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The gravity flow dynamics of submarine fan sedimentation in the Magura Basin of the Western Carpathians (Magura Nappe, Slovakia)

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Abstract: This article deals with the dynamics of the deep-water gravity flows sedimentation within the Magura Formation. This investigation is based on analysis of the Magura sandstone sedimentary structures studied on the outcrops. The final comparison of the sedimentary structures and cycles with the paleocurrent directions provided an interpretation of the gravity flows dynamics and helped to restore the migration of the sandy lobes in space and time. Three modes of sedimentation are recorded: regular cyclic sedimentation from the lobe, irregular sedimentation from the immature lobe and pelitic sedimentation on the basin plane without the lobe influence. We compared the occurrence of some sedimentary structures with the changes of the current directions and bed thickness. The following interpretations of gravity flow fan dynamics are results of this comparision: the fan consists of one or several lobes, the lobe branches out into branches with the radial current arrangement, the lobes laterally change position and the lobes suddenly die out.

Key words: Paleogene, Outer Western Carpathians, Magura Formation, paleogeography, submarine fan model, sedimentology, gravity flows.

Introduction

Marschalko & Potfaj (1982) already studied several sections in the Orava region with the help of sequence analysis in the past. Other interesting sections also occur in this area. Their study could complete the knowledge of the sedimentation not only in the southern part of the Magura Basin, but also in other deep-water basins. We will try to interpret the origin and features of cyclic sedimentation. This sedimentation formed the sandstone packets. Such packets are notable from morphology and from many sections of the whole Carpathian flysch belt.

We focus on the analysis of gravity flows deposits in three representative outcrops (Figs. 2 and 3) located in the Orava region (northern Slovakia, Fig. 1). The studied outcrops are situated at the end of Oravská Jasenica village in the Veselianka river bank. They are about 14, 23 and 109 meters long (Figs. 2 and 3). The exposed sediments represent the Lower and Upper Eocene Magura and Racibor Formations.

Geological setting

The flysch sediments form the study area. They were deposited in the Upper Cretaceous to Oligocene deep-water Magura Basin. Sediments of this basin were folded into the north-vergent imbricated folds and slices of the rootless Magura Nappe (Fig. 1). This nappe detached from its substratum mainly along the ductile claystone rich Upper Cretaceous beds. The thrust-sheets form the accretionary prism. This frame originated after the Oligocene. Three tectonofacies units have been distinguished in the western part of the Magura Nappe on the basis of the lithofacies differentiation. The Rača, Bystrica and Krynica Subunits were distinguished from the North to the South (Birkenmajer & Oszczypko 1989). Magura, Racibor and Malcov Formations were defined in Krynica (Oravská Magura) Subunit of the study area (Fig. 5; Potfaj et al. 1991). Different lithostratigraphy was recognized in the continuation of the Krynica Subunit into Poland (Birkenmajer & Oszczypko 1989).

Magura Formation *(Upper Paleocene–Middle Eocene)*

The Magura Formation (Fig. 3) (Potfaj et al. 1991) is a formation of sandstone flysch character up to 1200 m thick. Packets of predominatly sandstone flysch character a tens of meters thick (Fig. 3 — Ve4) alternate with over 30 m thick packets of thin-bedded flysch (Fig. 3 — Ve1). The Magura sandstone type dominates. It is fine- to coarse-grained greywacke sandstone forming beds from 2 to 400 cm thick, with Ta(b), Tabc, and Tbcd Bouma's divisions. It is from blue-grey to brown-grey, with the addition of larger sandy grains, plant detritus, claystone intraclasts and muscovite. Clasts up to 2 cm in diameter either disseminated or arranged in lenses, are common. Locally occurring fine-grained paraconglomerates mainly contain clasts of quartz and frequent mica schist, phyllite, feldspar, granite, cherty and pinkish quartz. Tops of the thick sandstone beds are characterized by reduced Tbc Bouma's division and common claystone intraclasts. Current marks on the bottom planes are expressive. Thick claystone intercalations are made of Bystrica type calcareous grey silty claystones with sharp conchoidal parting. The ratio of sandstones to claystones decreases from the bottom to the top of the formation from 10 : 1 up to 1 : 1 (Potfaj 1983; Potfaj et al. 1991). At the same time the amount of thin-

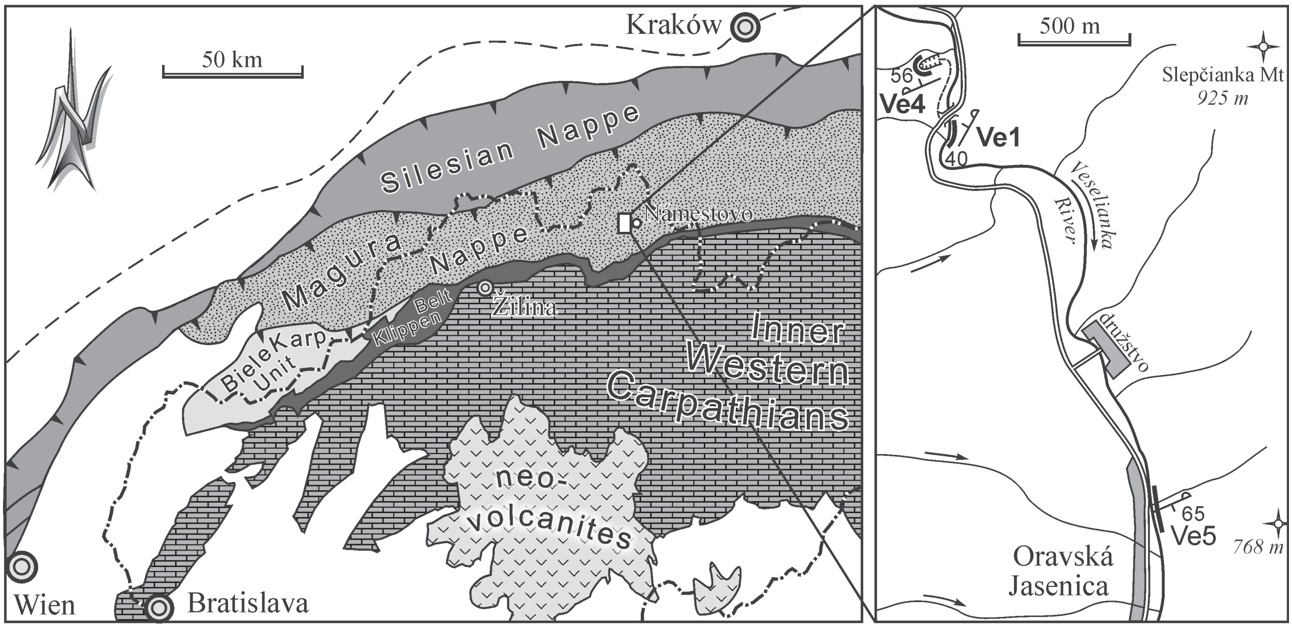


Fig. 1. Informative location map displaying the setting of the investigated outcrops in the Western Carpathians region.

bedded Racibor Facies intercalations increases upward. The age of the Magura Formation is from Late Paleocene to Middle Eocene (Potfaj et al. 1991). A younger age of this formation is also possible (Oszczypko-Clowes 2001).

Racibor Formation *(Middle Eocene–Lower Oligocene)*

The Racibor Formation (Fig. 2 — Ve5) (Potfaj et al. 1991) is a flysch formation about 600 meters thick with a high content of claystones, accompanied by fine- to medium-grained sandstones. The ratio of the sandstones to claystones is from 1:5 to 9:10. The formation has 0.9 to 6 sandstone beds for one meter of section. The sandstone beds are 5–90 (250) cm thick. They have an increased content of carbonate clasts. Tbc and Tabc Bouma's divisions are predominant sequences. The coarse- to medium-grained 60–150 cm thick Magura type graywacke sandstones are frequent especially in the lower part of the formation. Sandy-clayey 2–400 cm thick slump bodies are common. 15 cm to 3 m thick beds of mudstones, and thin beds or concretions of the pelosiderites are frequent in the higher part of this formation (Potfaj et al. 1991). Žecová (pers. com.) identified from the section Ve5 nannoplankton of the Priabonian or even Oligocene age (*Helicosphaera scissura* Müller, *H. carteri* (Wallich)).

Paleogeography of the Magura sandstone type

The Magura Basin was a deep-water basin about 200 km wide and more than 700 km long (width approximate estimation is based on knowledge of the length of tectonic folds, while we know the depth of the Magura Nappe's base and the volume of surface erosion; Teťák 2008). The sediments of the Magura sandstone type were deposited along the southern margin of the basin. Their source area was situated south of the Magura Basin.

The point-source sand-rich deep-water fan of the Magura sandstone type was deposited from the gravity flows (Fig. 6, Teťák 2008). A similar model of the point-source sand-rich fan was described by Reading & Richards (1994). In their opinion the sandy source type of the fan is characterized by moderate size of the fan, 10–100 km long fan, radial/lobate shape of fan, the slope gradient 2.5–36 m/km, close and moderate/small size source area, feeding by shelf failure or canyon, >70% sand percentage, the principal architectural elements of proximal area were channels and channelized lobes created a distal area, channel system: braided to low sinuosity impersistent channels and chutes, and rapid lateral migration of channels. Basic attributes of the Magura sandstone submarine fan were reconstructed from the current marks study and the grain size changes (Bromowicz 1992). The feeding canyon came into the basin from the south. The distributary channel or upper part of fan turned sharply to the west into the direction of the basin's axis and branched out into the fan. The measured current directions are oriented in the basin elongation direction (ENE–WSW).

Methods

We used the following parameters for determination of the cycles in sedimentological analyses: thicknesses of the beds, sandstone/claystone ratio, presence or absence of the sedimentary structures (Bouma's and Lowe's divisions; Bouma 1962; Lowe 1982), claystone intraclasts, slumps, marlstones, pelosiderite concretions, current directions and erosion on the base of the beds. The presence of the sedimentary structure in the specific parts of the cycle is important too.

The investigation of the sedimentary structures was just the first step of the facies analyses. The analysis of sediments continued by definition of the sedimentary cycles, investigation of the arrangement and succession of the sedimentary structures. The interpretation of the gravity flow dynamics result from the final comparison of the sedimentary cycles and structures with the current directions. This enables us to restore the migration of lobes in space and time.

Results — arrangement of the fan

Cycles of lobe sedimentation

The deposits of the deep-water gravity flows are in many places formed into cycles. We distinguished deposition cycles with the help of the sedimentological analyses of the investigated profiles. These cycles are characterized by the regular arrangement of beds. The thicknes of the beds gradually increases and/or decreases upward (mixed cycle sensu Marschalko & Potfaj 1982). The cycles were also described according to this manner by Mutti & Ricci-Lucchi (1975). The cycles with regular arrangement of the beds are also called regular cycles. We can divide the observed regular cycles into the cycles of the lobe sedimentation or the cycles of pelitic sedimentation on the basin plane. The sandstone beds with a massive structure deposited mainly from the debris flows compose the cycles of the lobe sedimentation. The thin bedded deposits or thick claystones usually represent the basin plane pelitic sedimentation. Clayey slumps, marlstones and pelosiderites are also common in the pelitic cycles. It is necessary to know the directions of the gravity currents for interpretation of the sedimentary evolution of the cycle.

Pelitic cycles III and VIII are in the opposition to the clastic cycles Ia–Ie, II, IV, V, VI, VII and IX (Fig. 2). The upward coarsening parts of the cycles IV and VII in section Ve5 (Fig. 2) are reduced while the upward thinning parts of these cycles are well developed. The cycles II, IV, Va, Vb and VII are well developed. The cycles Ia–Ie, VI and IX are very thin and irregular. They are composed only of 1 to 3 thicker beds. This is not sufficient for the determination of the cycle character.

The upward coarsening and thinning cycles differ not only by bed thickness changes, but also by many sedimentary structures. The characteristic signs of the *upward coarsening cycles* are: erosion of the base of the cycle, larger floated clasts, lenses or bedding planes with the coarser grains, amalgamation of the beds, absence of the pelitic interbeddings and grainflow origin of the sandstones absolutely prevail over the turbidity origin. These sedimentary signs indicate the dynamic conditions of the current sedimentation. The upward coarsening cycles were often reduced into several beds (2 to 4 beds). These are signs of the increasing energy of the lobe. The upward coarsening and upward thinning trends of the regular cycles are characteristic of the lobe sedimentation (sensu Mutti 1992).

The *upward thinning cycles* are usually formed by more beds than upward coarsening cycles. The thinning of the beds developed continuously with the preservation of the pelitic interbeddings. The turbidity origin part of the beds with preserved Bouma's divisions gradually prevails over the grainflow origin base of the beds.

The upward coarsening cycles represent the outer fan, but the upward thinning cycles represent the suprafan sedimentation (Walker 1978). We can localize the sections Ve5 (Fig. 2) into the suprafan and outer fan border. Both regular cycles developed simultaneously. The upward coarsening or thinning cycles were reduced, or undeveloped. The regular cycles were the products of the mature lobes. The successive rotation of the current directions indicates the continuous migration of these lobes. The lobes laterally migrate into the below situated inter-lobe planes (e.g. Marschalko & Potfaj 1982). The thickest graded or massive sandstone beds were deposited from the axial part of the currents (lobe). The paleocurrent directions in the thickest beds (Fig. 2) are parallel with the lobe elongation. The ENE–WSW lobe elongation corresponds to the Magura Basin axis. The lobe elongation kept constantly approximately the same direction (only slightly meandering). The thinner beds were deposited from the laterally retreated lobe.

The lateral migration of the lobe is responsible for the paleocurrents direction changes. Continuous rotation of the current direction can be observed in Fig. 2. The approach and retreat of the lobe caused these current direction rotations. The upward coarsening cycles represent the approach stage of the lobe. The upward thinning cycles represent the retreat of the lobe. The current erosion traces from the ENE to WSW are characteristic of deposits from the centre of the lobe. The counter clockwise rotation of the current directions in the upward thinning cycles signifies the shifting (retreat) of the lobe to the N. The reduced base of the upward coarsening cycle indicates the sudden impact of the lobe or erosion of the lower part of the cycle by high-energy current (cycle IV, Fig. 2 and middle part of the section Ve1, Fig. 3). The very well developed upward thinning cycles are products of the continuous retreat of lobe (cycles IV, Va, VII and II, Fig. 2).

Cycles Vb and Va were sedimented from different lobes or branches. Cycle Va represents the return of the lobe of cycle IV. Cycle Vb represents the shifting of the lobe to the N. At the same time the deposition rise affected by the approaching branch (see current directions from the NE). The sedimentation of the slumps and thick hemipelagic claystone bed (cycle VI, Fig. 2) suggests that the branch of cycle Vb suddenly died out. Walker (1978) also described several meters thick shale bed that blankets the suprafan lobe when it was completely abandoned by the channel switching (lobe died out).

Interpretation of the trend of cycles could be difficult or impossible in some cases. These indeterminate cycles are called irregular cycles (deposition).

Irregular cycles (deposition) from immature lobe

Irregular cycles are too thin or irregular to define their upward coarsening or upward thinning character. These cycles originated in the period when the arrangement of the lobes was unstable or the lobes did not even develop. The cycles Ia–Ie, VI and IX are irregular (Fig. 2). The cycle Ic resembles upward thinning cycle with regard to the bed thicknesses and the paleocurrents direction changes. On the other

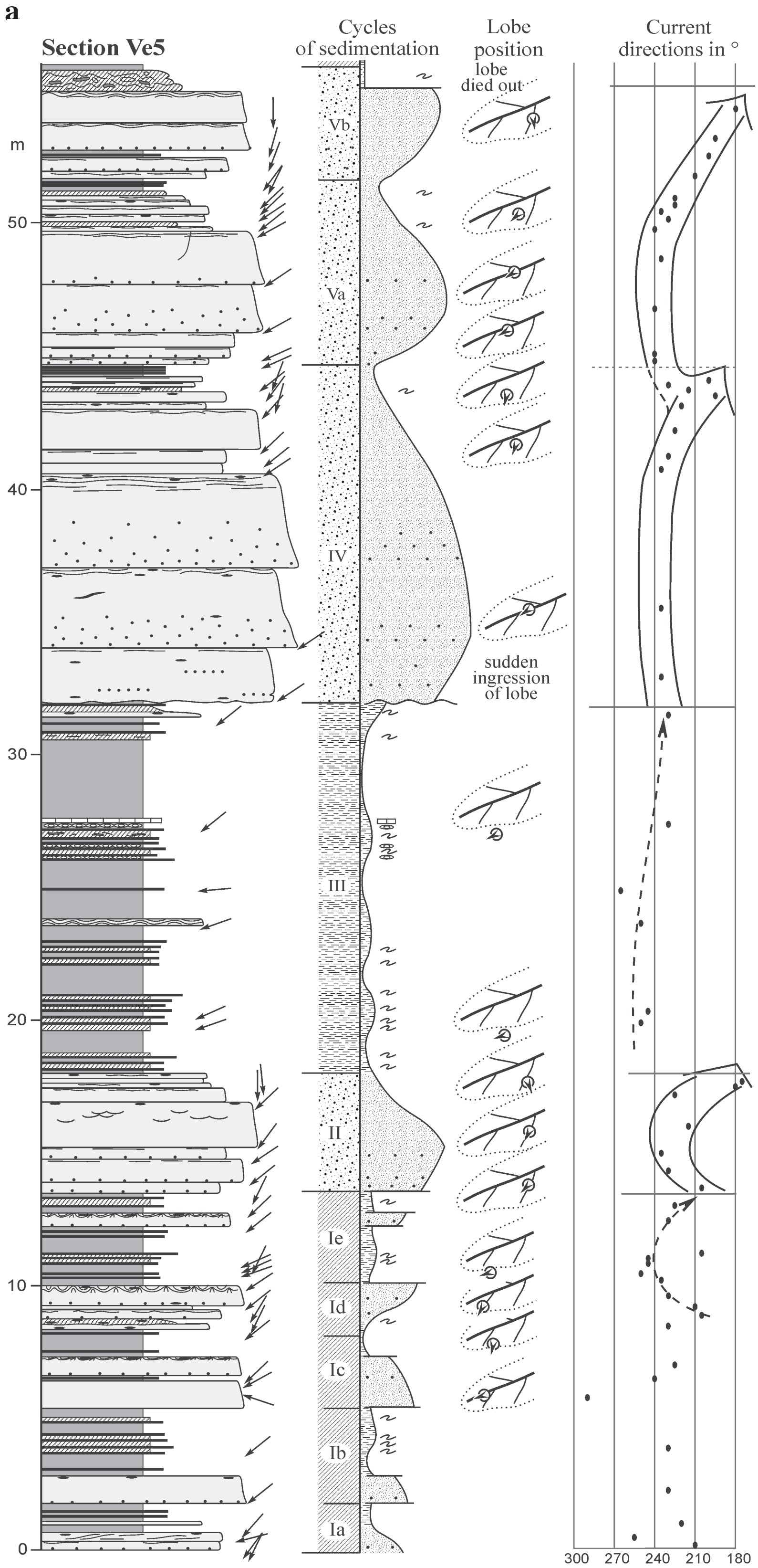


Fig. 2a,b. Section **Ve5** is situated near the Oravská Jasenica village. This section represents the sediments of the Racibor Formation. There is frequent switching of the cycles of the lobes and basin plane sedimentation. Disorganized irregular cycles also occur. The interpretation of lobe switching and migration is based on the relation between the cycles of sedimentation, sedimentary structures and current directions (description in text).

side the cycle Id resembles upward coarsening cycle. The lower parts of cycles Ie and VI resemble pelitic cycles.

Pelitic sedimentation on the basin plane

The domination of the claystones over sandstones, thin-bedded sedimentation, absence of the thicker sandstone beds, presence of the pelosiderite concretions, marlstones, slumps and the constant longitudinal paleocurrent arrangement are characteristic of the period of basin plain pelitic sedimentation in the Racibor Formation. The packets of thin sandstone beds were deposited in periods of minor fan activity revival of the distant lobe (cycles III, VIII, Fig. 2).

The material of the slumps is usually different from surrounding deposits. Composition of this material is in some cases intraformational breccia, but usually it is plastic mud. Slumps may be the product of tectonic activity of the South Magura Ridge in this case. Instability of canyon or channel walls is less probable. It appears from this that the deposition of slumps is not characteristic of basin plane deposition, but their occurrence in this type of sediments is striking.

The pelitic deposits have the character of sedimentation on the basin plane (Fig. 2) or on the stable distal part of the lobe (lower part of the section Ve1, Fig. 3). This interpretation is supported by the presence of the pelosiderite concretions and marlstones in the pelitic cycles. The sedimentation of marlstones is characteristic of slow deposition in times of high sea level. The supplement of the clastic material to the basin was reduced and the productivity of organic matter was increased (Leszczyński & Malik 1996).

The very stable longitudinal arrangement of current directions of the thin sandstone beds in the pelitic cycles is notable. They correspond to basin and lobe elongation.

The current directions of the thin beds deposited from the lobe are different. They are at an angle to the lobe elongation. These are the deposits on the elevated interchannel planes or levees.

The switching between the deposition of the lobe and basin plane can be caused by the migration of this lobe. This can also be caused by the global sequence change of the source area, for example by sea-level changes or tectonic activity. Similar dynamic sedimentation was striking in the thin-bedded deposits of the Beloveža Formation and the sandstone-claystones lithofacies of the Soláň Formation (Rača Subunit; Teťák 2008).

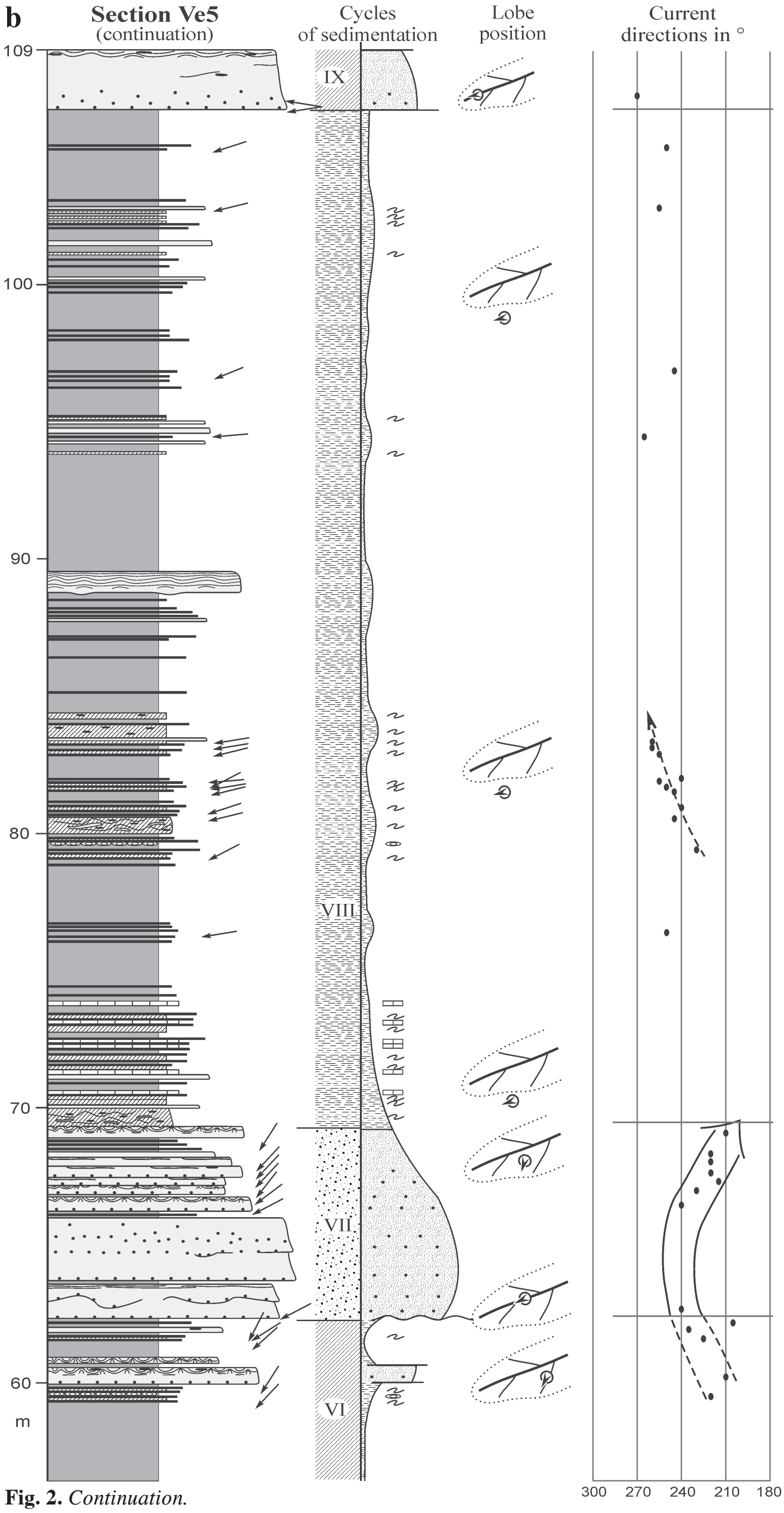
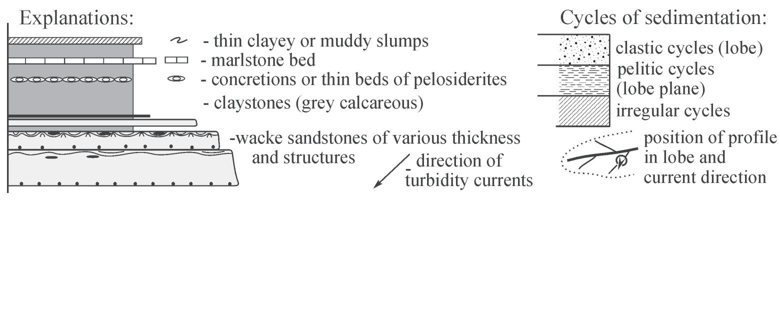


Fig. 2. *Continuation.*



Discussion — gravity flows

The term "gravity flow" was used intentionally, because we distinguished structures of both "turbidity current" and "debris flow" character in the sections (in the meaning of Shanmugam 1997). Beds originating from a single turbidity current were rarely observed. Shanmugam (1997) mentioned that normally graded Ta division (Bouma 1962) is of turbidity origin and the massive ungraded Ta division was sedimented from debris flow. Shanmugam (1997) also admits the conversion of the gravity flow sedimentation from debris flow to the turbidity current. We observed a normally graded base of the bed 1 to more than 20 cm thick. This sediment was deposited from a traction carpet. 10 to 250 cm thick massive sandstone overlay this base. The horizons or lenses include many coarse clasts without significant amalgamation, the water escape structures and worm escape burrows sometimes developed in the massive sandstone beds (S1, S2, S3 Lowe's divisions — Lowe 1982). In Päira Cava (France; see Bouma 1962) the single turbidity origin beds are also rare (personal investigation). Combined debris and turbidity origin beds prevail. The transition border of these two deposition processes is sharp and this border is often defined by a claystone intraclast horizon.

It is possible to interpret the succession of both the turbidity and debris character of the gravity flow (Fig. 4). The erosive frontal part of the current tore out pieces of the claystones from the sea bottom. The sedimentation followed after the erosive front of the current. The graded base of the bed was sedimented from the traction carpet. The frontal part of the current was followed up by the denser core of the sandy debris flow. The massive Ta division of the sandstone sedimented from this denser current core by its freezing. Lenses and horizons of the coarse clasts could be deposited from the suspension or traction carpet when a short gap occurred inside the sandy debris flow (short events — windows). They could also originate by bed amalgamation. Graded Ta division turbidity origin sandstone was deposited from suspension after freezing of the debris flow. This border is often emphasized by horizon of the claystone intraclasts, which floated on the denser debris flow. They were drifted by the denser current and fi-

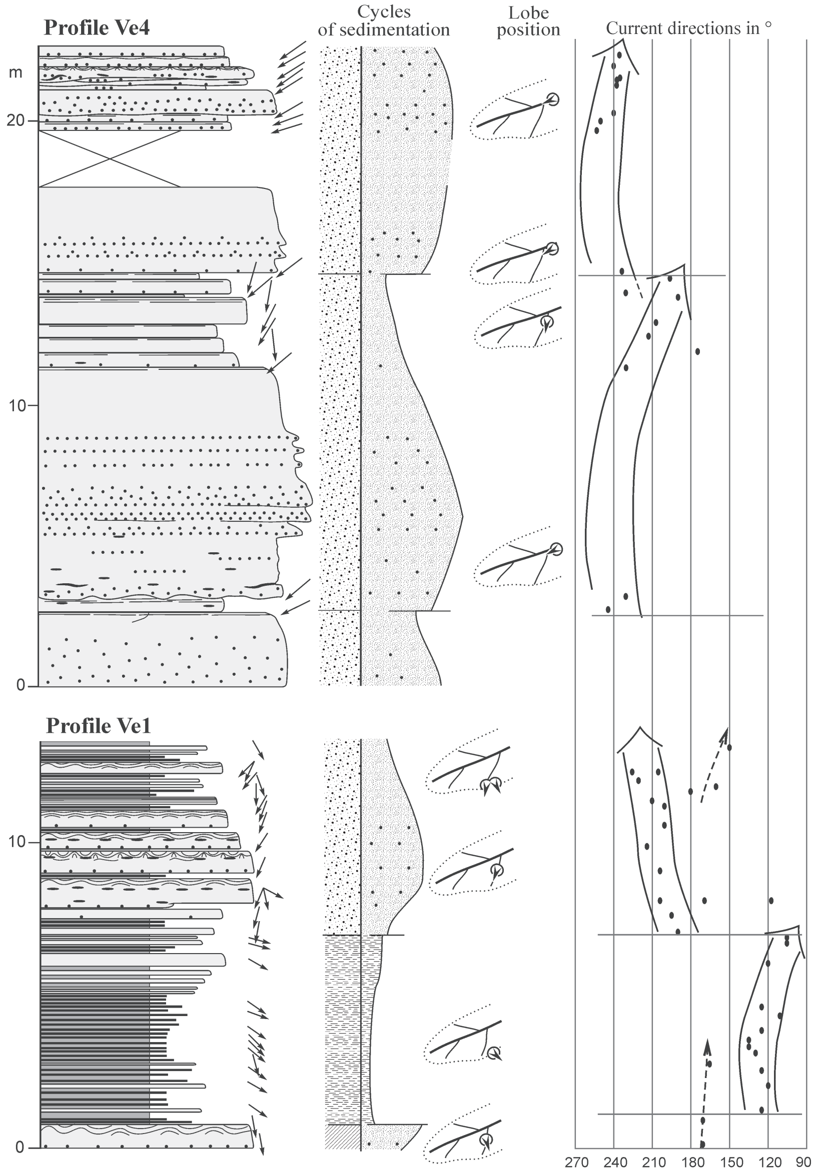


Fig. 3. Sections Ve4 and Ve1 are situated north of Oravská Jasenica village. Alternation of the horizons of the channel origin massive coarse-grained sandstones (Ve4) and interchannel thinner bedded flysch facies (Ve1) represents the switching and migration of the lobes in these sections. There are frequent alternations of the current directions between interchannel thin-bedded flysch and channel sandstones. Explanations see in Fig. 2.

nally sedimented when the current movement obtained the laminar/turbulent hydrodynamic interface. The thin Tb or Tbc laminated division sedimented by traction from the finer, washy and turbulent tail of flow (compare with the interpretation of the turbidity and laminar flow character of gravity flow in Fig. 4).

Sediments of the gravity currents form the fans with the system of lobes and channels. Reading & Richards (1994) worked out a classification of the deep-water fans acceptable for the Magura sandstone. This classification is based on the granular composition of the supplied material and on the number of its sources. On the other hand in Shanmugam's opinion (1997), debris flows, unlike the turbidites, do not form organized systems. Debris flows form only isolated bodies, which could be channelized or non-channelized. However, a significantly organized development of the gravity current sedimentation was observed in the Magura sandstone type in the Orava region (Marschalko & Potfaj 1982 and this paper). Packages of thick sandstone beds were arranged into cycles. Especially thicker beds originated from the debris flows. The debris flow products were usually overlaid by thinner and finer-grained turbiditic sequences. These sediments were deposited from the turbulent tail (cloud) behind the debris flow as a result of deposition from one gravity flow (Fig. 4).

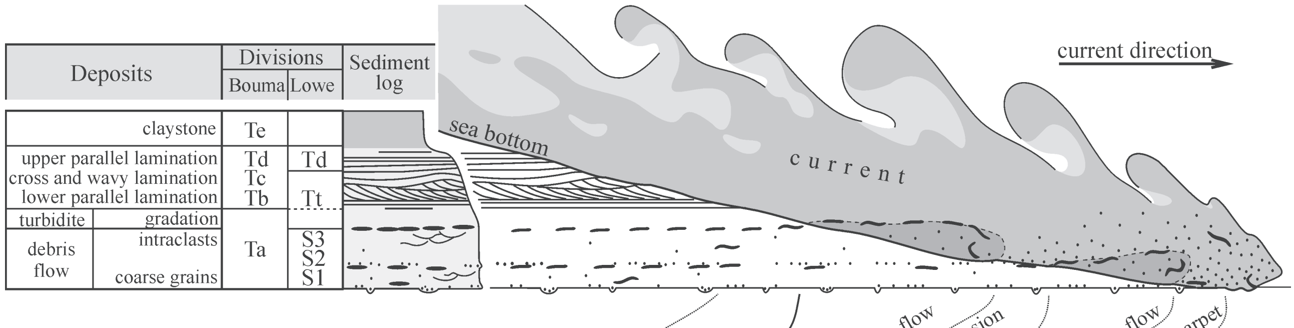
Conclusion

The illustrative model of the Magura Basin (Fig. 5 and Fig. 6) displays the deposition of the Magura sandstone type deep-water fan in the Middle Eocene in its midwest part within the Vsetín and Babia hora Mt. It is possible to interpret cyclic progress of the deep-water fan sedimentation from the sedimentary structures in many profiles. Their study is based on facies analyses. The final confrontation of the sedimentary cycles and structures with the paleocurrent directions gives rise to interpretation of the gravity flow fan dynamics. This enables us to reconstruct the migration of lobes in space and time.

The central part of the lobe was not necessarily channelized. The denser core of the current flowed mostly in the wide axial zone of the lobe. The current branches out from the lobe axis and flows over levees. Pickering et al. (1995) set the model of the recent and ancient turbidity systems architecture.

The thicker packets of the sandstone beds create mostly regularly developed cycles of sedimentation. Not much attention was paid to the gravity flow directions and their alternation in the upward thinning and upward thickening cycles. The gradual current direction changes seem to have evolved by the lateral migration of lobes. It is usually possible to interpret the approach, retreat, sudden birth and dying out of the lobe. We can also recognize whether the studied outcrop was deposited in the middle, left or right side of the lobe or fan. For example, three studied outcrops (Figs. 2 and 3) deposited on the left side and in the middle length of the fan (lobe).

We can recognize lobe position within the fan. This fan consists of several lobes at the same time. The lobe branches out into branches with a radial current pattern. They laterally change position by meandering lobe in the upper and middle



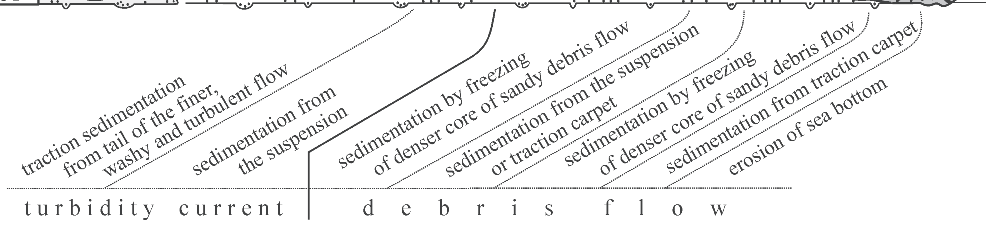
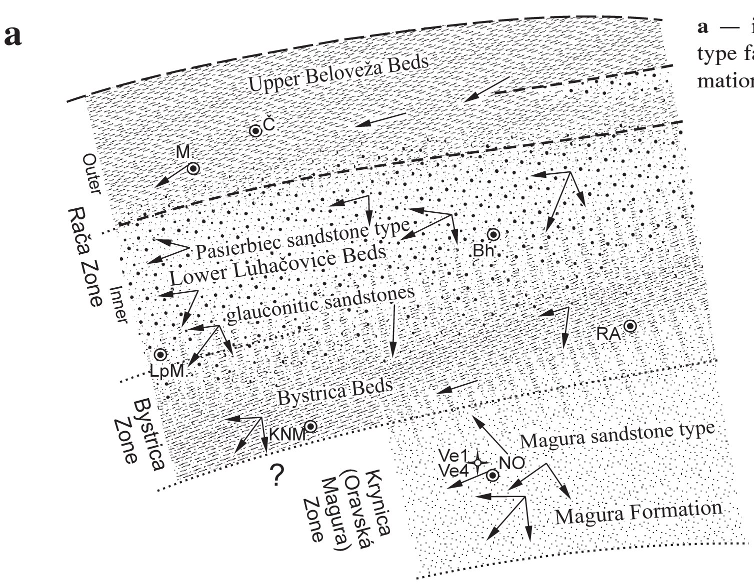


Fig. 4. The model of conversion from the debris flow to turbulent and/or laminar current was based on the sedimentary structures and process of their sedimentation. Interpretation of the debris flow and turbidite character of current was based on their reology and process of movement (Bouma 1962; Lowe 1982; Shanmugam 1997, 2000). This figure displays two sandy debris flow cores (grey) surrounded by the turbulent flow.

a



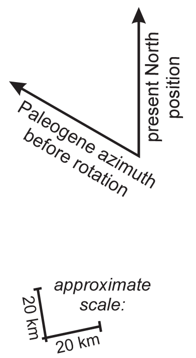
a — interfingering of the Pasierbiec and Magura sandstone type fans (Lower Luhačovice and Bystrica Beds/Magura Formation, **Middle Eocene**).

Range of the deep-water sedimentary fans:
- Pasierbiec sandstone type
- glauconitic sandstone type
- Magura (Kýčera) sandstone type
- marginal (wedging) part of the fan
- distal and basin facies (thin-bedded flysch)
- prevailing paleocurrent directions
- probable activity of synsedimentary faults

Reference points:
Č — Čadca, M — Makov,
LpM — Lysá pod Makytou,
KNM — Kysucké Nové Mesto,
NO — Námestovo, RA — Rabka,
Bh — Babia hora Mt
localization of the sections Ve1, Ve4, Ve5

b

b — interfingering of the glauconitic and Magura sandstone type fans (Zlín Formation, **Middle–Late Eocene**).



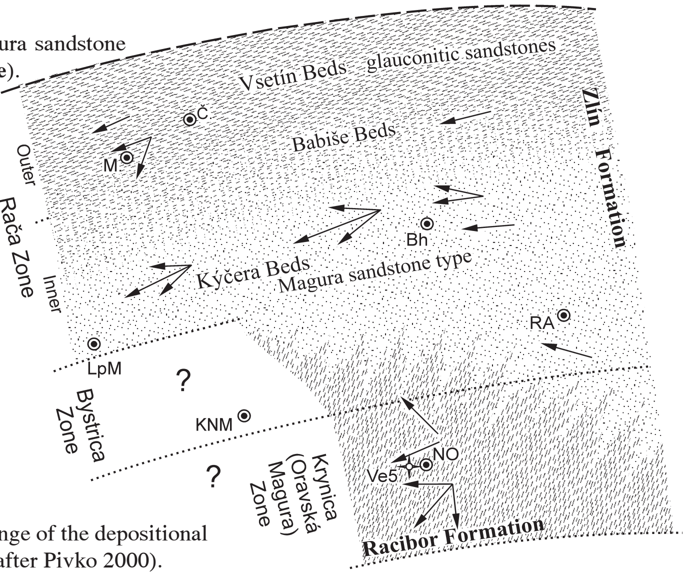


Fig. 5a,b. Palinspastic scheme of the distribution and range of the depositional fans in the western part of the Magura Basin (modified after Pivko 2000).

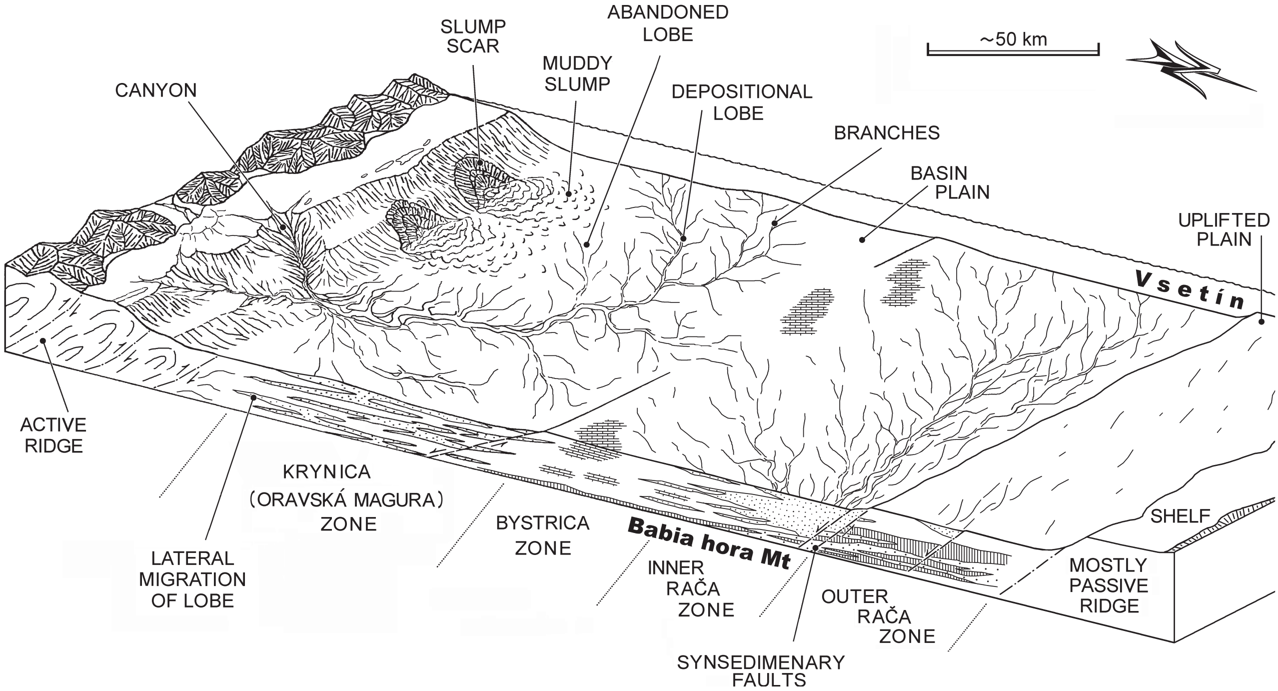


Fig. 6. Simplified model of the mud/sand-rich point-source submarine fan. This model displays the deposition of the Magura sandstone type in the context of the Middle Eocene paleogeography of the Magura Basin in its midwestern part within the Vsetín and Babia hora Mt. The Magura sandstone type deposited in the Oravská Magura Zone. The Magura sandstone type fan sharply turns to the west into the basin axis direction and branches out after inflow of the feed canyon into the basin from the S. Only the distal part of the Pasierbiec sandstone type fan reached the Bystrica Zone. The fan is situated in the Inner Rača Zone. It was separated by synsedimentary fault from the Outer Rača Zone uplifted plain (Beloveža Formation; Teťák 2008). The lobes migrate over the fan (based on the Książkiewicz 1966 and Teťák 2008).

fan and the lobe expires (dies out) when the supply of material terminates (chokes) from the deposit logs of the Magura sandstone type. These characteristic sedimentary features enable us to correlate flysch sequences more precisely and to restore evolution of the lobe system of the fan.

The shape of fans was also affected by depositional pressure of the adjacent fan. An example can be the contact of Kýčera and the glauconitic sandstone fans. The alternation of two types of sandstones can be demonstrated by the Zlín Formation evolution in the central zone of the Rača Subunit (Čertovy kameny and Luhačovice Anticlinal Zones, Babiše Beds; Teťák 2008). The Kýčera and the glauconitic sandstones distributional systems were built by fans with few point-sources. These fans coexisted simultaneously side by side in the Middle to Late Eocene (Zlín Formation, Fig. 5; compare Stráník 1965 from Eastern Slovakia). Their paleocurrent systems were similar from the NE to SW in the Javorníky Mts. Both fan systems interfingered. The northern margin of the glauconitic sandstone fan, from which Luhačovice Formation deposited, was significantly limited by the synsedimentary fault.

Knowledge of the relations of current direction alternation, sedimentation cycles and sedimentological structures to channel migration has plenty of uses in basin analyses and prediction of the stratigraphic traps of hydrocarbons.

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