Grid 3. Location: north crater rim (facing north) on Walker Lake cone (V3611) at an elevation of 2585 m.
Emplaced: July 21, 1992
First field survey: August 17, 1992
Second field survey: August 17, 1994

Cinder	Aug. 1992 position[1]	Distance moved (cm)	Direction moved (deg.)	Aug. 1994 position	Distance moved (cm)	Direction moved (deg.)
1	10.5, 22	12.0	178	–[3]	–	–
2	34, 42	34.9	156	–	–	–
3	32.5, 12	3.2	129	–	–	–
4	43.5, 21	11.5	162	–	–	–
5	49, 17	7.1	188	–	–	–
6	77, 91	82.8	168	–	–	–
7	72, 13.5	4.0	150	72, 98	88.0	179
8	75.5, 31.5	30.7	188	53, 191	183.0	188
9	–	–	–	–	–	–
10	100, 41	31.0	180	–	–	–
11	13, 28.5	9.0	161	–	–	–
12	16, 29	9.8	204	–	–	–
13	(30, 20)[2]	0	–	–	–	–
14	41, 19	1.4	46	77, 163	147.7	165
15	55, 23	5.8	120	63, 88	69.2	169
16	62, 31	11.2	170	–	–	–
17	77, 34.5	16.1	154	–	–	–
18	–	–	–	–	–	–
19	90.5, 30.5	10.5	177	–	–	–
20	102.5, 24	4.7	148	50, 148	137.4	201
21	10, 30.5	0.5	180	65, 136	119.4	153
22	22, 38	8.2	166	34, 177	147.7	175
23	32, 37	7.3	164	–	–	–
24	45.5, 38	9.7	145	44, 104	74.1	177
25	51, 32	2.2	153	–	–	–
26	60.5, 62	32.0	179	–	–	–
27	73.5, 38	8.7	156	66, 172	142.1	182
28	82, 38	8.2	166	–	–	–
29	90, 34.5	4.5	180	30, 143	127.9	208
30	(100, 30)	0	–	120, 144	115.7	170
31	26.5, 79.5	42.8	157	–	–	–
32	24, 52.5	13.1	162	–	–	–
33	28.5, 43	3.4	207	45, 168	128.9	173
34	38.5, 42	2.5	217	–	–	–
35	50, 46.5	6.5	180	64, 143	104.0	172
36	58.5, 43	3.4	206	–	–	–
37	68, 31	9.2	347	–	–	–
38	81.5, 38.5	2.1	46	77, 123	83.0	182
39	92.5, 45	5.6	153	64, 92	58.1	207
40	94.5, 49.5	11.0	210	–	–	–
41	11, 55	5.1	169	–	–	–
42	23, 50	3.0	90	–	–	–
43	29.5, 66	16.0	182	–	–	–
44	41.5, 63	13.1	173	50, 138	88.6	174
45	53.5, 89	39.2	175	–	–	–
46	60.5, 47	3.0	10	–	–	–
47	71.5, 86.5	36.5	178	94, 168	120.4	169
48	82, 48	2.8	46	–	–	–
49	91.5, 52.5	2.9	149	–	–	–
50	100.5, 52.5	2.6	169	–	–	–

[1] Grid coordinates (x = direction parallel to local slope contours, y = upslope/downslope direction perpendicular to the local slope contours or rows of cinders) measured in cm with stake #1 set at (0, 0) and downslope as the positive y-axis direction.

[2] No measurable movement from July 1992 position (in parenthesis).

[3] Unable to relocate or find painted cinder.

Grid 4. Location: south crater rim (facing south) on Walker Lake cone (V3611) at an elevation of 2530 m.
Emplaced: July 21, 1992
First field survey: August 17, 1992
Second field survey: August 17, 1994

Cinder	Aug. 1992 position[1]	Distance moved (cm)	Direction moved (deg.)	Aug. 1994 position	Distance moved (cm)	Direction moved (deg.)
1	(10, 10)[2]	0	–	–[3]	–	–
2	(20, 10)	0	–	–	–	–
3	30, 12	2.0	180	37, 31	22.1	162
4	(40, 10)	0	–	–	–	–
5	(50, 10)	0	–	53.5, 24.5	14.9	166
6	(60, 10)	0	–	80.5, 22	23.8	121
7	72, 11	2.2	115	68, 30	20.1	186
8	(80, 10)	0	–	82, 15.5	5.8	160
9	(90, 10)	0	–	89.5, 22	12.0	182
10	(100, 10)	0	–	95, 31	21.6	193
11	(10, 20)	0	–	10.5, 25.5	5.5	175
12	(20, 20)	0	–	21.5, 32	12.1	173
13	(30, 20)	0	–	32, 24	4.5	154
14	39.5, 22	2.1	194	36.5, 36	16.4	192
15	(50, 20)	0	–	54.5, 34	14.7	162
16	(60, 20)	0	–	60.5, 54.5	34.5	179
17	(70, 20)	0	–	–	–	–
18	(80, 20)	0	–	85, 32.5	13.5	158
19	(90, 20)	0	–	91.5, 34.5	14.6	186
20	(100, 20)	0	–	91, 51.5	32.8	196
21	10, 39	9.0	180	8.5, 51	21.0	184
22	(20, 30)	0	–	19.5, 35	5.0	186
23	(30, 30)	0	–	32, 40	10.2	169
24	(40, 30)	0	–	54, 38	16.1	120
25	(50, 30)	0	–	61.5, 41	15.9	134
26	(60, 30)	0	–	68, 40	12.8	141
27	(70, 30)	0	–	–	–	–
28	(80, 30)	0	–	80.5, 46	16.0	178
29	(90, 30)	0	–	91, 41.5	11.5	175
30	(100, 30)	0	–	91.5, 45	17.2	210
31	(10, 40)	0	–	9, 48.5	8.6	187
32	(20, 40)	0	–	19, 46.5	6.6	189
33	(30, 40)	0	–	34.5, 49.5	10.5	155
34	(40, 40)	0	–	44, 50	10.8	158
35	(50, 40)	0	–	54, 48.5	9.4	155
36	(60, 40)	0	–	63.5, 48	8.7	156
37	(70, 40)	0	–	72, 47	7.3	164
38	(80, 40)	0	–	80, 45.5	5.5	180
39	(90, 40)	0	–	92.5, 59	19.2	173
40	(100, 40)	0	–	–	–	–
41	(10, 50)	0	–	13, 75	25.2	173
42	21, 53	3.2	162	18.5, 56	6.2	194
43	(30, 50)	0	–	29, 58	8.1	187
44	(40, 50)	0	–	45.5, 56	8.1	137
45	(50, 50)	0	–	–	–	–
46	(60, 50)	0	–	62, 57.5	7.8	165
47	(70, 50)	0	–	–	–	–
48	(80, 50)	0	–	80, 58.5	8.5	180
49	(90, 50)	0	–	–	–	–
50	(100, 50)	0	–	109, 78	29.4	162

[1] Grid coordinates (x = direction parallel to local slope contours, y = upslope/downslope direction perpendicular to the local slope contours or rows of cinders) measured in cm with stake #1 set at (0, 0) and downslope as the positive y-axis direction.

[2] No measurable movement from July 1992 position (in parenthesis).

[3] Unable to relocate or find painted cinder.

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Morphological and geological evidence for glaciotectonics in the area of the Saalian Glaciation, with special reference to Middle Poland

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Abstract: The definition of glaciotectonics to include both the effects of glaciodynamic processes and the effects of glacioisostatic processes has been generally accepted. In Poland, the glaciotectonic style of the Wartian zone is one of the most distinctive features of the Saalian area; glaciotectonic symptoms are numerous in the western part, but disappear in the east. Such a division extends beyond the Polish borders – as continuous thrust ridges in the west and as a sporadic phenomenon in the east.

Attention is drawn to the relationships between geological structure and morphological features; they include such cases as: a direct reflection of thrusts in convex land forms, low-relief areas and relief inversion (in relation to the structure). Much importance has been attached to the marginal zone of the Łódź Plateau in Middle Poland.

This paper reviews the main genetic hypotheses which, usually, are based on the mechanism, rather than palaeogeographical conditions. Despite much discussion, several problems remain, e.g.:
– why, allowing that the mechanism was similar, are there such regional differences;
– why are the marginal zone of the Warta Stadial and the western part of Europe so well endowed in this respect;
– could palaeoclimatic conditions (different patterns of glaciation and deglaciation), and could postglacial vertical compensatory movements have conditioned the regional variation?

Key words: *glaciotectonics, relief, Saalian glaciation, Middle Poland*

The extent of the terms

Glaciotectonics, the term relating to processes and phenomena associated with the action of an ice sheet on its bedrock, is not always defined in the same way. Differences involve the acceptance or elimination of certain effects of that action, e.g. deformation structures which result from dead ice pressure. Contrary definitions may be cited as an example. Bartkowski (1968, 1974) proposed the term "glaciotectonics" in respect of "all disturbances of the structure of ice sheet material and its bedrock caused by dynamic pressure", where the term "dynamic pressure" is defined as "tangential pressure as a resultant of vertical static pressure of the ice mass and the horizontal "dynamic" movement of moving ice mass". Therefore, all diapiric effects, especially in dead ice conditions, cannot be glaciotectonic, as this author clearly points out (Bartkowski, 1974, p. 25). Jaroszewski (1985, p. 81) gave a radically different definition, according to which "glaciotectonic" is "deformation of ice sheet bedrock and material resulting from ice pressure and/or its friction with the bedrock". A similar opinion is expressed by Ruszczyńska-Szenajch (1983), who regards "glaciotectonics" as "the mechanical action of an ice sheet on the bedrock".

The author of the present work favours the view of Jaroszewski and Ruszczyńska-Szenajch. Thus, any further consideration of "glaciotectonics" in this paper will be based on their definitions, and the effects of differential ice pressure, such as diapiric movement of susceptible material in coarse-grained kame deposits. The latter are very often omitted from similar studies, but will be included in the present discussions.

By "the Saalian zone" (including the glaciotectonic section), the author means "the area in which glacial deposits of that age create the youngest Pleistocene member of a surface geological structure". This zone is E-W oriented, though gently deflected to the NE, and does not remain constant in width – several deep salients reach far to the south. The deepest of these indicates the presence of the Saalian ice sheet at the Moravian Gate, while shallower ones occur along the Vistula valley as far as the San river mouth and in the Nida Basin. As a generalisation, one might agree that the furthest reaches of the Saalian Glaciation entered depressions, such as the Silesian Lowland, the Nida Basin and the Vistula valley, and was not able to surmount such elevations of the pre-Quaternary surface as the Polish Jura Upland, the Holy Cross Mts, together with their Mezosoic northwestern margin, and the Lublin Upland (Fig. 1).

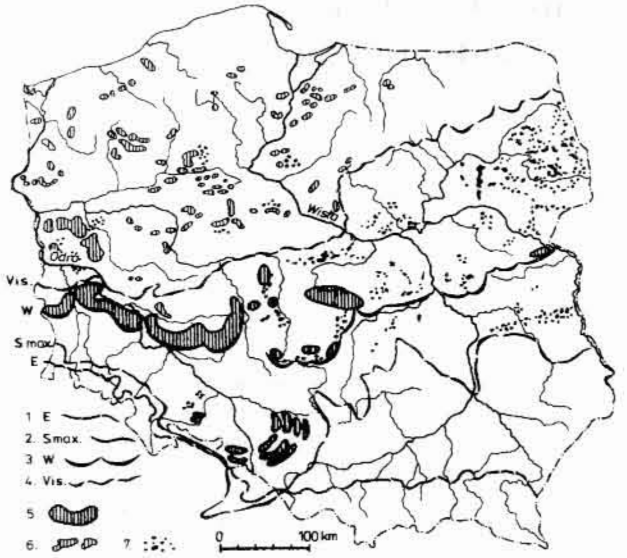

Fig. 1. The main glaciotectonic areas in the Saalian zone in Poland.

Extents of the ice sheets:

1 – Elsterian; 2 – Saalian max.; 3 – Wartian; 4 – Vistulian; 5 – main glaciotectonic areas of the Saalian zone; 6 – major glaciotectonic complexes in the area of the last glaciation (Vistulian); 7 – complexes of glacial accumulation forms, including those of surficial deglaciation (kames, kame terraces).

Between the ice margins of the Saalian and Vistulian glacial maxima in Poland, there is very important border – the maximum limit of the Warta Glaciation/Stadial. This is arcuate and attains its maximum southern extent in Middle Poland, dividing the Saalian zone into two parts. This reflects differences in the relief intensity as well as the thickness and character of Quaternary deposits, mainly the degree to which they have become dissociated.

The growth of interest in the importance of glaciotectonism in the evolution of Polish relief

The problem of the stratigraphic rank of the Wartian unit has been discussed at length but, as yet, no reliable data are available to solve the problem. The main debate, mainly among Polish and German scientists, concerns the difficulty that there are roughly the same number of reasons for accepting its individuality as there are against this. The evidence is variously of a geomorphic, geologic, stratigraphic and, most importantly, of a biostratigraphic nature.

One of the criteria for recognising the Warta unit is that of its marginal character, particularly in the western part of Poland. Here, this zone comprises huge, continuous thrust ridges in which both Quaternary and Tertiary deposits, pushed up from a considerable depth, are involved. For example, the origin and the age of the Trzebnica Hills (in the older literature sometimes called the Cat Hills (German: *Katzengebirge*), have been interpreted in various ways. In the first half of the present century, investigators tended to overestimate the role of tectonics. An example of such an inconclusive interpretation of the origin of the Trzebnica Hills is the detailed and extensive study of Czajka (1931). In this, the author could not decide whether solely endogenic or possibly also exogenic factors were involved or, alternatively, the one tended to dominate the other at particular times and in particular conditions. Gołąb (1951) in the work "The Geology of the Ostrzeszów Hills", based largely on his own studies, considered the following effects: 1) of tectonics provoked by orogenic movements, 2) of glaciotectonics resulting from tangential and vertical pressure and 3) of flow tectonics. He emphasised the role of the particular processes involved further, and the glaciotectonic provenance of huge and deeply rooted deformations elsewhere, as originally interpreted by reference to deep tectonics. Lencewicz's (1927) attempt to explain disturbances of Tertiary and Quaternary deposits at Dąbrówka-Strumiany near Łódź as a result of tectonics is an example of this. Srokowski (1927) similarly attributed the formation of what are now universally regarded as glaciotectonic hills at Dębowa Góra to orogenic movements before the last glaciation.

These studies, now largely discounted, are mentioned here merely to trace the evolution of opinions concerning the importance of glaciotectonics as a powerful local influence in the geomorphological evolution of an area so affected. Only recently has a glaciotectonic provenance been commonly accepted for certain landforms even though such structures were first described, sometimes, many decades ago: the Zielona Góra Ridge (Ciuk, 1953, 1955, 1974; Bartkowski, 1974; Dyjor, 1974, 1975; Barański, Kołodziejczyk, 1983), the Mużaków Arc (Ciuk, 1953, 1955, 1974; Dyjor, Chlebowski, 1973; Dyjor, 1974), the Dalków Hills (Wroński, 1967; Kraiński, 1977, 1983, 1989), the Trzebnica Hills (Pachucki, 1952; Różycki, 1957, 1968), and the Ostrzeszów Hills (Rotnicki, 1960, 1966, 1967; Połtowicz, 1961). There is no doubt that much of this newly acquired acceptance has been due to recent geological mapping which has provided many new data; sufficient, in fact, to confirm prevailing suspicions about the role of glaciotectonics in landscape evolution (Kucharewicz, 1973; Szałajdewicz, Czop, Łabno, 1974; Baranowski, 1975, 1976; Gizler, 1985, 1986; Winnicki, 1986, 1990; Milewicz, 1990).

Geological and morphological variations in the marginal zone of the Warta ice sheet

The continuous belt of deeply rooted glaciotectonic structures, which is well pronounced in the present-day topography, ends at the northern edge of the Ostrzeszów Hills (Fig. 1). Though, further northeastward, glaciotectonic features are recognised e.g. in the vicinity of Kalisz (Rotnicki, 1971, 1976a), these are forms where morphological expression, unlike the hills of Lower Silesia, is minimal. Only in the Malanów Ridge, in the region between the Warta and Prosna rivers, are glaciotectonics clearly related to the morphology.

Also, hills produced by glaciotectonic thrusting are rather poorly developed southeastwards, i.e. in the direction of the southern limit of the Warta ice sheet. Although the author of the present work has observed ice thrust structures near Wieluń (cited also by Lewandowski (1996)), as have Baraniecka and Sarnacka (1971) in areas north of here. This section of the Wartian marginal zone has been generally accepted to be an area where glacial accumulation has taken place. This opinion is supported by the own author's observations of the area near Łódź in the south and southeast, where the morphology is dominated by isolated kames and dead ice moraines. Thrust structures here are much rarer; they appear to the east of the kame developments and are poorly represented in the landscape (Klatkowa, 1972a).

The picture changes radically to the north of Łódź, where exceptionally common deformation structures, restricted to a quite limited area, are associated with high relief. However, the relief does not directly reflect the glaciotectonic deformation. This zone was originally considered to be an area of end moraines, thereby indicating the maximum extent of the Warta ice sheet. However, as early as 1927, Lencewicz demonstrated that "the Łódź Plateau is wanting an end moraine landscape" and that "this is exclusively an erosional landscape". This conclusion was later supported by Dylik (1952, 1953, 1961b) and Klatkowa (1965, 1967, 1972b). Nevertheless, most recent opinion holds that the area is one where terminal moraines have formed e.g. on the Sketch Geomorphological Map of Poland at a 1:500 000 scale, edited by Starkel (1982) and on the Detailed Geomorphological Map of Poland at 1:50 000 (Brzeziński, 1986). There can be no doubt that the landscape here is at least partly the result of denudational processes which have operated in the Vistulian and Holocene periods; the problem is the extend to which they have masked earlier glaciotectonic events, and whether or not these are dominant.

The Łódź region is the easternmost where glaciotectonic emphasis of the Wartian marginal zone can be recognised. Beyond Łódź, it is accepted that the landform are typical end moraines of fluvioglacial forms such as kame hillocks, kame plateaux and kame terraces. Occasionally dead ice moraines are recognised. In the vicinity of Biała Podlaska (Kornica), Białystok and in Mielnik on the Bug river, a glaciotectonic style is again encountered. The Chalk, exposed in Kornica, first described by Rühle (1947) was considered to have been elevated by glaciotectonic processes, a notion supported by Alexandrowicz and Radwan (1983). The presence of Tertiary and Quaternary deposits under the Chalk, as reported in 27 bore holes seems best explained by large-scale glaciotectonic thrusting of Chalk masses – a feature recognised elsewhere in Poland (Połtowicz, 1961; Dyjor, Chlebowski, 1973; Dyjor, 1974) and Germany (Brinkman, 1953). Possibly other Chalk outcrops in Mielnik and at some sites in Belarus, between Grodno and Volkovysk, are due to similar events.

The dual nature of the Saalian zone in Poland

The course and the width of the Warta marginal zone beyond the area where glaciotectonic effects can be traced must also be considered. It has already been mentioned that, in Poland, this zone is generally E-W oriented; however, it is capable of resolution into two distinct parts. The western part, the width of which is very limited in the west, expands eastwards, where the marginal zone is emphasised by thrust ridges which are WNW-ESE oriented. This section ends at the N-S trending accumulation margin of the Widawka lobe, and is accompanied in the north by a zone of intense glaciotectonic thrusts in the Łódź district. East of here, the direction (WSE-ENE) and nature of the marginal strip both change. Also, the width of the whole Wartian zone clearly increases northeastwards. The southern boundary, as commonly defined, lacks distinct forms, and, in some places, has no physiographical expression whatever. Accumulation forms are widely scattered over the whole strip (Fig. 1).

Between the maximum limit of the Saalian and the southern Warta boundary, a quite different picture emerges. This zone (described in Poland as the Odra Stadial, and comparable to the Drenthe unit in Germany) differs from that described above in respect of the much thinner Quaternary deposits and wider areas of drift-free terrain. Investigations to date show that glaciotectonic symptoms occur there only sporadically and merely in the western section. The largest complexes have been described by Lewandowski (1996) in the Silesian Upland, near Racibórz; a smaller system occurs near Otmuchów. Also, glaciotectonics have been reported in the Turoszów brown coal opencast mine (Alexandrowicz, 1971), but this lies outside the Saalian limit. No glaciotectonic phenomena have been reported in the eastern part, i.e. from the upper Warta valley (Starkel, 1982, [the Sketch Geomorphological Map of Poland at 1:500 000]). Neither have there been any reports concerning glaciotectonic phenomena in the marginal zone of the Saalian ice sheet.

Thus the attempt to characterize the Polish Saalian zone (together with the Warta zone) in respect of the intensity of glaciotectonic events reveals a double asymmetry: 1) those oriented east-west or very similar, 2) those oriented north-south which are rich in glaciotectonic traces and a southern zone which is extremely poor in these. The latter shows distinctive differences between the west, in which in morphological and geological traces of glaciotectonic processes are commonplace, and the east, where they are only poorly developed or absent. Of course, it hardly needs to be said here, that this is a generalisation which may simply reflect the prevalent altitudes of those researchers working in these areas. Those who are not looking for evidence of glaciotectonic processes are almost certainly not likely to find any i.e. an absence of reports does not necessary imply an absence of such phenomena.

In order to avoid such generalisations, it must be emphasised that differences may result, partly at least, from the very limited interest in the study of glaciotectonic processes in the investigated areas. Indeed, differences exist, not only in publications (where the main research problem depends on the author's option), but also on maps (such as the Geological Map of Poland at 1:200 000 and the Detailed Geological Map of Poland at 1:50 000). Both these maps and the Geomorphological Map of Poland have provided a great deal of data. Thus the spatial irregularity of glaciotectonic events is a geological and geomorphological fact. The author has tried to show this on the map (Fig. 1), objectively as far as possible.

The main glaciotectonic zone in Poland relative to the background of glaciotectonic research elsewhere in Europe

The glaciotectonic zone in Poland, as defined above, is not just a regional phenomenon but is merely a small part of a zone which extends right across Europe. This zone is particularly well documented in Western Europe. In Poland, as in other areas, glaciotectonic structures are best developed at the margin of the Warta Stadial (Fig. 2), where the distinctive differences between the western and eastern parts are revealed. The western portion extends without break from the neck of the Jutland Peninsula, through the Hamburg and Magdeburg areas; it enters Poland to the west of Głogów, where it changes direction from NW-SE to W-E. In Poland the zone is represented by the Dalków Hills, the Twardogóra Hills and, in the E, the Ostrzeszów Hills. Eastward from here, the zone is discontinuous; glaciotectonic complexes occur sporadically, e.g.: the Malanów Ridge and the marginal zone of the Łódź Plateau. It is emphasised that the occurrence of glaciotectonic phenomena coincides closely with the marginal zone of the Wartian Glacier where landforms are greatly subdued – neither thrust ridges nor the accumulation forms which are scattered over the whole Wartian area are prominent (Fig. 1). Kame hillocks and plateaux form the principal positive features in the landscape.

Terraces are commonplace, which indicates a regional deglaciation. There is no direct, clear evidence for a transgression by the ice sheet. Such isolated structures as have been documented are fossil; thus they have no morphological expression. The Wartian marginal zone in Belarus contains thrust ridges near Baranowicze and Minsk (Komarovsky, 1995).

The differences between the western and eastern part of the Wartian marginal zone are clear-cut and the

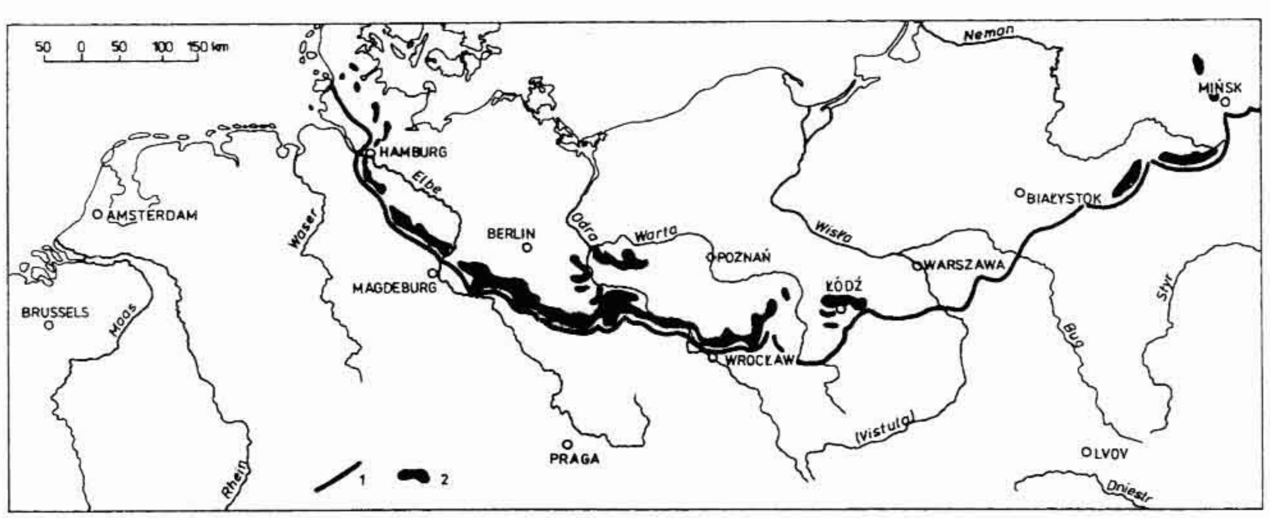

Fig. 2. Distribution of the largest glaciotectonic complexes along the limit of the Wartian ice sheet in Europe.
1 – the maximum extent line of the Wartian ice sheet, generalised; 2 – the largest geologic and morphologic complexes of glaciotectonic thrusts.

borderland between them occurs in Middle Poland. Thus the proposed division into "glaciotectonic" and "non-glaciotectonic" Poland along a N-S axis seems to be of wider European significance. However, before such an assumption is generally adopted, it is necessary to obtain more information about the nature of the Wartian zone in Eastern Europe.

The relationships between geological structure and geomorphic features in glaciotectonic areas

Geological and geomorphological evidence of glaciotectonics are not always coincident. There are numerous examples where huge thrusts correspond with equally large landforms. By contrast, many large structures are known which are not reflected in the morphology at all. Indeed, it is possible for glaciotectonic disturbances to produce a negative landform. The Wartian zone in Poland provides many examples of the different possible relationships of structure and landform.

Ridge forms with glaciotectonic structure

The Trzebnica Hills provide an excellent example of a glaciotectonic structure which is distinctly reflected in the morphology. These form a continuous ridge which rises to 255 m near Trzebnica. At their southern end, their base is about 140 m a.s.l. whereas, at the northern end it is slightly higher. The sharp outline of the ridge is due to its massive form; its height ranges from 110 to 140 m. The glaciotectonic origin of the ridge is now beyond doubt. The Tertiary sediments involved in the disturbances, as have been proved in boreholes, are also exposed in the brick-field in Trzebnica. The illustration of this morphologic form and the reconstruction of its geological structure are shown on the Detailed Geological Map of Poland, Oborniki Śląskie and Trzebnica sheets (Gizler, 1985; Winnicki, 1986).

The Malanów Ridge is a similar example, though at a smaller scale. This is a continuous form, which is north-south oriented and about 20 km long. It has a maximum width of 7–8 km; it attains absolute altitudes of 191 m a.s.l. and reaches a relative height of 40–60 m. It is formed almost exclusively from a till, although, occasionally, glacial sandy-gravel deposits are also involved in the deformations (Fig. 3).

The Malanów Ridge has been the subject of much interest over a long time. Krygowski (1961a, 1972) regarded the Malanów Ridge as "old-Pleistocene remains (generally of glaciotectonic structure inside)". Geomorphological and geological mapping (the Sketch Geological Map of Poland at 1:300 000) of this area by geomorphologists from Łódź (including the author of this paper) has confirmed its glaciotectonic structure. The Malanów Ridge inspired Dylik (1952) to formulate his concept of relief development under periglacial conditions. In an attempt to reconstruct the palaeogeography of the Younger Pleistocene of Middle Poland (Klatkowa, 1972a) the author made a rigid distinction between the glaciotectonic ridge and the meridional development of small kame hillocks. The Kotwasice sheet (586) of the Detailed Geological Map of Poland at a 1:50 000 scale and the legend were published by Mańkowska (1987) and Mańkowska, Gogołek (1988). These authors agreed that the Ridge was produced by ice thrusting, but they also considered the possibility of a superimposion of the Wartian processes and the possible effects of complex earlier events of a tectonic-erosional-glaciotectonic character (Mańkowska, Gogołek, 1988).

Clearly, from the foregoing, the Malanów Ridge shows at least some evidence of glaciotectonic action in its construction, but the succession of events is still controversial. The following problems are still unresolved: 1) is it a product of the maximum ice sheet transgression or one of its recession phases (Krygowski, 1972); 2) does it result from one ice sheet pressure (if so, which one?) or from repeated similar conditions, and if the latter is the case, then 3) what elements brought about such repetition here; 4) is it possible, on the basis of existing data, to assume that the maximum extent of the Vistulian ice sheet (the Leszno Phase) coincided with the Malanów Ridge? These problems need to be considered more fully, unfortunately, lack of space does not permit further consideration here.

There are many reports of ridges which have a glaciotectonic structure elsewhere. The whole western part of the Wartian marginal zone exhibits a similar structure and morphology (e.g. the Dalków Hills – Krainski, 1977, 1983, 1989; the Ostrzeszów Hills – Rotnicki, 1960, 1966, 1967, 1976b; Połtowicz, 1961).

Glaciotectonic associations: ridge – depression

This geological-morphological association is easily delected in the relief, viz. trench-like, originally closed depressions and associated elongated hills. Elements of the surface configuration relate in general to particular features of the geological structure, i.e. ridges often contain thrusted deposits derived from paired depressions. Since such associations are widely distributed, a specific term to describe the phenomenon has been adopted in the glaciotectonic literature. In the English literature, they are termed a "hill-hole pair" (Aber, Croot, Fenton, 1989), whereas, in the Russian – the term "glaciotectonopair" (Lewkow, 1980) is used. The latter has been adopted by Jaroszewski (1991). Ruszczyńska-Szenajch (1979, 1983) has used the term "glaciotectonic depression" and has related this to the origin of compressed end-moraines. However, because the authors may vary in opinions concerning particular

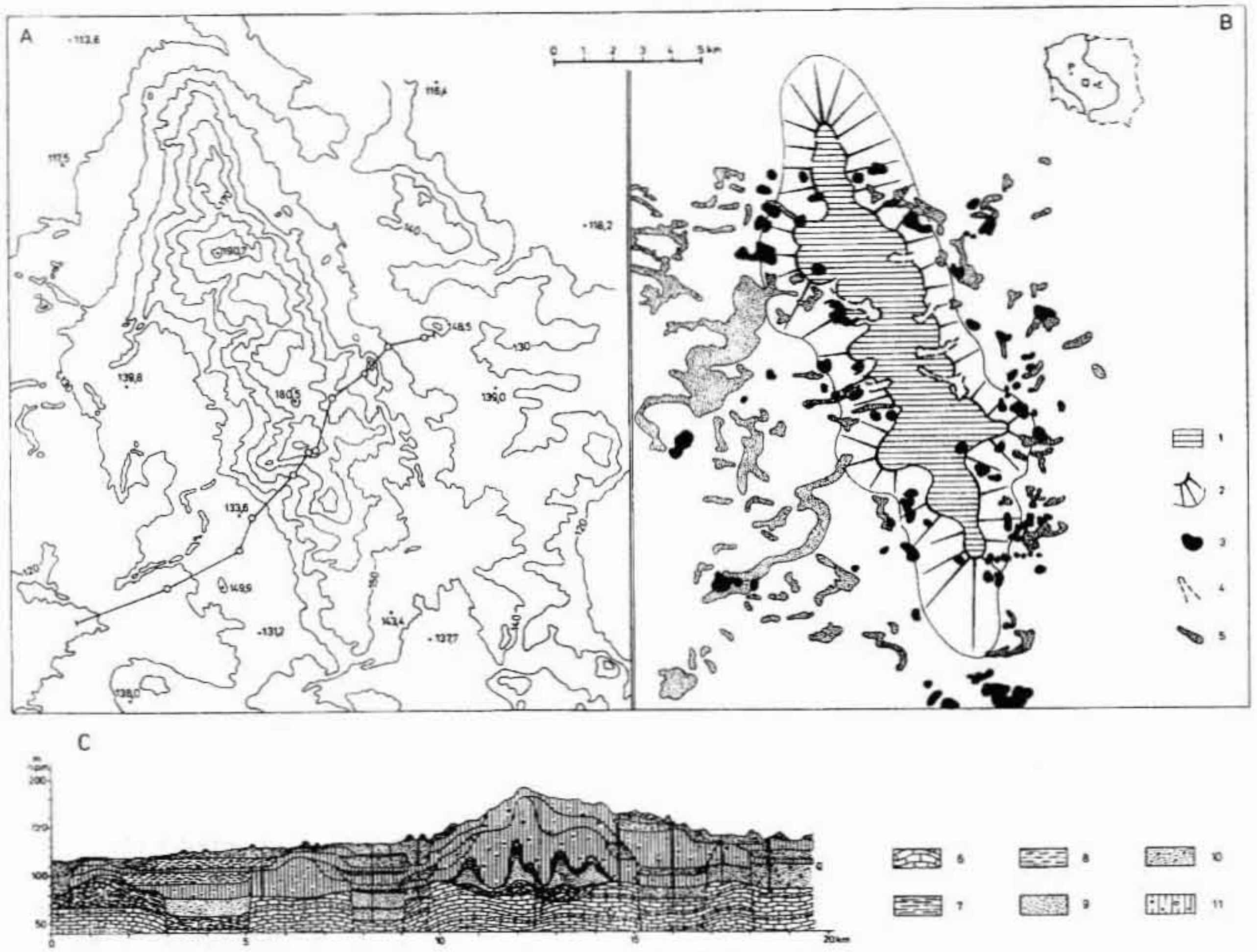

Fig. 3. The Malanów Ridge – an example of a continuous ridge form with glaciotectonic structure.
A – hypsometric sketch and the line of geological cross-section;
B – morphologic sketch: 1 – ridge surface made up largely of till; 2 – scarps and distinct slopes; 3 – kame hillocks at the foot and on the slopes; 4 – small denudational valleys; 5 – major dune complexes;
C – geological cross-section along the A-B line (after Mańkowska, 1987, generalised): 6 – limestones, marls and opokas; 7 – clays; 8 – silts; 9 – sands; 10 – glaciofluvial sands with gravels; 11 – tills.

processes or conditions (Jaroszewski, 1991), similarities in terminology do not necessarily indicate a close genetic relationship between the complexes.

Glaciotectonic-morphological associations have been recognized near Łódź, Middle Poland (Klatkowa, 1996). Two cases are shown in hypsometric sketches, schemes of the geological structures and photographs of the studied structures (Figs. 4, 5, 6, 7, 8).

Isolated kames with compressed cores

Glaciotectonic structures are quite often met in forms which, in general terms, would normally be considered to be forms typical of the accumulation province – i.e. those laid down by glaciofluvial melt water. Among these are kames (occasionally esker crests) where the contorted core consists of susceptible material (in the context of Middle Poland, this is mainly till or, less frequently, clay or lacustrine silt). In the areas where the subsurface of a rather thin Pleistocene cover contains variegated Pliocene clays, it is possible for such material to be ejected as diapirs, and to be injected into sandy and gravelly glaciofluvial sediments, usually as they were being deposited. Where contortions are visible, the glaciotectonic origin of structures is not normally in doubt. If susceptible material is not exposed, its existence may be deduced from circumstantial evidence, such as: 1) the limited range of layer strike within the overlying glaciofluvial deposits, and 2) the occurrence of a set of complementary faults within the deposits around the compressed core.

Examples of such structures and concomitant land forms have been discussed more fully in an earlier work by the author (Klatkowa, 1993). Here, we are concerned only with a brief description of the distortion of Pleistocene clay and of till swellings within glaciofluvial series (Figs. 9, 10). Recognized cases raise no doubt as to the efficacy of the glaciotectonic agent in producing such structures. Similar deformations may develop when the ice cover is thick as well as during an advanced deglaciation phase and involving only relatively small and thin ice blocks. In the latter case, it is the

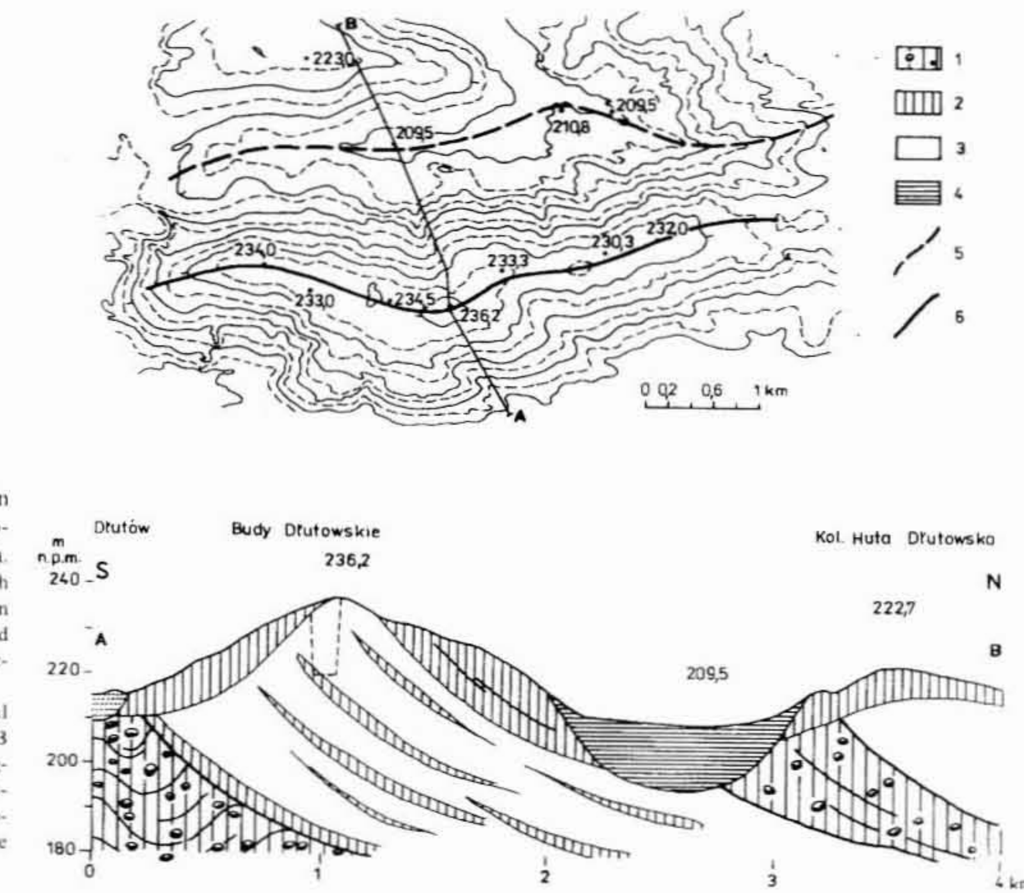

Fig. 4. Budy Dłutowskie. An example of glaciotectono-pair: depression-elevation.
A – hypsometric sketch with the axes of depression (broken line) and elevation (solid line), and the A-B cross-section line;
B – simplified geological cross-section along the A-B line: 1 – older till; 2 – younger till, glaciotectonically displaced; 3 – glaciofluvial deposits; 4 – glaciolacustrine sandy-silty deposits.

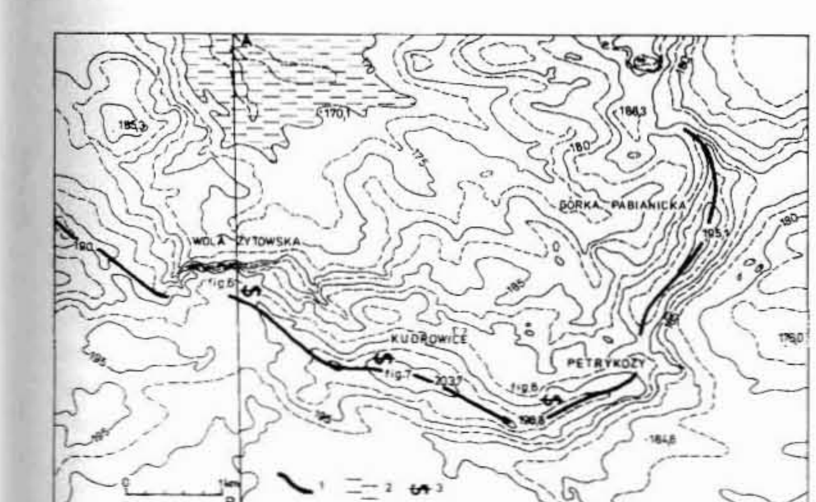

Fig. 5. The Kudrowice-Petrykozy Ridge near Łódź. An example of a glaciotectonic pair.
1 – morphologic axis of the ridge; 2 – the lowermost portion of the depression; 3 – glaciotectonic structures available for observation at the exposures, the A-B line designates a cross-section illustrating by the reconstruction in Fig. 6; sites shown in Photos 7, 8 marked similarly.

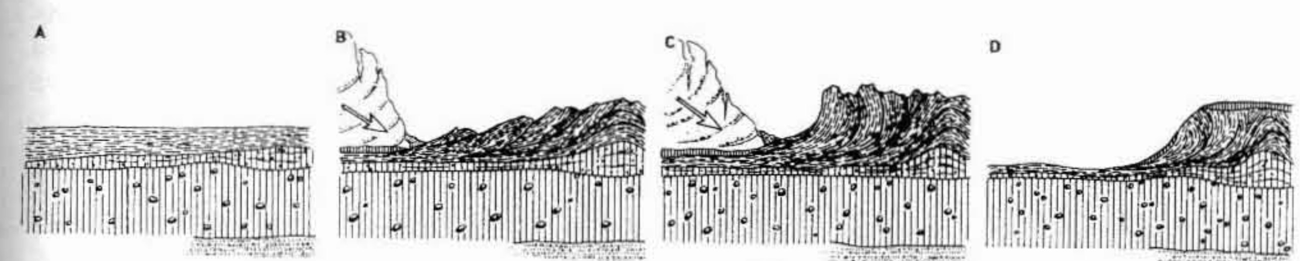

Fig. 6. Reconstruction of the formation of a glaciotectonic ridge: A-D sequence of the formation of depression-elevation association.

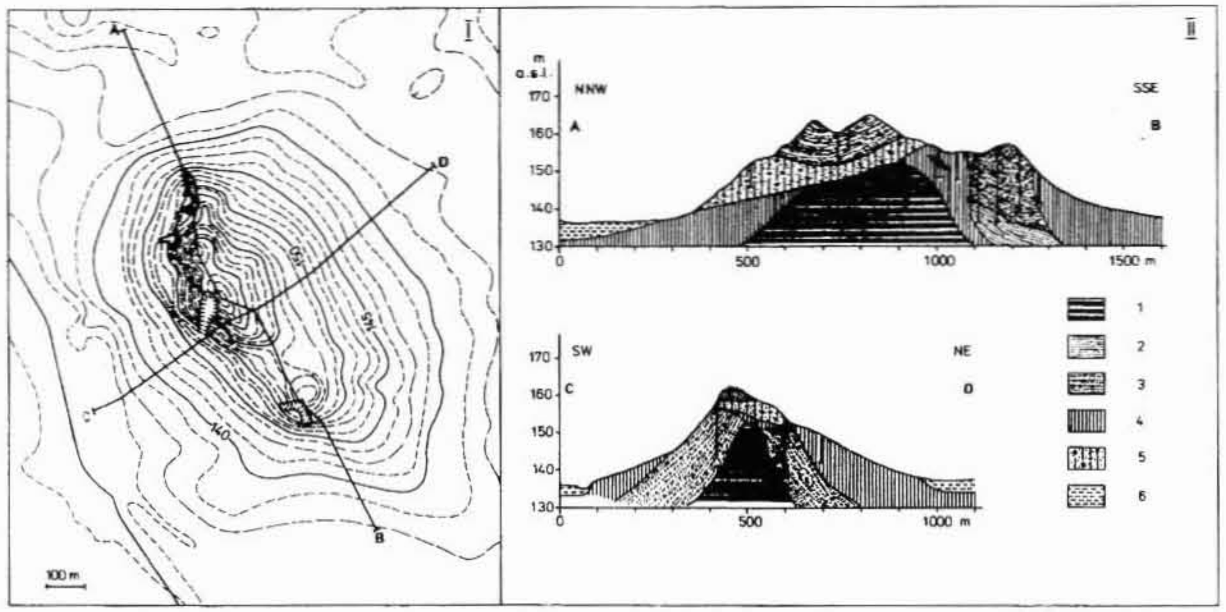

Fig. 9. Góra. Kame hillock with a squeezed core of Neogene clays (after Klatkowa, 1993).
I – sketch of the hillock: A-B and C-D – the lines of geological cross-sections;
II – geological cross-sections, lithologic symbols: 1 – Neogene clays; 2 – fine sands; 3 – glaciofluvial sands and gravels; 4 – till; 5 – till sands with gravel admixture; 6 – terrace sands.

presence of variable vertical pressure of the blocks involved which is critical. As the blocks are separated by crevasses, the author proposes the use of the term "static-crevasse" (Klatkowa, 1993).

Low-relief interfluve areas of glaciotectonic structure

In the three glaciotectonic-morphologic types discussed so far, the relief follows the structural features, which can therefore be used to indicate the existence of disturbances and their spacing. A further type does not show such concordance. Strongly disturbed and strongly thrust deposits may form undulating or flat interfluves or terrains characterized by low, extensive and rounded elevations with gentle slopes. Thus the processes can only be identified from exposures or, occasionally, from the form of the local water table where it is discontinuous or perched.

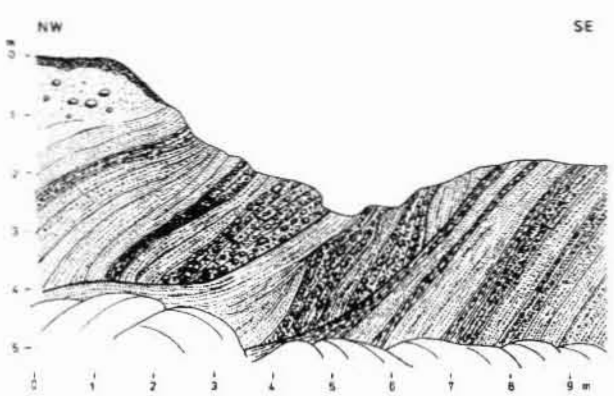

Fig. 11. Parzęczew. Monoclinal gravelly and sandy layers resulting from the lateral push.

This type of relief and structure is present, for example, NW of Łódź. On some interfluves, exclusively monoclinal structures were observed with some deviations to WSW-WNW (Klatkowa, 1996). The rather infrequent exposures there do not allow us to state confidently whether this is merely a chance effect. But it well may be that the interlobation zone which resulted from the division of the ice sheet into the Widawka lobe (SW) and the Rawka lobe (NE) has been subject to pressures directed outwards from the axes of both lobes. The weaker and less active SW lobe advanced more slowly (Klatkowa, 1972a); it spread over a wider area, and, irrespective of a translatory motion in the SE direction, acted tangentially on the periphery, thus creating push structures rather than contorted ones (Fig. 11). Such a sequence of events on this lobe advance may help to explain the monoclinal glaciotectonic disturbances over a wider area. A similar orientation of the axes of most such structures, as reconstructed in Fig. 12, illustrate the probable conditions of the ice sheet transgression.

Monoclinal disturbances of the original structure rarely involve a thick series of glacial deposits. It follows from the assumption that, when a shortening in the horizontal plane takes place i.e. when the orientation of the greatest normal stresses (s_1) is roughly horizontal and generally vertical to the axis of the least stresses (s_3), monoclinal folding will take place. Such a pattern may occur at such depth as to involve the ice sheet base, together with deposits frozen to its sole and englacial debris (Jaroszewski, 1991). The insignificant thickness of the resulting deformations in the SW lobe is probably a reflection of the weak dynamic regime and relatively thin ice cover here (Klatkowa, 1972a).

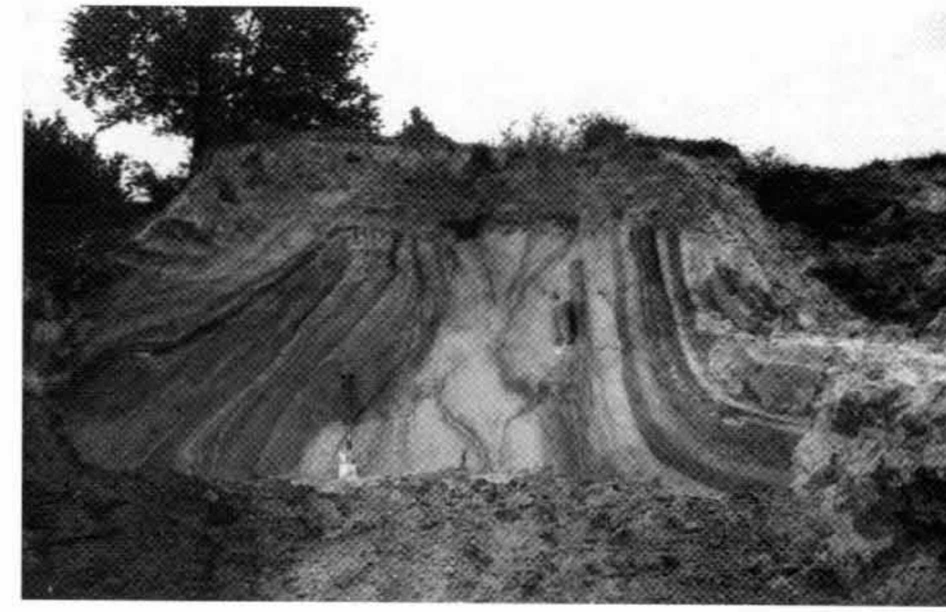

Fig. 7. Kudrowice. Upright fold formed in silts and very fine glaciolacustrine sands, truncated by till (photo by H. Klatkowa).

Fig. 8. Petrykozy. Two recumbent folds composed of silts and very fine glaciolacustrine sands (photo by H. Klatkowa).

Fig. 10. Ostrów. Till diapirs in the centre of the kame hillock, exposed by the exploitation of glaciofluvial sands and gravels (photo by H. Klatkowa).

Fig. 14. Modlna. Glaciotectonically deformed glaciofluvial sands and gravels at the front of the lowest step of the edge zone of the Łódź Plateau (photo by H. Klatkowa).

Fig. 18. Smardzew. The Czarnawka river terrace. Deposits glaciotectonically disturbed by the Wartian ice sheet, covered by Vistulian fluvial sands (photo by H. Klatkowa).

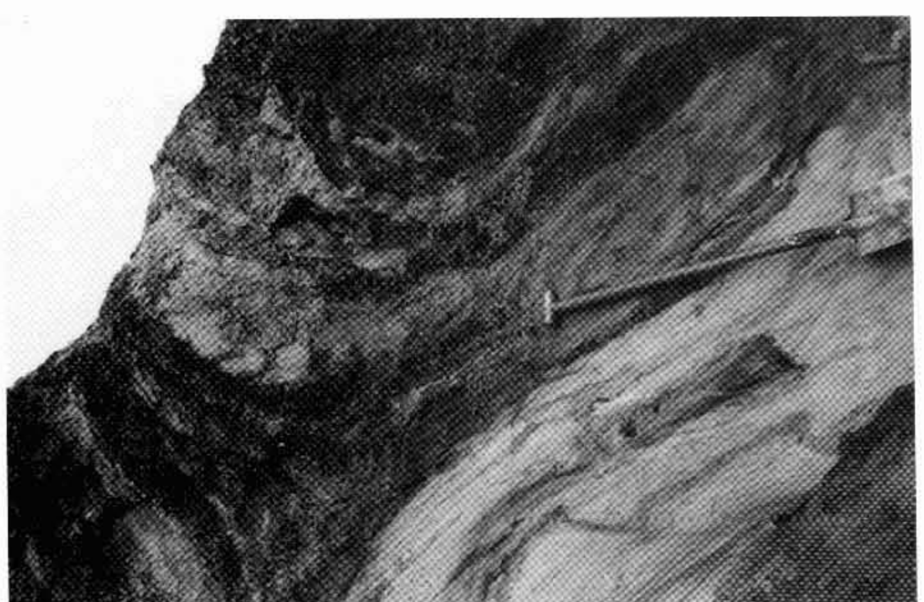

Fig. 19. Rudunki. Flexure folds developed in Pleistocene tills, clays, silts and sands (photo by H. Klatkowa).

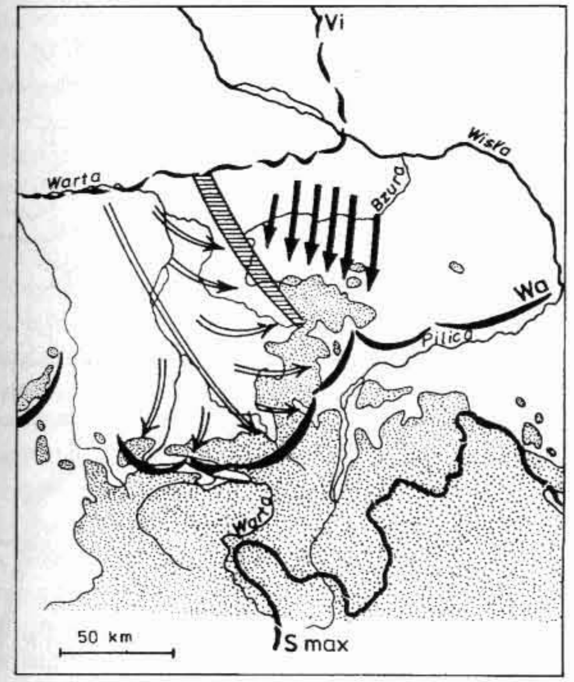

Fig. 12. Different action of the Wartian ice sheet during the transgression of the Łódź region.
– extents of the ice sheets: Vi – Vistulian, Wa – Wartian, S max. – Saalian max.;
– arrows show the direction and the dynamics of the advancing ice sheet:
– black arrows – active ice sheet;
– white arrows – static ice sheet;
– shaded area – the interlobation zone;
– dotted area – the terrain over 200 m a.s.l.

The glaciotectonic style of the edge zone of the Łódź Plateau

The Łódź region, especially its so-called edge zone, deserves to be considered separately. The Łódź Plateau has a maximum altitude of > 250 m a.s.l. along its northern edge. It slopes northwards to the Warszawa-Berlin Pradolina (100 m a.s.l.) with four breaks characterized by relatively flat surfaces and distinctively inclined forefronts (Klatkowa, 1965, 1972a). Along these steps, especially the highest ones, huge glaciotectonic structures, which often reach a considerable height (Figs. 13, 14), are commonplace. The structures form neither ridges nor well pronounced hills, but are involved in the internal structure and the present-day morphology of the macrorelief. Moreover, the glaciotectonic style of the geological structure is not in sympathy with the surface configuration; this problem will be discussed later.

The glaciotectonic deformations in this zone vary greatly in size, complexity and genetic type. Their vertical extent ranges from a few to over a hundred metres. Deeply rooted structures have brought Tertiary or even Mesozoic deposits to the present-day surface outcrop. For example, at the brick-field in Dąbrówka-Strumiany, Tertiary clay and brown coal, originating at a depth of about 100 m, are exposed at the ground surface (Fig. 15). In order to avoid uncertainty about the origin of that structure, it should be noted that a 67 m deep boring failed to reach the bottom of the brown coal series: thus it appears not to be a Tertiary raft surrounded by Quaternary deposits (Klatkowa, 1993; Fig. 7). Also, at numerous exposures in Rudunki near Zgierz (about 12 km to the north of Łódź), Tertiary clays and, occasionally, brecciated Cretaceous marls are visible. Therefore, in view of the large thickness of Quaternary deposits locally (almost 100 m) it seems reasonable to assume a considerable amplitude for the deformations. Further, in the edge zone of the Łódź Plateau, there are other localities where the elevated position of the Neogene surface must have resulted from deep compression.

Apart from the deformations of great vertical extent, shallow surface disturbances ranging from a few to several metres are also known. They differ in several respects, including their mode of origin. Essentially, their style of deformation is best explained by the action of relatively small scale, near-surface thrusting.

A comparison of the edge zone of the Łódź Plateau with other areas suggests a relative abundance of glaciotectonic symptoms in the former. Big differences are present in the area between the two adjacent lobes of the Wartian ice sheet: the southwestern (Widawka) lobe and the northeastern (Rawka) lobe. This provides a basis on which to infer that the lobes were subject to different dynamics, controlled, among other factors, by the sub-surface structure (Klatkowa, 1972a).

The tectonic character of the edge zone of the Łódź Plateau also contrasts with other geological and morphological patterns. Here, the Rawka lobe reveals features more typical of glacial accumulation zones. Such forms (e.g. the Domaniewice Hills, the Żelechinek Moraines) bear little resemblance to the edge zone near Łódź. It is, thus, the easternmost zone where a structural-morphological expression of glaciotectonics can easily be observed.

Examples of disharmonic relations: relief-glaciotectonic structure

So far, attention has been given only to cases where the primary properties of the surface configuration have survived, i.e. only those cases where the geomorphologic pattern follows geological structure. Some examples of areas characterised by very well developed glaciotectonic structures are now considered. These are Wartian in age, and are dominated by an erosional-denudational relief, which is Vistulian in age, and developed under non-glacial conditions. These areas form the highest level of the Łódź Plateau, the so called Smardzew Level.

The Smardzew region comprises an upper, N-S section of a small river (the Czarnawka) and a portion of

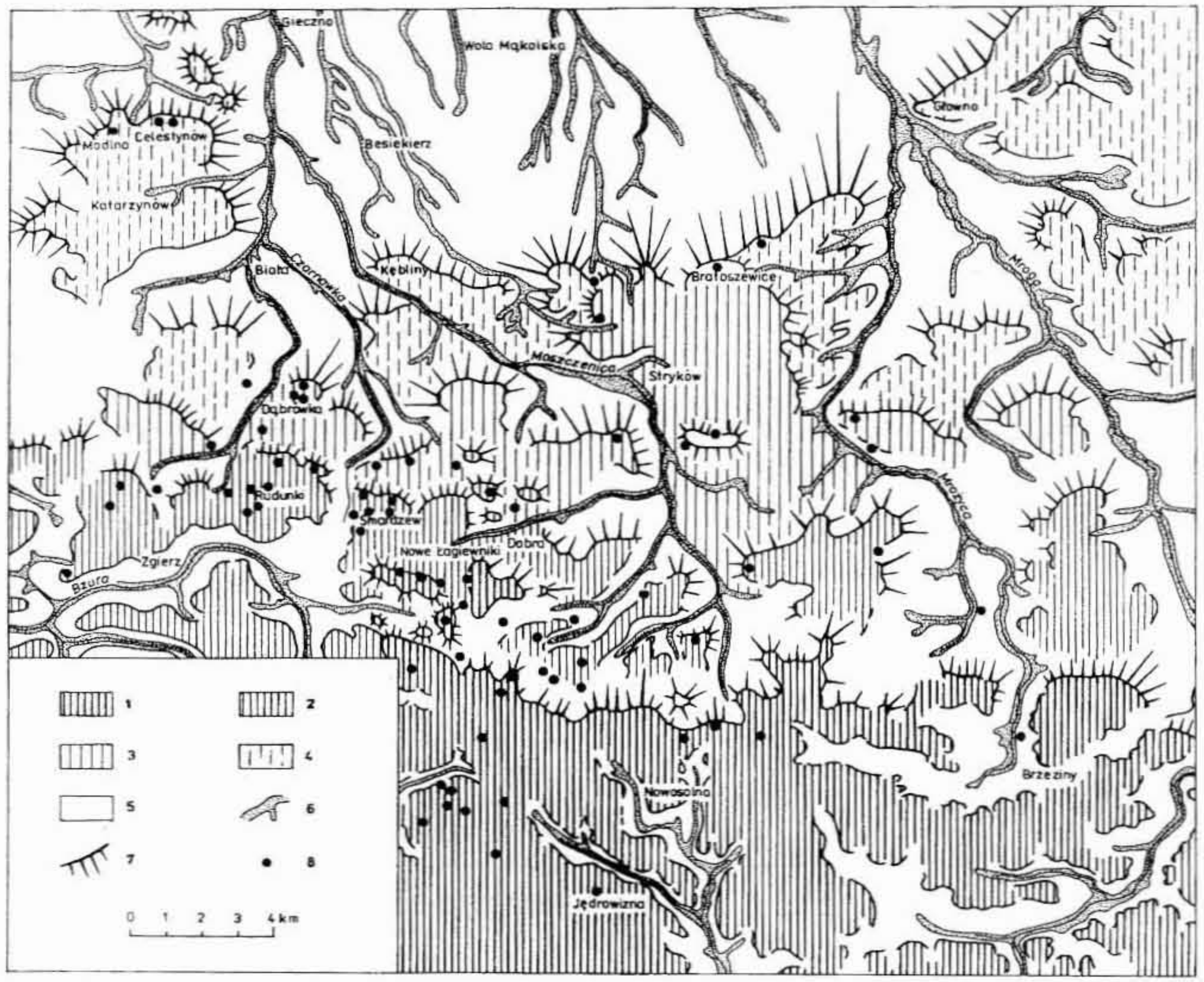

Fig. 13. Sites with glaciotectonic structures against the background of the steps of the edge zone of the Łódź Plateau.
1 – the plateau's surface – altitude to 283 m a.s.l.; 2 – the Smardzew Level – altitude 185–210 m a.s.l.; 3 – the Stryków Level – altitude 165–180 m a.s.l.; 4 – the Katarzynów Level – altitude 140–160 m a.s.l.; 5 – the Wola Mąkolska Plain – altitude from 137 m a.s.l. S to 117 m a.s.l. N; 6 – floors of river valleys; 7 – scarps and distinct slopes of interfluve areas; 8 – localities where glaciotectonic structures were recorded.

the adjacent interfluve. A cross-section of the valley shows a pronounced asymmetry – the W slope is gently inclined and descents gradually, while the E slope is steep and contains a Plenivistulian terrace, 6–8 m high. This, together with the adjoining interfluve, is cut by dry denudational valleys which hang over the present-day valley floor; the others join it by recently cut gullies. The valley floor and the lower part of the dry valley slopes contain deposits of Vistulian denudation processes, up to several metres thick. The upper slope sections are formed from Wartian glacial and glaciofluvial deposits, in which glaciotectonic deformations are common. This is located at the edge of the Smardzew Level and its steep front which descends towards the Stryków Level.

The typical periglacial features of the dry valleys and the Plenivistulian terrace of the Czarnawka valley have evolved on a postglaciotectonic base; its presence may be observed in the internal structure of the river terrace, in the floors of denudational valleys and in the spurs which separate them. The Smardzew situation is a classic example of a complete discordance between structure and morphology (Figs. 16, 17).

A similar situation has been observed and documented in detail elsewhere, e.g. near Zgierz, several kilometres north of Łódź. Here also, the zone adjacent to the front of the highest edge step reveals features of denudational and periglacial relief which developed on a strongly disturbed postglaciotectonic surface (Fig. 18). The deformation structures forming this surface reach the Tertiary and, occasionally, Mesozoic basement (Fig. 19).

There are also some localities where deformations are revealed as fossil forms. Not only are the deformations covered with deposits which are different in age and provenance, but also an uneven postglaciotectonic surface has been lowered (Fig. 20).

Therefore, the cases discussed in this section include both glaciotectonically complex structures which are accompanied by an independent present-day morphology and situations where "relief inversion" has taken place. The latter are forms which, unlike those discussed earlier, show pronounced discordance between relief and structure.

The main hypotheses about the origin of the structures and their controlling agencies

Not surprisingly, as more investigators deal with different glaciotectonic structures, an increasing number of hypotheses concerning their origin are formulated. However, no single hypothesis seems to apply in every case. To date, the best attempt to rationalise the different proposals is that of Jaroszewski (1991).

There is much support for the various hypotheses concerned with frontal dynamics, as first described by Zwierzycki (1949) and later variants by Bartkowski (1968), Aber (1982) and others. However, it must be remembered that the forces involved in frontal dynamics cannot extend to large depths; moreover, with such a mechanism, it is impossible for multiple structural series to be preserved and for so-called nappe duplexes to form (Jaroszewski, 1991). The bulldozer effect of pushing is too weak to produce such effects. However, it seems that some relatively shallow deformations of monoclinal character may develop in this manner. The author believes that this mechanism might explain the disturbances of low relief on the interfluve to the north-west of Łódź (vide section "Low-relief interfluve areas...", p. 26).

The concept of frontal statics, according to which large glaciotectonic deformations may result from ice

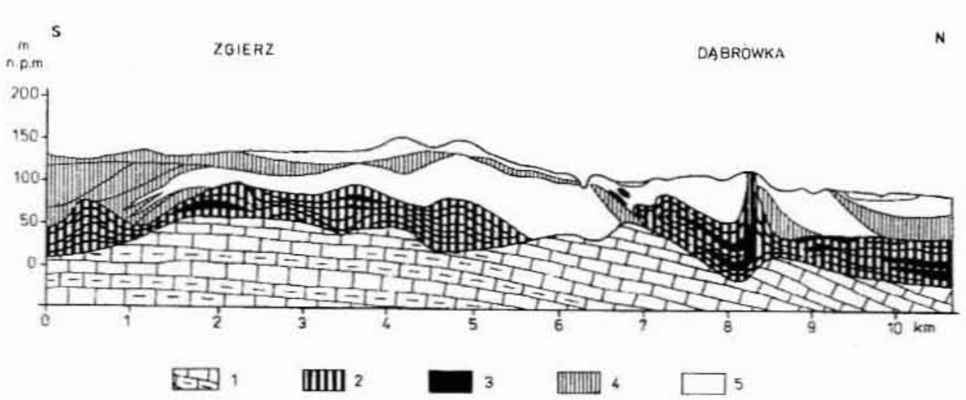

Fig. 15. Dąbrówka-Strumiany. Geological cross-section illustrating Tertiary deposits extruded at the surface.
1 – Cretaceous marls and opokas; 2 – Tertiary deposits; 3 – Tertiary brown coals; 4 – Pleistocene tills; 5 – Quaternary sandy deposits.

Fig. 16. Smardzew. Tertiary clay, squeezed up to the present-day surface, deformed Pleistocene deposits.
Glaciotectonically disturbed zone:
1 – Tertiary clay; 2 – Pleistocene sands.
Non-disturbed Vistulian deposits: 3 – gravel and pebbles; 4 – poorly sorted sand; 5 – fine sand; 6 – present-day soil.

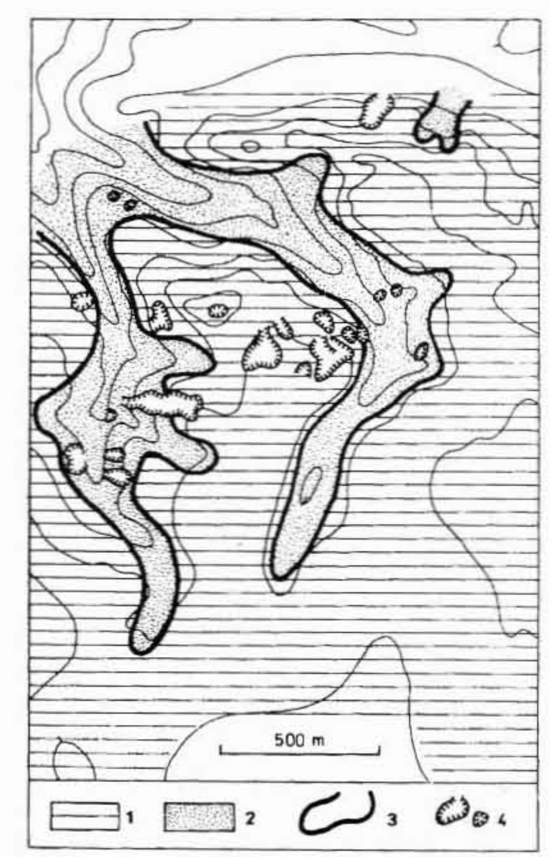

Fig. 17. Rudunki near Łódź. The area of intense glaciotectonic deformations and classic periglacial relief developed on them.
1 – flat portions of interfluve areas with glaciotectonic disturbances on the present-day surface; 2 – occurrence of glaciotectonic structures beneath a thin cover of Vistulian extraglacial deposits; 3 – outlines of denudational valleys and dells; 4 – major outcrops with deformations exposed.

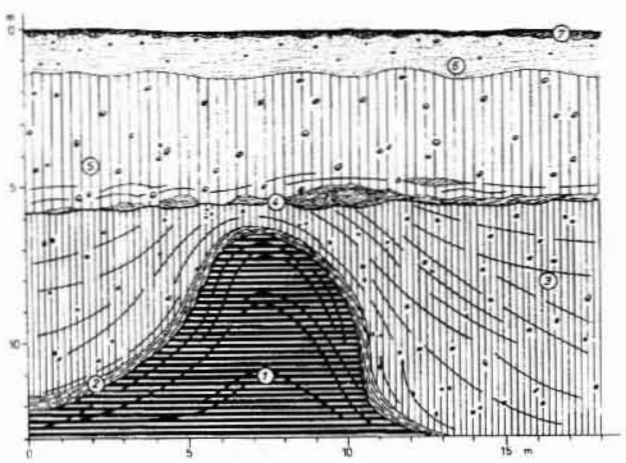

Fig. 20. Adamów. Diapiric extrusion of Tertiary clay and deformed older till, sheared with younger (Wartian) till.

loading (whereby the zone of intense disturbances occurs in the frontal strip and also just at the ice sheet front) has also received widespread support. In the frontal statics theory proposed by Rotnicki (1974), the mechanism is explained by slip surfaces beneath the ice sheet front. Ruszczyńska-Szenajch (1976, 1979, 1985) has suggested a similar mechanism involving the existence of glaciotectonic depressions and compressed end-moraines in their forelands. Earlier, the adjacent occurrence of convex and concave forms was reported by Krygowski (1961b) and Żynda (1967). The depression-elevation association has been also recognised elsewhere (Lewkow, 1980; Aber, Croot, Fenton, 1989). On the basis of a knowledge of frontal statics, Jaroszewski (1991) considered that formation of regular fold and slice structures by viscoplastic compression from the ice sheet front could not have taken place nor was it a multiple structure.

Although, in most cases, it is hard to apply this model, certain structures recognised during the direct field observations by the author have been regarded as being depression/elevation associations (for example, Budy Dłutowskie and Petrykozy).

The provenance of large deformations has proved to be a particularly contentious issue. The subglacial origin of glaciotectonic disturbances has been reported quite often in the Polish literature (among others, Dylik, 1961a, b; Krygowski, 1962a, b, 1963; Rotnicki, 1974). For example Bartkowski (1968) enthusiastically supported this notion, while Brodzikowski (1980, 1982, 1987) was firmly of the belief that large structures (>100 m) could have been produced exclusively beneath the ice sheet, especially in the zone of a rapid increase of gradients associated with a sudden increase of ice thickness, far from the ice sheet front. While most of the subglacial theories have received wide support, the hypothesis about large deformations in the zone of excess stress gradients has proved to be very controversial (Jaroszewski, 1991).

The role of morphologic palaeoscarps in the bedrock of an advancing ice sheet, which supposedly favour disturbances (or, at least, encourage them) has been accepted for a long time. Their importance has been widely confirmed (e.g. cliffs in Denmark) and described by many authors (Rutten, 1960; Viete, 1961). In Poland, likewise, the history of some glaciotectonic areas is perhaps best explained by the existence of morphologic obstacles (Dyjor, 1974, 1975; Brykczyński, 1982; Ber, 1987). This may apply to the Łódź region, where glaciotectonic disturbances were considered to result from transverse barriers in the Mesozoic bedrock (Klatkowa, 1972a). The role of such obstacles seems to be unquestionable. There are, however, well recognized areas with intense glaciotectonics, where it is clear that such features are absent; therefore, an alternative interpretation is needed in such cases.

The concept of valley glaciotectonics, introduced in Poland by Krygowski (1961a, 1962a, b, 1963, 1964, 1965, 1975), corresponds with some of Rutten's (1960) suggestions; it has been met with general approval. This approach emphasises the importance of extensive valley zones, filled with strongly saturated deposits and located across the advancing ice sheet. Also, the role of permafrost as the brittle layer seems to be important, in respect that the rocks so affected become broken by horizontal or tangential pressure into blocks which, afterwards, are thrust at the distal (in relation to the ice sheet front) scarp of a valley depression (note however that observations in arctic areas of Greenland have cast doubt about the brittleness of rocks under periglacial conditions; vide Mackay, 1971; Jahn, 1972). The hypothesis of valley glaciotectonics emphasises how pressure of water trapped beneath permafrost or/and advancing ice sheet might affect the development of plastic structures; the latter, while being produced deeper, eject rigid blocks upwards and can, as a result of the equalising process, generate the layered pattern of two superimposed types of quite different structures.

There can be no confusion from a purely mechanical point of view, about valley glaciotectonics, whereas the role of water, as elaborated by Krygowski, as the important structure-forming factor was eventually assumed to be a principal hydroglaciotectonic factor (Michalski, 1979, 1983). Certainly, it is agreed, it cannot apply in each and every case (Jaroszewski, 1991). Indeed, can there ever be any universal hypothesis in the study of glaciotectonics?

At the end of the 1970's, a new hypothesis was formulated in Poland, regarding the range of conditions involved (Michalski, 1979, 1983). Undoubtedly, this was stimulated by the work by Mathews and Mackay (1960) which emphasised the essential role of high pore-water pressure beneath permafrost in the glaciotectonic mechanism; subsequent works have widely

accepted this notion (Bluemle, Clayton, 1984; Wateren, 1985; Aber, Croot, Fenton, 1989).

According to Michalski's hypothesis, water is not only the fundamental control in making deposits more plastic but is also considered to be the single structure-forming factor. The author has suggested that, if in the forefield of the advancing ice sheet, permafrost was present, the water enclosed in it, as well as in the non-frozen deposits beneath, controlled the formation of the huge deformations in the Polish Lowland. Among the various factors considered, high water-pore pressures on freezing (which increased with the anisotropy of medium) were of the greatest importance. Migration of this wave could have caused, in addition to the advancing ice sheet, hydraulic rupture even far from the ice sheet front, and finally, could have been responsible for the formation of multiple structures.

Jaroszewski (1991) reviewed the various hypotheses concerning the origin of glaciotectonic deformations, and formulated an outline of his own concept, terming this "static-kinematic". The concept seems rather complex. On the one hand it covers some important elements of previously accepted concepts but, on the other, it eliminates many conditions and agents supposedly essential for glaciotectonic processes to take place. The author, aware of such simplifications, explained that this was in order to stress the structural-tectonic aspect, which very often previously had been ignored. It is, therefore, a somewhat narrow hypothesis.

Thus, what does the hypothesis involve? The general assumption is that the static factor plays a crucial role in the deformation processes (Dadlez, Jaroszewski, 1994, p. 409). Nevertheless: "Static load and motion are critical, that is why the concept has been termed static-kinematic" (Dadlez, Jaroszewski, 1994, p. 418). These seemingly mutually exclusive expressions are the essence of the concept which states that the basic control for the formation of particular structures in particular places is static load. However, static load can operate by an ice sheet advance, and simultaneously, by migration of the wave of high pore-water pressures and zones of cylindrical shearing, locally enhanced by bedding anisotropy. In other words, an ice sheet advance controls multiple structure-forming action and marks both potential zones of deep diapirism and shallower glaciotectonic depressions (Jaroszewski, 1991, Fig. 19).

Jaroszewski has tried to formulate a concept, as universal as possible, which applies in the largest number of cases. Nevertheless, it is still theoretical. It emphasises the structural-tectonic agent, thus the mechanism of the phenomenon as well as its result. Palaeogeographical conditions, which may significantly modify the consequences of these processes, have clearly not been considered fully. It is obvious that palaeogeographical reconstructions are difficult to ascertain and are sometimes purely hypothetical; yet, plainly, they cannot be omitted from overall assessments.

Yet another opinion was presented by Brodzikowski (1987), who made an attempt to foresee as many situations as possible. In consequence, he created sophisticated models with many variables. However, some of the combinations, being based on purely theoretical assumptions, are not always present in the real world.

Concluding remarks

A growth of interest in the study of glaciotectonics encourages students to make attempts to formulate universal genetic concepts. However, these are, of course, only theoretical concepts, and generally, are concerned with the process separated from the whole. The hypotheses presented above show that it is extremely difficult to draw general and clear inferences. Major problems lie in the recognition of the variety of possible mechanisms and environmental conditions in the past. Even if one could formulate a universal theory applicable to all known mechanisms, many questions would remain. These are as follows:

1) Why, assuming an identical mechanism, are there such regional differences in the spacing of known structural-morphologic complexes, and their size and continuity?

Why, for example, does the same marginal zone of the Wartian ice sheet, in the area north of Łódź, consist of deeply rooted glaciotectonic structures, whereas, S of the town, such structures do not exist or are insignificant in size and vertical extent?

2) Why, supposing only palaeoenvironmental conditions (very convincing in many cases) were crucial, do not theories of such as valley or valley-side glaciotectonics find support in respect of cases where valley zones or clear morphologic scarps exist at the bedrock; further, why do similar types of deformations occur both in the presence of scarps and in their absence?

3) Why do the huge glaciotectonic structures in the western part of Poland, which are very well pronounced in the morphology, disappear (or, rather, why are they invisible in the relief)?

4) Why do the largest structural-morphologic complexes, such as the Ostrzeszów Hills, the Trzebnica Hills, the Dalków Hills in Poland, and the so called Fläming moraines which extend westward as far as Denmark and the Netherlands evidently accompany the marginal zone of the Warta Stadial, whereas similar features are very difficult to investigate along the Odra/Drenthe limit?

5) Is it possible that a quite different pattern of deglaciation took place in the western and eastern parts of Europe – the result of climatic differences, and for

postglacial vertical compensatory movements to control this regional variation of glaciotectonic expression?

There are more such questions. Only one thing is certain; the root cause is not only the mechanism but also, to a significant degree, the environmental conditions. Here the author of the present work tends to favour Brodzikowski's (1987) main conclusion which states that the varying natural conditions have modified the course of glaciotectonic processes to a much larger extent than has generally been recognised hitherto.

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