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Erratics selection for cosmogenic nuclide exposure dating – an optimization approach

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Abstract The paper presents a method for the selection of large erratics to be sampled for terrestrial cosmogenic nuclide exposure dating (TCNED) in areas previously covered by Pleistocene ice sheets. Our approach is based on (1) a GIS analysis of an extensive dataset of erratics, (2) field inspection of pre-selected boulders and (3) Schmidt hammer (SH) testing of erratics selected for sampling. An initial database of 491 erratic boulders in NW Poland was filtered using a GIS software, based on their characteristics, digital elevation and surface geology. The secondary data set of pre-selected erratics consisted of 135 boulders – i.e. proper targets for field inspection. Ground-truthing in the field resulted in the final selection of 63 boulders suitable for sampling for TCNED. These erratics are located on moraine plateaux and hills formed during the Saalian glaciation (Marine Isotope Stage 6) as well as Leszno/Brandenburg, Poznań/Frankfurt and Pomeranian Phase ice marginal belts from the Weichselian glaciation (Marine Isotope Stage 2). The GIS desk-based analysis of erratics properties resulted in a 73% reduction of the initial dataset, which demonstrates the added value of this selection technique. The field inspection of pre-selected boulders resulted in a 53% reduction of the number of boulders suitable for TCNED. SH testing of the sampled erratics provided a quantitative proxy of their surface hardness. This allowed the quantification of their weathering degree and identification of erratics potentially affected by postglacial erosion. Our systematic approach to selecting erratics and their SH testing could be a useful tool for other researchers facing the problem of choosing appropriate erratics for TCNED in areas of continental Pleistocene glaciations.

Keywords *• erratics • terrestrial cosmogenic nuclide exposure dating • Schmidt hammer • Scandinavian Ice Sheet*

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INTRODUCTION

Terrestrial cosmogenic nuclide exposure dating (TCNED) is routinely used for direct numerical dating of moraines, enabling construction of robust chronologies for paleo-ice sheets retreat (e.g. Briner *et al*. 2006; Rinterknecht *et al*. 2006; Clark *et al.* 2009; Small *et al.* 2017). Stable erratics resting on moraines are usually targets for TCNED sampling (e.g. Philips *et al.* 1990; Ivy-Ochs *et al.* 1999; Briner *et al.* 2005; Sarikaya *et al.* 2017). However, the selection of a sufficient number of the most suitable boulders is crucial for the robustness of deglaciation chronologies based on TCNED. For moraines of an expected age of ~20 ka at least five boulders per one landform, e.g. terminal moraine, should be sampled in order to obtain a reliable moraine age (Putkonen, Swanson 2003). Because the exposure ages scatter may be large and because some outliers usually occur, the more erratics are sampled per moraine system, the better (Blomdin *et al.* 2016). The identified erratics must be carefully inspected in the field to eliminate boulders that have moved, rotated, or were exposed after the erosion of post-deglaciation sedimentary cover (Ivy-Ochs, Kober 2008). This could happen either due to erosion of landforms after ice sheet retreat, or because of human activity (e.g. boulders excavation, removal of erratic from the field; cf. Graf *et al.* 2007; Akçar *et al.* 2011). Thus, boulders suitable for TCNED should be intact, with the least surface erosion/weathering possible and stable in the environment since deglaciation. The 'datable' erratic boulder needs to have the following features (e.g. Gosse *et al.* 2005): (1) large dimensions (the bigger, the better) and significant height (the taller, the better), (2) be located on a flat, stable surface, (3) be embedded in the ground (indicating that it was most likely not moved), (4) have traces of glacial transport and erosion (e.g. striations, crescentic gouges), and (5) have a flat upper surface with no marks of human activity (e.g. carvings, worshiping marks).

Here, we present a procedure of large erratics selection for TCNED in areas covered by thick clastic sediments. NW Poland is a key-region to bridge the existing gap between the TCNED chronologies available in the 'west' and 'east' of the last SIS southern front. Moreover, the distances between the mapped limits of the Late Weichselian glacial phases in NW Poland are the largest within the southern front of the last SIS (Fig. 1). This enables the finding of the large number of erratics located on moraine landforms correlated with the Late Weichselian glacial phases. The procedure of selection is based on a GIS analysis of an extensive dataset of boulders, their field inspection and Schmidt hammer testing. The goal of this study is to propose a systematic approach in exploring and selecting large erratics for TCNED over extensive areas. The method shows: (1) how simple GIS analysis may help in a quick desk-based selection of suitable boulders for field inspection, (2) which properties of erratic are required as necessary to take the decision about which boulders are the best candidates for TCNED, (3) how SH testing may help in identifying erratics affected by postglacial erosion. Our attempt is the first SH testing of massive glacial boulders in the area of the last SIS southern sector. The proposed procedure may be used by researchers as an optimization for the selection of appropriate sites for exposure dating in areas of Pleistocene continental glaciations.

REGIONAL AND GEOLOGICAL SETTING

The study area is a vast region (~100 000 km^2) situated between the western Polish border (14°E) and the longitude 20°E, and between the southernmost position of the last SIS margin and the northern Polish coastline (Fig. 1). It covers roughly a quarter of the last SIS southern sector (Stroeven *et al.* 2016). It is characterised by well-preserved Late Weichselian glacial geomorphology with an extensive area of morainic landscape (Woldstedt 1935). Significant distance between belts of ice marginal landforms representing particular phases of deglaciation offers a unique opportunity to find considerable number of erratic boulders to date and thus to track the last SIS recession over a large area.

Surface sediments in NW Poland are dominated by Late Weichselian till and glaciofluvial (outwash) sands and gravels deposited during deglaciation (Marks *et al.* 2006). These sediments contain significant amount of rocks from Fennoscandia and the Baltic depression (Woźniak, Czubla 2015). They are mainly crystalline rocks from various regions of Sweden (e.g. Skåne, Småland, Uppland, Dalarna), SW Finland (e.g. Åland Islands; Schulz 2003), and Bornholm rocks from Denmark (Górska-Zabielska 2008). Rocks from Norway are absent or very rare in NW Poland due to the glacial transport directions of the SIS to the south and southwest (Woźniak, Czubla 2015), so these rocks are more frequent westwards. More than half of the glacial and glaciofluvial fine and coarse gravel derived from the Baltic depression are represented by Paleozoic sedimentary rocks, mainly limestones, dolomites and sandstones (e.g. Górska-Zabielska 2008; Czubla 2015; Woźniak, Czubla 2015, 2016). However, erratic boulders of these rocks are very rare or even unique, due to their low resistance to weathering and erosion and their use by humans, e.g. for construction purposes (Alexandrowicz *et al.* 1992, Woźniak *et al*. 2015). For the same reasons, big erratics of Mesozoic, Paleogene and Neogene rocks from the southern part of the Baltic depression and the northernmost part of Poland are also very rare in the studied area.

The present number of large erratics is probably significantly smaller compared to the initial population due to the use of the boulders by humans over the last few centuries (Hermann 1911; Krawiec 1938; Alexandrowicz *et al.* 1992). However, there is still a significant amount of erratic boulders to be selected for TCNED. A particularly high concentration of large erratics occur within the ice sheet extent during the Pomeranian Phase (Fig. 1; Czernicka-Chodkowska 1983).

MATERIALS AND METHODS

GIS database

An extensive database in the study area was built based on all available sources of information about erratic boulders: (1) lists of natural monuments available in the Regional Directorates for Environmental Protection in Poland, (2) database of geo-sites available in the Central Registry of the Geosites of Poland (http://geostanowiska.pgi.gov.pl) created by the Polish Geological Institute – National Research Institute (PGI-NRI), (3) information about large erratics found in catalogues, books, and articles (Hermann 1911; Krawiec 1938; Alexandrowicz *et al.* 1975, 1992; Czernicka-Chodkowska 1977, 1983, 1990; Górska-Zabielska 2010; Szarzyńska, Ziółkowski 2012; Gałązka *et al.* 2015; Woźniak *et al.* 2015), (4) un-

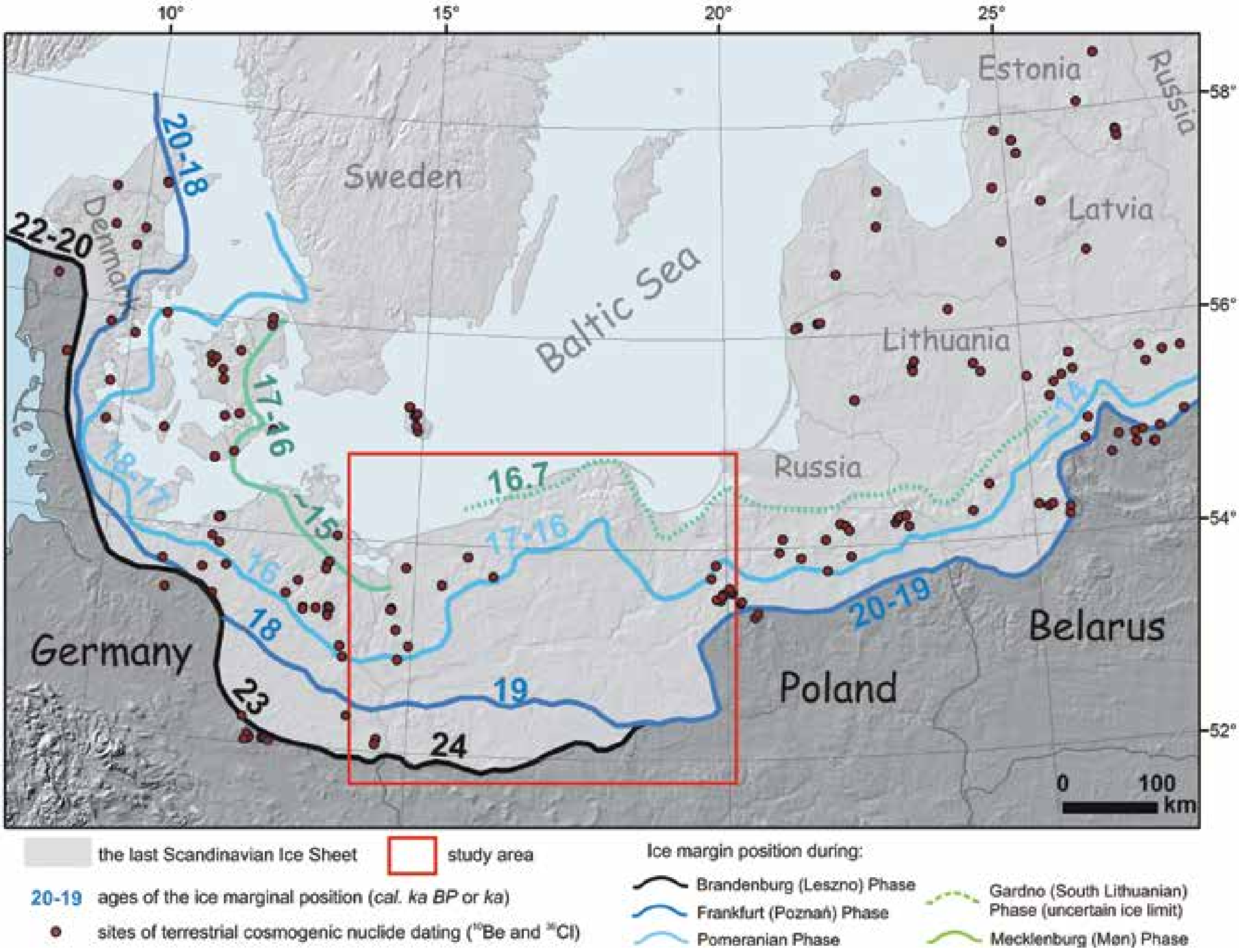

Fig. 1 The extent of the last Scandinavian Ice Sheet (SIS) south of the Baltic Sea and the study area (red box). The Late Weichselian ice sheet limits are compiled from Hughes *et al*. (2016) and Stroeven *et al*. (2016); ages of individual glacial limits are according to Rinterknecht *et al*. (2007, 2008, 2012), Wysota *et al*. (2009), Ehlers *et al*. (2011), Guobytė and Satkūnas (2011), Houmark-Nielsen *et al*. (2011), Marks (2012, 2015). Sites of terrestrial cosmogenic nuclide exposure dating (TCNED) at the southern fringe of the last SIS are compiled from Stroeven *et al*. (2016) and Dzierżek and Zreda (2007)

published bachelor and master theses (Kobiela 2008; Binkowski 2013; Ilewicz, Kobiela 2014; Sauter 2015), (5) topographic and geotourism maps, and (6) forest ranger interviews, local commune reports, and landscape parks reports.

The information was compiled in ArcGIS software as a single *shape* file (points) consisting of appropriate attributes in a table (coordinates or descriptive location, elevation above sea level, number of forestry district when located in the forest, perimeter and height, local name if given, rock type).

Analysis of boulders

The analysis of boulders involved two phases (Fig. 2A). The first phase is two-fold and includes a desk-based analysis of boulder dimensions (available in our GIS database), and their distribution against the digital elevation model (DEM) and geologic maps. First, we used a 25 m resolution DEM available for the Polish territory - DTED 2 and the geology layer from the Web Map Server (WMS) provided by the PGI-NRI on the geoportal Central Geological Database (http://geoportal.pgi.gov.pl). The server includes information about the surface geology compiled from the Detailed Geological Map of Poland 1:50 000 (Ber 2005). The comparison of the terrain relief from DEM with the surface sediments from the geology layer, provides the geomorphological context of individual boulders (i.e. the type of landform on which erratic is located). Eight types of landforms have been distinguished: (1) moraines and moraine plateaux, (2) kames, (3) kame terraces, (4) eskers, (5) glacial tunnel valleys, (6) outwash plains and fans, (7) river valleys, (8) beaches, from which only boulders located on landforms related to glacial or glaciofluvial accumulation (1, 2, 3, 4 and 6) are preferred as suitable for TCNED. This filtering allowed to achieve the set of pre-selected boulders potentially suitable for further investigation (Fig. 2A).

The second phase consisted of the ground-truthing

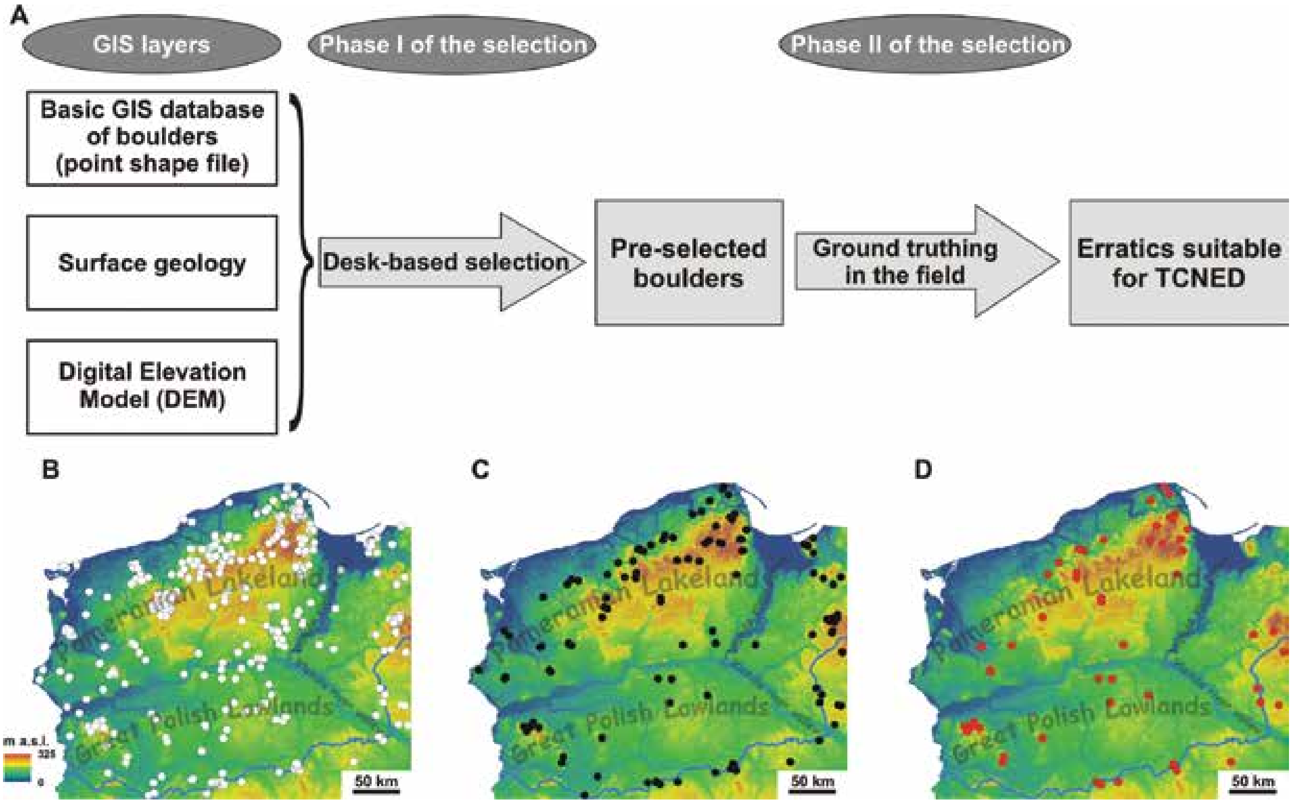

Fig. 2 The steps of analysis of the erratic boulders dataset. (A) Flowchart illustrating selections of erratics suitable for TCNED. (B) Map of the basic set of large erratics in NW Poland (white dots) – 491 boulders. (C) Map of erratic boulders distribution after desk-based pre-selection (black dots) – 135 boulders. (D) Map of distribution of erratic boulders suitable for TCNED (red dots) – 63 boulders. Blue line indicates the maximum extent of the last SIS in NW Poland according to Marks *et al.* (2006)

of the pre-selected boulders in the field. The following features of erratics were described: (1) dimensions (maximum perimeter, long and short axes, maximum height above the ground), (2) geomorphological position of the boulder (flat surface, top of the hill, edge of the hill, slope, valley floor), (3) embedding of the boulders within the ground, (4) type of rock (petrography), (5) traces of glacial erosion (polished surfaces, striations, crescentic gouges), (6) marks of postglacial weathering and erosion (rough surface, protruding crystals of relatively resistant minerals such as quartz), and (7) traces of human activity (carvings, worshiping marks, anthropogenic cracks, drilling holes, remnants of metalic rods).

Special focus was given to: geomorphological location of boulders, height above the ground, potential marks of anthropogenic impact and evidence of glacial erosion. In some cases, interviews with local farmers and forest rangers were necessary to reconstruct the 'history of the boulder' – especially linked to human impact in the past. Field inspection resulted in the selection of erratics suitable for TCNED (Fig. 2A). For these boulders an approximation of the true, minimum volume was calculated with formula of Schultz (2003) $V = 0.523 \cdot a \cdot b \cdot c$, where a is the length, b is the width and c is the height of erratic. The approximation results from irregular shape of erratic boulders, as well as unknown size of boulders under the ground.

Schmidt hammer testing

Erratic boulders selected as suitable for TCNED were tested with Schmidt hammer. It is a well-known method to quantify rock-surface hardness applicable in geology and geomorphology (Goudie 2006). Rebound values (R) obtained by the impact of SH decrease with increasing rock-surface weathering, and this could be used as a relative indicator of the time a rock-surface has been exposed to subaerial processes and to estimate the exposure history of erratic boulders (McCarroll 1989).

A N-type SH was used to test the upper surface of the most suitable erratic boulders. Some of the ground-truthed boulders were not tested with SH (14 erratics) due to significant cracks, very rough surfaces, or unsuitable rock textures (too coarse). Forty-nine boulders (36 granitoid, 7 gneisses and 6 granite gneisses) were tested and 40 blows of SH were recorded per boulder. On each tested boulder SH readings were collected from the solid, flat surface, on the spot located at least 10 cm away from edges and cracks. Forty blows of SH were spaced closely at one location on the upper surface, but the distance between particular impacts was not lower than 1 cm. R-values were corrected for the angle at which the SH was placed on the boulders (mostly vertically downward) according to the angle corrections proposed by Day and Goudie (1977).

Ten SH readings (25%), the most deviating from the mean R-value, were rejected and a new mean R-value was calculated for the remaining 30 values. Finally, the mean R-values of tested boulders were analysed with 95% statistical confidence intervals. The boulders were grouped according to their morphostratigraphic position: six from Saalian moraine plateaux, thirteen from Leszno Phase marginal belt, eleven of Poznań Phase marginal belt, and nineteen from Pomeranian Phase marginal belt. For each of these groups, Chauvenet`s criterion was applied to identify potential outliers (Taylor 1997). After rejecting outliers, a Shapiro-Wilk (1965) test was used to check normality of the remaining mean R-values distribution. The weighted average R-value (R_w) and weighed-mean standard deviation of the 95% confidence intervals (σ_w) were calculated for each erratic group.

RESULTS

GIS pre-selection

The basic GIS database consists of 491 erratic boulders. Targets were massive erratics located within the maximum extent of the last SIS and beyond the local Last Glacial Maximum (LGM) limit, which were not dated with cosmogenic nuclides (cf. Rinterknecht *et al.* 2005). The highest concentration of erratics is observed in the central and eastern Pomeranian Lakeland (Fig. 2B). The total number of massive erratics identified in the Pomeranian Lakeland is 339 (69.0% of analysed set). In the Great Polish Lowlands situated to the south of Pomerania, 16.1% of large erratics occurs (79 boulders). The eastern edges of the study area located east of the Vistula River valley (Fig. 2B) comprises 14.9% of all boulders (73 erratics).

For 280 boulders, information about their perimeter and height was available, for 178 erratics only information about their perimeter was available and for 3 boulders only their height was available. For 30 large erratics no information about dimensions were recorded, although it is known they are rather large, because they are mentioned in the lists of natural monuments or are marked on topographic and geotourism maps. The recorded perimeters vary from 1.8 to 44.0 m and values of height above the ground vary from 0.3 to 3.9 m. The petrographic types are listed for 177 boulders with a predominance of Scandinavian plutonic and metamorphic rocks: 112 boulders are granitoid (63.3%), 32 are gneisses (18.1%) and 18 are granite gneisses (10.2%). Other crystalline rocks are: porphyry (2 erratics), and a single erratic of: pegmatite, diabase, migmatite and eclogite. Sedimentary rocks are very rare (only 2 conglomerates and 2 quartz sandstones). A significant number of erratics (283; 57.6%) are located on moraine plateaux or moraine hills (like terminal moraines, dead-ice moraines), 98 erratics (20.0%) are situated within valleys (river valleys or former meltwater channels), 72 erratics (14.7%) on outwash plains and fans and 20 erratics (4.1%) in glacial tunnel valleys. Furthermore, 7 massive boulders (1.4%) were found on the Baltic Sea shore, 6 erratics (1.2%) on kames, 4 boulders (0.8%) on kame terraces, and one on an esker.

To pre-select boulders and to choose erratics for the next step of selection (field inspection) we used their dimension and geomorphological location. A perimeter ≥5.0 m and height ≥0.5 m were set to filter the basic GIS database in terms of erratic dimensions. In applying these criteria, 39 boulders (7.9%) were rejected. Based on the geomorphological location of the remaining 452 boulders, we selected those located on moraine plateaux, on moraine hills, on proximal parts of outwash plains and fans, and on small (confined) sandurs (Fig. 3A–C). Erratic boulders located on erosional landforms (meltwater channels, glacial tunnel valleys, and river valleys) or on edges of these erosional landforms were excluded (Fig. 3D–F). Massive boulders located within the extensive outwash plains in front of a particular ice margin or on beaches as a residuum from cliff retreat were also rejected. On the basis of geomorphological location 317 boulders were eliminated (64.6% of the basic GIS database). As a result of our desk-based selection, a list of 135 erratic boulders was created (Fig. 2C). Most of these erratics are located on moraine plateaux or moraine hills (112 boulders; 83.0%): 78 boulders (57.8 %) on moraine plateaux and 34 erratics (25.2%) on terminal moraines or dead-ice moraines. Twenty massive erratics (14.8%) are located on sandurs, 2 on kames, and 1 located on an esker was pre-selected as well.

Ground-truthing

Pre-selected boulders (135 erratics) were visited during two field seasons and in total 72 erratics (53.3%) were rejected. Twenty-three boulders (17.0%) were identified as located on sloping surfaces (Fig. 4A) and 4 erratics (3.0 %) were found in denudation valleys (Fig. 4B). Fifteen boulders (11.1%) were excavated by humans (Fig. 4C), and 11 boulders (8.1%) have traces of other anthropogenic activity (Fig. 4D, E). For 9 erratics (6.7%) we concluded from direct observations or from information from local inhabitants that they were mined and/or moved in the past (Fig. 4F). Three boulders (2.2%) were identified as too small (due to erroneous dimensions listed in the source material). We were unable to find 7 boulders (5.2%). This is either because their coordinates or descriptive locations are wrong or possibly because they do not exist anymore. As a result of the fieldwork, 63 boulders were selected for TCNED (Table 1).

Ground-truthed boulders are dominated by medium to coarse grained rocks: granitoid (71.4%), granite gneisses (11.1 %) and gneisses (11.1 %). Fine-grained structure was only found in 2 gneisses and 1 granite gneiss. One boulder is a coarse-grained gabbro. Fifty-two boulders (82.6%) are located on moraine plateaux or moraine hills, from which 32 boulders (50.8%) are on moraine plateaux, and 20 (31.8%) on terminal or dead-ice moraines. Nine boulders (14.3%) are situated on the proximal parts of outwash plains and fans or on small (confined) sandurs. One boulder is located on a kame and 1 on an esker. Dimensions of the finally selected boulders are characterised by perimeter from 5.9 to 44.0 m and height from 0.8 to 3.8 m. Their volume ranges from ~1.8 m^3 to ~253.2 m^3. Most erratics are characterized by volume smaller than ~10 m^3 (35 boulders) and from ~10 to ~20 m^3 (16 boulders). There are 12 boulders with a volume larger than 20 m^3, including 1 erratic (~253.2 m^3, the biggest in Poland) significantly deviating in size from the others (Table 1).

Schmidt hammer R-values

The mean R-values for tested boulders vary from 33.6 ± 1.6 to 63.5 ± 1.3 (Table 1). A Shapiro-Wilk test, applied after rejecting potential outliers with Chauvenet`s criterion, showed that remaining mean R-values reveal normal distributions (for p = 0.05) within all erratic groups. For six boulders located outside the maximum extent of the last SIS (Saalian boulders) the mean R-values show significant scatter from 33.6 ± 1.6 to 63.5 ± 1.3 with R_w (weighted average R-value) of 52.8 ± 1.4 (Fig. 5). These boulders are medium to coarse grained granitoid, including one erratic identified as a rapakivi granite. Boulders located within the area released from the ice sheet cover during the Leszno (Brandenburg) Phase are also characterised by scattered mean R-values

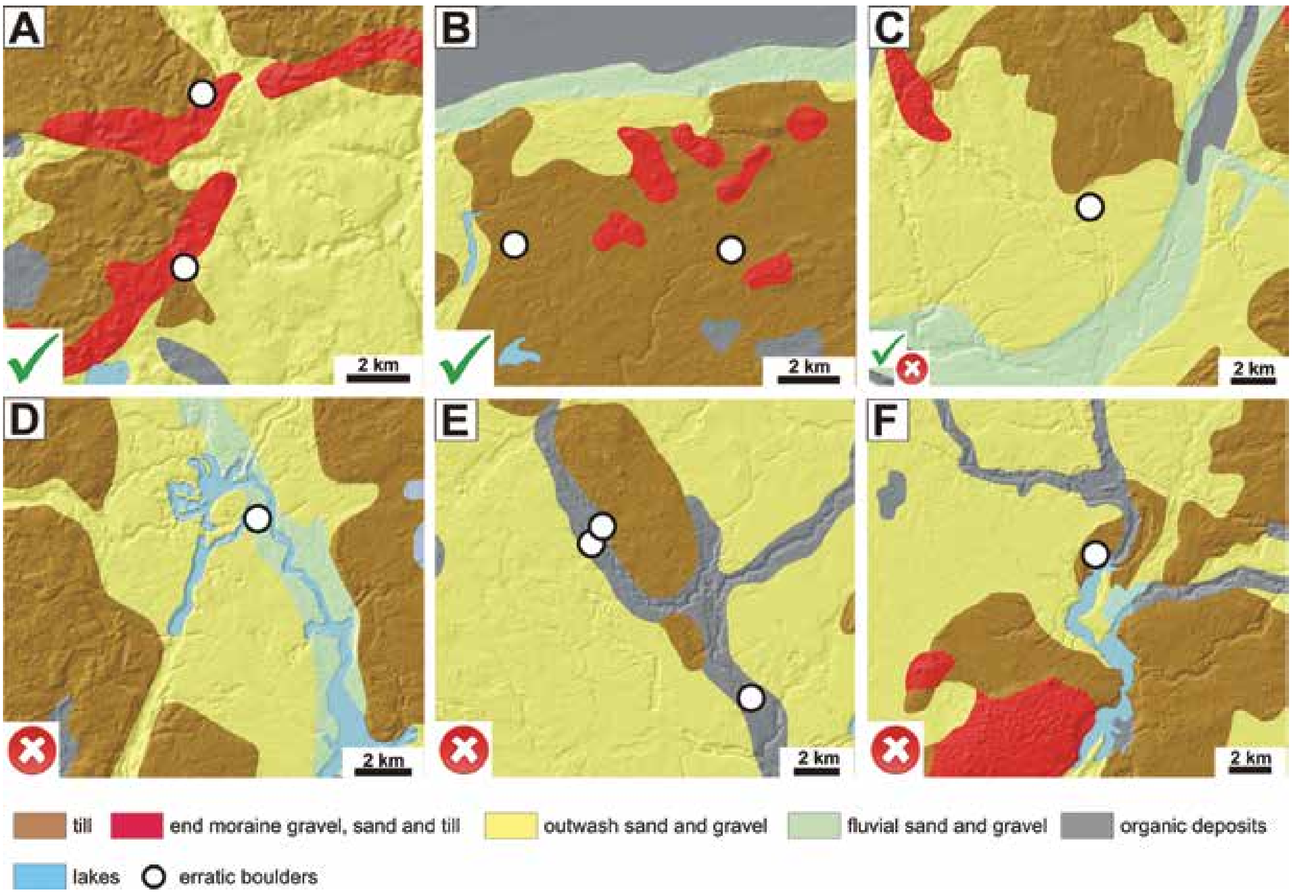

Fig. 3 Examples of geomorphological locations of the boulders. (A) Erratics located on terminal moraines – suitable for TCNED. (B) Erratics located on a moraine plateau – suitable for TCNED. (C) An erratic located on an outwash plain – suitable for TCNED when located on the proximal part of an outwash plain/fan and on a confined sandur, rejected when located within an extensive outwash plain. (D) An erratic located in a glacial tunnel channel – not suitable for TCNED. (E) Erratics located in river valleys – not suitable for TCNED. (F) An erratic located on the edge of a moraine plateau and a glacial channel – not suitable for TCNED. The surface geology after Marks *et al*. (2006)

(Fig. 5) ranging from 36.3 ± 1.4 to 59.4 ± 2.2 (calculated R_w is 46.2 ± 1.5). These 13 erratics are dominated by medium to coarse grained granitoid and granite gneisses. One boulder was identified as the medium grained gneiss (Table 1).

Erratics located within the area released from the ice sheet cover during the Poznań (Frankfurt) Phase are characterised by mean R-values ranging from 37.7 ± 1.3 to 61.6 ± 1.7. One boulder with a 37.7 ± 1.3 mean R-value was identified as an outlier according

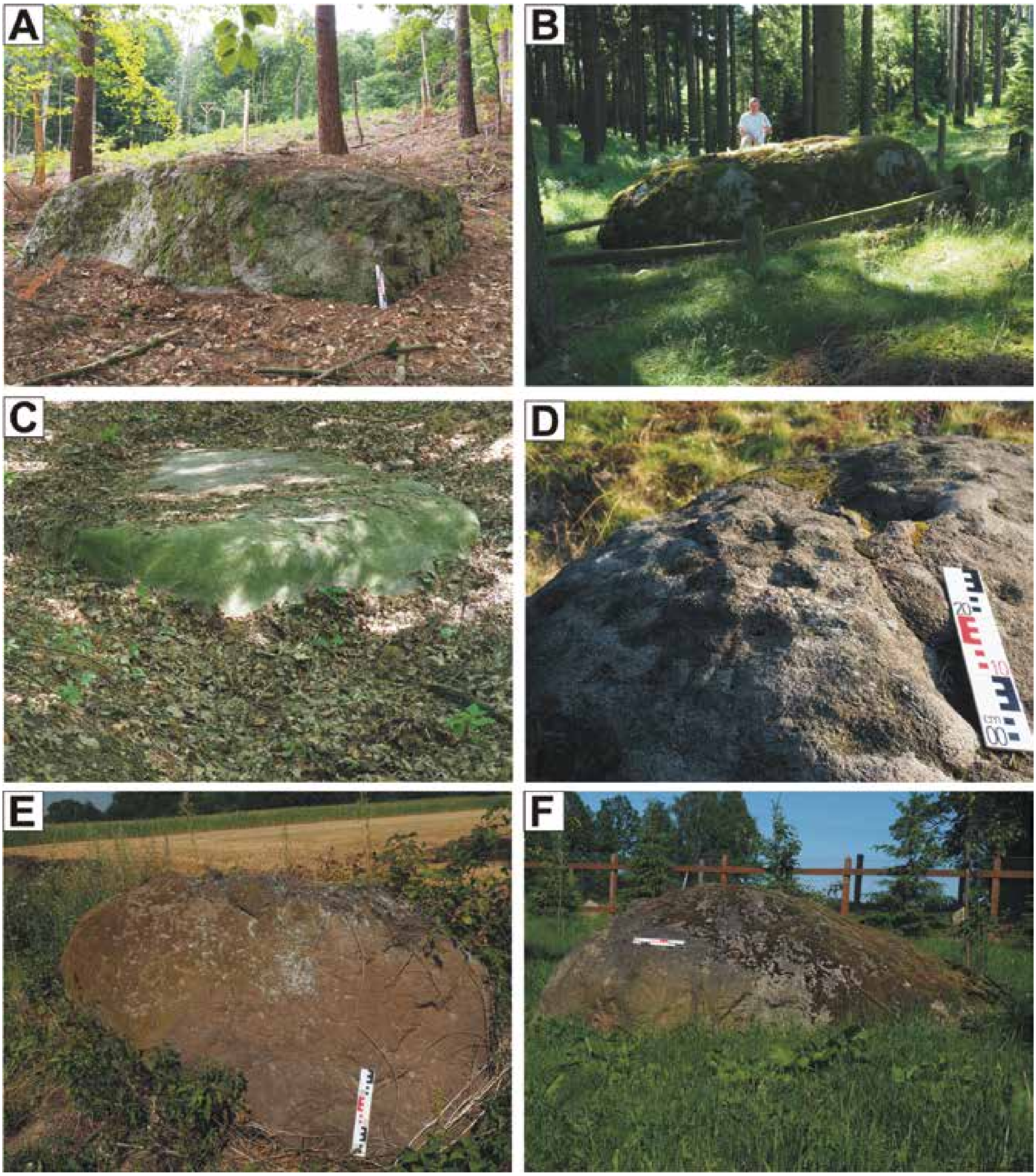

Fig. 4 Examples of erratic boulders rejected during the field screening. (A) A massive (perimeter 10.1 m, height 1.1 m) granitoid located on a slope. (B) A granitoid (perimeter 13.5 m, height 1.4 m) located on the floor of a denudation valley. (C) An excavated quartz sandstone (perimeter 13.3 m, height 0.5 m). (D) A granitoid with worshipping marks on the upper surface (circular recesses); perimeter 9.3 m, height 1.1 m. (E) A diabase with destroyed upper part; perimeter 7.5 m, height 1.2 m. (F) A piece of gneiss detached from the original boulder and transported to a farm; perimeter 9.8 m, height 1.0 m

Table 1 Erratic boulders of NW Poland selected as suitable for TCNED

No.	Position		Elevation [m a.s.l.]	Dimensions			Petrography	Geomorphological context	Schmidt hammer mean R values	Morphostratigraphic location
	Latitude (N)	Longitude (E)		Perimeter [m]	Height [m]	Volume [m³]				
1	54.8001	18.1278	30	20.5	2.7	51.3	coarse grained granitoid	moraine plateau	48.4 ± 1.3	Pomeranian ice marginal belt
2	54.7276	18.2105	102	13.4	2.4	23.2	fine grained gneiss	moraine hill	52.1 ± 1.6	
3	54.6664	17.9011	104	16.0	1.7	22.4	medium grained granite gneiss	moraine plateau	41.7 ± 1.9*	
4	54.5466	18.3146	171	12.5	1.8	14.8	medium/coarse grained granitoid	moraine plateau	46.9 ± 2.1	
5	54.5126	18.2352	207	10.0	0.9	4.0	medium grained granite gneiss	moraine hill	51.1 ± 1.3	
6	54.5038	18.2681	199	7.8	1.4	4.0	coarse grained granitoid	moraine hill	47.0 ± 1.4	
7	54.4910	18.2682	196	10.1	1.7	5.8	medium grained gneiss	outwash plain	44.4 ± 0.8	
8	54.4242	18.0064	191	17.6	3.1	58.4	medium grained granite gneiss	kettle hole	36.8 ± 1.4*	
9	54.3932	18.5100	115	12.5	2.7	23.7	coarse grained rapakivi granite	moraine plateau	46.9 ± 2.1	
10	54.3006	18.4038	166	15.0	1.4	12.9	medium grained granitoid	moraine plateau	47.1 ± 1.0	
11	54.2883	17.9010	250	13.7	2.0	16.9	medium/coarse grained granitoid	moraine hill	34.5 ± 1.1*	
12	54.2823	17.1412	135	12.5	1.4	11.8	medium/coarse grained rapakivi granite	moraine plateau	–	
13	54.2589	18.1045	228	6.1	1.5	3.0	coarse grained gneiss	moraine hill	63.9 ± 1.2*	
14	54.1910	18.4396	189	12.5	1.7	12.4	medium grained granitoid	outwash plain	–	
15	54.1910	18.4396	187	11.0	1.4	6.7	coarse grained granitoid	outwash plain	47.5 ± 1.9	
16	54.1909	16.7664	108	7.4	1.3	3.2	coarse grained granitoid	moraine plateau	–	
17	54.1860	16.7453	116	8.0	1.5	5.7	medium grained granite gneiss	moraine plateau	–	
18	54.1770	16.7886	115	8.0	1.3	2.1	medium grained granitoid	kettle hole	47.4 ± 1.9	
19	54.1706	16.8343	118	13.0	1.7	11.7	fine grained granite gneiss	moraine plateau	–	
20	54.0496	16.4278	100	10.5	1.6	8.6	medium grained granitoid	moraine plateau	51.0 ± 1.3	
21	53.9617	18.3506	111	14.8	2.5	22.0	medium grained gneiss	kettle hole	61.4 ± 1.2*	
22	53.9576	16.7262	181	6.6	1.3	2.5	coarse grained granitoid	moraine hill	–	
23	53.9316	16.2611	75	44.0	3.8	253.2	medium grained gneiss	moraine plateau	–	
24	53.9072	16.7199	174	10.8	1.0	4.6	medium grained gneiss	kettle hole	49.8 ± 1.1	
25	53.2181	16.2552	61	12.3	1.7	10.2	medium/coarse grained granitoid	moraine plateau	–	
26	53.2091	15.2299	62	7.0	1.2	2.6	coarse grained granitoid	moraine hill	–	
27	53.2130	15.2230	61	9.3	1.5	6.5	coarse grained granitoid	moraine hill	–	
28	52.9963	15.4031	96	13.5	1.5	12.4	medium grained granitoid	moraine plateau	47.4 ± 1.1	
29	52.9784	15.4213	95	12.5	1.8	15.7	medium grained granitoid	moraine plateau	47.9 ± 1.3	

No.	Position		Elevation [m a.s.l.]	Dimensions			Petrography	Geomorphological context	Schmidt hammer mean R values	Morphostratigraphic location
	Latitude (N)	Longitude (E)		Perimeter [m]	Height [m]	Volume [m^3]				
30	53.7271	17.1372	186	14.6	2.1	18.5	medium/coarse grained granitoid	moraine plateau	50.1 ± 1.1	Poznań (Frankfurt) ice marginal belt
31	53.6903	17.1372	171	20.5	1.9	41.0	fine grained gneiss	moraine plateau	57.3 ± 1.3	
32	53.5238	16.2029	150	19.0	3.4	53.2	coarse grained gneiss	kettle hole	–	
33	53.4187	19.9013	167	9.5	1.2	3.8	medium grained granitoid	kettle hole	37.7 ± 1.3*	
34	53.3874	19.5752	132	8.0	1.0	2.6	coarse grained rapakivi granite	esker	47.7 ± 1.6	
35	53.2823	17.5074	116	8.9	1.2	4.2	medium grained granitoid	moraine plateau	53.2 ± 2.1	
36	53.2409	15.7286	102	13.9	2.4	24.7	medium grained granitoid	moraine plateau	–	
37	52.9537	17.1255	89	17.5	2.2	25.4	medium grained granite gneiss	moraine plateau	59.4 ± 1.4	
38	52.9525	17.3370	95	13.5	1.3	8.8	coarse grained granitoid	kettle hole	54.8 ± 2.0	
39	52.8749	19.6290	115	9.0	0.8	2.5	coarse grained granitoid	outwash plain	46.7 ± 1.2	
40	52.8035	17.9141	107	13.1	2.9	20.4	coarse grained gabbro	moraine plateau	–	
41	52.7390	19.6783	144	14.3	1.4	11.3	coarse grained granitoid	moraine hill	61.6 ± 1.7	
42	52.7259	17.3231	105	20.5	1.1	14.6	medium grained granitoid	moraine plateau	58.4 ± 1.9	
43	52.4897	15.1843	116	8.7	1.6	4.9	coarse grained granitoid	moraine plateau	50.2 ± 1.4	
44	52.4471	15.1529	166	10.1	1.8	9.6	medium grained granitoid	moraine hill	59.1 ± 1.6	Leszno (Brandenburg) ice marginal belt
45	52.4489	15.1606	143	12.7	2.5	16.1	medium grained granitoid	moraine hill	59.4 ± 2.2	
46	52.4426	15.2819	178	8.2	1.6	5.4	coarse grained granitoid	moraine hill	46.9 ± 2.1	
47	52.4410	15.0488	143	6.5	1.3	2.1	coarse grained granitoid	moraine hill	57.6 ± 1.2	
48	52.3949	15.0943	134	7.0	0.8	2.1	medium/coarse grained granitoid	outwash plain	44.0 ± 1.7	
49	52.3703	16.2724	99	8.7	0.8	2.6	medium grained gneiss	kettle hole	37.5 ± 1.3	
50	52.1739	15.6817	132	5.9	1.9	3.0	medium/coarse grained granite gneiss	moraine hill	41.8 ± 1.4	
51	52.1511	18.3218	160	6.3	1.2	2.2	coarse grained granitoid	moraine hill	42.8 ± 1.9	
52	52.1457	18.3311	159	6.8	1.0	1.8	coarse grained granitoid	moraine hill	46.7 ± 1.3	
53	52.1303	18.3199	159	7.8	1.5	3.7	coarse grained granitoid	moraine hill	36.3 ± 1.4	
54	52.1185	15.6663	111	10.5	2.3	10.0	medium grained granite gneiss	outwash plain	42.7 ± 1.2	
55	51.9690	17.1330	120	13.5	1.2	10.8	coarse grained granitoid	outwash plain	48.5 ± 2.2	
56	51.9609	17.1492	110	10.4	2.6	13.4	medium grained granitoid	moraine hill	46.1 ± 1.3	
57	53.2182	20.0510	158	9.5	1.8	7.0	coarse grained granitoid	outwash plain	46.9 ± 2.1	Saalian moraine plateau
58	52.7110	19.9693	132	13.0	1.2	7.8	medium/coarse grained granitoid	moraine plateau	57.3 ± 1.4	
59	52.1714	19.2166	139	8.8	1.4	4.0	medium/coarse grained rapakivi granite	moraine hill	61.6 ± 1.1	
60	52.0883	18.3700	116	7.0	1.2	2.4	coarse grained rapakivi granite	moraine plateau	–	
61	51.9690	17.4716	120	9.5	1.1	4.0	medium/coarse grained granitoid	moraine plateau	63.5 ± 1.3	
62	51.9411	17.2008	123	9.7	1.3	4.8	coarse grained granitoid	moraine hill	33.6 ± 1.6	
63	51.9410	17.2008	123	11.1	1.7	10.8	coarse grained granitoid	moraine hill	38.8 ± 1.4	

* Mean R-values identified as outliers according to Chauvenet`s test.

to Chauvenet`s criterion and the R_w (53.1 ± 1.5) was calculated for the remaining 10 erratics (Fig. 5). The lithology of these boulders is dominated by 9 medium to coarse grained granitoid (including one granite identified as a rapakivi) (Table 1). Erratics situated within the ice sheet limit of the Pomeranian Phase (19 boulders) reveal significant scatter of the mean R-values from 34.5 ± 1.1 to 63.9 ± 1.2. Application of the Chauvenet`s criterion highlighted that 3 of the lowest mean R-values (34.5 ± 1.1; 36.8 ± 1.4; 41.7 ± 1.9) and 2 of the highest mean R-values (61.4 ± 1.2; 63.9 ± 1.2) are outliers. The remaining 14 erratics have a R_w of 47.8 ± 1.3 (Fig. 5). The lithology of the boulders is dominated by medium to coarse grained granitoid (11 erratics), including one rapakivi granite (Table 1).

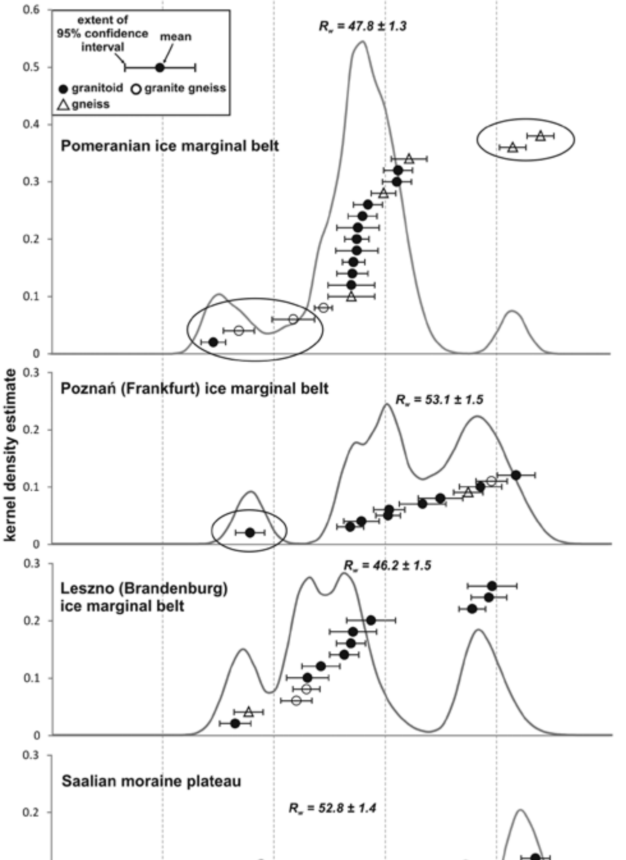

Fig. 5. The distribution of Schmidt hammer (SH) mean R-values with 95% confidence interval calculated for 49 boulders. Mean R-values are grouped according to the morphostratigraphic location of the boulders. The grey curve represents the kernel density estimate of mean R-values with 95% confidence intervals in specific erratic groups. The oval outlines indicate outliers. The weighted average R-values (R_w) ± weighted mean standard deviation of the 95% confidence intervals (σ_w) are given for specific erratic groups after excluding outliers

DISCUSSION

Selection for TCNED

Erratics were selected for potential TCNED mainly based on 2 parameters: dimensions and geomorphological location. There is no consensus in the literature about what would be the optimal dimension of a boulder for TCNED. The bigger and the more stable the boulder is, the better. At the southern periphery of the last SIS, erratics bigger than 1 m^3 were usually a target of TCNED (e.g. Heine *et al.* 2009; Houmark-Nielsen *et al.* 2012; Rinterknecht *et al.* 2012, 2014). The volume of a boulder with a perimeter of 5.0 m and a height of 0.5 m (minimum values set in our GIS pre-selection) would be ~0.66 m^3, assuming a circular base for the erratic. It is less than the usually used 1 m^3, but we argue that this dimension is enough for the first stage of the selection. Boulder height above the ground is also important, because of the risk of a potential coverage with colluvium and seasonal snow after the deglaciation. These factors may result in underestimating the exposure ages (Heyman *et al.* 2016). Statistical analyses based on a large dataset of boulders showed that the higher the boulders (on a particular landform), the more clustered the exposures ages were for that landform (Heyman *et al.* 2016). The best results are associated with boulders of considerable height (in the order of 2–3 m). Our field inspection of the desk-based pre-selected boulders (with height ≥0.5 m) resulted in a 53.7% reduction of the dataset. The final ground-truthed boulders are dominated by erratics of height in the range of 1–2 m (69.8% of boulders), and 28.3% of boulders are considerably higher (≥ 2 m). Almost all erratics (62 out of 63) are larger than 2 m^3 (Table 1), which indicates that they are rather massive boulders and suitable for TCNED (Heine *et al*. 2009; Rinterknecht *et al.* 2014).

The erratic geomorphological context is another essential factor for a robust TCNED deglaciation chronology (e.g. Dzierżek, Zreda 2007; Heine *et al.* 2009). It has often been argued, that moraine crests are the optimal boulder sites for cosmogenic exposure dating, when investigating glacier retreat (e.g. Philips *et al.* 1990; Ivy-Ochs *et al.* 1999; Kaplan *et al.* 2004). Sequences of terminal moraines provide very good records of paleo ice margins, because they directly indicate the positions of the paleo-ice front and show deglaciation pattern of a particular area (Blomdin *et al.* 2018). However, boulders from other glaciomorphological locations were considered in such analysis, including: moraine plateaux and dead-ice moraines (Dzierżek, Zreda 2007; Houmark-Nielsen *et al.* 2012), outwash plains/fans (Rinterknecht *et al.* 2014; Çiner, Sarikaya 2015), glaciofluvial deltas and eskers (Stroeven *et al.* 2011), and erosional features such as meltwater channels and terraces (Dzierżek, Zreda 2007). Stroeven *et al.* (2011) recommended a 'multiple morphological setting' as a valuable approach in the TCNED of warm-based ice sheet retreat. The potential of TCNED within meltwater channels has been shown in the bedrock area of northern Scandinavia (e.g. Stroeven *et al.* 2006, 2011; Harbor *et al.* 2006). However, in the area covered by clastic Quaternary sediments, boulders located in glacial channels (tunnel valleys or marginal channels) are in many cases the result of buried dead-ice blocks melting (cf. Marks 1994) or postglacial erosion of the substratum. Therefore, the exposure of boulders located within these landforms may significantly postdate deglaciation, and their suitability for the TCNED of the ice sheet retreat of the southern sector of the SIS seems to be questionable. Massive erratics located within river valleys or terraces were certainly exposed from below the sedimentary cover that occurred as a result of valley erosion after deglaciation. These boulders, as a residuum, should be rejected as well, and similarly boulders located on the Baltic Sea shore (mostly coming from the glacial till layers exposed on cliff sections). Among the boulders on outwash plains/fans, only erratics located in the proximal zones, at the paleo-ice sheets margins, or in small, confined sandurs should be chosen. All massive boulders located within the extensive outwash plains on the foreland of a particular ice margins were rejected, because of the possibility of catastrophic outburst floods during the ice sheet decay (e.g. Szafraniec 2010) and meltwater exhumation of large boulders from the sediments of older glaciation. Sandur erratics located at the paleo-ice sheet margins (proximal) were more likely directly released from the melting ice front, rather than exhumed from an older sediments. We also accepted erratics located within small outwash plains surrounded by moraines or moraine plateaux, because we suggest that this geomorphological setting is not favourable for extreme meltwater outbursts, in contrast to extensive outwash plains such as large sandurs in southern Pomerania (cf. Pisarska-Jamroży 2015). So in conclusion, erratic boulders located on landforms deposited by glacial or by glaciofluvial processes under the ice cover or in the ice marginal zone (moraine plateaux, terminal and dead ice moraines, kames, eskers, proximal outwash plains/fans, and small, confined sandar) are the best locations for boulders using in TCNED in NW Poland and areas of Pleistocene continental glaciations.

R-values as indicator of suitability for TCNED

The SH R-values have been used as a proxy for reconstructing the exposure history of erratic boulders and for constructing a relative chronology of deglaciation (e.g. Aa, Sjåstad 2000; Kłapyta 2013; Tomkins *et al.* 2016). If the degree of weathering is related mainly to the time of exposure, R-values will decrease with increasing exposure age of boulders. However, the magnitude of R-value reduction decreases through time (Sánchez *et al.* 2009; Stahl *et al.* 2013). The SH testing of erratics selected for TCNED, enables the identification of boulders with complex exposure history (e.g. redeposited boulders) which in turn will help to better interpret TCN ages (Nývlt *et al.* 2014).

Large erratics of NW Poland are composed mostly of Scandinavian variously weathered granitoides and gneisses. The weathering depends on the time they have been exposed to subaerial processes, local climatic conditions (temperature and humidity) and rock surface texture. Typical mean R-values for fresh surfaces of resistant igneous and metamorphic rocks such as granitoides and gneisses are in the order of 50–60 (Goudie 2006 after Selby 1993). Ericson (2004) recorded in southern Sweden the mean R values of 'fresh' granite surfaces (exposed within road cuts) in the range of 50–59. Our SH results show that Saalian boulders have the highest scatter of the mean R-values with exceptionally high values 63.5 ± 1.3, 61.6 ± 1.1 and 57.3 ± 1.4. This suggests postglacial erosion resulting in 'refreshment' of the rock surfaces which have been exposed to subaerial processes for ca. 130 ka and should display the lowest R-values in the analysed set. Although no signs of periglacial wind erosion have been found on these boulders, they might have been erased due to subsequent weathering. Most of the SH relative exposure dating focus on Holocene or Late Glacial surfaces (Aa, Sjåstad 2000; Kłapyta 2013), but few studies show SH testing on glacial surfaces older than 20 ka (Tomkins *et al.* 2016) or even 100 ka (Sánchez *et al.* 2009). However, Sanchez *et al.* (2009) concluded that the age inferences exclusively based on R-values for such old surfaces may not be realistic and SH could be a useful tool only for selecting surfaces for TCNED. Our SH results indicate that most Saalian boulders could potentially reveal exposure ages too young (due to postglacial erosion), as reported by Rinterknecht *et al.* (2014) for most of the dated erratics in front of the local LGM limit in Germany.

Difference in mean R-values occurs when comparing erratics released from the ice during the Leszno (Brandenburg) and Poznań (Frankfurt) Phases (R_w are 46.2 ± 1.5 and 53.1 ± 1.5 respectively). However, subpopulations with relatively high mean R-values of the Leszno (Brandenburg) and Poznań (Frankfurt) boulders (higher than 50, Fig. 5) are most likely related to the postglacial erosion and 'renewing' of the boulders' surface rather than to the original degree of weathering. Mean R-values higher than 50 are characteristic for 'fresh' Scandinavian granites

(Ericson 2004), so original granitic surface exposed for ~21–19 ka should have significantly lower mean R-values. This indicates the possibility of obtaining exposure ages too young for these boulders as well. Moreover, Pomeranian erratics do not follow the trend of R-values increase (R_w is 46.7 ± 1.3). Only two erratics are characterised by mean R-values >60, and clearly indicates postglacial erosion of the rock surface (protruding crystals of relatively more resistant minerals such as quartz) and potential problems for accurate TCNED. The postglacially eroded erratics will probably reveal too young exposure age, as a result of partial removal of in-situ produced cosmogenic nuclides due to erosion of the boulders surface.

CONCLUSIONS

Our procedure to select erratic boulders for the purpose of TCNED highlights the efficiency of the use of a GIS tool prior to any field work. Applying strict and basic criteria for the selection of suitable boulders, dimensions and geomorphological location of the boulders helped reduce by a quarter the number of objects to be ground checked. It excluded most of boulders located in an inappropriate geomorphological location and helped to minimize the time needed for the next selection steps.

The ground-truthing step is dedicated to further constrain the population of suitable boulders for sampling purposes. This visual check allows a precise appreciation of the boulder position in the field and the state of its top surface. In our case, the ground-truthing step further reduced the population of boulders by more than 2.

Both of these selection steps resulted in a considerable gain of time before the actual sampling of the best candidates for TCNED. Additional tests with the SH helped to some extent to identify the degree of weathering of the boulder surface. This information is useful to build relative chronologies and could be determinant in the interpretation of the strength of individual surface exposure age when available. This procedure could be recommended to researchers looking for an efficient approach in selecting suitable erratic boulders in wide areas formerly glaciated.

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