western Carpathians shows the studied area in the western part of the Magura Nappe.

ranges as part of the Alpine–Himalayan orogenic belt. Regionally, the Western Carpathians can be divided into the Inner and Outer Western Carpathians (Figs. 1, 2) (Hók et al. 2019; Stráník et al. 2021). The Outer Western Carpathians (synonym "Flysch Belt") are formed predominantly by deep-marine "flysch" deposits. Their sedimentary sequences contain an extensive paleogeography record of several basins and ridges. The term "flysch" was introduced by Studer (1827a, b) into geological literature in Switzerland due to the typically alternating sandstone and shale beds.

The Magura Nappe forms the tectonically highest member of the Outer Western Carpathians. The stratigraphic extent of exposed deposits is mostly from the Late Cretaceous (and to a small extent, the uppermost Jurassic) to the Oligocene/early Miocene (Cieszkowski 1992; Lexa et al. 2000; Oszczypko et al. 2015; Kaczmarek et al. 2016).

Nowadays, the Magura Nappe is completely detached from its substratum along the ductile Upper Cretaceous to Paleocene clayey formations. Rudimentarily-preserved Late Jurassic lithostratigraphic units in the external Magura Nappe in the region of Moravia (Pícha et al. 2006; Hrouda et al. 2009) and the Upper (Middle?) Jurassic lithostratigraphic units in the innermost Šariš Unit (Grajcarek) in Poland (Golonka et al. 2013; Oszczypko et al. 2015) suggest at least the Upper Jurassic deposition in the Magura Basin. "Flysch" character sediments were deposited mainly in the deep-marine environment and partly on the slope and shelf from gravity flows and by pelagic sedimentation (Fig. 3).

There are five tectono-lithofacies units of the Magura Nappe present in the studied area. From the most internal, they are: the Biele Karpaty, Krynica, Bystrica, and Rača units, as well as the northern part of the Rača Unit designated by Koszarski et al. (1974) in Poland as a Siary Unit (Fig. 1). The Biele Karpaty Unit occurs only in the south-western part of the investigated area and has a special status (Potfaj 1993; Teťák 2016). The units form a fold and thrust fan-shaped system of the Magura Nappe. The nappe was thrust over the Silesian Nappe and, together with other more external units of the Outer Western Carpathians, they were thrust over the inclined ramp of the Northern European Platform. Moreover, the Krynica Unit back-thrusted to the south over the Pieniny Klippen Belt (Pešková et al. 2012). Thus, the Outer Western

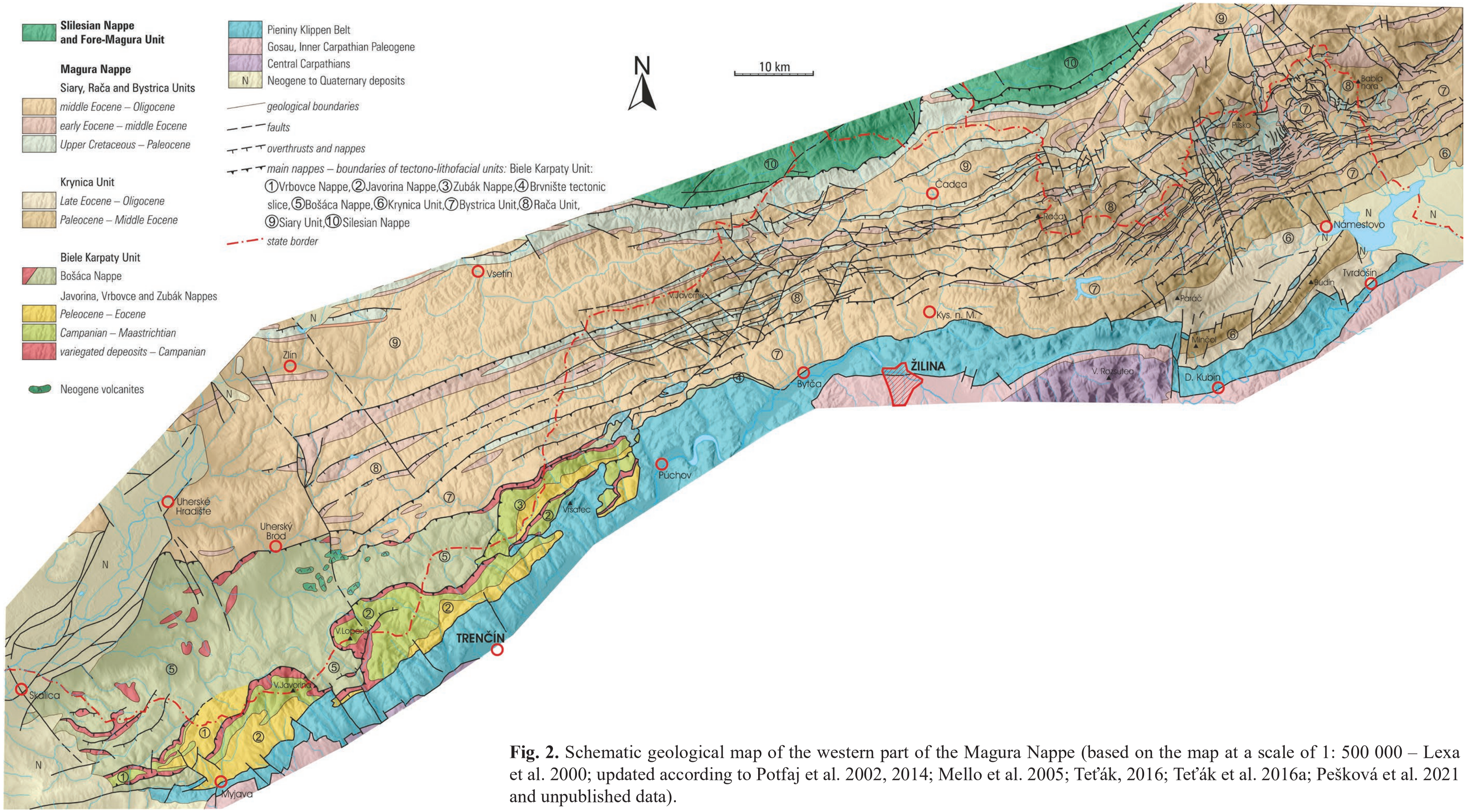

Fig. 2. Schematic geological map of the western part of the Magura Nappe (based on the map at a scale of 1: 500 000 – Lexa et al. 2000; updated according to Potfaj et al. 2002, 2014; Mello et al. 2005; Teťák, 2016; Teťák et al. 2016a; Pešková et al. 2021 and unpublished data).

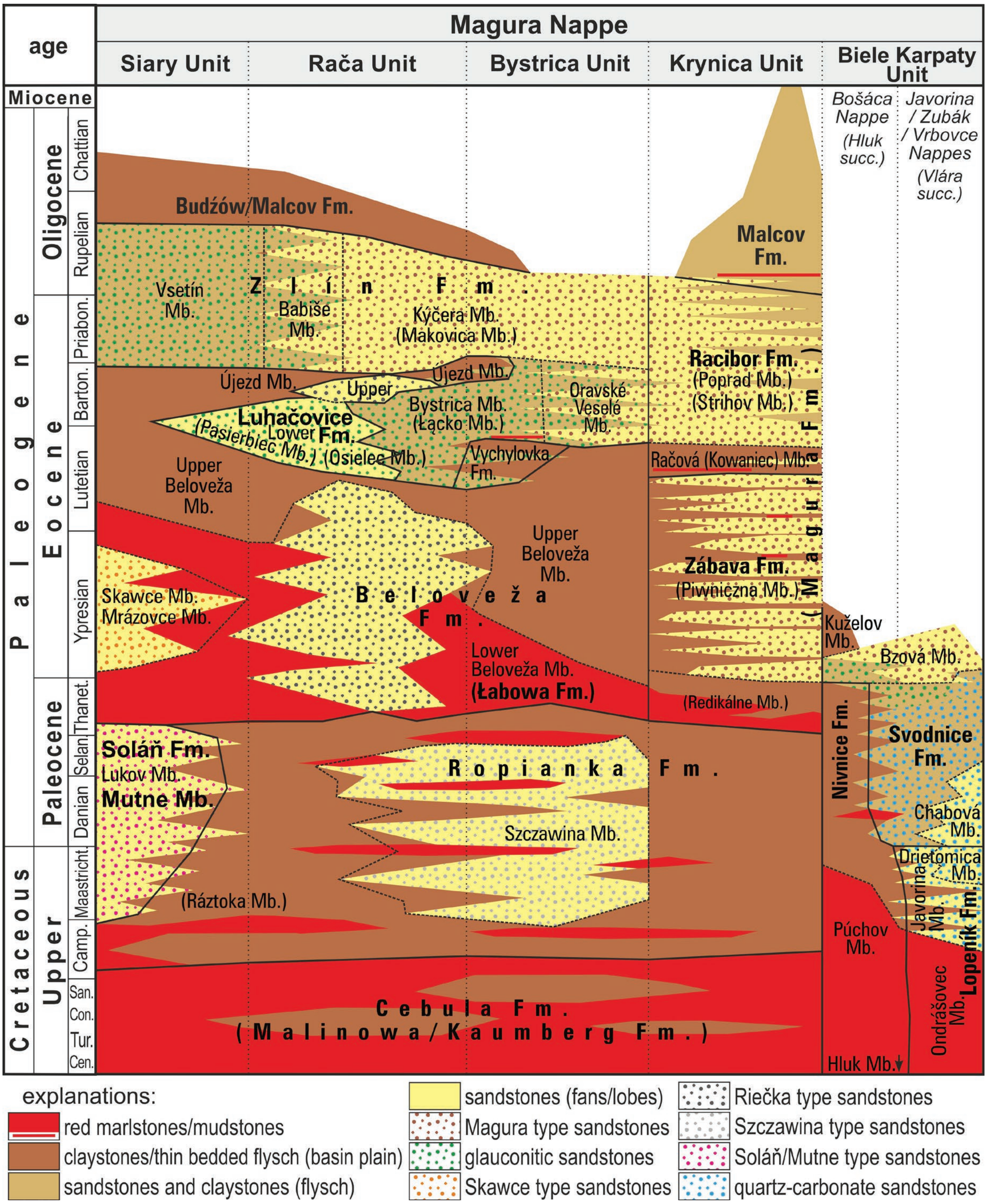

Fig. 3. Lithostratigraphic scheme of the Slovak western part of Magura Nappe (Hók et al. 2019).

Carpathians form a huge, wedge-like body of the fold and thrust belt. Recent cross-sections have been interpreted by Nemčok et al. (2000), Pícha et al. (2006), Ślączka et al. (2006), and Gągała et al. (2012).

The aforementioned tectono-lithofacies units of the Magura Nappe are composed of several lithostratigraphic units and consist of lithofacies and lithotypes, which are presented in Electronic supplement A and documented by photos in Electronic supplement B. Their relationships are graphically displayed in the lithostratigraphic scheme (Fig. 3) (Potfaj 1993; Mello et al. 2011; Teťák et al. 2016b).

The original basins bordered continental crust ridges and the orogenic wedge, which supplied a clastic material to the basin. The ridges, formerly named "cordilleras", were first defined in the Outer Western Carpathians Książkiewicz (1956, 1958a, 1962, 1965). The existence of the following ridges was responsible for the development of varied deposits of the Magura Basin: The Hostýn Ridge (Teťák et al. 2019), the Fore-Magura Ridge (Golonka et al. 2005), the Grybów Ridge (Cieszkowski 2002), the Bukowiec Ridge (Ślączka 2005), the Southern-Magura Ridge (Marschalko et al. 1976; Mišík et al. 1991b) and the Neopieninic Exotic Ridge (Mišík et al. 1991a).

Several of the documented logs are stratotypes of lithostratigraphic units. They are e.g., log BKs239, which is a stratotype of the Drietomica Member; logs BKs346 and BKs348 are the stratotypes of the Chabová Member; log Mk24 is a lithotype profile of the Riečky type sandstone of the Lower Beloveža Member (Potfaj et al. 2003); logs F193 and F345 are the stratotypes of the Oravské Veselé Member (Teťák et al. 2016b); log F772 is the stratotype of the Ropianka Formation (Teťák et al. 2017) and log F155 is the stratotype for the Redikálne Member (Teťák et al. 2016b) (the logs are part of Electronic supplements E and F).

Geological evolution

The precise time when the Magura Basin (Fig. 4) started to open has not yet been reliably confirmed. Therefore, the time span of the Early and Middle Jurassic to Late Cretaceous is assumed (Poprawa & Malata 2006; Golonka 2011). The stratigraphic extent of the exposed deposits of the Magura Nappe is mostly from the Late Cretaceous (Cenomanian) to the Late Oligocene/early Miocene (Fig. 3).

The sediments (Electronic supplement B) were deposited mainly in the deep-marine environment of the foreland of the Magura Basin and partly on its slopes – outer ramp and wedge-top basin (Fig. 4) (Mutti et al. 2003). The earliest period in the studied area represented the sedimentation of red claystones and hemipelagic marls of the Cebula Formation and subsequently the thin-bedded turbidity sandstones.

Coarse-grained sedimentation dominated in the basin from Maastrichtian, which is typical for the Mutne and Szczawina Members, as well as the Soláň Formation. The increased supply of clastic material into the Magura Basin was the result of the Hostýn, Fore-Magura, and Szczawina ridges uplift, including the approaching Central Carpathian orogen. The source areas supplied clastic material that was predominantly transported by dense gravity flows (debris flows) into the depositional area (Eliáš 1963; Pesl 1968).

The sea-level rise continued during the Paleocene and Eocene by subsidence and global warming (Poprawa & Malata 2006). These conditions culminated by the deposition of thin-bedded distal facies during the middle Eocene. The red claystones and thin-bedded sediments were deposited mainly in the central and northern part of the Magura Basin of the Beloveža Formation and Račová Member. The ridges supplied the Magura Basin with a large amount of clastic material, even during this relatively calm period due to the collision of the Magura Basin with the Inner Carpathian block (Teťák et al. 2019). The deposition of massive turbidity sandstone beds started in the middle Eocene and continued during the late Eocene. Quartzite sand enriched with glauconite and large foraminifera was derived from the Fore-Magura Ridge shelf. Magura-type sandstone was derived from the Southern Magura Ridge. This phenomenon was related to tectonic collision-induced uplift of the source areas and sea-level fall (Cieszkowski et al. 1998).

The Malcov Formation represents the last stage of the Magura Basin evolution during the late Eocene to the earliest Miocene. The sandy to clayey slumps and clay-rich deposits filled smaller sub-basins in the central and eastern part of the Magura Basin. During the Oligocene and up to the Badenian, the filling of the Magura Basin thrust over its foreland for a distance of at least 50 km. This led to the folded-sliced structure of the Magura Nappe and Outer Western Carpathians development (Kováč et al. 2016; Teťák et al. 2019).

Methodology

The sedimentological logs were documented at outcrops on riverbeds, road cuts, and quarries during geological mapping and research of the western part of Magura Nappe in Slovakia, specifically in the Biele Karpaty Mts., Javorníky Mts., Oravské Beskydy Mts., and Oravská Magura Mts. (Potfaj et al. 2002, 2003; Mello et al. 2005, 2011; Potfaj et al. 2014; Teťák et al. 2015; Pešková et al. 2021 and unpublished data). The thickest and most interesting logs come from documentation of a few inactive quarries. Many of these outcrops no longer exist (Fig. 5).

Up to 113 sedimentological logs, the thickness of which is up to 162 m, were documented bed by bed. The total thickness of the documented logs is 2022 m. Significant lateral changes of the beds can only be observed rarely at poorly exposed outcrops. They were presented in the case of erosion channels. The logs were chosen to include most of the lithostratigraphic units and their facies in the study area.

The sedimentary facies were formed by deposition from gravity flows of various characters, mostly by turbidite currents and debris flows (Talling et al. 2012). The Peïra Cava locality in the French Alps, where Bouma (1962) defined the Bouma sequence, can be generally considered as the standard for the description of gravity flow deposits. A typical sequence of sedimentary structures from the Peïra Cava can be seen in Electronic supplement E. Documentation and interpretation of sedimentary structures and sedimentological logs were based on the works of Kuenen & Migliorini (1950), Bouma (1962), Mutti & Ricci Lucchi (1972), Lowe (1982), Pickering et al. (1986), Ghibaudo (1992), Mutti (1992), Mutti et al. (2003), Talling et al. (2012), Shanmugam (1997), and Tinterri et al. (2020).

Two methods of the documentation of outcrops were used: logging by notation and logging graphically. The first method represents the logging by writing in a line using graphic signs

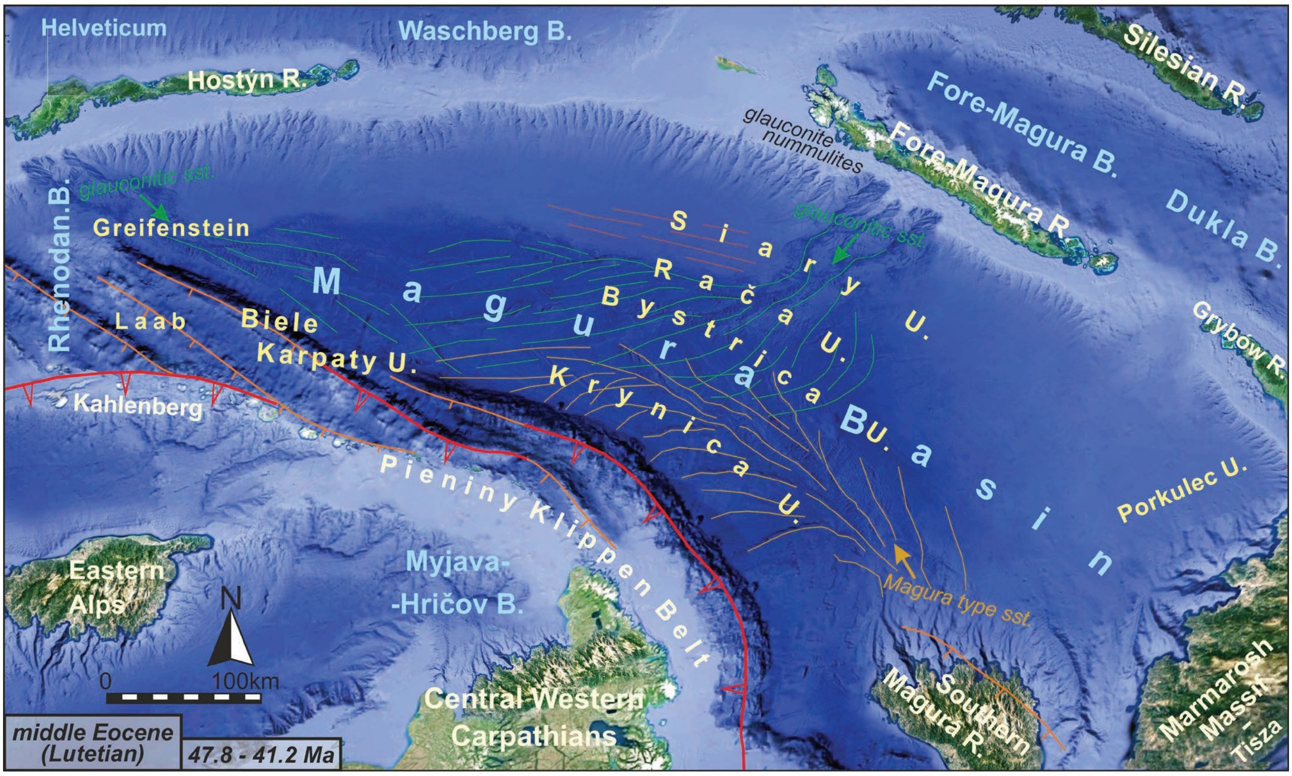

Fig. 4. Paleogeographic map of the Magura Basin during the period of deposition of the glauconitic and Magura-type sandstones (based on Teťák et al. 2019). R. – Ridge, B. – Basin, U. – Unit.

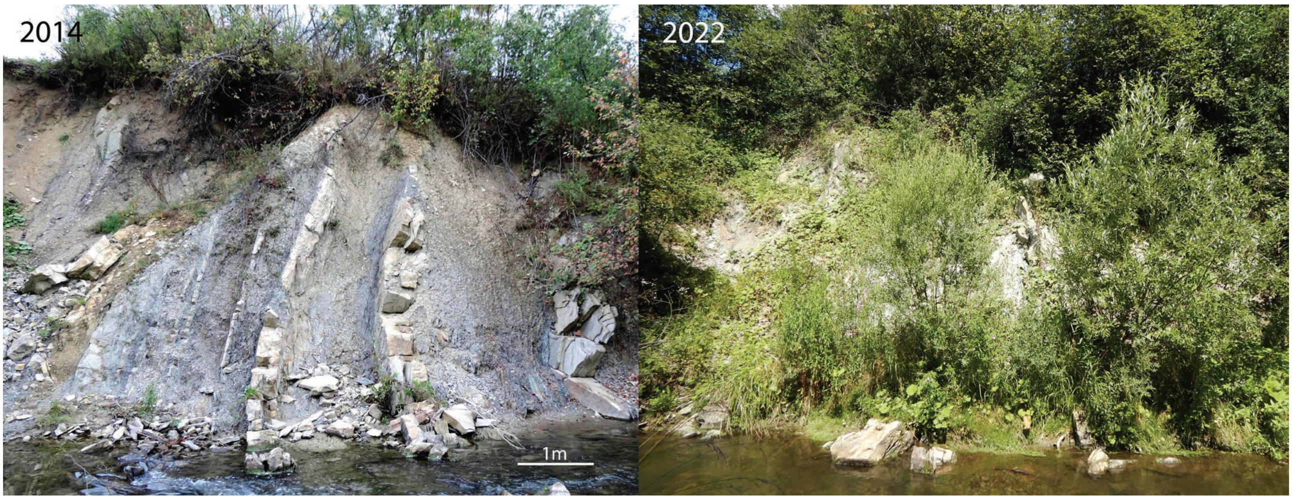

Fig. 5. Comparison of the outcrop preservation of the Malcov Formation on the left bank of the Hruštínka river between 2014 and 2022 (log T620 in the electronic supplement; WGS84: 49.335220°, 19.368789°).

and abbreviations (Fig. 6). An example and comparison of both logging methods are shown in Fig. 7.

Logging by notation is particularly suitable for the logging of thick and monotonous thin-bedded outcrops with poor or repeated sedimentary structures. In the case of a complex bed, it is advisable to log it graphically. The graphical method is more suitable for the logging of structurally, more diverse sequences. This method allows for a better display of the changes in grain size, the distribution of structures in the bed, and the contact of the beds. The graphical log is identical to the display of sedimentological logs in Electronic supplements E and F of this work (an example is given in Fig. 8).

The logs contain information on the thickness of beds, grain size, the character of bed boundaries, lithotype, sedimentary structures, rock colour, HCl acid response, dip and strike measurements, and if possible, the paleocurrent direction. Graphic symbols and abbreviations speed up and simplify the notation and reading of repetitive structures. Explanations of the graphic symbols and abbreviations used in the sedimentological logs are summarised in Fig. 6. The graphic symbols were modified according to Bouma (1962). The localization and lithostratigraphic classification of documented outcrops are summarised in Electronic supplements C and D.

The inclusion of paleocurrent measurements was an important element in the analysis (Teťák 2010). The direction of paleocurrents were measured from the sole marks, such as flute casts, load casts, groove casts, and prod casts found on the basal surface of sandstone beds. Rarely, the paleocurrent direction was determined from the orientation of the ripple cross-lamination. Measurements were made with an accuracy of 5°. The bed planes are mostly tilted or even overturned in the Magura Nappe outcrops. Due to a large number of measurements, the numerical methodology proposed by Teťák (2018) was used mostly to measure and retilt lineations. Simple numerical methodology of lineation retilting allows for the processing of hundreds of measurements, as well as saves time and minimizes the possibility of errors. A separate log was designed for logging of paleocurrent directions in the interpreted logs (Fig. 9 and Electronic supplements E and F) similar to Piazza & Tinterri (2020). The paleocurrent log helps to display and study changes in paleocurrent directions.

The next step was to distinguish sedimentary facies and cycles. Their interpretation was based on lithological features analysis according to the facies by Mutti & Ricci Lucchi (1975), Walker (1978), Marschalko & Potfaj (1982), Stow (1985), Reading & Richards (1994), Pickering et al. (1995), Mutti et al. (2009), McArthur et al. (2016), summarised and supplemented by Shanmugam (2016, 2018).

After cutting of the logs into A4 size pages, the sedimentological logs at a scale of 1:28 and their interpretation would take up more than 70 pages in printed form. Additionally, tearing the logs after inserting them on the page would undermine their informative value. Due to the range, the logs were displayed in two electronic supplements of the paper in PDF format. Thus, it is more appropriate to display and compare the logs as a digital attachment (Electronic supplements E and F). The logs have been arranged in the digital attachment in the same order as in Electronic supplement D. Several sedimentological details, such as erosive troughs and Zoophycos trace fossils supplemented them. The log F212 from the Zábava Formation was chosen as an example to present log interpretation in the print version of the paper (Fig. 9).

Vertical trend in bed thickness and changes in sedimentary structures were studied in the described logs. The cyclicity of the gravity flow deposits based on the change in beds thickness has been studied and described e.g., by Mutti & Ricci Lucchi (1972, 1975), Ricci-Lucchi (1975), Walker (1978), Mutti (1992), Mutti et al. (2009), and also in the Western Carpathians by Pesl (1964), Marschalko & Potfaj (1982), Teťák (2010) and Maceček (2021).

15 logs were selected as the most interesting for the construction of simplified logs and for the interpretation of sedimentation in the Magura Basin (Fig. 9 and Electronic supplements E and F). This choice is mainly due to the development of sedimentation cycles of Magura-type sandstones, accompanied by thin-bedded facies that are supported by a number of paleocurrent measurements. Simplified log display is more suitable for studying of vertical sedimentation trends. The interpretation of some of the mentioned logs has already been partly presented by Teťák (2010).

Results

Sedimentological analysis of outcrops remains the fundamental source of information for the interpretation of the depositional environment and paleogeographic evolution. The detailed sedimentological profiles presented in the digital appendix are the main contribution of the article (Electronic supplements E and F). Knowing the directions of gravity flows is essential for the interpretation of the sedimentary evolution and to interpret the position of the distributary channel and lobe from which the beds have been deposited. The inclusion of transport directions in the analysis is one of the benefits of this research.

Discussion

Interpretation of logs

The question of the existence of regular cycles of sedimentation in a submarine-fan system has not yet been satisfactorily explained. Application of cycles to determine depositional sub-environments have been presented previously by Malinverno (1997), Carlson & Grotzinger (2001), Talling (2001), Sylvester (2007), and Prekopová & Janočko (2009).

Most of the documented logs for the purpose of this article apparently do not have developed sedimentation cycles, which is consistent with the findings of Chen & Hiscott (1999). The vertical trend of bed-thickness seems to follow without any obvious rule. Some of the logs, however, show signs of cyclicity of the bed-thickness or a gradual change in the direction of the paleocurrents.

Chen & Hiscott (1999) statistically proved that asymmetric bed-thickness cycles essentially have no statistical significance in turbidite successions, and therefore cannot provide a key criterion for identification of sub-environments in submarine fan systems. Subsequently, models for submarine fans based on the widely-publicised hypothesis of common asymmetric cycles should be reconsidered. The same arguments are believed to hold for grain-size trends in a submarine-fan system, with one important exception of coarse-grained channel deposits, where upward fining is obvious.

Similar conclusions, but without statistical evidence, follow from the studied logs. This means that the cycles can be best observed in the channel-levee complexes (consistent with McArthur et al. 2016). Channel deposits are dynamically alternating with sediments of the terrace, as well as the inner and outer levee (Stow 1985; McArthur et al. 2016). The channel-levee complexes and associated cycles of sedimentation were best observed in the studied area in Magura type sandstones of the Krynica Unit (e.g., Fig. 9). Facies and environment of sedimentation were interpreted on the basis of sedimentary structures and sedimentological logs according to the works of Kuenen & Migliorini (1950), Bouma (1962), Mutti & Ricci Lucchi (1972), Lowe (1982), Pickering et al. (1986), Ghibaudo (1992), Mutti (1992), Mutti et al. (2003),

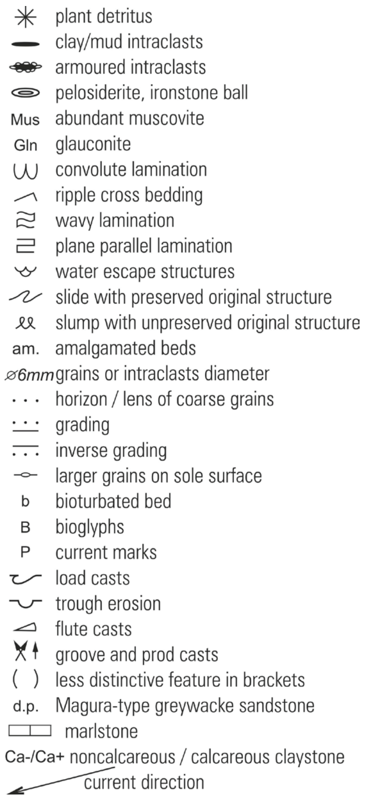

Fig. 6. Explanations of graphic symbols and abbreviations used in the sedimentological logs.

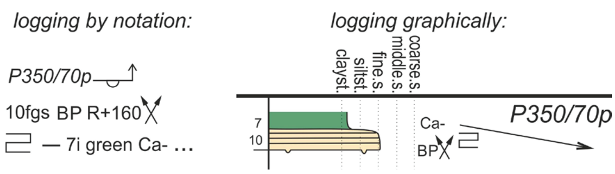

Fig. 7. An example and comparison of logging by notation and logging graphically. The logging by notation is read as follows: The dip of bedding incline 70° to the north (350°) and the sequence is overturned (p) – the profile is recorded towards the overburden – a 10 cm thick bed of fine-grained sandstone (fgs) is parallel-laminated with the bioglyphs and groove casts on the bedding plane (R+160 is the paleocurrent measurement based on the methodology of Teťák (2018)) – a 7 cm thick layer of green non-calcareous claystones follows.

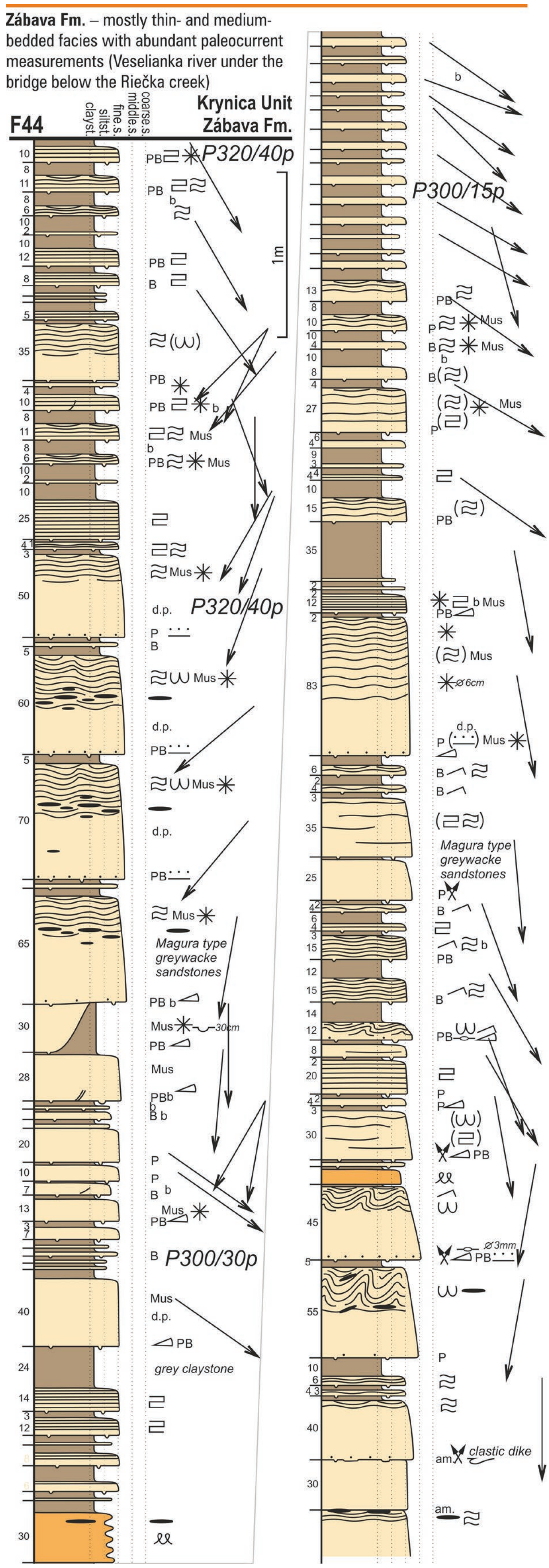

Fig. 8. Log example from the electronic supplement of this paper.

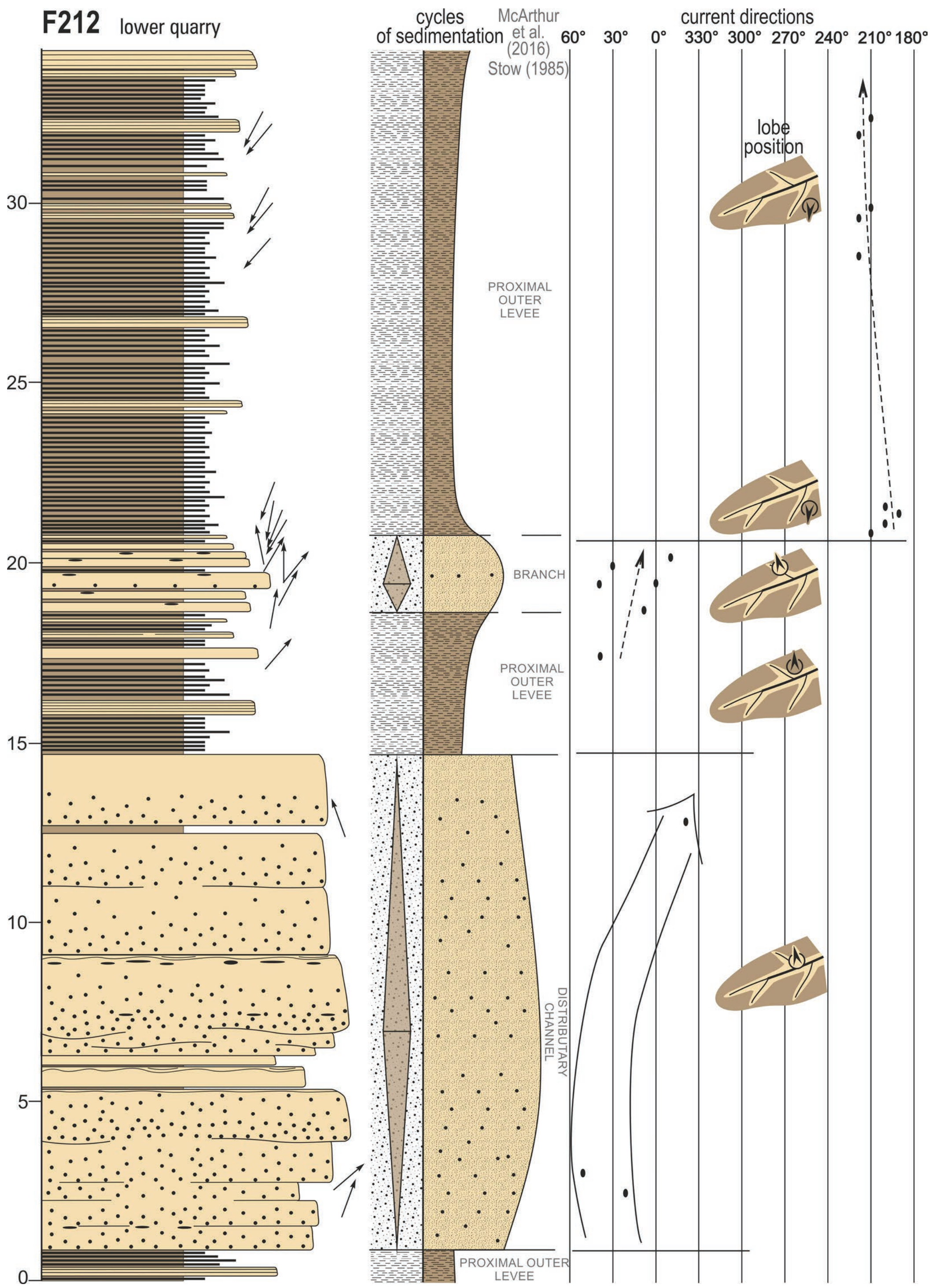

Fig. 9. Simplified log and its interpretation (log F212, quarry above the Goral settlement on the SE slope of the Oravská Magura Mts., Zábava Formation). Example from Electronic supplements E and F of this paper.

Talling et al. (2012) and Tinterri et al. (2020). Thanks to the measurement of paleocurrent directions, it is possible to recognise a certain regularity of sedimentation even in logs in which the vertical change of the layer thickness and grain size is significantly irregular (e.g., logs T56 and BKs339 in Electronic supplements E and F).

Mutti & Ricci Lucchi (1972) and similarly Walker (1978) and Mutti et al. (2009) interpreted the depositional environment of the thickening upward cycle as an outer-fan sequence and the thinning upward cycle as a middle-fan/suprafan sequence. The results from the Magura Basin do not fully support this interpretation. The vertical trends in bed thickness supported by the rotation of the paleocurrent directions indicate channel switching rather than the proximality and change of position from the outer-fan to middle-fan (Piazza & Tinterri 2020).

The slumps represent several-metres thick layers of intraformational breccia and unlithified mud/sand, and they occur together with slides. Slumps can occur in all facies and are most often the product of instability of the channel walls, but also of increased tectonic activity of the advancing front of the Central Carpathian orogen. The occurrence of thick slumps or slides is typical for sedimentation on the inner levee and terrace in the channel margin. Slumps coupled by thick hemipelagic claystone indicate that the channel suddenly died out (Electronic supplements E and F). Walker (1978) described several-metres thick shale which blankets the suprafan lobe when it was completely abandoned by the channel switching and the channel/branch died out.

The sedimentation of marlstones is characteristic for slow deposition during periods of high sea level. The supplement of the clastic material to the basin reduced and the productivity of organic matter increased (Leszczyński & Malik 1996).

An important element in the sedimentological analysis was the inclusion of paleocurrent measurements (Teťák 2010). A separate column was used for logging of paleocurrent directions in the interpreted logs. This method is another factor influencing facies analysis based on sedimentary structures according to Mutti & Ricci Lucchi (1975), Walker (1978), Pickering et al. (1995), Mutti et al. (2009), and Shanmugam (2016, 2018).

The stable longitudinal, e.g., parallel to the elongation of the basin, arrangement of paleotransport directions from east to west in thin-bedded facies, e.g, in the Ondrášovec Member and Ropianka and Beloveža formations, is remarkable. This facies represents the basin plain deposits, however, paleocurrents of similar thin-bedded facies deposited on the outer levee are different. They are mostly oblique to the basin and lobe/channel elongation and usually change direction gradually (Electronic supplements E and F).

Suitable examples of cyclic sedimentation come, in particular, from the Zábava Formation and Racibor Formation of the Krynica Unit (Electronic supplements E and F). Sandy bedsets of the Magura-type sandstones alternate with intervals of thin-bedded facies and thick beds of Bystrica type mudstones. The thickness of the intervals/cycles ranges from a few metres to tens of metres. Sandstone intervals represent, in this case, sedimentation from the distributary channels and partly from the terraces as well. The thin-bedded facies and thick mudstone beds represent the distal levee and interchannel/basin plain sedimentation outside the main volume of material transport area (Stow 1985; Teťák 2010; McArthur et al. 2016).

Magura Basin

In spite of the existing models that explain the main factors determining the evolution of gravity flow deposits and their impact on the architecture of deposits, understanding of the more detailed architecture of the deep-marine depositional systems still requires future research. Studies of recent and ancient deep-marine depositional systems show that several interacting factors have a decisive influence on the deposition in the siliciclastic basin (e.g., Covault & Graham 2010). They are namely: (1) source area – size, topography, geological structure, tectonic activity, weathering, climate; (2) transport of detrital material – length of transport, slope inclination, dynamics of current, granularity and amount of material, sorting; (3) depositional conditions in the sedimentary basin – tectonic activity, depositional depth, CCD, local or global variations of sea level, burial and diagenetic processes, bottom currents influenced by connection with the ocean.

The named factors had a fundamental influence on the provenance, value, grain size, and distribution of clastic sediments within the basin. Criteria, such as specific facies characteristics, large-scale geometry, and degree of sand-bed clustering may provide the best tools for discrimination of submarine fan facies and environments (Stow 1985; Pickering et al. 1986; Chen & Hiscott 1999; Stow & Mayall 2000).

The volume, rate, and character of supplied sediment and the switching between the dominance of fan sedimentation and the slow sedimentation on the basin plain were mainly affected by the size and tectonic activity of the source area, climate, weathering, rock types, global or local sea-level variations, coastal type, basin size and subsidence, but also locally by the lateral migration of the lobes (Stow 1985; Reading & Richards 1994; Prélat et al. 2009; Piazza & Tinterri 2020).

The Magura Basin is an excellent example of the interaction of the above-mentioned factors (Table 1). For a better picture, it was a foreland basin up to 600 km long and 400 km wide (Teťák 2008; Teťák et al. 2019). Inner, axial, and also outer foredeep basins are represented (Mutti et al. 2003). The deposits of its slopes, outer ramp, and wedge-top basin have not been preserved, or only to a very limited extent. At the end of its existence, it was a piggy-back basin. Deposits of gravity flows up to 5 km thick were derived from several sources. At least seven ridges/source areas were active during the Cretaceous to early Miocene. From the west clockwise, they are the Hostýn Ridge (Teťák et al. 2019), Fore-Magura Ridge (Golonka et al. 2005), Grybów Ridge (Cieszkowski 2002), Bukowiec Ridge (Ślączka 2005), Szczawina Ridge (Oszczypko & Salata 2005), Southern-Magura Ridge (Mišík et al. 1991b), and Neopieninic Exotic Ridge (Mišík et al. 1991a). The Magura Basin was directly connected to the adjacent depositional areas, such as the Rhenodanubian Basin and Dukla Basin.

Conclusions

Although the documentation of sedimentological logs is the basic field method, this method is significantly limited in the area of the Outer Western Carpathians due to weathering and vegetation. These factors are limiting for the creation,

Table 1: Characteristics of lithostratigraphic units occurring in the region by typical facies associations and morpho-dynamic forms of the depositional system according to Stow (1985), Reading & Richards (1994), and Bouma (2000).

Lithostratigraphic unit		Typical vertical sequences (Stow 1985)	Environmental model (Reading & Richards 1994)	Turbidite systems (Bouma 2000)
Zlín Fm.	***Vsetín Mb.***	sandy lobe, silty–sandy distal lobe, interchannel, proximal levee	mud/sand-rich system – point source submarine fan of glauconitic sandstones	fine-grained mud-rich turbidite system
	Babiše Mb.	sandy lobe, silty–sandy distal lobe, (interchannel)	mud/sand-rich system – interfingering of two point source submarine fans of Magura type and glauconitic sandstones	interfingering of fine-grained mud-rich and rather coarse-grained sand-rich turbidite system
	Kýčera Mb.	sandy lobe, silty–sandy distal lobe, distributary channels	mud/sand-rich system – point source submarine fan of Magura type sandstones	rather coarse-grained sand-rich turbidite system
	Újezd Mb.	over-supplied basin, silty–sandy distal lobe	basin plain facies and mud/sand-rich system – point source submarine fan	basin plain facies and fine-grained mud-rich turbidite system
	Bystrica Mb.	sandy lobe, silty–sandy distal lobe, interchannel	mud/sand-rich system – point source submarine fan of glauconitic sandstones	fine-grained mud-rich turbidite system
	Oravské Veselé Mb.	sandy lobe, silty–sandy distal lobe, interchannel	mud/sand-rich system – interfingering of two point source submarine fans of Magura type and glauconitic sandstones	interfingering of fine-grained mud-rich and rather coarse-grained sand-rich turbidite system
Vychylovka Fm.		over-supplied basin, silty–sandy distal lobe	basin plain facies and mud/sand-rich system – point source submarine fan	basin plain facies and fine-grained mud-rich turbidite system
Luhačovice Fm.	***Upper Luhačovice Mb.***	sandy lobe, silty–sandy distal lobe, distributary channels	sand-rich system – point source submarine fan of Riečky type sandstones	coarse-grained sand-rich turbidite system
	Lower Luhačovice Mb.	sandy lobe, silty–sandy distal lobe, distributary channels	mud/sand-rich system – point source submarine fan of glauconitic sandstones	fine-grained mud-rich turbidite system
Beloveža Fm.	***Upper Beloveža Mb.***	over-supplied basin	basin plain facies	basin plain facies
	Lower Beloveža Mb.	over-supplied basin, under-supplied basin, sandy lobe, silty–sandy distal lobe, distributary channels	basin plain facies and mud/sand-rich system – point source submarine fan of Riečky type sandstones	basin plain facies and coarse-grained sand-rich turbidite system
Ropianka Fm.	***Szczawina Mb.***	sandy lobe, silty–sandy distal lobe, distributary channels	mud/sand-rich system – point source submarine fan of Szczawina type sandstones	coarse-grained sand-rich turbidite system
	Ropianka Fm. s.s.	over-supplied basin, silty-sandy distal lobe	basin plain facies	basin plain facies
Soláň Fm.	***Lukov Mb.***	sandy lobe, silty–sandy distal lobe, distributary channels	mud/sand-rich system – multiple source ramp of Soláň type sandstones	coarse-grained sand-rich turbidite system
	Ráztoka Mb.	over-supplied basin, silty–sandy distal lobe	basin plain facies	basin plain facies
Cebula Fm.		under-supplied basin	basin plain facies	basin plain facies
Malcov Fm.		under-supplied basin, debris-slump masses, (silty–sandy distal lobe)	mud-rich system – slope apron linear source	fine-grained mud-rich turbidite system
Racibor Fm.	***Racibor Fm. s.s.***	sandy lobe, silty–sandy distal lobe, interchannel, (distributary channels), (debris–slump masses)	mud/sand-rich system – point source submarine fan of Magura type sandstones	rather coarse-grained sand-rich turbidite system
	Račová Mb.	under-supplied basin, interchannel, (silty–sandy distal lobe)	basin plain facies	basin plain facies
Zábava Fm.	***Zábava Fm. s.s.***	over-supplied basin/distal levee, distributary channels, sandy lobe, proximal levee	mud/sand-rich system – point source submarine fan of Magura type sandstones and basin plain facies	rather coarse-grained sand-rich turbidite system and basin plain facies
Svodnice Fm.	***Bzová Mb.***	sandy lobe	mud/sand-rich system – point source submarine fan of Magura type sandstones	rather coarse-grained sand-rich turbidite system
	Svodnice Fm. s.s.	sandy lobe, silty–sandy distal lobe, interchannel	mud/sand-rich system – point source submarine fan of quartz–carbonate sandstones	fine-grained mud-rich turbidite system
	Chabová Mb.	sandy lobe, silty–sandy distal lobe	sand-rich system – point source submarine fan of quartz–carbonate sandstones	coarse-grained sand-rich turbidite system
Lopeník Fm.	***Drietomica Mb.***	distributary channels, sandy lobe	sand-rich system – point source submarine fan of quartz–carbonate sandstones	coarse-grained sand-rich turbidite system
	Javorina Mb.	over-supplied basin/distal levee, proximal levee, sandy lobe	mud/sand-rich system – point source submarine fan of quartz–carbonate sandstones / basin plain facies	rather coarse-grained sand-rich turbidite system
	Ondrášovec Mb.	over-supplied basin, under-supplied basin	basin plain facies	basin plain facies

extent, and preservation of outcrops. The presented article provides a record of 113 sedimentological logs with a total thickness of 2022 m processed during more than 20 years of fieldwork in the Magura Nappe. The investigated outcrops were chosen to include most of the lithostratigraphic units and their facies varieties in the study area. Simplified logs and interpretation of the sedimentation environment was additionally developed for 15 of the most interesting logs. Deposition in the environment of the distributary channel, terrace, levee, interchannel, and basin plain was interpreted. The deep-marine environment of the Magura Nappe lithostratigraphic units occurring in the region is characterised by typical facies associations and morpho-dynamic forms of the depositional system.

The work contains a summary map with the location of the logs, as well as a table with the GPS location of the outcrops, their length, and lithostratigraphic classification. Most of the studied outcrops no longer exist or they are significantly altered, overgrown with vegetation, or are difficult to access. The presented sedimentological logs imply a fundamental contribution to detail documentation and archiving of outcrops for further research, including their access to geologists from the surrounding countries as comparative material for further lithostratigraphic and sedimentological research. The photographic appendix complements the previous characteristics of the lithostratigraphic units.

Thanks to the measurement of paleocurrent directions, it is possible to recognise a certain regularity of paleocurrent directions rotation even in logs in which the vertical change of the layer thickness and grain size is significantly irregular. Paleotransport measurements in the case of regular cycles indicate the shifting of the channel/lobe. New outcrops will continue to emerge, therefore, geological research in the area must continue with further research and expand into a broader area.

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Electronic supplementary material is available online:

Supplements A, B, C and D at http://geologicacarpathica.com/data/files/supplements/GC-73-6-Tetak_Suppl_ABCD.pdf

Suppl. A. Properties of the lithostratigraphic units distinguished in the western part of the Magura Nappe (modified after Teťák et al., 2019).
Suppl. B. Photo attachment.
Suppl. C. Map of localization of documented outcrops.
Suppl. D. Thickness, GPS location, tectonic and lithostratigraphic classification of documented outcrops.

Supplement E at http://geologicacarpathica.com/data/files/supplements/GC-73-6-Tetak_Suppl_E.pdf

Suppl. E. Detailed documented sedimentological logs of the studied area of the Magura Nappe. Selected logs are generalised and supplemented by facies interpretation.

Supplement F at http://geologicacarpathica.com/data/files/supplements/GC-73-6-Tetak_Suppl_F.pdf

Suppl. F. Detailed documented sedimentological logs of the studied area of the Magura Nappe. Selected logs are generalised and supplemented by facies interpretation.