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Verification of gravity-flow models: case study from the Lower Eocene sediments (Tylmanowa site, SE Poland)

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Abstract. The thick-bedded, deep-water sandstone succession was described at the Tylmanowa site from the Polish Outer Carpathians. This part of the Carpathians is built mainly of the Upper Jurassic to Paleogene deep-water rocks. Succession at the Tylmanowa site is composed of massive, ripple-cross laminated, planar and trough cross-stratified, horizontally laminated and deformed sandstones as well as massive and horizontally laminated mudstones. All these sediments derived from gravity flows that prograde downslope from a basin margin towards the widespread abyssal plain. Exposed succession records the gradual transition from a decelerating debris flow to a turbidity current what is extraordinary in the recent investigations of deep-water sediments. The study succession has been compared with the widely known sediment models, such as: the classic Bouma Sequence (Bouma 1962), the high-density turbidite model (Lowe 1982), the fluxoturbidite model (Ślączka, Thompson 1981) and the hybrid event bed model (Haughton *et al.* 2009).

Keywords: *fluxoturbidites; hybrid event beds; sediment-gravity flow; Eocene; Carpatian Flysh Belt*

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INTRODUCTION

Sediment gravity flows can easily travel through the continental slope and reach the abyssal plain. They are responsible for delivering sediment to a deep-water environment (e.g. Stow *et al.* 1996; Mulder, Alexander 2001; Davis *et al.* 2009). Sediments can move as slides that represent a coherent, translational transport, where sediment mass moves on a planar shear-surface without internal deformation. Further downslope, slides can transform into slumps, where a coherent but rotational transport mode causes deformation. The shear surface is shaped concave-up. As sediments become water-saturated, slumped sediment can transform into a cohesive debris flow. It transports sediments as an incoherent body that flows laminar and undergoes internal deformations (Shanmugam 2006). Debris flows behave as plastic flows and their transformation from cohesive to poorly cohesive or non-cohesive flow is continuous (Talling *et al.* 2012). Further increase in fluid content can lead to the evolution into a turbidity current that moves as an oversaturated turbulent flow (e.g. Piper *et al.* 1999; Shanmugam 2006). First, a high-density turbidity current appears, which then gradually evolves into a low-density turbidity current. The larger the transport distance, the greater the disintegration of transported sediment. The well-known models of deep-water sediment gravity flows assume only one main mode responsible for their transport, e.g. sediment concentration (Bagnold 1962), sediment-support mechanism (Middleton and Hampton 1973), flow state (Sanders 1965; Postma 1986) or rheology (Dott 1963). Each of the above-mentioned flows has different characteristics of movement and settlement, which is reflected in their deposits (e.g. Middleton, Hampton 1976). However, flows-transformation processes are not yet thoroughly researched.

The only one sedimentary record of rheologically complex flows are fluxoturbidites (Dżułyński *et* *al.* 1959), also known as the high-density turbidites (Lowe 1982), megaturbidites (Bouma 1987; Labaume *et al.* 1987), deep-water massive sands (Stow, Johansson 2000) or hybrid event beds (Haughton *et al.* 2009). The term fluxoturbidite (Dżułyński *et al.* 1959) was originally used to describe the thick gravelly, sandy and muddy succession with weakly developed textural grading and numerous massive beds or ripple cross-laminated beds. The mechanism that led to the fluxoturbidite deposition is interpreted as intermediate between deep-water landslides and turbidity currents (see e.g. Unrug 1963; Ślączka, Thompson 1981; Leszczyński 1989). Therefore, the fluxoturbidites as deposited on the proximal parts of submarine fans are rather coarse-grained in contrast to the classic turbidites (see Bouma 1962).

The objective of this paper focuses on a detailed characteristic of the thick-bedded sandstones of the fluxoturbidite succession exposed at the Tylmanowa site. Most of the Outer Carpathians deposits are interpreted as classic turbidites, whereas only about 15% are considered fluxoturbidites (Felix *et al.* 2009). The aim of the study is: (1) to characterize lithofacies at the Tylmanowa site, (2) to identify the main sedimentary processes responsible for sediment transport and deposition, (3) to comprise study succession with the existing models of deep-water gravity flows, and (4) to reinterpret previously done studies at the Tylmanowa site.

GEOLOGICAL SETTING

The Tylmanowa site is located in the Lower Eocene Piwniczna Sandstone Member (Magura Formation) in the Outer Carpathians (Carpathian's Flysch) (Fig. 1). The Carpathian Flysch contains the Upper Jurassic to Paleogene detrital, sedimentary rocks which were deposited in a deep-water environment and were folded during the Neogene.

The Piwniczna Sandstone Member, deposited from the Lower to Upper Eocene, consists of the thick-bedded, muscovite-rich, medium and coarse-grained sandstones with the intercalations of non-calcareous mudstones and intercalations of pebbly mudstones (Oszczypko *et al.* 2005). The Piwniczna Sandstone Member deposits are usually massive, but graded bedding is observed at the bottom part of individual beds, and horizontal lamination or ripple cross-lamination – at the uppermost part (Birkenmajer, Oszczypko 1989). Amalgamation surfaces are common among the thick sandstone beds; however, the sharp lower boundaries occur commonly in sandstones (Birkenmajer, Oszczypko 1989). Soft-sediment clasts, load structures and deformation structures that are commonly found at the Tylmanowa site typically occurred in submarine landslides (e.g. Barnes, Lewis 1991; Stow, Johansson 2000; Shanmugam 2017). The lower boundary of the entire Piwniczna Sandstone Member is gradual, while the upper contact is

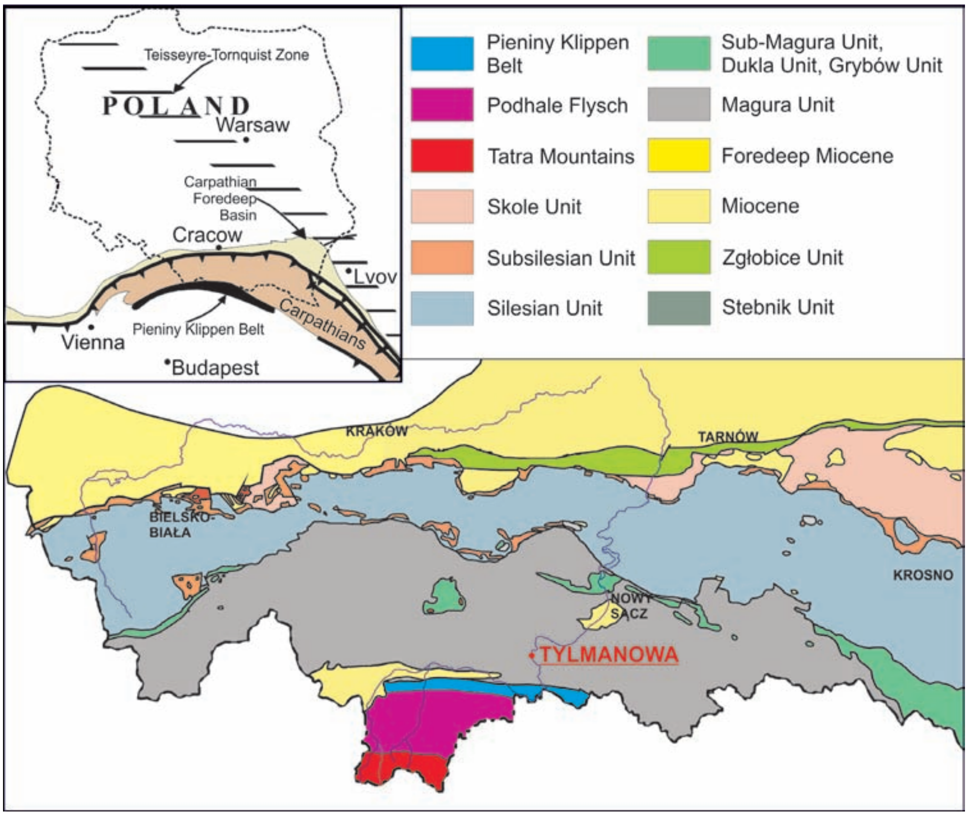
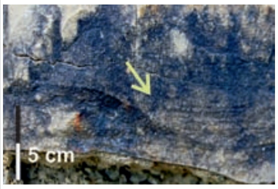
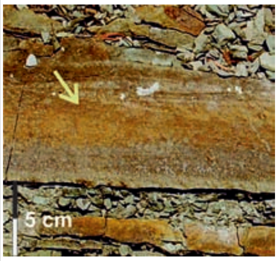
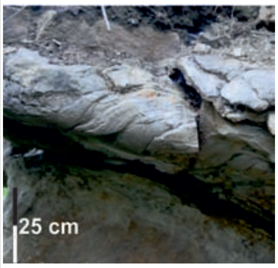
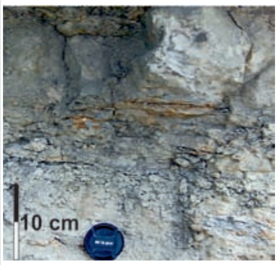


Fig. 1 Localization of the study site in the Magura Unit (Polish Outer Carpathians). Modified after Porębski and Dziadzio (2002)

marked by the occurrence of variegated shale (see Ostrowiecka 1979). Up to now, the Piwniczna Sandstone Member is interpreted in terms of the middle submarine fan deposits. It is assumed that they are a product of a deep-water turbidity current deposited within the distributary channels and lobes (Oszczypko, Porębski 1985, 1986).

Table 1 Main features and interpretation of lithofacies from the Tylmanowa site

Lithofacies code	Description	Photography	Fraction	Grading	Thickness [m]	Interpretation	Equivalent lithofacies
Sm	Massive sandstones with amalgamation surfaces and load structures		sand (f, m, c)	ungraded	0.15–4.00	• poorly cohesive debris flow • non-cohesive debris flow • grain flow	• Ta (Bouma 1962) • F2 or F5 (Ślączka, Thompson 1981) • S3 (Lowe 1982) • F8 (Mutti 1992) • H1 (Haughton et al. 2009)
	Sandstones with graded bedding		sand (f, m, c)	normal	0.13–2.00		
	Sandstones with water-escape structures		sand (vf, f, m)	ungraded	0.15–1.60		
Sr	Sandstones with ripple cross-lamination		sand (vf, f)	ungraded normal	cm scale	• traction • bed load, lower flow regime • a certain phase of a low-density turbidity current	• Tc (Bouma 1962) • T0-T2 (Stow, Shanmugam 1980) • F9 (Mutti 1992) • H4 (Haughton et al. 2009)
Sp, St	Sandstones with planar and trough cross-stratification		sand (f,m)	ungraded normal	>1.00	• low-density turbidity current under channel flow conditions	• S1 (Lowe 1982)
Sh	Sandstones with horizontal lamination		sand (f)	no obvious grain size differences	0.13–0.69	• plane bed, upper flow regime • high-density turbidity current, transition phase from high to low sedimentation rate	• Tb (Bouma 1962) • F9 (Mutti 1992) • H4 (Haughton et al. 2009)
Sd	Deformed sandstones		sand to mud	ungraded normal inverse	~1.50	• catastrophic event • lateral failure of semi-consolidated sediments	
Fm	Massive mudstones		mud	ungraded normal	0.01–1.20	• low energy deposition • deposition from suspension • mud flocs deposition	• Te (Bouma 1962) • TE2 (Piper 1978) • F9 (Mutti 1992) • H5 (Haughton et al. 2009)

METHODS

Fifty metres of the Lower Eocene Piwniczna Sandstone Member exposed at the Tylmanowa site were described in details. This includes textural (grain size and grading), structural and deformational features, as well as bed thickness and lateral extent, type of boundaries, and inclination of sedimentary structures. Furthermore, the vertical arrangement of sediments was described. The deposits types (lithofacies) have been labelled using Zieliński and Pisarska-Jamroży (2012) code (Table 1). A twofold division of deposits was used, with the distinction of lithofacies and lithofacies associations. The term "lithofacies" corresponds to the general structural and textural features within individual lithological beds that were formed under the same depositional conditions, whereas the term "lithofacies association" means a set of genetically related lithofacies that is a product of the deposition in a specific sedimentary environment. The general purpose of using the lithofacies analysis is to reconstruct the origin of sedimentary formation and to create its descriptive-genetic sedimentary model.

SEDIMENTARY SUCCESSION

Eight different lithofacies (Table 1) and three lithofacies associations (Table 2) were recognized at the Tylmanowa site. A detailed description of the sedimentary succession exposed at the Tylmanowa site (Fig. 2) is made below.

Lithofacies association of massive sandstones

Description

The first lithofacies association contains mostly (78%) massive sandstones (Sm), and the remaining seven lithofacies (Sd, Sr, Sh, Sp, St, Fm, Fh) constitute 22%. This is the reason why the lithofacies association is monofacial. This lithofacies association occurs three times within exposed succession: A member at the bottom- (2 m thick), B member in the middle- (15 m thick) and C member at the top part (20 m thick) of the succession at the Tylmanowa site (Fig. 3).

The massive sandstone is composed of fine-, medium- and coarse-grained sandstone and has normal grading with coarse-grained sandstone at the base. Its boundaries are generally planar and sharp, whereas erosional lower boundaries are less common. Ripple cross-laminated sandstone (Sr) is composed of very fine- to fine-grained sandstone, and horizontally laminated sandstone (Sh) of fine-grained sandstone. Their boundaries are usually gradational, rarely sharp and planar. The planar cross-stratified (Sp) and trough cross-stratified (St) sandstones are made of a medium sandstone and form rhythm (Sp→St). The boundaries of lithofacies Sp and St are sharp; erosional basal surfaces occur in trough cross-stratified lithofacies (St). Deformed sandstones (Sd) are dominated by fine-grained sandstone and subordinately by mudstone. The bottom boundaries of lithofacies Sd are erosional, while the upper are planar. The lithofacies Sd occur as a set of beds (approx. 1.5 m thick), and a separate bed has gradational or erosional boundaries, always poorly marked.

The thinning of beds and fining of grain size upwards prevails at the A member and at the uppermost part of the C member (see Fig. 2). The thickening of beds and coarsening of grain size upwards occurs only at the lower part of the C member (see Fig. 2). Furthermore, one sedimentary sequence of the Bouma's type Sm→Sh→Sr and rhythm Sr→Sh with a slight thickness from 0.5 to 0.2 m were noted.

Interpretation

The lithofacies association of massive sandstones is interpreted to be deposited from a poorly cohesive or from a non-cohesive debris flow (see Talling 2013). Massive thick-bedded sandstones with normal gradation and coarse grains at the base indicate a rapid deposition from the gravity mass flows. A high concentration of sediment in the mass flow inhibits the development of turbulence and thus suppresses grain segregation (see Lowe 1976). The entire sedimentary record of massive sandstones at the Tylmanowa site may be considered a result of the deceleration of a grain flow or a low-cohesive (poorly cohesive) debris flow that leads at first to the settling of coarsest grains (i.e. coarse sand) and afterwards provides an evidence of a transition from a debris flow to a turbidity current (Talling *et al*. 2004). However, it is worth emphasizing that turbidity currents can also form massive and even ungraded sand deposits (Kneller, Branney 1995;

Table 2 Main features and interpretation of lithofacies associations from the Tylmanowa site

Lithofacies association		Dominated lithofacies	Subordinately lithofacies	Thickness	Interpretation
I	Massive sandstones	Sm	Sr, Sp, St, Sd, Fm, Fh	~15m	channel-fill deposits
II	Sandstones interbedded by mudstones	Sr, Sh	Sm, Fm, Fh	~6m	middle fan channel-margin levees deposits, overbank deposits
III	Mudstones interbedded by sandstones	Fm, Fh	Sh, Sr	~6m	upper fan channel-margin levees deposits

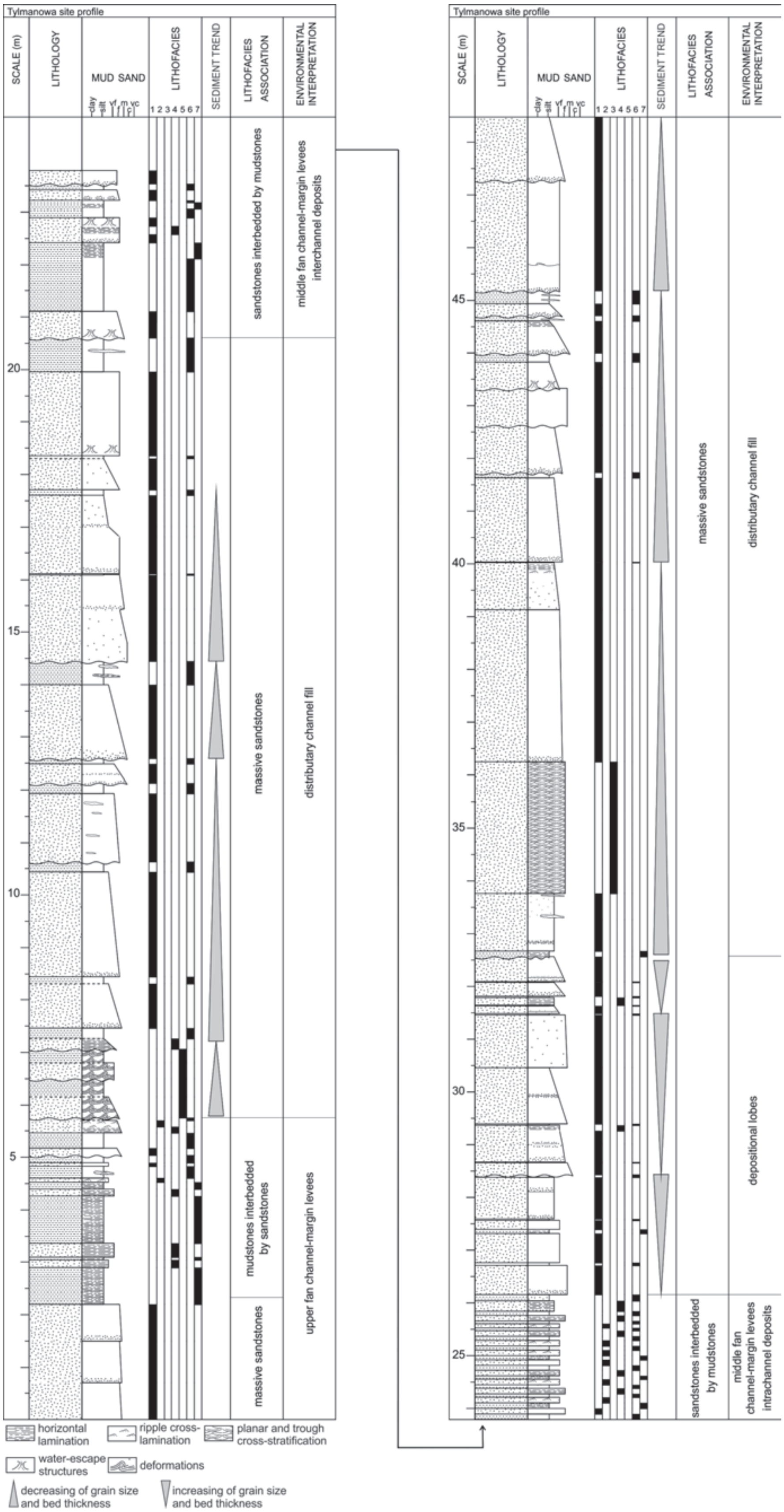


Fig. 2 Profile of the sedimentary succession exposed at the Tylmanowa site. Lithofacies symbols correspond to: 1 – massive sandstones (Sm), 2 – sandstones with ripple cross-lamination (Sr), 3 – sandstones with planar and trough cross-stratification (Sp, St), 4 – sandstones with horizontal lamination (Sh), 5 – deformed sandstones (Sd), 6 – massive mudstones (Fm), 7 – mudstones with horizontal lamination (Fh). Lithofacies code symbols according to Zieliński and Pisarska-Jamroży (2012)

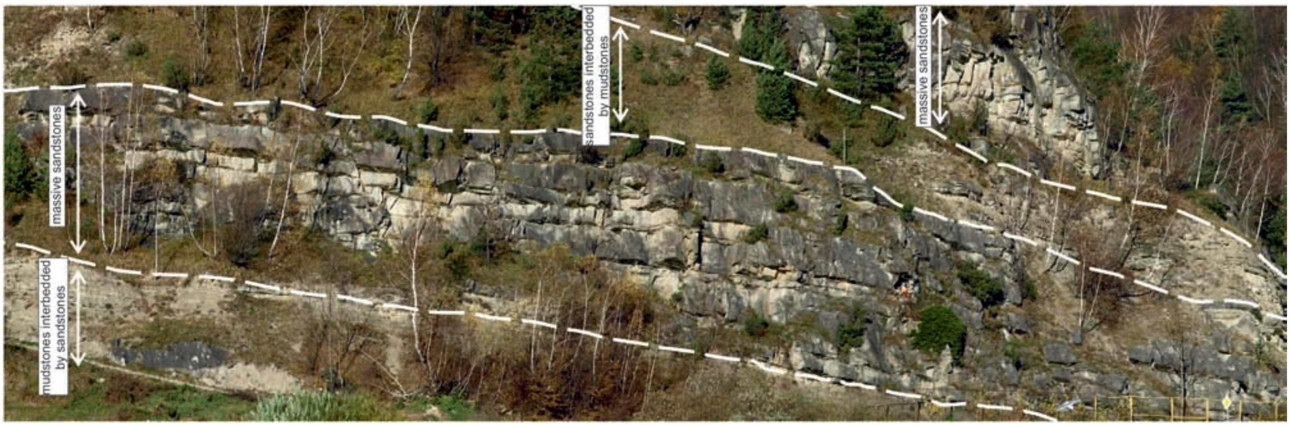


Fig. 3 Sedimentary succession exposed at the Tylmanowa site with vertically arranged lithofacies associations. The boundaries between lithofacies associations are marked with the broken lines

Branney, Kokelaar 2002; Talling *et al.* 2012). Massive sandstones from the Tylmanowa site seem to bear similarity to those from the Marnoso Arenacea Formation, described by Talling *et al.* (2004) and classified as thick, well-sorted sandstones. Such massive deposits are commonly found in the coarse-grained and thick beds in the proximal submarine fan settings (Sadler 1982).

Horizontally laminated sandstones (Sh) are considered to be products of the sandy, low-density but relatively fast turbidity currents (e.g. Lowe 1982; Mutti 1992; Hodgson 2009) that are transitional to the traction currents (Kuenen 1953; Lowe 1982; Ghibaudo 1992; Słomka 1995), which was recorded as a gradual transition from horizontal lamination to cross-lamination; or products of deposition from the suspended clouds that travel over the seabed (see Książkiewicz 1954; Dżułyński, Radomski 1955).

Planar and trough cross-stratified sandstones (Sp and St) are associated with the development of bedforms like submarine dunes (Fig. 4A). The former (i.e. Sp) arises from the migration of straight-crested dunes, whereas the latter (i.e. St) from the migration of sinuous-crested dunes. Such traction structures of a considerable size (few meters) are products of the channel flow conditions, preceding the complete channel filling stage. Cross-stratification formed in the same grain size as ripple-lamination indicates a reduction in the formation time of dunes associated with increased amount of mud (Sumner *et al.* 2012). The adequate amount of mud causes the generation of an internal shear layer that contributes to decreased turbulence (Baas *et al.* 2011).

The origin of ripple cross-laminated sandstone (Sr) is linked to the depositional conditions of the accompanying lithofacies (Fig. 4B). If the ripple cross-laminated of sandstone forms individual beds, then its occurrence is associated with the ripples migration under the lower flow regime and the deposition from the saltation. This phase is characterized by low transport intensity. Ripple cross-laminated lithofacies may be interpreted as deep-water traction structures, testifying the bottom-current reworking process (see Shanmugam *et al.* 1993). On the other hand, when ripple cross-laminated lithofacies occur in the vicinity of underlying horizontally laminated lithofacies, such traction structures are interpreted as a product of the settlement of grains from the suspension of a decelerating turbidity current and then further transport of those grains below the moving flow mass. This results in the loss of the original features of sediments (horizontal lamination) and development of new ones (ripple cross-lamination). In such a situation, the determination of the origin of the deposits that build horizontal or ripple cross-lamination is difficult because they may be a result of a turbidity current or a sediment bed load (see Shanmugam 1997).

Deformed sandstones (Sd) provide an evidence of a catastrophic event that results in a lateral failure of the semi-consolidated sediments due to the disturbed gravity balance on the channel walls (slumped deposits). The initial convolute lamination (Fig. 4C) suggests that the sediment almost reached the threshold of liquidity during the deformation or it was completely liquefied, but the time was insufficient for convolutions to fully develop. Convolute lamination is considered to be the most common type of the soft-sediment deformation structures in the completely developed turbidites (Bouma 1962; Dżułyński, Walton 1965; Allen 1985; Maltman 1994; Dżułyński 2001; Tinterri *et al.* 2016).

Thinning of beds and fining of grain size upwards are a typical feature of the distributary channel-fill deposits in a submarine fan environment. Here, it may reflect the process of a channel progressive backfilling during the lateral migration (e.g. Howell, Normark 1982; Mutti, Normark 1987). Yet, the thinning and fining upwards trend proves the channel abandonment (Posamentier, Walker 2006), whereas the thickening of beds and coarsening of grain size upward

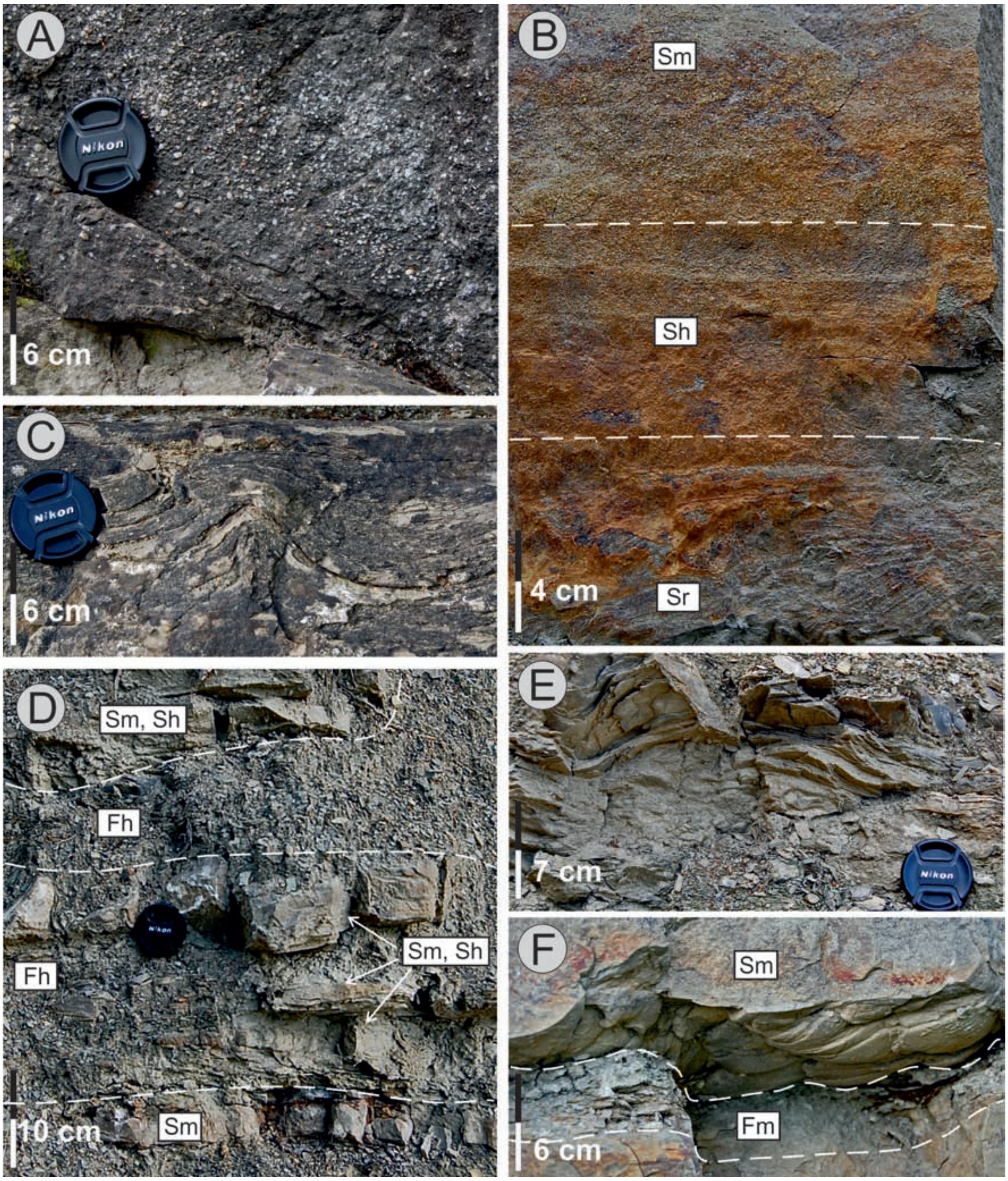


Fig. 4 Sedimentary features of studied deposits. A – A gravelly ripple within sandstones with planar and trough cross-stratification (Sp, St). B – Composed sandstone bed with ripple cross-lamination (Sr), horizontal lamination (Sh) and massive sandstone (Sm). Formation of the composed sandstone beds is associated with the deposition of the inverse turbidite. It is a product of the flow overtaking. Upper, more diluted part of the turbidity current flows, faster and overtakes its lower, more concentrated part, resulting in uncommon vertical arrangement. C – An initial convolute lamination in a fine-graded sandstone. D – Finely horizontally-laminated mudstones (Fh) with the inserts of massive sandstones (Sm) and sandstones with horizontal lamination (Sh). Finely horizontally-laminated mudstones (Fh) display a parting lineation. E – Deformation of massive mudstones (Fm). F – Erosional contact between massive sandstone (Sm) and massive mudstone (Fm)

indicates the progradational stacking pattern of lobe deposits and thus the progradation of the entire fan system. Due to the fact that described lobe succession is superimposed on the channel fill deposits, it can be assumed that the development of depositional lobes proceeded in accordance with the topographical depression. And in turn, its progression was replaced by the formation and filling of the next distributary channel whose sediments lie above. Therefore, the lithofacies association of massive sandstones can be interpreted as deposits of the distributary channel fill that progressively passes into the depositional lobe (Fig. 5). The channel-fill deposits at the Tylmanowa site (Fig. 6) may be interpreted as the stacked channels sequences of a fan channel-lobe complex (see Stow, Johansson 2000).

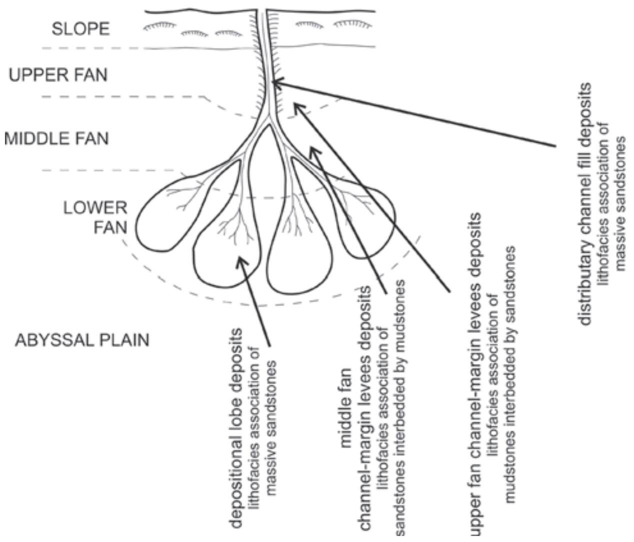


Fig. 5 Depositional model of the submarine point source fan with marked zones of the deposition of lithofacies associations, distinguished at the Tylmanowa site

Lithofacies association of sandstones interbedded by mudstones

Description

The second lithofacies association is composed mainly (65%) of massive sandstone (Sm), horizontally laminated sandstone (Sh) and ripple cross-laminated sandstone (Sr); additionally (35%) massive mudstone (Fm) and horizontally laminated mudstone (Fh). The lithofacies association is 6 m thick. The thicknesses of the sandstone and mudstone lithofacies vary from 0.1 to 0.5 m. Sandstones prevail in the whole association, especially at the upper part (mudstone:sandstone ratio reaches 1:2). The fine- and very fine-grained sandstones show ripple cross-lamination (Sr) and horizontal lamination (Sh) which forms thin, sheet-like beds with thicknesses ranging from 0.2 m to 0.5 m. The thickness of the horizontally laminated sandstones (Sh) decreases towards the top. Less common in the

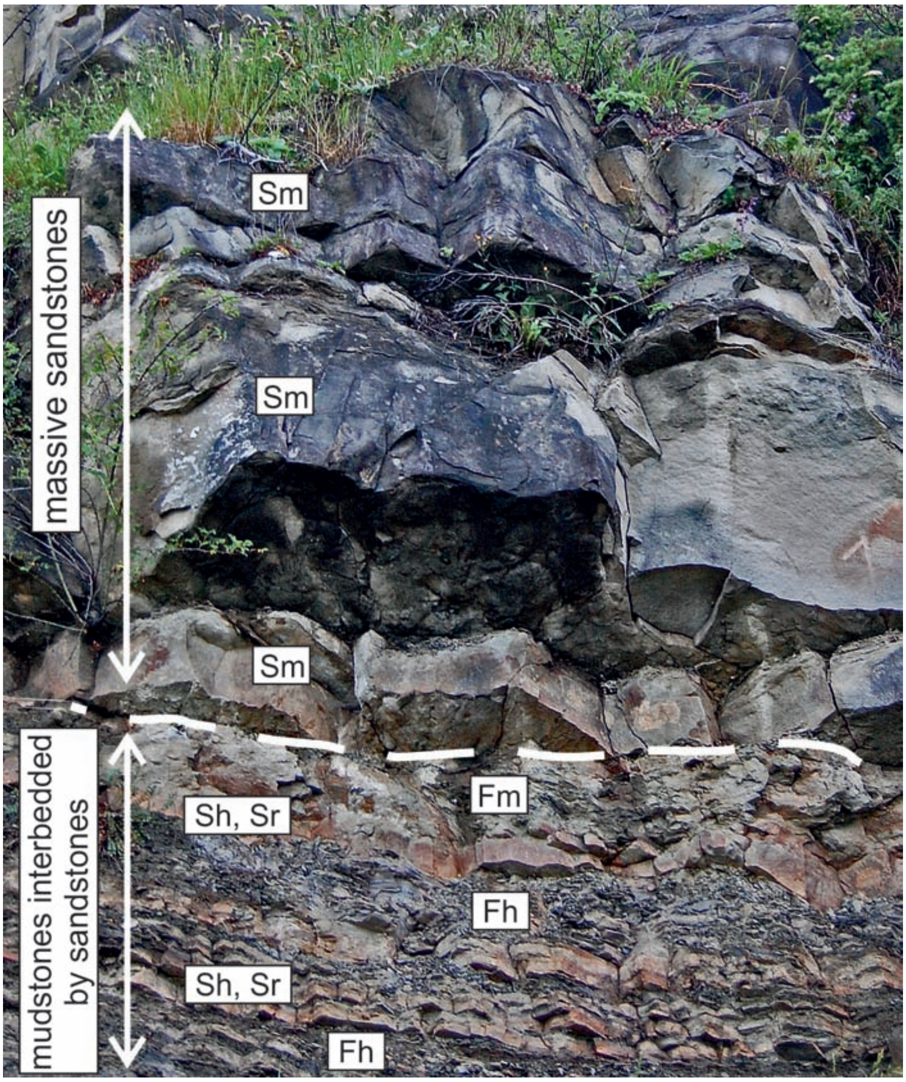


Fig. 6 Lithofacies association of mudstones interbedded by sandstones (channel-fill deposits) and overlaid lithofacies association of massive sandstones (channel-levee deposits). The boundary between lithofacies associations are marked with dashed lines

lithofacies association is the graded bedding which occurs only within the lowermost part of sandstone beds, while in the remaining part of individual beds, graded bedding does not occur. Water-escape structures occur rarely and are poorly developed. Mudstones are represented by massive (Fm = 36%) and faintly horizontally laminated (Fh = 15%) sediments. Their thicknesses vary from 0.1 to 0.8 m. Massive mudstone (Fm) sometimes displays a nodular appearance. The base surfaces of mudstone beds are planar and well marked. The upper boundaries are usually sharp and contain numerous load casts of overlying sandstones. Mudstones can contain chaotically arranged oversized grains or discontinuous sandstone inserts. Locally, massive mudstones occur as angular, soft-sediment clasts, the size of which does not exceed dozen centimetres. Horizontally laminated mudstones (Fh) are poorly marked (Fig. 4D). Their thickness is small, ranging from a few to a dozen or so centimetres. The boundary between massive mudstones (Fm) and overlying horizontally laminated (Fh) ones is usually gradational.

Interpretation

The lithofacies association of sandstones interbedded by mudstones represents classic turbidite deposits, reflecting some divisions of the Bouma Sequence – alternating thin-bedded sandstones with mudstones (c.f. Woźniak, Pisarska-Jamroży 2018). Generally, this association relates to the sedimentation from the decelerating turbidity currents during a gradual abandonment of the distributary channel. This resulted in increased sediment spilling to the interchannel areas.

The interpretation of the ripple cross-laminated sandstones (Sr) and horizontally laminated sandstones (Sh) is the same as presented in the previous subchapter. However, the fine-grained texture of mudstone, its well sorting and lack of the traction structures (Fm) can suggest the deposition from a diluted, low-density turbidity current, followed by the deposition of fine-grained sandstone sediments from suspension. Thus, mudstones were deposited between successive, more sandy flow events (see Bouma 1962). It was found that flocs (mud particles gather into larger aggregates; see e.g. Talling *et al*. 2012) may be transported as bedload and deposited at relatively high flow speeds (up to 15–25 cm/s). The flocs deposition phenomenon may be an explanation of the occurrence of muddy soft-sediment clasts; however, inserts at the lower parts of beds suggest erosion process (e.g. Pisarska-Jamroży, Weckwerth 2013).

Horizontally laminated mudstones (Fh) are identified with pelagic and hemipelagic settling of mud in a deep-water environment (Shanmugam 2006). Slightly marked normal gradation and parting lineation indicate the deposition from a turbidity current. Sequences of horizontally laminated mudstones in the flysch deposits have sometimes been described as ultra-distal turbidites (c.f. Shanmugam 1978; Walker 1978).

This lithofacies association of sandstones interbedded by mudstones was probably deposited in the middle fan setting, such as channel-margin levee or interchannel (overbank; Fig. 5). The process responsible for the formation of submarine levee deposits is called overspill and assumes that flow moves down both within and outside the channel (e.g. Hay 1987a, b; Hiscott *et al.* 1997; Skene *et al.* 2002). Because the uppermost part of a turbidity current commonly exceeds the channel banks, the spillover is a continuous process (Posamentier, Walker 2006). Once the flow crosses the channel boundary, the flow velocity drops quickly, resulting in a rapid deposition. Such a deposition is controlled mainly by the levees morphometry, i.e. the difference in the height of the channel base and levee surface, as well as the velocity and accumulation ratio in the moving flow. According to the downstream flow development, levee deposits along the proximal channels are coarser than those found in the distal locations.

The formation of the overbank deposits at the Tylmanowa site is a response to the spillover process and flow stripping (e.g. Piper, Normark 1983; Migeon *et al.* 2000; Weimer, Slatt 2004; Posamentier, Walker 2006). Flow spillover generally results from the extent of the current beyond the channel zone, as described above, while flow stripping is a process of enhanced spillover assuming the separation of a lower, more dense part of the flow from its upper part. Flow stripping contributes to the levees break, especially on the outer channel bends, where the flow has a relatively high energy. Such flows are enriched in a sandy fraction that settle down rapidly in the interchannel zone. This leads to the development of crevasse splays beyond the channel levees the deposits of which are similar to those of frontal splays, but consist of finer grain size sediments (Posamentier, Kolla 2003). Crevasse or frontal splays sandstone beds thin or pinch out laterally, indicating the sheet-like morphology, same as described at the Tylmanowa site. Yet, sediment grain size decreases along with the bed thickness in a distal direction from the channel zone.

Lithofacies association of mudstones interbedded by sandstones

Description

The third lithofacies association is dominated mainly (70%) by massive (Fm) and finely horizontally laminated mudstones (Fh); additionally (30%), sandstones with horizontal lamination (Sh) and ripple cross-lamination (Sr), as well as massive sandstones

(Sm) are noted. The sandstone:mudstone ratio is 1:2.5. Features of mudstone lithofacies Fm and Fh are similar to those described in the previous subchapter. An additional feature of mudstone occurred in this lithofacies association is local deformations of inserted sandstone (Fig. 4E). Horizontally laminated sandstones (Sh) reach the maximum thickness of 0.26 m. Boundaries of lithofacies are planar and sharp. Ripple cross-laminated sandstones (Sr) with locally occurred climbing structures form lenticular-shaped beds the thicknesses of which do not exceed 0.1 m. The lower boundaries of ripple cross-laminated lithofacies are usually erosional and cutting down into the lower-lying mudstone (Fig. 4F). Moreover, mudstone soft-sediment clasts or weakly developed water-escape structures occur locally in sandstones.

Interpretation

All the lithofacies that are part of the lithofacies association of mudstones interbedded by sandstones have already been interpreted in the previous subchapter; however, this lithofacies association shows a significantly higher content of mudstone lithofacies than in the lithofacies association of sandstones interbedded by mudstones (see this subchapter). A higher content of the muddy fraction may indicate a higher contribution of sedimentation from a residual, extremely diluted turbidity current or a debris flow, but the distinction between vertically graded turbidite mud and ungraded debrite mud is impossible (Talling *et al.* 2012). The occurrence of ripple cross-laminated sandstones (Sr) and horizontally laminated sandstones (Sh) at the Tylmanowa site, show the deposition from traction currents and bedforms formation. This lithofacies association indicates a relatively lower energy of the flow than in the case of the previously mentioned lithofacies association of sandstones interbedded by mudstones (see previous subchapter).

The lithofacies association of mudstones interbedded by sandstones represents channel-margin levee deposits of the upper submarine fan. A high content of mudstone deposits indicates rather outer levee sub-environment and shows the deposition from the upper, more dilute part of a bipartite flow. Thereby, massive sandstones (Sm) that lie under the lithofacies association of mudstones interbedded by sandstones are interpreted as a part of the channel fill deposits associated with the same flow event, but deposited from the bottom, dense part of the flow. The following deposition of fine-grained deposits is probably a record of the termination of the levee activity due to a major shift in a depocentre or a rise in the relative sea level (see Hickson, Lowe 2002). The origin of the channel-margin levee is in compliance with Posamentier and Walker (2006) statement that thin-bedded turbidites in levees deposits containing climbing ripple-lamination or convolute lamination are more common in proximal fan settings. Moreover, the occurrence of the soft-sediment clasts that have not been disintegrated may prove the deposition on the proximal part of a submarine fan, indicating a relatively short distance of the sediment transport. The lithofacies association of mudstones interbedded by sandstones together with the basal massive sandstones (Sm) can be interpreted as channel-margin levee deposits of the upper submarine fan (Fig. 5).

DISCUSSION

Due to the lack of direct monitoring, the designation of the flow behaviour in a deep-water environment and consequent sediment deposition process is not a trivial problem (e.g. Kneller, Buckee 2000; Mulder, Alexander 2001; Talling *et al.* 2004). The understanding of the sediment gravity-flow evolution depends mainly on information inferred from the sedimentary records, laboratory experiments and, recently, on numerical modelling (e.g. Cartigny *et al.* 2013, 2014; Salles *et al.* 2008; Talling *et al.* 2004). The search for an universal model bringing both transport mechanisms and the characteristics of resulting deposits is the reason for the creation of many vertical lithofacies schemes (e.g. Bouma 1962; Kuenen 1964; Mutti, Ricci Lucchi 1972; Shanmugam, Benedict 1978; Stow, Shanmugam 1980; Ślączka, Thompson 1981; Lowe 1982; Walker 1985; Mutti 1992; Haughton *et al.* 2009). A considerable number of the sedimentary models rises a question about their usage. Moreover, different flow processes may result in a creation of similar deposits. From this standpoint, it seems that sediment gravity flows are so complex and little-known processes that they cannot be arranged or categorized by the strict framework of any scheme. The following questions still remain: Which sedimentary model reflects the natural conditions most precisely? Which model should be widely used to make the sediment comparison possible? How to link the observed sediment features formed in a relatively short deposition stage with a much longer flow transport process?

A short comparison with well-known and widely used sediment models were made. This includes: the Bouma Sequence (Bouma 1962), the high-density turbidite model (Lowe 1982), the fluxoturbidite model (Ślączka, Thompson 1981)), and the hybrid event bed model (Haughton *et al.* 2009). This comparison aims to show that a significant number of deep-water sediment models affect the further interpretations and often hamper the direct comparison instead of facilitating it.

Comparison to the Bouma Sequence

Some lithofacies noted at the Tylmanowa site succession may be interpreted as the sections of the Bouma Sequence (Fig. 7). The lithofacies of massive sandstones (Sm) may correspond to the T_a Bouma's division; horizontally laminated sandstones (Sh) to the T_b division; sandstones with ripple cross-lamination (Sr) to the T_c division; horizontally laminated mudstones (Fh) to the T_d division; and massive mudstones (Fm) to the T_e division of the Bouma Sequence. Based on this understanding, the interpretation can be fraught with some discrepancies and ambiguities, as it is showed below.

Massive sandstones (Sm) are usually identified as a low-density turbidity current and the T_a division of the Bouma's Sequence or the F_7 division of the model by Mutti (1992). The origin of massive sandstone deposits has aroused a great controversy among the researchers, which contributed to the creation of the numerous theories (see e.g. Bouma 1962; Stauffer 1967; Walker 1967; Lowe 1976; Lowe 1982; Arnott, Hand 1989; Kneller, Branney 1995; Shanmugam, Moiola 1995; Shanmugam 1996; Sumner *et al.* 2008). Currently, two depositional modes are assumed to form thick, deep-water massive sandstones: 1) a progressive layer-by-layer aggradation from the high-density turbidity currents and 2) *en masse* freezing of debris flows (see Talling *et al.* 2012). The ungraded, massive structure indicates that the flow concentration was sufficient to prevent grain segregation (Amy *et al.* 2005; Dorrell *et al.* 2011) and the deposition rates were high enough to suppress the bedform formation (Leclair, Arnott 2005; Sumner *et al.* 2008, 2012) while a normally graded structure may be formed

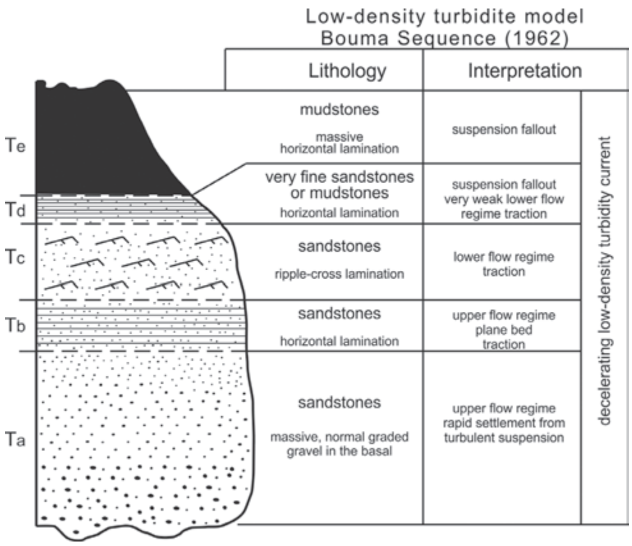


Fig. 7 Sedimentary model of classic turbidites, i.e. the Bouma Sequence with the main sedimentary features and interpretation of the depositional mechanisms (modified after Bouma 1962)

due to a fast fallout from the turbulent suspension of a high-density turbidity current (Lowe 1982). The sharp grain-size breaks, occurring especially between massive sandstones and overlying mudstones, may correspond to the boundary between a poorly cohesive debris flow and a trailing weak turbidity current (see Talling 2013), whereas the intralayer grain-size breaks, strictly associated with coarse fraction and related to coarse-tail normal grading, indicate settling during the terminal stage of the flow (see Marr *et al.* 2002).

Horizontally laminated sandstones (Sh) are usually characterised as the T_b division of the Bouma Sequence. It was long thought that this structure is attributed to the deposition from the low-density turbidity currents (e.g. Lowe 1982; Mutti 1992) and thus the low sedimentation rates (Best, Bridge 1992). However, recently it is known that horizontal lamination can be formed at the lowest part of a highly concentrated flow and hence results from the high-density turbidity currents (Leclair, Arnott 2005). Contrary to Lowe (1982), horizontal lamination may be the most abundant sandy lithofacies in the basin plain settings (Sumner *et al.* 2012). Generally, it arises due to the activity of a diluted turbidity current and traction processes (Kuenen 1953).

Sandstones with ripple cross-lamination (Sr) are considered to display the T_c division of the Bouma Sequence and traction processes under the lower flow regime. Its formation may be associated with the turbidity currents (Sanders 1963, 1965; Shanmugam 1997), bottom current reworking (Shanmugam *et al.* 1993) or sediment bed-load (Shanmugam 1997). Dune-scale cross-stratification (i.e. planar and trough cross-stratification; Sp and St, respectively) is an uncommon structure within the turbidite deposits due to the insufficient time necessary for its formation (Walker 1965) or inadequate sedimentation rates that suppress dune creation (Lowe 1988). However, it has been noted from the numerous turbidite systems (e.g. Kneller, McCaffrey 2003; Sylvester, Lowe 2004; Hodgson 2009). Ripple cross-lamination and dune-scale cross-stratification are an unequivocal evidence of the deposition from a low-density turbidity current (e.g. Baas 1994; Talling *et al.* 2012). This structure corresponds to the S_1 division of the Lowe's model (1982).

Horizontally laminated mudstones (Fh), as well as subordinately, horizontally laminated sandstones (Sh) seem to correspond to the T_d Bouma's division and to the F_9 of the Mutti's division (1992). Yet, it reflects a very weak, lower flow-regime traction process that leads to the formation of the individual laminae. Lowe (1982) interpreted laminated mudstones as a transitional division towards an overlying hemipelagic and pelagic sedimentation.

Massive mudstones (Fm) are the last T_e division of the Bouma Sequence and correspond to the F_9 division of the Mutti's model. These deposits reflect the deposition in a low-energy, hemipelagic or pelagic environment (Lowe 1982; Shanmugam 1997), which is characterized by a calm and continuous settlement from the suspension. Thus, they form also via *en masse* deposition from a diluted, fluid mud layer (Sumner *et al.* 2012).

Despite the 50 m thick succession at the Tylmanowa site displays sedimentary structures commonly associated with the Bouma Sequence, turbidite successions or their incomplete fragments are observed rarely. In fact, each of distinguished lithofacies could be associated to the appropriate part of the Bouma Sequence. However, an orderly vertical manner is generally lacking, and only locally some vertical successions, usually thin and poorly marked, are visible. The first one includes massive sandstone (Sm) overlaid by sandstone with horizontal lamination (Sh) followed by the ripple cross-lamination (Sr). Such a vertical sequence (Sm→Sh→Sr) bears similarity to the T_{abc} Bouma's divisions. Second sequence exhibits sandstone with horizontal lamination (Sh) that gradually passes into more finer sandstone with the ripple cross-lamination (Sr). This sequence (Sh→Sr) corresponds to the T_{bc} Bouma's divisions. Third sequence contains the transition from sandstone with ripple cross-lamination (Sr) to fine-grained sandstone with horizontal lamination (Sh) or horizontally laminated mudstone (Fh), reflecting the T_{cd} divisions (Sr→Sh/Fh). Less commonly, fine-grained sandstone with horizontal lamination (Sh) or horizontally laminated mudstone (Fh) passes into massive mudstone (Fm), displaying the T_{de} divisions (Sh/Fh→Fm). These quoted examples are rare, and no vertical succession of the Bouma's type is fully developed. Thereby, it seems that the individual beds should not be referred to the turbidity current deposition. The following questions arise: When should incomplete fragments of the Bouma succession be called and interpreted as a part of the turbidite beds? Is the adjacent occurrence of only two divisions enough? And, what if there is only one division? Theoretically, considering the gravity flow among its entire movement path, it is obvious that the investigation of its lateral continuity and sediment lateral manner is possible. And then, the single occurrence of an upper division of the Bouma Sequence without any underlying lower Bouma's division is justified. The lateral transitions of the individual sedimentary structures seem to be a promising aim of the future research. Furthermore, is there a minimum thickness of the succession or a minimum number of the vertically arranged sedimentary structures, determining the definition of any sediments as a turbidity bed? And how to explain the occurrence of the upper Bouma's division (e.g. the T_c division corresponding to the ripple cross-laminated structure) in the sandstone inserts that stuck within the mudstone deposits? Can the conditions of a single flow be really so varied? Further studies on the relationship between the nature of an individual gravity flow and the characters of its deposits are required.

Comparison to the Lowe's model

The division of the Lowe's model (Fig. 8) of the high-density turbidites into a high-density (S divisions) and low-density (T divisions) interval can be referred to the succession studied at the Tylmanowa site. The lower part of the Tylmanowa site succession (first 25 m of the succession; see Fig. 2), including the lithofacies association of mudstones interbedded by sandstones, followed by the lithofacies association of massive sandstones and lithofacies association of sandstones interbedded by mudstones, can be interpreted as the sedimentary record of the relatively low-density turbidity currents. It is testified by a relatively high mud content. In contrary, the upper part of the succession (from the height of 26 m to the end of the succession; see Fig. 2) indicates the deposition from the high-density turbidity currents. Especially, the large traction structures occurring in the uppermost lithofacies association of massive sandstones correspond to the S_1 division of the Lowe's model. Such structures are considered to be characteristic of the thick-bedded, deep-water sandstones of a proximal fan setting (Mutti, Ricci Lucchi 1972; Middleton, Hampton 1976; Walker 1978). According to the Lowe's model, the large traction structures (S_1 division) should be overlaid by the deposits of a traction

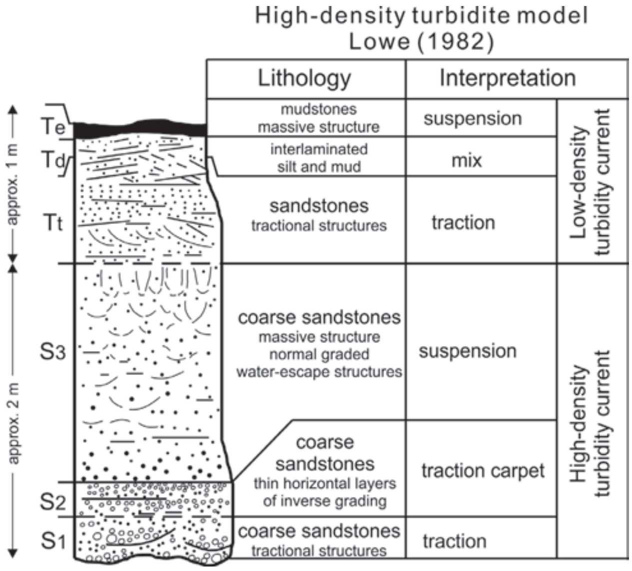


Fig. 8 Sedimentary model of the high-density turbidites with the main sedimentary features and interpretation of the depositional mechanisms (modified after Lowe 1982)

carpet. However, those are not observed at the Tylmanowa site. This can be explained by the fact that whether the deposit consists of a very fine- and fine-grained sediment, the formation of a traction carpet is suppressed due to insufficiently dispersive pressure (Lowe 1982). The uppermost part of the Tylmanowa site succession consisting of a massive sandstone association (from the height of 26 m to the end of the succession; see Fig. 2) may be determined as the S_3 division, due to its significant thickness and massive structure that possess normal grading or water-escape structures. Thus, indicating the deposition from the suspension.

Comparison to the fluxoturbidites model

The fluxoturbidites model (Ślączka, Thompson 1981; Fig. 9) assumes the deposition from a composite sediment gravity flow and therefore includes turbidity currents, grain flows and liquefied sediment flows. Although debris flows are not evidently proved, deposits at the Tylmanowa site seem to be similar to the fluxoturbidites. The lithofacies association of massive sandstones may correspond to the F_2 or F_5 division of the fluxoturbidites model. The first one, F_2 division of the Ślączka and Thompson's model, consists of sandstones with a thin gravel cluster at the bottom and crudely graded towards the top. This division reflects the inhomogeneities of the flow rheology. The second one, F_5 division of the Ślączka and Thompson's model, is composed of the oversized grains dispersed in a sandy matrix and scattered mudstone clasts. It is overlaid by deposits of a low-density current, i.e. T divisions, adapted from the Bouma Sequence. The boundary between the F_5 and T_a divisions is transitional, which can be successfully referred to the deposits at the Tylmanowa site. Moreover, the thickness of the classical fluxoturbidite succession is determined to be about 5 m, but may range up to at least 10 m, while only the uppermost 10–20% displays the Bouma Sequence (Ślączka, Thompson 1981). Therefore, considering a large thickness of the massive sandstone lithofacies association, deposits at the Tylmanowa site may be referred as an example of the fluxoturbidites.

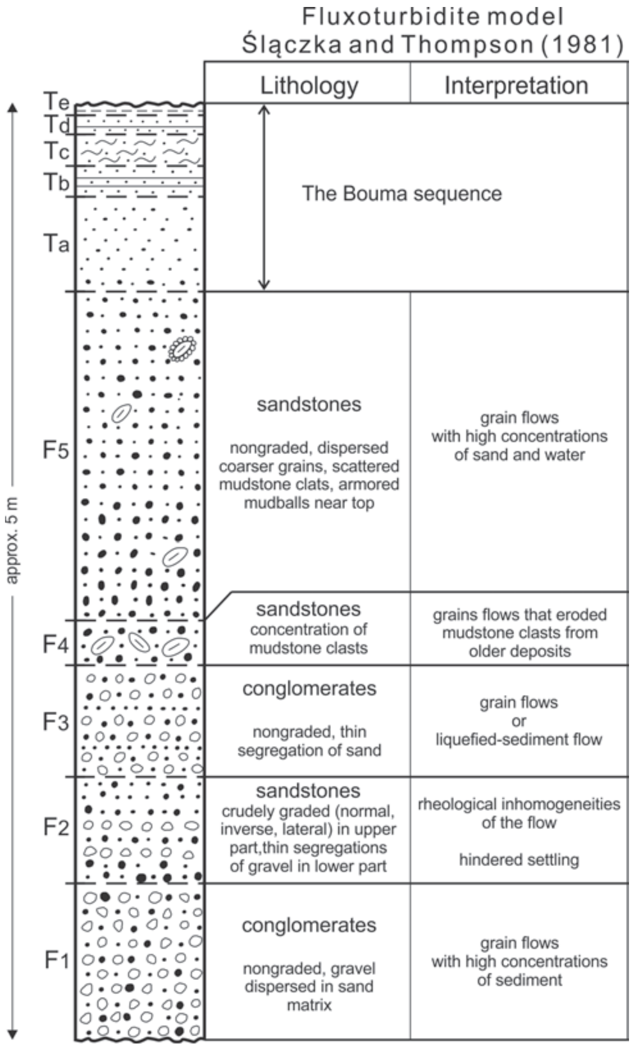


Fig. 9 Sedimentary model of the fluxoturbidites with the main sedimentary features and interpretation of the depositional mechanisms (modified after Ślączka, Thompson 1981)

The fluxoturbidite concept and its origin (Dżułyński *et al.* 1959) based mainly on the deposits defined as the products of the fully mixed flows, where the transformation of a debris flow into a turbidity current is fully developed (*sensu* Felix *et al.* 2009). However, the succession exposed at the Tylmanowa site is interpreted to display a rather different flow-transformation mechanism. These thick-bedded, massive sandstones bear similarity to the debrites overlain by the thin turbidites, resulting from dense debris flows that undergo some transformation towards the turbidity currents (type A flows, *sensu* Felix *et al.* 2009). Thereby, most of the flow remains untransformed and its sedimentary record displays features associated with a bipartite flow. The boundary between the adjacent debrite and turbidite is marked by a sharp grain-size break (see Felix *et al.* 2009). Therefore, fluxoturbidites from the Tylmanowa site are interpreted as the deposits of dense debris flows that display a very initial stage of the transition towards the turbidity currents.

Comparison to the hybrid bed model

The hybrid bed model (Haughton *et al.* 2009; Fig. 10) depicts the sedimentary record of the transition from a non-cohesive to a cohesive flow behaviour, followed by the deposition of variably developed, dilute turbidity current. Deposits at the Tylmanowa site are interpreted to bear similarity mainly to the H_1 division of the hybrid bed model that origins from the

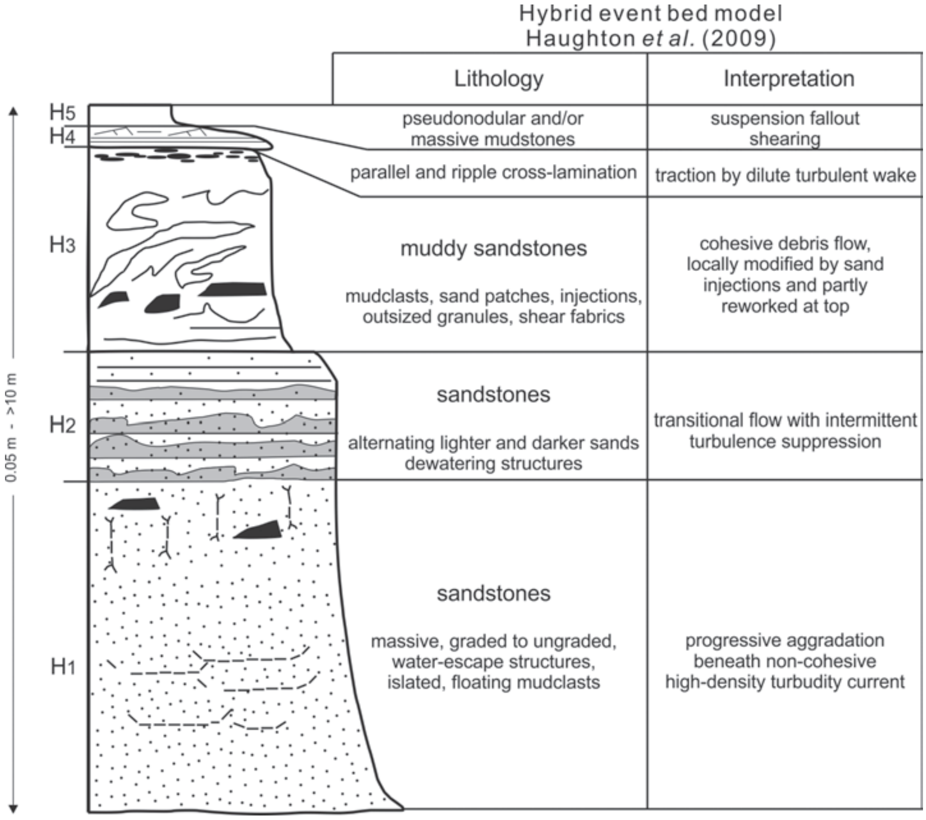


Fig. 10 Sedimentary model of the hybrid event bed with the main sedimentary features and interpretation of the depositional mechanisms (modified after Haughton *et al*. 2009)

progressive aggradation from a non-cohesive, high-density turbidity current. This division consists of a graded or ungraded, massive, well-sorted sandstone with mud clasts at the top. Moreover, the lithofacies of sandstones with horizontal lamination (Sh) and sandstones with ripple cross-lamination (Sr) correspond to the H_4 division of the hybrid bed model formed as a result of the traction of a dilute turbulent flow. At least, massive mudstones (Fm) and mudstones with finely horizontal lamination (Fh) are included in the H_5 division that reflect the suspension fallout process. According to the hybrid bed assumptions, transitional and (cohesive) debris flow deposits occur as the H_2 and H_3 divisions, but the studied succession does not contain it. The increased amount of the mud, particularly at the bottom part of the Tylmanowa site succession (first 25 m of the succession; see Fig. 2), would suggest the deposition from a more complex and rheologically heterogeneous gravity flow compared to the uppermost, sandy part of the succession (from the height of 26 m to the end of the succession; see Fig. 2). Due to a large thickness of the individual sandstone beds, succession exposed at the Tylmanowa site may be interpreted as an example of the debrite-turbidite 'megabeds' or, subordinately, as the turbidites with linked debrites (*sensu* Haughton *et al.* 2009). Finally, it should be strongly emphasized that in the case of the Tylmanowa site succession, the flow transformation seems to originate from a relatively dense debris flow to a more dilute turbidity current. In the light of the flow transformation studies, the precise definition of an individual transformation phase and its parameters, as well as the determination of its direction (i.e. whether debris flows have formed from turbidity currents or debris flows have contributed to the formation of turbidity currents) are necessary. The general classification of flow transformation processes and resulting sediments is challenging at the time.

CONCLUSIONS

The following conclusions can be drawn:

• Eight lithofacies were distinguished at the Tylmanowa site and were interpreted as the products of various sediment gravity flows that prograde downslope from a basin margin towards the widespread abyssal plain. Most of the flows are classified as debris flows or turbidity currents.

• Three lithofacies associations (massive sandstones, sandstones interbedded by mudstones, and mudstones interbedded by sandstones) at the Tylmanowa site represent: (1) the distributary channel fills, (2) the middle fan channel-margin levees, and (3) the upper fan channel-margin levees.

• Deposits of massive sandstones are predominant at the Tylmanowa site succession. They are interpreted to be deposited *en masse* from poorly cohesive and non-cohesive debris flows (*sensu* Lowe 1976).

• Studied deposits were deposited from complex, internally-stratified gravity flows, being a combination of plastic and fluid flow states. Succession at the Tylmanowa site records a certain phase of the gradual transition from a decelerating, dense debris flow to a strongly diluted turbidity current (*sensu* Talling *et al.* 2004), corresponding to an early stage of type A flows (*sensu* Felix *et al.* 2009). The last one seems that the debris flow did not have enough time and space to fully develop and evolve. This can indicate the proximal setting of a submarine fan.

• Succession at the Tylmanowa site bears great similarity to the fluxoturbidite model (*sensu* Ślączka, Thompson 1981) rather than to the high-density turbidity current model (*sensu* Lowe 1982). Moreover, the sedimentary record shares the features of both turbidity current and debris flow deposits, and thereby the interpretation as the hybrid event bed (*sensu* Haughton *et al*. 2009), is desirable.

• The succession at the Tylmanowa site was deposited in the middle and upper part of a proximal submarine fan as the elements of a sandy, perchance mud-sand, channelized, point source submarine fan (*sensu* Reading, Richards 1994).

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REFERENCES

Allen, P.A. 1985. Hummocky cross-stratification is not produced purely under progressive gravity. *Nature 313*, 562–564.

Amy, L.A., Talling, P.J., Peakall, J., Wynn, R.B., Arzola Thynne, R.G. 2005. Bed geometry used to test recognition criteria of turbidites and (sandy) debrites. *Sedimentary Geology 79*, 163–174.

Arnott, R.W.C., Hand, B.M. 1989. Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. *Journal of Sedimentary Research 59 (6)*, 1062–1069.

Baas, J.H. 1994. A flume study on the development and equilibrium morphology of current ripples in fine sand. *Sedimentology 41 (2)*, 185–209.

Baas, J.H., Best, J.H., Peakall, J. 2011. Depositional processes, bedform development and hybrid bed formation in rapidly decelerated cohesive (mud-sand) sediment flows. *Sedimentology 58 (7)*, 1953–1987.

Bagnold, R.A. 1962. Auto-suspension of transported sediment; turbidity currents. *Proceedings of the Royal Society of London 265 (1322)*, 315–319.

Barnes, P.M., Lewis, Y.B. 1991. Sheet slides and rotational failures on a convergent margin: the Kidnappers Slide, New Zealand. *Sedimentology 38 (2)*, 205–221.

Best, J., Bridge, J. 1992. The morphology and dynamics of low amplitude bedwaves upon upper stage plane beds and the preservation of planar laminae. *Sedimentology 39 (5)*, 737–752.

Birkenmajer, K., Oszczypko, N. 1989. Cretaceous and Paleogene lithostratigraphic units of the Magura Nappe, Krynica Subunit, Carpathians. *Annales Societatis Geologorum Poloniae 59*, 145–181.

Bouma, A.H. (ed.) 1962. *Sedimentology of some flysch deposits*. Elsevier, Amsterdam, 168 pp.

Bouma, A.H. 1987. Megaturbidite: An acceptable term? *Geo-Marine Letters 7 (2)*, 63–67.

Branney, M.J., Kokelaar, P. 2002. Pyroclastic density currents and the sedimentation of ignimbrites. *Geological Society Memoir 27*, London, 152 pp.

Cartigny, M.J.B., Eggenhuisen, J.T., Hansen, E.W.M., Postma, G. 2013. Concentration-dependent flow stratification in experimental high-density turbidity currents and their relevance to turbidite facies models. *Journal of Sedimentary Research 83 (12)*, 1047–1065.

Cartigny, M.J.B., Ventra, D., Postma, G., Van Den Berg, J.H. 2014. Morphodynamics and sedimentary structures of bedforms under supercritical-flow conditions: new insights from flume experiments. *Sedimentology 61 (3)*, 712–748.

Davis, C., Haughton, P., McCaffrey, W., Scott, E., Hogg, N., Kitching, D. 2009. Character and distribution of hybrid sediment gravity flow deposits from the outer Forties Fan, Palaeocene Central North Sea, UKCS. *Marine and Petroleum Geology 26 (10)*, 1919–1939.

Dorrell, R.M., Hogg, A.J., Sumner, E.J., Talling, P.J. 2011. The structure of the deposit producted by sedimentation of polydisperse suspensions. *Journal of Geophysical Research 116 (F1)*.

Dżułyński, S. (ed.) 2001. *Atlas of sedimentary structures from the Polish Flysch Carpathians*. Institute of Geological Sciences, Jagiellonian University, Cracow, 132 pp.

Dżułyński, S., Radomski, A. 1955. Pochodzenie śladów wleczenia na tle teorii prądów zawiesinowych. *Acta Geologica Polonica, 5 (1)*, 47–66. [In Polish].

Dżułyński, S., Walton, E.K. (eds.) 1965. *Sedimentary features of flysch and greywackes*. Elsevier, Amsterdam, 274 pp.

Dżułyński, S., Książkiewicz, M., Kuenen, Ph.H. 1959. Turbidities in flysch of the Polish Carpathians. *Bulletin of the Geological Society of America 70*, 1089–1118.

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 (10)*, 2011–2020.

Ghibaudo, G. 1992. Subaqueous sediment gravity flow deposits: particular criteria for their description and classification. *Sedimentology 39 (3)*, 423–454.

Haughton, P., Davis, C., McCaffrey, W., Barker, S. 2009. Hybrid sediment gravity flow deposits - classification, origin and significance. *Marine and Petroleum Geology 26 (10)*, 1900–1918.

Hay, A.E. 1987a. Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia 1. Surge observations. *Journal of Geophysical Research 92 (C3)*, 2875–2881.

Hay, A.E. 1987b. Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia 2. The roles of continuous and surge-type flow. *Journal of Geophysical Research 92 (C3)*, 2883–2900.

Hickson, T.A., Lowe, D.R. 2002. Facies architecture of submarine fan channel-levee complex: the Juniper Ridge Conglomerate, Coalinga, California. *Sedimentology 49 (2)*, 335–362.

Hiscott, R.N., Hall, F.R., Pirmez, C. 1997. Turbidity-current overspill from the Amazon Channel; texture of the silt/sand load, paleoflow from anisotropy of magnetic susceptibility and implications for flow processes. *Proceedings of the Ocean Drilling Program, Scientific Results 155*, 53–78.

Hodgson, D.M. 2009. Distribution and origin of hybrid beds in sand-rich submarine fans of the Tanqua depocentre, Karoo basin, South Africa. *Marine and Petroleum Geology 26 (10)*, 1940–1956.

Howell, D.G., Normark, W.R. 1982. Sedimentology of submarine fans. *American Association of Petroleum Geologists Memoir 31*, 365–404.

Kneller, B.C., Branney, M.J. 1995. Sustained high-density turbidity currents and the deposition of thick massive sands. *Sedimentology 42 (4)*, 607–616.

Kneller, B.C., Buckee, C. 2000. The structure and fluid mechanics of turbidity currents: a review of some recent studies and their geological implications. *Sedimentology 47 (1)*, 62–94.

Kneller, B.C., McCaffrey, W.D. 2003. The interpretation of vertical sequences in turbidite beds: The influence of longitudinal flow structure. *Journal of Sedimentary Research 73 (5)*, 706–713.

Książkiewicz, M. 1954. Uwarstwienie frakcjonalne i laminowane we fliszu karpackim. *Rocznik Polskiego Towarzystwa Geologicznego 22 (4)*, 399–450 [In Polish].

Kuenen, Ph.H. 1953. Significant features of graded bedding. *American Association of Petroleum Geologists Bulletin 37 (6)*, 1044–1066.

Kuenen, P.H. 1964. Deep-sea sands and ancient turbidities. In: Bouma, A.H., Brouwer, A. (eds.). *Turbidities*. Developments in Sedimentology, 3. Elsevier, Amsterdam, 3–33.

Labaume, P., Mutti, E., Seguret, M. 1987. Megaturbidites: A depositional model from the eocene of the SW-Pyrenean Foreland basin, Spain. *Geo-Marine Letters 7 (2)*, 91–101.

Leclair, S.F., Arnott, R.W.C. 2005. Parallel lamination formed by high-density turbidity currents. *Journal of Sedimentary Research 75 (1)*, 1–5.

Leszczyński, S. 1989. Characteristics and origin of fluxoturbidites from the Carpathian flysch (Cretaceous-Palaeogene), South Poland. *Annales Societatis Geologorum Poloniae, 59 (3–4)*, 351–390.

Lowe, D.R. 1976. Grain flows and grain flow deposits. *Journal of Sedimentary. Petrology 46 (1)*, 188–199.

Lowe, D.R. 1982. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology 52 (1)*, 279–297.

Lowe, D.R. 1988. Suspended-load fallout rate as an independent variable in the analysis of current structures. *Sedimentology 35 (5)*, 765–776.

Maar, J.H., Harff, P.A., Shanmugam, G., Parker, G. 2002. Experiments on subaqueous gravity flows: the role of clay and water content in flow dynamics and depositional structures. *Geological Society of America Bulletin 113 (11)*, 1377–1386.

Maltman, A. (ed.) 1994. *The geological deformation of sediments*. Chapman & Hall, London, 362 pp.

Middleton, G.V., Hampton, M.A. 1973. Subaqueous sediment transport and deposition by sediment gravity flows. In: Middleton, G.V., Bouma, A.H. (eds.). *Turbidites and Deep water sedimentation*. Society of Economic Paleontologists Mineralogists, Short course 1, Anaheim, 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.

Migeon, S., Savoye, B., Faugeres, J.C. 2000. Quaternary development of migrating sediments waves in the Var deep-sea fan: distribution, growth pattern and implication for levee evolution. *Sedimentary Geology 133 (3–4)*, 265–293.

Mulder, T., Alexander, J. 2001. The physical character of subaqueous sedimentary density flow and their deposits. *Sedimentology 48 (2)*, 269–299.

Mutti, E. (ed.) 1992. *Turbidite sandstones*. Agip, Instituto di geologia, Universita di Parma, Milan, 275 pp.

Mutti, E., Ricci Lucchi, F. 1972. Turbidites of the northern Apennines: Introduction to facies analysis. *International Geology Review 20 (2)*, 125–166.

Mutti, E., Normark, W.R. 1987. Comparing examples of modern and ancient turbidite systems: problems and concepts. In: Legget, J.K., Zuffa, G.G. (eds.). *Marine clastic sedimentology – concepts and case studies*. Graham & Trotman, London, 1–38.

Ostrowiecka, H., 1979. Stratygrafia płaszczowiny magurskiej w okolicach Piwnicznej. *Rocznik Polskiego Towarzystwa Geologicznego 44 (1/2)*, 76–78. [In Polish].

Oszypko, N., Oszczypko-Clowes, M., Golonka, J., Krobicki, M. 2005. Position of the Marmarosh Flysch (Eastern Carpathians) and its relations to the Magura

Nappe (Western Carpathians). *Acta Geologica Hungarica 48 (3)*, 259–282.
Oszczypko, N., Porębski, S. 1985. Explanations to stop 68-Życzanów Stream. In: Birkenmajer, K. (ed.). *Main Geotraverse of the Polish Carpathians (Kraków – Zakopane). Guide to excursion 2*, Geological Institute of Poland, 175–178.
Oszczypko, N., Porębski, S. 1986. Stratygrafia, sedymentologia i tektonika jednostki magurskiej. In: Birkenmajer, K. (ed.), *Przewodnik LVII Zjazdu Polskiego Towarzystwa Geologicznego, Pieniny.* Wydawnictwo AGH, 113–134. [In Polish].
Piper, D.J.W., Cochonat, P., Morrison, M.L. 1999. The sequence of events around the epicentre of the 1929 Grand Banks earthquake: initiation of the debris flows and turbidity current inferred from side scan sonar. *Sedimentology 46 (1)*, 79–97.
Piper, D.J.W., Normark, W.R. 1983. Turbidite depositional patterns and flow characteristics, Naby submarine fan, California Borderland. *Sedimentology 30 (5)*, 681–694.
Pisarska-Jamroży, M., Weckwerth, P. 2013. Soft-sediment deformation structures in a Pleistocene glaciolacustrine delta and their implications for the recognition of subenvironments in delta deposits. *Sedimentology 60 (3)*, 637–665.
Porębski, S.J., Dziadzio, P. 2002. Deep-sea, massive sandstones in the Polish Carpathians. Fieldguide. *Polish Association of Oil and Gas Engineers Gorlice Branch,* 1–17.
Posamentier, H.W., Kolla V. 2003. Seismic geomorphology and stratigraphy of depositional elements in deepwater settings. *Journal of Sedimentary Research 73 (3)*, 367–388.
Posamentier, H.W., Walker, R.G. 2006. Deep-water turbidite and submarine fans. *Society of Sedimentary Geology Special Publications 84*, 399–520.
Postma, G. 1986. Classification for sediment gravity-flow deposits based on flow conditions during sedimentation. *Geology 14 (4)*, 291 pp.
Reading, H.G., Richards, M. 1994. Turbidite system in deep-water basin margins classified by grain size and feeder system. *American Association of Petroleum Geologists Bulletin 78 (5)*, 792–822.
Sadler, P. 1982. Bed-thickness and grain size of turbidites. *Sedimentology 29 (1)*, 37–51.
Salles, T., Lopez, S., Eschard, R., Lerat, O., Mulder, T., Cacas, M.C. 2008. Turbidity current modelling on geological time scale. *Marine Geology 248 (3–4)*, 127–150.
Sanders, J.E. 1963. Concepts of fluid mechanics provided by primary sedimentary structures. *Journal of Sedimentary Petrology 33 (1)*, 173–179.
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.* Society of Economic Paleontologists and Mineralogists Special Publications, 12, 192–219.
Schieber, J., Southard, J. 2009. Bedload transport of mud by floccule ripples – direct observation of ripple migration process and their implications. *Geology 37 (6)*, 483–486.
Schieber, J., Southard, J.B., Thaisen, K. 2007. Accretion of mudstone beds from migrating floccule ripples. *Science 318 (5857)*, 1760–1763.
Shanmugam, G. 1978. The stratigraphy, sedimentology and tectonics of the Middle Ordovician Sevier Shale Basin in east Tennessee. *The University of Tennessee,* 222 pp.
Shanmugam, G. 1996. Perception vs. reality in deep-water exploration. *World Oil 217*, 37–41.
Shanmugam, G. 1997. The Bouma Sequence and the turbidite mind set. *Earth-Science Reviews 42 (4)*, 201–229.
Shanmugam, G. (ed.) 2006. *Deep-water processes and facies models: implications for sandstones petroleum reservoirs. Handbook of petroleum exploration and production, 5*. Elsevier, Amsterdam, 469 pp.
Shanmugam, G. 2017. Global case studies of soft-sediment deformation structures (SSDS): Definitions, classifications, advances, origins, and problems. *Journal of Paleogeography 6 (4)*, 251–320.
Shanmugam, G., Benedict, G.L. 1978. Fine-grained carbonate debris flow, Ordovician basin margin, Southern Appalachians. *Journal of Sedimentary Petrology 48 (4)*, 1233–1240.
Shanmugam, G., Moiola, R.J. 1995. Reinterpretation of depositional processes in a classic flysch sequence (Pennsylvanian Jackfork Group), Ouachita Mountains, Arkansas and Oklahoma. *American Association of Petroleum Geologists Bulletin 79*, 672–695.
Shanmugam, G., Spalding, T.D., Rofheart, D.H. 1993. Process sedimentology and reservoir quality of deep-marine bottom-current reworked sands (sandy conturites): An example from the Gulf of Mexico. *American Association of Petroleum Geologists Bulletin 77 (7)*, 1241–1259.
Skene, K.I., Piper, D.J.W., Hill, P.S. 2002. Quantiative analysis of variations in depositional sequences thickness from submarine channel levees. *Sedimentology 49 (6)*, 1411–1430.
Ślączka, A., Thompson, S. 1981. A revision of the fluxoturbidite concept based on type examples in the polish Carpathian flysch. *Rocznik Polskiego Towarzystwa Geologicznego 51 (1/2)*, 3–44.
Słomka, T. 1995. Głębokomorska sedymentacja silikoklastyczna warstw godulskich Karpat. *Wydawnictwo Polskiej Akademii Nauk 139*, 1–132 [In Polish].
Stauffer, P.H. 1967. Grain-flow deposits and their implications, Santa Ynez Mountains, California. *Journal of Sedimentary Petrology 37 (2)*, 25–43.
Stow, D.A.V., Reading, H.G., Collinson, J.D. 1996. Deep seas. In: Reading H.G. (ed.). *Sedimentary environments: processes, facies and stratigraphy*. Blackwell Science, Oxford, 704 pp.
Stow, D.A.V., Johansson, M. 2000. Deep-water massive sands: nature, origin and hydrocarbon implications. *Marine and Petroleum Geology 17 (2)*, 145–174.

Stow, D.A.V., Shanmugam, G. 1980. Sequence of structures in fine-grained turbidites: comparison of recent deep-sea and ancient flysch sediments. *Sedimentary Geology 25 (1–2)*, 23–42.

Sumner, E.J., Amy, L.A., Talling, P.J. 2008. Deposit structure and processes of sand deposition from decelerating sediment suspensions. *Journal of Sedimentary Research 78 (8)*, 529–547.

Sumner, E.J., Talling, P.J., Amy, L.A., Wynn, R.B., Stevenson, C.J., Frenz, M. 2012. Facies architecture of individual basin-plain turbidites: Comparison with existing models and implications for flow processes. *Sedimentology 59 (6)*, 1850–1887.

Sweet, M.L., Campion, K.M., Beaubouef, R.T. 2007. Deep-water-slope to basin-floor-fan deposits of the Eocene Tyee Formation, Oregon, USA. In: Nilsen, T.H., Shew, R.D., Steffens, G.S., Studlick, J.R.J. (eds.). *Atlas of deep-water outcrops*. American Association of Petroleum Geologists Studies in Geology, 56, 1–7.

Sylvester, Z., Lowe, D.R. 2004. Textural trends in turbidites and slurry beds from the Oligocene flysch of the Carpathians, Romania. *Sedimentology 51 (5)*, 945–972.

Talling, P.J. 2013. Hybrid submarine flow comprising turbidity current and cohesive debris flow: Deposits, theoretical and experimental analyses and generalized models. *Geosphere 9 (3)*, 460–488.

Talling, P.J., Amy, L.A., Wynn, R.B., Peakall, J., Robinson, M. 2004. Beds comprising debrite sandwiched within co-genetic turbidite: origin and widespread occurrence in distal depositional environments. *Sedimentology 51 (1)*.

Talling, P.J., Masson, D.G., Sumner, E.J., Malgesini, G. 2012. Subaqueous sediment density flows: depositional processes and deposit types. *Sedimentology 59 (7)*, 1937–2003.

Tinterri, R., Muzzi Magalhaes, P., Tagliaferri, A., Cunha, R.S. 2016. Convolute lamination and load structures in turbidites as indicators of flow reflections and decelerations against bounding slopes. Examples from the Marnoso-arenacea Formations (northern Italy) and Annot Sandstones (south eastern France). *Sedimentary Geology 344*, 382–407.

Unrug, R. 1963. Istebna Beds – a fluxoturbidity formation in the Carpathian Flysch. *Annales Societatis Geologorum Poloniae 33*, 49–92.

Walker, R.G. 1965. The origin and significance of the internal sedimentary structures of turbidites. *Yorkshire Geological Society Proceedings 35,* 1–32.

Walker, R.G. 1967. Turbidite sedimentary structures and their relationship to proximal and distal environments. *Journal of Sedimentary Petrology 37 (1)*, 25–43.

Walker, R.G. 1978. Deep-water sandstone facies and ancient submarine fans: model for exploration for stratigraphic traps. *American Association of Petroleum Geologists Bulletin 62 (6)*, 932–966.

Walker, R.G. 1985. Mudstones and thin-bedded turbidites associated with the Upper Cretaceous Wheeler Gorge conglomerates, California; a possible channel-levee comples. *Journal of Sedimentary Petrology 55 (2)*, 279–290.

Weimer, P., Slatt, R.M. 2004. Deepwater reservoir elements: Channel and their sedimentary fill. In: Weimer, P., Slatt, R.M. (eds.). *Petroleum systems of deepwater settings*. *Society of exploration geophysicists distinguished instructor series*, *7*, 4-1-4-98 pp.

Woźniak, P.P., Pisarska-Jamroży, M. 2018. Debris flows with soft-sediment clasts in a Pleistocene glaciolacustrine fan (Gdańsk Bay, Poland). *Catena 165,* 178–191.

Zieliński, T., Pisarska-Jamroży, M. 2012. Jakie cechy litologiczne osadów warto kodować, a jakie nie? *Przegląd Geologiczny 60 (7)*, 387–397 [In Polish].