

REVISED STRATIGRAPHY AND PALAEOGEOGRAPHY OF THE ROSTAN HILLS IN NORTHWESTERN UKRAINE

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Abstract

This paper presents a new approach to stratigraphy and palaeogeography of NW Ukraine. So far, the glacial landforms near the Rostan area have been interpreted as end moraines derived from the Saalian ice-sheet. Sedimentological and petrographic analyses conducted at the Rostan site shed new light on the dynamics and age of the ice-sheet that formed the examined glaciogenic forms. Sedimentological analysis of glacial deposits documented the sedimentary environment of a glaciofluvial fan deposited by the ice-sheet front characterised by varying dynamics, i.e. advancing, stationary and retreating. Petrographic analysis proved an older age of deposits, i.e. Elsterian, and not Saalian as interpreted so far. These results shed new light on palaeogeography and stratigraphy of this area. The occurrence of the Elsterian deposits on the surface gives evidence of the absence of younger – Saalian – glaciation in this area, which relates to the recently announced new approaches to palaeogeography and stratigraphy of neighbouring areas in eastern Poland.



Key words: ice-sheet dynamics, petrographic analysis, lithofacies analysis, Elsterian ice sheet, MIS 12, NW Ukraine

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INTRODUCTION

The youngest Elsterian ice sheet (Sanian 2 in Poland, Tilihul/Krukynyczi in the Ukraine; Fig. 1) has been a subject of numerous studies, also on ice-sheet dynamics, but so far most of these studies were focused on the peripheral zone, in which the ice-sheet maximum extent was indicated (e.g. Salamon, 2017; Łanczont *et al.*, 2019). Much less is known about the younger Elsterian ice sheet in the inner zone, where the ice sheet was advancing/retreating. This may be due to the superimposition of glacial relief derived from younger glaciations, which may result in poor access to deposits or misinterpretation of their stratigraphic age. Such a case is presented in this paper.

Geological research in this part of Volhynian Polesie dates back to the end of the 18th century. The Rostan Hill located in north-western Ukraine has been an object of stratigraphic and palaeogeographic research since the beginning of the 20th century. Tutkovskiy (1902) was the first to address the geomorphology of this area. Geological research in the Rostan area was conducted by Palienko and

Gruzman (1978), Zalesskij (1978), Bogucki *et al.* (1998, 2003), Lindner (2005) and Zalesskij *et al.* (2014). Two profiles were documented, one on the northern and one on the southern slope of the Rostan hill (Bogucki *et al.*, 1998; Lindner, 2005). Glaciofluvial and glaciolacustrine sediments were observed there. They were probably dissected by two glacial till horizons of different age. According to Palienko (1982) and Bogucki *et al.* (2003), the Rostan Hills belong to the zone hills and correlate with hills occurring in the landscape of the Włodawa hump in the Polish border area. They were all interpreted as the post-maximum extent of the Pripyat' Lobe of the younger Saalian glaciation (Odranian in Poland, Dnieper 2 in the Ukraine). A slightly different interpretation was given by Lindner (2005), i.e. both the lower and upper layers of till are derived from the Saalian glaciation, but the lower layer comes from the older Saalian (Krznanian in Poland, Dnieper 1 in the Ukraine) and the upper one – from the younger Saalian (Odranian in Poland; Dnieper 2 in the Ukraine). This was in contradiction with Bogucki *et al.* (1998), who correlated the lower till with a glaciation “older than Saalian” and the upper till

stratigraphy		WESTERN EUROPE after Gibbard <i>et al.</i> (2005)	POLAND after Lindner <i>et al.</i> (2013); Lindner & Marks (2018)	UKRAINE after Zalesskij <i>et al.</i> (2014); tanczont <i>et al.</i> (2019)	MIS	AGE ka BP after Railsback (2015)
Late Pleistocene		Wechselian	Vistulian	Valdai		115
		Eemian	Eemian	Pryluky (Horikhiv)	5e	130
Middle Pleistocene	Saalian	Drenthe+Warthe	Odranian (Odra+Warta)	Dnieper 2 (Tyasmin loess)	6	191
			Lublinian	Kaydaky	7	243
			Krznanian	Dnieper 1	8	300
		Wacken/Domnitz	Zbójnian	Potygalivka	9	337
		Fuhne	Liwecian	Orel loess	10	374
		Holstenian	Mazowian	Zavadivka	11	424
		Elsterian	Sanian2	Tilihul loess (Krukienyczi)	12	

Fig. 1. Stratigraphic chart of the late Mid and Late Pleistocene of Poland and Ukraine and its pan-European correlation, with reference to marine isotope stages (MIS), Railsback *et al.*, 2015; glacial and loess episodes are in grey.

with the younger Saalian glaciation (Odranian in Poland; Dnieper 2 in the Ukraine).

This paper has two objectives: 1) interpretation of ice-sheet dynamics based on sedimentary environments of glacial deposits documented with a use of sedimentological analysis; 2) verification of the stratigraphic age of glacial deposits with a use of petrographic analysis in order to complete the stratigraphy of this area.

STUDY AREA

The Rostan site (N 51°35'30"; E 23°43'06") is located in the region of Shatskyi Lakes of Volhynian Polesie (Zalesskij *et al.*, 2014) in the north-western Ukraine close to the border with Poland and Belarus (Fig. 2A). This area is a part of the Volhyn Oblast and Shatsk Rayon, about 18 km NW from the town of Shatsk and about 13 km NE from the town of Włodawa (Fig. 2A). The outcrop is located 1.5 km SE of Rostan, on a latitudinally elongated end moraine, which is 2.5 km long, 0.5 km wide on the average, with its elevation at 189.4 m a.s.l. The relative altitude of the hill is 30 m and it is part of a moraine ridge running from west to east (Tutkovskiy, 1902; Zalesskij *et al.*, 2014). Detailed documentation was conducted within the outcrop located in the western part of the ridge (Fig. 2B), on its proximal slope (Fig. 2C). The Campanian (Late Cretaceous) deposits were found at the bottom of the outcrop, at 173 m a.s.l. A thickness of glacial deposits is estimated at ca 10 m (Zalesskij *et al.*, 2014). The ridge is a culmination of an upland lobe, surrounded by glaciofluvial deposits (Fig. 2D) and was

interpreted as an end moraine (Zalesskij *et al.*, 2014). It extends from the village of Pereshpa in the west to the village of Kamianka in the east and from the "Hasanowo" Nature Area near the village of Chrypsk (Khryps'k) in the north to the "Barłowa Miedza" Nature Area at the Lake Pulemets in the south (Fig. 2B). An erratic boulder with a diameter of over 2 m was found at a distance of less than 100 m NE of the documented site.

MATERIAL AND METHODS

The reconstruction of the Elsterian ice-sheet dynamics at the Rostan site consisted of the following stages: 1) identification of morphological and geological situation on the basis of available maps; 2) sedimentological analysis and 3) petrographic analysis.

Morphological and geological analysis

The identification of the morphological and geological situation involved the analysis of hypsometric and geological maps of NW Ukraine. Digital Terrain Elevation Data DTED2 were used for this analysis to build up a Digital Elevation Model of the surveyed terrain with a resolution of 25 x 25 m after conversion from WGS to PL1992 (Polish Military Geographical Institute), a WIG (Polish Military Geographical Institute) topographic map in scale 1:200,000 and a geological map in scale 1:50,000 in I. Zalesskij's version and the State Geological Map of Ukraine in scale 1:200,000 (Tutkovskiy, 1902; Zalesskij, 2014).

Sedimentological analysis

Detailed sedimentological analysis was conducted for all documented sedimentary profiles (Fig. 3). This involved examination of: A) sedimentary features of deposits i.e. texture and structure, scale, geometry and contacts between sedimentary units, orientation of palaeocurrents of glaciofluvial deposits with trough cross-stratification using Curray's method (1956), till fabric, i.e. orientation of long axes of clasts with a length of more than 2 cm derived from a glacial till and an eigenvalue vector (S_1), noting strength of their orientation according to Davis (1973); B) deformation features of deposits, i.e. type, scale and orientation of faults (with the amount of slip), which reflect the type and direction of deformation forces.

All collected geomorphological and geological data, recorded in sedimentary logs and photographic documentation, were subjected to lithofacies analysis. According to its principles, a three-step division of sedimentary units was used: 1) lithofacies – an individual layer of deposits; 2) lithofacies association – a set of lithofacies with comparable features and frequencies and 3) lithofacies unit – a set of associations with comparable lithological characteristics. Lithofacies and lithofacies associations were marked using

the lithofacies code proposed by Miall (1977), modified by Zieliński and Pisarska-Jamroży (2012).

Petrography of till clasts

Petrographic analysis of a glacial till was performed to determine the petrographic composition of gravel in qualitative and quantitative terms and to follow these changes in a regional context. The analysis was based on the methodology based on East Germany till clast analysis standard TGL 25 232, 4–10 mm (Kleingeschiebe), (Böse, 1989; Górska-Zabielska, 2010). Glacial till from profile RIII was examined. A sample of glacial till, not less than 0.015 m³ was collected by the furrow method from a vertical profile in an exposed wall of the outcrop. A total of 399 gravel types of 4.0–10.0 mm grain size were analysed and assigned to 10 petrographic groups based on the Polish standard used in the Polish Geological Institute – National Research Institute in Warsaw (Instruction, 2004). The results of the analysis were presented in a graphic form as a juxtaposition of calculated petrographic factors, based on the percentage of rocks: O – Paleozoic sedimentary rocks, K – crystalline rocks and quartz originating from their disintegration, W – carbonate rocks, A – not resistant to destruction and B – very resistant to destruction. O/K, K/W and A/B factors were calculated based on the relative proportions of rocks of Scandinavian origin in gravels of a glacial till and presented in a linear graph. The values of the factors were used for stratigraphic correlation of the till (Lisicki, 2003).

RESULTS

Lithology

Detailed analysis was carried out in four sedimentological profiles RI–RIV located on the proximal slope of the ridge in the western wall with a height of about 13.5 m. A series of 5 lithofacies units of deposits was documented (Fig. 3).

Unit of gravel-sand and sand (U1), with a maximum thickness of 5 m, is located in the lowest part of the outcrop and is composed of the GSm, Sh and (Sm) lithofacies association. The first lithofacies consists of medium-scale, massive gravel in a sandy matrix (GSm) with a thickness of 10–30 cm (Fig. 3, profiles I and II; Fig. 4A–C). Their characteristic features are: increasing grain diameter towards the upper part of the unit, from medium- (\emptyset up to 2 mm; profile RI) to coarse-grained gravel (\emptyset up to 6 cm; profile RII) and increasing thickness from 10 cm in the lower part of the unit (profile RI) to 30 cm in its upper part (profile RII). The second lithofacies is composed of coarse- and medium-grained, horizontally stratified (Sh), medium-scale sand with decreasing thickness of sheets from 40 cm (lower part of the outcrop – profile RI) to 10 cm (upper part of the unit – profile RII). Accessory sediments

of fine-grained massive sand (Sm), 10–15 cm thick and massive silty sand (STm), with about 10 cm thick are found within the lithofacies (Fig. 3, profile I). Sediments of the unit U1 are deformed. A number of brittle deformations were found there, mainly small faults with an azimuth of 109° and an inclination of 78° (Fig. 3).

The Unit U2 was documented above the sediments of lithofacies unit U1 in the profile RII at 7.0–6.3 m depth (Fig. 3; profile RII). It is a sandy massive diamicton Dm(m₁) with a relatively high content of gravel clasts and a dispersed framework of grains. It forms an inclined layer with irregular shapes – marked by faults – and is 10–70 cm thick. The upper and lower boundaries of the unit U2 sediments are sharp and deformable (Fig. 4C). Deformations are represented by normal faults with a throw of up to 40 cm, with a visible rosette spread of measurements, but with azimuth 194° and 55° dip of (Fig. 3). Longer axes of cobbles in the diamicton are in a range of 320–360° and indicate the NNW direction of the advance (336°). Samples for petrographic analysis of gravels were collected from a depth of 1.0–1.5 m (profile RII). Values of the factors were 1.06–1.04–0.87, which indicates correlation with the lithotype S2 (Lisicki, 2003), corresponding to the Elsterian glaciation (MIS 12).

Sediments of the unit U3 (profile RII) occur above the sediments of the unit U2, from about 6.7 m depth. Their sedimentological features are similar in structure to U1, but they are distinguished by a finer fraction. The unit U3 is built of sandy and sandy-silty sediments in the association of lithofacies Sm, STm, GSm (Fig. 4C). These are deformed, vari-grained massive sand Sm, approximately 10 cm thick, interbedded with massive sandy gravel GSm with a similar thickness (ca. 10 cm). Only massive, deformed silty sand STm is more thick (40 cm). Sediment deformations of this unit correspond to deformations of the underlying sediments and involve the same faults with 194° azimuth, 55° dip and a throw of up to 40 cm (Fig. 3).

Further down the profile, starting from a depth of about 2.0 m, sediments of the lithofacies unit U4 are exposed, consisting of the lithofacies Sh association with a thickness of 40 cm (Fig. 3, profile III; Fig. 4D–E). It is a vari-grained sand with horizontal stratification in medium-scale strata, i.e. 5–10 cm, containing single gravel clasts. Sediment deformations include primarily normal faults, which in some places form units of complementary faults, disappearing upon contact with overlaying sediments.

Deposits of the unit U5 are exposed in the uppermost part of the hill and comprise the association of the following lithofacies: GSe, GSDe, SGe (Fig. 3, profiles III and IV; Fig. 4F–G). They are represented mainly by gravel and gravel-sandy deposits, filling large-scale erosion channels with a width of several metres (12–15 m). The thickness of channel fillings observed in the outcrop reaches about 2 m. They feature a characteristic texture variation of the gravel fraction. Medium-grained (\emptyset up to 2 cm) gravel GSe occurs in the lower part of the channel fillings, in a sheet with a thickness of ca. 80 cm. Their thickness increases towards the upper part of the profile (60 cm) and they turn into a coarse-grained gravel (\emptyset up to 6 cm) and boulder of

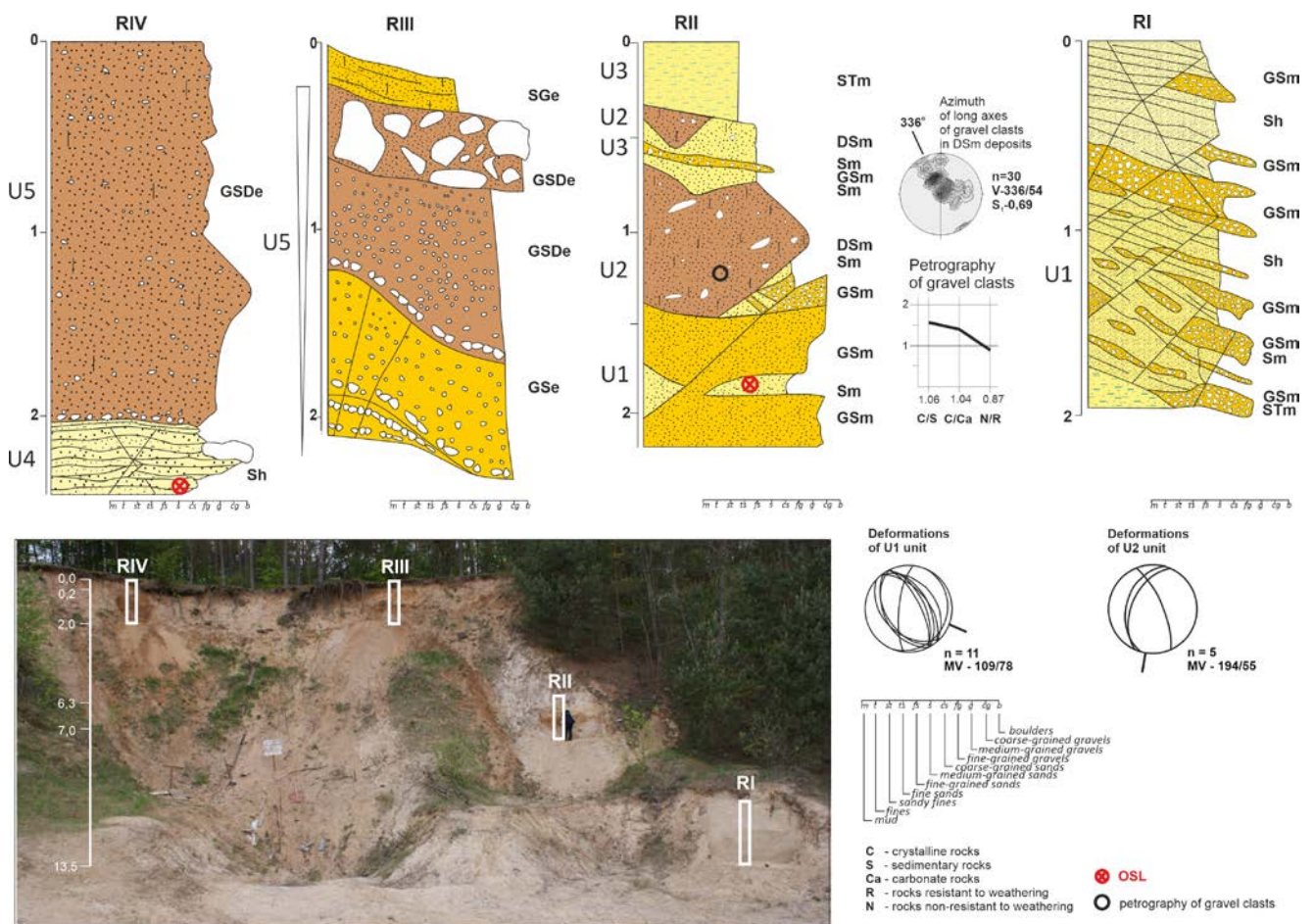


Fig. 3. Sedimentological profiles of glaciogenic deposits documented in the Rostan site; GSDe – sandy-diamictic gravel in erosional infillings, GSe – sandy gravel in erosional infillings, GSsm – massive sandy gravel, SGe – gravelly sand in erosional infillings, Sh – horizontally-stratified sand, Sm – massive sand, STm – massive silty sand.

up to 30 cm in diameter, which form a layer ca. 40 cm thick. Coarse-grained gravel and boulders are distinguished by presence of the clay fraction in the matrix (GSDe). The uppermost part of the vertical sequence of the association is formed by gravelly sand SGe in a sheet, 40 cm thick. The measured direction of erosion channel structures indicates their SSW direction (264°).

Interpretation

The documented deposits of the Rostan site allow identification of their sedimentary environment and successive stages of their deposition.

At first, deposits of the Rostan site were accumulated by slowly flowing sheetfloods, bearing predominantly sandy material, which is evidenced by massive or tabular layers of the lithofacies Sh, Sm and STm at the bottom of the unit U1. In the subsequent stages of deposition, the frequency of gravel was increasing, which is reflected in increasing grain diameter and varying thickness of the sets towards the upper part of the unit, i.e. decreasing thick-

ness of sand deposits and increasing thickness of gravel deposits. Such changing lithofacial features in the profile are characteristic of Pleistocene ice-marginal fan deposits and evidence the slow transgression of the ice-sheet front (glacier terminus) (Włodarski and Godlewska, 2016). The active ice-sheet front is marked by distinct cracks and faults with an azimuth to the SSW. This direction of deformation is transverse to direction of the ice sheet advance.

The massive diamicton of the unit U2, deposited above the sediments of the unit U1, should be associated with a glacial till ($Dm(m_1)$). The deformable contact of sediments of this unit with the underlying sediments, massive structure and strong concentration of gravel clasts correspond to a subglacial till deposited at the foot of the ice sheet (cf. Evans *et al.*, 2006). Its deformable features, inclination and irregular shape most likely indicate deposition during the slow advance of the ice sheet front in the SSE direction.

The overlying deposits of U3 and U4 units document a change in a sedimentary environment under low energy conditions and in a distal part of a glaciofluvial fan. This is indicated by sandy (Sm) and thicker sandy-silty sediments (STm) of the lithofacies Sm, STm, (GSsm). They

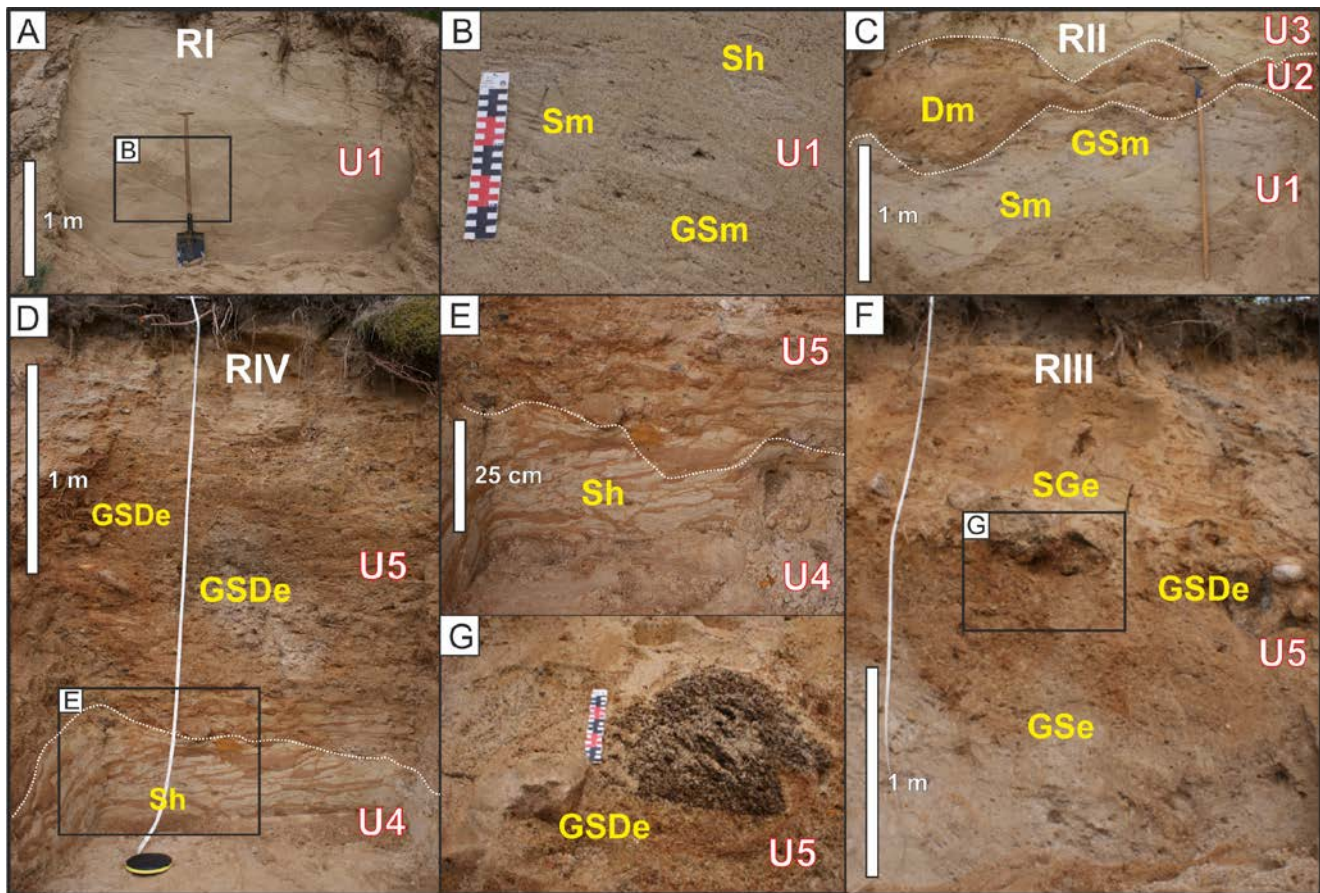


Fig. 4. Photo of the Rostan site profiles.

were interrupted by single episodes of fast and short-term flood waves, as evidenced by deposition of less thick accessory gravel-sand sediments (GSm). With a development of the ice-marginal fan, the ice-sheet front melting rate increased and sedimentation conditions changed into transitional between low- to high-energy ones. This is recorded in sandy sediments with horizontal lamination Sh(G) and single gravel clasts. Their deposition took place under supercritical flow conditions (cf. Zieliński and Van Loon, 1999).

The last stage of sedimentation is recorded in the sediments of the unit U5, in the association of the lithofacies GSe, GSDe and SGe, and indicates a change to the high-energy depositional environment. This is evidenced by concentrated SW flows, depositing gravel-sand sediments in erosion channels. Initially, the increase in the meltwater flow rate was followed by intensive erosion of large-scale scours and – at the early stage of flood-wave subsidence – deposition of large-scale gravel-sand sediments (GSe). The presence of diamictic gravel GSDe in the profile results from the increased concentration of the material in the flow and its intermediate nature between fluvial and hydraulic flow. In such a case, the displacement of concentrated suspended matter enables a rapid deposition of transported boulders. The presence of these boulders is responsible

for a formation of complementary faults in the underlying sediments of the unit U4, the formation of which should be associated with a load, triggered by deposition of material containing heavy boulders. In a final deposition stage, a descent of the meltwater flood wave is evidenced by a presence of SGe sediments deposited in the uppermost part of the unit and characterised by a finer fraction, clearer stratification and better sorting. The interpreted conditions of the unit U5 deposition are similar to the high-energy flow conditions at the peak of the devastating ablation (cf. Maizels, 1993) and are documented as a flow till in the Pleistocene ice-marginal fans (*vide* Zieliński and Van Loon, 1999).

Ice sheet dynamics reconstruction

Sedimentological analysis of the examined deposits at the Rostan site allows us to track successive stages of the ice-sheet dynamics:

- When the ice-sheet front was located within a short distance to the north from Rostan, a glaciofluvial fan began to develop in its foreland, dominated by sheetfloods, which is evidenced by sediments of the unit U1. The fine-grained sediments at the bottom of the profile tes-

tify to the initial deposition in the distal zone of the fan. The increasing content of the coarse-grained fraction and deformations of the unit U1 sediments indicate a slow approach of the active ice sheet front and a change of environment from a distal to a proximal fan (Fig. 5A).

- The advance of the ice sheet over the Rostan site is recorded in deformations observed in deposits of the unit U1 and accumulation of the unit U2, i.e. a subglacial till (Fig. 5B). A transverse direction of fault planes in relation to the ice sheet advance and the analysed till fabric are the evidence of the ice-front movement to the SSE.
- The glacial advance was followed by a clear change in the activity of the ice sheet front marked by its stagnation. At first, it was a stagnation of the ice sheet, when the melting rate was slow. This is recorded by glaciofluvial sediments of U3 and U4 units, which are structurally similar to the unit U1 (Fig. 5C).
- A distinct decay of the ice front, which is evidence of the passive ice, is recorded in the deposits of the unit U5 (Fig. 5D). The change in grain size, initially increasing up the profile and then decreasing, indicates an initial increase in the ice melting rate and waxing flows of ice waters, followed by waning flows due to a decrease in ice melting rate.

Such an interpretation is consistent with palaeogeographic description of NW Ukraine, i.e. occurrence of the end moraines with deformations in deposits derived from the active ice sheet (Tutkowski, 1902; Palijenko and Gruzman, 1978; Zalesskij *et al.*, 2014).

DISCUSSION

Two diamicton layers examined at the Rostan site are the subject of the stratigraphic discussion. The documented diamicton of the unit 2, occurring at the examined depth of 6.7–7.0 m, can be correlated with the lower till of the profile Rostan-1 *vide* Bogucki *et al.* (1998). This is also confirmed by the NNW direction measured for gravel clasts in the till, which is consistent with results for the samples 1, 2, 4 and 5 obtained for the profile Rostan-1 (Bogucki *et al.*, 1998) and which can be related to the presence of diamicton on the proximal, iceward slope of the ridge. According to heretofore research, this diamicton was interpreted as derived from the older Saalian glaciation – Dnieper 1 in the Ukraine, which corresponds to Krznanian in Poland (Lindner *et al.*, 2007). However, according to the stratigraphic correlation of glacial tills (Lisicki, 2003), the petrographic analysis of the unit U2 diamicton allows correlating the examined till with the advance of the youngest Elsterian (MIS 12) ice sheet (in Poland – San 2; in the Ukraine – Tilihul (Krukienyczi). Glacial tills with similar petrographic factors were also described in the neighbourhood, i.e. in eastern Poland, e.g. in the area of Sosnowica (boreholes 14 and 50, respectively: 1.17–1.09–0.73 and 1.10–1.05–0.85), (Dolecki *et al.*, 1990), Orzechów Nowy (boreholes 2 and 7, respectively: 1.12–0.99–0.93 and 1.23–0.91–0.97) (Buraczyński and

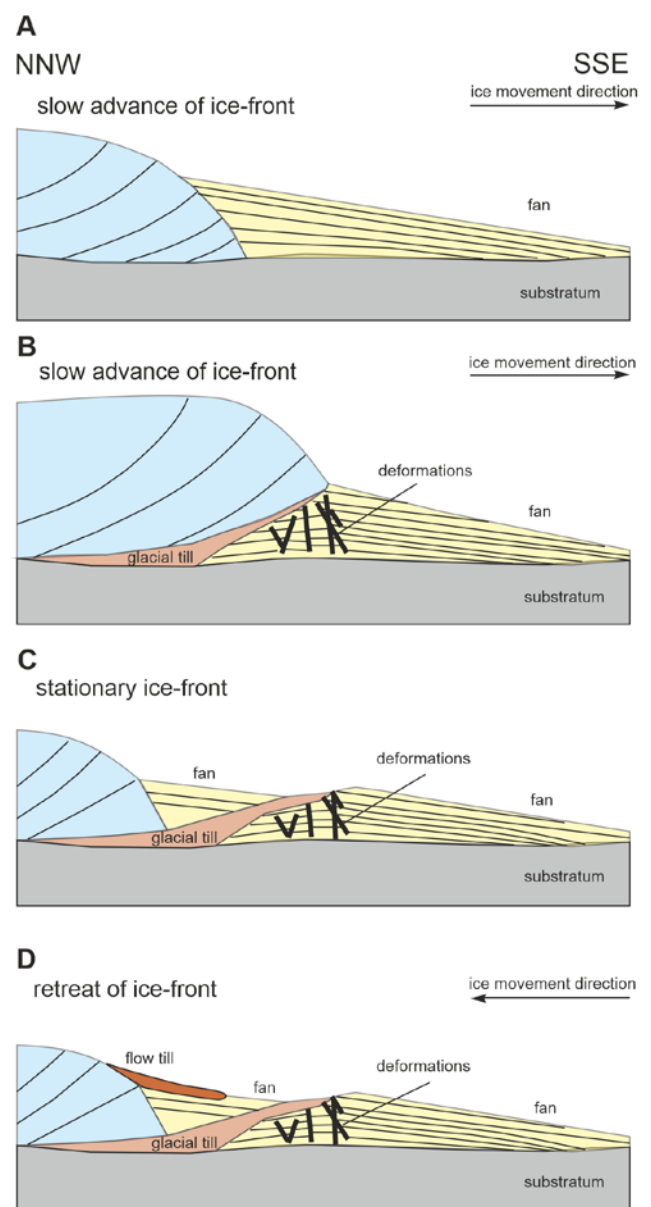


Fig. 5. Palaeogeographical model for sediment succession and landform formation at Rostan site.

Wojtanowicz, 1982), Sosnowka (borehole Matiaszówka: 0.96–1.23–0.70) (Wodyk, 2000) and in the area of Kołaczce (borehole Brusy: 0.97–1.21–0.72) (Buraczyński and Wojtanowicz, 1982) and Sobibór (borehole Józefów 1: 0.97–1.27–0.67) (Marszałek, 2001). They were correlated with the Sanian 2.

The second examined diamicton of flow till genesis, described at 0.2–2.5 m depth in the profiles RI and RII, can be associated with the upper till of the Rostan-1 profile, occurring at the same depth and classified as the younger Saalian glaciation – Dnieper 2 in the Ukraine, or the Odranian glaciation in Poland (Bogucki *et al.*, 1998). The research shows that there are no traces of a clear erosion boundary in the sediments of the entire profile, espe-

cially between the diamicton and the underlying/overlying sediments. This allows us to believe that they are a record of the ice sheet front dynamics of a single glaciation, i.e. Elsterian (Tilihul in the Ukraine and Sanian 2 in Poland). This also seems to be confirmed by the analysis of the composition of indicator erratics from the upper till in the Rostan 1 profile (Bogucki *et al.*, 1998), which shows a clear dominance of Dalarna rocks, which may indicate a trend in the glaciations of southern Poland (Gałązka, 2004; Czubla, 2015).

Furthermore, a stratigraphic research carried out in recent years proves that glacial tills recorded in the neighbouring areas have features typical of the younger Elsterian till (Sanian 2 in Poland; Tilihul in the Ukraine), suggesting that the younger Saalian ice sheet had a smaller extent. Similar conclusions were reached by Terpiłowski *et al.* (2014) based on examination of the Holsteinian (MIS 11) warm temperate fluvial deposits in eastern Poland and not overlain by another glacial till, or Czubla (2015) and Czubla *et al.* (2019) according to the petrographic analysis of the Scandinavian erratics derived from glacial tills of central and eastern Poland. Our research at the Rostan site confirms this new approach.

CONCLUSIONS

The results obtained from the examined glacial sediments at the Rostan site led to the following conclusions:

- The vertical sequence of sediments documented at the Rostan site is a record of their deposition in a glacial sedimentary environment of a glaciofluvial fan. Various structures of deposits are evidence of differentiated deposition derived from higher or lower energy water-flow, resulting from different ice melting. All features characterise varying dynamics of the ice front, i.e. advancing, stationary and passive.
- The applied sedimentological analysis of glacial sediments allows us to confirm a subglacial origin of the lower diamicton (U2) and to reinterpret the upper diamicton, i.e. documenting its runoff rather than subglacial genesis, as previously believed.
- The age of the lower diamicton was determined based on the applied petrographic analysis, i.e. until now correlated with the Dnieper 1 ice sheet 1 (Krznanian glaciation). The results of this analysis indicate the Sanian 2 glaciation. Moreover, the sedimentological analysis of all examined glacial sediments indicates the same age as the reinterpreted diamicton. This is evidenced by: no traces of erosion in the entire profile, i.e. no erosion boundaries between the diamicton sediments and the underlying and overlying sediments.
- The research confirms the hitherto evidenced genesis of the Hill in Rostan as an end moraine with deformations of deposits derived from the active ice sheet.
- Lack of deposits younger than the Elsterian ice sheet suggests the absence of younger glaciations, i.e. the Early Saalian, in this area.

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