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CLASSIFICATION OF ESKER MORPHOLOGY ON SOFT BEDS IN THE AREA OF THE SAALIAN AND ELSTERIAN GLACIATIONS IN POLAND

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Abstract. The study provides a morphologic classification of eskers formed on a soft bed in Poland during the Saalian and Elsterian Glaciations. The classification is based on morphometry, including esker fragmentation, length, sinuosity, ridge elongation and presence of tributary ridges. Five esker types and a total of ten subtypes were distinguished. The most common esker types to the south of the LGM in Poland include 1a – continuous, short, straight esker ridges, 1b – continuous, short, sinuous esker ridges, and 4c – segmented, long, sinuous eskers. The eskers were formed in subglacial N-, R-, N-R and open channels. A synchronous model of esker formation was dominant, but some time-transgressively formed eskers consisting of beads also occur. The analysed eskers have common features with eskers on a hard bed and some of them originated in a similar way, but many eskers exhibit dissimilarity due to different conditions of their formation. The study shows that current esker morphogenetic classifications need to be extended to also include the character of eskers on soft beds.

Key words: eskers, morphometry, glacialgeomorphology, N-channels, permeable substrate, Polish Lowlans

Introduction

Eskers are fluvioglacial landforms formed in subglacial and englacial tunnels, supraglacial and ice-walled channels or re-entrants into the ice front (Banerjee, McDonald 1975; Ashley, Warren 1997; Brennand 1994, 2000). They predominantly consist of long, narrow, sinuous ridges formed in glacial tunnels during the recession of the ice margin (Banerjee, McDonald 1975; Brennand, Shaw 1996; Brennand 2000; Delaney 2001; Mäkinen 2003; Burke *et al.* 2009; Storrar *et al.* 2014; Perkins *et al.* 2016; Hewitt, Creyts 2019; Livingstone *et al.* 2020). Eskers provide very important information on the submarginal meltwater flow system beneath past ice sheets. Sometimes they constitute the only source of knowledge about it. Substrate lithology is a key control on subglacial meltwater drainage and formation of eskers. Meltwater flow on rigid and impermeable substrates occurs in channels, linked cavities and water films (Kamb 1987; Hubbard, Nienow 1997; Brennand 2000). Three forms of channels were distinguished: R-channels – cut in ice and filled with water with flow under hydrostatic pressure (Röthlisberger 1972), H-channels – cut in ice but with flow under atmospheric pressure (Hooke 1984) and N-channels – cut in substrate (Nye 1973). On soft beds it was

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often assumed that subglacial drainage occurs by porous and advective flow, thin water film and shallow, braided canals (Clark, Walder 1994; Walder, Flower 1994). Eskers are often considered as unlikely to form on soft beds. Hence, in most esker studies, models of their formation and esker classifications focus on eskers on hard beds and formed in R-channels (Brennand 2000; Boulton *et al.* 2007, 2009; Livingstone *et al.* 2015; Perkins *et al.* 2016; Hewitt, Creyts 2019; Lewington *et al.* 2020; Dewald *et al.* 2021). However, numerous studies show that eskers may also form in areas of permeable sediments (Rotnicki 1960; Michalska 1969; Wright 1973; Brennand 2000; Storrar *et al.* 2014; Frydrych 2020, 2021, 2022; Szuman *et al.* 2021). In Poland, eskers were formed on a soft bed in N-channels, R-channels and combination N-and-R channels (N-R channels) (Michalska 1969, 1971; Buraczyński, Superson 1992; Fard, Gruszka 2007; Frydrych 2016, 2021, 2022; Roman 2016; Salamon, Mendecki 2021). There is still limited knowledge about eskers formed on a soft bed and eskers formed in previous glaciations. The present study provides new insight into the characteristics and development of eskers and channelised meltwater drainage in areas of permeable substrate.

The study is part of broader research into eskers in Poland. The purpose of this study is to determine a morphologic classification of eskers formed on soft beds. This is the first step in preparing a morphogenetic classification of eskers including forms that originated in N-channels and N-R channels. Together with sedimentologic investigation of eskers, a morphologic classification can broaden the knowledge about esker formation and the relation between their morphology and subglacial processes. The classification of eskers in the area of older glaciations can show whether or not eskers formed in earlier glaciations have different morphologies.

Geological setting

The study area covers roughly 200 000 km^2 of central and southern Poland (Fig. 1A, B). Located to the south of the Last Glacial Maximum limit, the area was glaciated during the Middle Pleistocene and older glaciations (MIS 6-22) (Marks *et al.* 2016). The dominant part is covered by glacial and glaciofluvial sediments – mainly tills, sands, gravels and glaciolacustrine silts and clays (Fig. 2). Their thickness generally increases northwards and varies from less than 1 m to more than 100 m (Rdzany 2009; Hall, van Boeckel 2020). The analysed eskers were formed during the Wartanian Glaciation (Warthe – MIS 6 – Lindner *et al.* 2013), Odranian Glaciation (Drenthe – MIS 6 – Lindner *et al.* 2013; MIS 8 – Terpiłowski *et al.* 2021) and Sanian 2 Glaciation (Elsterian – MIS 12) (Fig. 1). During the latest glaciations in the study area, ice sheets moved mainly on the surface of permeable, soft sediments of older glaciations or also permeable sediments from the Palaeogene and Neogene. In the southern part of the area, the substrate was made up of pre-Quaternary rocks such as sandstones, limestones, dolomites or marls. After the deglaciation, some areas were covered by aeolian sands and loess in the conditions of periglacial climate (Fig. 2). During this time, glacial forms were reshaped and modified to a varying degree. The importance of periglacial morphogenesis has been discussed by many authors (Dylik 1952, 1953; Petera-Zganiacz 2011; Roman *et al.* 2014; Dzieduszyńska *et al.* 2020).

Eskers in the study area are usually associated with different types of meltwater channels (Fig. 3A–C) (Michalska 1969, 1971; Fard, Gruszka 2007; Roman 2016; Frydrych 2021, 2022; Salamon, Mendecki 2021; Szuman *et al.* 2021). Eskers formed in N-channels occupy the entire width of these channels (Fig. 3A – – in some sections). They often occur in much wider meltwater channels (Fig. 3B) or tunnel valleys (Fig. 3C) but in the area to the south of the LGM their relations are much less clearly visible than in the area of the Vistulian Glaciation. Many eskers in Poland have a complex genesis and were initially formed in a subglacial tunnel and then, after roof collapse, in an open (ice-walled) channel (Michalska 1969; 1971; Wysota 1990; Buraczyński, Superson 1992; Jaksa, Rdzany 2002; Fard, Gruszka 2007; Frydrych 2016, 2020, 2021; Roman 2016).

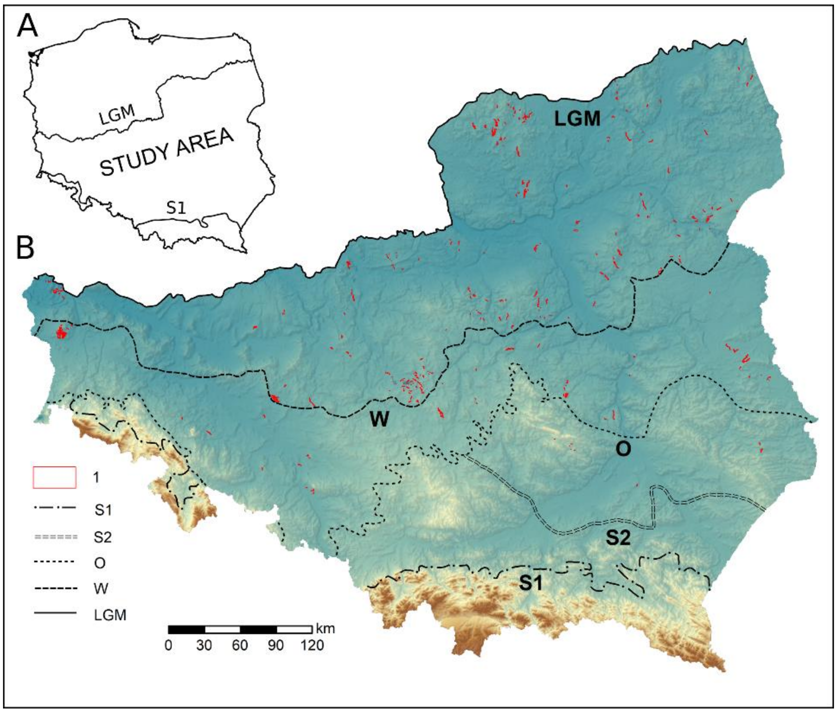

Fig. 1. Study area
A – location in Poland, B – eskers of the study area
1 – eskers mapped based on the 1:50 000 Detailed Geological Map of Poland, DEM 1m (Geoportal 2022), S1 – extent of Sanian 1 Glaciation (Marks *et al.* 2016), S2 – extent of Sanian 2 Glaciation (Elsterian) (Marks *et al.* 2016), O – extent of Odranian Glaciation (Saalian) (Marks *et al.* 2016), W – extent of Wartanian Glaciation (Saalian) (Mojski 2005), LGM – Last Glacial Maximum limit – extent of Vistulian Glaciation (Weichselian Glaciation)

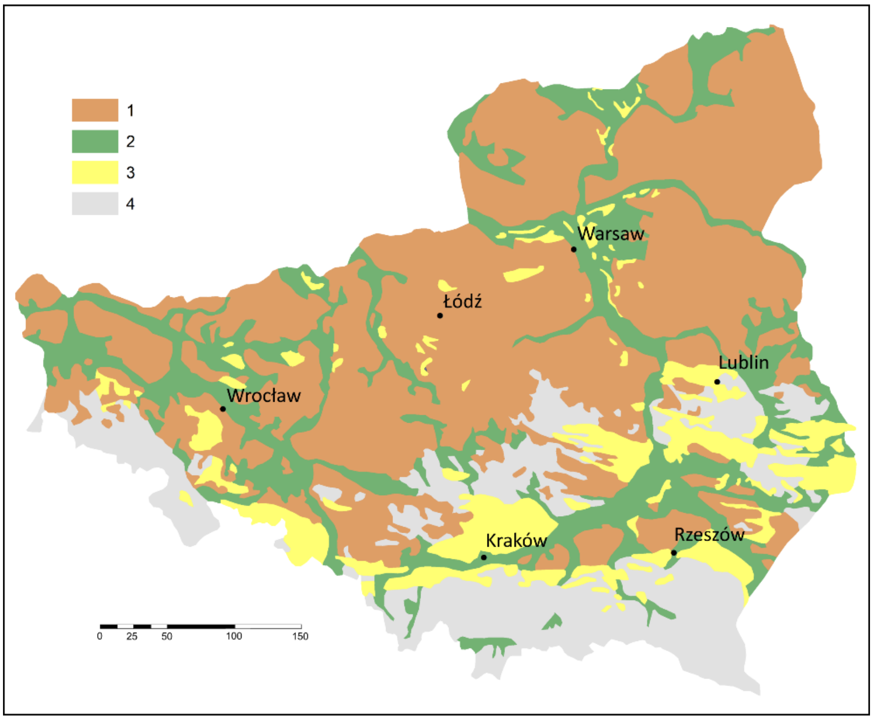

Fig. 2. Lithology of study area
1 – Glacial, glaciofluvial and glaciolacustrine related setting: till, sand, gravel, silt and clay, 2 – river plain system and lacustrine sediments: gravel, sand, mud and organic sediment, 3 – aeolian sands and loess, 4 – Pre-Quaternary rocks (Marks, Jóźwik 2020 – generalized)

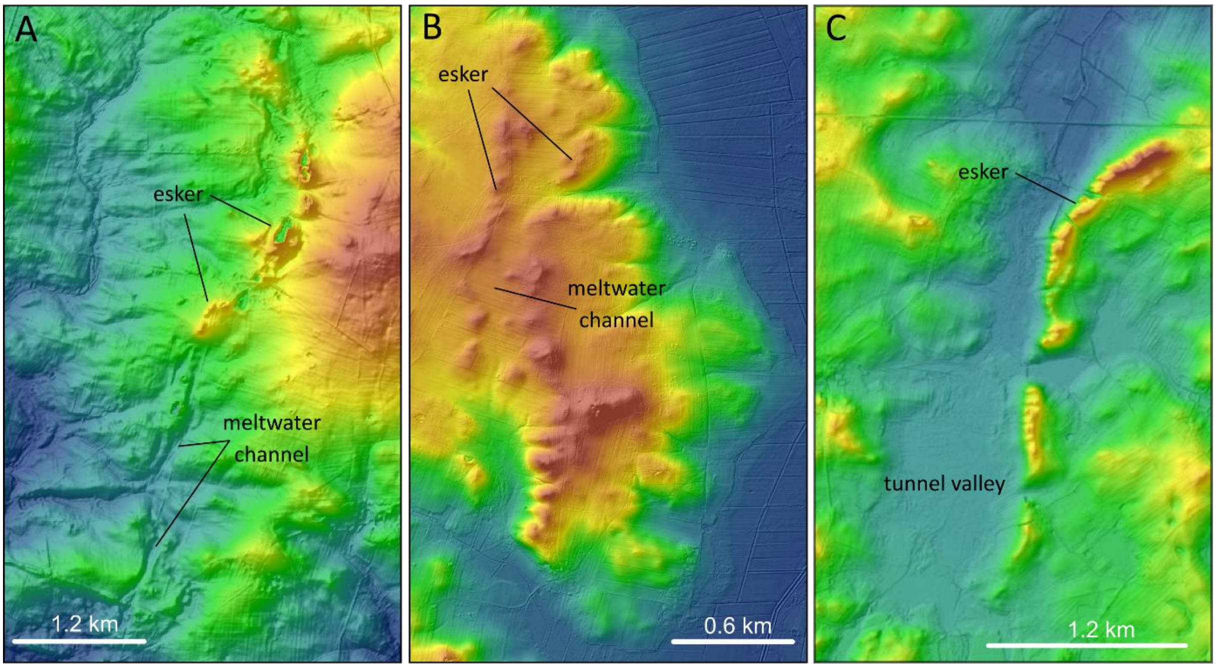

Fig. 3. Eskers associated with meltwater channels
A – eskers infilling the N-channel in some sections, B – eskers occur in meltwater channel, C – eskers occur in tunnel valley

Materials and methods

In this article, the term "esker ridge" refers to an individual segment of an esker (Fig. 4A). A single, isolated ridge or a sequence of ridges aligned along the same axis and divided by gaps is referred to as "an esker" (Fig. 4B). Esker ridges of the study area were mapped on the basis of the 1:50 000 Detailed Geological Map of Poland (SMGP). A total of 573 raster map sheets were analysed, and all objects denoted as eskers were vectorised. The dataset of mapped eskers consists of 798 polygons. In order to determine the parameters for complete forms, and not only their fragments, boundaries of eskers were delimited on the basis of a Digital Elevation Model, GRID 1 m (Geoportal 2022) and 1:10 000 topographic maps. Forms were drawn in ArcMap 10.7 software as polygon shapefiles. The dataset of eskers includes 293 polygons. A detailed methodology of esker dataset preparation was described by Frydrych (2022).

The main criteria for distinguishing esker types were: length of forms, fragmentation, and presence of tributary and distributary ridges. The sinuosity of eskers and elongation of individual ridges were used for distinguishing subtypes. The division assumed that long eskers are those of ≥2 km in length. Eskers with the sinuosity value of ≥1.1 were assumed to be sinuous. At the sinuosity value of 1.1 or more, the form is already noticeably sinuous. The indicated values were based on the arithmetic mean and median of the length and sinuosity.

Fragmentation was determined as the number of individual esker ridges that constitute the complete form. The length is the distance between the beginning and end of the ridges (l_{em}) or the esker trunk (l_{ei}) along its crestline (Fig. 4C). The sinuosity of an esker is the ratio of its length (l_{ei}) and the length of the straight line (l_s) connecting the beginning and the end of the form. The maximum width (w_m) was

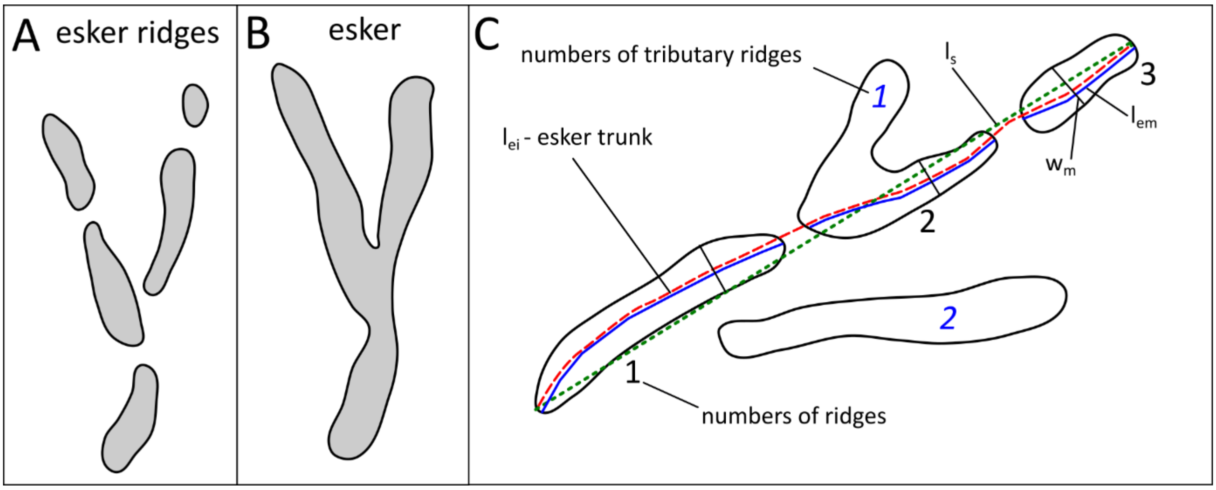

Fig. 4. Visualisation of terms and methodology of calculating esker morphology (based partially on Storrar *et al.* 2014)
A – esker ridges, B – eskers, C – parameters of esker morphometry:
l_{ei} – length of esker trunk, l_{em} – length of mapped ridges, l_s – length of straight line connecting beginning and end of form, w_m – width of mapped ridges, black numbers – fragmentation by count, blue numbers in italic – numbers of tributary ridges

calculated as the length of the straight line perpendicular to the length of the form at its broadest part. Elongation is the ratio of ridge length (l_{em}) to maximum ridge width (w_m). The maximum width and elongation were measured for individual ridges. The tributary and distributary ridges are segments connected with the esker trunk (Fig. 4C). Their number and order were calculated according to the Strahler method (designed for stream ordering).

Results

The 293 delimited eskers have a total length of 715.52 km. The longest esker in the study area is approximately 12 km long. Their average length is 2.4 km. Eskers longer than 2 km constitute 45% of the whole population. Of the eskers, 55.6% are built of a single ridge. The rest consist of two or more mostly elongated ridges. More than 75% of ridges have a length of at least double their width. The average sinuosity of eskers is 1.12. A minority of eskers have at least one tributary ridge (35.5%). Detailed information about the esker morphology of the study area was presented and discussed by the author in another article (Frydrych 2022).

On the basis of esker shapes, five morphological types and a total of ten subtypes were distinguished. The esker types are presented along with their morphometric characteristics and description in Table 1 and visualised in Figure 5.

Type 1 – continuous, short eskers

Eskers qualified as type 1 are continuous, often isolated ridges of less than 2 km long. Their elongation does not exceed 15. They are characterised by a lack of tributary and distributary ridges. Two subtypes can be distinguished based on sinuosity: 1a – straight eskers (Fig. 6A) and 1b – sinuous eskers (Fig. 6B). In the study area, type 1a eskers have an average length of 0,84 km and average sinuosity of 1.04. In type 1b, the average length is 1.24 km and sinuosity 1.19. Type 1 eskers constitute the most numerous group of forms in the analysed area (43.7%). Forms belonging to subtype 1a constitute 28%, and subtype 1b – 15.7% (Fig. 7).

Type 2 – continuous, long eskers

Type 2 eskers are long (≥2 km), continuous ridges with clear elongation (≥5). They have occasional short, single tributary ridges. They are divided into 2a – straight eskers (Fig. 8A) and 2b – sinuous forms (Fig. 8B). Eskers belonging to type 2a have an average length of 2.72 km and sinuosity of 1.05. In type 2b eskers,

Table 1

Morphological types of eskers in Poland, to the south of the Last Glacial Maximum

Type	Fragmenta-tion	Length	Sinuosity	Elongation	Tributary and distributary ridges	Description
1a	1	<2	<1.1	<15	none	continuous, short, straight esker ridges
1b	1	<2	≥1.1	<15	occasional, singular and short	continuous, short, sinuous esker ridges
2a	1	≥2	<1.1	≥5	occasional, singular and short	continuous, long, straight esker ridges
2b	1	≥2	≥1.1	≥5	occasional, singular and short	continuous, long, sinuous esker ridges
3a	>1	<2	<1.1	<15	occasional, singular and short	segmented, short, straight eskers
3b	>1	<2	≥1.1	<15	occasional, singular and short	segmented, short, sinuous eskers
4a	>1	≥2	<1.1	≥10	occasional, singular and short	long, straight eskers built of clearly elongated ridges (elong. ≥5)
4b	>2	≥2	<1.1	≥5	none	long, straight eskers built of isometric or slightly elongated ridges (elong. <5)
4c	>1	≥2	≥1.1	≥5	singular and mostly short	segmented, long, sinuous eskers
5	>1	≥3	>1	≥10	>1, long	esker systems

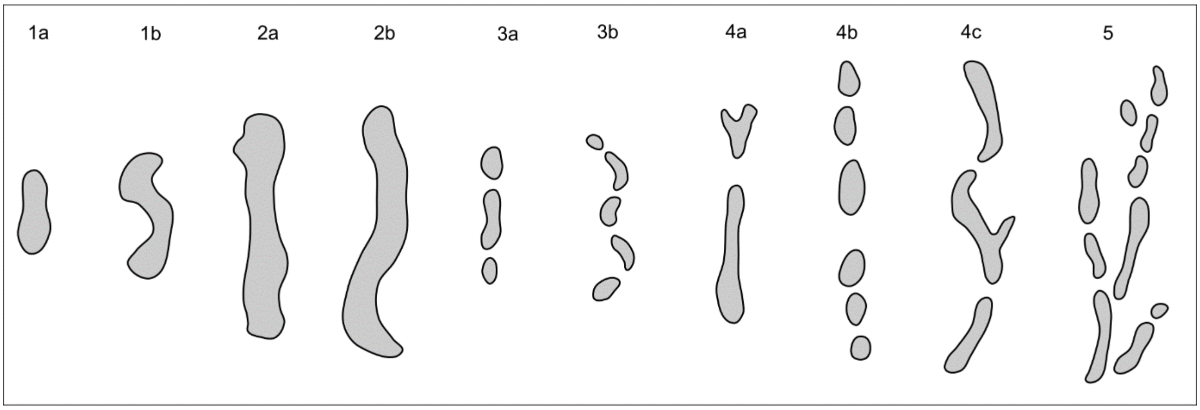

Fig. 5. Morphological types of eskers, distinguished based on length, sinuosity, fragmentation, elongation and presence of distributary ridges. Detailed description presented in text of article

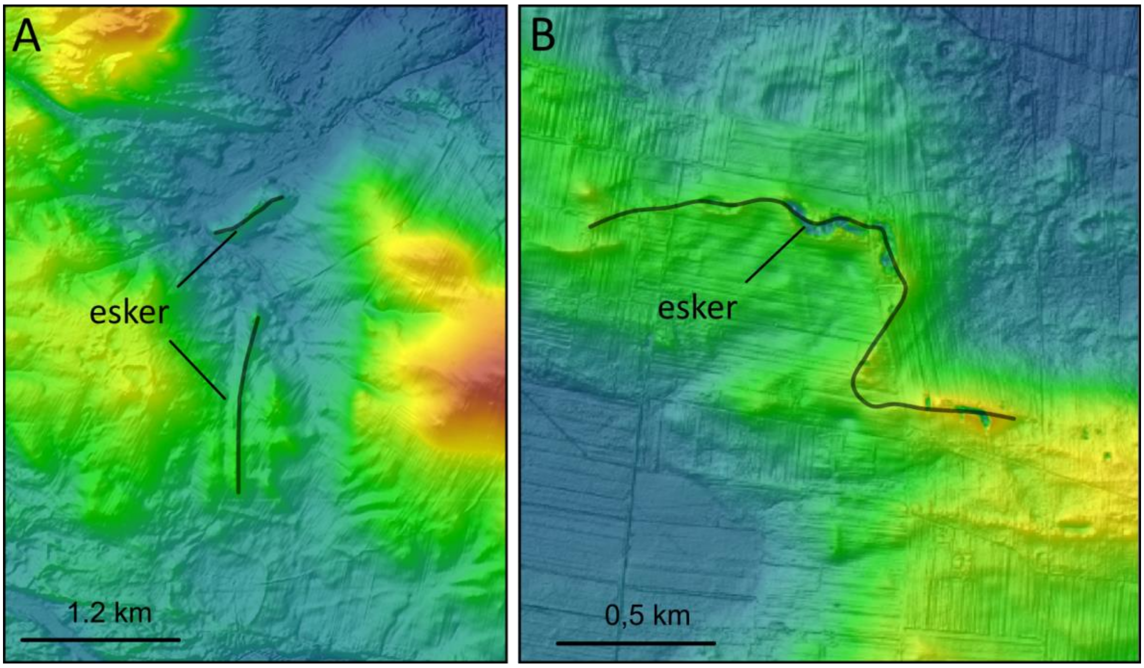

Fig. 6. Eskers qualified as type 1a (A) and 1b (B)

these values are respectively 2.84 km and 1.2. Eskers belonging to type 2 constitute 12,6%, including 7.2% of subtype 2a forms and 5.5% of subtype 2b (Fig. 7).

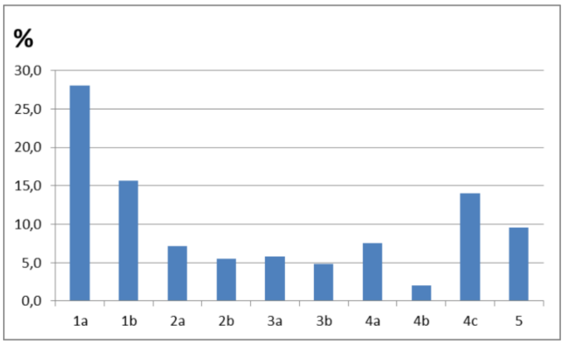

Fig. 7. Distribution of occurrence rate of individual morphological types in study area

Type 3 – segmented, short eskers

Forms belonging to type 3 are built of more than one segment. Their length is lower than 2 km and elongation is lower than 15. Occasionally, they have short, single tributary ridges. Among them, straight eskers (3a) (Fig. 9A) and sinuous eskers (3b) (Fig. 9B) can be distinguished. The average length of type 3a eskers is 1.31 km, and sinuosity is 1.05. In type 3b, the average length is 1.58 km. The average sinuosity is 1.2.

Forms qualified as type 3 constitute 10.6%. The value is 5.8% for subtype 3a and 4.8% for 3b (Fig. 7).

Type 4 – segmented, long eskers

Eskers qualified as type 4 may be divided into three further subtypes with regard to the number and character of the segments they comprise, as well as their sinuosity. Their common feature is their length of at least 2 km and their consisting of more than one segment. Subtype 4a includes forms consisting of at least two clearly elongated segments, with the elongation value of ≥5 (Fig. 10A). The sinuosity of the entire form does not exceed 1.1 here. These forms occasionally have short, single tributary ridges. Subtype 4b includes forms built of at least three segments with isometric shape or slightly elongated (<5) (Fig. 10B). These eskers do not have any tributary or distributary ridges. Their sinuosity is lower than 1.1. Eskers of subtype 4c are characterised by clear sinuosity of ≥1.1 (Fig. 10C). They are composed of at least two segments for which the elongation value is not lower than 5. They include single, usually short tributary and distributary ridges, although at a higher rate than in the former subtypes. In the study area, the average length of esker

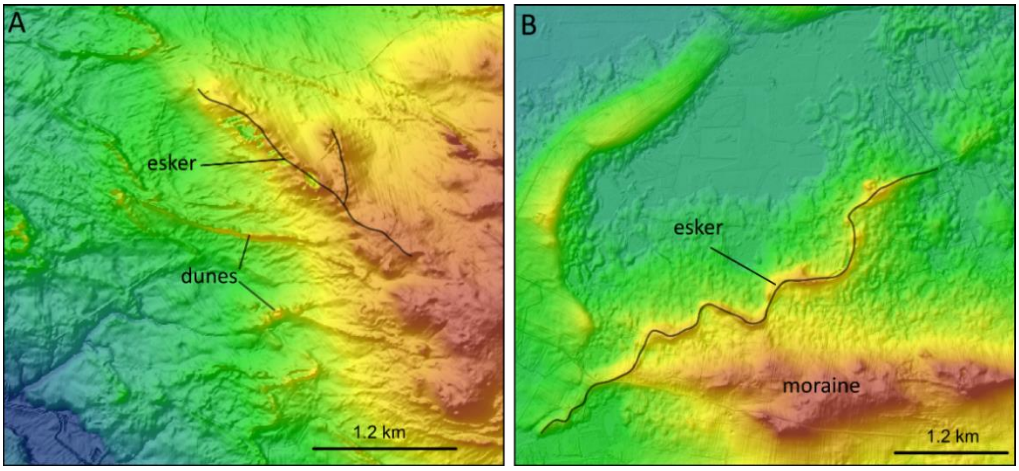

Fig. 8. Eskers qualified as type 2a (A) and 2b (B)

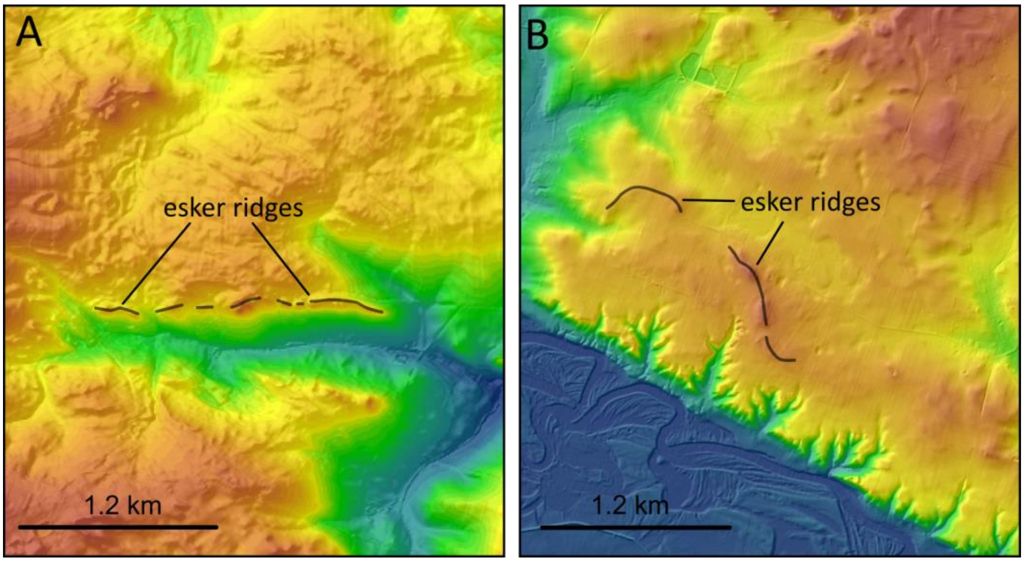

Fig. 9. Eskers qualified as type 3a (A) and 3b (B)

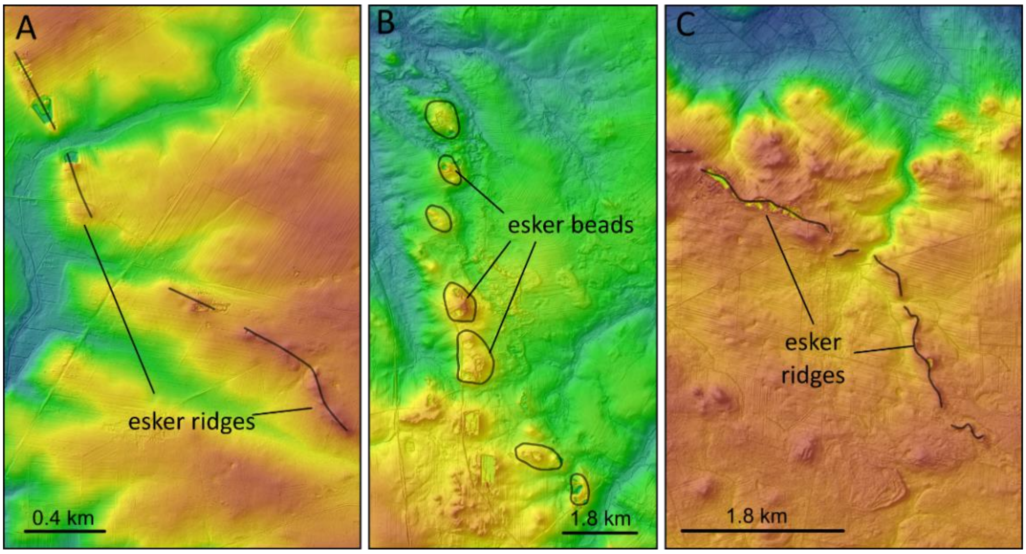

Fig. 10. Eskers qualified as type 4a (A), 4b (B) and 4c (C)

subtypes is as follows: 4a – 3.15 km, 4b – – 4.11 km, 4c – 4.19 km. The respective values of average sinuosity are as follows: 4a – 1.05, 4b – 1.06, 4c – 1.18. Eskers of type 4 constitute 23.5% of all eskers. Values for the subtypes are as follows: 4a – 7.5%, 4b – 2%, 4c – 14% (Fig. 7).

Type 5 – esker systems

Forms of type 5 constitute complex esker systems (Fig. 5, 11A, B). They are built of at least two segments and have at least two tributary or distributary ridges, usually of significant length. The length of the main ridge is ≥3 km and the elongation is ≥10. Their sinuosity may be either low or high. Sometimes it may differ considerably between some sections or between the main ridge and the tributary ridges. In the analysed area, the average length of type 5 eskers is 6.31 km. Sinuosity falls within the range from 1.04 to 1.45. The average sinuosity is 1.22. The share of complex esker systems in the analysed forms is 9.6% (Fig. 7).

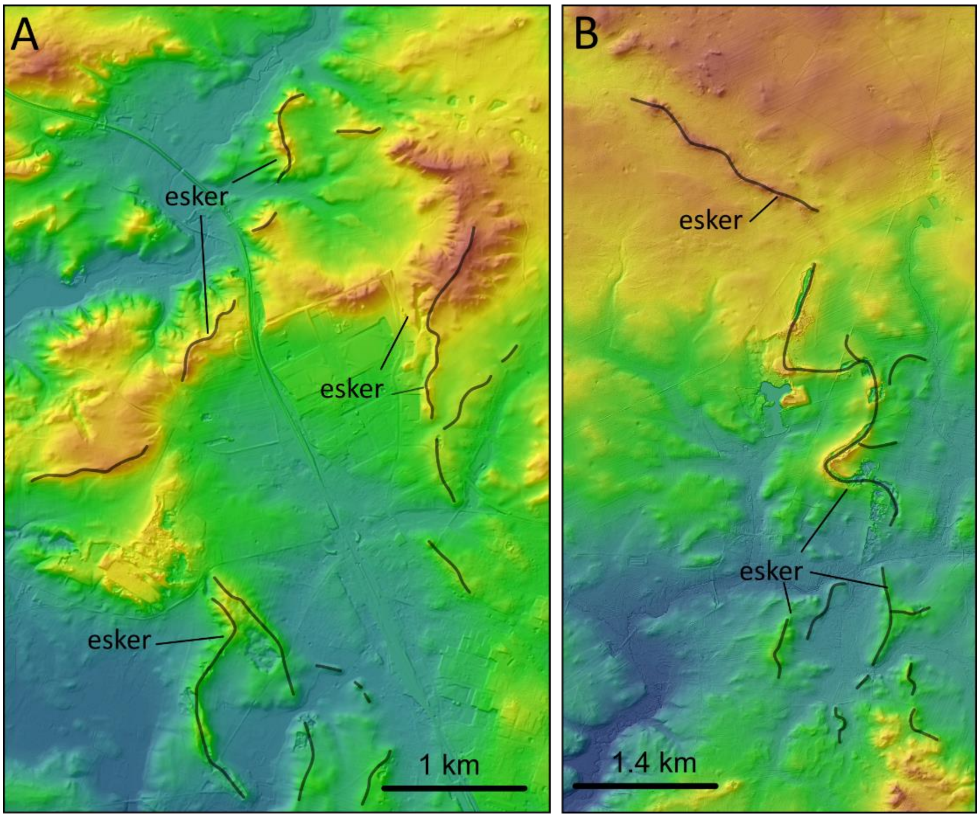

Fig. 11. Eskers qualified as type 5 (A and B)

Discussion

The morphogenetic classifications of eskers are based on morphological and sedimentological studies. Present classifications were developed during the study of eskers in areas of impermeable beds (Brennand 2000; Aylsworth *et al.* 2012; Perkins *et al.* 2016; Lewington 2020). They originated beneath the Laurentide Ice Sheet during the Wisconsin Glaciation. The eskers analysed here were formed in permeable sediments. There are many distinctions between eskers in Poland and eskers in Canada or Fennoscandia (Frydrych 2022). The most significant is their length. The longest esker in Canada exceeds 760 km long (Shreve 1985; Brennand 2000; Storrar *et al.* 2014), whereas the longest one in the study area is about 12 km long. The analysed eskers are also far less morphologically complex. They have fewer tributary and distributary ridges, which are maximally of the second order (Frydrych 2022). The eskers of the study area were formed during older glaciations (Saalian, Sanian – MIS 6-22) and were remodelled due to erosion–denudation and accumulation processes for much longer than forms of the Last Glaciation. Those post-depositional processes played a significant role in preserving the eskers and their current morphology.

Brennand (2000) proposed a morphologic classification of Laurentide eskers in Canada. She identified three types of esker morphology: long, dendritic eskers (I), short, subparallel eskers (II) and short, deranged eskers (III). Type I in this classification is comparable to type 5 in the study area. Eskers of type 5 are much shorter and less complex but they constitute the longest among the analysed forms and are built of esker trunk and tributary and distributary ridges. According to Brennand (2000), eskers of this type were deposited in extensive, synchronous R-channels. Such esker characteristics as relatively continuous ridges, the presence of fans in the terminal position of the esker, a regional trend in clast characteristics and coarse sediments with macroforms all support the hypothesis of long-distant transport of the sediments (Brennand 1994, 2000; Brennand, Shaw 1996). The analysed eskers are also relatively continuous. The average percentage of gaps in their length is 23%. They are mainly built of coarse-grained sediments with elements formed during long-distance transport (presence of macroforms, high roundness of gravel clasts) and accumulation in confined channels (Frydrych 2020). The morphological and sedimentological characteristics support their deposition in synchronous N-, R- and N-R channels. Type II and III in Brennand's classification (2000) include short eskers composed of ridges combined sometimes with subaqueous fans. They are organised subparallel to each other or exhibit deranged regional patterns. In the study area, the majority of eskers fit that division (type 1a, 1b, 2a, 2b, 3a, 3b, 4a, 4b, 4c) due to their length and lack of dendritic character. However, many were formed in N- and N-R channels, and they differ in terms of how each was created. The analysed eskers are subparallel more often than dendritic but many of them occur as isolated forms. The formation of short eskers could be associated with limited, short-distance supply of supraglacial meltwater or sediment (Brennand 2000). The importance of meltwater and sediment supply and the role of the balance between them were broadly discussed by Burke *et al.* (2015). They draw attention to the location of morphologically diverse eskers. According to them, the largest eskers occur within broad meltwater valleys, whereas the shortest are located in areas dominated by clast-poor till. The abundance of sediments like gravels and sands in meltwater valleys allows eskers to grow to bigger sizes. High water and sediment supply lead to ice tunnel growth and the development of macroforms (Brennand 1994; Brennand, Shaw 1996; Burke *et al.* 2015). This could also be an important factor controlling the distinction between short and long eskers in Poland. The lack of broader study of that relation does not allow a definite conclusion to be drawn. Further research into the relation of esker morphology, sedimentology and relation to their substrate is needed. Esker length could also be influenced by erosion and accumulation during their formation, immediately after the formation was completed or later in different environments (Frydrych 2022).

Perkins *et al.* (2016) identified three morphogenetic types and two subtypes of eskers near the margins of the last Cordilleran Ice Sheet in British Columbia. Type 1 eskers have a single-ridge planform and are often located within meltwater corridors or valleys. They are divided into two subtypes: 1a eskers are long forms of low continuity that contain widenings and were formed synchronously in subglacial tunnels during glacial lake outburst floods (GLOFs); 1b eskers are short forms of higher continuity that often terminate in fan-like widenings and were formed in subglacial tunnels close to the ice margin during lower magnitude flows than type 1a. Type 2 eskers are single, continuous, mid-length, sinuous and rarely set within valleys. They were formed in supraglacial channels or high-englacial tunnels. Type 3 eskers are highly continuous, flat-crested, mid-length forms of low sinuosity. They originated in ice-walled channels or re--entrants (Perkins *et al.* 2016). Esker fragmentation is often used to deduce about esker formation (Brennand 2000; Storrar *et al.* 2014; Perkins *et al.* 2016; Frydrych 2022). High continuity of eskers is linked to their formation in supraglacial or ice-walled channels (Perkins *et al.* 2016). In the study area, type 1a, 1b, 2a and 2b eskers exhibit the highest continuity. Their originating in supraglacial channels is unlikely, due to the low preservation potential of supraglacial eskers (Jewtuchowicz 1962; Fitzsimons 1991). They are often smaller in size than subglacial forms and their capacity to remain in relief is lower. The sinuosity of the analysed eskers also does not support their formation in supraglacial channels but this possibility cannot be ruled out. Some of the type 1b or 2b eskers may, due to their higher sinuosity, have originated in supraglacial channels. A more plausible assumption is that eskers of type 1a, 1b, 2a and 2b may have originated in open channels. Types 1b and 2b, especially, are, due to low sinuosity, the most probable to have formed in that way. Type 4a eskers, if their fragmentation results from post-depositional erosion, may also fit that scenario. According to sedimentological research, many eskers in Poland have a complex genesis and were initially formed in subglacial tunnels and then, after roof collapse, in an open channel (Michalska 1969; 1971; Wysota 1990; Buraczyński, Superson 1992; Jaksa, Rdzany 2002; Fard, Gruszka 2007; Roman 2016; Frydrych 2016, 2020, 2021). Single ridge or highly continuous forms were also documented as a result of accumulation in subglacial tunnels (Brennand 1994; 2000; Storrar *et al.* 2014). Esker ridge crest types (round-, sharp-, flat- and multi-crested) strongly reflect the type of meltwater channel. So far, there are no broad studies on crest types that include N-channel and N-R channel eskers. However, if we assume that N-channel forms can in some cases look similar to those that originated in open channels, and N-R channel eskers can be comparable to R-channel ones (Frydrych 2020, 2022), then ridge crest type can help in distinguishing between them. Unfortunately, there is a problem with using this criterion in areas of older glaciations (such as the study area) due to the surface having been remodelled in periglacial climate conditions. It is likely that most sharp edges in the relief were smoothed. Therefore, the previously flat-crested eskers can now have more rounded crests. In the study area, examples of this situation have been documented in a few eskers whose sedimentation ended in open channels (Frydrych 2020, 2021). At this point, without profound sedimentary analyses, it is difficult to verify whether continuous eskers originated in subglacial tunnels or in open channels. The most probable assumption is that both ways of formation occurred in the study area.

Gaps between esker ridges may be attributed to syndepositional or post-depositional erosion, time-transgressive formation, lack of accumulation in some parts of the tunnel or accumulation in an N-channel with uneven thalweg line and crestline (Szupryczyński 1965; Shreve 1972; Banerjee, McDonald 1975; Brennand 1994; Stoker *et al.* 2021; Frydrych 2022). However, there is a visible difference between eskers built of elongated ridges and those composed of beads. Elongated ridges can be either straight or sinuous and they are divided by gaps of different lengths. They are interpreted as having formed in ice tunnels (Brennand 1994, 2000; Burke *et al.* 2012, 2015; Storrar *et al.* 2014; Perkins *et al.* 2016; Ahokangas *et al.* 2021). Synchronous (Brennand 1994, 2000; Burke *et al.* 2012, 2015; Perkins *et al.* 2016) and time-transgressive (Banerjee, McDonald 1975; Mäkinen 2003; Livingstone *et al.* 2020) models of their formation have been proposed and documented. Some authors identified both models occurring in a single form (Stroker *et al.* 2021). In the study area, a synchronous model of esker formation has been proposed as more likely (Frydrych 2022). Among the analysed forms, type 4a, 4c and 5 eskers consist of elongated ridges, as do some type 3a and 3b eskers. These forms were most probably formed synchronously in subglacial N-, R- and N-R channels. Beaded eskers are highly fragmented and consist of hills ranging in shape from isometric to fan-shaped forms (Lewington 2020). Beads are separated by gaps of usually similar length and form chains. Beaded eskers are interpreted to have formed in tunnel mouths during ice-margin recession, and they are linked with the time-transgressive model of esker formation (Banerjee, McDonald 1975; Saunderson 1975; Ringrose 1982; Lewington 2020; Livingstone *et al.* 2020). Beads are typical of 4b type and many 3a and 3b type eskers. It is plausible that these forms originated time-transgressively in re-entrants at the ice--sheet margins.

In the study area, it is not easy to classify some eskers into the current morphogenetic types. This is because many of them have a complex genesis and were initially formed in subglacial N- or N-R channels under hydrostatic pressure and then in open channels under atmospheric pressure (Michalska 1969; 1971; Buraczyński, Superson 1992; Jaksa, Rdzany 2002; Frydrych 2016, 2020, 2021). This complexity generates the need to extend morphological classifications and include the character of esker formation in areas of soft bed. The key factors influencing esker morphology in the study area were formed in N- and N-R channels, with a dominance of the synchronous model of esker formation, diverse sediment supply and complex genesis of eskers.

In the author's opinion, incorporating more morphological characteristics into classification would provide more accurate information about esker formation. This might allow us to distinguish eskers formed synchronously and time-transgressively or eskers formed in subglacial channels and open channels. Morpho-sedimentary relationships and the geomorphic context of eskers can, with larger datasets, provide insight into the depositional environment and evolution of ice tunnels (Burke *et al.* 2015). The research into eskers indicates their relation with meltwater discharge, sediment supply, ice surface thickness, velocity and slope, ice-margin dynamics, bed topography, substrate characteristics, tunnel type, duration of deposition and post-depositional modifications (Brennand 2000; Delaney 2001; Fard 2003; Storrar *et al.* 2014, 2020; Burke *et al.* 2015; Perkins *et al.* 2016; Hewitt, Creyts 2019; Stoker *et al.* 2021; Frydrych 2022). This shows the necessity for further research into the dependence between esker morphology and sedimentology and their geomorphologic and geologic context.

Conclusions

The eskers were classified based on their morphological characteristics. Five esker types and a total of ten subtypes were distinguished in the analysed area:
- 1a – continuous, short, straight esker ridges,
- 1b – continuous, short, sinuous esker ridges,
- 2a – continuous, long, straight esker ridges,
- 2b – continuous, long, sinuous esker ridges,
- 3a – segmented, short, straight eskers,
- 3b – segmented, short, sinuous eskers,
- 4a – long, straight eskers built of clearly elongated ridges,
- 4b – long, straight eskers built of isometric or slightly elongated ridges,
- 4c – segmented, long, sinuous eskers,
- 5 – esker systems.

The most common esker types to the south of the LGM in Poland are 1a, 1b and 4c.

Most esker types of the study area were formed in subglacial N-, R- and N-R channels. In some eskers, accumulation ended in an ice tunnel, but in others it continued in an open channel after ice roof collapse. The fragmentation and sinuosity could provide useful information on the distinction between them. The majority of analysed eskers were formed synchronously in confined flow under hydrostatic or atmospheric pressure. However, some are built of beads and correspond to a time-transgressive model of esker formation in re-entrants during ice sheet retreat. Fragmentation, elongation of segments and sinuosity are the most suitable morphological features for their distinction. The lengths of eskers can provide information about their position relative to ice-margin, meltwater and sediment supply or the degree of remodelling.

The presented study provides new insight into esker characteristics, especially in areas of soft bed and older glaciations, where the level of knowledge is much lower than in areas of hard bed within the range of Last Glacial Maximum. This draws attention to the need to include the different characters of esker formation in areas of soft bed.

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