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Dynamics of the last Scandinavian Ice Sheet's southernmost sector revealed by the pattern of ice streams

IZABELA SZUMAN, JAKUB Z. KALITA, MAREK W. EWERTOWSKI, CHRIS D. CLARK AND STEPHEN J. LIVINGSTONE

Szuman, I., Kalita, J.Z., Ewertowski, M.W., Clark, C.D., Livingstone, S.J.: Dynamics of the last Scandinavian Ice Sheet's southernmost sector revealed by the pattern of ice streams.

Izabela Szuman (szuman@amu.edu.pl), Jakub Z. Kalita and Marek W. Ewertowski, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University of Poznan, Krygowskiego 10, 61-680 Poznan, Poland; Chris D. Clark and Stephen J. Livingstone, University of Sheffield, Winter St, Sheffield S10 2TN, UK

Abstract: The Polish sector of the last Scandinavian Ice Sheet is a key area for studying ice sheet drainage and decay from its local Last Glacial Maximum (LGM) extent, as it is located at the terrestrial terminus of the large and dynamic Baltic Ice Stream Complex. Geomorphological mapping, based on a 0.4 m LIDAR digital elevation model, revealed about 940 streamlined bedforms, many of which are shown for the first time and consisting of mega-scale glacial lineations and drumlins. The lineation flow-sets together with associated landforms were used to identify seventeen ice streams, occupying 80% of the study area. We demonstrated that subtle topographic variations played an important role in influencing ice sheet dynamics. Variations in ice dynamics were a response to external climatic forcing that controlled deglaciation at the ice sheet scale as well as internal reorganisation due to the influence of topography, subglacial hydrology and glacier thermal regime. During the local LGM, the southern sector of the Scandinavian Ice Sheet in Poland was dominated by four simultaneously operating ice streams, likely active for several millennia, followed by fast active recession interrupted by three main periods of ice stream stagnation. Increased ice flow dynamics during the period of the Young Baltic advances is suggested to be caused by variations in subglacial hydrology and the polythermal structure of the ice sheet.

Keywords: mega-scale glacial lineations, drumlins, crevasse-squeeze ridges, surge, Poland, Last Glacial Maximum, Scandinavian Ice Sheet

The stability and behaviour of modern ice sheets are controlled by ice stream activity (Bennett 2003; Joughin *et al.* 2014). Ice streams contribute, for example, up to 90% of the discharge of the Antarctic Ice Sheet (Bamber *et al.* 2000) and 40% of the discharge of the Greenland Ice Sheet (van den Broeke *et al.* 2016), with the Northeast Greenland Ice Stream draining 12% of the entire ice sheet (Larsen *et al.* 2018). Therefore, knowledge about the location, and spatial and temporal activity of former ice streams is crucial for reconstructing palaeo-ice sheet behaviour (Alley *et al.* 1987; Stokes & Clark 2001; Stokes & Tarasov 2010; Winsborrow *et al.* 2010; Margold *et al.* 2015; Stokes *et al.* 2015).

The trough-shaped bed configuration and soft substrates in the Baltic Sea area are interpreted to have acted as a wide (up to 300 km) zone that could have facilitated fast ice flow (Holmlund & Fastook 1995; Patton *et al.* 2016; Stroeven *et al.* 2016; Patton *et al.* 2017); some have called this the Baltic Ice Stream Complex (Boulton *et al.* 2001, 2004; Kalm 2012). One of the possible consequences of this area of ice-flow enhancement is the expansion of the Scandinavian Ice Sheet's (SIS) southern extent in western Poland and eastern Germany. The highly lobate geometry of the landforms marking the southern margin of the SIS led to the idea that the Baltic Ice Stream fed a series of rapidly adjusting lobes (Boulton *et al.* 2001).

The aim of our study was to reconstruct the dynamics of the southernmost sector of the SIS by identifying the behaviour and complex relationships between individual ice lobes during deglaciation. This was achieved by (i) mapping ice-marginal and ice-flow-related landforms, (ii) investigating their superposition and relative ages, and (iii) analysing factors governing ice lobes location and behaviour. In this study we use a high-resolution digital elevation model (DEM) to map ice-margin positions and ice lobes in central western Poland to reconstruct the ice dynamic glacial history.

Scandinavian Ice Sheet's southernmost sector

The presence of glacial lineations associated with the Baltic Ice Stream Complex has been reported in the Bothnian Sea (Greenwood *et al.* 2016) and to either side of the study area, outside the southern Baltic Sea sector (Kleman & Borgström 1996; Kjær *et al.* 2003; Houmark-Nielsen 2010; Kalm 2012). Hermanowski *et al.* (2019) also report over 1000 streamlined subglacial bedforms in NW Poland, to the NW of the study area.

Traditional reconstructions of Late Weichselian glaciation in central Europe are based on three main still-stand positions (Fig. 1): Leszno/Brandenburg (LGM, 25-21 ka), Poznań/Frankfurt (17 ka), and Pomeranian (16 ka; Kozarski 1995; Lüthgens & Böse 2012; Marks 2012; Tylmann *et al.* 2019). Typically, these still-stands, marked by prominent moraine systems, are used as a framework for describing SIS activity along its southern sector. The Late Weichselian glaciation in the central European plains is associated with the activity of the Baltic Ice Stream Complex (B1-B5; Punkari 1997; Boulton *et al.* 2001; Stokes & Clark 2001), with ice stream branches B2 and B3, which operated over a soft-bedded landscape of relatively gentle topography, controlling glaciation in Poland (Punkari 1997; Boulton *et al.* 2001). The Young Baltic ice streaming advances (Stephan 2001; Kjær *et al.* 2003; Kalm 2012; Lasberg & Kalm 2013) have been associated with the Poznań and Pomeranian phases (Stroeven *et al.* 2016). However, the large lobate geometry of the LGM ice margin occupying central west Poland (Fig. 1A) hints at a more extensive history of ice streaming. The discovery of mega-scale glacial lineations (MSGLs) between the B2 and B3 ice stream paths (Fig. 1; Ewertowski & Rzeszewski 2006; Przybylski 2008) revealed a more complex network of ice streams (named as the Sława, Leszno and Września ice streams). It has been suggested that the Baltic Ice Stream B2 and the Sława, Leszno and Września ice streams were in fact the same ice stream (Przybylski 2008), but this remains an open question given the different spatial and temporal scales and lack of geomorphological evidence.

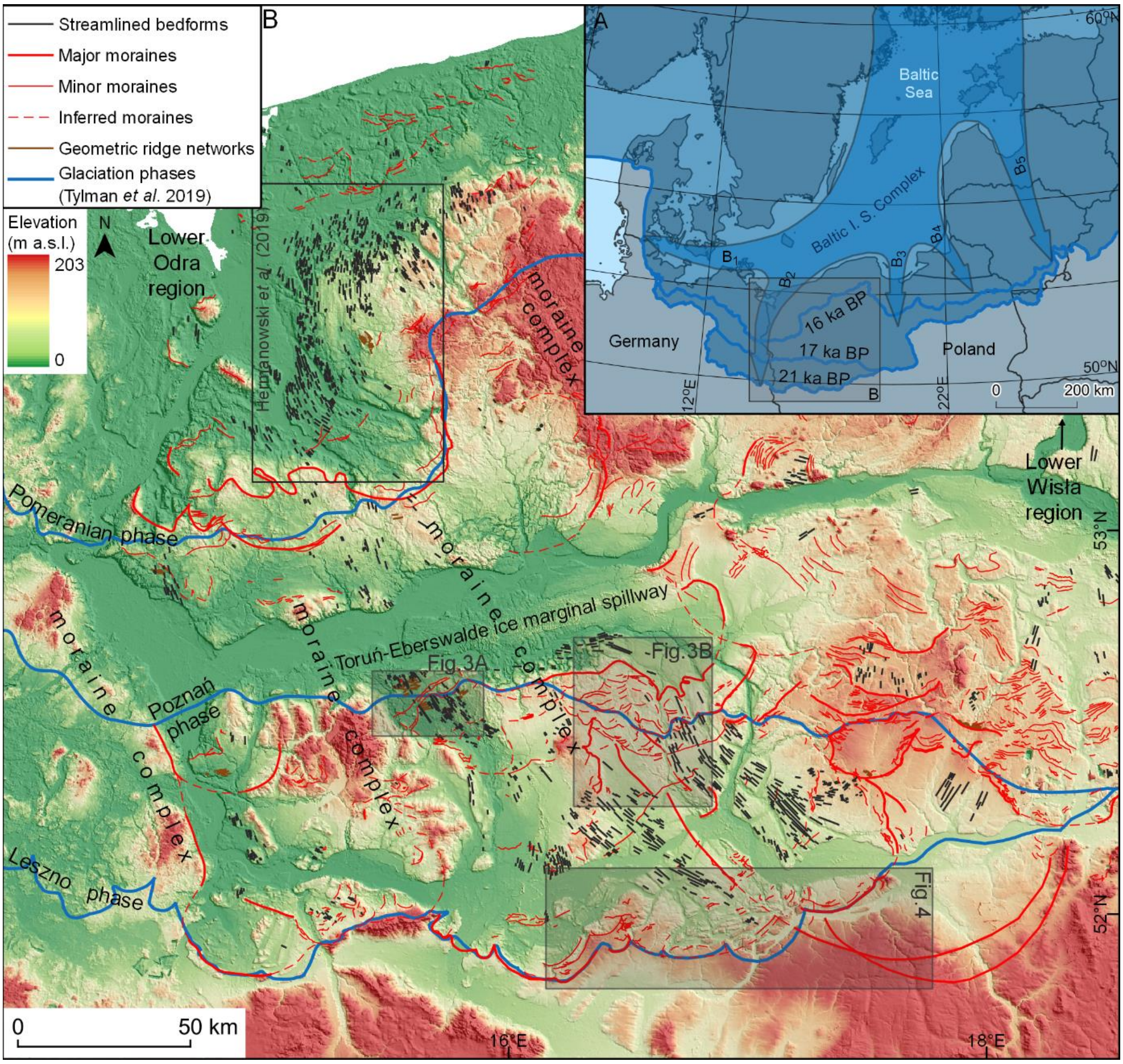

Fig. 1. A. Study area, LGM (Leszno/Brandenburg 25-21 ka BP), and major recessional phases (Poznań/Frankfurt 17 ka BP; Pomeranian 16 ka BP) in central Europe (Marks 2012; Tylmann *et al.* 2019) and the Baltic Ice Stream Complex modified from Punkari (1997). B. Streamlined bedforms, geometric ridge networks and moraine ridges over central western Poland based on geomorphological mapping from LiDAR-based Digital Elevation Model (DEM) conducted in this study.

Geomorphological mapping – datasets and methods

Previous attempts to identify and map streamlined bedforms across the study area were based on SRTM (90 m DEM), DTED2 (30 m DEM) and 1: 10 000 topographic maps (Ewertowski & Rzeszewski 2006; Przybylski 2008; Szuman *et al.* 2013; Spagnolo *et al.* 2016; Szuman *et al.*

2018). Here, we used high-resolution LiDAR data (GUGiK 2017) comprising raw classified point cloud datafiles each covering areas of 1x1 km or 0.5x0.5 km. The DEM model was generated using PDAL library (PDAL Contributors 2018) with a 0.4 m ground sampling distance over an area of 75000 km^2. The DEM was visualized using four orthogonal hillshade directions (15, 45, 315 and 345 degrees) to limit azimuth bias (Smith & Clark 2005).

The final dataset comprised only the landforms identified independently by three operators (mappers), to minimise the uncertainty of the mapping process. Geomorphological mapping enabled identification of streamlined bedforms (i.e. MSGLs, drumlins), ribbed moraines, moraine ridges, and geometric ridge networks interpreted as crevasse-squeeze ridges (Rea & Evans 2011) many of which are recognised for the first time (Fig. 1). Moraine ridges were morphologically classified as major or minor; major moraine chains are typically associated with the terminal moraines of major ice flow phases or main still-stands (Leszno, Poznań and Pomeranian phases). We mapped minor recessional and re-advance moraines to reproduce the changing shape of the ice margin during overall retreat.

The streamlined bedforms were grouped as flow-sets and assigned to specific flow phases based on their association with major moraines (cf. Kleman *et al.* 2006). Where landform evidence is absent, the margins of particular flow-sets were inferred by approximation of lobate terminal margin positions up- and downstream (Fig. 5B). Abrupt lateral margins, clear trunk zones, diverging termini and highly elongated bedforms were used to identify the records of palaeo-ice streaming (Patterson 1997; Stokes & Clark 1999). We also identified hummocky and push moraines, ice-marginal valleys, eskers and hill-hole pairs, which were used to support interpretations of ice streams dynamics and recession (Table 1).

In this study, we applied two naming systems, conventional and symbolic (Table 1). The symbolic naming convention defines the ice streaming events and allows us to easily present spatio-temporal relationships (Fig. 6) of glacial events. In the symbolic name, the first symbol refers to the phase (MW i.e. Middle Weichselian, and phases I-III i.e. I – LGM/Leszno phase, II – Poznań phase, III – Pomeranian phase), the second symbol to region which the ice stream originated (B2 related to Lower Odra region or B3 to Lower Wisła region), the third symbol refers to ice stream paths along which the ice stream is located (1-3 for B2, and 1-4 for B3; see Fig. 5). The splitting of the ice stream near the margin is indicated by *a* and *b*. The conventional naming system is based on previous investigations of the glacial history and in most cases the ice stream names are taken from the names of the cities located near the ice stream margin during a particular flow phase. We adopt this approach to conform with the existing regional naming convention, and add to it where we identify new ice flow phases (Table 1).

Results

Glacial landforms

The first group of streamlined bedforms, MSGLs and drumlins (Figs 2A-B, S1B), comprise a broad spectrum of lengths, typically from 200 to 4000 m with a mean of 1800 m. Most of their elongation ratios are between 1:1.2 and 1:10, with smooth transitions in form across the dataset. Maximal lengths and elongation ratios reach 9000 m and 1:18 respectively, with only 4% of the forms having respective parameters above 4000 m and 1:10. Elevation amplitudes are typically between 1.5 and 4.5 m, with the highest (up to 10 m), in the vicinity of the Lwówek-Rakoniewice Rampart, a N-S oriented topographic ridge thought to be a remnant of the Saalian glaciation (Fig. 3B; Stankowski 1968).

A separate group of streamlined bedforms (Figs 2C, 3A) comprise narrow (from 50 to 100 m), elongated forms with lengths between 1000 and 5700 m, amplitudes between 1 and 3 m, and an irregular spacing (contrary to regularly spaced MSGLs; Spagnolo *et al.* 2014). These bedforms are only related to the Poznań phase limit and morphologically differ from other MSGLs recognised across the study area by elongation, width and spacing (cf. Fig. 2A, C). However, they can be placed at the border of the morphological cluster of MSGL group (Ely et al. 2016) and thus can be classified as MSGLs (cf. Putkinen *et al.* 2017).

There are three main orientations of the streamlined bedforms: i) bedforms associated with the Lower Odra region are orientated S to SE; ii) streamlined bedforms associated with the Lower Wisła region have orientations from S to SW; and iii) streamlined bedforms present along the Toruń-Eberswalde ice marginal spillway (originating from both the Lower Odra region and Lower Wisła region) orientated E to W (Figs 1, 3B). Some bedforms show changes in their morphology along inferred ice flow direction, i.e. from drumlins on top of the Lwówek-Rakoniewice Rampart (Fig. 3B), to MSGLs downstream, or from MSGLs toward drumlins close to ice margins. In total, our geomorphological mapping revealed about 940 streamlined bedforms interpreted as MSGLs and drumlins (Fig. 1). Streamlined bedforms present in the Lower Odra region were not included in this analysis as they have been described in detail by Hermanowski *et al.* (2019, 2020) and Hermanowski & Piotrowski (2019).

We mapped three fields of geometric ridge networks interpreted as crevasses-squeeze ridges near the Poznań phase limit (e.g. Figs 2E, S1C). The ridges have a wavy shape, are orientated obliquely to the inferred ice flow direction and have a 80 to 1000 m spacing and amplitudes from 2 to about 10 m. Some of the ridges can be found superimposed on narrow, elongated MSGLs (Fig. 2E) or overlapped by eskers (Fig. S1C).

Parallel-spaced ridges transverse to the inferred ice flow direction occur at the flanks of regions occupied by streamlined bedforms (Figs 2D, 3B). The ridges are gentle, up to about 400 m wide and up to 2 km long, with amplitudes of about 2 m. Groups of ridges are up to 20 km long. We interpret them as ribbed moraines and use them to help constrain the ice streams' lateral margins (cf. Dyke *et al.* 1992; Hättestrand & Kleman 1999; Vérité *et al.* 2020).

Major moraines are identified as clear arcuate ridges and remnants of lobate-shaped hillocks, and are about 500 m wide with amplitudes up to 15 m, and locally up to 40 m (e.g. Figs 2F, 4). Minor moraines typically mimic the arcuate shape of the associated major moraine. Locally, minor moraines comprise corrugated areas (Fig. 2F) with spacing up to 400 m and amplitudes below 3 m, although in other localities the spacing is up to several kilometres and amplitudes reach up to 10 m. The western part of the study area has relatively few, mostly major moraines but many well preserved streamlined bedforms. Conversely, the eastern part of the study area is covered by numerous closely spaced moraines and few streamlined bedforms (Figs 1B, 2F).

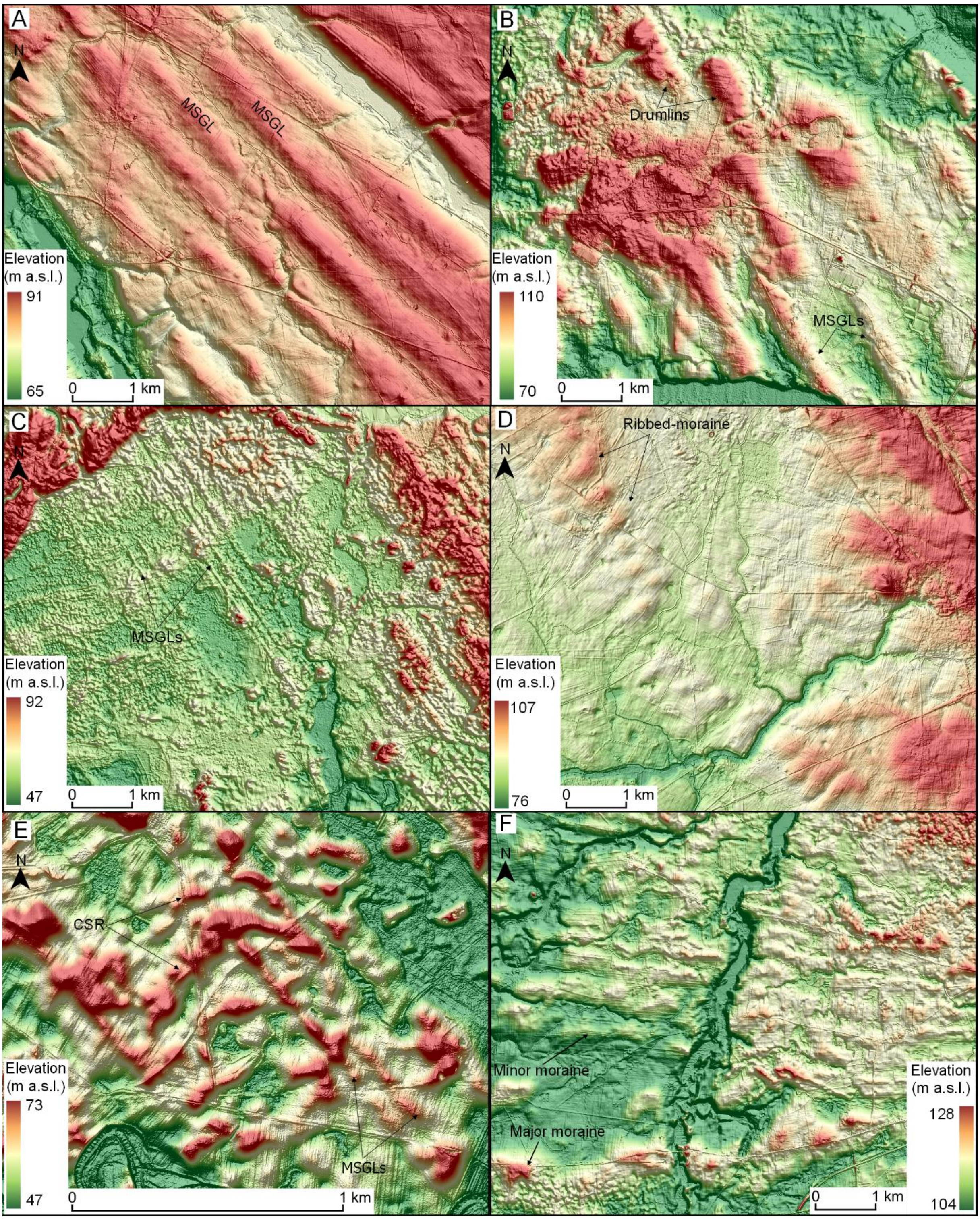

Fig. 2. Examples of (A) mega-scale glacial lineations, (B) drumlins, (C) narrow, elongated mega-scale glacial lineations, (D) ribbed moraine, (E) crevasse-squeeze ridges, (F) major and minor moraines, identified during the mapping process. Note that the scale in all sub-figures is the same, except (E). High-resolution version of this figure is available as Fig. S2. The close-ups for localisation of (A) to (F) are included on Fig. S1A.

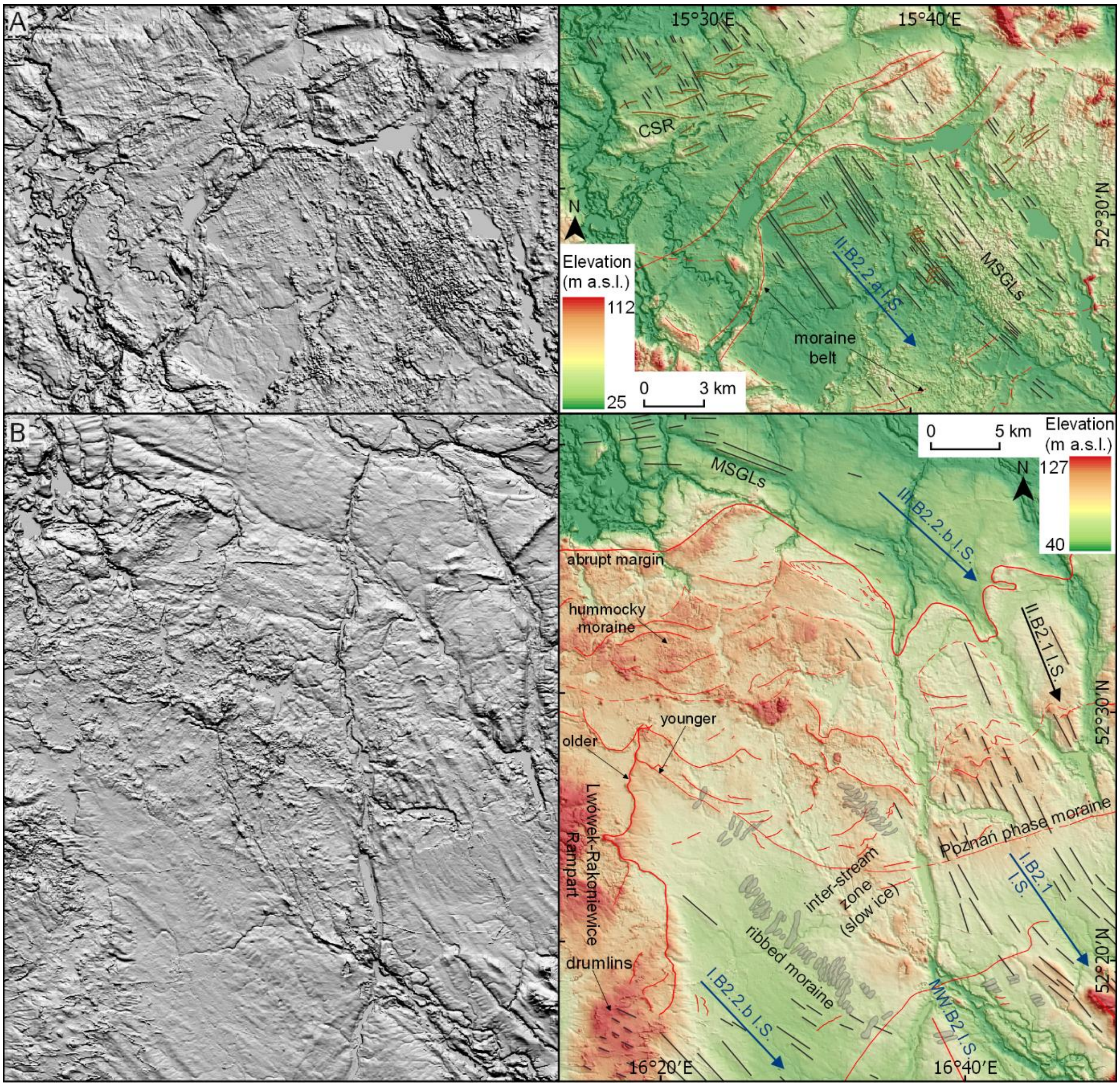

Fig. 3. A. System of moraines (major – bold face and minor – thin red solid lines) superimposed over mega-scale glacial lineations (black solid lines) and crevasse-squeeze ridges (CSR) (brown) formed beneath the III.B2.2.a (Pszczew) Ice Stream. B. The signature of the III.B2.2.b (Oborniki) Ice Stream manifested by MSGLs (see also Fig. 1) and an abrupt margin. The ice stream is confined within the Toruń-Eberswalde ice marginal spillway. Note that the ice flow direction shifted from SE to E during retreat to the north. Further to the south is a moraine complex probably related to the II.B2.1 (Wągrowiec) Ice Stream. An area occupied by the I.B2.1 (Września) and I.B2.2.b (Leszno) ice streams is separated by a funnel-shaped inter-stream zone indicated by chains of ribbed moraines (gray polygons). The influence of bed topography on ice flow is indicated by a transition from drumlins at the Lwówek-Rakoniewice Rampart to MSGLs in the downstream direction. Dashed red lines mark locations of moraine chains inferred from fragmented moraines. For localisation see Fig. 1. High-resolution version of this figure is available as Fig. S3.

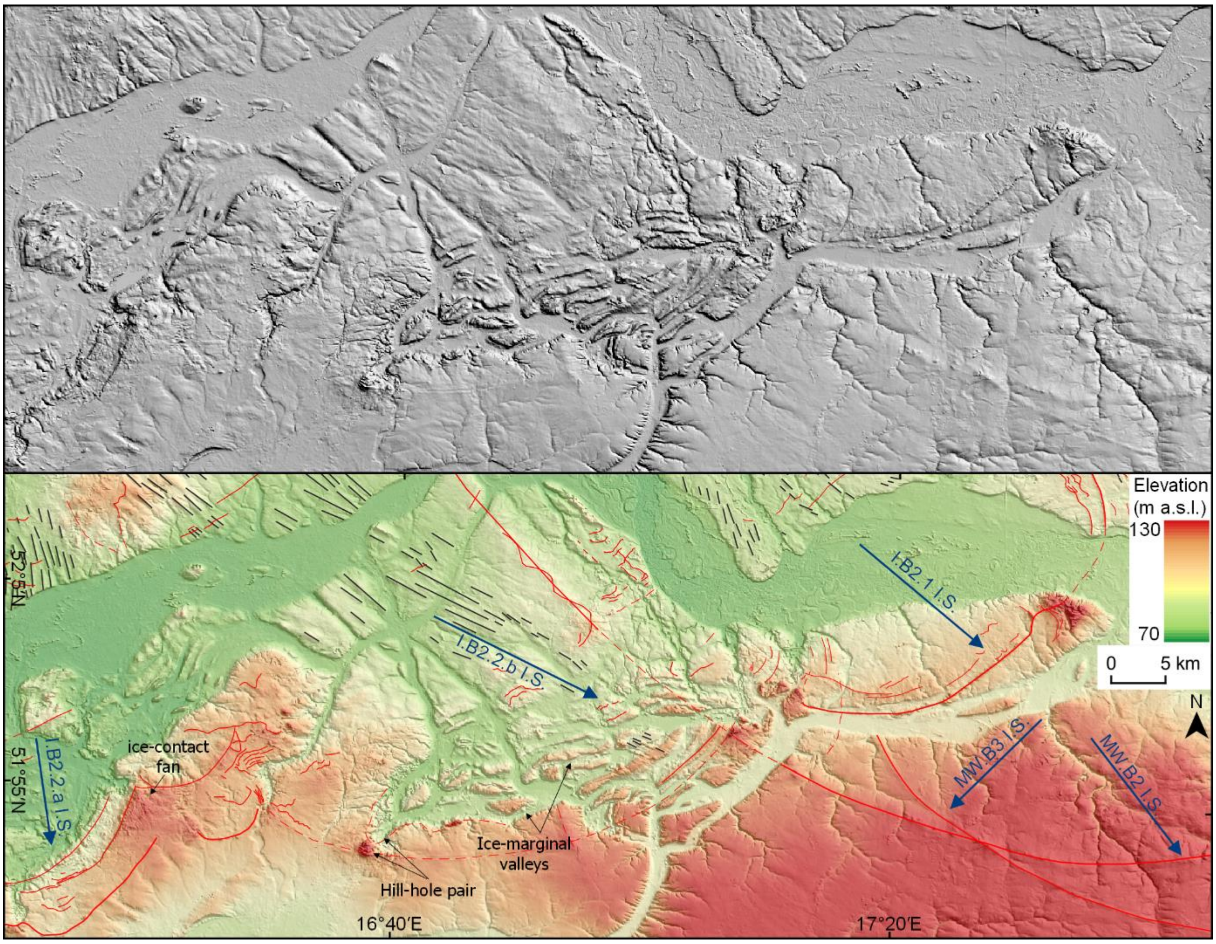

Fig. 4. Cross-cutting of major terminal moraines enabling the sequence of ice-streaming events to be reconstructed. Two Middle Weichselian ice streams overlap each other; the MW.B2 (Pleszew) Ice Stream moraine is overridden by the MW.B3 (Jarocin) Ice Stream moraine. Younger, Late Weichselian ice streams – I.B2.2.b (Leszno) and I.B2.1 (Września) override the MW.B2 (Pleszew) Ice Stream moraine. The prominent ridge-trough structures near the termini of I.B2.2.b (Leszno) Ice Stream are interpreted as ice-marginal valleys. For localisation see Fig. 1. High-resolution version of this figure is available as Fig. S4.

Ice streams

We identified seventeen active ice streaming events revealing a more complex pattern compared to traditional reconstructions (Punkari 1997 – B2 and B3; Przybylski 2008). In Table 1 we provide an updated inventory of ice streams within the study area, including already established cases (e.g. Przybylski 2008; Wysota *et al.* 2009), uncertain ice streams that we are able to confirm from our detailed mapping (cf. Kozarski 1962) and nine newly detected ice streams. Ice streams recognised in the study area are typically 20-25 km wide, with the exception of two ice streams about 60 km wide, with traces that extend beyond the traditionally determined LGM ice limit.

The regional-scale mapping reveals that the position of the ice streams is not random. The up-ice zone of ice streams associated with the Lower Odra region conform with a wide (about 115 km) and relatively shallow depression, which splits southward into three troughs each conform with the location of ice streams – named 2.1, 2.2 and 2.3 (from east towards west, respectively; Fig. 5A). These three troughs are 20 to 40 m deep and extend from the Lower

Odra region towards the LGM margin. The lateral extent of the ice streams is constrained by longitudinally oriented moraine complexes (Fig. 5A): the westernmost one, located in Germany, limits the third trough from the west; the second one is located between the third and second trough; the Lwówek-Rakoniewice Rampart separates the I.B2.2.a (Sława) and I.B2.2.b (Leszno) ice streams and the fourth one is a distinct moraine complex to the north-east of the III.B2.1 (Krzyż) Ice Stream. In contrast, ice streams from the Lower Wisła region were focused along one deep (up to 100 m deep and 80 km wide) upstream valley, that becomes more subdued downstream. These ice streams were closer spaced with divergence demarcated by marginal moraines sequences.

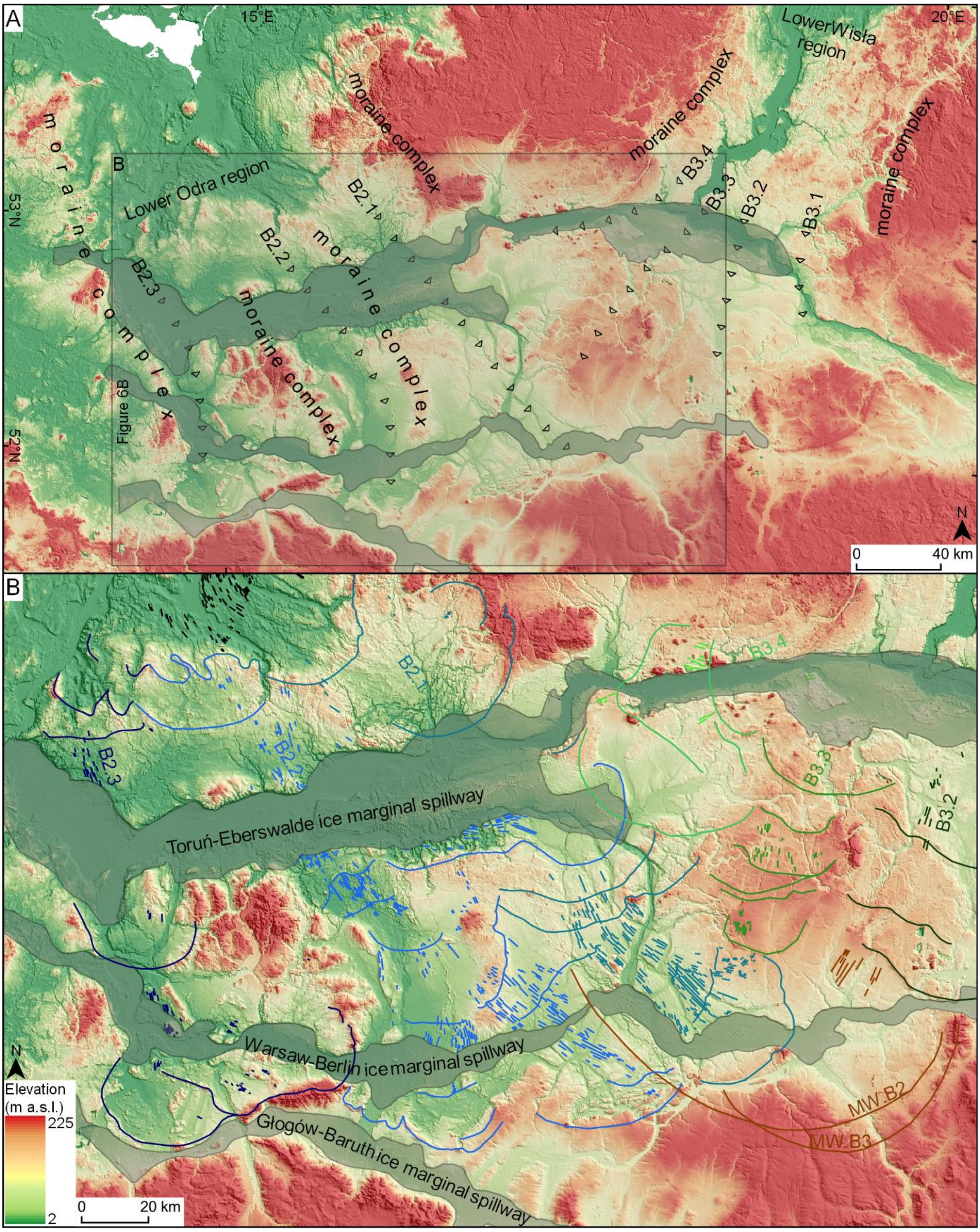

Fig. 5 A. Study area morphology; longitudinal moraine complexes restrict troughs that controlled ice streams distribution. Ice stream paths are marked with small triangles. B. Ice streams retreat paths approximated by correlating major and minor moraines and inferred moraines with streamlined bedforms. The names of the ice streams paths and assigned moraines are indicated by colours. For localisation see Fig. 1.

Table 1. Geomorphic evidence for ice streaming events recognised in this study.

Phase	Symbolic name	Conventional name	Streamlined bedforms	Lateral margin	Terminal margin	Other geomorphic characteristics
Middle Weichselian	MW.B2	Pleszew	None	Overridden arcuate moraine	Arcuate morainic crest (Fig. 4)	Lobate margin continuous for 150 km, high uncertainty
	MW.B3	Jarocin	MSGLs	Abrupt margin	Arcuate morainic crest (Fig. 4)	Dimensions similar to the Pleszew Ice Stream
Local LGM (Leszno phase)	I.B2.1	Września	MSGLs, drumlins (Figs 2A-B, S1B)	Ribbed moraines (Fig. 2D)	Arcuate morainic crest (Fig. 4)	Preserved footprint of well-developed fan-shaped ice margin
	I.B2.2.a	Sława	MSGLs, drumlins (Fig. 4)	Abrupt margin	Arcuate morainic crest (Fig. 4)	Glaciotectonic deformations, thrust moraines, ice-contact fans (Fig S4, see Kasprzak 2003)
	I.B2.2.b	Leszno	MSGLs, drumlins (Figs 4)	Ribbed moraines (Fig. 2D)	Arcuate morainic crest, hill-hole pair (Fig. 4), thrust moraine blocks	Sequence of lobate ice-marginal valleys (Fig. 4) and moraine crests near terminus (see Kasprzak 2003), convergent MSGLs pattern
	I.B2.3	Lubuski	MSGLs, drumlins	Fragmentary abrupt margin	Arcuate morainic crest	Thrust moraine blocks (e.g. Chmal 2001; Nowak 2003)
Around Poznań phase	II.B2.1	Wągrowiec	None	Uncertain	Arcuate morainic crest	Arcuate push moraine (Kozarski 1962); sparse landforms do not enable clear classification
	II.B2.2	Lwówek	Drumlins	Uncertain	Abrupt arcuate indistinct margin	Drumlins 2-3 km from the margin
	II.B2.3	Rzepin	MSGLs	Uncertain	Arcuate morainic crest, abrupt margin	Small field of crevasse-squeeze ridges 7 km from termini
	II.B3.2	Gopło complex	MSGLs, drumlins	Fragmentary abrupt margin	Arcuate morainic crest	Streamlined area 14 km from termini, closely spaced recessional moraines
	II.B3.3	Gniezno complex	MSGLs, drumlins	Uncertain	Arcuate morainic crest, thrust moraine	Closely spaced push moraines (Fig. 2F; see Kozarski 1962); complex of lobes with variable width
	II.B3.4	Rogoźno	None	Uncertain	Arcuate morainic crest	The most of marginal zone is destroyed by water erosion, weak evidence for its existence, B2-B3 contact zone (see Kozarski 1962)
Before Pomeranian phase	III.B2.1	Krzyż	Drumlins	Abrupt margin	Arcuate morainic crest	Sparse, vestigial streamlined bedforms
	III.B2.2a	Pszczew	MSGLs (Fig. 2C)	Abrupt margin	Abrupt margin	Crevasse-squeeze ridges present 40 km from termini (Figs 2E, S1C)
	III.B2.2b	Oborniki	MSGLs, drumlins (Fig. 3B)	Abrupt margin	Arcuate (in general), fragmented morainic crest	Terminal morainic crest following terrain irregularities
	III.B2.3	Słubice	MSGLs	Abrupt margin	Abrupt margin	Narrow elongated MSGLs superimposed on MSGLs N of Toruń-Eberswalde ice marginal spillway
	III.B3.4	Chodzież complex	MSGLs (Fig. S1D), drumlins	Moraine chains and abrupt margin	Arcuate morainic crest	Closely spaced push moraines, thrust moraines and hill-hole pairs (Fig. S1D; see also Kozarski 1962), disrupted drumlins, hummocky moraines (Fig. S1E)

Ice stream dynamics

Of the seventeen identified ice streams tracks (Table 1), eight of them (Fig. 6): MW.B2 and MW.B3 (Pleszew, Jarocin), I.B2.1-3 (Wrzesnia, Sława, Leszno, Lubuski), II.B3.2 (Gopło) and III.B2.2b (Oborniki) are characterised by high parallel conformity of the lineations within each flow-set. This suggests synchronous formation of the lineations rather than incremental formation (time-transgressively) behind a retreating ice margin (cf. Clark 1999). Their traces are mainly located between the local LGM and the Poznań phase limit (Fig. 1). Only two ice streams were located N of the Poznań phase limit. Another, three ice streams (Table 1): III.B2.1 (Pszczew), III.B2.2a (Słubice) and III.B3.4 (Chodzież,) have elongated, narrow MSGLs locally associated with crevasse-squeeze ridges that we interpret to possibly indicate surging. In this interpretation the difference in morphology of the streamlined bedforms is a result of ice flow dynamics.

The footprint of six flow-sets of II.B2.1-3 (Rzepin, Lwówek, Wągrowiec), III.B2.1 (Krzyż), and II.B3.3-4 (Rogoźno, Gniezno) is locally highly eroded or covered with hummocky moraines (Fig. 3B), recessional corrugations (Fig. 2F) and remoulded by subsequent flow phases (e.g. Fig 3B). These regions contain sparse streamlined bedforms up to 2 km long, suggestive of slower ice flow (Barchyn *et al.* 2016). However, we interpret them as ice streams due to the lobate geometry of their margin and their protruding extent. These ice streams lack abrupt lateral margins, possibly due to small velocity variations across the multiple neighbouring ice streams (Fig 6B, C).

Several minor topographic rises across the study area appear to have impacted ice stream dynamics. Our results show that the longitudinally oriented Lwówek-Rakoniewice Rampart, composed of three topographic bumps (Fig. 3B), had a complex role in the dynamics of the I.B2.2 (Sława, Leszno) ice streams. The morphology, distribution and downstream transitions of the streamlined bedforms is consistent with a continuum between drumlins and MSGLs (Ely *et al.* 2016). Assuming a positive relationship between ice velocities and bedform elongation (Jamieson *et al.* 2016), a switch from drumlins on top of the Lwówek-Rakoniewice Rampart middle bump (Fig. 3B), to MSGLs downstream can be interpreted to record acceleration of ice velocity after passing the middle bump. The I.B2.2 (Sława, Leszno) ice stream splits into the I.B2.2.a (Sława) and IB2.2.b (Leszno) at the southern part of Lwówek-Rakoniewice Rampart on a reverse slope that may have influenced the flow and caused divergence (cf. Ng 2015).

Well preserved MSGLs on the beds of the I.B2.1-3 (Września, Leszno, Sława) ice streams, accompanied by sparse recessional landforms suggest that retreat was fast and continuous (cf. Kasprzak 2003; Ó Cofaigh *et al.* 2008; Fig. 1B). Conversely, the eastern ice streams of II.B2.1 (Wągrowiec) and II.B3.2-4 (Gopło, Gniezno, Rogoźno) have numerous moraines indicating slower retreat. This is in agreement with Kozarski (1962) who characterised deglaciation of the eastern part of the study area as oscillating based on closely-spaced push moraines. The II.B2 and II.B3 ice streams are interpreted to have undergone active temperate retreat, similar to modern Icelandic temperate ice margins (cf. Evans & Twigg 2002).

Chronology

We suggest that the oldest ice flow phase was the MW.B2 (Pleszew) Ice Stream. This is based on cross-cutting relationships: the moraine associated with the MW.B3 (Jarocin) Ice Stream is superimposed on the marginal moraine of the MW.B2 (Pleszew) Ice Stream (Fig. 4). The association of MSGLs leading to the terminal moraine of the MW.B3 (Jarocin) Ice Stream (Fig. 1B) suggests that it originated in the Lower Wisła region. Several pre-LGM radiocarbon ages east of the MW.B3 (Jarocin) Ice Stream (Wysota *et al.* 2002; Wysota *et al.* 2009 and reported in Hughes *et al.* 2016) and similarity between shapes and extents of the MW.B2

(Pleszew) and MW.B3 (Jarocin) ice stream terminal moraines suggest that both ice streams could be related to one of two Middle Weichselian advances (between 50 and 30 ka; Wysota *et al.* 2002; Wysota *et al.* 2009; Houmark-Nielsen 2010). Even though expansion of ice south of the Lower Odra region during the Middle Weichselian is controversial (Stankowska & Stankowski 1988; Stankowski 2000; Wysota *et al.* 2009 after Wysota *et al.* 2002), such an interpretation fits well with several surface exposure ^{10}Be ages located in close vicinity of the MW.B2 (Pleszew) and I.B2.2.b (Leszno) terminal moraines (boulder samples LGM-06 to 08 and SAAl-01 to 03 with ages between 44 to 64 ka; Tylmann *et al.* 2019).

The arrangement of landforms, i.e. MSGLs and major moraines, near the LGM margin (Fig. 1B) indicates the existence of four major ice streams the I.B2 (Września, Leszno, Sława and Lubuski) complex that were active during the local LGM (Fig. 6A). The development of the symmetrical funnel-shaped inter-ice stream zone, characterised by chains of ribbed moraines (Figs 2D, 3B), between the I.B2.2.b (Leszno) and I.B2.1 (Września) ice streams, indicate that they operated simultaneously. The terminal moraines of I.B2.2.b (Leszno) and I.B2.1 (Września) ice streams and part of the ribbed moraines dividing their activity both override the MW.B2 (Pleszew) Ice Stream moraine.

The temporal activity of the I.B2.3 (Lubuski) Ice Stream is poorly constrained (Kraiński 2002; Urbański 2005). However, we assign it to the local LGM based on its common origin, extent similar to other I.B2 ice streams in the Lower Odra region, and the similar morphological character of MSGLs between the I.B2.3 (Lubuski) and I.B2.1-2 (Września, Sława, Leszno) ice streams. There is limited evidence of ice flow in the Lower Wisła region during the local LGM (Leszno phase; see Fig. 6A). This is supported by the well-developed fan of MSGLs along the eastern part of the I.B2.1 (Września) Ice Stream, which suggests that its forefield was free of ice. Thus, expansion of ice from the Lower Wisła region during the Leszno phase didn't reach as far south as ice from the Lower Odra region. The up-ice contact zone between the I.B2.1 (Września) Ice Stream and II.B3.3 (Gniezno) Ice Stream suggest that both reached their maximal extent at a similar time.

During northward ice margin retreat from its LGM position (Poznań phase), the II.B2.1-3 (Wągrowiec, Lwówek, Rzepin) ice streams originating in the Lower Odra region and II.B3.2-4 (Gopło, Gniezno, Rogoźno) ice streams originating in the Lower Wisła region (Fig. 6B, see also Kozarski 1962, 1995; Pettersson 2002; Wysota *et al.* 2009) were active. The interaction between the B2 and B3 ice streams was previously noted by Kozarski (1962) who identified orthogonally arranged subglacial channels and moraines and a prominent S-oriented subglacial channel at the confluence zone. Extrapolation of cross-cutting relationships between ice streams (Fig. 1B) indicate that the II.B3.4 (Rogoźno) Ice Stream preceded the activity of the II.B2.1 (Wągrowiec) Ice Stream.

Proglacial fluvial activity and the advance of ice to the B2/B3 confluence zone after the Poznań phase has degraded the footprint of older phases. However, the arrangement of moraine-dammed lake and terminal moraines 15 km apart (Fig. S1E), shows that the III.B2.1 (Oborniki) Ice Stream and III.B3.4 (Chodzież) Ice Stream Complex operated at the same time, but did not directly interact with each other. The activity of the III.B2.2.a and III.B2.3 (Pszczew, Słubice) ice streams is linked to after the Poznań phase. The B3.4 (Chodzież) Ice Stream (cf. Kozarski 1962, 1995; Dzierżek 1997; Pettersson 2002) was likely strongly controlled by topography as it trended W along the axis of the Toruń-Ebesrwalde ice marginal spillway. The III.B2.1 (Krzyż) Ice Stream is the youngest recognized flow phase and is located within the Pomeranian phase marginal belt of the Lower Odra region fragment.

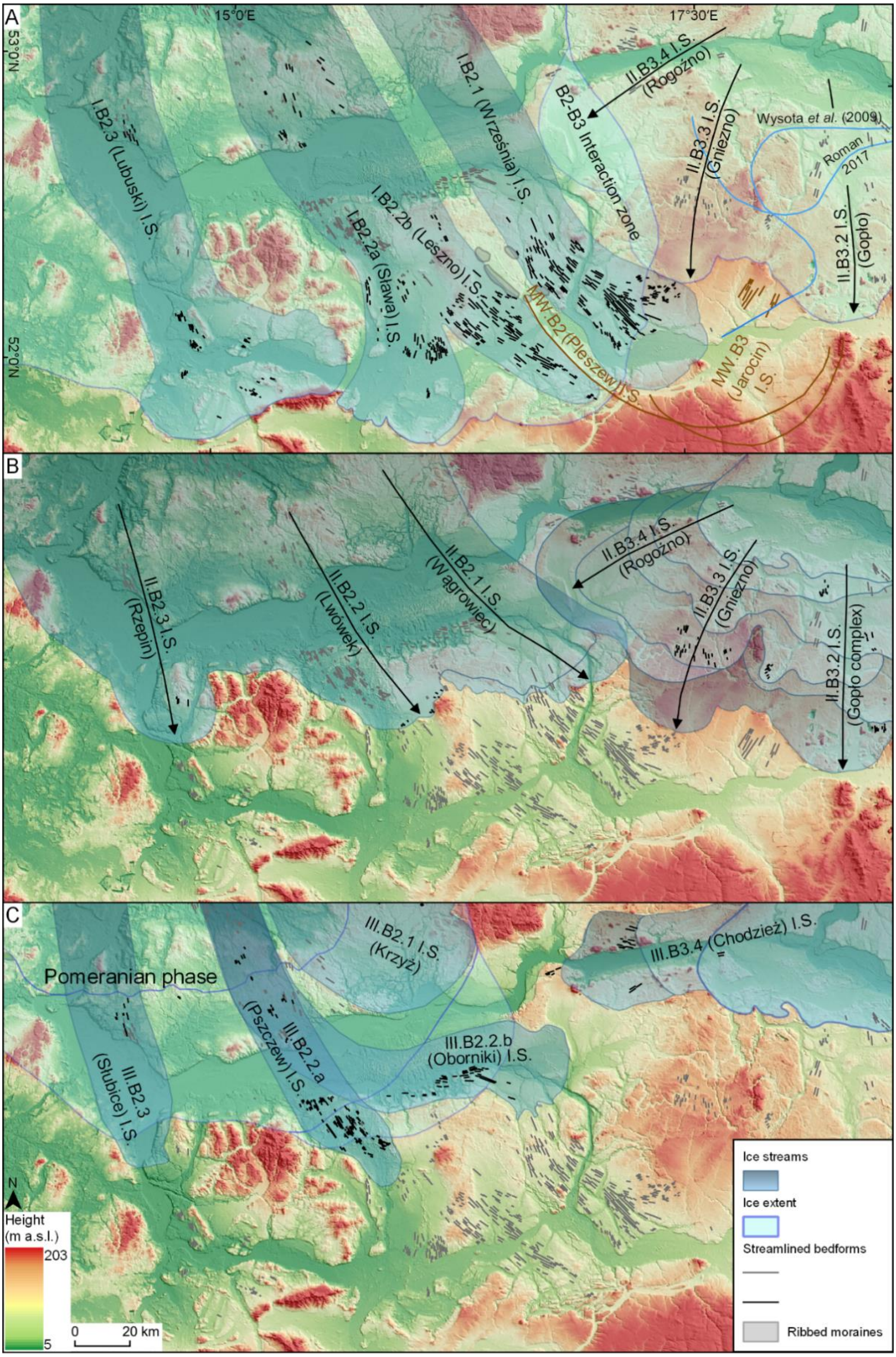

Fig. 6. Reconstruction of ice retreat events in central western Poland. Events are grouped by their probable time of occurrence and correspondence to the following phases: A. Leszno phase (LGM). The age of moraine chains in the terminal part of the I.B2.3 (Lubuski) Ice Stream is not yet well established (see Kraiński 2002; Urbański 2005). MW.B2 (Pleszew) and MW.B3 (Jarocin) ice streams were active ealier, during the Middle Weichselian. B. Poznań phase. C. Pomeranian phase. For localisation see Fig. 1.

Discussion

The Baltic Ice Stream Complex and its analogues

The original identification of the Baltic Ice Stream Complex enabled only a general interpretation of the SIS southern sector at the scale of several hundreds of kilometres (Punkari 1997). Our mapping results show that about 80% of the study area was covered by closely-spaced ice streams, indicating that during the local LGM, the generalised B2 lobe comprised a series of neighbouring ice streams, analogous to the Siple Coast ice streams in West Antarctica (Rignot *et al.* 2011) and terrestrially terminating ice lobes of the southern Laurentide Ice Sheet (Jennings 2006). These ice stream systems all had relatively flat beds composed of soft sediments that would have facilitated fast ice flow (e.g. Alley *et al.* 1986; Patterson 1998; Jennings 2006; Margold *et al.* 2015; Spagnolo *et al.* 2016). Elevated geothermal heat flux is also suggested to be an important factor controlling the activity of ice stream both in central western Poland and Siple Coast regions (Raymond 2000; Szuman *et al.* 2018).

The location of ice streams seems to have been at least partially controlled by upstream topography, with the Polish ice streams controlled by the Baltic trough and the ice lobes of the Laurentide Ice Sheet influenced by, and participated in formation of, the basins of the Great Lakes (Margold *et al.* 2018). In their upstream region, the ice lobes of the Great Lakes, operated over and helped erode well-developed troughs (Larson & Schaetzl 2001; Kehew *et al.* 2005), which are similar to the Lower Odra and Wisła regions presented in this study area. The topographic steering of ice in both regions likely promoted accelerated ice flow velocities that might have been important in triggering the initiation of ice streaming. Developing a 20-m deep trough for an ice stream operating for 4000 years (as assumed for the duration of the LGM phase) requires an average erosion rates of 5 mm a^{-1}, which is rather high when compared to observations from contemporary ice streams (e.g. Bougamont & Tulaczyk 2003). This is consistent with the troughs being occupied and enlarged over multiple glaciations. Increased ice flow velocities in the Baltic region would result in lowered ice profiles of the extended ice streams, reducing basal shear stress and impacting subglacial water routing (Livingstone *et al.* 2013). Such a setting would have led to preferential ice margin expansion during advance resulting in the lobate extension of the ice limit beyond the general pattern of the SIS southern sector (Fig. 1A).

The ice streams mapped in this study are typically about 25 km wide, which is towards the narrower end but comparable with other ice streams identified in glaciated settings (Margold *et al.* 2015). In particular, these are similar in width to the Siple Coast ice streams (30 to 80 km). By contrast, the Great Lake ice streams are about 100 km wide (Margold *et al.* 2015, 2018), similar in size to the general Baltic Ice Streams (e.g. B2 and B3), although recent high-resolution mapping of the eastern Great Lakes region has multiple narrower (about 25 km) ice streams within one of the larger general tracks (Sookhan *et al.* 2018).

Neighbouring ice streams that are not tightly topographically constrained are capable of influencing each other. Such behaviour was common for ice streams of the Great Lakes in North America, which were characterised by competing ice streams, with the influence of particular lobes changing through time (Kehew *et al.* 2005; Margold *et al.* 2015 after Mickelson & Colgan 2003), and the Siple Coast ice streams, which have undergone ice-flow reorganisation due to water piracy (Anandakrishnan & Alley 1997) and changes in ice geometry (Bougamont *et al.* 2015). The relation between lobate terminal pattern of I.B2.1 (Września) Ice Stream and convergent pattern of I.B2.2.b (Leszno) Ice Stream could be suggestive of competition between those ice streams.

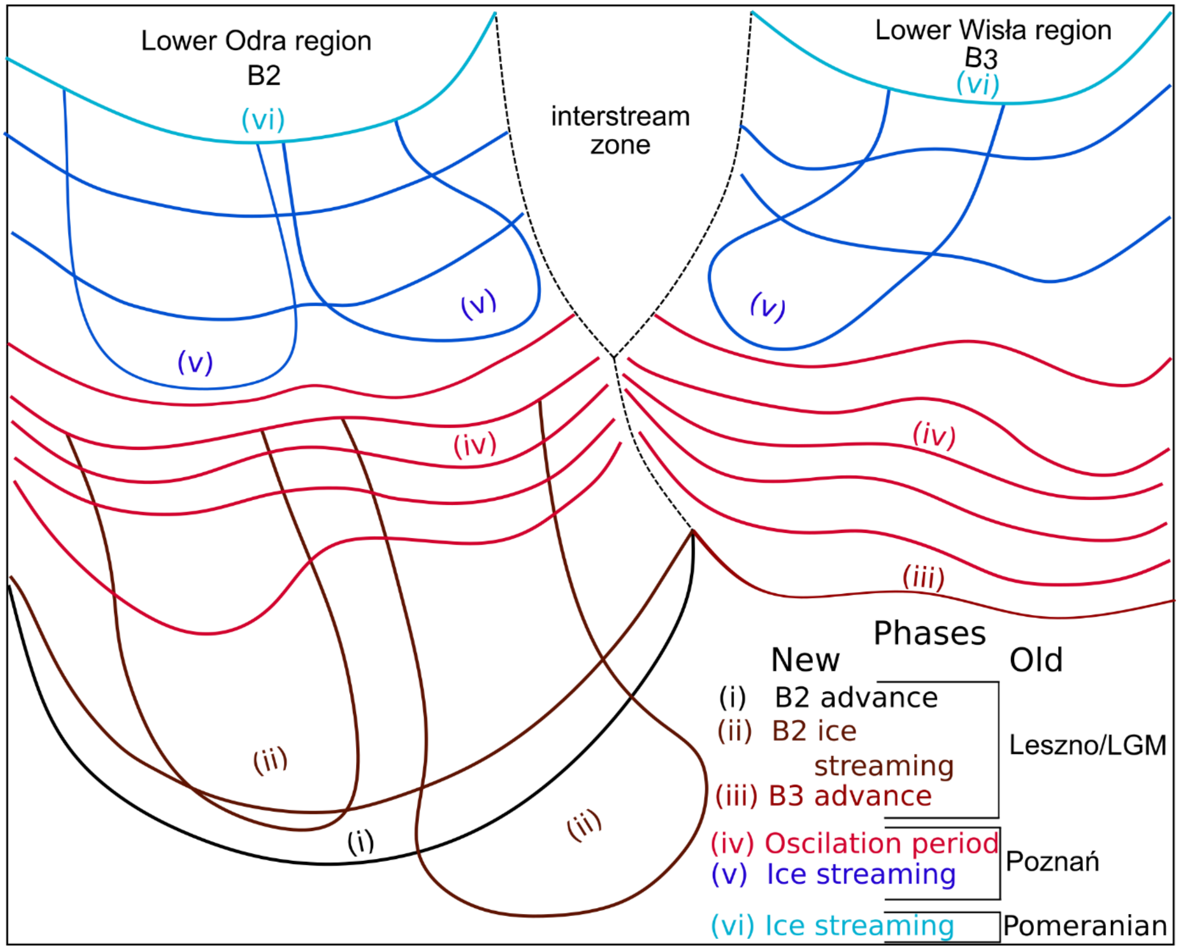

Fig. 7. A provisional interpretation of the spatio-temporal framework for Late Weichselian glaciation across the study area.

Switches in ice flow behaviour and a new deglaciation framework

The conventional framework includes the Leszno, Poznań and Pomeranian phases that are assumed to correspond to E-W oriented still-stand positions (Fig. 1A). Our high-resolution mapping has enabled identification of numerous individual ice streams, broadly corresponding to these well-known ice limits, but revealing a much more complex record of ice recession, and with ice limits firmly linked to their up-ice area flow geomorphology. To update the conventional scheme for reconstructing scenarios of Late Weichselian glaciation we use our new landform data and flow-set and superposition relationships to propose the following framework (Fig. 7): (i) B2 initial advance in which the SIS attained its southernmost position; (ii) B2 ice streaming phase (LGM/Leszno phase) associated with rapid deglaciation; the ice streams of this phase were active through millennia and locally exceeded in places the extent of initial advance; (iii) B3 advance that attained maximal extent while the B2 ice streams were still active; (iv) an oscillatory period of slow retreat with a major still-stand (i.e. Poznań Phase); (v) an ice streaming phase (first Young Baltic Advance); and (vi) a further ice streaming phase (second Young Baltic Advance) preceded by a major still-stand (i.e. Pomeranian phase).

The ice streams over central western Poland were typically 20-25 km wide, with the exception of the MW.B2 (Pleszew) and MW.B3 (Jarocin) ice streams (both ~ 60 km wide). It can be estimated that a single ice stream, 25 km wide and 300 m thick, flowing with velocity of 1 km a^{-1} (Szuman *et al.* 2018) is able to drain approximately 7.5 km^3 a^{-1} of ice (similar to the modern ice stream fluxes reported in Antarctica; cf. King *et al.* 2009; Stokes *et al.* 2016). According to ice sheet modelling, the total mass loss of the whole ice sheet concentrated during the first half of the climatically stable period of 23.0-19.5 ka BP (ii B2 ice streaming phase), was about 0.15 10^6 km^3 (Patton *et al.* 2017) and would require about 9 to 21 continuously operating ice streams of such size and flow speed (assuming that 40 to 90% of the ice was drained by ice streams; cf. Bamber *et al.* 2000; van den Broeke *et al.* 2016; Flowers 2018). The concentration of ice stream activity in the Lower Odra region modelled during the local LGM (Patton *et al.* 2016), suggests that several ice streams in western Poland must have operated simultaneously and for multi-millennia to discharge such a large ice flux. This is consistent with the Tylmann *et al.* (2019) geochronology, which indicates that the local LGM period was between 25 and 21 ka BP after which deglaciation started at 20.7 ka BP.

Sparse recessional or ice stagnation landforms are present on top of streamlined bedforms of the I.B2.1 (Września) and I.B2.2.b (Leszno) ice streams and near the LGM margin (Fig. 4). This indicates active ice stream retreat (cf. Stokes *et al.* 2008). Deglaciation during period (ii) was fast and therefore associated with rapid ablation (cf. Ó Cofaigh *et al.* 2008). Well-preserved, delicate single-crested terminal moraine at the margin of the I.B2.1 (Września) Ice Stream (Fig. 4) indicates a period of short-term balance between discharge and ablation.

The extent of ice in the eastern part of the study area is equivocal during the local LGM. However, it did not likely conform with the conventional LGM extent (see Wysota *et al.* 2002; Roman 2017). This is because the fan-shaped pattern of the I.B2.1 (Września) Ice Stream indicates that its NE terminal margin was not restricted by slowly flowing ice, and it therefore extended into an ice-free area (see Fig. 6A). The asynchrony in ice extent between areas associated with the Lower Odra and Lower Wisła regions could be caused by preferential steering of ice through the Lower Odra region during the LGM phase (ii) leading to increased ice flow and an over-extended general B2 ice stream. The advance of the ice margin originating in the Lower Wisła region to its maximal extent during phase (iii) at a time when the Lower Odra region ice streams were rapidly retreating suggests a reorganisation of SIS flow geometry and eastward migration of an ice divide, north of the Baltic area (see Patton *et al.* 2016).

The presence of closely spaced recessional moraines across II.B3.2-3 (Gopło, Gniezno; Fig. 2F) ice streams during phase (iv) indicate that they were actively flowing during recession and that the ice discharge was periodically balanced by the ablation. Active retreat during phase (iv) was interrupted by ice stream stagnation indicated by major recessional moraines and prominent hummocky terrain (e.g. Fig. 3B).

Based on elongated streamlined bedforms and margins that protrude beyond the main ice sheet limits, phase (v) is interpreted to have been associated with enhanced ice flow and ice stream reactivation resulting in the III.B2 (Krzyż, Oborniki, Pszczew, Słubice) and III.B3.4 (Chodzież) events. Decaying and thinning ice became increasingly topographically focused, as evidenced by major shifts in ice flow direction from the SW to W along the Toruń-Eberswalde ice marginal spillway (Fig. 6C). The topographical steering is even stronger in subsequent phases of SIS decay. In other parts of the SIS southern sector, the Young Baltic advances (18-16 ka BP; Houmark-Nielsen & Kjær 2003) were characterised by streamlined bedforms constrained to topographic troughs, indicating subglacial topographic steering due to ice decay and thinning (Kjær *et al.* 2003; Kalm 2012; Lasberg & Kalm 2013). This is consistent with modelling by Patton *et al.* (2017) who suggest that after 19 ka BP ice volume decreased faster than area, resulting in ice thinning and increased alignment of advancing ice along topographic troughs.

Ice thinning and surface lowering can promote seasonal temperature fluctuations that penetrate to the bed, and an increase in conductive upward heat losses leading to progressive basal freezing. This is common for small glaciers (Lovell *et al.* 2015; Sevestre & Benn 2015), however, it is expected that on larger ice masses warm-based conditions are maintained except at the terminus (Benn *et al.* 2019). In such cases, glaciers can develop increasing enthalpy gradients as a consequence of the positive thermal balance in temperate parts of the bed, and this can facilitate surges (Benn *et al.* 2019). Such a mechanism could have influenced the Young Baltic advances across the study area and wider southern sector of the SIS (Stephan 2001; Kjær *et al.* 2003; Kalm 2012). The shift from temperate to warm polythermal marginal conditions also coincided with surging of the southwest Laurentide Ice Sheet (Evans *et al.* 2014).

Degradation of glacial forms and uncertainty in the conventional framework

In the study area, multiple advances along the main troughs obscure the potential footprint of preceding ice stream activity due to either remoulding or erosion. Landforms indicative of ice streaming have been draped by deglacial and aeolian sediments and degraded by water erosion and human activity. Much of the subglacial evidence of streaming was removed by meltwater drained through two east-west ice-marginal spillways (Fig. 5B). The location of ice streams in their upstream area is estimated based on limited MSGL remnants, lobate margins and an assumption that the ice streams did not migrate between deglaciation phases, but rather followed troughs developed by their predecessors, taking into consideration progressive dependence on topography between phases.

Our reconstruction of ice streaming in the Polish southern sector of the SIS reveals a dynamic deglacial history that is difficult to fit into the traditional, three-step framework (Leszno, Poznań and Pomeranian still-stands). For example, moraines commonly associated with the Poznań phase (Fig. 1), do not represent a major still-stand that can be continuously traced across the study area, but rather reflect the shape of separate receding ice streams associated with Lower Odra (B2) and Lower Wisła regions (B3), respectively (Fig. 6B, C). The direction of ice stream recession was towards these regions where the ice flux was concentrated. Similarly, the Young Baltic ice streaming advances have been associated with the Poznań and Pomeranian still-stand phases (Stroeven *et al.* 2016), whereas our reconstruction suggests that the first Young Baltic advance was after the Poznań phase still-stand and the second Young Baltic advance was before the Pomeranian phase still-stand. Using the fixed three-step deglacial framework is likely the cause of millennial scale disagreement between the timing of models that are fixed to still-stand phases and that merge B2 and B3 lobes into a single continuous E-W oriented margin. This is particularly true for models applied to the eastern part of the study area, associated with the Lower Wisła region (cf. 22 ka BP - Hughes *et al.* 2016; 19 ka BP - Tylmann *et al.* 2019).

Conclusions

Geomorphological mapping, using a 0.4-m LIDAR-based digital elevation model, revealed about 940 streamlined bedforms and over 1000 other glacial landforms or their fragments, many of which are shown for the first time. The lineation flow-sets together with associated landforms were used to identify: seventeen ice streaming across the study area. The study also presents the vestiges of ice advances preceding the Late Weichselian period, possibly related to the Middle Weichelian. Our new relative chronology of deglaciation reveals a complex pattern of ice streaming that requires a more complex framework than the traditional main deglaciation phases (LGM/Leszno, Poznań, Pomeranian). We propose the following events: (i) B2 initial advance; (ii) B2 ice streaming phase (LGM/Leszno phase) with fast deglaciation; (iii) B3 advance with reduced dynamics; (iv) oscillation period of slow temperate recession; (v) ice streaming phase (first Young Baltic advance); (vi) ice streaming phase (second Young Baltic Advance).

Bed topography and the competition between ice streams influenced their location and activity. The western part of the study area has a different topographical character than the eastern part. In the west, topography played an important role in controlling the spatial distribution and dynamics of ice streams. The impact of topography increased during deglaciation as the ice thinned. The eastern part of the study area is characterised by a long and wide trough in the upstream area and a lack of topographic obstacles in the downstream area.

The concentration of ice activity in the Lower Odra region during the local LGM suggests that several ice streams in western Poland must have operated simultaneously and for multi-millennia. After the local LGM, active recession was widespread across the study area. The reason for fast active retreat is suggested to be connected with a wider reorganization of the ice sheet flow geometry after which ice streams dynamics was reduced. Our results suggest that ice retreated towards the two gateways of the Lower Odra and Wisła regions in a lobate configuration. These erosional basins topographically steered ice flow, similar to the Great Lakes region of the southern Laurentide Ice Sheet. Apart from asynchronous ice behaviour during the local LGM phase, the region is characterised by the regularity of ice streams longitudinal extent between ice originating in the Lower Odra and Wisła regions. Assuming similar ice fluxes, this enables temporal classification of each particular event based on the lobate-shaped extent.

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Author contributions. – IS, JZK, MWE devised the research concept, generated the DEM model and conducted geomorphological mapping. IS and JZK took the lead in writing the manuscript. SJL, CDC provided critical scientific editing. All authors contributed to the analysis, ideas and helped to shape the study. The authors declare no conflict of interest.

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Supporting Information

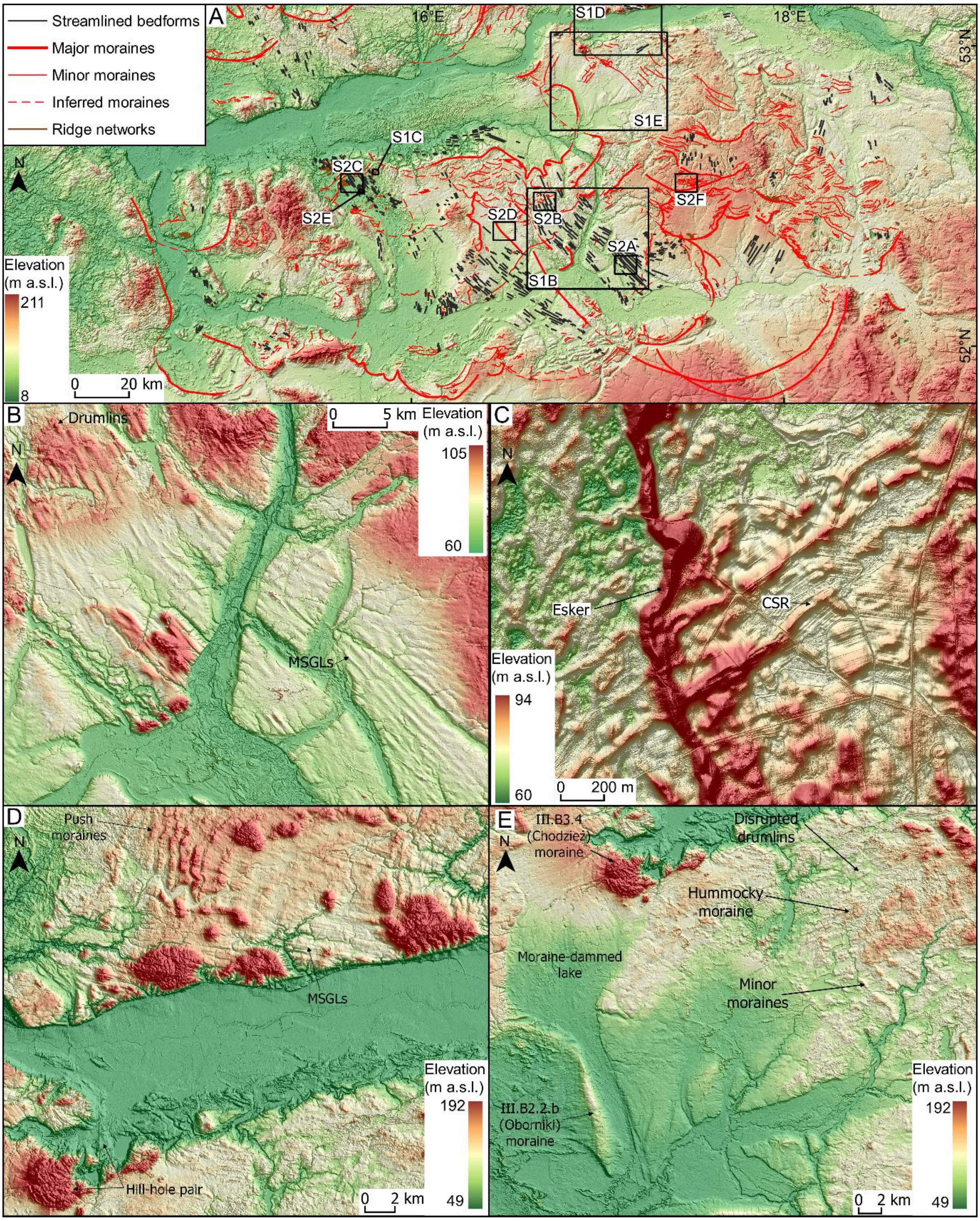

Fig. S1. A. Overview of close-ups presented in Figs S1 and S2. Examples of (B) drumlins and mega-scale glacial lineations flow-set, I.B2.1 (Września) Ice Stream; (C) crevasse-squeeze ridges overlapped by esker; (D) footprint of III.B3.4 (Chodzież) Ice Stream with push moraines, mega-scale glacial lineations, hill-hole pairs; and (E) the B2/B3 confluence zone – moraines of III.B2.2.b (Oborniki) and II.B3.4 (Chodzież) ice streams with a moraine-dammed lake in between. The streamlined bedforms of II.B3.4 (Chodzież) Ice Stream are disrupted, partly covered by moraines.

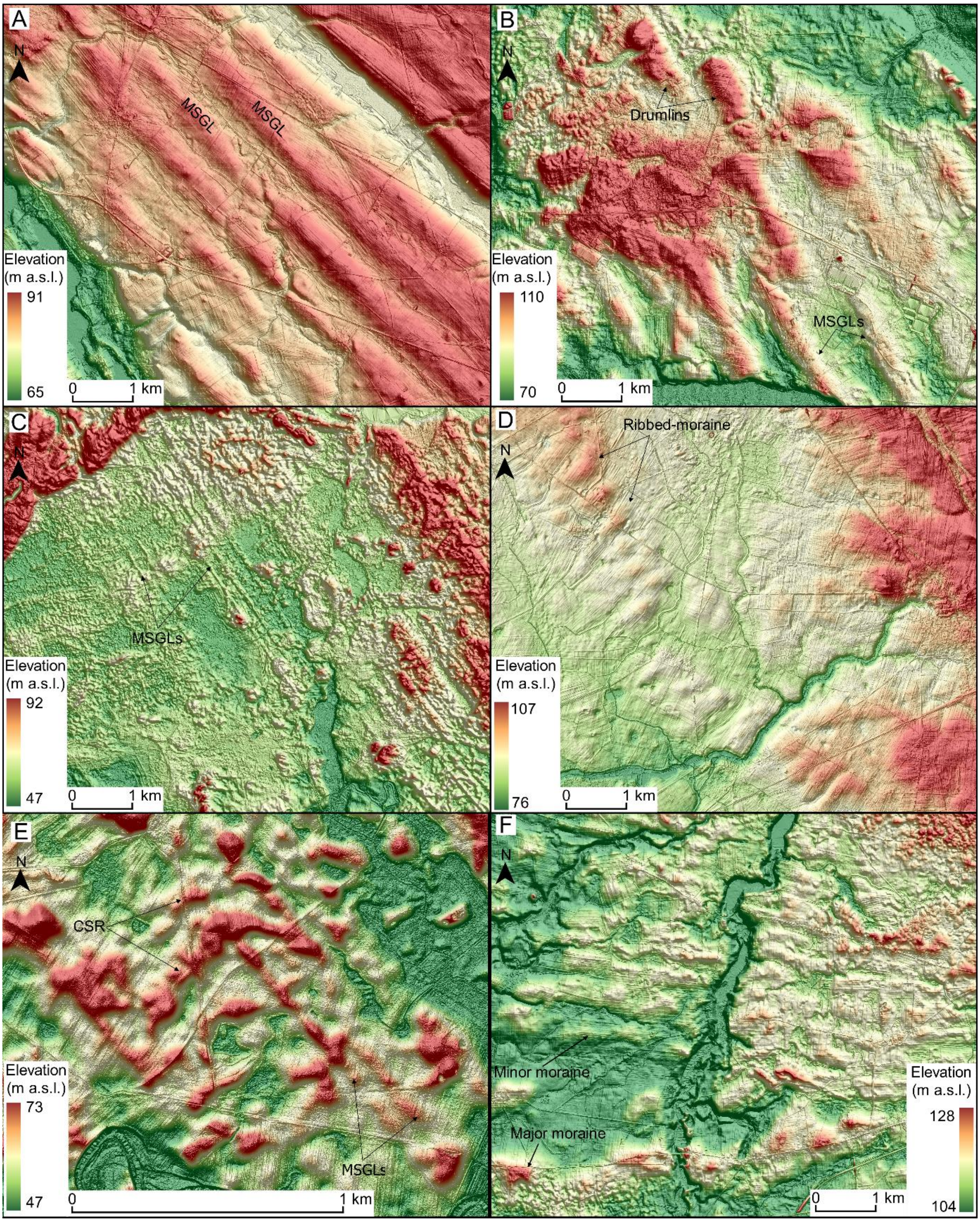

Fig. S2. Examples of (A) mega-scale glacial lineations, (B) drumlins, (C) narrow, elongated mega-scale glacial lineations, (D) ribbed moraines, (E) crevasse-squeeze ridges, and (F) major and minor moraines.

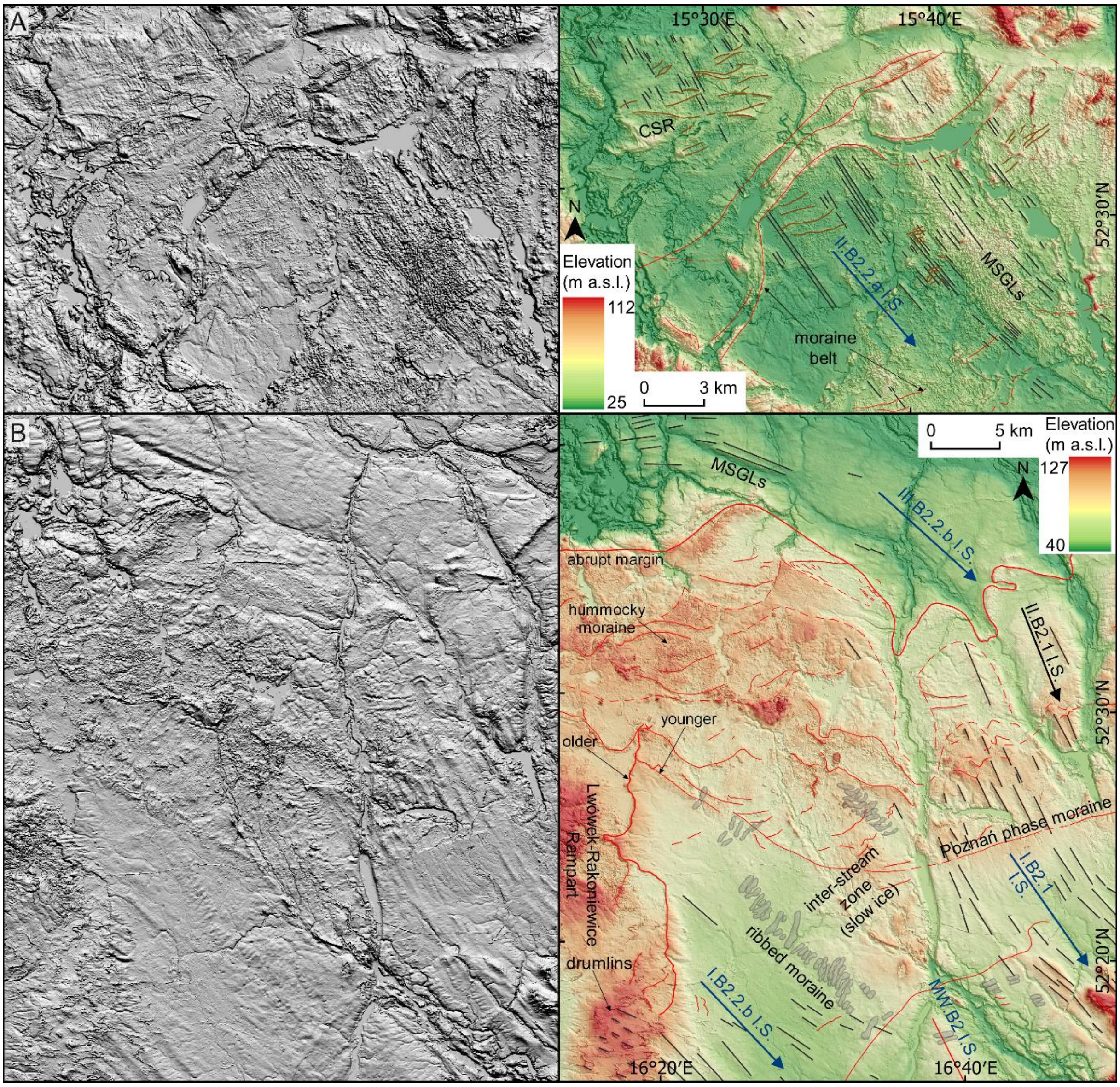

Fig. S3. A. System of moraines (major – bold face and minor – thin red solid lines) superimposed over mega-scale glacial lineations (black solid lines) and crevasse-squeeze ridges (brown) formed beneath the III.B2.2.a (Pszczew) Ice Stream. B. The signature of the III.B2.2.b (Oborniki) Ice Stream manifested by MSGLs and an abrupt margin.

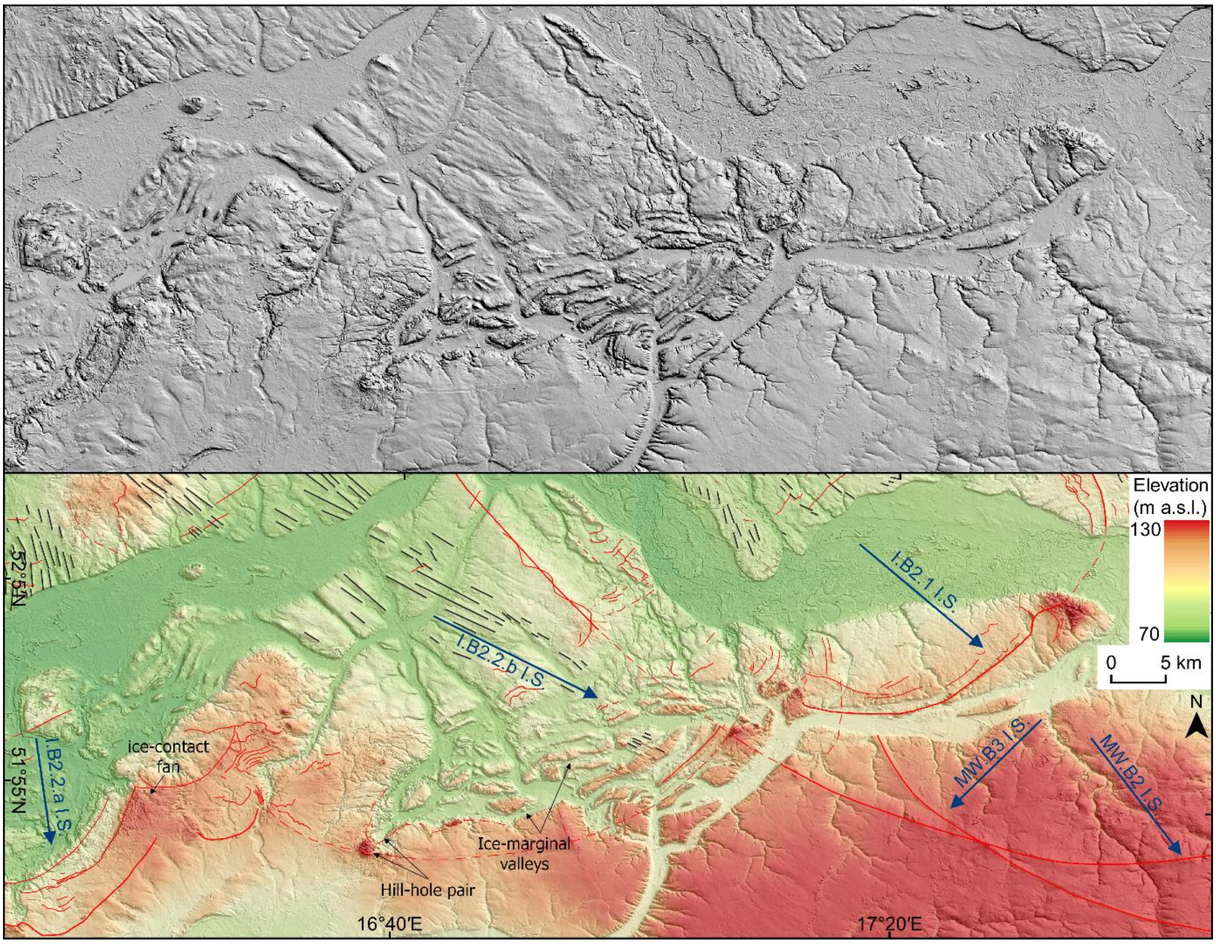

Fig. S4. Cross-cutting of major terminal moraines enabling the sequence of ice-streaming events to be reconstructed.