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Complex genesis of N-channel eskers illustrated with the example of an esker near Tosie (east-central Poland)

Złożoność genezy ozów powstałych w tunelach typu N na przykładzie ozu okolic Tosi (środkowo-wschodnia Polska)

Abstract

The study presents the problem of complex genesis of eskers formed in N-channels on the example of an esker located near Tosie in east-central Poland. The lithofacies analysis revealed a high diversity of structural and textural characteristics of sediments in this form. The esker consists of three sedimentation units. Coarse sediments of the esker core were deposited in the sub-environment of a subglacial tunnel, as an effect of bedforms migration under hydrostatic pressure. Opening of the tunnel resulted in the forming of an open crevasse, in which the cover of the esker core sediments was accumulated. These deposits recorded a significant variability of flow energy and sedimentation mechanisms, which indicates a strong influence of the ice-sheet ablation dynamics. During the final deglaciation stage, a part of the esker was covered with diamicton. Numerous soft-sediment deformation structures were identified within the esker. The sediments were dislocated vertically to the elevation of more than 8 metres. They constitute the record of buried dead-ice masses melting in the esker core sediments. Melting of the masses resulted in vertical displacement of sediments and formation of "the dead-ice structure". The complexity of esker genesis is characteristic of postglacial areas in Poland, where most eskers were formed in subglacial N-channels. Numerous research results confirm a considerably more frequent occurrence of the facies sequence of subglacial tunnel and open crevasse in eskers formed in N-channels than R-channels. This is indicated by a much greater dissimilarity of processes during different stages of esker formation on soft bed and solid substratum.

Keywords Esker, subglacial tunnel, open crevasse, glaciofluvial deposits, Saalian, Poland.

Zarys treści

Badania ukazują problem złożoności genezy ozów powstających w tunelach typu N na przykładzie ozu okolic Tosi w środkowo-wschodniej Polsce. Analiza litofacjalna wykazała duże zróżnicowanie strukturalnych i teksturalnych cech osadów tworzących formę. Oz zbudowany jest z trzech jednostek sedymentacyjnych. Gruboziarniste osady jądra ozowego powstawały w subśrodowisku tunelu subglacjalnego na skutek migracji form dna pod ciśnieniem hydrostatycznym. Otwarcie się tunelu spowodowało powstanie rozpadliny lodowej, w której następowała akumulacja jednostki pokrywającej osady jądra ozu. W osadach tych zapisała się znaczna zmienność energii przepływu oraz mechanizmów sedymentacji, co wskazuje na duży wpływ dynamiki ablacji lodowca. Podczas ostatniego etapu deglacjacji część ozu pokryta została diamiktonem. W ozie stwierdzono liczne struktury deformacyjne. Osady zostały przemieszczone pionowo na wysokość ponad 8 m. Stanowią one zapis wytapiania się pogrzebanych brył martwego lodu w osadach jądra ozu. Wytapianie się brył powodowało pionowe przemieszczanie się osadów i powstawanie tzw. *dead-ice structure*. Złożoność genezy ozów jest charakterystyczna dla obszarów polodowcowych Polski, gdzie większość ozów powstaje w rynnach subglacjalnych. Liczne badania potwierdzają znacznie częstsze występowanie następstwa facji subglacjalnego tunelu i otwartej rozpadliny w ozach powstających w tunelach typu N niż typu R. Wskazuje to na dużo większą odmienność procesów podczas różnych etapów formowania się ozów na nieskonsolidowanym oraz litym podłożu.

Słowa kluczowe Oz, tunel subglacjalny, rozpadlina lodowa, osady glacifluwialne, zlodowacenie warty, Polska.

1. Introduction

Eskers have constituted the objects of scientific research by many authors since the 19th century (Hummel 1874; De Geer 1897; Gregory 1921; Röthlisberger 1972; Banerjee and McDonald 1975; Shreve 1985; Gorrell and Shaw 1991; Clark and Walder 1994; Brennand 1994, 2000; Brennand and Shaw 1996; Fard 2002; Mäkinen 2003; Fard and Gruszka 2007; Burke *et al.* 2008, 2009, 2010, 2015; Gruszka and Van Loon 2011; Storrar *et al.* 2014ab, 2015; Dewald *et. al.* 2021, and others). They are commonly considered as glaciofluvial forms which originate within glaciers or ice sheets in subglacial or englacial tunnels and supraglacial channels. After deglaciation, they constitute elongated sandy-gravelly ridges with various degrees of sinuosity. On poorly permeable substrate, built mostly of solid rocks, R-channel eskers predominate (Röthlisberger 1972). These tunnels are formed in glacier bottom and the flow inside them takes place under hydrostatic pressure (Röthlisberger 1972; Brennand 1994, 2000). H-channels also originate upon solid substratum (Hooke 1984), cut into the bottom of the glacier, but sediment transport takes place under atmospheric pressure. They are not completely filled with water and are formed under thin ice. Where glacial water causes erosion of channels cut into the substratum, N-channel eskers are formed

(Nye 1973). Forms of this kind prevail in areas with substratum built of non-consolidated, sedimentary rocks. Such conditions dominate in the postglacial areas of Poland.

A review of studies into eskers reveals a great diversity of many of their characteristics, resulting from different circumstance of their development, which are often conditioned regionally. This is why regional studies seem to provide the key to understanding many research problems concerning eskers. A world-wide papers focused on eskers are dominated with studies related to landforms originating in areas with solid substratum as compared with those formed upon soft bed. Research conducted in N-channel eskers can still provide many new facts about sedimentation mechanisms and formation of eskers (Fard and Gruszka 2007; Salamon 2009; Roman 2016; Frydrych 2016, 2020).

Research for this article was conducted in an esker near the village of Tosie, within the extent of the Saalian Glaciation in east-central Poland. It was aimed at a sedimentological analysis of an esker formed in an N-type subglacial channel and reconstruction of its origin. Study results contribute to the discussion about the genesis of eskers and, in particular, about the differences in the formation of eskers in areas with solid and non-consolidated substratum.

2. Regional setting

The study area is located in east-central Poland (Fig. 1A), on the northern edge of the Siedlce Upland. It includes small eskers located near the village of Tosie. This area was most recently glaciated during the Late Saalian (Wartanian) glaciation (MIS 6) (Marks *et al.* 2016). The thickness of Quaternary sediments is 80–100 m. The eskers are surrounded by fluvioglacial plains and flat moraine plateaus. The thickness of glacial till is variable and reaches a maximum of approximately 35 m (Wrotek 2002). In some places, the plateaus are covered with sheets of glacial sands and gravels. Near the esker are small hummocks of dead-ice moraines and terminal moraines, built of sands, gravels and boulders (Fig. 1B). The area has numerous aeolian forms (Fig. 1B, 1C).

According to Wrotek (1998), there are 4 esker ridges in the analysed area, separated with a dead-ice moraine. The north-eastern (I) and south-western (II) sections constitute a form with a total length of 2 km (Fig. 1C). This main ridge of the form has a sinuosity of 1.1. Its width ranges from approx. 70 to 130 m. The axis of the form is oriented in the N–S direction (Fig. 1B, 1C). The orientation of the 580-metre long north-western section (III) is NW–SE and it is a tributary of the main ridge. The length of the south-eastern section (IV) is 800 m and it is not clearly connected with the remaining segments (Fig. 1C). The relative heights are small and reach approx. 5 m. The northern and southern parts of the main ridge have a clearly noticeable crest and symmetrical slopes. Esker sediments reaches a thickness of more than 20 m (Fig. 1D). Drillings data and morphology of the forms indicate that the channels are narrow and their slopes are steep, particularly in the case of the channel of the western main ridge. The contemporary surface of the eskers has been strongly transformed by numerous quarries. The research was conducted in the only operating pit in the southern part of the main ridge (Fig. 1C).

3. Materials and methods

The research was conducted in an outcrop in the main ridge of the esker (Fig. 1C). Lithofacial characteristics of the esker sediments were prepared on the basis of structural and textural features, which were presented in log profiles, with the use of Miall's lithofacies code (1977) as modified by Zieliński and Pisarska-Jamroży (2012) – Table 1. Directions of palaeoflows were determined on the basis of orientation of layers and clast fabric. The mean vector (V1, MV) and eigenvalues (S1, S3) were calculated. Orientation of faults and deformation structures were measured. Grain-size distribution was analysed using the sieve method, direct measurements in the outcrop and Automated Grain Sizing (AGS) using the Digital Gravelometer software (Graham *et al.* 2005). To obtain quantitative information on the conditions present during the esker formation, palaeohydraulic analysis was carried out. Critical shear stress (τ_{cr}) was established using the formula for gravel bottom according to Costa (1983): $\tau_{cr} = 0.16\,D_{MPS}{}^{1,21}$, where: τ_{cr} – Pa, D_{MPS} – mean size of 10 largest clasts in mm. Water flow velocity was estimated from the following formulae: $V_{av} = 0.18\,D^{0,487}$ (Costa 1983), where: V_{av} – mean critical flow velocity in m s^{-1}, D – mean size of 5 largest clasts in mm, and $V_{av} = V_1/V_2$, $V_1 = 0.065D_{95}{}^{0,5}$, $V_2 = 0.46D_{95}{}^{0,5}$ (Wiliams 1983), where: V_{av} – mean flow velocity in m s^{-1}, V_1 and V_2 – critical flow rates in m s^{-1}, D_{95} – 95th percentile of the sediment's grain size distribution.

Table 1. Lithofacies code used in the study after Miall (1977) with modifications by Zieliński i Pisarska-Jamroży (2012)

Tabela 1. Zastosowany kod litofacjalny według Mialla (1977) w modyfikacji Zielińskiego i Pisarskiej-Jamroży (2012)

Code	Texture	Structure
Gm, GSm	gravel, sandy gravel	massive
SGm, Sm	gravelly sand, sand	massive
Gp, GSp, SGp	gravel, sandy gravel, gravelly sand	planar cross--stratification
Gt, GSt, SGt	gravel, sandy gravel, gravelly sand	trough cross--stratification
Sx	sand	cross-stratification
Gh, GSh	gravel, sandy gravel	horizontal stratification
SGh, Sh	gravelly sand, sand	horizontal stratification
Sr	sand	ripple cross-lamination
Gd, Sd	gravel, sand	deformed
SFd, FSd, Fd	sand and fines, sandy fines, fines	deformed
Dd	diamicton	deformed

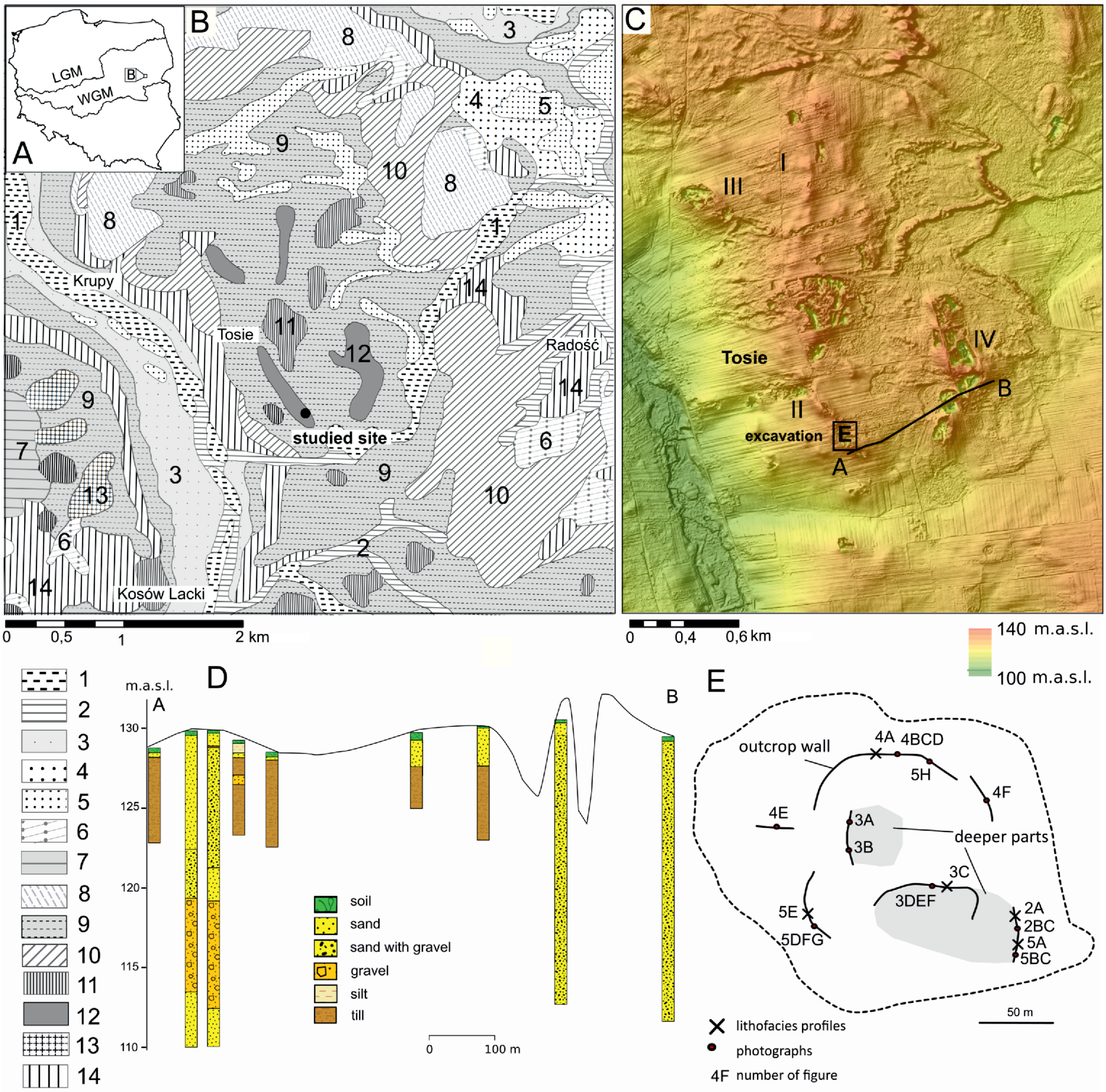

Fig. 1. Study area: A – study area at the background of the extent of glaciations: LGM – Late Glacial Maximum, WGM – maximum extent of the Late Saalian (Wartanian) glaciation; B – geological structure of the study area (Wrotek 1998); 1 – peats, 2 – sands, gravels and mud of valleys and flood plains, 3 – fluvial sands and gravels of high terraces, 4 – aeolian sands, 5 – aeolian sands in dunes, 6 – eluvial sands, 7 – glaciolacustrine sands, silts, clays and tills, 8 – fluvioglacial sands, gravels and tills, 9 – fluvioglacial sands and gravels, 10 – fluvioglacial sands and gravels on till, 11 – sands, gravels, boulders and glacial till of dead-ice moraines, 12 – esker sands and gravels, 13 – sands, gravels, boulders and tills of terminal moraines, 14 – glacial tills; C – terrain map of the study area; D – geological profiles in the transverse profile through esker ridges (based on data from The Central Geological Database of Polish Geological Institute) – visible cut of the subglacial tunnel sediments into the diamicton sediments; E – sketch of the outcrop with marked lithofacies profiles and photographs presented in the article

Ryc. 1. Obszar badań: A – obszar badań na tle zasięgów zlodowaceń: LGM – zlodowacenie wisły, WGM – zlodowacenie warty; B – budowa geologiczna obszaru badań (Wrotek 1998); 1 – torfy, 2 – piaski, żwiry i namuły den dolinnych, 3 – piaski i żwiry rzeczne teras nadzalewowych, 4 – piaski eoliczne, 5 – piaski eoliczne w wydmach, 6 – piaski eluwialne, 7 – piaski, muły, iły i gliny wytopiskowe, 8 – piaski, żwiry i gliny wodnolodowcowe, 9 – piaski i żwiry wodnolodowcowe, 10 – piaski i żwiry wodnolodowcowe na glinie, 11 – piaski, żwiry, głazy i gliny zwałowe moren martwego lodu, 12 – piaski i żwiry ozów, 13 – piaski, żwiry, głazy i gliny moren czołowych, 14 – gliny lodowcowe; C – ukształtowanie terenu obszaru badań; D – profile geologiczne w profilu poprzecznym przez wały ozowe (na podstawie danych z Centralnej Bazy Danych Geologicznych Państwowego Instytutu Geologicznego) – widoczne wcięcie osadów rynny subglacjalnej w osady diamiktonowe; E – szkic odsłonięcia z zaznaczonymi profilami litofacjalnymi oraz fotografiami zaprezentowanymi w artykule

4. Results

4.1. The esker core deposits (Unit TS1)

Unit TS1 forms the lower part of the lithofacies profile revealed in the outcrop. It is mainly made of gravelly lithofacies of horizontally and planar cross-stratified gravels, sandy gravels and massive matrix- to clast-supported gravels (Fig. 2A–C, Fig. 3A–E).

Large scale planar cross-stratified gravels and sandy gravels – Thickness of the Gp and GSp lithofacies in the outcrop exceeds 3 m. A clear vertical variability of grading is noticeable (Fig. 2B). Gravels are mostly matrix-supported and poorly sorted (Fig. 2C). In some places the sorting is better, and the gravels are clast-supported. There are some lenses of openwork gravels with normal and reverse grading. The MPS fluctuates from approx. 10 to 27 cm. The sediments contain some boulders, whose diameters exceed 30 cm (Fig. 2B). In the upper part of the unit, the content of sand increases and the GSp and SGp lithofacies are present. Elongated clasts are oriented towards NNW–SSE, i.e. in accordance with the direction of the stratifications.

Massive matrix- to clast-supported gravels – Sediments of Gm and GSm lithofacies are revealed at places in the deepest part of the outcrop along a section of approximately 10 metres. Diverse sediments are visible from matrix-supported gravels (with clasts of up to 30 cm in diameter) to clast-supported gravels (with diameters not exceeding 10 cm). Thickness of the sediments is more than 3 m (Fig. 3AB).

Horizontally stratified gravels and sandy gravels – Thickness of the Gh and GSh lithofacies visible in the outcrop reaches approx. 4 m. It shows extremely variable sorting of sediments (Fig. 3D). Gravels are matrix-supported to clast-supported. The content of sandy fraction is 5–32%. There are lenses and interbeddings of openwork gravels. Grading is polymodal and bimodal. In finer gravels, there are numerous boulders (Fig. 3E). Diameters of the largest documented boulders reach 34 cm, whereas the MPS is 27.2 cm. Clast orientation displays a NE–SW direction. Vertical continuity of sediments in the central part of the outcrop is broken by discordance between them and sediments of unit TS2 (described below) (Fig. 3F). Sediments in the contact zone with unit TS2 reveal an inclination (up to 20°) towards the west.

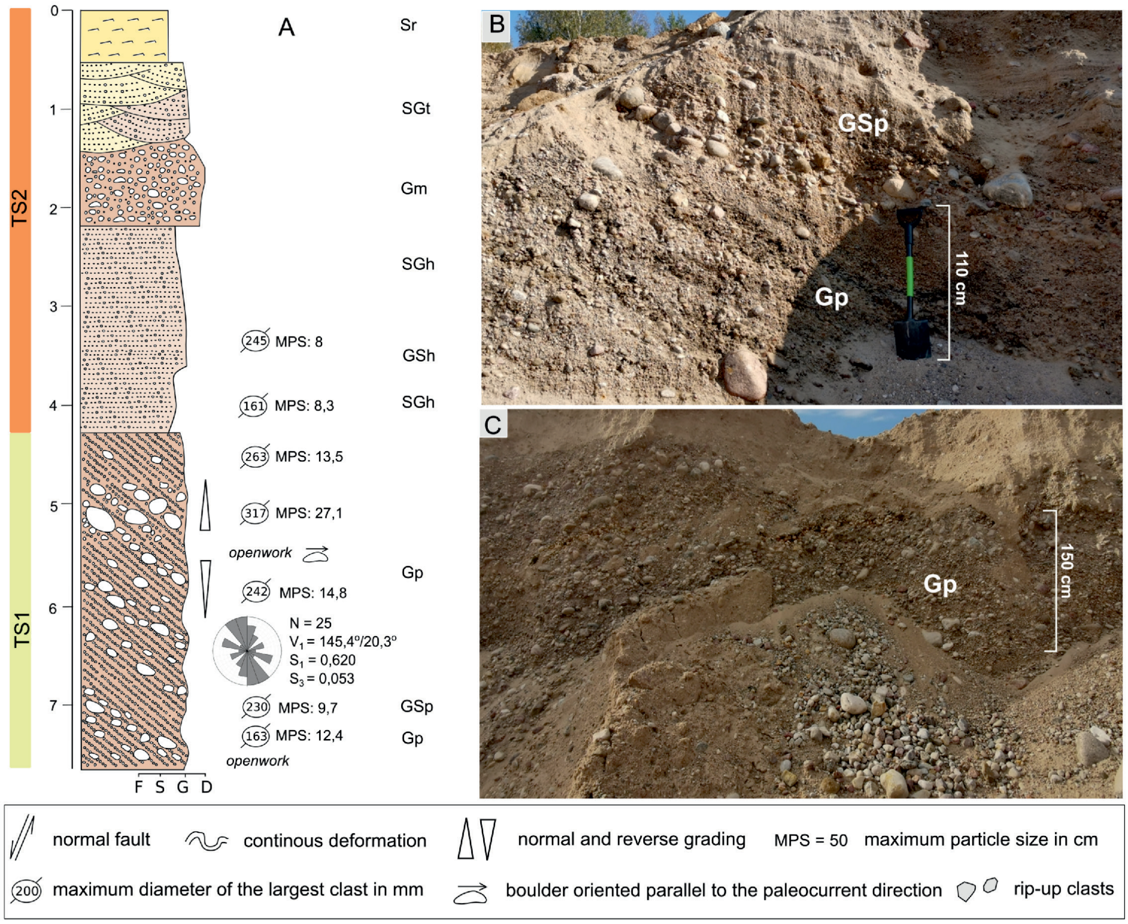

Fig. 2. Sediments of units TS1 and TS2: A – lithofacies profile of sediments, rose diagram of clast fabric in Gp, B – planar cross-stratified gravels with single boulders and sandy gravels, C – matrix-supported planar cross-stratified gravels; the legend applies to all the following profiles

Ryc. 2. Osady jednostek TS1 i TS2: A – profil litofacjalny osadów, róża wiatrów orientacji klastów w Gp, B – przekątnie płasko warstwowane żwiry z pojedynczymi głazami i żwiry piaszczyste, C – przekątnie płasko warstwowane żwiry z rozproszonym szkieletem ziarnowym; legenda dla wszystkich zamieszczonych profili

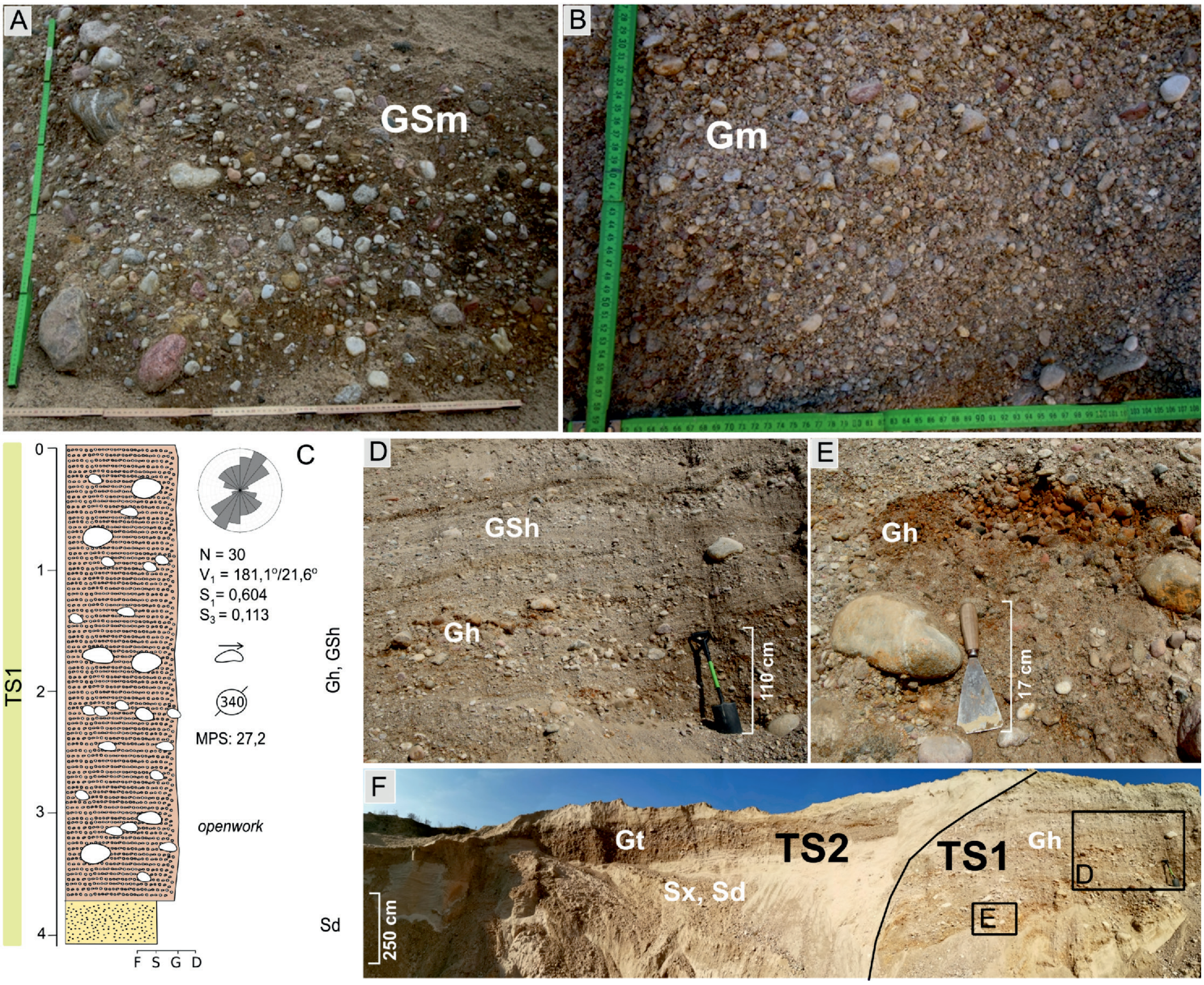

Fig. 3. Sediments of units TS1 and TS2: A – massive matrix-supported gravels, B – massive clast-supported gravels, C – lithofacies profile of sediments of unit TS1, rose diagram od clast fabric in Gh, D – inclined strata of horizontally stratified gravels, E – clast-supported horizontally stratified gravels, F – contact of deformed sediments of unit TS2 with sediments of horizontally stratified gravels of unit TS1

Ryc. 3. Osady jednostek TS1 i TS2: A – piaszczyste żwiry o masywnej strukturze, B – masywne żwiry, C – profil litofacjalny osadów jednostki TS1, róża wiatrów orientacji klastów w Gh, D – pochylone warstwy horyzontalnie warstwowanych żwirów, E – żwiry warstwowane horyzontalnie ze zwartym szkieletem ziarnowym, F – kontakt zaburzonych osadów jednostki TS2 z osadami warstwowanych horyzontalnie żwirów jednostki TS1

4.2. The core mantling deposits (Unit TS2)

Unit TS2 is characterised by the occurrence of a greater variety of sediments and the presence of deformations. Its bottom is irregular and in the central part of the outcrop, there is discordance between the sediments of unit TS2 and TS1.

Horizontally stratified sands and gravels and cross--stratified sands – Directly above the sediments of unit TS1 are sands and sandy gravels: SGh, GSh, Sx, Sd (Fig. 2A, Fig. 3F). In the western part of the form, sediments of this series are characterised by finer grading than in the eastern part (mainly Sx and Sd) and a significant number of faults (Fig. 3F). The sands are well sorted. Sediments were displaced vertically by approx. 4 m there. A deformation zone covers sediments with partially deformed and partially original structure developed. Due to the deformations, it is difficult to determine the thickness of sediments, which exceeds 2 m in the outcrop. In the eastern part of the outcrop, above unit TS1, there are cross and horizontally stratified sands and sands with gravel SGh, Sx, and gravels with sand GSh (Fig. 2A, Fig. 4A). Sx sediments are inclined to the east at an angle of 10–30°. Their thickness is 1–1.5 m. The thickness of SGh and GSh sediments is variable and reaches 2 m. In some places, they are covered with massive gravels.

Trough cross-stratified gravels and sandy gravels – The higher medium and large scale lithofacies Gt, GSt, SGt, whose thickness reaches 2 m, were also vertically displaced (Fig. 3F). They are characterised by high diversity as regards sediment sorting. The sediments are matrix--supported to clast-supported (Fig. 4B). In some places, openwork gravels are present. Grain-size distribution is polymodal or bimodal. Normal fractional grading occurs. Clast diameters in this series exceed 25 cm. Normal faults with throw values of >1 m are present.

Massive matrix to clast-supported gravels – Above the Gt and SGt lithofacies, alternating strata of gravels and sands with silts occur, in which there are strong disturbances (Fig. 4A–C, Fig. 5D–H). The minimum thickness of the lowest stratum of gravels is 1.5 m. They are massive matrix to clast-supported gravels GSm, Gm (Fig. 5EF). They are characterised by poor or very poor sorting and MPS of 15–18 cm. Grain size distribution is polymodal. The content of fraction finer than sand is 1–3%. In these sediments, openwork gravels were identified as well as individual rip-up clasts (Fig. 5D). Clasts are oriented towards the W–E direction. In some places, they include Gp and Gh lithofacies with thickness of up to 20 cm (Fig. 4A). Normal and reverse faults occur in sediments. Locally the strata were deflected, and their continuity was not broken (Fig. 4B).

Sands and sandy silts – Gravelly sediments are separated with lithofacies of ripple, massive or deformed sands and silts: Sr, Sm, SFd, FSd (Fig. 4BD, Fig. 5GH). Fine and very fine, poorly sorted sands prevail. They occur in two sets, separated with sediments of horizontally stratified gravels. Owing to the exploitation, the upper set is revealed only fragmentarily. The thickness of the Sr lithofacies reaches 70 cm, whereas that of Sm – up to 2 m. There are zones of deformed and non-deformed sediments in them. In the deformed zones are numerous faults and the sediments were dislocated to the height of 1.5 m (Fig. 4B). In the marginal part of the deformation zones, there are major faults (oppositely directed, normal and reverse). The faults form horst and graben structures (Fig. 4C).

Horizontally stratified gravels – The first set of ripple cross-laminated sands is covered with horizontally stratified gravels Gh. Their thickness reaches approx. 1 m (Fig. 4AB). They are characterised by poor sorting and polymodal grain size distribution. They are revealed only fragmentarily.

The averages of mean grain diameter, sorting and skewness of analysed lithofacies show wide variety of that parameters. Fig. 6 shows the diversity of sediment grading.

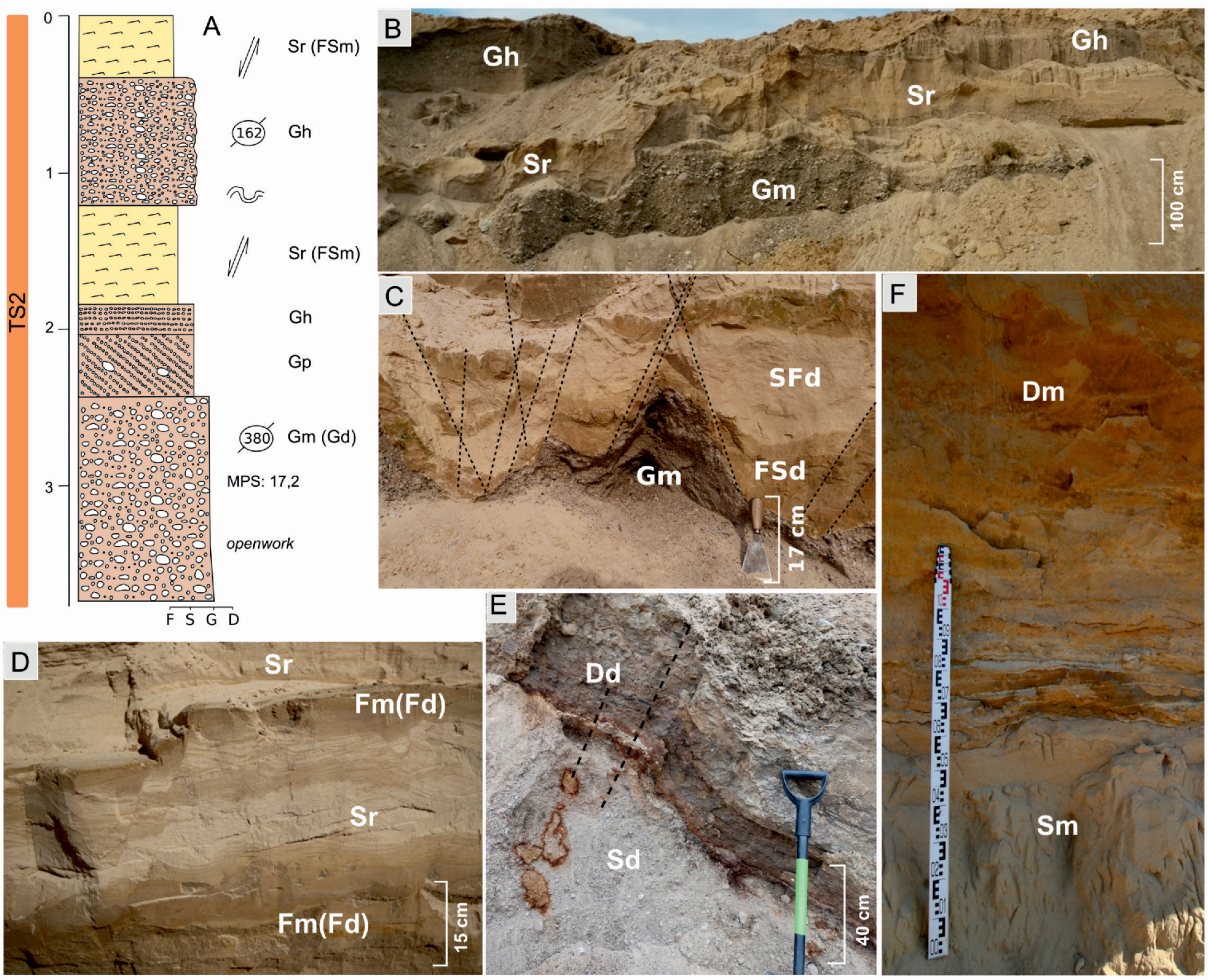

Fig. 4. Sediments of unit TS2 and TS3: A – lithofacies profile of sediments TS2, B – fragment of the upper part of unit TS2, C – deformed gravels, D – lithofacies of ripple cross-laminated sands and massive or deformed silts, E – contact between deformed sands and deformed diamicton (TS3), F – contact between massive sands and diamicton (TS3)

Ryc. 4. Osady jednostki TS2 i TS3: A – profil litofacjalny osadów TS2, B – fragment górnej części jednostki TS2, C – zdeformowane żwiry, D – litofacje przekątnie riplemarkowo laminowanych piasków oraz masywnych i zdeformowanych mułków, E – kontakt pomiędzy zdeformowanymi piaskami i zdeformowanym diamiktonem (TS3), F – kontakt pomiędzy masywnymi piaskami i diamiktonem (TS3)

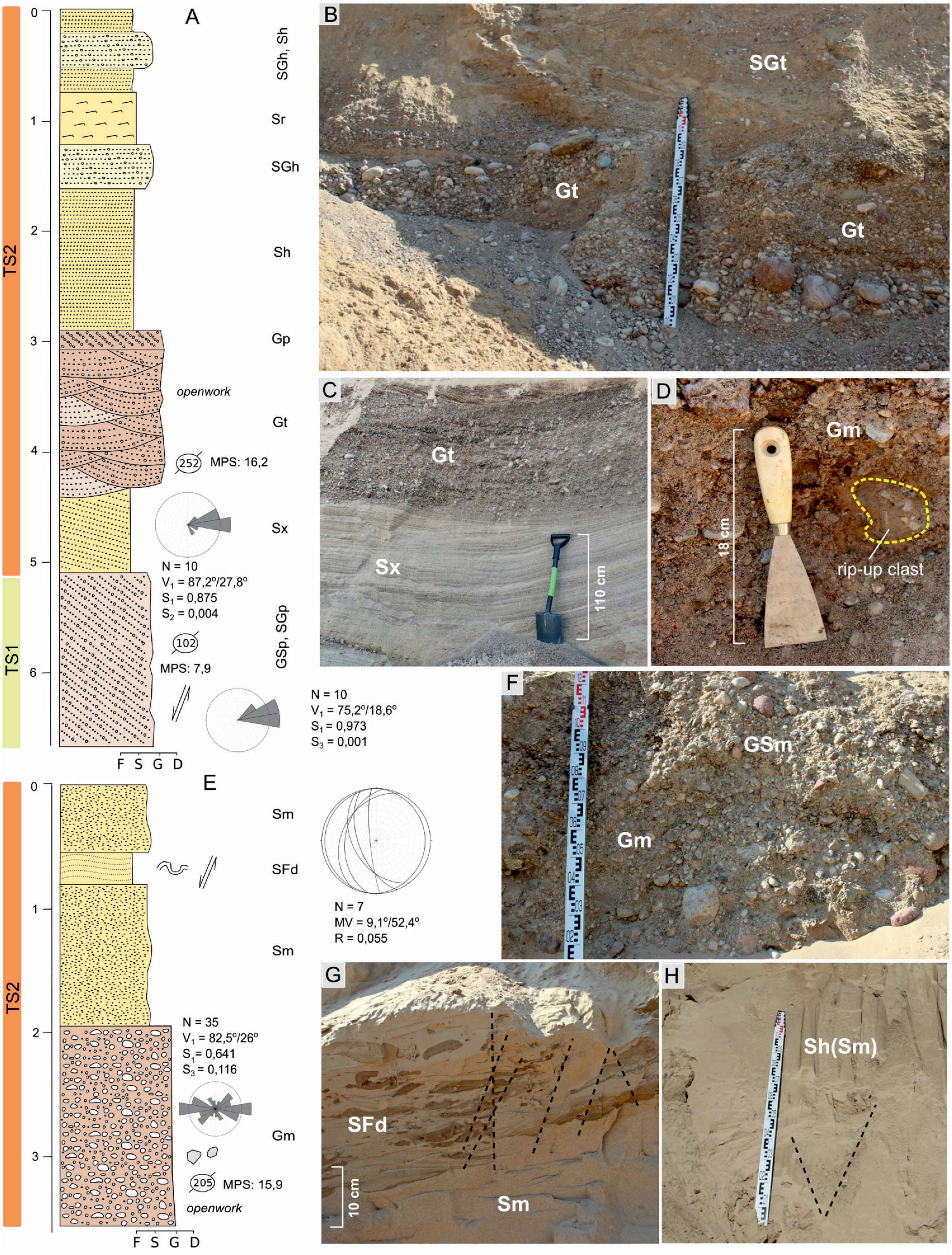

Fig. 5. Sediments of units TS1 and TS2: A – lithofacies profile of sediments of units TS1 and TS2, wind rose indicates orientation of cross stratification sediments, diagram of fault orientation, B – trough cross-stratified sands with gravel and gravels, locally clast-supported, C – cross-stratified sands and trough stratified gravels, D – rip-up clast in massive gravels, E – lithofacies profile of sediments of unit TS2, F – matrix-supported massive gravels, G – discontinued stratum of silts and sands with silts, cut with faults, H – horizontally stratified and massive sands

Ryc. 5. Osady jednostek TS1 i TS2: A – profil litofacjalny osadów jednostek TS1 i TS2, róża wiatrów pokazuje orientację osadów przekątnego warstwowania, diagram orientacji uskoków, B – przekątnie rynnowo warstwowane piaski ze żwirem i żwiry z lokalnie zwartym szkieletem ziarnowym, C – przekątnie warstwowane piaski oraz żwiry warstwowane rynnowo, D – intraklasty w masywnych żwirach, E – profil litofacjalny osadów jednostki TS2, F – żwiry masywne z rozproszonym szkieletem ziarnowym, G – porozrywana i poprzecinana uskokami warstwa mułków i piasków z mułkami, H – masywne i horyzontalnie warstwowane piaski

4.3. Diamicton cover (Unit TS3)

In the western part of the mine, a 1.5-metre-thick diamicton Dd is exposed. Its horizontal range reaches 4 m. It is characterised by brown and grey colour with streaking (Fig. 4E). It covers deformed sands and sands with gravel. Its bottom is undulated and deformed. The lower part of the diamicton is characterised by pseudo-stratification and fluidal structures corresponding to the boundary with sands (Fig. 4E). The diamicton is clayey with a gravely fraction. In the eastern part of the outcrop, a stratum of massive, sandy diamicton overlays the sediments of massive sands, deformed at places. Its thickness reaches 2 m (Fig. 4F). In the lower part of the sediements vague stratification is visible. There are also interbeddings of massive sand (Fig. 4F).

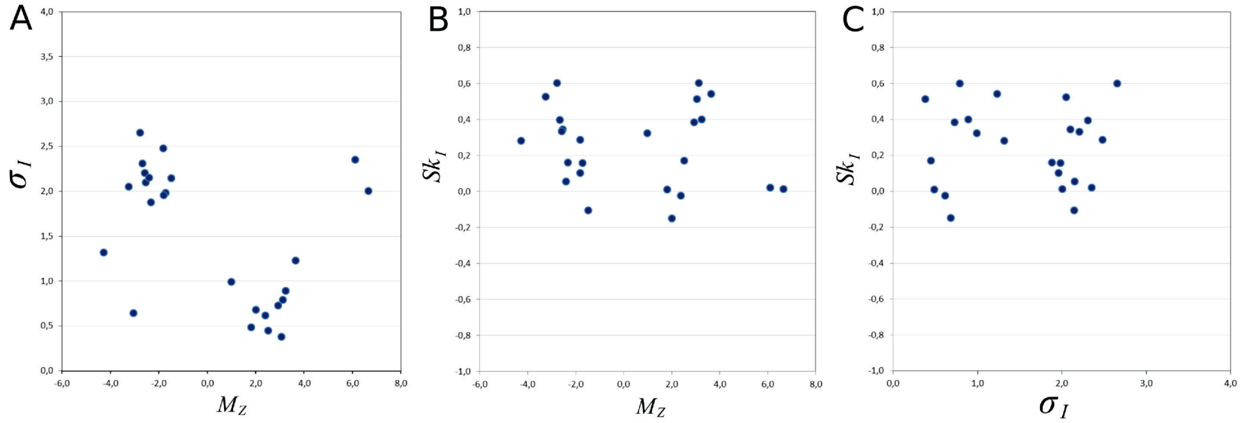

Fig. 6. Textural characteristics of sediments of the Tosie esker: A – ratio of sediment sorting to the mean grain diameter, B – ratio of skewness to mean grain diameter, C – ratio of skewness to sorting

Ryc. 6. Cechy teksturalne osadów ozu w Tosi: A – stosunek wysortowania osadów do średniej średnicy ziaren, B – stosunek skośności do średniej średnicy ziaren, C – stosunek skośności do wysortowania

5. Discussion

5.1 Interpretation of sediments

5.1.1. Interpretation of the esker core deposits (Unit TS1)

Accumulation of sediments of unit TS1 took place in a N-type subglacial channel (Nye 1976), which had been preceded with subglacial water erosion. This is indicated by clear rooting of the form in relation to the neighbouring plateau (Fig. 1D). GSm and Gm sediments are similar to the lithofacies described by Brennand (1994) as heterogeneous gravels, interpreted as an effect of accumulation under hydrostatic pressure in an enclosed glacial tunnel. They appear in composite macroforms and pseudoanticlinal macroforms documented in esker cores (Brenannd 1994; Brennand and Shaw 1996). Gh and GSh lithofacies were accumulated in the conditions of upper plane bed from a traction carpet and formed gravel sheets. They also might have created macroforms typical of subglacial channels (Brennand, Shaw 1996). The water flow rate exceeded 4 m s^{-1} and the shear stress was 140 Pa. Large scale Gp and GSp sediments with varied sorting are interpreted as a record of progradation of gravelly bars in deep channels with high-energy flow (Baker 1978; Carling 1996). Brennand (1994) and Brennand and Shaw (1996) interpret such sediments in the subglacial environments as a record of composite macroforms originating through progradation of their front towards the broadening of the subglacial tunnel. Accumulation of these sediments took place when the channel was completely filled with water (Brennand 1994). Variable grading and sorting of sediments in vertical profile indicate temporary changes of the conditions of transport and sedimentation. Poor sorting of sediments provides evidence for rapid aggradation (Smith 1986). The presence of reverse and normal grading is a record of increases and reductions of flow competence during high levels of ablation water (Maizels 1997; Russell and Knudsen 2002). Flow rates ranged from 2 to more than 4 m s^{-1} and shear stress ranged in the interval of 60–140 Pa. These values are typical measured characteristics of the esker core (Frydrych 2020). Sediments of unit TS1 were formed during high-energy flows with rich material supply, which is indicated by high thickness and coarseness of the sediments (Russell *et al.* 2001).

5.1.2. Interpretation of the core mantling deposits (Unit TS2)

The beginning of sedimentation of unit TS2 is related to a decrease of energy and accumulation of sediments in the conditions of flat upper bed and migration of channel forms (lithofacies: SGh, GSh and Sx). Reduced flow energy was probably related to changed conditions in the channel and free water flow under atmospheric pressure. The majority of sediments of unit TS2 lack any signs of accumulation under hydrostatic pressure (Brennand 1994; Fard and Gruszka 2007). Lithofacies Gt, SGt and SGt were formed as a result of migration of three-dimensional megaripples in channels of 2–10 m in depth.

During the formation of the upper part of unit TS2, sudden increases in flow energy and accumulation of Gm and Gh lithofacies alternated with flow competence reductions and low energy flows responsible for the formation of the Sr lithofacies. Interbedding of the Sr lithofacies in esker sediments is interpreted as a result of the presence of pulsations in glacial water flow (Huddart *et al.* 1999; Fard 2002) or blockages in water at certain sections (Ashmore 1991). Periodically, stagnant-water bodies were formed, in which silts were accumulated. During more violent flows, older sediments were eroded, and rip-up clasts got incorporated into the gravels. Their presence, as well as the massive structure and poor sorting of the Gm lithofacies may provide evidence for accumulation from hyperconcentrated flow (Smith 1986; Maizels 1997; Pisarska-Jamroży and Zieliński 2012). Flow rate values were estimated at 2–3 ms^{-1} and critical shear stress at approx. 80 Pa. Rhythmical occurrence of gravels and sands in eskers is interpreted as seasonal variability of accumulation conditions related with ice-sheet ablation (Banerjee and McDonald 1975; Ringrose 1982) or episodic floods (Shaw 1972; Nye 1976).

Strong deformations in the form of faults and vertical dislocation of sediments to the elevation of more than 8 m are most probably the record of melting buried dead--ice masses in esker sediments. Ice masses were buried during accumulation of unit TS1, which is indicated by the nearly vertical contact between its sediments and the overlying unit TS2 at some locations (Fig. 3F). After losing the support, sediments were displaced downwards and formed the graben-like structure. Such deformations in esker sediments caused by buried dead ice masses have also been identified in other studies (Brennand and Shaw 1996; Gruszka and Van Loon 2011).

5.1.3. Interpretation of the diamicton cover (Unit TS3)

During the retreat of ice walls, sediment flows occurred and part of the slopes were covered with flow diamicton. The presence of fluidal structures and deformations within the diamicton provides evidence for flow, as does its very irregular bottom, corresponding to the slopes of the form (Bennett and Glasser 2009). Its weight resulted in the appearance of deformations in the underlying – most probably water--saturated – sands. A part of the form was in turn covered with a thick diamicton cover in the form of melt-out till. Such an interpretation is supported by thickness of the sediment, location in the marginal part of the form, massive structure and occurrence of stratification in the lower part of the diamicton (Evans *et al.* 2006; Bennett and Glasser 2009).

5.2. The depositional model of the Tosie esker

The esker in Tosie originated in an N-type subglacial channel (Nye 1973), whose depth reaches 20 m. Its formation had been preceded by cutting a channel in glacial sediments, as a result of erosional activity of glacial meltwater (Fig. 7A).

At the first stage of formation, accumulation took place in a closed subglacial tunnel, completely filled with water (Fig. 7B). Deposition took place in the conditions of upper plane bed and as an effect of migration of composite macroforms (Brennand 1994; Brennand and Shaw 1996). Coarse sediments typical of esker cores were accumulated (Saunderson 1975; Gorrel and Shaw 1991; Fard and Gruszka 2007; Ahokangas and Mäkinen 2014). The flows were high in energy. Periodic subglacial floods occured, during which the flow rate might have exceeded 4 m s^{-1}. At this stage of the functioning of the channel, the ice roof fell or collapsed of at a certain section. It might have been caused by rapid melting of the ice-sheet and its strong fracturing, or by broadening of the tunnel as a result of high energy of the water flow (Lundqvist 1997; Fard 2002). As regards the place and time of the fall, two scenarios can be distinguished:

(1) The fall occurred at the location of the contemporary outcrop, and the blocks were set and buried at the location of the fall.

(2) The fall took place in the upper part of the tunnel, and the ice-blocks were transported by glacial water and deposited downflow from the location of the fall (where the contemporary outcrop is found). The second scenario is favoured by the sedimentational continuity of deposits in which the ice-blocks were buried. During accumulation and burying of the ice-blocks, the flow conditions were still typical of subglacial channels. Thus, there is no evidence for simultaneous opening of the tunnel with the accumulation of ice-blocks. Besides, no deformations were identified which might be linked to the fall itself, which can have a strong effect on esker sediments (Gruszka and Van Loon 2011; Frydrych 2020).

Soon after burying the ice-blocks, there was a sudden drop in the water flow energy and accumulation of much finer sediments began. This sudden change may be related to the formation of a crevasse in the roof of the channel and transition from hydrostatic flow to atmospheric one (Frydrych 2020). Further accumulation took place in a narrow ice-walled channel as a result of migration of bedforms (Fig. 7C).

Continuing ice-sheet decay resulted in broadening of the channel. The flow conditions, which constitute a record of the changing rate of ice-sheet ablation, were very variable (Banerjee and McDonald 1975; Ringrose 1982). High water levels alternated with periods of low energy flow. The occurrence of floods is indicated by the presence of massive gravelly lithofacies with poor sorting and rip-up clasts (Maizels 1989; Russell and Knudsen 1999; Russell *et al.* 2001). It is probable that the flow was hyperconcentrated (Nemec and Steel 1984; Maizels 1997). They were separated by periods of slow water flow and short-term glacilacustrine accumulation (Fig. 7D).

During the melt-out of ice walls, releases of ablation material and partial covering of the esker slopes with flow till occurred. After sediment deposition ceased, gradual melt-out of ice blocks buried in the sediments of the esker core began. Concluding from the sediment profile at locations where no deformations were identified, the ice-blocks were covered with sediments at least 8 m thick. Melt-out of the blocks resulted in dislocation of the sediments and origination of numerous deformations with the character of dead-ice structures (Van Loon 2009) (Fig. 7E).

The model of esker sedimentation indicates its complex genesis and origination in different sedimentation sub-environments. The esker is built of sediments of subglacial channel facies and facies of open crevasse. Many eskers in Poland reveal a similar sequence of sedimentation units (Michalska 1969; Wysota 1990; Buraczyński and Superson 1992; Jaksa and Rdzany 2002; Fard and Gruszka 2007; Roman 2016; Frydrych 2016, 2020). Such a development of sediment profiles is much less frequently found in the structure of eskers in the Fennoscandian Peninsula or Canada, where the majority of eskers were formed in R-channels (Brennand 2000; Storrar 2014; Lewington *et al.* 2020a, 2020b).

Structural and textural characteristics of sediments which are typical of the subglacial environment have been broadly discussed in the literature (Gorrell and Shaw 1991; Brennand 1994; Brennand and Shaw 1996; Shulmeister 1989; Delaney 2001; Fard and Gruszka 2007; Ahokangas and Mäkinen 2014). The sediments were documented in the majority of eskers and include massive clast-supported gravels with openwork texture or bimodality, sliding-bed facies, heterogeneous gravels, planar-cross stratified gravels and boulders in composite macroforms and pseudoanticlinal macroforms (Saunderson 1977; Wysota 1990; Buraczyński and Superson 1992; Gorrell and Shaw 1991; Brennand 1994, Brennand and Shaw 1996; Fard and Gruszka 2007; Ahokangas and Mäkinen 2014; Roman 2016; Frydrych 2020). The most frequent forms of eskers located in the territory of Canada include the following: (1) long esker ridges built of sediments accumulated in subglacial conditions in R-channels (Brennand 1994; Brennand 2000; Storrar 2014; Lewington *et al.* 2020a, 2020b; Sharpe *et al.* 2021), (2) short eskers or esker beds interpreted as the record of time-transgressive eskers with characteristics of subaqueous or subaerial fans (Banerjee and McDonald 1975; Cheel and Rust 1982, 1986; Henderson 1988; Gorrell and Shaw 1991; Brennand 1994; Lewington *et al.* 2020a, 2020b; Livingstone *et al.* 2020), (3) eskers with lateral splay (Lewington *et al.* 2020a, 2020b). Long esker ridges formed in R-channels are usually built of sediments of the subglacial facies. Sediments interpreted as accumulated under atmospheric pressure are mostly linked to deposition in H-channels (Hooke 1984; Brennand 1994, 2000) or open channels near ice margin where e.g. sliding-bed facies are formed (Saunderson 1977; Ringrose 1982; Gorrell and Shaw 1991; Brennand 2000). Brennand (1994) reports that there are eskers which form kame-esker complexes, although such forms should be treated as exceptions rather than the rule of esker dewelopment in R-channels (Brennand 2000; Lewington *et al.* 2020a, 2020b; Livingstone *et al.* 2020; Sharpe 2021). An opposite situation occurs in the territory of Poland, especially within the extent of the Saalian Glaciation, where eskers built exclusively of the subglacial facies or ones which form fans occur less frequently (Frydrych 2020). This indicates a different model of esker formation not only at the initial stage of origination of the subglacial channel but also at the final stage of form accumulation.

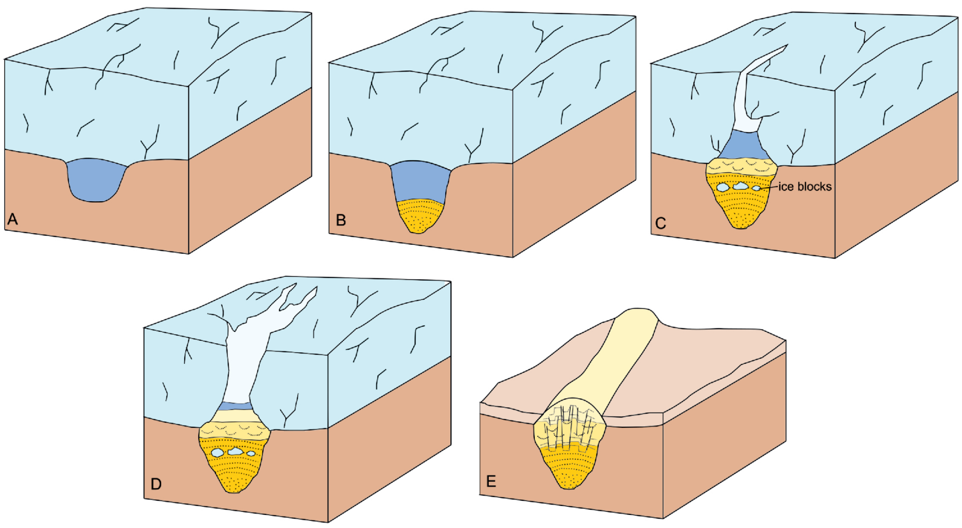

Fig. 7. Stages of formation of the Tosie esker: A – erosion of a subglacial channel, B – accumulation in the channel under hydrostatic pressure, C – fall from the channel roof and burying of dead ice blocks, accumulation in the expanded channel under atmospheric pressure, D – accumulation in a narrow ice-walled channel, E – melting of dead ice blocks and formation of "dead-ice structures"

Ryc. 7. Etapy kształtowania ozu w Tosiach: A – erozja rynny subglacjalnej, B – akumulacja w kanale pod ciśnieniem hydrostatycznym, C – obryw stropu kanału i pogrzebanie brył martwego lodu, akumulacja w powiększonym kanale pod ciśnieniem atmosferycznym, D – akumulacja w rozpadlinie lodowej, E – wytapianie brył martwego lodu i powstanie *dead-ice structures*

6. Conclusions

The analysed esker in Tosie is an example of an N-channel form on non-consolidated substratum. It consists of three sedimentation units:

(1) The esker core deposits, dominated by coarse-grained sediments of massive and horizontally and cross-stratified gravels.

(2) The core mantling deposits – the unit which consists of alternating strata of coarse and fine sediments, which constitute a record of changing ice-sheet ablation. It is dominated by massive and stratified gravels, separated by sandy and silty deposits with massive structure, horizontal or ripple lamination.

(3) The diamicton cover, occurring at places, in the form of melt-out till and flow till.

The formation of esker in Tosie took place in several stages: (1) formation of a subglacial tunnel as a result of subglacial water erosion, (2) accumulation of coarse sediments in the conditions of high-energy flows under hydrostatic pressure, (3) collapse of tunnel roof and burial of ice blocks, (4) accumulation of sediments under atmospheric pressure in an ice-walled channel, (5) melting of buried dead-ice blocks and formation of dead-ice structures.

Significant changes in the mode of sediment transport and deposition indicate high dynamics of the esker sedimentation environment. The complex cycle of esker formation, initially in a subglacial channel and later in an open crevasse, is typical of forms in the area of the Saalian Glaciation in Poland. This way of esker formation occurs much more frequently in N-channel forms than R-channel ones. This indicates a much greater difference in the origination of these forms both at the initial and the final stage of their accumulation.

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