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Sedimentary processes and architecture of Upper Cretaceous deep-sea channel deposits: a case from the Skole Nappe, Polish Outer Carpathians

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Abstract: Deep-sea channels are one of the architectonic elements, forming the main conduits for sand and gravel material in the turbidite depositional systems. Deep-sea channel facies are mostly represented by stacking of thick-bedded massive sandstones with abundant coarse-grained material, ripped-up clasts, amalgamation and large scale erosional structures. The Manasterz Quarry of the Ropianka Formation (Upper Cretaceous, Skole Nappe, Carpathians) contains a succession of at least 31 m of thick-bedded high-density turbidites alternated with clast-rich sandy debrites, which are interpreted as axial deposits of a deep-sea channel. The section studied includes 5 or 6 storeys with debrite basal lag deposits covered by amalgamated turbidite fills. The thickness of particular storeys varies from 2.5 to 13 m. Vertical stacking of similar facies through the whole thickness of the section suggest a hierarchically higher channel-fill or a channel complex set, with an aggradation rate higher than its lateral migration. Such channel axis facies cannot aggrade without simultaneous aggradation of levee confinement, which was distinguished in an associated section located to the NW from the Manasterz Quarry. Lateral offset of channel axis facies into channel margin or channel levee facies is estimated at less than 800 m. The Manasterz Quarry section represents mostly the filling and amalgamation stage of channel formation. The described channel architectural elements of the Ropianka Formation are located within the so-called Łańcut Channel Zone, which was previously thought to be Oligocene but may have been present already in the Late Cretaceous.

Keywords: Carpathians, sedimentary processes, architectural elements, deep-sea channel, massive sandstone, turbidite, debrite.

Introduction

The architectural elements concept is widely accepted for analysis of deep-sea depositional environments (Mutti & Normark 1987). According to this concept, sedimentary bodies are distinguished as parts of a hierarchically organized deep-sea fan model. A high variety of architectural elements are conditioned by material deposited, size and latitudinal position of depositional system, sea level changes, tectonic regime and sedimentary processes (e.g., Stow & Mayall 2000; Mulder 2011; Cossu et al. 2015; Shanmugam 2016). Architectural elements are usually distinguished in very well exposed depositional systems through analysis of facies associations (e.g., Gardner et al. 2003; Prélat et al. 2009; Hubbard et al. 2014; Bayliss & Pickering 2015a, b; Pickering et al. 2015). However, this concept was so far not applied to numerous formations, including the Ropianka Formation (Turonian–Paleocene) in the Skole Nappe (Polish Carpathians). This formation, up to 1.6 km thick, contains a succession of deep-sea deposits with numerous facies associations suggesting occurrence of different architectural elements (e.g., Bromowicz 1974; Kotlarczyk 1978, 1988; Łapcik in press), which remain almost undetermined. Tectonic deformation and poor exposure of the Ropianka Formation make difficulties in correlations of facies and architectural elements over longer distances. Nonetheless, large outcrops with high contribution of thick-bedded sandstones give a chance to distinguish such bodies in some places, for example, in the Słonne section, where Łapcik (in press) distinguished over 140 m thick lobe complex.

In this paper, deep-sea channel-fill and its internal architecture are presented in structureless and graded thick-bedded sandstones from the Manasterz Quarry, in references to associated sections. Moreover, depositional processes are interpreted on the basis of sedimentary structures and the internal architecture of the channel-fill.

Geological setting

This study is focused on the Ropianka Formation (after Kotlarczyk 1978), also known as the Inoceramian Beds (Uhlig 1888), which is referred to sand-rich deposits in the northern part of the Skole Nappe (also known as the Skyba Nappe). The formation comprises a succession of turbidity current, debris flow, slump, pelagic and hemipelagic deposits of the Turonian–Palaeocene age up to about 1.6 km thick (e.g., Kotlarczyk 1978, 1988). The Skole Nappe is the most external major tectonic unit in the Polish Carpathians (Fig. 1A). Deposits of the Skole Nappe accumulated in a separate sub-basin (e.g., Kotlarczyk 1988), however, some authors regard part of the Skole Basin as the Carpathian marginal zone which corresponds to the basin slope (e.g., Jankowski et al. 2012). Sedimentation in the Outer Flysch Carpathians started in the Late Jurassic. The Carpathians evolved from a rift basin (since the Late Jurassic) to a remnant foreland basin in the Oligocene (Golonka et al. 2006; Nemčok et al. 2006; Ślączka et al. 2006, 2012; Gągała et al. 2012) and ultimately during the Miocene the basin was folded and thrusted upon the Carpathians Foredeep. During the Turonian–Paleocene times, the sediments of the Skole Basin are thought to have been derived from the southern part of the Upper Silesia and Małopolska blocks to the north (Książkiewicz 1962; Bromowicz 1974; Salata & Uchman 2013) and from the side of the Subsilesian Ridge (Węglówka Ridge) to the south (Książkiewicz 1962). The petrographic variety of the source area was repeatedly mentioned in the literature (e.g., Salata & Uchman 2013; Salata 2014; Łapcik et al. 2016 and references therein).

Four lithostratigraphic members of the Ropianka Formation were distinguished based on repeated carbonate-siliciclastic deposits (Fig. 1B; Kotlarczyk 1978). Each member (excluding the Wola Korzeniecka Member) contains carbonate-rich succession which passes into siliciclastic dominated deposits towards the top. Moreover, a decreasing contribution of carbonate material from the proximal area to the north to the distal area to the south of the Skole Basin is observed (Kotlarczyk

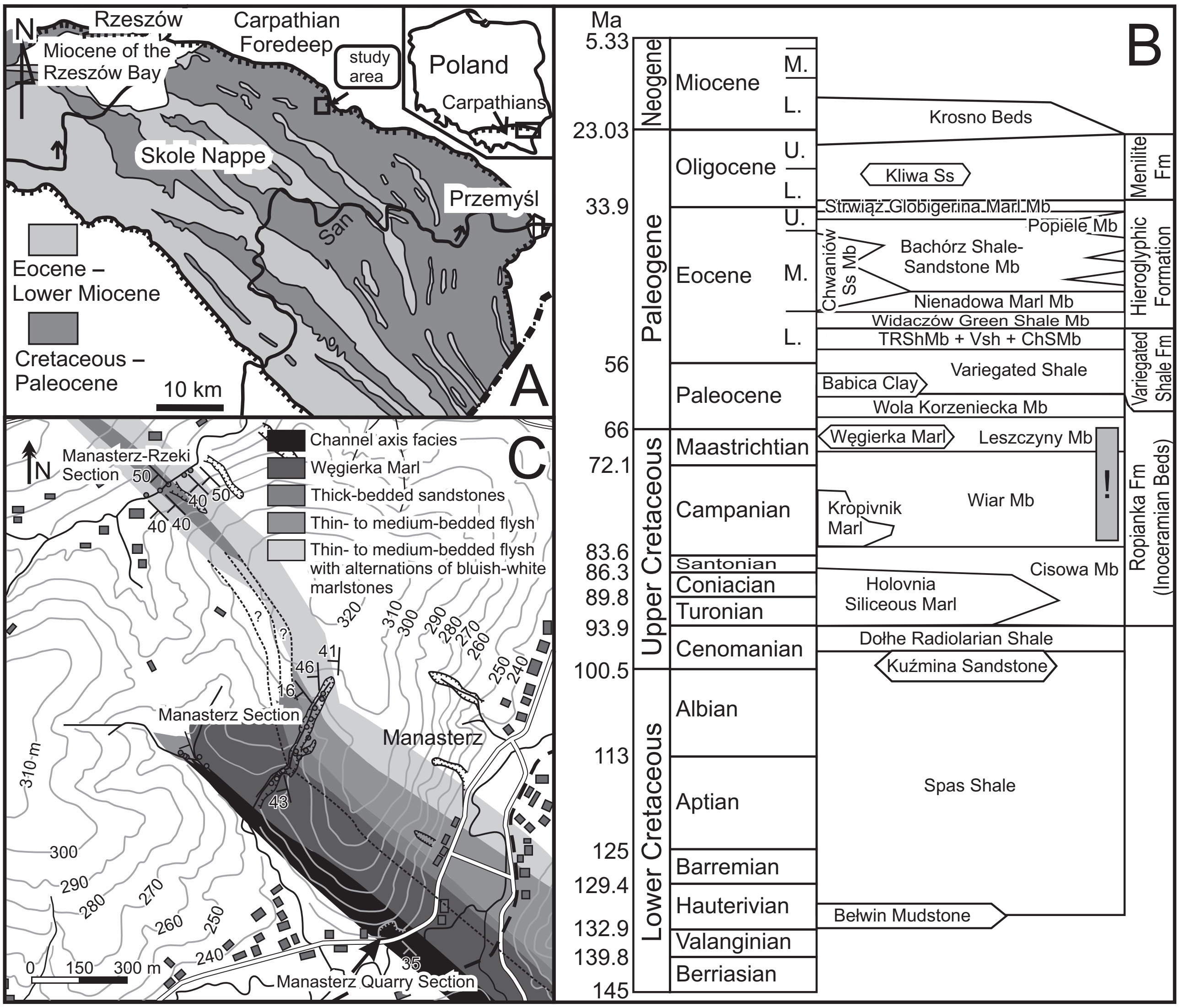

Fig. 1. Geographical and stratigraphic location of studied area. **A** — location map of the studied area in the Skole Nappe. Based on Kotlarczyk (1988) and modifications by Gasiński & Uchman (2009 and references therein); **B** — location of the Manasterz-Rzeki, Manasterz and Manasterz Quarry sections with some indicators of the orientation of beds as measured in the field and prediction of spatial distribution of facies; **C** — stratigraphic column of the Skole Nappe. Based on Kotlarczyk (1988), Rajchel (1990), Rajchel & Uchman (1998), Ślączka & Kaminski (1998), with further corrections based on further data by Gedl (1999) and Kotlarczyk et al. (2007). The investigated interval indicated by „!". The time scale is after Gradstein et al. (2012). TRSh Mb — Trójca Red Shale Member, VSh — Variegated Shale, ChS Mb — Chmielnik Striped Sandstone Member.

1978). Some areas show domination of mass transport deposits typical of slope areas (Burzewski 1966; Bromowicz 1974; Kotlarczyk 1978, 1988; Dżułyński et al. 1979; Geroch et al. 1979; Malata 2001; Jankowski et al. 2012; Łapcik et al. 2016). Foraminiferid assemblages point to deposition of the Ropianka Formation in bathyal depths below and above the calcite compensation depth (Uchman et al. 2006). The lithostratigraphy of the Ropianka Formation is still debated (e.g., Malata 1996; Jankowski et al. 2012).

Methodology

The fieldwork was based on sedimentological and facies analysis of sandy dominated thick-bedded deposits. The texture and primary structure of these deposits were described during detailed profiling. Grain-size analysis was conducted in order to determine the depositional processes of the thick-bedded sandstones and estimate the thickness of amalgamated beds. Fifty samples were taken for grain-size and petrographic analysis which was conducted as described in Łapcik (in press). The samples for grain-size analysis were collected from 4–5 cm thick layers with different distance intervals described further in the text. The orientation of the longer axis of 103 mudstone and marlstone clasts, orientation of grains and pebbles imbrication and orientation of the axis of flute casts from the MQ section were measured by mean of a geological compass in order to determine direction of palaeotransport. The last stage of the sedimentological and facies analysis of the thick-bedded sandstones was distinguishing the channel elements.

The sections studied

The studied deposits belong to the internally deformed Husów Thrust Sheet (Wdowiarz 1949), which is the second thrust sheet from the northern margin of the Carpathians. The majority of research was focused on sandy deposits in the well exposed Manasterz Quarry (MQ). Additional sedimentological study was conducted in two associated sections. Description of the whole Manasterz section is presented below in the stratigraphic order.

The Manasterz-Rzeki section

The oldest part of the section studied is located in a small gorge of an unnamed stream, a tributary of the Husówka Stream at Manasterz-Rzeki (Fig. 1C). The section is represented by five isolated outcrops containing thin- to thick-bedded sandstones, siltstones, mudstones and marlstones (Fig. 2). Beds are dipping to the SW at angles of 40°–50° (Fig. 1C). The contribution of each facies class in particular outcrops is presented in Figure 3. Sandstones are quartz-dominated, very fine- to medium-grained, with abundant parallel, convolute and cross-laminations underlined by carbonized plant detritus. Medium- and thick-bedded sandstones are graded or structureless at the basal part. Sole marks are numerous with a high contribution of the trace fossils *Ophiomorpha* and *Thalassinoides*. Some thin-bedded sandstones rich in plant detritus show chaotic structure, which probably resulted from bioturbation (the trace fossil *Scolicia* is present). Sandstones are alternated with grey mudstones, which often include thin layers of parallel and cross-laminated siltstones. The latest lithology is represented by bluish-white marlstones with sandstone alternations, which are 0.2–1 cm thick. Abundant bioturbation structures within marlstones are dominated by *Planolites* and *Chondrites*.

The Manasterz-Rzeki section begins as thin-bedded flysch with abundant alternation of marlstones (Fig. 2). Contribution of marlstones decreases in the middle part of the section with simultaneous significant increase in medium- and thick-bedded sandstones (Fig. 3). The top of the section is again represented by thin-bedded flysch with abundant alternation of marlstones similar looking to the bottom part of the section. The total thickness of the Manasterz-Rzeki section is 116 m with a 28 m-thick middle part showing numerous medium and thick sandstone beds. The Manasterz-Rzeki section belongs to the Campanian Wiar Member (Fig. 1B; Kotlarczyk 1978).

The Manasterz section

Higher part of the section crops out in gorges of unnamed tributaries of the Mleczka River, south of Manasterz-Rzeki, where beds dip to the W and SW (Fig. 1C). The lower part of the section is represented by thin-bedded flysch with alternation of marlstones showing similar appearance to the top and bottom part of the Manasterz-Rzeki section (Fig. 2). To the top of the section, the contribution of marlstones decreases with simultaneous increasing of mudstones (Fig. 2). The higher part of the section contains a medium- and thick-bedded sandstone interval. These sandstones are dominated by fractionally graded and parallel laminated parts with abundant, clasts of coal. However, some of the medium- and thick-bedded sandstones are structureless at their base. Above the sandy interval, packages of fine-grained, structureless, muddy sandstones with clasts of mudstone and marlstone are alternated with up to tens of centimetres thick, silty and sandy calcareous, structureless mudstones with dispersed quartz pebbles. This type of deposit is abundant in the external (northern) part of the Skole Nappe and they are known as the Węgierka Marl (Baculites Marl). This unit is included in the Leszczyny Member (upper Maastrichtian–lower Palaeocene). The Manasterz section is 375 m thick (Fig. 2). Tectonic deformations leave uncertainty if the thick-bedded sandstone interval in the Manasterz section corresponds to the similar one in the Manasterz-Rzeki section (Fig. 1C).

The Manasterz Quarry section

The highest part of the section studied is exposed in a small quarry at Manasterz where beds are inclined to the south-west

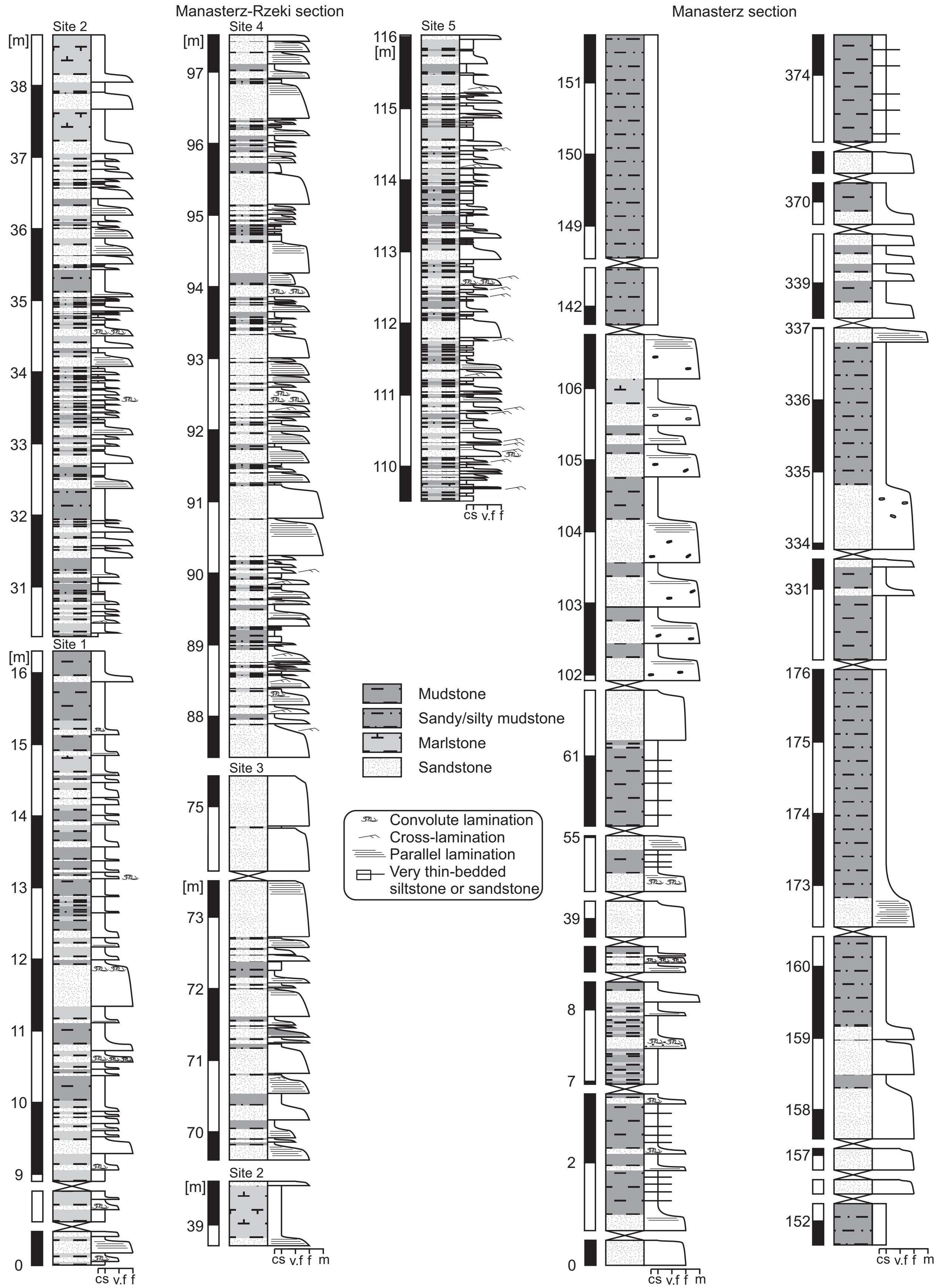

Fig. 2. Lithological columns of the Ropianka Formation at the Manasterz. Logs refer to the Manasterz-Rzeki and the Manasterz sections.

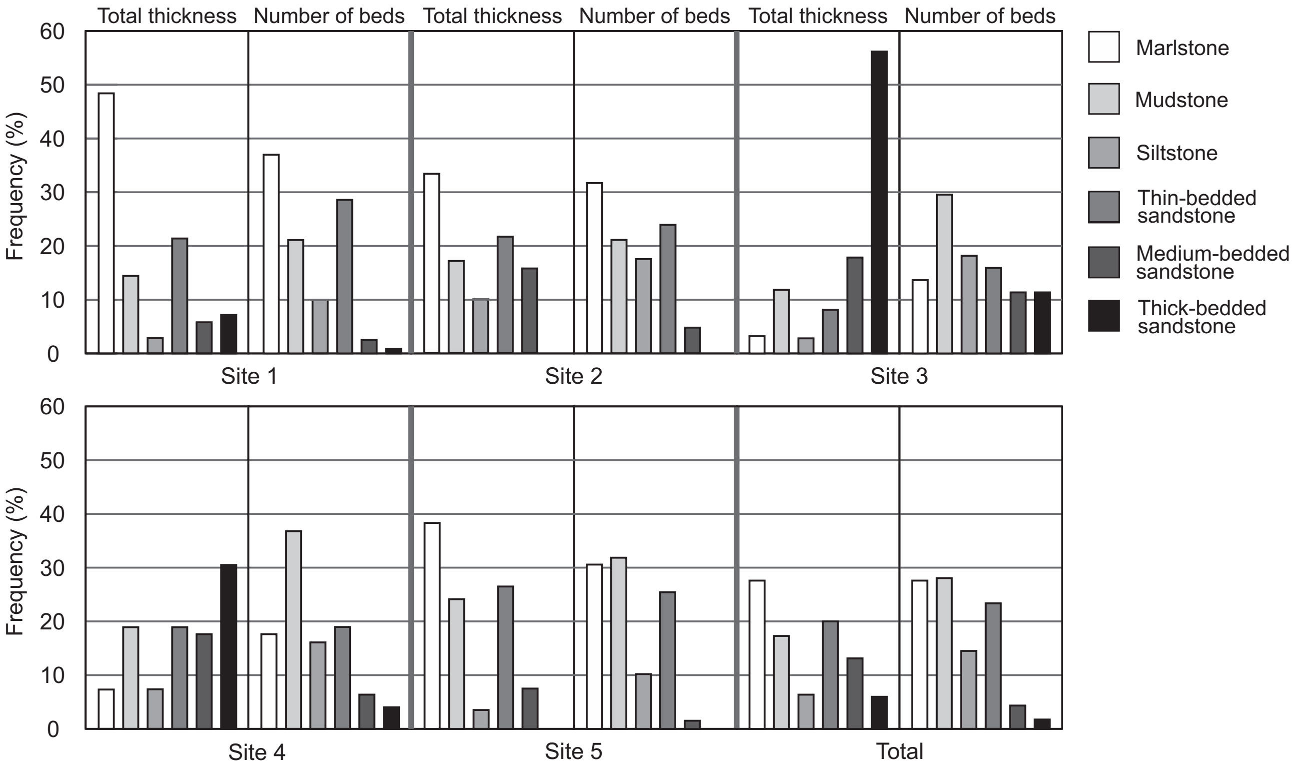

Fig. 3. Facies class abundance in the Manasterz-Rzeki section.

at angles of 30–40°. The quarry is 85 m long and up to 12 m high. The outcrop consists of 31 m of fully sandstone section where yellowish-orange, graded and structureless, amalgamated sandstones are fine- to coarse-grained with locally abundant dispersed quartz gravel, mudstone and marlstone cobbles and boulders (Fig. 4). Mudstone clasts are usually very poor in microfauna, however, some contain abundant bryozoans. The sandstones are quartz arenites, which contain minor admixture of siliceous grains, muscovite, sericite, glauconite, biotite, feldspar, mica schists, pyrite concretions, granite, gneiss and coal. A minor contribution of biogenic material is represented by abraded bivalve shells, siliceous sponge spicules and agglutinated benthic foraminifer tests. The contribution of accessory components never exceeds a few percent in total. Quartz grains are almost always well rounded. Polymineralic grains are limited to the largest fractions of 0.25–2 mm. The sandstone contains variable amounts of carbonate, silica and clay minerals cement and passes from hard lithified to almost loose sand. The MQ sandstone facies significantly differ from the thick-bedded sandstone intervals from the Manasterz-Rzeki and Manasterz sections. A detailed description of the MQ section is presented in “Material studied”.

In a similar stratigraphic position, to the NW of the quarry, thin- to medium-bedded sandstones alternated with grey mudstones are present (Figs. 1C, 2). These deposits are very similar to these in the lower part of the Manasterz section and they represent a lateral facies equivalent of the Manasterz section.

Material studied

The Manasterz Quarry facies

The majority of research was focused on the well exposed MQ sandy deposits. Sedimentological and facies analyses of the structureless and graded sandstones allowed to distinguish two or optionally three facies, descriptions and interpretations of which are presented below.

Facies 1

The majority of deposits in the MQ section are represented by fine- to coarse-grained, graded or macroscopically structureless sandstones with quartz gravel and clasts of mudstone and marlstone. Their bedding is poorly expressed because of abundant amalgamation and paucity of sedimentary structures. The amalgamation surfaces are uneven and marked by abrupt grain-size changes (Fig. 5A), which tend to decline laterally in the scale of metres. Some of the sandstones show crude lamination, which is underlined by parallel orientation of coarse grains and pebbles and very rare imbrication. Clasts are similar to mudstones and marlstones from the Manasterz and Manasterz-Rzeki sections and are mostly oriented parallel to the bedding (Fig. 5B). Clasts of mudstone are usually several tens of centimetres long and a few centimetres thick, whereas, clasts of marlstone are mostly rounded to subrounded and do not exceed 20 cm in diameter. Marlstones contain abundant *Chondrites*, *Planolites* and some

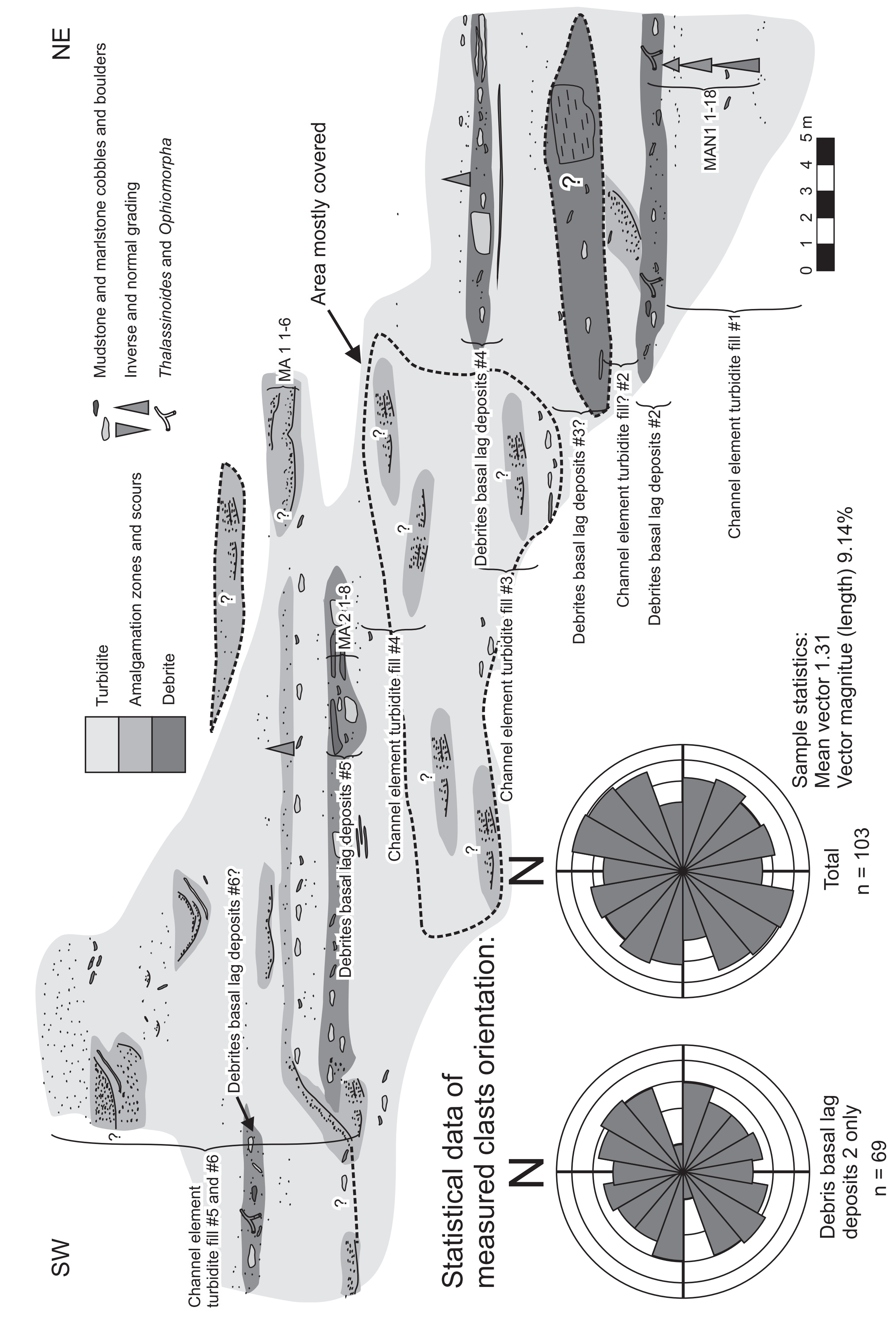

Fig. 4. Interpretation of the Manasterz Quarry section with distinguishing of the channel elements and statistical data of measured clast orientation.

unidentified bioturbation structures. Several erosional incisions up to 1.5 m deep and 2.5–6.5 m wide, with margins inclined at angles from 30° to almost 90° occur within the massive sandstones. They are filled with sandstone with quartz pebbles and shell debris. These structures are considered as mega-flutes. Some of them are filled exclusively with coarse-grained material, whereas others contain coarse-grained deposits in the lower part which is covered by medium- to fine-grained macroscopically structureless sandstone (Fig. 5C). However, coarse-grained layers can occur in multiple levels in one mega-flute. Particular coarse-grained layers may show normal or inverse to normal grading. Most of the mega-flutes are partly covered by recent debris or they are partly truncated by recent erosion. Therefore, their total width was impossible to estimate. Moreover, smaller, several centimetres thick scours are abundant within the macroscopically structureless and graded sandstone (Fig. 5A). The measured mean axis of the scours and grain imbrication indicate N–S and NW–SE orientations.

In order to determine the depositional process of facies 1 sandstones, two series of samples for grain-size analysis were collected (Fig. 6). Series MAN1 1–16 was collected in 20–30 cm intervals from 3.8 m thick bottom part of the section (Fig. 4). This sandstone interval rarely contains small mudstone clasts and amalgamation surfaces, which disappear at the distance of 1–3 m. Clasts are oriented parallel to the bedding in a discrete horizons. Grain-size analysis showed that sampled interval contains three fractionally graded amalgamated beds with mud content never exceeding 15 % by weight (Fig. 6). Estimated beds thickness decreases from 180 cm at the bottom, 80 cm in the middle to 40 cm at the top of the sampled interval (Fig. 6).

The second series of samples MA1 1–6 was collected in 10 cm intervals, from the middle part of the section, which include coarse-grained amalgamated sandstone (Fig. 4). The series starts at the bottom of an abrupt coarsening surface and includes two such surfaces. The analysis shows presence of the normal grading at the bottom amalgamation surface and the inverse to normal grading in the upper one (Fig. 6). The contribution of mud does not exceed 12 % by weight in the whole sample series (Fig. 6).

Interpretation: Facies 1 sandstones are interpreted as deposits of high-density turbidity currents mostly formed by layer-by-layer incremental deposition (e.g., Lowe 1982; Talling et al. 2012). Rapid fallout of grains from turbulent suspension suppressed the formation of sedimentary structures (Lowe 1982), however, grading was preserved. Mathematical modelling studies of Baas (2004) showed that lack of T_{bc} Bouma intervals in the top of structureless sandstones cannot be explained by abrupt deceleration of density flow only. Macroscopically structureless and graded sandstone beds at the MQ have no sign of water escape structures and lamination in the upper part, they are within grain-size limit for ripple lamination (<0.7 mm), show wide grain-size distribution (Fig. 6), and they do not have bioturbation structures. Therefore, the laminated top of structureless beds was eroded or bedforms are too thin to be recognized if duration of flow was too short within plane bed and ripple stability fields (Baas 2004). Occurrence of amalgamation surfaces, clasts of mudstone and marlstone and scours directly indicate strong erosional forces of the flows. Moreover, grain-size analysis showed that amalgamation surfaces are not restricted only to macroscopically abrupt grain-size coarsening but also occur within the structureless part. Therefore, amalgamation surfaces are more abundant than Figure 4 shows.

Isolated and laterally discontinuous mega-flutes reflect complex internal structure of the concentrated density flows (*sensu* Mulder & Alexander 2001) responsible for their origin. Such flows are featured by abrupt lateral transition from erosional through bypass to depositional conditions near the bottom. Fillings of the mega-flutes record a variety of depositional conditions which are expressed by lateral changes in the texture and primary structure of sediments (e.g., Leszczyński 1989 and references therein). Coarse-grained flute filling and coarse-grained amalgamation zones are basal lag deposits, which represent the thickest material carried by traction near the bottom (e.g., Dżułyński & Sanders 1962; Lowe 1982; Postma et al. 1988; Sohn 1997; Strzeboński 2015). Vertical multiple grain-size coarsening surfaces within some mega-flutes indicate deposition from an unsteady fluctuating flow or multiple filling of the flute by different events. Origin from multistage filling from independent flows is more probable because particular events would erode the top of the previous filling and leave lag deposits to underline amalgamation surface. Moreover, particular coarse-grained layers within the mega-flute fills show normal grading and inverse to normal grading from one coarse layer to another (Fig. 5C). Inversely graded coarse-grained amalgamation zones like the one from the M1 1–6 sampled interval imply deposition from high concentrated frictional traction where inversely grading is formed in the basal layer by shearing and kinematic sieving (Sohn 1997; Cartigny et al. 2013). Sediments deposited from traction are also confirmed by rare occurrence of coarse grains and imbrication of pebbles.

One of the features of the high-density turbidites is concentration of clasts in discrete horizons like in some structureless and graded sandstones in the MQ (Talling et al. 2012). Clast transportation within the high-density turbidity current is mostly on the rheological boundary between the turbulent damped bottom part of the flow and the more turbulent top or highly concentrated, turbulent damped, near bottom layer driven by turbulence from a more diluted top (e.g., Postma et al. 1988). Most of the elongated mudstone clasts suggest transportation on top of the highly concentrated bottom part of the high-density turbidity current, which prevented their further erosion and allowed them to keep their longitudinal shape. However, some authors suggest that preservation of mudstone clasts and their planar concentration to the top of bed is rather typical of sandy debrites (e.g., Shanmugam 2006; Strzeboński 2015). The well-rounded marlstone clasts imply relatively long traction transportation. Therefore, two importantly different shapes of clasts of lithologies which are easily

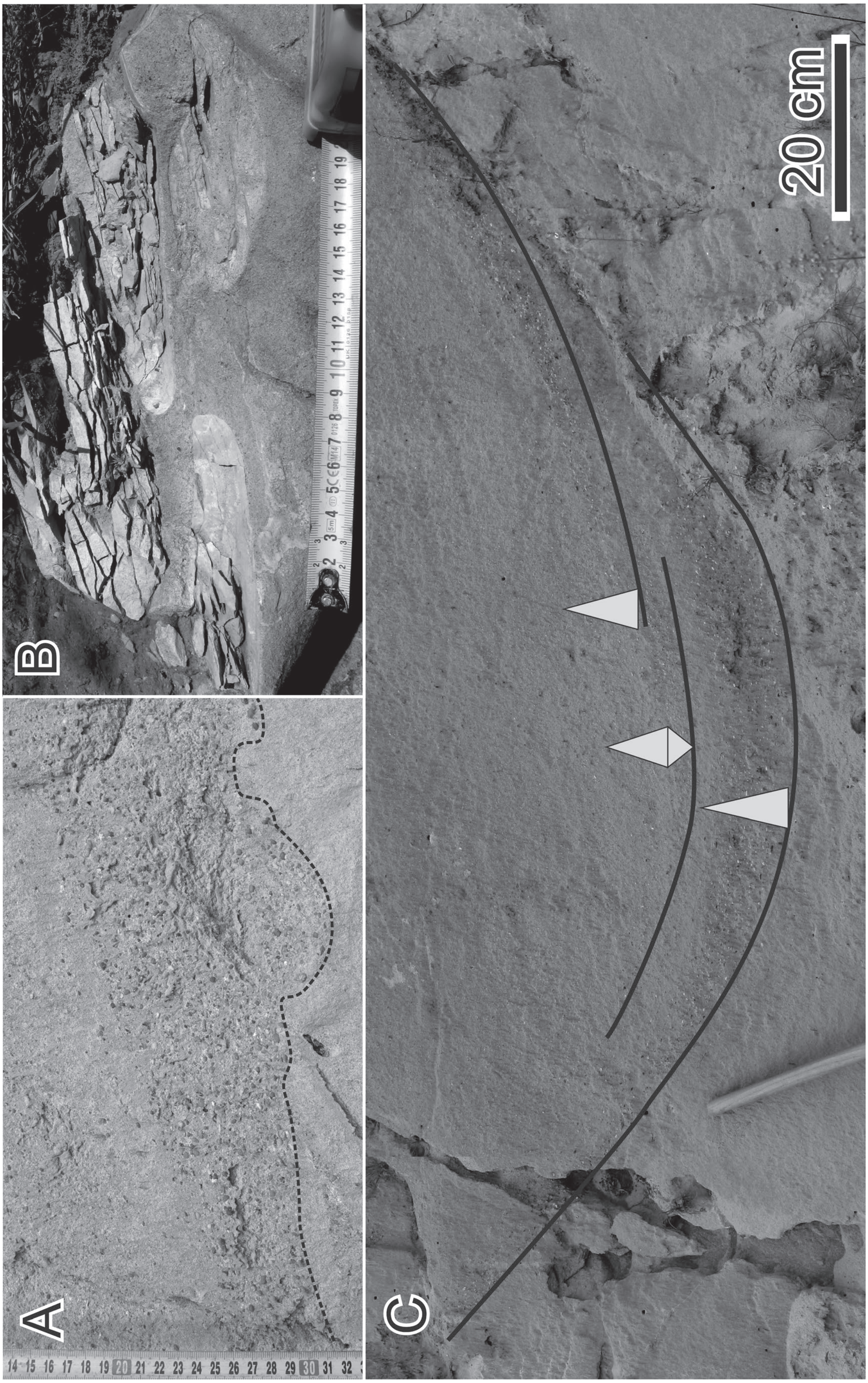

Fig. 5. Sedimentological features of facies 1 from the Manasterz Quarry section. **A** — coarse-grained amalgamation surface with small scale scours within the structureless sandstone of facies 1; **B** — well-rounded clasts of bluish-white marlstone oriented parallel to the bedding in a discrete horizon; **C** — large scour within the massive sandstone of facies 1 filled with multiple levels of coarse-grained layers. Particular coarse-grained layers show normal grading or inverse to normal grading which correspond to multistage filling of the scour.

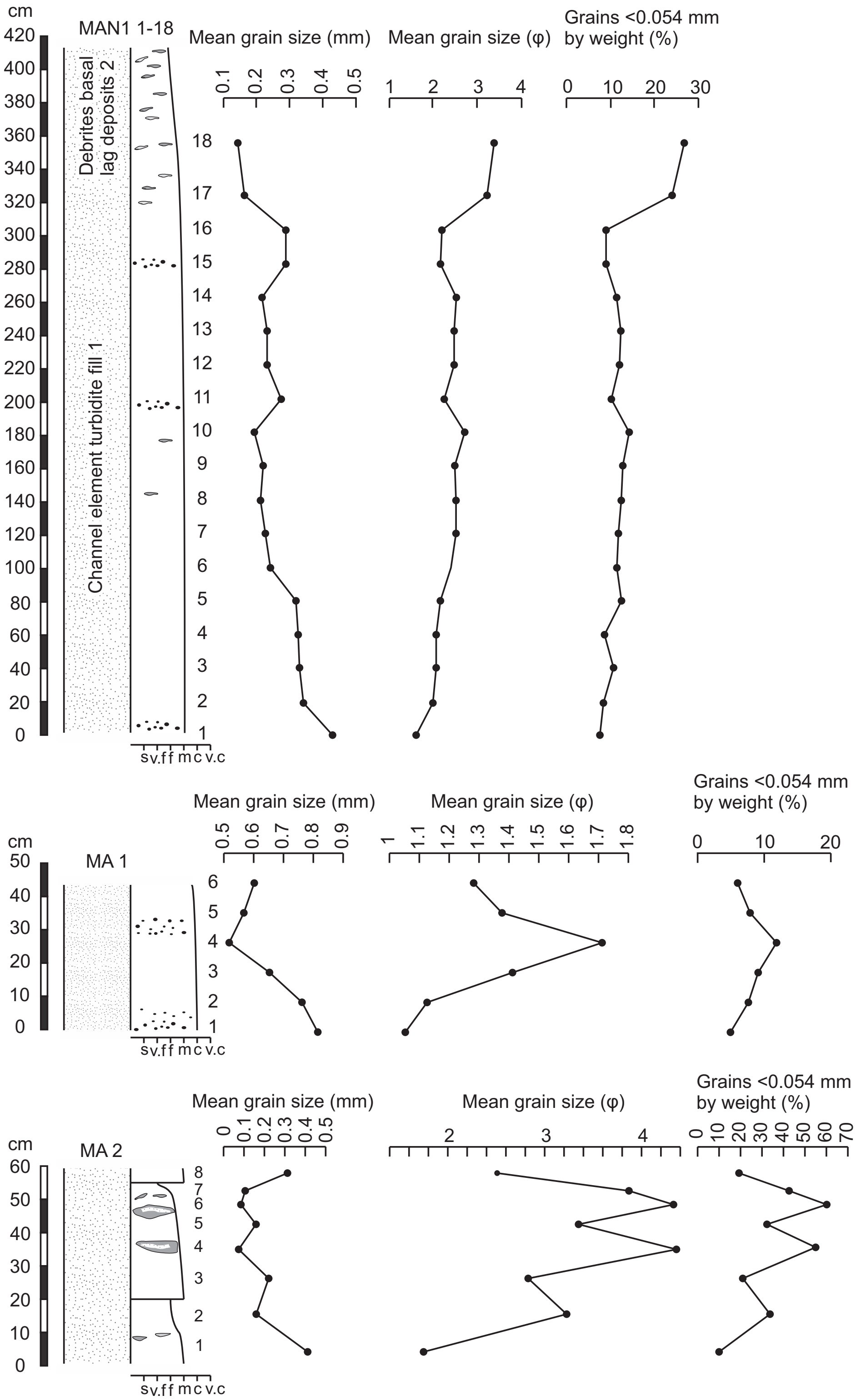

Fig. 6. Grain-size trends and mud content in MAN1 1–18, MA 1 1–6 and MA 2 1–8 sample series from the Manasterz Quarry section.

abraded suggest two different sources of the material and different distance of transportation. The marlstones clasts suggest erosion in a more proximal slope setting and longer transportation, whereas, elongated mudstones probably originated from undercutting of local overbanks.

The relatively small contribution of mud (Fig. 6) probably corresponds to flow stripping, which caused grain segregation in the long run confined flows and bypass of muddy dilute upper part of the stratified density flow (e.g., Piper & Normark 1983; Peakall et al. 2000; Posamentier & Walker 2006;

McHargue et al. 2011). In such a case, sediments of the MQ should be deposited in the relatively distal area to have enough time for grain segregation during transportation.

Facies 2

The MQ section contains a few layers of very fine- to coarse-grained sandstones with abundant large clasts of grey and reddish-brown mudstone and bluish-white marlstones (Fig. 7A). The layers are 1–2 m thick and can be traced over distance up to tens of metres. The boundary between facies 1 and facies 2 is usually reflected by a change in grain-size and mud content. Nevertheless, some beds of facies 1 seem to pass into structureless clast-rich sandstone of facies 2 with no sharp boundary. Angular to sub-rounded clasts represent the same lithology as in the facies 1. However, marlstones in some clasts, which are much thicker and poorly bioturbated, lithologically resemble the Węgierka Marl (e.g., Burzewski 1966; Geroch et al. 1979; Fig. 7B). Clasts are mostly oriented with their longer axis parallel to the bedding with maximum size up to 150x60 cm. However, those with size up to tens of centimetres in diameter dominate. Some clasts contain incised sand- and gravel-size grains chaotically distributed within the clasts or filling clastic veins. Matrix is represented by fine- to coarse-grained sandstone with slightly higher contribution of mud than in facies 1, which laterally may pass into fine- to medium-grained, dark, muddy sandstone with abundant small mudstone clasts and veins and lenses of clean sandstone similar to facies 1. Chaotic distribution of coarse grains within the matrix is reflected by their nest or patchy distribution and lateral changes in their density (Fig. 7C). Fine-grained matrix contains *Thalassinoides* and *Ophiomorpha* preserved as endichnial full reliefs. Moreover, some of the trace fossils cross-cut marlstone clasts and are filled by the matrix (Fig. 7D).

Grain-size analysis of clast-rich layers includes samples MAN1 17–18 from the bottom part and MA2 1–8, which were collected in 5–10 cm intervals from the middle part of the section (Fig. 5). Samples MAN1 17–18 show relatively muddy (>25 % of mud content by weight) fine-grained sandstones. There is an important decrease in mean grain-size and mud content from facies 1 to facies 2 in the sample series MAN1 1–18.

Samples MA2 1–8 show alternations of fine- to medium-grained, graded, clean sandstone and muddy sandstone. Layers of muddy fine-grained sandstone are discontinuous laterally and change their thickness from a few to tens of centimetres. They correspond to matrix with veins and lenses of clean sandstone described above. Amalgamation surfaces are present at the bottom of the lower structureless clean sandstone and above the fine-grained sandstone and stand as boundaries between facies 1 and facies 2. Similarly to MAN1 1–18, muddy layers are much finer-grained than in facies 1 clean sandstones.

Orientation of the longer axes of 103 clasts was measured in different clast-rich layers (Fig. 4). Most of the clasts, which were accessible for measurement, are concentrated within the lowermost clast-rich layer. These data do not correlate with orientation of erosional structures and grain imbrication, which indicate NW-SE and N-S palaeotransport direction. Collected data show that majority of clasts are oriented randomly without any specific trend which may indicate palaeoflow direction (Fig. 4).

Interpretation: Fine- to coarse-grained, clast-rich, muddy structureless sandstones of facies 2 are interpreted as debrites. Numerous, chaotically oriented huge clasts could be transported only by matrix supported debris flows (e.g., Shanmugam 2006; Strzeboński 2015). Moreover, patchy and nest distribution of coarse-grains imply poor conditions for grain segregation, which is the feature typical of laminar flow. Each clast-rich layer represents one or more debrites, which in some cases tend to abruptly pinch out laterally. Abrupt change in thickness and pinch-out of clast layers over a distance of several metres agrees with the spatial shape typical of debrites (e.g., Amy & Talling 2006). In some case laterally discontinuous muddy type of matrix with veins and lenses of clean sandstone may represent large eroded muddy boulders, which were poorly mixed during transportation with sandy matrix of the previous flow. Moreover, the poor roundness of larger clasts confirms weak interactions between components during transportation. Parallel orientation of clasts to the bedding and occurrence of veins filled by sand- and gravel-size grains imply matrix internal shear stress during debris flows movement. The occurrence of huge boulders of marlstone typical of the Węgierka Marl suggests shelf origin of some debrites and therefore, relatively long distance of transportation. However, rare occurrence of thin, tens of centimetres long, unfolded mudstone clasts imply that there were also short-lived slides with internal shear low enough to prevent clast deformation and folding. Similarly to facies 1, they may derived from undercutting of local overbank deposits. The erosional potential of some debris flows is reflected by uneven bottom surfaces and incision of debrites into turbiditic sandstone of facies 1.

Particle-size analysis shows important change in grain-size and mud contribution from deposits of turbidity currents and debris flows in both MAN1 and MA2 samples series (Fig. 6). Some of the debris flows were probably transformed from concentrated to hyperconcentrated density flows by increasing contributions of cohesive mud from disintegration of eroded clasts (Mulder & Alexander 2001), which agrees with the abundance of clasts and poor boundary between some beds of facies 1 and 2.

Occurrence of clasts of marlstone cross-cut by bioturbation structures filled with surrounding matrix implies bioturbation after deposition of debrites (Fig. 7C). This indicates good post-depositional environmental oxic conditions for benthic life. Preferential occurrence of bioturbation structures within the debrites may result from higher contributions of supplied nutrients or from periods of decreased sedimentation rate after deposition of debrites. Nevertheless, lack of bioturbation structures at the top of facies 1 beds may result from erosion.

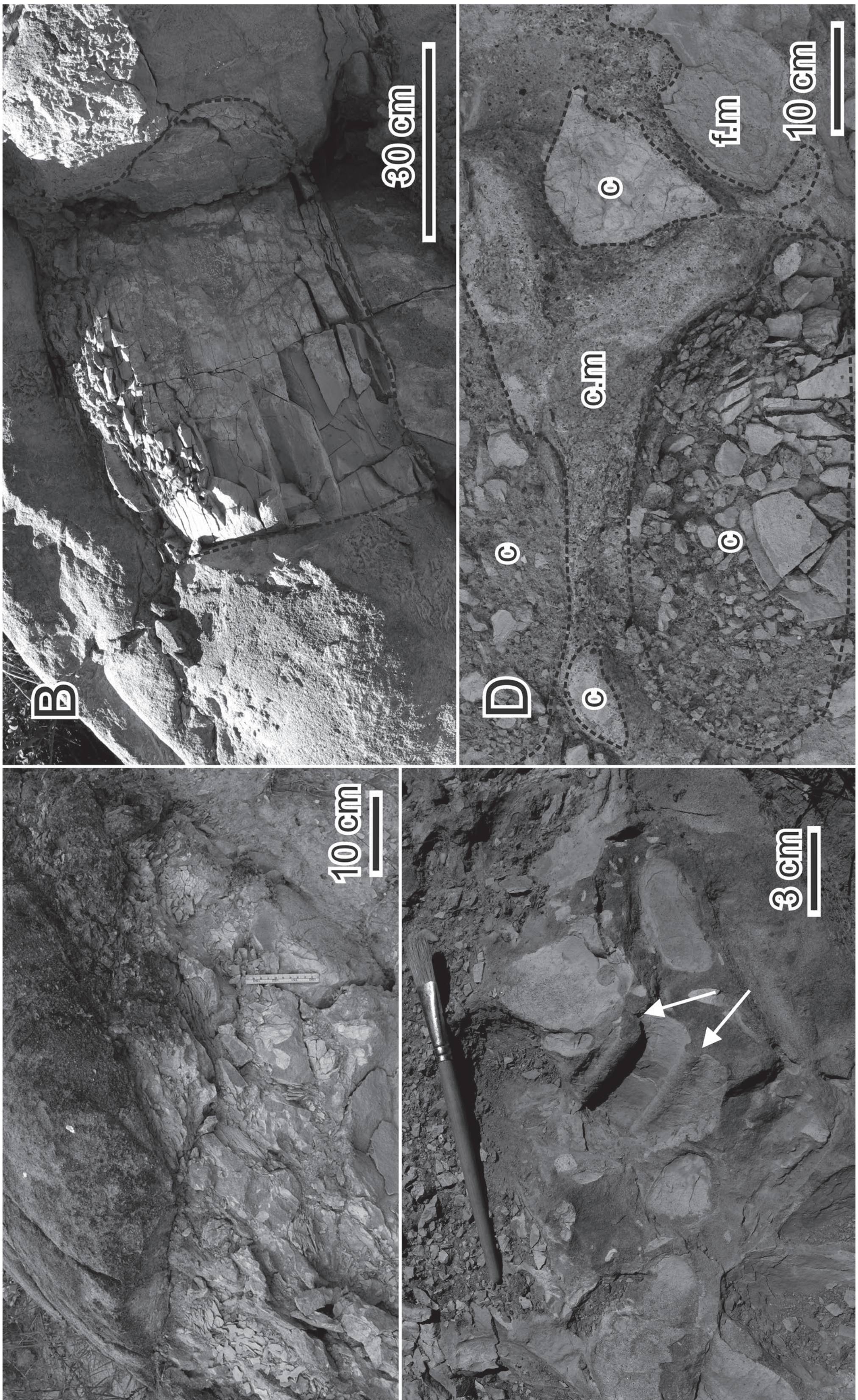

Fig. 7. Sedimentological feature of facies 2 from the Manasterz Quarry section. **A** — clast-rich sandy debrite; **B** — a huge boulder of bluish-white marlstone similar to the Węgierka Marl in the sandy debrite of facies 2; **C** — sandy debrite with clast of marlstone cross-cut by bioturbation structures filled with surrounded matrix. White arrows show bioturbation structures; **D** — clast-rich (c) sandy debrite with sharp boundary between coarse-grained (c.m) and fine-grained matrix (f.m).

Facies 3 or large boulder?

In the lower part of the MQ section, a 1.8 m thick layer of grey to bluish-white, calcareous mudstone with rare alternation of <0.6 cm thick siltstone is present. To the top and bottom, sharp boundary with sandstone of facies 1 is observed. Laterally, mudstone layer is continuous over a distance of at least 3 m. Nevertheless, incomplete exposition does not allow determination of its true lateral size and continuity. The mudstone is structureless and it shows no sign of bioturbation. The siltstone is laminated and rich in plant detritus. It shows sharp bottom boundaries.

Interpretation: Grey, calcareous mudstones are hemipelagic to pelagic facies typical of basin slope. Laminated siltstones are interpreted as deposits of dilute low-density turbidity currents and correspond to the T_d Bouma division, but their origin from bottom currents cannot be totally excluded. Uncertain lateral continuation and exceptional thickness suggest that this mudstone-dominated layer may represent a large boulder within a debris flow rather than a cape of thick sandstones from below. Moreover, some transition from very thick-bedded sandstone to very thick mudstones might be expected, but it is absent in the section studied. Nevertheless, such a mudstone layer may also originate from an abrupt decrease of activity in the source area, which resulted in vanishing of sand deposition in the study area.

Manasterz Quarry section as a channel-fill

Deep-sea channels are often thought as prolongation of deep-sea canyons or gullies, which distribute boulder to clay size material from upper and middle slope to abyssal plain. Deep-sea channels show many different forms with two end members where dominating processes are erosion (incising channels) or aggradation (constructive channels) respectively (e.g., Normark 1970; Flood et al. 1991; Hübsher et al. 1997; Babonneau et al. 2002). Deep-sea channels are distinguished as one of the hierarchical elements within deep-water depositional systems. Stacking of storeys or channel elements form channel complexes, channel complex sets and channel systems (Sprague et al. 2002, 2005; Abreu et al. 2003). Channels are relatively temporary structures, which migrate laterally by avulsion and lateral accretion. In this paper the MQ section facies are interpreted as deep-sea channel deposits with features and characteristics that are discussed below.

Channel characteristics of the Manasterz Quarry section

The MQ section shows the following features typical of deep-sea channel facies: high sand-to-mud ratio, occurrence of thick structureless and graded sandstones with paucity of sedimentary structures, a relatively high contribution of coarse material, numerous amalgamation surfaces, abundant scours and rip-up clasts and basal lag deposits (e.g., Mutti & Normark 1987; Shanmugam & Moiola 1988; Mayall et al. 2006; McHargue et al. 2011; Hubbard et al. 2014). Facies comparison in the same basin is a useful tool for distinguishing between particular facies of deep-sea channels (McHargue et al. 2011). The MQ section shows an extremely high sand-to-mud ratio in comparison to other outcrops of the Ropianka Formation (e.g., Bromowicz 1974; Kotlarczyk 1978). In the close vicinity of the study area, only a few small isolated outcrops with facies similar to the MQ section are available (Salata & Uchman 2013; Łapcik et al. 2016). This may suggest that deposits in the MQ section are related to a channel axis depositional environment.

An important feature of deep-sea channels is the lateral transition from channel axis to channel margin and channel-levee facies (e.g., Campion et al. 2000; Sprague et al. 2002, 2005; Gardner et al. 2003; Mayall et al. 2006; McHargue et al. 2011; Hubbard et al. 2014). Usually, the transition from channel axis to channel margin facies occurs at a distance of a few hundreds of metres (e.g., Shanmugam & Moiola 1988; Bruhn & Walker 1997; Campion et al. 2000; McHargue et al. 2011; Hubbard et al. 2014). The MQ thick-bedded sandstones are estimated to totally pinch-out to the NW at a distance of no more than 800 m (Fig. 1C). The outcrops which occupy similar stratigraphic positions to the MQ sandstones are dominated by thin- and medium-bedded sandstones alternated with mudstones and siltstones (Fig. 2). This facies change suggests a lateral offset of channel facies, which passes into channel margin or channel levee facies. In the close vicinity to the SE, facies similar to the MQ section are unknown (Gucik et al. 1980). Therefore, thick-bedded sandstones probably pinch-out laterally at a distance of tens to hundreds of metres. The total width of the Manasterz Quarry channel should not exceed a few hundreds of metres.

Formation and filling of the Manasterz Quarry channel

Deep-sea channels can be filled by turbidites, debrites, slumps and hemipelagic deposits with different contributions of these components but with a generally decreasing quantity of mass transport deposits downcurrent (e.g., Shanmugam & Moiola 1988; Dakin et al. 2013; Bayliss & Pickering 2015a). Channel incision is mostly attributed to erosion by previous high-density turbidity currents or the current responsible for channel filling. However, some of them can be created during bypass of debris flows when erosion can reach tens of metres (e.g., Dakin et al. 2013). The MQ channel is filled with mixed deposits of high-density turbidity currents and debris flows. Numerous amalgamation surfaces and alternations of turbidites and debrites imply a multistage process of filling characterized by repetitive transitions from deposition with a basal lag through erosion of the lag and to channel filling with domination of structureless and graded sandstones (e.g., Clark & Pickering 1996; Gardner et al. 2003). Thickness of the MQ channel reaches at least 31 m and is in range of channel-fill thickness (e.g., Sprague et al. 2005; Mayall et al. 2006; McHargue et al. 2011; Hubbard et al. 2014). The lowest hierarchical architectural element in channel settings are storeys or channel elements with thicknesses usually does not exceeding 5 m (Sprague et al. 2002). The internal architecture of the MQ section allowed to distinguish storeys with two basic elements, which repeatedly occur within the section. The first basic element includes debrites of facies 2, which correspond to basal lag deposits at the bottom of a particular storey (e.g., Mayall et al. 2006). Occurrence of these deposits determines the boundary between different storeys located at their base. Facies 1 represents storey-fill, deposited after sedimentation of debrite basal lag deposits. The MQ section consists of five storey-fills alternating with three debrite basal lag deposits (Figs. 4, 8). It is uncertain if the channel element turbidite fill 5 represents two different elements separated by poorly exposed debrite or one very thick storey-fill (Figs. 4, 8). Thickness of particular storey varies from 2.5 m to 8 m or up to 13 m if the channel element 5 represents one channel element (Fig. 4). The thickness of particular debrite basal lag deposits is much thinner and reaches 1–2 m. The cover of the bottom part of the section does not allow us to distinguish the basal lag deposits of the first storey. Alternatively, debrites may represent event deposits, which randomly interrupted turbidite sedimentation during formation of the channel-fill. However, multiple repetition of 1) deposition of debrite lag deposits, 2) erosion of debrite lag deposits and 3) deposition of high-density turbidites supports the first alternative.

Thick-bedded structureless and graded sandstone facies and their vertical stacking suggest that the MQ section may represent an area near the thickest part of the channel where the coarsest material is stacked. Moreover, vertical stacking of couplets of facies 1 and facies 2 suggests affiliation to a larger channel-fill or a channel complex set with an aggradation rate higher than its lateral migration. Such channel facies cannot aggrade without simultaneous aggradation of levee confinement (McHargue et al. 2011). Hence, interpretation of the outcrops in the similar stratigraphic position to the NW as channel margin or channel levee is most probable (Figs. 1C, 2).

Channel formation can be subdivided into three stages: 1) erosion and bypass when large scale erosional surfaces up to tens of metres are formed and capped by lag deposits, 2) channel fill when the coarsest material is repeatedly deposited and eroded with simultaneous sediment spill outside the channel, and 3) abandonment when the finest material caps and separates two channel elements (e.g., Clark & Pickering 1996; Gardner et al. 2003; Mayall et al. 2006; Labourdette et al. 2008; Dakin et al. 2013; Bayliss & Pickering 2015a, b). Abundant amalgamation and small scale erosion, relatively low contribution of lag deposits and domination of deposits of collapsing flows imply that the MQ deposits represent the channel fill stage. According to McHargue et al. (2011), early filling and amalgamation of a channel begins after stabilization of the equilibrium profile by the previous erosional stage. Despite lower energy of the flows during the filling stage, erosion is still prominent, especially near the channel axis. Moreover, occurrence of clast-rich debrites is common during the early amalgamation stage (McHargue et al. 2011). Most of the models assume that the last stage of the channel formation is abandonment recorded by sedimentation of thin-bedded deposits. Lack of fining and thinning upward trend in the MQ section may derive from poor exposure where all deposits represent only a small part of a larger channel complex set. Alternatively, the presence of a nearby strongly developed levee, may also preclude development of fining and thinning upward trends (Shanmugam & Moiola 1988). Such a levee may be represented by previously mentioned facies in the similar stratigraphic position to the NW of the MQ. It is possible to speculate that highly amalgamated deposits forming architecture of the MQ channel correspond probably to abundant avulsion and low aggradation of secondary (inner) overbank on the scale of channel elements (Deptuck et al. 2003; Posamentier & Kolla 2003; McHargue et al. 2011).

Location of the Manasterz channel in the Skole Basin

Abundance of mass movement and sediment gravity flow deposits with extrabasinal material and distribution of marlstone facies suggest that sedimentation of the most external part of the Ropianka Formation took place on the middle or lower basin slope or close to the base of the slope (e.g., Burzewski 1966; Bromowicz 1974; Kotlarczyk 1978, 1988; Jankowski et al. 2012; Łapcik et al. 2016). Analysis of heavy minerals from the Ropianka Formation showed that its deposits derive from an immature passive margin setting (Salata & Uchman 2013). The MQ section represents an area of abundant erosion and abrupt waning flows, which correspond to hydraulic jump of the flow. The channel-lobe transitional zone is considered as a site of abundant hydraulic jump with common scouring and erosional structures (e.g., Mutti & Normark 1987; Wynn et al. 2002, Gardner et al. 2003). However, the channel-lobe transitional zone usually includes traction structures (often large scale), which are absent at the MQ (e.g., Mutti & Normark 1987; Wynn et al. 2002). High contribution of large intrabasinal rip-up clasts in the MQ section suggests strong erosional forces in the previous flow stage. Hence, the MQ channel is probably incised into mudstone- and marlstone-rich deposits of the Skole Basin slope or such clasts derived from undercutting of the channel levees. The occurrence of extrabasinal, shallow water material in the MQ deposits suggests a strong relationship with the Skole Basin shelf. Carbonate mud and shell debris were redeposited into offshore and afterwards slope areas probably by lowering of the storm wave base. Such material suggests a relationship with canyons or gullies which captured it after redeposition by storm events from more proximal areas.

Previously postulated simultaneous aggradation of overbank deposits and channel-fill is strongly related to contribution of overspilled mud from turbidity currents and with proximal-to-distal position of the channel. The height of levees can reach hundreds of metres and decreases downcurrent with decreasing amounts of the fine-grained cohesive material which stabilize levee banks (Damuth & Flood 1985). The low contribution of mud within deposits of high-density turbidity current in the MQ section suggests spillover and bypass of more muddy parts of the flow. Further evidence for

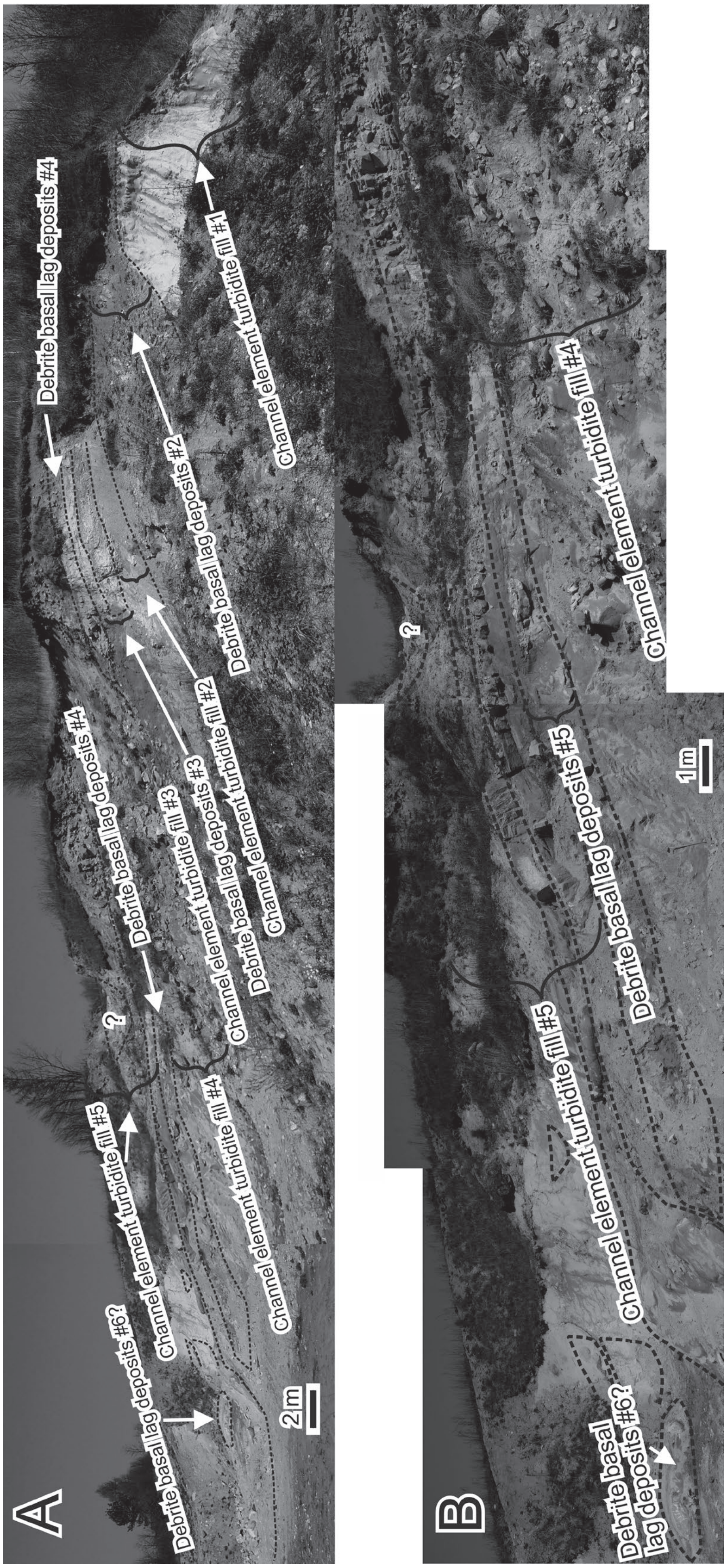

Fig. 8. The Manasterz Quarry section with distinguished channel elements. **A** — the Manasterz Quarry with distinguished channel elements. **B** — top of the Manasterz Quarry with distinguished channel elements.

strong bypass is the almost complete lack of organic detritus and coal debris in the MQ section. Such material is often an important component of thick-bedded sandstones in the Ropianka Formation (e.g., Kotlarczyk & Śliwowa 1963; Łapcik et al. 2016; Łapcik in press). It is unlikely that these deposits are related to another source area than sandstones from the lower part of the section (Manasterz-Rzeki) because such material is known from even younger deposits (e.g., Kotlarczyk & Śliwowa 1963). Therefore, the most probable scenario is bypass of organic detritus and coal, which was deposited in a more distal area, for example, in the lobe-like deposition of the Słonne section (Łapcik in press). Hence, the MQ channel should be situated in relatively proximal area on the lower slope or near base of the slope. According to Gardner et al. (2003), the MQ section shows features of the fill stage of a channel situated in the lower slope or base of the slope. This also stands in agreement with the proximal location of the MQ section within the second thrust sheet from the northern Carpathian margin.

Palaeotransport directions and sinuosity of the Manasterz Channel

Deposits of the Ropianka Formation show directions of the palaeotransport from NW, N and NE with dominance of the NW direction in the vicinity of the study area (Książkiewicz 1962; Bromowicz 1974). The palaeotransport data from the MQ include only measurements of scour orientation and grain imbrication within the structureless and graded sandstones, which indicate transportation from the NW. Nevertheless, directions of transport in a deep-sea channel may be variable and are rarely unidirectional. Spatial distribution and orientation of long belts of thick-bedded sandstone facies in the external part of the Ropianka Formation is consistent with the presented data and also point to the NW–SE axis (Gucik et al. 1980). All these data are premises for deposition of thick-bedded sandstone facies in the vicinity of the study area longitudinal to the slope of the Skole Basin. Most of these facies suggest a strong relationship with the Łańcut Channel Zone proposed by Kotlarczyk & Leśniak (1990) for the Oligocene deposits (see also Salata & Uchman 2012, 2013). It seems that this channel zone was already active during the Late Cretaceous.

The previously mentioned lateral offset of the facies from the channel axis to the channel margin or channel levee from the MQ section to the Manasterz section allows speculation about sinuosity of the studied channel. Otherwise, axial or off-axial channel facies would be continued to the NW in the Manasterz section. Hence, the channel facies outcropping in the MQ should change their orientation to the N or the W to evade the Manasterz channel levee facies. Nevertheless, the MQ section does not appear to have lateral accretion packages that have been described in other meandering channel-fill deposits (e.g., Bouma & Coleman 1985; Mutti & Normark 1991; Abreu et al. 2003; Janocko et al. 2013). Unfortunately, covering of the area, tectonic deformations and inclination of beds does not allow tracking of the channel facies.

Interpetation of the Manasterz-Rzeki and Manasterz facies

Bottom and top parts of the Manasterz-Rzeki and the Manasterz section

The bottom and top parts of the Manasterz-Rzeki section show many similarities to the bottom part of the Manasterz section (Fig. 2). Thin- to medium-bedded sandstones and marlstones with abundant parallel, cross and convolute laminations probably correspond to channel levee or inter-channel deposits. The decreasing contribution of marlstones in the bottom part of the Manasterz section suggests that this interval is situated above the second marlstone-rich interval of the Manasterz-Rzeki section (Figs. 1C, 2). Such marlstones are widely distributed in the Ropianka Formation in the whole marginal part of the Skole Nappe (e.g., Kotlarczyk 1978, 1988; Leszczyński et al. 1995). The marlstones are considered as calciturbidites with their source area situated in the shelf surrounding the Skole Basin. They were deposited by low-density turbidity currents in the marginal part of the Skole Basin, which probably corresponds to the basin slope and base of the slope. However, marlstone clasts from the MQ derive from erosion of marlstones form the older part of the Ropianka Formation. After partly lithification they, were ripped up by high-density turbidity currents and redeposited into a more distal area.

Thick-bedded sandstones occur in the Manasterz-Rzeki and Manasterz sections. Stacking of thick-bedded, structureless and graded sandstones often with parallel laminated top alternating with thin- and medium-bedded laminated sandstones suggest channel or depositional lobe facies. However, the thickness and sand-to-mud ratio of these intervals together with sparse amalgamation and scours suggest some distance from the axis of such bodies in comparison to the MQ section. Both sections represent progradation and aggradation of some sand-rich body. Decreasing contribution of marlstones with simultaneous increase in thick-bedded sandstones (Fig. 3) may imply: 1) decreasing activity in the carbonate source area, 2) progradation of a sand body which temporarily became an obstacle for calciturbidites, or 3) increasing activity in the siliciclastic source area, sediments from which diluted the carbonate sedimentation. The relative proximity of these deposits can be referred to the marginal position of the study area in the Skole Nappe (second thrust sheet from the Carpathians margin). Tectonic deformations of the study area do not allow certain correlation between the sections studied. It is not clear whether the two thick-bedded intervals of the Manasterz-Rzeki and Manasterz sections represent the same sand body or two different sand bodies. The main difference between these thick-bedded sandstones is abundance of coal debris in the Manasterz section. However, this is too weak a premise to exclude any alternative. If the two intervals represent different bodies, the interval with decreasing contribution of marlstones at the bottom of the Manasterz section may correspond to the lateral offset of channel or lobe facies of the Manasterz-Rzeki section, and the upper part of the Manasterz-Rzeki section may correspond to channel abandonment facies or channel levee facies. These speculations also imply on lateral migration of sandy bodies at the distance of hundreds of metres derived probably from avulsion (Fig. 1C).

The Węgierka Marl

The Węgierka Marl is widely known from the Ropianka Formation in the external part of the Skole Nappe and is mostly represented by packages of fine-grained, muddy sandstones with mudstone and marlstone clasts, up to tens of centimetres thick, and sandy calcareous mudstones with dispersed quartz pebbles and clasts of marlstone. Moreover, huge marlstone olistoliths are also known (Burzewski 1966; Kotlarczyk 1978, 1988; Geroch et al. 1979). Such deposits mostly represent slumps and debris flows originating in the middle to lower slope setting. Their abundance and spatial distribution suggest their classification as mass transport deposits complex, which influenced the basin floor morphology. Mass transport deposits often occur at the bottom of channels and channel complexes (Clark & Pickering 1996; Mayall et al. 2006; Bayliss & Pickering 2015a). In the study area, the Węgierka Marl facies are located at the bottom of the MQ channel facies. Hence, the Manasterz Quarry channel complex was formed on its floor with abundant debrites which could stand as confinement of the initial channel zone. In the Leszczyny Member, the Węgierka Marl and thick-bedded sandstones often alternate (e.g., Burzewski 1966; Bromowicz 1974; Kotlarczyk 1978, 1988; Geroch et al. 1979) but it is not clear if massive sandstones of the MQ section are situated only at the top of the Węgierka Marl, or if they also border with them laterally and/or are capped by them. Some of the debrites in the MQ section contain huge boulders of marlstone very similar to the Węgierka Marl. This suggests that mass transport of the Węgierka Marl deposits also filled some channels and that the channel filling is influenced by sea-level changes or short tectonic activities, which may trigger deposition of the Węgierka Marl mass transport deposits complex (Burzewski 1966; Geroch et al. 1979). Incision of the channels reflects direct changes in the slope equilibrium profile and may additionally suggest sea-level changes (e.g., Kneller 2003). The whole composite Manasterz section represents transition from lobe or channel off-axis facies alternating with inter-channel or overbank deposits of the Wiar Member to the MQ channel axis facies incised into the Węgierka Marl mass transport deposits complex of the Leszczyny Member.

Conclusions

1. Sandstones of the Manasterz Quarry represent channel axial or near axial facies with abundant amalgamation, coarse lag deposits, intra- and extrabasinal material. The studied section is dominated by deposits of high density turbidity currents (facies 1) with a smaller contribution of debrites (facies 2).
2. The Manasterz Quarry section represents channel-fill with total thickness of 31 m and width up to several hundreds of metres. The channel includes 5–6 storeys with debrite basal lag deposits at the bottom of storeys capped by channel turbidite fill. The basal lag deposits are 1–2 m thick, whereas the turbidite channel are 1.5–11.5 m thick. The channel-fill was formed by repeated deposition and amalgamation of turbidites and debrites.
3. Strong bypass, occurrence of lag deposits with material deriving from shallower zones and location relatively close to the northern margin of the Skole Basin suggest slope or base of slope setting of the Manasterz Quarry channel. The Manasterz Quarry deposits correspond to channel fill and amalgamation stage (Gardner et al. 2003; McHargue et al. 2011).
4. The section to the NE of the Manasterz Quarry represents levee or inter-channel deposits related to the Manasterz Quarry channel-fill. Its similar stratigraphic position and occurrence on the path of the palaeoflow direction of the Manasterz Quarry section are premises for sinuosity of the Manasterz Quarry channel.
5. The whole composite Manasterz section represents a transition from lobe off-axis or channel off-axis facies alternated with inter-channel or overbank deposits of the Wiar Member (lower Campanian–lower Maastrichtian) to the Manasterz Quarry channel axis facies incised into the Węgierka Marl mass transport deposits complex of the Leszczyny Member (lower Maastrichtian–lower Palaeocene).
6. The described channel architectural elements of the Ropianka Formation are located within the so-called Łańcut Channel Zone, which was previously proposed for the Oligocene sediments but may already be present in the Late Cretaceous.

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Supplementum

Table S1: Localization of studied samples

The Manasterz-Rzeki section:	49°56’7” N, 22°19’17” E
	49°56’8” N, 22°19’20” E
	49°56’8” N, 22°19’20” E
	49°56’9” N, 22°19’23” E
	49°56’10” N, 22°19’24” E
The Manasterz section:	49°55’36” N, 22°19’35” E
	49°55’37” N, 22°19’36” E
	49°55’38” N, 22°19’36” E
	49°55’38” N, 22°19’37” E
	49°55’38” N, 22°19’38” E
	49°55’40” N, 22°19’39” E
	49°55’40” N, 22°19’39” E
	49°55’41” N, 22°19’42” E
	49°55’42” N, 22°19’41” E
	49°55’43” N, 22°19’42” E
	49°55’45” N, 22°19’43” E
	49°55’45” N, 22°19’44” E
	49°55’46” N, 22°19’44” E
	49°55’40” N, 22°19’40” E
	49°55’39” N, 22°19’40” E
	49°55’39” N, 22°19’25” E
	49°55’40” N, 22°19’22” E
	49°55’40” N, 22°19’21” E
	49°55’40” N, 22°19’21” E
	49°55’40” N, 22°19’20” E
	49°55’40” N, 22°19’24” E
The Manasterz Quarry section:	49°55’21” N, 22°19’53” E