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Corresponding Author:	David R Bridgland Durham University Durham, UNITED KINGDOM
First Author:	David R Bridgland
Order of Authors:	David R Bridgland
	Dariusz Krzyszkowski
	Peter Allen
	Rob Westaway
	Lucyna Wachecka-Kotkowska
	Jerzy Czerwonka
Abstract:	Detailed study of subsurface deposits in the Polish Sudeten Foreland, particularly with reference to provenance data, has revealed that an extensive pre-glacial drainage system developed there in the Pliocene - Early Pleistocene, with both similarities and differences in comparison with the present-day Odra (Oder) system. This foreland is at the northern edge of an intensely deformed upland, metamorphosed during the Variscan orogeny, with faulted horsts and grabens reactivated in the Late Cenozoic. The main arm of pre-glacial drainage of this area, at least until the early Middle Pleistocene, was the palaeo-Nysa Kłodzka, precursor of the Odra left-bank tributary of that name. Significant pre-glacial evolution of this drainage system can be demonstrated, including incision into the landscape, prior to its disruption by glaciation in the Elsterian (Sanian) and again in the early Saalian (Odranian), which resulted in burial of the pre-glacial fluvial archives by glacial and fluvio-glacial deposits. No later ice sheets reached the area, in which the modern drainage pattern became established, the rivers incising afresh into the landscape and forming post-Saalian terrace systems. Issues of compatibility of this record with the progressive uplift implicit in the formation of conventional terrace systems are discussed, with particular reference to crustal properties.

Durham University

Department of Geography

Durham University
Science Laboratories
South Road
Durham DH1 3LE, UK
Direct dial: **0191 334 1875**
Fax: **0191 334 1801**

Email: D.R.Bridgland@durham.ac.uk

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Lewis Owen
Editor-in-Chief
Quaternary Research

Dear Lewis

QUA-17-205R1

I am resubmitting the Krzyszkowski *et al.* paper for the FLAG special issue. I have adopted all your suggestions for the text, although making additional minor changes (all marked in green in the version with edits shown). I have also reformatted Table 1 to remove vertical lines. I have retained horizontal lines, which do not seem to be precluded in the instructions to authors, as they help with understanding of this complex table. If that is a problem then perhaps wider spacing would serve a similar purpose. The suggested improvements to the figures have also been made, along with others picked up by co-authors after final scrutiny. I have added the lat/long coordinates to the other two maps in the series. Captions have also been reviewed and enhanced.

Many thanks for your help and advice in connection with this paper.

Yours sincerely

David Bridgland
Professor in Quaternary Environmental Change (Physical Geography)

Drainage evolution in the Polish Sudeten Foreland in the context of European fluvial archives

Dariusz Krzyszkowski[1], David R. Bridgland[2 +], Peter Allen[3], Rob Westaway[4], Lucyna Wachecka-Kotkowska[5], Jerzy A. Czerwonka[6]

[1] Institute of Geography and Regional Development, University of Wrocław, Pl. Uniwersytecki 1, 50-137 Wrocław, Poland. E-mail: dariusz.krzyszkowski@uwr.edu.pl

[2] Department of Geography, Durham University, DH1 3LE, UK. E-mail: d.r.bridgland@durham.ac.uk

[3] 13 Churchgate, Cheshunt, Hertfordshire, EN8 9NB. E-mail: peter.allen6@virgin.net

[4] School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK. E-mail: robert.westaway@gla.ac.uk

[5] Faculty of Geographical Sciences, Department of Geomorphology and Palaeogeography, University of Łódź, 90–139 Łódź, Narutowicza 88, Poland. E-mail: lucyna.wachecka@geo.uni.lodz.pl

[6] Wejherowska 9/2, 54-239 Wrocław, Poland. E-mail: jerzy.czerwonka@gazeta.pl

ABSTRACT:

Detailed study of subsurface deposits in the Polish Sudeten Foreland, particularly with reference to provenance data, has revealed that an extensive pre-glacial drainage system developed there in the Pliocene – Early Pleistocene, with both similarities and differences in comparison with the present-day Odra (Oder) system. This foreland is at the northern edge of an intensely deformed upland, metamorphosed during the Variscan orogeny, with faulted horsts and grabens reactivated in the Late Cenozoic. The main arm of pre-glacial drainage of this area, at least until the early Middle Pleistocene, was the palaeo-Nysa Kłodzka, precursor of the Odra left-bank tributary of that name. Significant pre-glacial evolution of this drainage system can be demonstrated, including incision into the landscape, prior to its disruption by glaciation in the Elsterian (Sanian) and again in the early Saalian (Odranian), which resulted in burial of the pre-glacial fluvial archives by glacial and fluvio-glacial deposits. No later ice sheets reached the area, in which the modern drainage pattern became established, the rivers incising afresh into the landscape and forming post-Saalian terrace systems. Issues of compatibility of this record with the progressive uplift implicit in the formation of conventional terrace systems are discussed, with particular reference to crustal properties, which are shown to have had an important influence on landscape and drainage evolution in the region.

Keywords Pliocene – Early Pleistocene, Ziębice Group, Elsterian glaciation, Odranian (early Saalian) glaciation, palaeodrainage, crustal properties, Polish Sudetes

INTRODUCTION

The Sudeten (Sudety) Mountains, or Sudetes, form a NW–SE-trending range with its western end in Germany and separating SW Poland from the Czech Republic (Czechia). With its highest peak reaching 1603 m, this represents an uplifted block of rocks metamorphosed during the Variscan orogeny, in the late Devonian to early Carboniferous (Don and Zelaźniewicz, 1990). The Variscan involved complex faulting and thrusting, forming horsts and graben-basins, the latter infilled during later tectonically quiescent geological episodes, prior to significant reactivation of these structures in the Neogene–Quaternary (Oberc 1977; Dyjor, 1986, Mignoń, 1997). The foreland region north of these mountains, into which these structures extend, is drained by the Odra (Oder) and several of its left-bank tributaries, the main river flowing NW and then northwards, forming the western boundary of Poland, towards the Baltic (Fig. 1). An earlier, somewhat different drainage pattern in the Sudeten Foreland is evident from the subsurface preservation of buried valley fragments, recognized from boreholes and quarries and now largely buried by glacigenic and later fluvial sediments (Krzyszkowski *et al*., 1998; Michniewicz, 1998; Przybylski *et al*., 1998). It is apparent, therefore, that this drainage system was disrupted by glacial advances of Scandinavian ice from the north and NW (Krzyszkowski, 1996; Krzyszkowski and Ibek, 1996; Michniewicz, 1998; Salamon, 2008; Salamon *et al*., 2013; Fig. 1). The drainage has also been disrupted during the Quaternary by slip on the Sudeten Marginal Fault, the effects of which are readily visible in terms of vertical offset in terrace heights either side of the faultline (e.g., Krzyszkowski *et al*., 1995, 1998, 2000; Krzyszkowski and Bowman, 1997; Krzyszkowski and Biernat, 1998; Krzyszkowski and Stachura, 1998; Migoń et al., 1998; Štěpančíková *et al*., 2008; cf. Novakova, L., 2015). To these glacial and tectonic influences can now be added the effects on Quaternary landscape evolution of a complex history of crustal behaviour, potentially related to the characteristics of the Proterozoic to Palaeozoic crust in the region, as will be discussed in this paper.

The repeated glaciation of this region has been well researched and is documented by the glacigenic deposits that form much of the surface cover, burying the evidence for the aforementioned pre-glacial drainage. The most extensive glaciation was that during the Elsterian, the 'Sanian glaciation' of Polish nomenclature (Marks, 2011). This glaciation, assumed to have occurred during Marine Isotope Stage (MIS) 12 (Krzyszkowski *et al*., 2015), may not have been the first within the study area, as there are well-developed cold-stage minima within the marine oxygen isotope record in the latest Early Pleistocene, in MIS 22, and the early Middle Pleistocene: especially MIS 16, represented by the Don glaciation in the northern Black Sea region (e.g., Turner, 1996; Matoshko *et al*., 2004). No pre-MIS 12 glacigenic deposits have been recognized in the Sudetic marginal region, however, and it is clear that any such glaciation was less extensive than that in the Elsterian. The next most extensive glaciation was the Early Saalian (Odranian), with a limit typically 0–18 km short of the Elsterian (Sanian) ice front (Fig. 1, inset); it is generally attributed to MIS 6 (Marks, 2011). Then followed the Late Saalian glaciation, termed the Middle Polish Complex or Wartanian, and the Weichselian (last) glaciation, the North Polish Complex or the Vistulian. The highest massifs within the Sudetes supported small-scale local Weichselian glaciers (Migoń, 1999; Traczyk, 2009) and such glaciers would also have existed during earlier major glaciations, albeit with little effect on foreland drainage evolution.

The study area coincides with the southern edge of the northern European glaciated zone in which fluvial drainage courses have been strongly influenced by repeated glaciation from the north. That zone, from the western Baltic states through Poland and into Germany, is characterized by broadly west–east aligned valleys that were formed when drainage from the south was deflected towards the Atlantic by ice sheets blocking the lower courses of the various Baltic rivers: the urströmtäler of Germany and pradolina of Poland (e.g., Kozarski, 1988; Marks, 2004). Deflection of drainage by the Elsterian and, later, by the Odranian ice is likely to have influenced the modern position of the river valleys in the lowland north of the Sudetic margin (Krzyszkowski,2001).

The major existing rivers of the Sudeten foreland have well-developed terrace systems that record valley incision since the most recent glaciation of the region, which was during the Odranian, given that the later Late Saalian (Wartanian) and Weichselian (Last Glacial Maximum: LGM) ice sheets failed to reach the mountain front (Fig. 1, inset). Terrace systems are well documented in the two largest Sudetic tributaries of the Odra, the Bystrzyca (Berg, 1909; Krzyszkowski and Biernat, 1998) and the Nysa Kłodzka (Zeuner, 1928; Krzyszkowski *et al*., 1998), as well as in several of the smaller systems. The Quaternary record in this area was thoroughly reviewed in a 1998 special issue of *Geologia Sudetica* (Krzyszkowski, 1998) that was dedicated to Frederick E. Zeuner, who conducted his doctoral research in the region (Zeuner, 1928; see online supplement, Fig. S1), from which he formulated many of his influential views on river-terrace formation (Zeuner, 1945, 1946, 1958, 1959). Since the formation of the Fluvial Archives Group (Add citation of the FLAG editorial paper), debate about the genesis of river terraces has led to a consensus that they are generally a result of uplift, with strong climatic and isostatic influences (e.g., Maddy, 1997; Antoine *et al*., 2000; Bridgland, 2000), the latter seen to vary in relation to crustal type (Westaway *et al*., 2003, 2006, 2009; Bridgland and Westaway, 2008a, b, 2012, 2014; Bridgland *et al*., 2012, 2017).

Landscape evolution in the study area has been complex, with combined influences from glaciation, active faulting and regional crustal processes. The present-day topography is almost entirely the result of post-glacial fluvial erosion, in combination with the various processes that modify valley-side slopes and convey sediment into valley bottoms. 'Post-glacial' in this region means post-Sanian (Elsterian) or post-Odranian (Early Saalian), these being the only Pleistocene glacials during which ice sheets are known to have reached the Sudetic Foreland (see above; Fig. 1, inset). The modern valleys have thus formed since these ice sheets encroached upon the region and their flanks preserve latest Middle Pleistocene–Late Pleistocene river-terrace sequences (Fig. 2). These valleys are incised into a landscape substantially formed in late Middle Pleistocene glacigenic deposits, including diamictons, outwash sands and gravels and lacustrine sediments (Krzyszkowski, 1998, 2013). Evidence from boreholes and quarry exposures has shown that this glacigenic sedimentation was overprinted onto a pre-glacial drainage system, recognizable as a complex pattern of palaeo-valleys now entirely buried beneath the modern land surface. Thus pre-glacial fluvial sediments, which have been attributed to the Pliocene, Lower Pleistocene and lower Middle Pleistocene, are generally buried beneath later Pleistocene deposits and occupy a relatively low position with the landscape, especially in basin situations (see above). This is in apparent conflict with the expectations of standard river-terrace stratigraphy, in which progressively older deposits would be anticipated in positions progressively higher above the modern valley floor. This standard terrace stratigraphy has, however, been shown to occur only in association with certain, albeit widespread and common, crustal types, as will be explained in the next section.

Relation of fluvial archives to crustal type

Westaway *et al*. (2003) made the important observation that classic river terrace staircases do not occur in regions of cold, ancient and densely crystallized crust, particularly the cratons that represent fragments of the earliest continental lithosphere. They attributed this phenomenon to the absence of mobile lower crust in such regions, which they realised was essential to provide a positive-feedback response to erosional isostatic uplift, the same uplift that has caused terrace staircases to form on younger crust, including in areas remote from tectonic influence (see Westaway, 2001, 2002, a, b; Westaway *et al*., 2002, Bridgland and Westaway, 2008a, b, 2014). Subsequent reviews of fluvial archives from different crustal provinces showed distribution patterns that can be related to crustal type; in this the northern Black Sea hinterland, ~1000 km to the ESE of the present research area, represents a valuable case-study region, where the range of dating proxies is exemplary (Bridgland and Westaway, 2008a, b, 2014; Bridgland *et al*., 2017; cf. Matoshko *et al*., 2004; Fig. 3). The significant differences in preservation patterns of fluvial archives between crustal provinces with different characteristics point to important contrasts in landscape evolution, in particular relating to the extent of valley incision (Westaway *et al*., 2003, 2009), as well as the propensity for loss of fluvial archives to erosional processes, which will be greater in areas of dynamic and rapidly uplifting crust. Investigations have led to the concept that these geomorphic effects are controlled by a combination of crustal properties, namely heat flow (see Fig. 4C) and the depth of the base of the felsic crustal layer, since these properties govern the thickness of the plastic crustal layer beneath the brittle upper part of the crust, the base of which corresponds to a temperature of ~350 °C. Thus, if this plastic layer is absent, as in cratonic regions, the crust is extremely stiff and thus ultra-stable. If the mobile layer is thick (thickness >~6 km), it plays a major role in isostatic adjustment, and continuous uplift occurs, at rates that vary in response to rates of erosional forcing and thus to climate change (see Fig. 3). On the other hand, if this layer has an intermediate thickness (~4–6 km), a more complex isostatic response occurs, characterized by alternations of uplift and subsidence, possibly because under such conditions the isostatic responses in the mobile lower crust and in the asthenospheric mantle occur at comparable rates but on different timescales (Westaway and Bridgland, 2014).

Different patterns of fluvial sediment preservation are indeed evident in Poland, and can be interpreted according to the different crustal regions within which they occur (see Fig. 4). The occurrence of buried Pliocene and Lower Pleistocene fluvial deposits, as reported in the present study region, has also been observed in the middle reaches of the Vistula river system (Mojski, 1982; Bridgland and Westaway, 2014; Fig. 5), the catchment of which accounts for 56% of Poland. The Middle Vistula flows across the East European Platform (EEP), a crustal province consolidated during the Early or Middle Proterozoic that is relatively stable in comparison with the younger crust to the west, including that beneath the Sudeten Mountains, which is part of the Variscan province, stretching from SW Poland to western Europe (southern England–Iberia; Fig 4). Further SE within the EEP, patterns of fluvial-archive preservation in which older deposits are buried by younger terraced sequences have again been observed, for example in the valley of the River Don, one of the northern Black Sea rivers, near Voronezh (Matoshko *et al*., 2004; Bridgland and Westaway, 2008a, b, 2014; Fig. 3). The alternation between uplift and subsidence implicit in these preservation patterns has been ascribed to the properties of the crust of the EEP; such crust is highly consolidated and relatively cold, with a lower mobile layer of limited thickness (probably a few kilometres at most), making it very much less dynamic than younger crustal types (Westaway and Bridgland, 2014; Bridgland and Westaway, 2017; cf. Kutas *et al*., 1979).

Further north, the Lower Vistula, in its course towards the Baltic, flows across a region that would appear to have experienced continuous subsidence during the late Middle and Late Pleistocene, as indicated by the stacking of younger Pleistocene deposits, including fluvial, glacial and even marine sediments, above older (cf. Marks, 2004). This could reflect the wider influence of isostatically induced subsidence of the long-standing depocentre of the Baltic basin, where the crust has been progressively depressed beneath the sedimentary load. In marked contrast there are areas in the extreme SE of Poland, in the uppermost Vistula catchment, which display the only extensive staircases of river terraces in the country, similar to those on the younger, more dynamic crust of NW Europe. These terrace staircases (Fig. 5) can be found in the catchments of the Rivers Dunajec (Zuchiewicz, 1992; Olszak, 2011) and San (Starkel, 2003), as well as in other tributaries of the Vistula that drain the continental crust forming the Western Carpathian Mountains (e.g., Zuchiewicz, 2011; Pliszczyńska, 2012). These archives generally occur on crust bordering the Western Carpathians that was affected by the Caledonian orogeny and is thus more dynamic than that of the EEP. (For a description of the Late Cenozoic palaeogeographical evolution of this area see Brud, 2004.) As Bridgland and Westaway (2014) noted, the headwaters of the San are close to those of the Dniester, a river flowing southwards to the Black Sea that has an impressive and well-dated terrace staircase (Matoshko *et al*., 2004; Fig. 3B). Thus, despite their flowing in opposite directions, the San and the Dniester have similar styles of fluvial archive preservation, attributable to the nature of the crust in that region rather than hydrological or base-level influences (cf. Bridgland and Westaway, 2014). Elsewhere in Poland there is localized downwarping as a result of salt diapirism, particularly at Bełchatów, near Łódź (Krzyszkowski, 1995; Krzyszkowski and Szuchnik, 1995; Wieczorek *et al*., 2015).

Bridgland and Westaway (2014) suggested that, although the prevalence of stacked sequences in northern Poland might reflect proximity to the Baltic Basin, aspects of the fluvial archive preservation pattern in Central Poland that have traditionally been attributed to the effects of glaciation, or glaciation interspersed with marine transgression (e.g., Marks, 2004), might instead result from the characteristics of the crust. They envisaged three provinces within the Vistula: (1) an upstream, uplifting province, with well-developed terraces, (2) a central province in which the comparative stability of the EEP is dominant and (3) a downstream (northern) province with increasing influence of subsidence around the Baltic Basin and the effects of repeated glaciation.

The fluvial sedimentary archives in parts of the Sudetic foreland suggest inversion in vertical crustal movement, with alternation of subsidence and uplift, as surmised previously in systems such as the Don (Westaway and Bridgland, 2014; Bridgland *et al*., 2017; Fig. 3D). In previous reviews of the preservation patterns shown by fluvial archives, in which causal linkages have been observed with crustal type, such archives indicative of alternating subsidence and uplift were found to be associated commonly with Early or Middle Proterozoic crustal provinces with thick 'roots' of mafic material at the base of the crust, restricting the thickness of the mobile lower crustal layer (Westaway and Bridgland, 2014; Bridgland *et al*., 2017). In the Sudetes this phenomenon is apparent in basinal areas, which are separated by structural ridges (horsts) of older, generally crystalline rocks (Dyjor, 1986; see above).

EVIDENCE FOR PRE-GLACIAL RIVER SYSTEMS IN THE SUDETEN FORELAND

Quarrying and boreholes have allowed the reconstruction of considerable detail with regard to river sytems that existed in the Sudetic Foreland in pre-glacial times (i.e., prior to the Elsterian ice advance, which is the meaning of pre-glacial in this region). It should be noted, however, that this reconstruction is based on small 'windows' of subsurface evidence, providing limited scope for detailed reconstruction of areal three-dimensional form. Beneath the Sanian and Odranian glacial deposits, fluvial sediments of several different types have been recorded, much work having been done in order to characterize and distinguish these, in particular clast-lithological analysis of their gravel components and heavy-mineral analysis of sand grains (Czerwonka *et al*., 1994; Krzyszkowski and Bowman, 1997; Krzyszkowski *et al*., 1998; Przybylski *et al*. 1998; Krzyszkowski, 2001; Krzyszkowski and Karanter, 2001; Krzyszkowski, 2013). Many of these early fluvial deposits are kaolinitic, from the weathering of gneiss, gabbro, serpentinite, schist and other feldspathic rocks, which, in company with a dominance of rudaceous quartz, gave rise to the term 'white gravels'; they have also been referred to as the 'preglacial series' (Dyjor 1983, 1986, 1987a, b, 1993; Jahn *et al*. 1984; Dyjor *et al*. 1992). The matching of these components to source areas is illustrated in Fig. 6. They lie above the Upper Miocene – Lower Pliocene Poznań (Clay) Formation , sometimes with channel or palaeo-valley geometries apparent from the subsurface data (Ciuk and Piwocki, 1979; Ciuk and Pożaryska, 1982; Peryt and Piwocki, 2004). Indeed, there is some evidence of incision and even terrace formation within the preglacial sequence (see online supplement, Figs S2 and S3), much of which is however a continuation of the stacked basin-fill represented by the Neogene Poznań Formation. The pre-glacial fluvial deposits can be collectively described under the name Ziębice Group, this being the amalgam of several formations, representing different pre-glacial river systems, defined by their heavy mineral content and non-quartz gravel-clast petrography (Czerwonka and Krzyszkowski, 2001; Table 1; Figs 7 and 8). The Ziębice locality in central Poland, formerly called Münsterberg, was where fluvial 'white gravel' sediments, lacking Scandinavian material, were first described (Jentzsch and Berg, 1913; Frech, 1915; Lewiński, 1928, 1929; Zeuner, 1928; Krzyszkowski *et al*., 1998; Przybylski *et al*., 1998;Czerwonka and Krzyszkowski, 2001; online supplement Fig. S1).

Emplacement of the Ziębice Group as a whole can probably be attributed in part to increased mountain uplift and active faulting in the Sudetes and their foreland, perhaps resultant from the global climatic cooling that characterized the mid-Pliocene (e.g., Westaway *et al*., 2009); downthrown fault basins would have guided the main drainage lines. Each component formation represents sequences deposited by a specific fluvial system originating in the Sudeten Mountains. Within the group as a whole, four informal members (I–IV) have been recognized (Czerwonka and Krzyszkowski, 2001), their distinction being broadly age dependent, which is why they have not been formally defined, although there are no means for precise dating. These members are variously represented within the different formations, only two of which have all four members (Table 1; Fig. 9), with each numbered member believed to have been formed approximately synchronously in the different rivers across the region. The supposed ages of the members are relative and rely on superposition (see online supplement) and sporadic but rare preservation of biostratigrahical evidence (Czerwonka and Krzyszkowski, 2001; see below). Supplementary evidence for distinguishing between the members comes from erosional hiatuses at the bases of Members 1, III and IV and for the distinct widening of the valley systems between Members I and III (Czerwonka and Krzyszkowski, 2001; compare Figs 9 and 10). The sedimentology and range and type of facies suggests a meandering fluvial regime for Members I – III, especially away from the mountain front, and a braided river envrionment for member IV (Czerwonka and Krzyszkowski, 2001). Systematic analyses have been undertaken from exposures and boreholes, including sand heavy mineralogy and gravel clast lithology, arguably the most valuable, combined with particle-size analysis, quartz (sand) grain angularity–roundness analysis and palaeocurrent measurements (Czerwonka *et al*., 1994; Krzyszkowski and Bowman, 1997; Przybylski *et al*. 1998; Krzyszkowski *et al*., 1998; Krzyszkowski and Karanter, 2001; Krzyszkowski, 2001; Table 1; see online supplement).

As summarized in Table 1, six main pre-glacial river systems have been recognized, each with characteristic heavy-mineral signatures and some with distinctive clast-lithological assemblages. These are (1) the Palaeo-Odra, characterized by a zircon–rutile heavy-mineral assemblage and gravel clasts of Carpathian origin, represented by the Chrząszczyce Formation, (2) the Palaeo-Biała Głuchołaska (staurolite-amphibole mineralogy), represented by the Dębina Formation, (3) the Palaeo-Nysa Kłodzka (staurolite–garnet/amphibole–garnet), represented by the Kłodzko–Stankowo Formation, (4) the Palaeo-Bystrzyca (zircon, sillimanite and various) , represented by the Bojanice Formation (as well, potentially, as the Pogalewo and Wichrów formations), (5) the Palaeo-Strzegomka (sillimanite–garnet), represented by the Mielęcin–Wołów Formation, and (6) the Palaeo-upper Bóbr/Kaczawa (andalusite), as represented by the Rokitki–Bielany Formation. Of these the Palaeo-Nysa Kłodzka appears to have been the trunk river throughout the 'pre-glacial' period (see Figs 9–12). Evidence for four additional systems has been recognized but is more localized; these are the Palaeo-Wierzbiak, represented by the Snowidza Formation, the Palaeo-Budzówka, represented by the Ząbkowice Formation, and two other local rivers, near Bardo/Potworów and Szydłów, identified only by gravel-clast analysis (Przybylski *et al*., 1998) and impossible to match with existing rivers.

These drainage systems probably originated during the Early Miocene, since the Miocene–Lower Pliocene Poznań Formation is thought to represent the low-energy sediments of anastomosing river or inland-delta environments (Peryt and Piwocki, 2004), which, from the available evidence, persisted with relatively little change until disrupted by glaciation in the Middle Pleistocene. It should be noted that those formations with 'double-barrelled' names (Kłodzko–Stankowo, Mielęcin–Wołów and Rokitki–Bielany) are traced for significant distances from the mountain front and have 'proximal' type locailties (giving the first part of the name) near the Sudetes and 'distal' type localities further downstream. The lack of Scandinavian clasts in these various pre-glacial fluviatile sediments distinguishes them from the glacial deposits (Elsterian and Lower Saalian) and from the terrace deposits of the post-glacial rivers, in which reworked glacially-derived material occurs (Schwarzbach, 1955; Jahn, 1960, 1980; Czerwonka and Krzyszkowski, 1992; Krzyszkowski 1995, 2013; Czerwonka *et al*. 1997).

Turning to the informal members, I–III have generally been attributed to the Pliocene–lowermost Pleistocene and IV to the lower Middle Pleistocene (Cromerian Complex). This seemingly points to a hiatus spanning much of the first half of the Pleistocene, although there may well be unrecognized representation of this interval amongst sequences that are notoriously difficult to date and which include components that have yet to be defined and characterized fully. Alluvial-fan sediments occur within all members at localities near the mountain front. The Pliocene members can be presumed to represent rivers draining northwards to join the erstwhile Baltic River, which existed as a major east–west flowing system at that time (e.g., Gibbard, 1988). The drainage represented by members I–III was sinuous, as indicated by sediment geometry (Figs 9–11) as well as sedimentology (see above), in contrast to the braided-river deposits of member IV. This perhaps indicates sedimentation of members I–III during periods of temperate and relatively moist climate, whereas member IV records more variable conditions, with evidence of both temperate (interglacial) and cold (periglacial) climates. This contrast could, indeed, be a reflection of climatic cooling in the Early Pleistocene, a trend that would culminate in the glaciations of the Baltic region in the Middle Pleistocene.

The evidence for different pre-glacial rivers, precursors of the modern drainage of the Polish Sudetic margin, will be described in east to west sequence, starting with the Palaeo-Odra, the post-glacial successor of which forms the principle arm of the modern regional drainage.

The Palaeo-Odra (Chrząszczyce Formation)

Within the research area the Chrząszczyce Formation, which is thought to represent the main palaeo-Odra river, is restricted to locations >20 km from the Sudetic mountain front, entering the region from the south-east in the area south of Opole (Figs 7 and 9–11). It has been studied at relatively few localities at and to the west of Opole and west of Wrocław, with representation only of Members I–III (Table 1; Figs 9–11). Only at Chrząszczyce, the type locality ~5 km SSW of Opole (Figs 7 and 8; online supplement, Fig. S4), have all three of these members been observed. Gravel analysis has only been possible from the Member III sediments at Ose (Figs 7 and 8), where the occurrence of Carpathian siliceous rocks (silicified limestones and sandstones, radiolarites, etc.) amongst a quartz-dominated assemblage provides important support for origin within the Odra catchment (Czerwonka and Krzyszkowski, 1992). There are subtle changes in heavy mineralogy between members I–III (Table 1): all have assemblages dominated by zircon, with staurolite and tourmaline, plus garnet in members I and III and rutile in II and III. Member III at Tulowice has yielded plant macrofossils (leaves and fruit) with close affinity to those of the underlying uppermost Poznań Formation: i.e. not older than late Pliocene (Przybylski *et al*., 1998).

The Palaeo-Biała Głuchołaska (Dębina Formation)

This is a relatively minor formation, representative of a subordinate river, the most south-easterly that drained the Sudetes Mountains within the study area. Only Member I has been recognized, made up of quartzose gravels with a staurolite–amphibole heavy-mineral suite (Table 1). It has been recognized at a small number of sites from Strybowice to the type locality at Dębina, ~30 km SSW of Opole (Fig. 7). Although its occurrences trace a course from SSW to NNE, the petrography of the Ziębice Group as a whole, plus knowledge of the bedrock surface, suggests that the palaeo-river turned sharply to the NW in the vicinity of Dębina to a confluence with the Palaeo-Nysa Kłodzka, rather than continuing NNE-wards to join the palaeo-Odra (Fig. 9). It uncertain whether any of the Dębina Formation sequences continue upwards into Member II but the existence of a Palaeo-Biała Głuchołaska flowing NE from the Sudetes has been reconstructed for that time-span, joining a considerably wider Palaeo Nysa Kłodzka (Fig. 10) in comparison with that reconstructed for Member I. The continued existence of such a river during later times can only be speculative (Krzyszkowski *et al*., 1998).

The Palaeo-Nysa Kłodzka (Kłodzko–Stankowo Formation)

This formation accounts for the vast majority of the pre-glacial series, being represented at sites over an area of considerable width from its proximal type locality (see above) at Kłodzko, in the south (in the Kłodzko [intermontane] basin) eastwards towards (but not reaching) Opole and then northwards to Wrocław and beyond (Fig. 7). This distribution demonstrates the dominance of the Palaeo-Nysa Kłodzka during pre-glacial times (Figs 9–12). Its distal type locality, at Stankowo (Fig. 7, site [1]), is at the northern periphery of the study area, ~20 km NE of Leszno (Fig. 1; supplement, Fig. S5). The recognition of this formation is based on a gravel clast lithology reflecting the characteristic geology of the Kłodzko Basin, including gneisses and other cystalline rocks, notably porphyries, together with Mesozoic sandstones and 'flint' (Table 1; Figs 6 and 7). The heavy mineralogy is complex and regionally variable, also changing from staurolite–garnet dominance in Members I–III to garnet and amphibole in Member IV (Table 1).

With the formation represented at >50 sites (Figs 7 and 8), the comparative distribution of the different members reveals significant changes in the course of this trunk river, with Member I tracing a relatively confined WSW–ENE reach from Kłodzko to Gnojna (Fig. 7 [35]), diverging northwards from the modern Nysa Kłodzka course, and then a wider but still confined reach (in comparison with younger members) from here to Wrocław and Taborek (Fig. 7 [3]), by which point the Palaeo-Odra was converging from the east (Fig. 9). At the time of Member II emplacement, both reaches were considerably wider, that east of Kłodzko spreading southwards to envelop the course of the modern river, whereas in its northward-flowing reach it extended eastwards to meet the Palaeo-Odra ~10 km west of Opole and spread out north-eastwards across the foreland to encompass an area from that of its earlier course across to that around Ostrów Wielkolpolski and beyond (Fig. 10).

By Member III times the palaeo-river had been diverted from near Ziębice into a more confined northerly course towards Wrocław, sweeping across the area south and east of this city towards Ostrów Wielkolpolski, turning northwards as it met the palaeo-Odra, by this time of almost equal size, and other drainage from the east, possible the 'Bełchatów River', as recognized in central Poland at the large lignite quarry by the same name (Krzyszkowski, 1995; Krzyszkowski *et al*., 2015; Fig. 11).

By member IV times there is little evidence that the Palaeo-Nysa Kłodzka extended north-eastwards of the modern Odra course, except in the area NW of Wrocław. This suggests that a Palaeo-Odra closely following its modern valley had come into existence by this time, perhaps as a result of early Middle Pleistocene glaciation (Zeuner, 1928; Fig. 12), otherwise poorly documented because its extent was less than the ice sheets of the Elsterian, the suggestion being that the line of the Odra across the northern edge of the Sudetic foreland might be of early ice-marginal ('pradolina') origin (see above).

The Palaeo-Budzówka (Ząbkowice Formation)

The Budzówka is a minor left-bank tributary of the Nysa Kłodzka, joining the latter ~20 km downstream of Kłodzko. Its pre-glacial forebear is represented by probable Member IV deposits that occur at two sites, the Ząbkowice type locality [73] and Albertów [107] (Figs 7, 8 and 12). These deposits are characterized by gravel in which the dominant clast type is Sowie Góry gneiss, with subordinate quartz and other siliceous rocks; there is a garnet–amphibole heavy mineral suite (Table 1).

The Palaeo-Bystrzyca (Bojanice, Wichrów and Pogalewo formations)

The River Bystrzyca, which is the next important Odra tributary moving to the NW along the Sudetes margin, flows through the town of Świdnica on its SW–NE course towards a confluence with the trunk river ~7 km NW of Wrocław; ~15 km upstream of that confluence it receives a substantial left-bank tributary, the Strzegomka (Fig. 7). Pre-glacial versions of both these rivers are represented amongst the Ziębice Group sediments, although with courses that appear to have been entirely separate until the trunk river was reached; at that time the latter was the Palaeo-Nysa Kłodzka (Figs 9–12.

Three different pre-glacial formations are potential products of deposition by the palaeo-Bystrzyca. First is the Bojanice Formation, of which Members II, III and possibly IV occur in the vicinity of Świdnica, in the form of porphyry-rich quartz gravels, also containing melaphyre, Sowie Góry gneiss and quartzite, although the uppermost (potentially Member IV) deposits lack rudaceous components (Table 1). The heavy minerology of these upper deposits is dominated by sillimanite, whereas that of the gravelly facies is dominated by zircon and garnet (Table 1).

The Wichrów Formation is represented by a small group of sites, of which the Wichrów type locality is one, ~20–30 NNE of Świdnica, in the modern catchment of the Strzegomka tributary (Figs 7 and 8[45]). Only the basal part of the sequence is present, with Member I and a possible extension into Member II, sharing the zircon-rich mineralogy of the lower members within the Bojanice Formation (Table 1). Despite its modern location within the tributary catchment, the Wichrów Formation sites seem likely to represent a downstream continuation of the palaeo-Bystrzyca from the Świdnica area (Fig. 9).

The Pogalewo Formation is identified in the area much further from the mountain front, to the north of the modern River Odra downstream of Wrocław. Members I, II and III are all recognized, albeit at different sites (Figs 7 and 8). Member I is identified only at the Pogalewo type locality [31], on the northern side of the Odra valley ~30 km downstream of Wrocław (Fig. 9; online supplement Fig. S3). It is the only member of this formation to have yielded rudaceous material, this being quartz gravel with local flint and a trace of porphyry; it has a zircon–tourmaline-rutile heavy mineralogy (Table 1).

Further upstream (both within the modern Odra system and the pre-glacial palaeovalley), ~5–10 km east from Pogalewo, is a small cluster of sites that represent Member III, which have the same dominant mineralogy but with additional epidote, kyanite, amphibole and staurolite (Table 1). The intervening Member II, although perhaps represented by the uppermost deposits at Pogalewo, is optimally recorded much further downstream, at Chałupki [51], ~30 km SW of Głogów (Fig. 7). The mineralogy of this member is different again, with kyanite in addition to the zircon–tourmaline–rutile suite but lacking epidote, amphibole and staurolite (Table 1). Although given a separate name, the deposits of the Pogalewo Formation are most readily interpreted as more distal (downstream) palaeo-Bystrzyca sediments, implying a separate northward course far from the mountain front, especially during emplacement of Member II (Fig. 10).

The Palaeo-Strzegomka (Mielęcin–Wołów Formation)

As noted above, the modern River Strzegomka joins the Bystrzyca ~15 km upstream of the confluence between the combined river and the Odra. Prior to the Middle Pleistocene, however, it seems likely that the precursors of these rivers maintained separate courses to the trunk palaeo-Nysa Kłodzka (Figs 9–11). The palaeo-Strzegomka is represented by the Mielęcin–Wołów Formation, as is apparent from the preservation of that formation at sites close to the mountain front within the modern Strzegomka catchment, including the Mielęcin (proximal) type locality (Fig. 7 [47]; online supplement Fig. S6). The deposits here comprise quartzose–porphyry-rich gravels representing Members I–III, also containing local siliceous rocks (flint), conglomerate, spilite, diabase, greenschist and quartzite from the Wałbrzych Upland, Strzegom granite and local schist (phyllite), as well as a sillimanite–garnet heavy-mineral suite (Table 1; Fig. 6). The distal type locality, at Wołów, where only Member I is represented, is located north of the modern Odra, approximately equidistant between Wrocław and Głogów (Fig. 8 [32]). Member IV of the Mielęcin–Wołów Formation is recognized at two sites, Sośnica [43], in the modern Bystrzyca valley upstream of its confluence with the Strzegomka, and Brzeg Dolny 3 [108], north of the modern Odra, where it overlies Member I of the Kłodzko–Stankowo Formation (Figs 8 and 12; online supplement Fig. S2). This upper member lacks gravel but is characterized by a sillimanite-dominated heavy mineralogy (Table 1).

The Palaeo-upper Bóbr/Kaczawa (Rokitki–Bielany Formation)

The next Odra tributary north-westwards along the mountain front is the River Kaczawa, which has a confluence with the trunk river ~20 km downstream from Legnica. Its pre-glacial forebear, however, had a catchment that penetrated deeper into the mountain zone, including areas now drained by the headwaters of the Bóbr, a yet more westerly Odra tributary that flows NW from the Sudetes to join the trunk river well to the west of the study area (Fig. 7). This is indicated by the characteristic clast lithology of the Rokitki–Bielany Formation, which has rudaceous sediments representing all four members with contents that show drainage from the Bóbr catchment: these are quartzose gravels with porphyry, Karkonosze granite, crystalline rocks, schist, quartzite, with the addition, in Member IV, of Cretaceous sandstone and Wojcieszów limestone (Table 1). The heavy mineralogy is characterized by andalusite and tourmaline, with the addition of epidote in Member I and of kyanite, zircon, garnet, amphibole and sillimanite in Member IV (Table 1). The proximal type locality of this formation, Rokitki [55], is situated in the Kaczawa valley, ~ 8 km upstream of its catchment with the Nysa Szalona, a right-bank tributary (Fig. 7). Members I–III are attributed to a palaeo-Bóbr–Kaczawa that drained northwards, to the west of Legnica, towards Głogów (Figs 9–11). Member IV of this formation is recognized only at sites in the interfluve area between the Strzegomka and the Kaczawa, at Kępy [95] and Bielany [50] (Fig. 12; online supplement Fig. S7), where it overlies older members of the Mielęcin–Wołów Formation that represent the earlier northward drainage of the palaeo- Strzegomka (see above; Figs 1 and 9). Bielany is the distal type locality of th#e Rokitki–Bielany Formation, although it lies further south than Rokikti (Fig. 7 [50]). The most northerly Mielęcin–Wołów site is Polkowice [62], <20 km south of Głogów, where only Member III occurs (Figs 7, 8 and 11).

Other minor rivers

Fluvial tracts of more localized rivers have been traced. The Snowidza Formation, known from a single locality (Fig. 8), represents a possible ancestral River Wierzbiak, the modern river of the same name being a right-bank Kaczawa tributary that joins the latter ~10 km downstream of Legnica (Fig. 7). The sole representation of the Snowidza Formation is probably equivalent to Member I of other Ziębice Group formations (Fig. 8). The deposits of two other local rivers have been recognized (Fig. 7) in the vicinity of Bardo [96–97], Potworów [98–99]and Szydłów [101] on the basis of gravel-clast petrography (Przybylski *et al*., 1998). These occurrences are again of probable Member I affinity (Fig. 8).

DATING THE ZIĘBICE GROUP

Much of the dating of the individual components of the Ziębice Group is dependent on their relative stratigraphical positions within the sequence and their relation to the underlying Poznań Formation and overlying Middle Pleistocene glacial deposits. At Gnojna (~55 km NE of Kłodzko; Fig. 7: [35]) palynological analyses of the uppermost member of the Poznań Formation, immediately below member I of the Kłodzko–Stankowo Formation, have yielded a flora indicative of the earliest Pliocene (Sadowska, 1985; Badura *et al*., 1998a). A similar Early Pliocene flora has been obtained from Sośnica (Stachurska *et al*., 1973; Sadowska, 1985, 1992; Fig. 7 [43]), where it is overlain by member IV of the Mielęcin–Wołów Formation. Macrofossil analysis of the Poznań Formation at Ziębice, Sośnica and Gnojna have revealed the presence of Late Miocene to Early Pliocene leaves and fruits (Kräuzel, 1919, 1920; Łańcucka-Środoniowa *et al*., 1981; Krajewska, 1996). These occurrences provide a maximum (limiting) age for the Ziębice Group

A very few sites have yielded palaeobotanical remains from sediments of Ziębice Group formations. At Kłodzko (Figs 7 and 8 [68]; online supplement Fig. S8) an organic deposit was recorded at the top of a sequence that potentially represented member II and/or member III of the Kłodzko–Stankowo Formation (cf. Krzyszkowski *et al*., 1998). Pollen and macrofossils from this deposit have been attributed to the Reuverian Stage of the Late Pliocene (Jahn *et al*., 1984; Sadowska, 1995). Poorly preserved leaf macrofossils from member III of the Chrząszczyce Formation at Tułowice (~15km SW of Opole; Figs 7 and 8 [74]) represent a temperate-climate assemblage of trees and shrubs that cannot be dated with precision but is unlikely to be older than late Pliocene (Przybylski *et al*., 1998). The fossiliferous deposits here are thus attributed to the palaeo-Odra, although they overlie member II deposits that are attributed to the palaeo-Nysa Kłodzka and thus the Kłodzko–Stankowo Formation (Fig. 8). Further west, nearer the modern Nysa Kłodzka and in sediments attributed to the Kłodzko–Stankowo Formation, organic remains and leaf impressions have been found at Niemodlin 2 [80] and Magnuszowiczki [83] in member II (Figs 7 and 8); Przybylski *et al*. (1998) noted that the leaf impressions occurred in laminated silty alluvial sediments.

Zeuner (1928, 1929) described pre-glacial organic deposits at Jonsbach (now Janowiec) that would appear to have been part of member IV of the Kłodzko–Stankowo Formation (Figs 2, 7 [72], 8 and 12): part of a pre-glacial fluvial ('white gravel') sequence ~11 m thick, located just downstream of the Sudeten Marginal Fault (cf. Krzyszkowski *et al*., 1998). The limited pollen record (Stark and Overbeck, 1932; Badura *et al*., 1998b; Krzyszkowski *et al*., 1998) lacks Tertiary relics and is thus suggestive of the early Middle Pleistocene (Cromerian Complex). Attempts to relocate these deposits and provide a more detailed analysis have proved unsuccessful.

This is meagre evidence upon which to base an age model for the Ziębice Group, but broad inference from these data points to Pliocene–earliest Pleistocene deposition of members I–III and to early Middle Pleistocene emplacement of member IV. That inference concurs well enough with the sedimentological evidence for a meandering fluvial regime during deposition of members I–III and a braided gravel-bed river at the time of member IV emplacement (Czerwonka and Krzyszkowski, 2001; see above), given that the change could readily be attributed to the greater severity of cold-stage climatic episodes in the early Middle Pleistocene, following the Mid-Pleistocene Revolution. The latter, which saw the transition to 100 ka glacial–interglacial climatic cyclicity (e.g., Maslin and Ridgwell, 2005), has been noted to have had a profound effect on valley evolution in many parts of the world, notably causing enhanced valley deepening and concomitant isostatic uplift (e.g., Westaway *et al*., 2009; Bridgland and Westaway, 2014;.cf. Stange *et al*., 2013).

POST-GLACIAL LANDSCAPE EVOLUTION OF THE SUDETIC MARGIN

Following the Middle Pleistocene glaciation of the Sudetic foreland, the present-day rivers, established in the courses they still occupy, have incised their valleys by varying amounts. In the vicinity of the Bardo Gorge (sites 96 and 97, Fig. 7), in an uplifting inter-basinal location, the Nysa Kłodzka has cut down >50 m below the level of the Odranian till, forming five terraces during the process (Krzyszkowski *et al*., 2000; Fig. 2A), presumably in response to post-Odranian regional uplift (Krzyszkowski and Stachura, 1997; Krzyszkowski *et al*., 1998, Migoń *et al*., 1998; Starkel 2014), perhaps with a component of glacio-isostatic rebound (cf. Bridgland and Westaway, 2014).

As Krzyszkowski *et al*. (1995, 2000) have shown, the amount of fluvial incision (and thus of uplift) differs markedly on either side of the Sudetic Marginal Fault, the displacement suggesting ~15–25 m of additional uplift on the upthrow side (related to continued elevation of the Sudeten Mountains) since formation of the 'Main Terrace', the oldest post-Elsterian river terrace. Previous authors have ascribed this main terrace to the Odranian, since it is overlain by till of that age (e.g., Krzyszkowski and Biernat, 1998; Krzyszkowski *et al*., 2000); it is essentially the starting point for post-glacial incision by the Sudetic marginal rivers such as the Bystrzyca and Nysa Kłodzka (Fig. 2). If attribution of the Odranian to MIS 6 is correct then several terraces have been formed during the relatively short interval represented by the Late Pleistocene. Dating evidence is generally lacking, however. The following is a general summary of the sequence:

i. Upper terrace (erosional /depositional) ~10–18 m above alluvial plain (MIS 6; Wartanian)
ii. Middle Upper terrace (depositional) ~4–8 m above alluvial plain (MIS 3; mid-Weichselian)
iii. Middle Lower terrace (depositional) ~2–5 m above alluvial plain (MIS 2; Vistulian/ Weichselian /LGM)
iv. Lower terraces of the recent alluvial plain (Holocene) - see Fig. 2.

DISCUSSION: PLIOCENE–QUATERNARY LANDSCAPE EVOLUTION IN THE POLISH SUDETEN FORELAND AND THE WIDER REGION

The landscape of Poland represents a mosaic of crustal provinces, as illustrated in Fig. 4A and in more detail in Fig. 4B. The boundaries between these provinces have been delineated by many studies, initially outcrop investigations, later borehole studies and, most recently, deep controlled-source seismic-profiling projects (e.g., Grad *et al*., 2002, 2003, 2008; Hrubcová *et al*., 2005; Malinowski *et al*., 2013; Mazur *et al*., 2015). NE Poland is thus known to be located within ancient (Early-Middle Proterozoic) continental crust overlying the relatively thick lithosphere of the EEP (see above). The boundary between this region and the younger crustal province to the SW was first identified in the late 19th century in territory now in SE Poland and western Ukraine by Teisseyre (1893; Teisseyre and Teisseyre, 2002). This boundary, nowadays known as the Teisseyre–Tornquist Zone (TTZ) or Trans-European Suture Zone, marks the suture of the Tornquist ocean, which formerly separated the ancestral continents of Baltica (to the NE) and Avalonia (to the SW), and closed during the Caledonian orogeny, when the crust SW of the TTZ experienced deformation (e.g., Grad *et al*., 2003). At a later stage, SW Poland, including the Sudetes, was deformed during the Variscan orogeny, the northern and eastern limits of the region thus affected being now concealed in the subsurface by younger sediments. Figure 4B indicates one interpretation of these limits; Grad *et al*. (2003) provide another. The Variscan orogeny in this part of Europe involved northward subduction of the Rheic ocean beneath the southern margin of Avalonia, followed by the continental collision between the Armorica continent (more specifically, its eastern part, Saxothüringia) and various microcontinents with Avalonia (e.g., Mazur *et al*., 2006). The Sudeten massif in the extreme SW of Poland, in the core of the Variscan orogeny, experienced pervasive deformation, metamorphisim, and granitic magmatism. This region was also affected at this time by NW–SE-oriented left-lateral strike-slip faulting (including slip on the Sudetic Boundary Fault and Intra-Sudetic Fault), creating a collage of fragmented crustal blocks of extreme complexity (e.g., Aleksandrowski *et al*., 1997; Aleksandrowski and Mazur, 2002; Franke and Żelaźniewicz, 2002; Gordon *et al*., 2005; Jeřábek *et al*., 2016; Kozłowski *et al*., 2016; Fig. 1). Much later, SE Poland was affected by Late Cenozoic plate motions, involving southward or south-westward subduction of the former Carpathian Ocean (Fig. 3B); as a result, the mosaic of continental fragments affected by the Variscan orogeny in what is now Slovakia (which were formerly located further southwest) became juxtaposed against SE Poland (e.g., Plašienka *et al*., 1997; Szafián *et al*., 1997; Stampfli *et al*., 2001, 2002; Von Raumer *et al*., 2002, 2003; Bielik *et al*., 2004; Schmid *et al*., 2004; Alasonati-Tašárová *et al*., 2009; Handy *et al*., 2014; Broska and Petrík, 2015). Thus the crustal structure of Poland is highly variable, reflecting the complex tectonic history of the wider region.

The ideas about different crustal types having very different landscape evolution histories presented above were developed without reference to fluvial sequences in Poland, although data from neighbouring countries, such as Ukraine, were taken into account, as exemplified by the example of the northern Black Sea rivers (Fig. 3). Application of these ideas to Poland, and in particular to the data under consideration in this paper, thus provides a valuable test of the underlying theories. This task has been facilitated by the aforementioned deep seismic projects, from which have been published crustal transects with the required spatial resolution; indeed, some of the transects combine crustal structure and heat flow, for example those across Poland from SW to NE presented by Grad *et al*. (2003). The first such transect, likewise combining crustal structure and heat flow, was prepared in a similar location by Majorowicz and Plewa (1979); comparison between the two indicates the technical progress over the intervening decades, although the main features identifiable in the modern cross-sections can also be resolved on the older one. One aspect of particular importance for the present investigation is identification (from its relatively high seismic velocity) of the presence of mafic underplating at the base of the crust. Such a layer remains rigid (or brittle) under the temperatures typically experienced (<~550 °C) and thus behaves mechanically as part of the mantle lithosphere, any mobile lower-crustal layer present being restricted to shallower depths in the felsic lower crust. The phenomenon was mentioned above in connection with Early or Middle Proterozoic crustal provinces in which fluvial archives point to past alternation subsidence and uplift.

The seismic transect studied by Grad *et al*. (2003) crosses the TTZ ~150 km NW of Warsaw with ESE–WSW orientation, revealing a layer of mafic underplating at the base of the crust persisting from here to a point ~100 km NW of Wrocław. According to Grad *et al*. (2003), emplacement occurred during magmatic rifting of eastern Avalonia from the Precambrian supercontinent Rodinia during the latest Proterozoic or Cambrian. This layer is up to ~10 km thick, its top locally as shallow as ~25 km depth; it evidently extends beneath the external part of the Variscides, including the high-heat-flow region around Poznań, depicted in Fig. 4C, but no long-timescale fluvial sequences are evident in this region due to the effect of multiple glaciations. The subparallel transect studied by Grad *et al*. (2008) starts just SW of the TTZ, ~170 km west of Warsaw, crosses the Czech–Polish border in the extreme SW of Poland, then through the NW extremity of the Czech Republic before entering Germany. It again reveals up to ~10 km of mafic underplating at the base of the crust, its top locally as shallow as ~22 km, persisting WSW for ~250 km and dying out in the vicinity of the Intra-Sudetic Fault Zone. Mafic underplating, with thickness up to ~8 km, its top locally as shallow as ~18 km, resumes in the western part of the Bohemian Massif near the Czech–German border, as the transect approaches Saxothüringia, the intervening crustal provinces (Barrandia, forming the central Bohemian Massif) being free of underplating. The NW–SE seismic transect across the Bohemian Massif, reported by Hrubcová *et al*. (2005), confirms the presence of underplating beneath Saxothüringia but not beneath Moldanubia (the SE Bohemian Massif) or Barrandia.

As already discussed, the structure of the Sudeten Mountains is complex; as a result of the Variscan left-lateral faulting it consists of small fragments of crustal blocks that have become juxtaposed. Jeřábek *et al*. (2016) have recently demonstrated that this process included transposition of Saxothüringian crust (presumably including its characteristic layer of mafic underplating) beneath fragments of Barrandia. It would thus appear that mafic underplating persists beneath much of the Sudeten Mountains region, as Majorowicz and Plewa (1979) inferred, even though this was not resolved in the Grad *et al*. (2008) study. The heat flow typically decreases southward across the Sudeten Mountains, reaching values of <70 mW m^{-2} in the Kłodzko area (Fig. 4C); it can thus be inferred that this effect, along with the presence of mafic underplating derived from Saxothüringian crust, constricts the mobile lower-crustal layer, resulting in the pattern of alternations of uplift and subsidence that are evident in the fluvial records, particularly in basinal areas (see above). A noteworthy record comes from Kłodzko [site 68], which gives its name to the Kłodzko Basin and is the proximal type locality of the Kłodzko–Stankowo Formation, which represents the pre-glacial River Nysa Kłodzka. Here in the basin the pre-glacial gravels extend to below river level, suggesting the sort of reversal in vertical crustal motion described above. This can be compared with the situation ~12km downstream at the Bardo Gorge, on the inter-basinal ridge (see above), where it is evident that uplift has been more continuous (Compare Figs 2A and 2B).

Another good example of the low level of the pre-glacial deposits in parts of the Sudetic Foreland, as well as their geomorphological inter-relationship, is the site at Brzeg Dolny in the Odra valley downstream of Wrocław [site 108], where Members I and II of the Kłodzko–Stankowo Formation occur in superposition, their base ~10 m above the level of nearby Holocene valley-floor sediments. Member IV of the Mielęcin–Wołów Formation (representing the palaeo- Strzegomka) occurs nearby, incised to a lower level. Given the tributary status of the palaeo- Strzegomka, this relationship implies rejuvenation between the Pliocene (Member I) and early Middle Pleistocene (Member IV), when the latter river traversed an area formerly occupied by the pre-glacial Nysa Kłodzka; this is a clear example of terrace formation within the pre-glacial sequence (see online supplement Fig. S2).

In some parts of the Sudetes, thick plutons of highly radiothermal granite were emplaced during the Variscan orogeny, their radioactive heat production resulting in local heat-flow highs; for example, Bujakowski *et al*. (2016) inferred temperatures as high as ~390 °C at 10 km depth beneath the Karkonosze granite pluton (see Fig. 6 for location). However, this is one locality where Jeřábek *et al*. (2016) inferred that the Variscan orogeny emplaced Saxothüringian crust beneath crust of Barrandian provenance, so that here it can be anticipated that the mafic underplating will constrict the mobile crustal layer, notwithstanding the high surface heat flow.

South of the Sudeten Mountains, in the Bohemian Massif, rivers such as the Vltava and Labe (affluents of the Elbe) have substantial terrace staircases (e.g., Tyracek *et al*., 2004), with no indications of alternations in vertical crustal motion. The heat flow in the central Bohemian Massif is ~50-60 mW m^{-2} (e.g., Čermák, 1979), less than in the Sudeten Mountains. However, as already noted, the crust in this region, up to ~35 km thick in Barrandia (in which the Vltava terrace staircase is located) and up to ~40 km thick in Moldanubia, is free of mafic underplating (Hrubcová *et al*., 2005). The felsic lower crust is thus much thicker in this region, and concomitantly much hotter near its base, than in the Sudeten Mountains. The different landscape response between these areas can thus be explained: the mafic underplating accounts, via the mechanism advocated by Westaway and Bridgland (2014), for the observed pattern of sedimentary archives in parts of the Sudetes; the importance of underplating is underlined by evidence for sustained upward vertical crustal motion, despite lower heat flow, in the central Bohemian Massif, where underplating is absent (cf. Štěpančíková *et al.,* 2008).

Wider crustal comparisons can also be made between fluvial sequences in the Sudeten Mountains and elsewhere in Poland. Comparison of Figs 4A and B indicates that the surface heat flow increases from ~70 mW m^{-2} at the external (northern) margin of the Carpathians to ~80 mW m^{-2} along the Poland-Slovakia border, for example along the upper reaches of the River San. No modern deep seismic profile in this area is known to the authors, but by analogy with other localities further NW it can be inferred that the region consists of ~40 km thick crust with ~10 km of mafic underplating (cf. Grad *et al*., 2003, 2008). However, during the Late Cenozoic plate convergence this crust became buried beneath up to ~7 km of young sediment (e.g., Oszczypko, 1997). The 'thermal blanketing' effect of this sediment will significantly raise the temperature in the underlying crust, reducing the constriction effect of the underplating on the thickness of mobile lower crust; 7 km of sediment of thermal conductivity 2 W m^{-1} $°C^{-1}$ overlying crust in which the heat flow is 80 mW m^{-2} will raise the temperature in this bedrock by 7 km × 80 mW m^{-2} / 2 W m^{-1} $°C^{-1}$ or ~280 °C. Westaway and Bridgland (2014) suggested an analogous explanation for the disposition of the terrace deposits of the River Dniester in the Ukraine–Moldova border region further to the SE (see Fig. 3A).

Comparison is also possible with the crust underlying the fluvial sequence laid down by the River Vistula in the Warsaw area. As illustrated in Fig. 5D, Pliocene deposits here occur near the present river level, and Early Pleistocene deposits at a height ~30 m lower. After these were laid down, the ancestral Vistula cut down to ~50 m below its present level before laying down a stack of Middle and Late Pleistocene sediments, including Holocene temperate-climate deposits overlying their Eemian and Holsteinian counterparts. Overall, this sequence indicates a transition from uplift in the Pliocene and Early Pleistocene to subsidence thereafter. Warsaw is ~50 km inside the EEP (Fig. 4B). From Grad *et al*. (2003) and Mazur *et al*. (2015), the crust is locally ~45 km thick with ~20 km of underplating at its base, overlain by ~19 km of basement and ~3 km of sediments, which are mainly Mesozoic (in contrast with the much thicker sequences dominated by Palaeozoic shale, closer to the TTZ). The surface heat flow in the Warsaw area is ~60 mW m^{-2} (Fig. 4C); if the sediment and basement are assumed to have thermal conductivities of 2.5 and 3.5 W m^{-1} $°C^{-1}$, respectively, the ~350 °C isotherm can be expected at ~19 km depth, making the mobile lower crustal layer ~6 km thick, within the range of values where alternations of uplift and subsidence have been observed in fluvial sequences elsewhere (Westaway and Bridgland, 2014). Other fluvial sequences within the EEP, with alternations of uplift and subsidence evident, include those of the River Dnieper in Ukraine and the Rover Don in SW Russia (e.g., Westaway and Bridgland, 2014; Fig. 3).

A final point on the effect of lateral variations of crustal properties, with resultant lateral variations in uplift, on the disposition of fluvial terrace deposits concerns the occasional occurrence of back-tilted fluvial deposits, in cases where rivers have flowed from regions of colder to warmer crust, with an example evident from the Sudetic margin. It is evident that the ancestral drainage from the Sudeten Mountains was directed northward, from the Wrocław area and points further east to the Poznań area, before adjusting (probably around the start of the Early Pleistocene) to its modern configuration. Fig. 4C indicates that the former drainage was directed across the high heat-flow region between Wrocław and Poznań, raising the possibility that the subsequent drainage adjustment was the result of faster uplift of the latter region. As already noted, the Grad *et al*. (2003) seismic profile passes through this high-heat-flow region, indicating that the top of the mafic underplating is at ~25 km depth and that the sedimentary sequence in the overlying crustal column is thin. Assuming a thermal conductivity of 3.5 W m^{-1} $°C^{-1}$ in the basement, as before, and a typical heat flow of ~90 mW m^{-2}, the ~350 °C isotherm can be expected at a depth of ~14 km, making the thickness of the mobile lower crust ~11 km, significantly greater than in other parts of Poland and high enough (based on comparisons with other regions) to sustain significant uplift rates. Recorded heights of pre-glacial fluvial deposits in this region (Czerwonka and Krzyszkowski, 2001; Supplement, Table S1) indeed reveal evidence of back tilting. The best such evidence is provided by comparison of the heights of the Pliocene deposits along the ancestral River Odra, between Chrzaszczyce(Fig. 7 [76/77]), Smardzow [33], 77.3 km further downstream, and Stankowo [1], 84.9 km further downstream, the latter site adjoining the confluence with the ancestral Nysa Kłodzka (Fig. 7). The top of the deposits assigned to Member I of the Ziębice Group is 180, 72, and 99 m a.s.l. at these sites, thus indicating back-tilting over the reach between Smardzow and Stankowo, the long-profile gradients being ~1.4 and ~-0.3 m km^{-1} along these two reaches, respectively. Thus, if this river had an original gradient of ~1 m km^{-1}, the deposit at Stankowo is now 81 m higher in the landscape, and that at Smardzow 34 m lower, than would be expected if all three sites had experienced the same history of vertical crustal motion. In the absence of detailed modelling the precise sequence of processes in this region cannot be ascertained, but this pattern is consistent with the interpretation that lower-crustal material was drawn from beneath the Smardzow area to beneath the hotter Stankowo area, as a result of the lateral pressure gradient at the base of the brittle upper crust caused by the variation in heat flow between these two regions. An established analogue of this effect is the back-tilting of the deposits of the early Middle Pleistocene Bytham River in the East Midlands of England; this river flows eastward from the northern part of the London Platform, a region of relatively low heat flow, into the higher-heat-flow zone of crustal deformation during the Caledonian orogeny, at the NE margin of Avalonia (Fig. 4A), its sediments now being gently tilted in an upstream direction (Westaway *et al*., 2015).

The explanation for the fluvial archives in the marginal area of the Sudeten Mountains promoted here has a more general analogue in records from SW England, in the rivers of Cornwall and west Devon (Westaway, 2010). In that region radiothermal Variscan granites are underlain by thick mafic underplating and the crust is relatively strong, as indicated by the minimal Late Cenozoic vertical crustal motions deduced from fluvial sequences. The principal difference is that the mafic underplating beneath SW England was emplaced after the Variscan orogeny, as a result of the Palaeocene British Tertiary Igneous Province magmatism, whereas the underplating beneath the Sudeten Mountains is evidently derived from fragments of pre-Variscan Saxothüringian crust.

The different styles of fluvial archive preservation in the different parts of the European continent described above are an important consideration in the understanding of Quaternary stratigraphy in these regions, given that fluvial sequences provide valuable templates for the Late Cenozoic terrestrial record (Vandenberghe, 2002; Bridgland *et al*., 2004; Bridgland and Westaway, 2014). It has been shown that the most stable regions, in which the fluvial archives suggest a complete or near absence of net uplift during the Quaternary, coincide with the most ancient cratonic crustal zones, such as parts of the EEP and in particular the Ukrainian Shield (Bridgland and Westaway, 2008, 2014; Fig. 3). Such highly stable regions are the exception for the EEP, however; over much of its area there has been limited net uplift as a result of alternations of vertical crustal movements, resulting in periods of terrace generation with intervening periods of subsidence and burial. In Fig. 13 the fluvial archive from the Sudetic margin, using the optimal example of the Nysa Kłodzka at Bardo (see above), is compared with that of the River Don at Voronezh. Despite the differences in size (catchment area and, therefore, discharge) of the fluvial systems in question and the very different glacial influences (the Don here was reached only by glaciation in MIS 16), there are significant points of comparison. Contrastingly, the difference between the fluvial records from the EEP and those from the youngest and most dynamic European crust is quite profound, albeit that many of the comparisons made above are with crust of somewhat intermediate age, such as the Variscan and Avalonia provinces (Fig. 4). This is because much of the youngest crust, in the Alpine and Carpathian provinces (Fig. 4), remains tectonically active (i.e., continues to be affected by active plate motions) and so has fluvial archives that are less clearly related to regional vertical crustal movements.

CONCLUSIONS

The rivers of the Polish Sudeten foreland have pre-glacial precursors, their courses recognized from sediments that generally underlie the Middle Pleistocene glacial deposits and which date from the Early Pliocene – Early Pleistocene, being substantially different from those of their modern successors. The pre-glacial fluvial formations are preserved in the subsurface, in part as buried valley fills, and recorded as the Ziębice Group. They were partly destroyed and buried by the Middle Pleistocene Scandinavian ice sheets that entered the Sudeten Foreland, covering the previously formed valleys with glacial deposits: the Elsterian (= Sanian) and the early Saalian (= Odranian). No post-Odranian ice sheet reached the Sudeten Foreland, where renewed incision (brought about by post-Odranian uplift) led to post-glacial river-terrace formation. In addition to glacial and tectonic influences on fluvial evolution, the overall pattern of fluvial archive preservation is commensurate with the Variscan crustal province in which they are developed. However, the effects of mafic underplating, emplaced by the incorporation of pre-Variscan crustal material, may have been considerable, as this can explain reduced net Pleistocene uplift and reversals in vertical crustal motion, especially in basinal areas. Differential uplift in reflection of crustal type may have led to disruption of former downstream gradients in the palaeovalleys, with an example of back-tilting identified in the case of the Palaeo-Odra. In addition, some younger terraces can be shown to have been offset by slip on active faults of the Sudeten Marginal Fault system.

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Figure captions

Figure 1 Geology and location of the research area. The inset shows the limits of the various Quaternary glaciations of Poland and the course of the River Odra. Modified from Czerwonka and Krzyszkowski (2001).

Figure 2 Cross sections through key fluvial sequences in the study area: A - the River Nysa Kłodzka in the Bardo area (sites 96 and 97 in Figs 7 and 8), where the river has cut a gorge through an inter-basinal (progressively uplifting) ridge, the inset showing the sequence a few km downstream, in the Janowiec–Ożary area (sites 72 and 71 in Figs 7 and 8); B - the sequence in the Kłodzko Basin in the Kłodzko–Leszczyna area (site 68 in Figs 7 and 8), both modified from Krzyszkowski *et al.* (1998); C - The River Bystrzyca near Lubachów (modified from Krzyszkowski and Biernat, 1998); for location see FIg. 7.

Figure 3 The Rivers of the northern Black Sea region (modified from Bridgland and Westaway, 2014; after Matoshko *et al*., 2002; 2004). A - The locations of parts B–D in relation to the Ukrainian Shield. B - Idealized transverse profile through the Middle–Lower Dniester terrace sediments, which represent a classic river terrace staircase (with approximately one terrace per 100 ka climate cycle following the Mid-Pleistocene Revolution) inset into Miocene fluvial basin-fill deposits. This region has higher heat flow than might be expected from its location at the edge of the EEP (see A), for reasons discussed in detail by Westaway and Bridgland (2014). C. - Transect across the Middle Dnieper basin,~100 km downstream of Kiev (~240 km long), showing a record typical of an area with no considerable net uplift or subsidence during the Late Cenozoic, as typifies cratonic crustal regions (cf. Westaway *et al*., 2003). D. - Transect through the deposits of the Upper Don near Voronezh, showing a combined stacked and terraced sequence that points to fluctuation between episodes of uplift and of subsidence during the past ~15 Ma.

Figure 4 Crustal characteristics. A - Crustal provinces in the European continent and neighbouring areas. Modified from Pharaoh *et al*. (1997); the location of parts B and C is shown. B - Crustal provinces in Poland. Modified from Mazur et al. (2006). DFZ = Dolsk Fault Zone; OFZ = Odra Fault Zone. C - Borehole heat flow measurement sites and resulting contours of surface heat flow in Poland. Modified from Bujakowski et al. (2016), using data from Szewczyk and Gientka (2009). Plus and minus signs are used to aid interpretation in grayscale; for the colour diagram, see the online pdf version.

Figure 5 Comparison of fluvial archives in different parts of the River Vistula system. A – location; B – Transect through the valley of the River Dunajec, central Carpathians (modified from Zuchiewicz, 1992, 1998); C –. Transect through the valley of the River San (after Starkel, 2003); D – Idealized transverse sequence through the deposits of the Middle Vistula, based on data from upstream (Mojski, 1982) and downstream (Zarski, 1996; Marks, 2004) of Warsaw.

Figure 6 Distribution of provenance indicator materials. Modified from Czerwonka and Krzyszkowski (2001).

Figure 7 Location of pre-glacial sites (identified by number, with different symbols for the various formations, which represent different river systems). For locality names see Fig. 8. Modified from Czerwonka and Krzyszkowski (2001).

Figure 8 Occurrence of the different pre-glacial fluvial formations and their constituent members, showing which are present at the various localities. Numbers and symbols correspond with those in Figs 7 and 9–12. Modified from Czerwonka and Krzyszkowski (2001).

Figure 9 Palaeodrainage during emplacement of Member I deposits. Numbers and symbols correspond with those in Figs 7 and 8. Modified from Czerwonka and Krzyszkowski (2001).

Figure 10 Palaeodrainage during emplacement of Member II deposits. Numbers and symbols correspond with those in Figs 7 and 8. Modified from Czerwonka and Krzyszkowski (2001). For key see Fig. 9.

Figure 11 Palaeodrainage during emplacement of Member III deposits. Numbers and symbols correspond with those in Figs 7 and 8; for key see Fig. 9.

Figure 12 Palaeodrainage during emplacement of Member IV deposits. Numbers and symbols correspond with those in Figs 7 and 8; for key see Fig. 9.

Figure 13 Comparison between the fluvial archives from the Sudetes, in the form of the Nysa Kłodzka (Krzyszkowski *et al.,* 1998*,* 2000), and the River Don in the vicinity of Voronezh, Russia (showing suggested MIS correlations; see also Fig. 3D and Matoshko *et al*. (2004), who provided further stratigraphical details.

Table 1 Characteristic clast data (gravel petrography and heavy mineralogy) used in differentiation of Ziębice Group formations

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Manuscript

Drainage evolution in the Polish Sudeten Foreland in the context of European fluvial archives

Dariusz Krzyszkowski[1], David R. Bridgland[2 +], Peter Allen[3], Rob Westaway[4], Lucyna Wachecka-Kotkowska[5], Jerzy A. Czerwonka[6]

[1] Institute of Geography and Regional Development, University of Wrocław, Pl. Uniwersytecki 1, 50-137 Wrocław, Poland. E-mail: dariusz.krzyszkowski@uwr.edu.pl

[2] Department of Geography, Durham University, DH1 3LE, UK. E-mail: d.r.bridgland@durham.ac.uk

[3] 13 Churchgate, Cheshunt, Hertfordshire, EN8 9NB. E-mail: peter.allen6@virgin.net

[4] School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK. E-mail: robert.westaway@gla.ac.uk

[5] Faculty of Geographical Sciences, Department of Geomorphology and Palaeogeography, University of Łódź, 90–139 Łódź, Narutowicza 88, Poland. E-mail: lucyna.wachecka@geo.uni.lodz.pl

[6] Wejherowska 9/2, 54-239 Wrocław, Poland. E-mail: jerzy.czerwonka@gazeta.pl

ABSTRACT:

Detailed study of subsurface deposits in the Polish Sudeten Foreland, particularly with reference to provenance data, has revealed that an extensive pre-glacial drainage system developed there in the Pliocene – Early Pleistocene, with both similarities and differences in comparison with the present-day Odra (Oder) system. This foreland is at the northern edge of an intensely deformed upland, metamorphosed during the Variscan orogeny, with faulted horsts and grabens reactivated in the Late Cenozoic. The main arm of pre-glacial drainage of this area, at least until the early Middle Pleistocene, was the palaeo-Nysa Kłodzka, precursor of the Odra left-bank tributary of that name. Significant pre-glacial evolution of this drainage system can be demonstrated, including incision into the landscape, prior to its disruption by glaciation in the Elsterian (Sanian) and again in the early Saalian (Odranian), which resulted in burial of the pre-glacial fluvial archives by glacial and fluvio-glacial deposits. No later ice sheets reached the area, in which the modern drainage pattern became established, the rivers incising afresh into the landscape and forming post-Saalian terrace systems. Issues of compatibility of this record with the progressive uplift implicit in the formation of conventional terrace systems are discussed, with particular reference to crustal properties, which are shown to have had an important influence on landscape and drainage evolution in the region.

Keywords Pliocene – Early Pleistocene, Ziębice Group, Elsterian glaciation, Odranian (early Saalian) glaciation, palaeodrainage, crustal properties, Polish Sudetes

INTRODUCTION

The Sudeten (Sudety) Mountains, or Sudetes, form a NW–SE-trending range with its western end in Germany and separating SW Poland from the Czech Republic (Czechia). With its highest peak reaching 1603 m, this represents an uplifted block of rocks metamorphosed during the Variscan orogeny, in the late Devonian to early Carboniferous (Don and Zelaźniewicz, 1990). The Variscan involved complex faulting and thrusting, forming horsts and graben-basins, the latter infilled during later tectonically quiescent geological episodes, prior to significant reactivation of these structures in the Neogene–Quaternary (Oberc 1977; Dyjor, 1986, Mignoń, 1997). The foreland region north of these mountains, into which these structures extend, is drained by the Odra (Oder) and several of its left-bank tributaries, the main river flowing NW and then northwards, forming the western boundary of Poland, towards the Baltic (Fig. 1). An earlier, somewhat different drainage pattern in the Sudeten Foreland is evident from the subsurface preservation of buried valley fragments, recognized from boreholes and quarries and now largely buried by glacigenic and later fluvial sediments (Krzyszkowski *et al*., 1998; Michniewicz, 1998; Przybylski *et al*., 1998). It is apparent, therefore, that this drainage system was disrupted by glacial advances of Scandinavian ice from the north and NW (Krzyszkowski, 1996; Krzyszkowski and Ibek, 1996; Michniewicz, 1998; Salamon, 2008; Salamon *et al*., 2013; Fig. 1). The drainage has also been disrupted during the Quaternary by slip on the Sudeten Marginal Fault, the effects of which are readily visible in terms of vertical offset in terrace heights either side of the faultline (e.g., Krzyszkowski *et al*., 1995, 1998, 2000; Krzyszkowski and Bowman, 1997; Krzyszkowski and Biernat, 1998; Krzyszkowski and Stachura, 1998; Migoń et al., 1998; Štěpančíková *et al*., 2008; cf. Novakova, L., 2015). To these glacial and tectonic influences can now be added the effects on Quaternary landscape evolution of a complex history of crustal behaviour, potentially related to the characteristics of the Proterozoic to Palaeozoic crust in the region, as will be discussed in this paper.

The repeated glaciation of this region has been well researched and is documented by the glacigenic deposits that form much of the surface cover, burying the evidence for the aforementioned pre-glacial drainage. The most extensive glaciation was that during the Elsterian, the ‘Sanian glaciation’ of Polish nomenclature (Marks, 2011). This glaciation, assumed to have occurred during Marine Isotope Stage (MIS) 12 (Krzyszkowski *et al*., 2015), may not have been the first within the study area, as there are well-developed cold-stage minima within the marine oxygen isotope record in the latest Early Pleistocene, in MIS 22, and the early Middle Pleistocene: especially MIS 16, represented by the Don glaciation in the northern Black Sea region (e.g., Turner, 1996; Matoshko *et al*., 2004). No pre-MIS 12 glacigenic deposits have been recognized in the Sudetic marginal region, however, and it is clear that any such glaciation was less extensive than that in the Elsterian. The next most extensive glaciation was the Early Saalian (Odranian), with a limit typically 0–18 km short of the Elsterian (Sanian) ice front (Fig. 1, inset); it is generally attributed to MIS 6 (Marks, 2011). Then followed the Late Saalian glaciation, termed the Middle Polish Complex or Wartanian, and the Weichselian (last) glaciation, the North Polish Complex or the Vistulian. The highest massifs within the Sudetes supported small-scale local Weichselian glaciers (Migoń, 1999; Traczyk, 2009) and such glaciers would also have existed during earlier major glaciations, albeit with little effect on foreland drainage evolution.

The study area coincides with the southern edge of the northern European glaciated zone in which fluvial drainage courses have been strongly influenced by repeated glaciation from the north. That zone, from the western Baltic states through Poland and into Germany, is characterized by broadly west–east aligned valleys that were formed when drainage from the south was deflected towards the Atlantic by ice sheets blocking the lower courses of the various Baltic rivers: the urströmtäler of Germany and pradolina of Poland (e.g., Kozarski, 1988; Marks, 2004). Deflection of drainage by the Elsterian and, later, by the Odranian ice is likely to have influenced the modern position of the river valleys in the lowland north of the Sudetic margin (Krzyszkowski,2001).

The major existing rivers of the Sudeten foreland have well-developed terrace systems that record valley incision since the most recent glaciation of the region, which was during the Odranian, given that the later Late Saalian (Wartanian) and Weichselian (Last Glacial Maximum: LGM) ice sheets failed to reach the mountain front (Fig. 1, inset). Terrace systems are well documented in the two largest Sudetic tributaries of the Odra, the Bystrzyca (Berg, 1909; Krzyszkowski and Biernat, 1998) and the Nysa Kłodzka (Zeuner, 1928; Krzyszkowski *et al*., 1998), as well as in several of the smaller systems. The Quaternary record in this area was thoroughly reviewed in a 1998 special issue of *Geologia Sudetica* (Krzyszkowski, 1998) that was dedicated to Frederick E. Zeuner, who conducted his doctoral research in the region (Zeuner, 1928; see online supplement, Fig. S1), from which he formulated many of his influential views on river-terrace formation (Zeuner, 1945, 1946, 1958, 1959). Since the formation of the Fluvial Archives Group (Add citation of the FLAG editorial paper), debate about the genesis of river terraces has led to a consensus that they are generally a result of uplift, with strong climatic and isostatic influences (e.g., Maddy, 1997; Antoine *et al*., 2000; Bridgland, 2000), the latter seen to vary in relation to crustal type (Westaway *et al*., 2003, 2006, 2009; Bridgland and Westaway, 2008a, b, 2012, 2014; Bridgland *et al*., 2012, 2017).

Landscape evolution in the study area has been complex, with combined influences from glaciation, active faulting and regional crustal processes. The present-day topography is almost entirely the result of post-glacial fluvial erosion, in combination with the various processes that modify valley-side slopes and convey sediment into valley bottoms. 'Post-glacial' in this region means post-Sanian (Elsterian) or post-Odranian (Early Saalian), these being the only Pleistocene glacials during which ice sheets are known to have reached the Sudetic Foreland (see above; Fig. 1, inset). The modern valleys have thus formed since these ice sheets encroached upon the region and their flanks preserve latest Middle Pleistocene–Late Pleistocene river-terrace sequences (Fig. 2). These valleys are incised into a landscape substantially formed in late Middle Pleistocene glacigenic deposits, including diamictons, outwash sands and gravels and lacustrine sediments (Krzyszkowski, 1998, 2013). Evidence from boreholes and quarry exposures has shown that this glacigenic sedimentation was overprinted onto a pre-glacial drainage system, recognizable as a complex pattern of palaeo-valleys now entirely buried beneath the modern land surface. Thus pre-glacial fluvial sediments, which have been attributed to the Pliocene, Lower Pleistocene and lower Middle Pleistocene, are generally buried beneath later Pleistocene deposits and occupy a relatively low position with the landscape, especially in basin situations (see above). This is in apparent conflict with the expectations of standard river-terrace stratigraphy, in which progressively older deposits would be anticipated in positions progressively higher above the modern valley floor. This standard terrace stratigraphy has, however, been shown to occur only in association with certain, albeit widespread and common, crustal types, as will be explained in the next section.

Relation of fluvial archives to crustal type

Westaway *et al*. (2003) made the important observation that classic river terrace staircases do not occur in regions of cold, ancient and densely crystallized crust, particularly the cratons that represent fragments of the earliest continental lithosphere. They attributed this phenomenon to the absence of mobile lower crust in such regions, which they realised was essential to provide a positive-feedback response to erosional isostatic uplift, the same uplift that has caused terrace staircases to form on younger crust, including in areas remote from tectonic influence (see Westaway, 2001, 2002, a, b; Westaway *et al*., 2002, Bridgland and Westaway, 2008a, b, 2014). Subsequent reviews of fluvial archives from different crustal provinces showed distribution patterns that can be related to crustal type; in this the northern Black Sea hinterland, ~1000 km to the ESE of the present research area, represents a valuable case-study region, where the range of dating proxies is exemplary (Bridgland and Westaway, 2008a, b, 2014; Bridgland *et al*., 2017; cf. Matoshko *et al*., 2004; Fig. 3). The significant differences in preservation patterns of fluvial archives between crustal provinces with different characteristics point to important contrasts in landscape evolution, in particular relating to the extent of valley incision (Westaway *et al*., 2003, 2009), as well as the propensity for loss of fluvial archives to erosional processes, which will be greater in areas of dynamic and rapidly uplifting crust. Investigations have led to the concept that these geomorphic effects are controlled by a combination of crustal properties, namely heat flow (see Fig. 4C) and the depth of the base of the felsic crustal layer, since these properties govern the thickness of the plastic crustal layer beneath the brittle upper part of the crust, the base of which corresponds to a temperature of ~350 °C. Thus, if this plastic layer is absent, as in cratonic regions, the crust is extremely stiff and thus ultra-stable. If the mobile layer is thick (thickness >~6 km), it plays a major role in isostatic adjustment, and continuous uplift occurs, at rates that vary in response to rates of erosional forcing and thus to climate change (see Fig. 3). On the other hand, if this layer has an intermediate thickness (~4–6 km), a more complex isostatic response occurs, characterized by alternations of uplift and subsidence, possibly because under such conditions the isostatic responses in the mobile lower crust and in the asthenospheric mantle occur at comparable rates but on different timescales (Westaway and Bridgland, 2014).

Different patterns of fluvial sediment preservation are indeed evident in Poland, and can be interpreted according to the different crustal regions within which they occur (see Fig. 4). The occurrence of buried Pliocene and Lower Pleistocene fluvial deposits, as reported in the present study region, has also been observed in the middle reaches of the Vistula river system (Mojski, 1982; Bridgland and Westaway, 2014; Fig. 5), the catchment of which accounts for 56% of Poland. The Middle Vistula flows across the East European Platform (EEP), a crustal province consolidated during the Early or Middle Proterozoic that is relatively stable in comparison with the younger crust to the west, including that beneath the Sudeten Mountains, which is part of the Variscan province, stretching from SW Poland to western Europe (southern England–Iberia; Fig 4). Further SE within the EEP, patterns of fluvial-archive preservation in which older deposits are buried by younger terraced sequences have again been observed, for example in the valley of the River Don, one of the northern Black Sea rivers, near Voronezh (Matoshko *et al*., 2004; Bridgland and Westaway, 2008a, b, 2014; Fig. 3). The alternation between uplift and subsidence implicit in these preservation patterns has been ascribed to the properties of the crust of the EEP; such crust is highly consolidated and relatively cold, with a lower mobile layer of limited thickness (probably a few kilometres at most), making it very much less dynamic than younger crustal types (Westaway and Bridgland, 2014; Bridgland and Westaway, 2017; cf. Kutas *et al*., 1979).

Further north, the Lower Vistula, in its course towards the Baltic, flows across a region that would appear to have experienced continuous subsidence during the late Middle and Late Pleistocene, as indicated by the stacking of younger Pleistocene deposits, including fluvial, glacial and even marine sediments, above older (cf. Marks, 2004). This could reflect the wider influence of isostatically induced subsidence of the long-standing depocentre of the Baltic basin, where the crust has been progressively depressed beneath the sedimentary load. In marked contrast there are areas in the extreme SE of Poland, in the uppermost Vistula catchment, which display the only extensive staircases of river terraces in the country, similar to those on the younger, more dynamic crust of NW Europe. These terrace staircases (Fig. 5) can be found in the catchments of the Rivers Dunajec (Zuchiewicz, 1992; Olszak, 2011) and San (Starkel, 2003), as well as in other tributaries of the Vistula that drain the continental crust forming the Western Carpathian Mountains (e.g., Zuchiewicz, 2011; Pliszczyńska, 2012). These archives generally occur on crust bordering the Western Carpathians that was affected by the Caledonian orogeny and is thus more dynamic than that of the EEP. (For a description of the Late Cenozoic palaeogeographical evolution of this area see Brud, 2004.) As Bridgland and Westaway (2014) noted, the headwaters of the San are close to those of the Dniester, a river flowing southwards to the Black Sea that has an impressive and well-dated terrace staircase (Matoshko *et al*., 2004; Fig. 3B). Thus, despite their flowing in opposite directions, the San and the Dniester have similar styles of fluvial archive preservation, attributable to the nature of the crust in that region rather than hydrological or base-level influences (cf. Bridgland and Westaway, 2014). Elsewhere in Poland there is localized downwarping as a result of salt diapirism, particularly at Bełchatów, near Łódź (Krzyszkowski, 1995; Krzyszkowski and Szuchnik, 1995; Wieczorek *et al*., 2015).

Bridgland and Westaway (2014) suggested that, although the prevalence of stacked sequences in northern Poland might reflect proximity to the Baltic Basin, aspects of the fluvial archive preservation pattern in Central Poland that have traditionally been attributed to the effects of glaciation, or glaciation interspersed with marine transgression (e.g., Marks, 2004), might instead result from the characteristics of the crust. They envisaged three provinces within the Vistula: (1) an upstream, uplifting province, with well-developed terraces, (2) a central province in which the comparative stability of the EEP is dominant and (3) a downstream (northern) province with increasing influence of subsidence around the Baltic Basin and the effects of repeated glaciation.

The fluvial sedimentary archives in parts of the Sudetic foreland suggest inversion in vertical crustal movement, with alternation of subsidence and uplift, as surmised previously in systems such as the Don (Westaway and Bridgland, 2014; Bridgland *et al*., 2017; Fig. 3D). In previous reviews of the preservation patterns shown by fluvial archives, in which causal linkages have been observed with crustal type, such archives indicative of alternating subsidence and uplift were found to be associated commonly with Early or Middle Proterozoic crustal provinces with thick ‘roots’ of mafic material at the base of the crust, restricting the thickness of the mobile lower crustal layer (Westaway and Bridgland, 2014; Bridgland *et al*., 2017). In the Sudetes this phenomenon is apparent in basinal areas, which are separated by structural ridges (horsts) of older, generally crystalline rocks (Dyjor, 1986; see above).

EVIDENCE FOR PRE-GLACIAL RIVER SYSTEMS IN THE SUDETEN FORELAND

Quarrying and boreholes have allowed the reconstruction of considerable detail with regard to river sytems that existed in the Sudetic Foreland in pre-glacial times (i.e., prior to the Elsterian ice advance, which is the meaning of pre-glacial in this region). It should be noted, however, that this reconstruction is based on small 'windows' of subsurface evidence, providing limited scope for detailed reconstruction of areal three-dimensional form. Beneath the Sanian and Odranian glacial deposits, fluvial sediments of several different types have been recorded, much work having been done in order to characterize and distinguish these, in particular clast-lithological analysis of their gravel components and heavy-mineral analysis of sand grains (Czerwonka *et al*., 1994; Krzyszkowski and Bowman, 1997; Krzyszkowski *et al*., 1998; Przybylski *et al*. 1998; Krzyszkowski, 2001; Krzyszkowski and Karanter, 2001; Krzyszkowski, 2013). Many of these early fluvial deposits are kaolinitic, from the weathering of gneiss, gabbro, serpentinite, schist and other feldspathic rocks, which, in company with a dominance of rudaceous quartz, gave rise to the term 'white gravels'; they have also been referred to as the 'preglacial series' (Dyjor 1983, 1986, 1987a, b, 1993; Jahn *et al*. 1984; Dyjor *et al*. 1992). The matching of these components to source areas is illustrated in Fig. 6. They lie above the Upper Miocene – Lower Pliocene Poznań (Clay) Formation , sometimes with channel or palaeo-valley geometries apparent from the subsurface data (Ciuk and Piwocki, 1979; Ciuk and Pożaryska, 1982; Peryt and Piwocki, 2004). Indeed, there is some evidence of incision and even terrace formation within the preglacial sequence (see online supplement, Figs S2 and S3), much of which is however a continuation of the stacked basin-fill represented by the Neogene Poznań Formation. The pre-glacial fluvial deposits can be collectively described under the name Ziębice Group, this being the amalgam of several formations, representing different pre-glacial river systems, defined by their heavy mineral content and non-quartz gravel-clast petrography (Czerwonka and Krzyszkowski, 2001; Table 1; Figs 7 and 8). The Ziębice locality in central Poland, formerly called Münsterberg, was where fluvial 'white gravel' sediments, lacking Scandinavian material, were first described (Jentzsch and Berg, 1913; Frech, 1915; Lewiński, 1928, 1929; Zeuner, 1928; Krzyszkowski *et al*., 1998; Przybylski *et al*., 1998;Czerwonka and Krzyszkowski, 2001; online supplement Fig. S1).

Emplacement of the Ziębice Group as a whole can probably be attributed in part to increased mountain uplift and active faulting in the Sudetes and their foreland, perhaps resultant from the global climatic cooling that characterized the mid-Pliocene (e.g., Westaway *et al*., 2009); downthrown fault basins would have guided the main drainage lines. Each component formation represents sequences deposited by a specific fluvial system originating in the Sudeten Mountains. Within the group as a whole, four informal members (I–IV) have been recognized (Czerwonka and Krzyszkowski, 2001), their distinction being broadly age dependent, which is why they have not been formally defined, although there are no means for precise dating. These members are variously represented within the different formations, only two of which have all four members (Table 1; Fig. 9), with each numbered member believed to have been formed approximately synchronously in the different rivers across the region. The supposed ages of the members are relative and rely on superposition (see online supplement) and sporadic but rare preservation of biostratigrahical evidence (Czerwonka and Krzyszkowski, 2001; see below). Supplementary evidence for distinguishing between the members comes from erosional hiatuses at the bases of Members 1, III and IV and for the distinct widening of the valley systems between Members I and III (Czerwonka and Krzyszkowski, 2001; compare Figs 9 and 10). The sedimentology and range and type of facies suggests a meandering fluvial regime for Members I – III, especially away from the mountain front, and a braided river envrionment for member IV (Czerwonka and Krzyszkowski, 2001). Systematic analyses have been undertaken from exposures and boreholes, including sand heavy mineralogy and gravel clast lithology, arguably the most valuable, combined with particle-size analysis, quartz (sand) grain angularity–roundness analysis and palaeocurrent measurements (Czerwonka *et al*., 1994; Krzyszkowski and Bowman, 1997; Przybylski *et al*. 1998; Krzyszkowski *et al*., 1998; Krzyszkowski and Karanter, 2001; Krzyszkowski, 2001; Table 1; see online supplement).

As summarized in Table 1, six main pre-glacial river systems have been recognized, each with characteristic heavy-mineral signatures and some with distinctive clast-lithological assemblages. These are (1) the Palaeo-Odra, characterized by a zircon–rutile heavy-mineral assemblage and gravel clasts of Carpathian origin, represented by the Chrząszczyce Formation, (2) the Palaeo-Biała Głuchołaska (staurolite-amphibole mineralogy), represented by the Dębina Formation, (3) the Palaeo-Nysa Kłodzka (staurolite–garnet/amphibole–garnet), represented by the Kłodzko–Stankowo Formation, (4) the Palaeo-Bystrzyca (zircon, sillimanite and various) , represented by the Bojanice Formation (as well, potentially, as the Pogalewo and Wichrów formations), (5) the Palaeo-Strzegomka (sillimanite–garnet), represented by the Mielęcin–Wołów Formation, and (6) the Palaeo-upper Bóbr/Kaczawa (andalusite), as represented by the Rokitki–Bielany Formation. Of these the Palaeo-Nysa Kłodzka appears to have been the trunk river throughout the 'pre-glacial' period (see Figs 9–12). Evidence for four additional systems has been recognized but is more localized; these are the Palaeo-Wierzbiak, represented by the Snowidza Formation, the Palaeo-Budzówka, represented by the Ząbkowice Formation, and two other local rivers, near Bardo/Potworów and Szydłów, identified only by gravel-clast analysis (Przybylski *et al*., 1998) and impossible to match with existing rivers.

These drainage systems probably originated during the Early Miocene, since the Miocene–Lower Pliocene Poznań Formation is thought to represent the low-energy sediments of anastomosing river or inland-delta environments (Peryt and Piwocki, 2004), which, from the available evidence, persisted with relatively little change until disrupted by glaciation in the Middle Pleistocene. It should be noted that those formations with 'double-barrelled' names (Kłodzko–Stankowo, Mielęcin–Wołów and Rokitki–Bielany) are traced for significant distances from the mountain front and have 'proximal' type locailties (giving the first part of the name) near the Sudetes and 'distal' type localities further downstream. The lack of Scandinavian clasts in these various pre-glacial fluviatile sediments distinguishes them from the glacial deposits (Elsterian and Lower Saalian) and from the terrace deposits of the post-glacial rivers, in which reworked glacially-derived material occurs (Schwarzbach, 1955; Jahn, 1960, 1980; Czerwonka and Krzyszkowski, 1992; Krzyszkowski 1995, 2013; Czerwonka *et al*. 1997).

Turning to the informal members, I–III have generally been attributed to the Pliocene–lowermost Pleistocene and IV to the lower Middle Pleistocene (Cromerian Complex). This seemingly points to a hiatus spanning much of the first half of the Pleistocene, although there may well be unrecognized representation of this interval amongst sequences that are notoriously difficult to date and which include components that have yet to be defined and characterized fully. Alluvial-fan sediments occur within all members at localities near the mountain front. The Pliocene members can be presumed to represent rivers draining northwards to join the erstwhile Baltic River, which existed as a major east–west flowing system at that time (e.g., Gibbard, 1988). The drainage represented by members I–III was sinuous, as indicated by sediment geometry (Figs 9–11) as well as sedimentology (see above), in contrast to the braided-river deposits of member IV. This perhaps indicates sedimentation of members I–III during periods of temperate and relatively moist climate, whereas member IV records more variable conditions, with evidence of both temperate (interglacial) and cold (periglacial) climates. This contrast could, indeed, be a reflection of climatic cooling in the Early Pleistocene, a trend that would culminate in the glaciations of the Baltic region in the Middle Pleistocene.

The evidence for different pre-glacial rivers, precursors of the modern drainage of the Polish Sudetic margin, will be described in east to west sequence, starting with the Palaeo-Odra, the post-glacial successor of which forms the principle arm of the modern regional drainage.

The Palaeo-Odra (Chrząszczyce Formation)

Within the research area the Chrząszczyce Formation, which is thought to represent the main palaeo-Odra river, is restricted to locations >20 km from the Sudetic mountain front, entering the region from the south-east in the area south of Opole (Figs 7 and 9–11). It has been studied at relatively few localities at and to the west of Opole and west of Wrocław, with representation only of Members I–III (Table 1; Figs 9–11). Only at Chrząszczyce, the type locality ~5 km SSW of Opole (Figs 7 and 8; online supplement, Fig. S4), have all three of these members been observed. Gravel analysis has only been possible from the Member III sediments at Ose (Figs 7 and 8), where the occurrence of Carpathian siliceous rocks (silicified limestones and sandstones, radiolarites, etc.) amongst a quartz-dominated assemblage provides important support for origin within the Odra catchment (Czerwonka and Krzyszkowski, 1992). There are subtle changes in heavy mineralogy between members I–III (Table 1): all have assemblages dominated by zircon, with staurolite and tourmaline, plus garnet in members I and III and rutile in II and III. Member III at Tulowice has yielded plant macrofossils (leaves and fruit) with close affinity to those of the underlying uppermost Poznań Formation: i.e. not older than late Pliocene (Przybylski *et al*., 1998).

The Palaeo-Biała Głuchołaska (Dębina Formation)

This is a relatively minor formation, representative of a subordinate river, the most south-easterly that drained the Sudetes Mountains within the study area. Only Member I has been recognized, made up of quartzose gravels with a staurolite–amphibole heavy-mineral suite (Table 1). It has been recognized at a small number of sites from Strybowice to the type locality at Dębina, ~30 km SSW of Opole (Fig. 7). Although its occurrences trace a course from SSW to NNE, the petrography of the Ziębice Group as a whole, plus knowledge of the bedrock surface, suggests that the palaeo-river turned sharply to the NW in the vicinity of Dębina to a confluence with the Palaeo-Nysa Kłodzka, rather than continuing NNE-wards to join the palaeo-Odra (Fig. 9). It uncertain whether any of the Dębina Formation sequences continue upwards into Member II but the existence of a Palaeo-Biała Głuchołaska flowing NE from the Sudetes has been reconstructed for that time-span, joining a considerably wider Palaeo Nysa Kłodzka (Fig. 10) in comparison with that reconstructed for Member I. The continued existence of such a river during later times can only be speculative (Krzyszkowski *et al*., 1998).

The Palaeo-Nysa Kłodzka (Kłodzko–Stankowo Formation)

This formation accounts for the vast majority of the pre-glacial series, being represented at sites over an area of considerable width from its proximal type locality (see above) at Kłodzko, in the south (in the Kłodzko [intermontane] basin) eastwards towards (but not reaching) Opole and then northwards to Wrocław and beyond (Fig. 7). This distribution demonstrates the dominance of the Palaeo-Nysa Kłodzka during pre-glacial times (Figs 9–12). Its distal type locality, at Stankowo (Fig. 7, site [1]), is at the northern periphery of the study area, ~20 km NE of Leszno (Fig. 1; supplement, Fig. S5). The recognition of this formation is based on a gravel clast lithology reflecting the characteristic geology of the Kłodzko Basin, including gneisses and other cystalline rocks, notably porphyries, together with Mesozoic sandstones and 'flint' (Table 1; Figs 6 and 7). The heavy mineralogy is complex and regionally variable, also changing from staurolite–garnet dominance in Members I–III to garnet and amphibole in Member IV (Table 1).

With the formation represented at >50 sites (Figs 7 and 8), the comparative distribution of the different members reveals significant changes in the course of this trunk river, with Member I tracing a relatively confined WSW–ENE reach from Kłodzko to Gnojna (Fig. 7 [35]), diverging northwards from the modern Nysa Kłodzka course, and then a wider but still confined reach (in comparison with younger members) from here to Wrocław and Taborek (Fig. 7 [3]), by which point the Palaeo-Odra was converging from the east (Fig. 9). At the time of Member II emplacement, both reaches were considerably wider, that east of Kłodzko spreading southwards to envelop the course of the modern river, whereas in its northward-flowing reach it extended eastwards to meet the Palaeo-Odra ~10 km west of Opole and spread out north-eastwards across the foreland to encompass an area from that of its earlier course across to that around Ostrów Wielkolpolski and beyond (Fig. 10).

By Member III times the palaeo-river had been diverted from near Ziębice into a more confined northerly course towards Wrocław, sweeping across the area south and east of this city towards Ostrów Wielkolpolski, turning northwards as it met the palaeo-Odra, by this time of almost equal size, and other drainage from the east, possible the 'Bełchatów River', as recognized in central Poland at the large lignite quarry by the same name (Krzyszkowski, 1995; Krzyszkowski *et al*., 2015; Fig. 11).

By member IV times there is little evidence that the Palaeo-Nysa Kłodzka extended north-eastwards of the modern Odra course, except in the area NW of Wrocław. This suggests that a Palaeo-Odra closely following its modern valley had come into existence by this time, perhaps as a result of early Middle Pleistocene glaciation (Zeuner, 1928; Fig. 12), otherwise poorly documented because its extent was less than the ice sheets of the Elsterian, the suggestion being that the line of the Odra across the northern edge of the Sudetic foreland might be of early ice-marginal ('pradolina') origin (see above).

The Palaeo-Budzówka (Ząbkowice Formation)

The Budzówka is a minor left-bank tributary of the Nysa Kłodzka, joining the latter ~20 km downstream of Kłodzko. Its pre-glacial forebear is represented by probable Member IV deposits that occur at two sites, the Ząbkowice type locality [73] and Albertów [107] (Figs 7, 8 and 12). These deposits are characterized by gravel in which the dominant clast type is Sowie Góry gneiss, with subordinate quartz and other siliceous rocks; there is a garnet–amphibole heavy mineral suite (Table 1).

The Palaeo-Bystrzyca (Bojanice, Wichrów and Pogalewo formations)

The River Bystrzyca, which is the next important Odra tributary moving to the NW along the Sudetes margin, flows through the town of Świdnica on its SW–NE course towards a confluence with the trunk river ~7 km NW of Wrocław; ~15 km upstream of that confluence it receives a substantial left-bank tributary, the Strzegomka (Fig. 7). Pre-glacial versions of both these rivers are represented amongst the Ziębice Group sediments, although with courses that appear to have been entirely separate until the trunk river was reached; at that time the latter was the Palaeo-Nysa Kłodzka (Figs 9–12.

Three different pre-glacial formations are potential products of deposition by the palaeo-Bystrzyca. First is the Bojanice Formation, of which Members II, III and possibly IV occur in the vicinity of Świdnica, in the form of porphyry-rich quartz gravels, also containing melaphyre, Sowie Góry gneiss and quartzite, although the uppermost (potentially Member IV) deposits lack rudaceous components (Table 1). The heavy minerology of these upper deposits is dominated by sillimanite, whereas that of the gravelly facies is dominated by zircon and garnet (Table 1).

The Wichrów Formation is represented by a small group of sites, of which the Wichrów type locality is one, ~20–30 NNE of Świdnica, in the modern catchment of the Strzegomka tributary (Figs 7 and 8[45]). Only the basal part of the sequence is present, with Member I and a possible extension into Member II, sharing the zircon-rich mineralogy of the lower members within the Bojanice Formation (Table 1). Despite its modern location within the tributary catchment, the Wichrów Formation sites seem likely to represent a downstream continuation of the palaeo-Bystrzyca from the Świdnica area (Fig. 9).

The Pogalewo Formation is identified in the area much further from the mountain front, to the north of the modern River Odra downstream of Wrocław. Members I, II and III are all recognized, albeit at different sites (Figs 7 and 8). Member I is identified only at the Pogalewo type locality [31], on the northern side of the Odra valley ~30 km downstream of Wrocław (Fig. 9; online supplement Fig. S3). It is the only member of this formation to have yielded rudaceous material, this being quartz gravel with local flint and a trace of porphyry; it has a zircon–tourmaline-rutile heavy mineralogy (Table 1).

Further upstream (both within the modern Odra system and the pre-glacial palaeovalley), ~5–10 km east from Pogalewo, is a small cluster of sites that represent Member III, which have the same dominant mineralogy but with additional epidote, kyanite, amphibole and staurolite (Table 1). The intervening Member II, although perhaps represented by the uppermost deposits at Pogalewo, is optimally recorded much further downstream, at Chałupki [51], ~30 km SW of Głogów (Fig. 7). The mineralogy of this member is different again, with kyanite in addition to the zircon–tourmaline–rutile suite but lacking epidote, amphibole and staurolite (Table 1). Although given a separate name, the deposits of the Pogalewo Formation are most readily interpreted as more distal (downstream) palaeo-Bystrzyca sediments, implying a separate northward course far from the mountain front, especially during emplacement of Member II (Fig. 10).

The Palaeo-Strzegomka (Mielęcin–Wołów Formation)

As noted above, the modern River Strzegomka joins the Bystrzyca ~15 km upstream of the confluence between the combined river and the Odra. Prior to the Middle Pleistocene, however, it seems likely that the precursors of these rivers maintained separate courses to the trunk palaeo-Nysa Kłodzka (Figs 9–11). The palaeo-Strzegomka is represented by the Mielęcin–Wołów Formation, as is apparent from the preservation of that formation at sites close to the mountain front within the modern Strzegomka catchment, including the Mielęcin (proximal) type locality (Fig. 7 [47]; online supplement Fig. S6). The deposits here comprise quartzose–porphyry-rich gravels representing Members I–III, also containing local siliceous rocks (flint), conglomerate, spilite, diabase, greenschist and quartzite from the Wałbrzych Upland, Strzegom granite and local schist (phyllite), as well as a sillimanite–garnet heavy-mineral suite (Table 1; Fig. 6). The distal type locality, at Wołów, where only Member I is represented, is located north of the modern Odra, approximately equidistant between Wrocław and Głogów (Fig. 8 [32]). Member IV of the Mielęcin–Wołów Formation is recognized at two sites, Sośnica [43], in the modern Bystrzyca valley upstream of its confluence with the Strzegomka, and Brzeg Dolny 3 [108], north of the modern Odra, where it overlies Member I of the Kłodzko–Stankowo Formation (Figs 8 and 12; online supplement Fig. S2). This upper member lacks gravel but is characterized by a sillimanite-dominated heavy mineralogy (Table 1).

The Palaeo-upper Bóbr/Kaczawa (Rokitki–Bielany Formation)

The next Odra tributary north-westwards along the mountain front is the River Kaczawa, which has a confluence with the trunk river ~20 km downstream from Legnica. Its pre-glacial forebear, however, had a catchment that penetrated deeper into the mountain zone, including areas now drained by the headwaters of the Bóbr, a yet more westerly Odra tributary that flows NW from the Sudetes to join the trunk river well to the west of the study area (Fig. 7). This is indicated by the characteristic clast lithology of the Rokitki–Bielany Formation, which has rudaceous sediments representing all four members with contents that show drainage from the Bóbr catchment: these are quartzose gravels with porphyry, Karkonosze granite, crystalline rocks, schist, quartzite, with the addition, in Member IV, of Cretaceous sandstone and Wojcieszów limestone (Table 1). The heavy mineralogy is characterized by andalusite and tourmaline, with the addition of epidote in Member I and of kyanite, zircon, garnet, amphibole and sillimanite in Member IV (Table 1). The proximal type locality of this formation, Rokitki [55], is situated in the Kaczawa valley, ~ 8 km upstream of its catchment with the Nysa Szalona, a right-bank tributary (Fig. 7). Members I–III are attributed to a palaeo-Bóbr–Kaczawa that drained northwards, to the west of Legnica, towards Głogów (Figs 9–11). Member IV of this formation is recognized only at sites in the interfluve area between the Strzegomka and the Kaczawa, at Kępy [95] and Bielany [50] (Fig. 12; online supplement Fig. S7), where it overlies older members of the Mielęcin–Wołów Formation that represent the earlier northward drainage of the palaeo- Strzegomka (see above; Figs 1 and 9). Bielany is the distal type locality of th#e Rokitki–Bielany Formation, although it lies further south than Rokikti (Fig. 7 [50]). The most northerly Mielęcin–Wołów site is Polkowice [62], <20 km south of Głogów, where only Member III occurs (Figs 7, 8 and 11).

Other minor rivers

Fluvial tracts of more localized rivers have been traced. The Snowidza Formation, known from a single locality (Fig. 8), represents a possible ancestral River Wierzbiak, the modern river of the same name being a right-bank Kaczawa tributary that joins the latter ~10 km downstream of Legnica (Fig. 7). The sole representation of the Snowidza Formation is probably equivalent to Member I of other Ziębice Group formations (Fig. 8). The deposits of two other local rivers have been recognized (Fig. 7) in the vicinity of Bardo [96–97], Potworów [98–99]and Szydłów [101] on the basis of gravel-clast petrography (Przybylski *et al*., 1998). These occurrences are again of probable Member I affinity (Fig. 8).

DATING THE ZIĘBICE GROUP

Much of the dating of the individual components of the Ziębice Group is dependent on their relative stratigraphical positions within the sequence and their relation to the underlying Poznań Formation and overlying Middle Pleistocene glacial deposits. At Gnojna (~55 km NE of Kłodzko; Fig. 7: [35]) palynological analyses of the uppermost member of the Poznań Formation, immediately below member I of the Kłodzko–Stankowo Formation, have yielded a flora indicative of the earliest Pliocene (Sadowska, 1985; Badura *et al*., 1998a). A similar Early Pliocene flora has been obtained from Sośnica (Stachurska *et al*., 1973; Sadowska, 1985, 1992; Fig. 7 [43]), where it is overlain by member IV of the Mielęcin–Wołów Formation. Macrofossil analysis of the Poznań Formation at Ziębice, Sośnica and Gnojna have revealed the presence of Late Miocene to Early Pliocene leaves and fruits (Kräuzel, 1919, 1920; Łańcucka-Środoniowa *et al*., 1981; Krajewska, 1996). These occurrences provide a maximum (limiting) age for the Ziębice Group

A very few sites have yielded palaeobotanical remains from sediments of Ziębice Group formations. At Kłodzko (Figs 7 and 8 [68]; online supplement Fig. S8) an organic deposit was recorded at the top of a sequence that potentially represented member II and/or member III of the Kłodzko–Stankowo Formation (cf. Krzyszkowski *et al*., 1998). Pollen and macrofossils from this deposit have been attributed to the Reuverian Stage of the Late Pliocene (Jahn *et al*., 1984; Sadowska, 1995). Poorly preserved leaf macrofossils from member III of the Chrząszczyce Formation at Tułowice (~15km SW of Opole; Figs 7 and 8 [74]) represent a temperate-climate assemblage of trees and shrubs that cannot be dated with precision but is unlikely to be older than late Pliocene (Przybylski *et al*., 1998). The fossiliferous deposits here are thus attributed to the palaeo-Odra, although they overlie member II deposits that are attributed to the palaeo-Nysa Kłodzka and thus the Kłodzko–Stankowo Formation (Fig. 8). Further west, nearer the modern Nysa Kłodzka and in sediments attributed to the Kłodzko–Stankowo Formation, organic remains and leaf impressions have been found at Niemodlin 2 [80] and Magnuszowiczki [83] in member II (Figs 7 and 8); Przybylski *et al*. (1998) noted that the leaf impressions occurred in laminated silty alluvial sediments.

Zeuner (1928, 1929) described pre-glacial organic deposits at Jonsbach (now Janowiec) that would appear to have been part of member IV of the Kłodzko–Stankowo Formation (Figs 2, 7 [72], 8 and 12): part of a pre-glacial fluvial (‘white gravel’) sequence ~11 m thick, located just downstream of the Sudeten Marginal Fault (cf. Krzyszkowski *et al*., 1998). The limited pollen record (Stark and Overbeck, 1932; Badura *et al*., 1998b; Krzyszkowski *et al*., 1998) lacks Tertiary relics and is thus suggestive of the early Middle Pleistocene (Cromerian Complex). Attempts to relocate these deposits and provide a more detailed analysis have proved unsuccessful.

This is meagre evidence upon which to base an age model for the Ziębice Group, but broad inference from these data points to Pliocene–earliest Pleistocene deposition of members I–III and to early Middle Pleistocene emplacement of member IV. That inference concurs well enough with the sedimentological evidence for a meandering fluvial regime during deposition of members I–III and a braided gravel-bed river at the time of member IV emplacement (Czerwonka and Krzyszkowski, 2001; see above), given that the change could readily be attributed to the greater severity of cold-stage climatic episodes in the early Middle Pleistocene, following the Mid-Pleistocene Revolution. The latter, which saw the transition to 100 ka glacial–interglacial climatic cyclicity (e.g., Maslin and Ridgwell, 2005), has been noted to have had a profound effect on valley evolution in many parts of the world, notably causing enhanced valley deepening and concomitant isostatic uplift (e.g., Westaway *et al*., 2009; Bridgland and Westaway, 2014;.cf. Stange *et al*., 2013).

POST-GLACIAL LANDSCAPE EVOLUTION OF THE SUDETIC MARGIN

Following the Middle Pleistocene glaciation of the Sudetic foreland, the present-day rivers, established in the courses they still occupy, have incised their valleys by varying amounts. In the vicinity of the Bardo Gorge (sites 96 and 97, Fig. 7), in an uplifting inter-basinal location, the Nysa Kłodzka has cut down >50 m below the level of the Odranian till, forming five terraces during the process (Krzyszkowski *et al*., 2000; Fig. 2A), presumably in response to post-Odranian regional uplift (Krzyszkowski and Stachura, 1997; Krzyszkowski *et al*., 1998, Migoń *et al*., 1998; Starkel 2014), perhaps with a component of glacio-isostatic rebound (cf. Bridgland and Westaway, 2014).

As Krzyszkowski *et al*. (1995, 2000) have shown, the amount of fluvial incision (and thus of uplift) differs markedly on either side of the Sudetic Marginal Fault, the displacement suggesting ~15–25 m of additional uplift on the upthrow side (related to continued elevation of the Sudeten Mountains) since formation of the ‘Main Terrace’, the oldest post-Elsterian river terrace. Previous authors have ascribed this main terrace to the Odranian, since it is overlain by till of that age (e.g., Krzyszkowski and Biernat, 1998; Krzyszkowski *et al*., 2000); it is essentially the starting point for post-glacial incision by the Sudetic marginal rivers such as the Bystrzyca and Nysa Kłodzka (Fig. 2). If attribution of the Odranian to MIS 6 is correct then several terraces have been formed during the relatively short interval represented by the Late Pleistocene. Dating evidence is generally lacking, however. The following is a general summary of the sequence:

i. Upper terrace (erosional /depositional) ~10–18 m above alluvial plain (MIS 6; Wartanian)
ii. Middle Upper terrace (depositional) ~4–8 m above alluvial plain (MIS 3; mid-Weichselian)
iii. Middle Lower terrace (depositional) ~2–5 m above alluvial plain (MIS 2; Vistulian/ Weichselian /LGM)
iv. Lower terraces of the recent alluvial plain (Holocene) - see Fig. 2.

DISCUSSION: PLIOCENE–QUATERNARY LANDSCAPE EVOLUTION IN THE POLISH SUDETEN FORELAND AND THE WIDER REGION

The landscape of Poland represents a mosaic of crustal provinces, as illustrated in Fig. 4A and in more detail in Fig. 4B. The boundaries between these provinces have been delineated by many studies, initially outcrop investigations, later borehole studies and, most recently, deep controlled-source seismic-profiling projects (e.g., Grad *et al*., 2002, 2003, 2008; Hrubcová *et al*., 2005; Malinowski *et al*., 2013; Mazur *et al*., 2015). NE Poland is thus known to be located within ancient (Early-Middle Proterozoic) continental crust overlying the relatively thick lithosphere of the EEP (see above). The boundary between this region and the younger crustal province to the SW was first identified in the late 19th century in territory now in SE Poland and western Ukraine by Teisseyre (1893; Teisseyre and Teisseyre, 2002). This boundary, nowadays known as the Teisseyre–Tornquist Zone (TTZ) or Trans-European Suture Zone, marks the suture of the Tornquist ocean, which formerly separated the ancestral continents of Baltica (to the NE) and Avalonia (to the SW), and closed during the Caledonian orogeny, when the crust SW of the TTZ experienced deformation (e.g., Grad *et al*., 2003). At a later stage, SW Poland, including the Sudetes, was deformed during the Variscan orogeny, the northern and eastern limits of the region thus affected being now concealed in the subsurface by younger sediments. Figure 4B indicates one interpretation of these limits; Grad *et al*. (2003) provide another. The Variscan orogeny in this part of Europe involved northward subduction of the Rheic ocean beneath the southern margin of Avalonia, followed by the continental collision between the Armorica continent (more specifically, its eastern part, Saxothüringia) and various microcontinents with Avalonia (e.g., Mazur *et al*., 2006). The Sudeten massif in the extreme SW of Poland, in the core of the Variscan orogeny, experienced pervasive deformation, metamorphisim, and granitic magmatism. This region was also affected at this time by NW–SE-oriented left-lateral strike-slip faulting (including slip on the Sudetic Boundary Fault and Intra-Sudetic Fault), creating a collage of fragmented crustal blocks of extreme complexity (e.g., Aleksandrowski *et al*., 1997; Aleksandrowski and Mazur, 2002; Franke and Żelaźniewicz, 2002; Gordon *et al*., 2005; Jeřábek *et al*., 2016; Kozłowski *et al*., 2016; Fig. 1). Much later, SE Poland was affected by Late Cenozoic plate motions, involving southward or south-westward subduction of the former Carpathian Ocean (Fig. 3B); as a result, the mosaic of continental fragments affected by the Variscan orogeny in what is now Slovakia (which were formerly located further southwest) became juxtaposed against SE Poland (e.g., Plašienka *et al*., 1997; Szafián *et al*., 1997; Stampfli *et al*., 2001, 2002; Von Raumer *et al*., 2002, 2003; Bielik *et al*., 2004; Schmid *et al*., 2004; Alasonati-Tašárová *et al*., 2009; Handy *et al*., 2014; Broska and Petrík, 2015). Thus the crustal structure of Poland is highly variable, reflecting the complex tectonic history of the wider region.

The ideas about different crustal types having very different landscape evolution histories presented above were developed without reference to fluvial sequences in Poland, although data from neighbouring countries, such as Ukraine, were taken into account, as exemplified by the example of the northern Black Sea rivers (Fig. 3). Application of these ideas to Poland, and in particular to the data under consideration in this paper, thus provides a valuable test of the underlying theories. This task has been facilitated by the aforementioned deep seismic projects, from which have been published crustal transects with the required spatial resolution; indeed, some of the transects combine crustal structure and heat flow, for example those across Poland from SW to NE presented by Grad *et al*. (2003). The first such transect, likewise combining crustal structure and heat flow, was prepared in a similar location by Majorowicz and Plewa (1979); comparison between the two indicates the technical progress over the intervening decades, although the main features identifiable in the modern cross-sections can also be resolved on the older one. One aspect of particular importance for the present investigation is identification (from its relatively high seismic velocity) of the presence of mafic underplating at the base of the crust. Such a layer remains rigid (or brittle) under the temperatures typically experienced (<~550 °C) and thus behaves mechanically as part of the mantle lithosphere, any mobile lower-crustal layer present being restricted to shallower depths in the felsic lower crust. The phenomenon was mentioned above in connection with Early or Middle Proterozoic crustal provinces in which fluvial archives point to past alternation subsidence and uplift.

The seismic transect studied by Grad *et al*. (2003) crosses the TTZ ~150 km NW of Warsaw with ESE–WSW orientation, revealing a layer of mafic underplating at the base of the crust persisting from here to a point ~100 km NW of Wrocław. According to Grad *et al*. (2003), emplacement occurred during magmatic rifting of eastern Avalonia from the Precambrian supercontinent Rodinia during the latest Proterozoic or Cambrian. This layer is up to ~10 km thick, its top locally as shallow as ~25 km depth; it evidently extends beneath the external part of the Variscides, including the high-heat-flow region around Poznań, depicted in Fig. 4C, but no long-timescale fluvial sequences are evident in this region due to the effect of multiple glaciations. The subparallel transect studied by Grad *et al*. (2008) starts just SW of the TTZ, ~170 km west of Warsaw, crosses the Czech–Polish border in the extreme SW of Poland, then through the NW extremity of the Czech Republic before entering Germany. It again reveals up to ~10 km of mafic underplating at the base of the crust, its top locally as shallow as ~22 km, persisting WSW for ~250 km and dying out in the vicinity of the Intra-Sudetic Fault Zone. Mafic underplating, with thickness up to ~8 km, its top locally as shallow as ~18 km, resumes in the western part of the Bohemian Massif near the Czech–German border, as the transect approaches Saxothüringia, the intervening crustal provinces (Barrandia, forming the central Bohemian Massif) being free of underplating. The NW–SE seismic transect across the Bohemian Massif, reported by Hrubcová *et al*. (2005), confirms the presence of underplating beneath Saxothüringia but not beneath Moldanubia (the SE Bohemian Massif) or Barrandia.

As already discussed, the structure of the Sudeten Mountains is complex; as a result of the Variscan left-lateral faulting it consists of small fragments of crustal blocks that have become juxtaposed. Jeřábek *et al*. (2016) have recently demonstrated that this process included transposition of Saxothüringian crust (presumably including its characteristic layer of mafic underplating) beneath fragments of Barrandia. It would thus appear that mafic underplating persists beneath much of the Sudeten Mountains region, as Majorowicz and Plewa (1979) inferred, even though this was not resolved in the Grad *et al*. (2008) study. The heat flow typically decreases southward across the Sudeten Mountains, reaching values of <70 mW m^{-2} in the Kłodzko area (Fig. 4C); it can thus be inferred that this effect, along with the presence of mafic underplating derived from Saxothüringian crust, constricts the mobile lower-crustal layer, resulting in the pattern of alternations of uplift and subsidence that are evident in the fluvial records, particularly in basinal areas (see above). A noteworthy record comes from Kłodzko [site 68], which gives its name to the Kłodzko Basin and is the proximal type locality of the Kłodzko–Stankowo Formation, which represents the pre-glacial River Nysa Kłodzka. Here in the basin the pre-glacial gravels extend to below river level, suggesting the sort of reversal in vertical crustal motion described above. This can be compared with the situation ~12km downstream at the Bardo Gorge, on the inter-basinal ridge (see above), where it is evident that uplift has been more continuous (Compare Figs 2A and 2B).

Another good example of the low level of the pre-glacial deposits in parts of the Sudetic Foreland, as well as their geomorphological inter-relationship, is the site at Brzeg Dolny in the Odra valley downstream of Wrocław [site 108], where Members I and II of the Kłodzko–Stankowo Formation occur in superposition, their base ~10 m above the level of nearby Holocene valley-floor sediments. Member IV of the Mielęcin–Wołów Formation (representing the palaeo- Strzegomka) occurs nearby, incised to a lower level. Given the tributary status of the palaeo- Strzegomka, this relationship implies rejuvenation between the Pliocene (Member I) and early Middle Pleistocene (Member IV), when the latter river traversed an area formerly occupied by the pre-glacial Nysa Kłodzka; this is a clear example of terrace formation within the pre-glacial sequence (see online supplement Fig. S2).

In some parts of the Sudetes, thick plutons of highly radiothermal granite were emplaced during the Variscan orogeny, their radioactive heat production resulting in local heat-flow highs; for example, Bujakowski *et al*. (2016) inferred temperatures as high as ~390 °C at 10 km depth beneath the Karkonosze granite pluton (see Fig. 6 for location). However, this is one locality where Jeřábek *et al*. (2016) inferred that the Variscan orogeny emplaced Saxothüringian crust beneath crust of Barrandian provenance, so that here it can be anticipated that the mafic underplating will constrict the mobile crustal layer, notwithstanding the high surface heat flow.

South of the Sudeten Mountains, in the Bohemian Massif, rivers such as the Vltava and Labe (affluents of the Elbe) have substantial terrace staircases (e.g., Tyracek *et al*., 2004), with no indications of alternations in vertical crustal motion. The heat flow in the central Bohemian Massif is ~50-60 mW m^{-2} (e.g., Čermák, 1979), less than in the Sudeten Mountains. However, as already noted, the crust in this region, up to ~35 km thick in Barrandia (in which the Vltava terrace staircase is located) and up to ~40 km thick in Moldanubia, is free of mafic underplating (Hrubcová *et al*., 2005). The felsic lower crust is thus much thicker in this region, and concomitantly much hotter near its base, than in the Sudeten Mountains. The different landscape response between these areas can thus be explained: the mafic underplating accounts, via the mechanism advocated by Westaway and Bridgland (2014), for the observed pattern of sedimentary archives in parts of the Sudetes; the importance of underplating is underlined by evidence for sustained upward vertical crustal motion, despite lower heat flow, in the central Bohemian Massif, where underplating is absent (cf. Štěpančíková *et al.,* 2008).

Wider crustal comparisons can also be made between fluvial sequences in the Sudeten Mountains and elsewhere in Poland. Comparison of Figs 4A and B indicates that the surface heat flow increases from ~70 mW m^{-2} at the external (northern) margin of the Carpathians to ~80 mW m^{-2} along the Poland-Slovakia border, for example along the upper reaches of the River San. No modern deep seismic profile in this area is known to the authors, but by analogy with other localities further NW it can be inferred that the region consists of ~40 km thick crust with ~10 km of mafic underplating (cf. Grad *et al*., 2003, 2008). However, during the Late Cenozoic plate convergence this crust became buried beneath up to ~7 km of young sediment (e.g., Oszczypko, 1997). The 'thermal blanketing' effect of this sediment will significantly raise the temperature in the underlying crust, reducing the constriction effect of the underplating on the thickness of mobile lower crust; 7 km of sediment of thermal conductivity 2 W m^{-1} °C^{-1} overlying crust in which the heat flow is 80 mW m^{-2} will raise the temperature in this bedrock by 7 km $\times$ 80 mW m^{-2} / 2 W m^{-1} °C^{-1} or ~280 °C. Westaway and Bridgland (2014) suggested an analogous explanation for the disposition of the terrace deposits of the River Dniester in the Ukraine–Moldova border region further to the SE (see Fig. 3A).

Comparison is also possible with the crust underlying the fluvial sequence laid down by the River Vistula in the Warsaw area. As illustrated in Fig. 5D, Pliocene deposits here occur near the present river level, and Early Pleistocene deposits at a height ~30 m lower. After these were laid down, the ancestral Vistula cut down to ~50 m below its present level before laying down a stack of Middle and Late Pleistocene sediments, including Holocene temperate-climate deposits overlying their Eemian and Holsteinian counterparts. Overall, this sequence indicates a transition from uplift in the Pliocene and Early Pleistocene to subsidence thereafter. Warsaw is ~50 km inside the EEP (Fig. 4B). From Grad *et al*. (2003) and Mazur *et al*. (2015), the crust is locally ~45 km thick with ~20 km of underplating at its base, overlain by ~19 km of basement and ~3 km of sediments, which are mainly Mesozoic (in contrast with the much thicker sequences dominated by Palaeozoic shale, closer to the TTZ). The surface heat flow in the Warsaw area is ~60 mW m^{-2} (Fig. 4C); if the sediment and basement are assumed to have thermal conductivities of 2.5 and 3.5 W m^{-1} °C^{-1}, respectively, the ~350 °C isotherm can be expected at ~19 km depth, making the mobile lower crustal layer ~6 km thick, within the range of values where alternations of uplift and subsidence have been observed in fluvial sequences elsewhere (Westaway and Bridgland, 2014). Other fluvial sequences within the EEP, with alternations of uplift and subsidence evident, include those of the River Dnieper in Ukraine and the Rover Don in SW Russia (e.g., Westaway and Bridgland, 2014; Fig. 3).

A final point on the effect of lateral variations of crustal properties, with resultant lateral variations in uplift, on the disposition of fluvial terrace deposits concerns the occasional occurrence of back-tilted fluvial deposits, in cases where rivers have flowed from regions of colder to warmer crust, with an example evident from the Sudetic margin. It is evident that the ancestral drainage from the Sudeten Mountains was directed northward, from the Wrocław area and points further east to the Poznań area, before adjusting (probably around the start of the Early Pleistocene) to its modern configuration. Fig. 4C indicates that the former drainage was directed across the high heat-flow region between Wrocław and Poznań, raising the possibility that the subsequent drainage adjustment was the result of faster uplift of the latter region. As already noted, the Grad *et al*. (2003) seismic profile passes through this high-heat-flow region, indicating that the top of the mafic underplating is at ~25 km depth and that the sedimentary sequence in the overlying crustal column is thin. Assuming a thermal conductivity of 3.5 W m^{-1} °C^{-1} in the basement, as before, and a typical heat flow of ~90 mW m^{-2}, the ~350 °C isotherm can be expected at a depth of ~14 km, making the thickness of the mobile lower crust ~11 km, significantly greater than in other parts of Poland and high enough (based on comparisons with other regions) to sustain significant uplift rates. Recorded heights of pre-glacial fluvial deposits in this region (Czerwonka and Krzyszkowski, 2001; Supplement, Table S1) indeed reveal evidence of back tilting. The best such evidence is provided by comparison of the heights of the Pliocene deposits along the ancestral River Odra, between Chrzaszczyce(Fig. 7 [76/77]), Smardzow [33], 77.3 km further downstream, and Stankowo [1], 84.9 km further downstream, the latter site adjoining the confluence with the ancestral Nysa Kłodzka (Fig. 7). The top of the deposits assigned to Member I of the Ziębice Group is 180, 72, and 99 m a.s.l. at these sites, thus indicating back-tilting over the reach between Smardzow and Stankowo, the long-profile gradients being ~1.4 and ~-0.3 m km^{-1} along these two reaches, respectively. Thus, if this river had an original gradient of ~1 m km^{-1}, the deposit at Stankowo is now 81 m higher in the landscape, and that at Smardzow 34 m lower, than would be expected if all three sites had experienced the same history of vertical crustal motion. In the absence of detailed modelling the precise sequence of processes in this region cannot be ascertained, but this pattern is consistent with the interpretation that lower-crustal material was drawn from beneath the Smardzow area to beneath the hotter Stankowo area, as a result of the lateral pressure gradient at the base of the brittle upper crust caused by the variation in heat flow between these two regions. An established analogue of this effect is the back-tilting of the deposits of the early Middle Pleistocene Bytham River in the East Midlands of England; this river flows eastward from the northern part of the London Platform, a region of relatively low heat flow, into the higher-heat-flow zone of crustal deformation during the Caledonian orogeny, at the NE margin of Avalonia (Fig. 4A), its sediments now being gently tilted in an upstream direction (Westaway *et al*., 2015).

The explanation for the fluvial archives in the marginal area of the Sudeten Mountains promoted here has a more general analogue in records from SW England, in the rivers of Cornwall and west Devon (Westaway, 2010). In that region radiothermal Variscan granites are underlain by thick mafic underplating and the crust is relatively strong, as indicated by the minimal Late Cenozoic vertical crustal motions deduced from fluvial sequences. The principal difference is that the mafic underplating beneath SW England was emplaced after the Variscan orogeny, as a result of the Palaeocene British Tertiary Igneous Province magmatism, whereas the underplating beneath the Sudeten Mountains is evidently derived from fragments of pre-Variscan Saxothüringian crust.

The different styles of fluvial archive preservation in the different parts of the European continent described above are an important consideration in the understanding of Quaternary stratigraphy in these regions, given that fluvial sequences provide valuable templates for the Late Cenozoic terrestrial record (Vandenberghe, 2002; Bridgland *et al*., 2004; Bridgland and Westaway, 2014). It has been shown that the most stable regions, in which the fluvial archives suggest a complete or near absence of net uplift during the Quaternary, coincide with the most ancient cratonic crustal zones, such as parts of the EEP and in particular the Ukrainian Shield (Bridgland and Westaway, 2008, 2014; Fig. 3). Such highly stable regions are the exception for the EEP, however; over much of its area there has been limited net uplift as a result of alternations of vertical crustal movements, resulting in periods of terrace generation with intervening periods of subsidence and burial. In Fig. 13 the fluvial archive from the Sudetic margin, using the optimal example of the Nysa Kłodzka at Bardo (see above), is compared with that of the River Don at Voronezh. Despite the differences in size (catchment area and, therefore, discharge) of the fluvial systems in question and the very different glacial influences (the Don here was reached only by glaciation in MIS 16), there are significant points of comparison. Contrastingly, the difference between the fluvial records from the EEP and those from the youngest and most dynamic European crust is quite profound, albeit that many of the comparisons made above are with crust of somewhat intermediate age, such as the Variscan and Avalonia provinces (Fig. 4). This is because much of the youngest crust, in the Alpine and Carpathian provinces (Fig. 4), remains tectonically active (i.e., continues to be affected by active plate motions) and so has fluvial archives that are less clearly related to regional vertical crustal movements.

CONCLUSIONS

The rivers of the Polish Sudeten foreland have pre-glacial precursors, their courses recognized from sediments that generally underlie the Middle Pleistocene glacial deposits and which date from the Early Pliocene – Early Pleistocene, being substantially different from those of their modern successors. The pre-glacial fluvial formations are preserved in the subsurface, in part as buried valley fills, and recorded as the Ziębice Group. They were partly destroyed and buried by the Middle Pleistocene Scandinavian ice sheets that entered the Sudeten Foreland, covering the previously formed valleys with glacial deposits: the Elsterian (= Sanian) and the early Saalian (= Odranian). No post-Odranian ice sheet reached the Sudeten Foreland, where renewed incision (brought about by post-Odranian uplift) led to post-glacial river-terrace formation. In addition to glacial and tectonic influences on fluvial evolution, the overall pattern of fluvial archive preservation is commensurate with the Variscan crustal province in which they are developed. However, the effects of mafic underplating, emplaced by the incorporation of pre-Variscan crustal material, may have been considerable, as this can explain reduced net Pleistocene uplift and reversals in vertical crustal motion, especially in basinal areas. Differential uplift in reflection of crustal type may have led to disruption of former downstream gradients in the palaeovalleys, with an example of back-tilting identified in the case of the Palaeo-Odra. In addition, some younger terraces can be shown to have been offset by slip on active faults of the Sudeten Marginal Fault system.

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Figure captions

Figure 1 Geology and location of the research area. The inset shows the limits of the various Quaternary glaciations of Poland and the course of the River Odra. Modified from Czerwonka and Krzyszkowski (2001).

Figure 2 Cross sections through key fluvial sequences in the study area: A - the River Nysa Kłodzka in the Bardo area (sites 96 and 97 in Figs 7 and 8), where the river has cut a gorge through an inter-basinal (progressively uplifting) ridge, the inset showing the sequence a few km downstream, in the Janowiec–Ożary area (sites 72 and 71 in Figs 7 and 8); B - the sequence in the Kłodzko Basin in the Kłodzko–Leszczyna area (site 68 in Figs 7 and 8), both modified from Krzyszkowski *et al.* (1998); C - The River Bystrzyca near Lubachów (modified from Krzyszkowski and Biernat, 1998); for location see FIg. 7.

Figure 3 The Rivers of the northern Black Sea region (modified from Bridgland and Westaway, 2014; after Matoshko *et al*., 2002; 2004). A - The locations of parts B–D in relation to the Ukrainian Shield. B - Idealized transverse profile through the Middle–Lower Dniester terrace sediments, which represent a classic river terrace staircase (with approximately one terrace per 100 ka climate cycle following the Mid-Pleistocene Revolution) inset into Miocene fluvial basin-fill deposits. This region has higher heat flow than might be expected from its location at the edge of the EEP (see A), for reasons discussed in detail by Westaway and Bridgland (2014). C. - Transect across the Middle Dnieper basin,~100 km downstream of Kiev (~240 km long), showing a record typical of an area with no considerable net uplift or subsidence during the Late Cenozoic, as typifies cratonic crustal regions (cf. Westaway *et al*., 2003). D. - Transect through the deposits of the Upper Don near Voronezh, showing a combined stacked and terraced sequence that points to fluctuation between episodes of uplift and of subsidence during the past ~15 Ma.

Figure 4 Crustal characteristics. A - Crustal provinces in the European continent and neighbouring areas. Modified from Pharaoh *et al*. (1997); the location of parts B and C is shown. B - Crustal provinces in Poland. Modified from Mazur et al. (2006). DFZ = Dolsk Fault Zone; OFZ = Odra Fault Zone. C - Borehole heat flow measurement sites and resulting contours of surface heat flow in Poland. Modified from Bujakowski et al. (2016), using data from Szewczyk and Gientka (2009). Plus and minus signs are used to aid interpretation in grayscale; for the colour diagram, see the online pdf version.

Figure 5 Comparison of fluvial archives in different parts of the River Vistula system. A – location; B – Transect through the valley of the River Dunajec, central Carpathians (modified from Zuchiewicz, 1992, 1998); C –. Transect through the valley of the River San (after Starkel, 2003); D – Idealized transverse sequence through the deposits of the Middle Vistula, based on data from upstream (Mojski, 1982) and downstream (Zarski, 1996; Marks, 2004) of Warsaw.

Figure 6 Distribution of provenance indicator materials. Modified from Czerwonka and Krzyszkowski (2001).

Figure 7 Location of pre-glacial sites (identified by number, with different symbols for the various formations, which represent different river systems). For locality names see Fig. 8. Modified from Czerwonka and Krzyszkowski (2001).

Figure 8 Occurrence of the different pre-glacial fluvial formations and their constituent members, showing which are present at the various localities. Numbers and symbols correspond with those in Figs 7 and 9–12. Modified from Czerwonka and Krzyszkowski (2001).

Figure 9 Palaeodrainage during emplacement of Member I deposits. Numbers and symbols correspond with those in Figs 7 and 8. Modified from Czerwonka and Krzyszkowski (2001).

Figure 10 Palaeodrainage during emplacement of Member II deposits. Numbers and symbols correspond with those in Figs 7 and 8. Modified from Czerwonka and Krzyszkowski (2001). For key see Fig. 9.

Figure 11 Palaeodrainage during emplacement of Member III deposits. Numbers and symbols correspond with those in Figs 7 and 8; for key see Fig. 9.

Figure 12 Palaeodrainage during emplacement of Member IV deposits. Numbers and symbols correspond with those in Figs 7 and 8; for key see Fig. 9.

Figure 13 Comparison between the fluvial archives from the Sudetes, in the form of the Nysa Kłodzka (Krzyszkowski *et al.,* 1998*,* 2000), and the River Don in the vicinity of Voronezh, Russia (showing suggested MIS correlations; see also Fig. 3D and Matoshko *et al*. (2004), who provided further stratigraphical details.

Table 1 Characteristic clast data (gravel petrography and heavy mineralogy) used in differentiation of Ziębice Group formations

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Table 1
Characteristic clast data (gravel petrography and heavy mineralogy) used in differentiation of Ziębice Group formations

Formation	Member(s)	Gravel lithologies: Primary	Gravel lithologies: Secondary	Gravel lithologies: Others	Heavy minerals	Interpretation
Chrząszczyce	***III***	quartz	Carpathian siliceous rocks		zircon, rutile, garnet, staurolite, tourmaline	Main palaeo-Odra
	I–II				zircon, tourmaline, staurolite [+ garnet in Mbr I; + rutile, in Mbr II]	
Dębina	***I***	quartz	quartzite		staurolite, amphibole	Palaeo-Biała Głuchołaska
Kłodzko–Stankowo	***IV***	various gneiss types of the Kłodzko Basin	porphyry quartz	Permian (red), Carboniferous (grey) and Cretaceous (white) sandstone, Carboniferous mudstone, siliceous rocks (local flint)	garnet, amphibole	Palaeo-Nysa Kłodzka
	I–III	quartz	porphyry, siliceous rocks (local flint)	crystalline rocks (including gneisses of the Kłodzko Basin), Permian (red) and Cretaceous (white) sandstone	staurolite, garnet, (+ local admixtures of zircon + rutile, andalusite + kyanite and sillimanite	
Ząbkowice	***IV?***	Sowie Góry gneiss	quartz	siliceous rocks (local flint)	garnet, amphibole	Palaeo-Budzówka
Bojanice	***IV***				Sillimanite	Palaeo-Bystrzyca
	II–III	quartz	porphyry melaphyre	Sowie Góry gneiss, quartzite	zircon, garnet, sillimanite	
Pogalewo	***II–III***				zircon, garnet, tourmaline [+,kyanite in Mbr II] (in Mbr III epidote, kyanite, amphibole, staurolite)	Palaeo-Bystrzyca or local river
	I	quartz		siliceous rocks (local flint), porphyry	zircon, tourmaline, rutie	
Wichrów	***I***				zircon, tourmalline, epidote, kyanite	Palaeo-Bystrzyca or local river
Mielęcin–Wołów	***IV***				Sillimanite	Palaeo-Strzegomka
	I–III	quartz	porphyry	siliceous rocks (local flint), rocks from the Wałbrzych Upland (conglomerate, spilite, diabase, greenschist, quartzite), Strzegom granite, local schist (phyllite)	sillimanite, garnet	
Snowidza	***I***				andalusite, zircon	Palaeo-Wierzbiak
Rokitki–Bielany	***IV***	quartz	porphyry	crystalline rocks, schist, quartzite Cretaceous sandstone, Wojcieszów limestone	andalusite, kyanite, tourmaline, zircon, garnet (amphibole, sillimanite)	Palaeo-Bóbr (upper Bóbr–Kaczawa)
	I-III	quartz	Karkonosze granite porphyry	other crystalline rocks, quartzite	andalusite, tourmaline [+ epidote in Mbr I]	

Figure 1

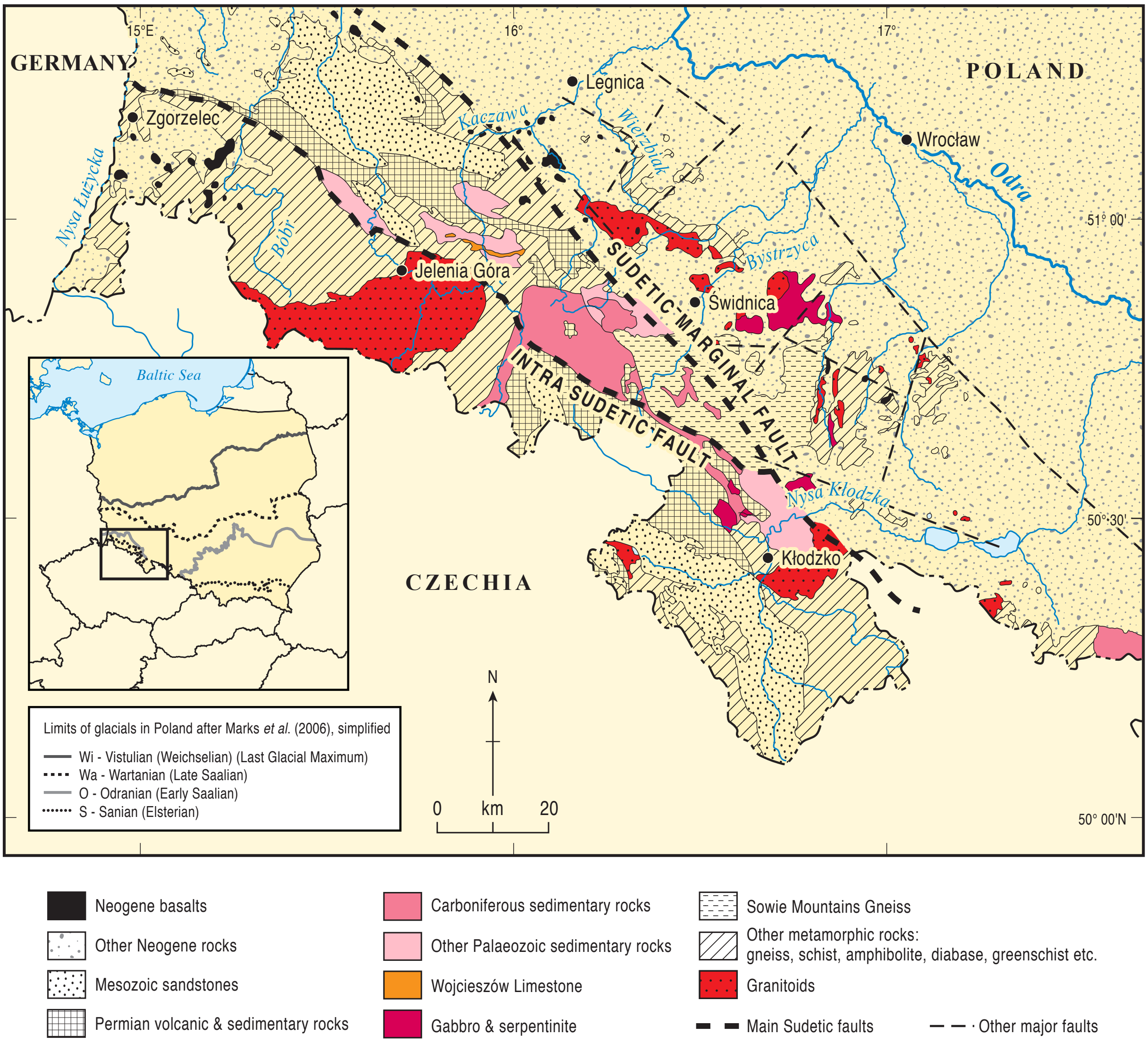

15°E
16°
17°
GERMANY
POLAND
CZECHIA
Legnica
Zgorzelec
Wrocław
Jelenia Góra
Świdnica
Kłodzko
Kaczawa
Wierzbiak
Odra
Nysa Łużycka
Bóbr
Bystrzyca
Nysa Kłodzka
SUDETIC MARGINAL FAULT
INTRA SUDETIC FAULT
51° 00'
50° 30'
50° 00'N
Baltic Sea
N
0
km
20
Limits of glacials in Poland after Marks et al. (2006), simplified
Wi - Vistulian (Weichselian) (Last Glacial Maximum)
Wa - Wartanian (Late Saalian)
O - Odranian (Early Saalian)
S - Sanian (Elsterian)
Neogene basalts
Other Neogene rocks
Mesozoic sandstones
Permian volcanic & sedimentary rocks
Carboniferous sedimentary rocks
Other Palaeozoic sedimentary rocks
Wojcieszów Limestone
Gabbro & serpentinite
Sowie Mountains Gneiss
Other metamorphic rocks:
gneiss, schist, amphibolite, diabase, greenschist etc.
Granitoids
Main Sudetic faults
Other major faults

Figure 2

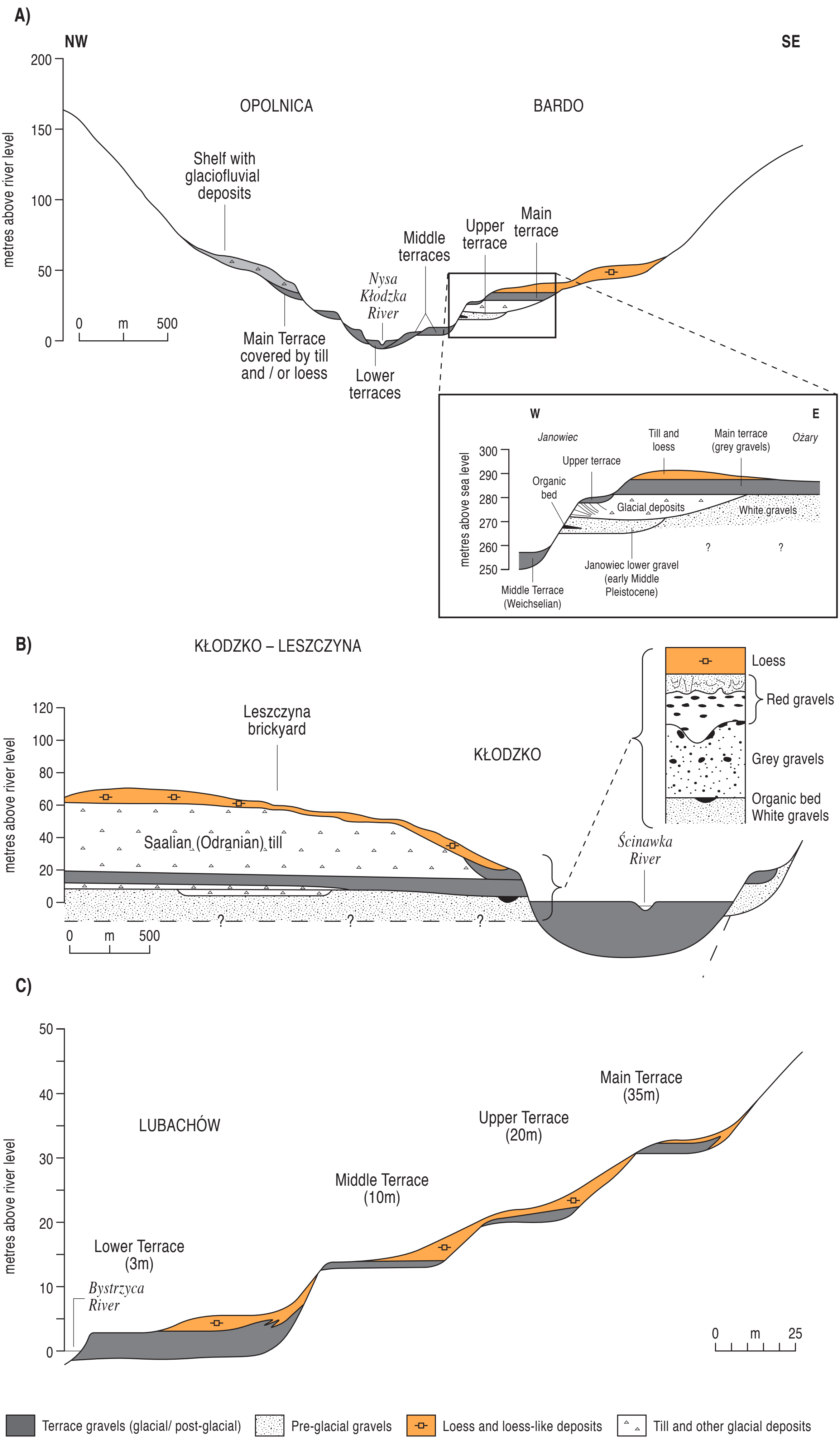
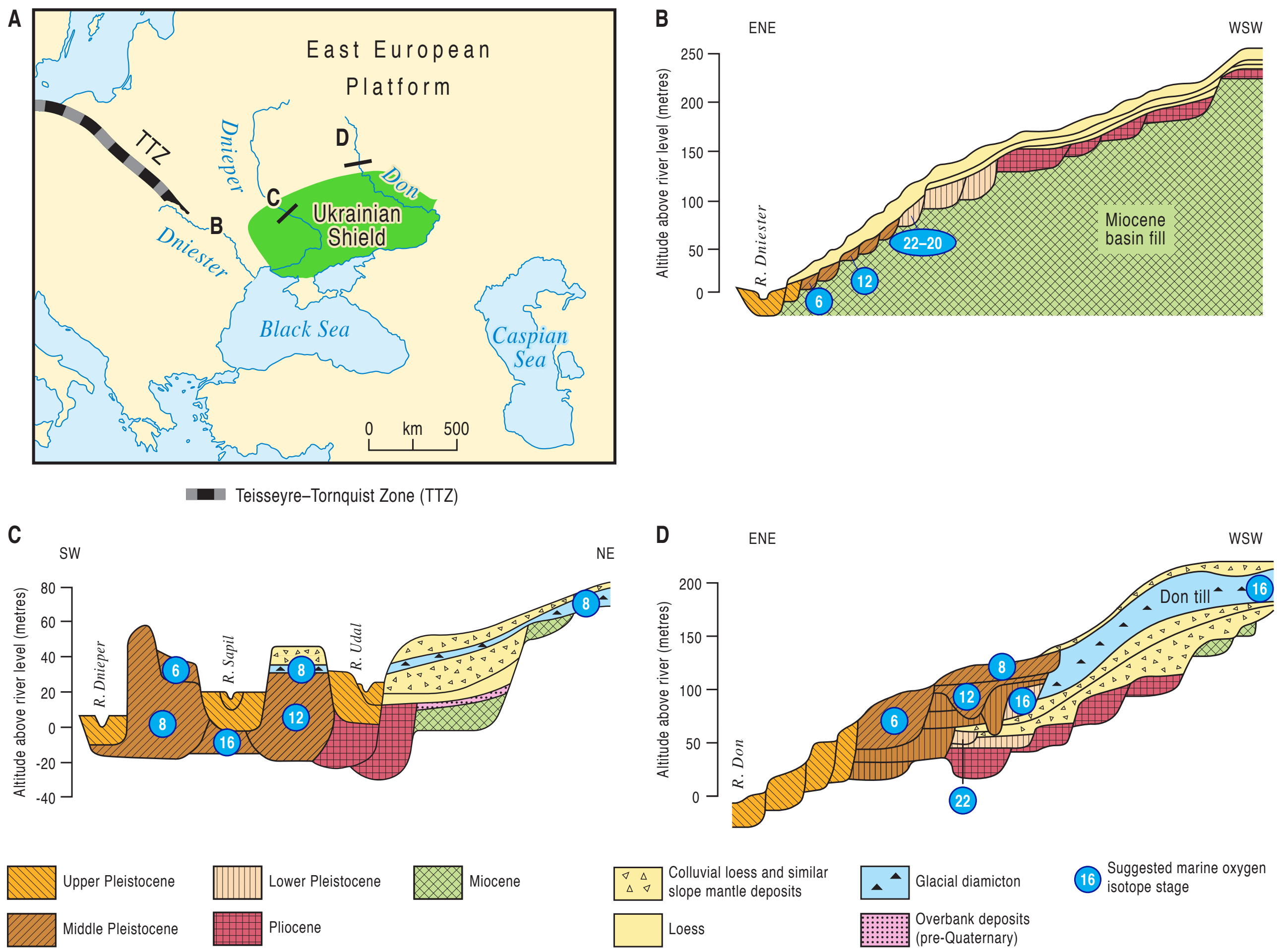

A)
NW
SE
OPOLNICA
BARDO
metres above river level
Shelf with glaciofluvial deposits
Main Terrace covered by till and / or loess
Nysa Kłodzka River
Lower terraces
Middle terraces
Upper terrace
Main terrace
0 m 500
W
E
Janowiec
Ożary
Till and loess
Main terrace (grey gravels)
Upper terrace
Organic bed
Glacial deposits
White gravels
metres above sea level
Janowiec lower gravel (early Middle Pleistocene)
Middle Terrace (Weichselian)
B)
KŁODZKO – LESZCZYNA
Leszczyna brickyard
KŁODZKO
Saalian (Odranian) till
Ścinawka River
Loess
Red gravels
Grey gravels
Organic bed
White gravels
0 m 500
C)
LUBACHÓW
Lower Terrace (3m)
Bystrzyca River
Middle Terrace (10m)
Upper Terrace (20m)
Main Terrace (35m)
0 m 25
Terrace gravels (glacial/ post-glacial)
Pre-glacial gravels
Loess and loess-like deposits
Till and other glacial deposits

Figure 3

Click here to download Figure Figure 3.pdf



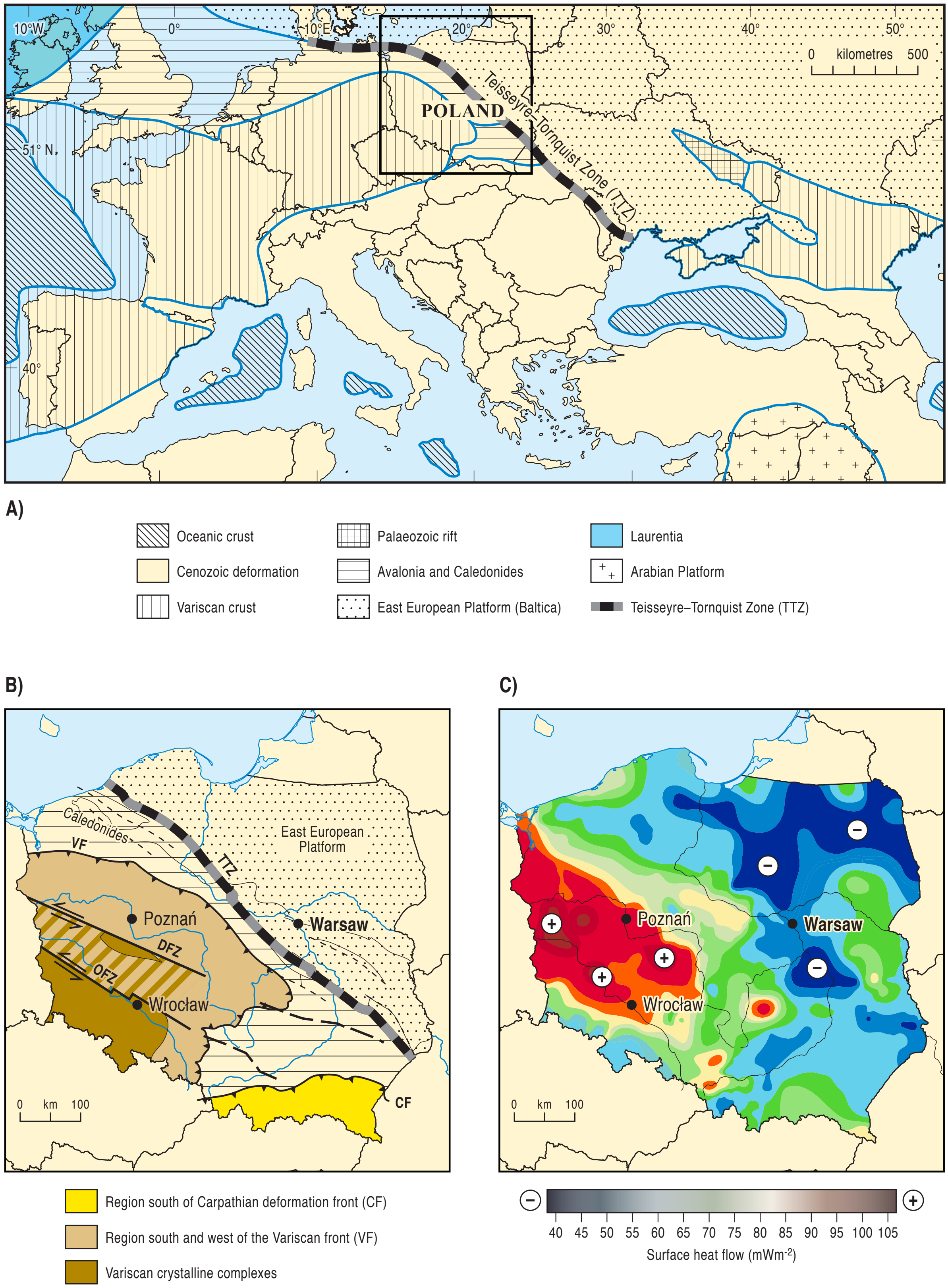
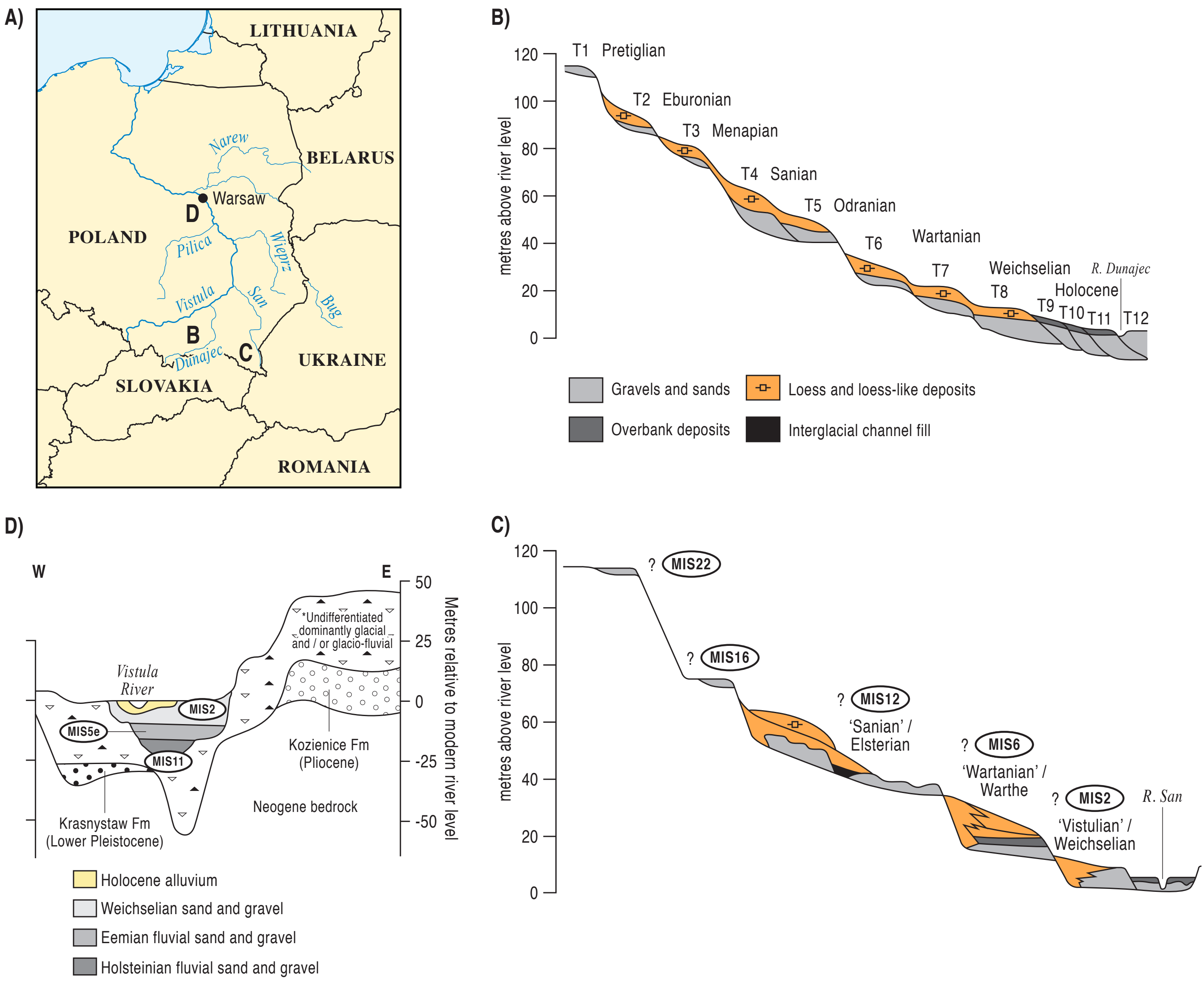

10°W
0°
10°E
20°
30°
40°
50°
51° N
40°
0 kilometres 500
POLAND
Teisseyre–Tornquist Zone (TTZ)
A)
Oceanic crust
Cenozoic deformation
Variscan crust
Palaeozoic rift
Avalonia and Caledonides
East European Platform (Baltica)
Laurentia
Arabian Platform
Teisseyre–Tornquist Zone (TTZ)
B)
Caledonides
VF
TTZ
East European Platform
Poznań
Warsaw
DFZ
OFZ
Wrocław
CF
0 km 100
Region south of Carpathian deformation front (CF)
Region south and west of the Variscan front (VF)
Variscan crystalline complexes
C)
Poznań
Warsaw
Wrocław
0 km 100
40 45 50 55 60 65 70 75 80 85 90 95 100 105
Surface heat flow (mWm-2)

Figure 5



A)
LITHUANIA
BELARUS
POLAND
UKRAINE
SLOVAKIA
ROMANIA
Warsaw
D
B
C
Narew
Pilica
Wieprz
Vistula
San
Bug
Dunajec
B)
metres above river level
T1 Pretiglian
T2 Eburonian
T3 Menapian
T4 Sanian
T5 Odranian
T6
Wartanian
T7
Weichselian
T8
R. Dunajec
Holocene
T9
T10
T11
T12
Gravels and sands
Loess and loess-like deposits
Overbank deposits
Interglacial channel fill
D)
W
E
Metres relative to modern river level
Vistula River
MIS2
MIS5e
MIS11
*Undifferentiated dominantly glacial and / or glacio-fluvial
Kozienice Fm (Pliocene)
Neogene bedrock
Krasnystaw Fm (Lower Pleistocene)
Holocene alluvium
Weichselian sand and gravel
Eemian fluvial sand and gravel
Holsteinian fluvial sand and gravel
C)
metres above river level
? MIS22
? MIS16
? MIS12
'Sanian' / Elsterian
? MIS6
'Wartanian' / Warthe
? MIS2
'Vistulian' / Weichselian
R. San

Figure 6 Click here to download Figure Figure 6.pdf

Figure 7

Click here to download Figure Figure 7.pdf

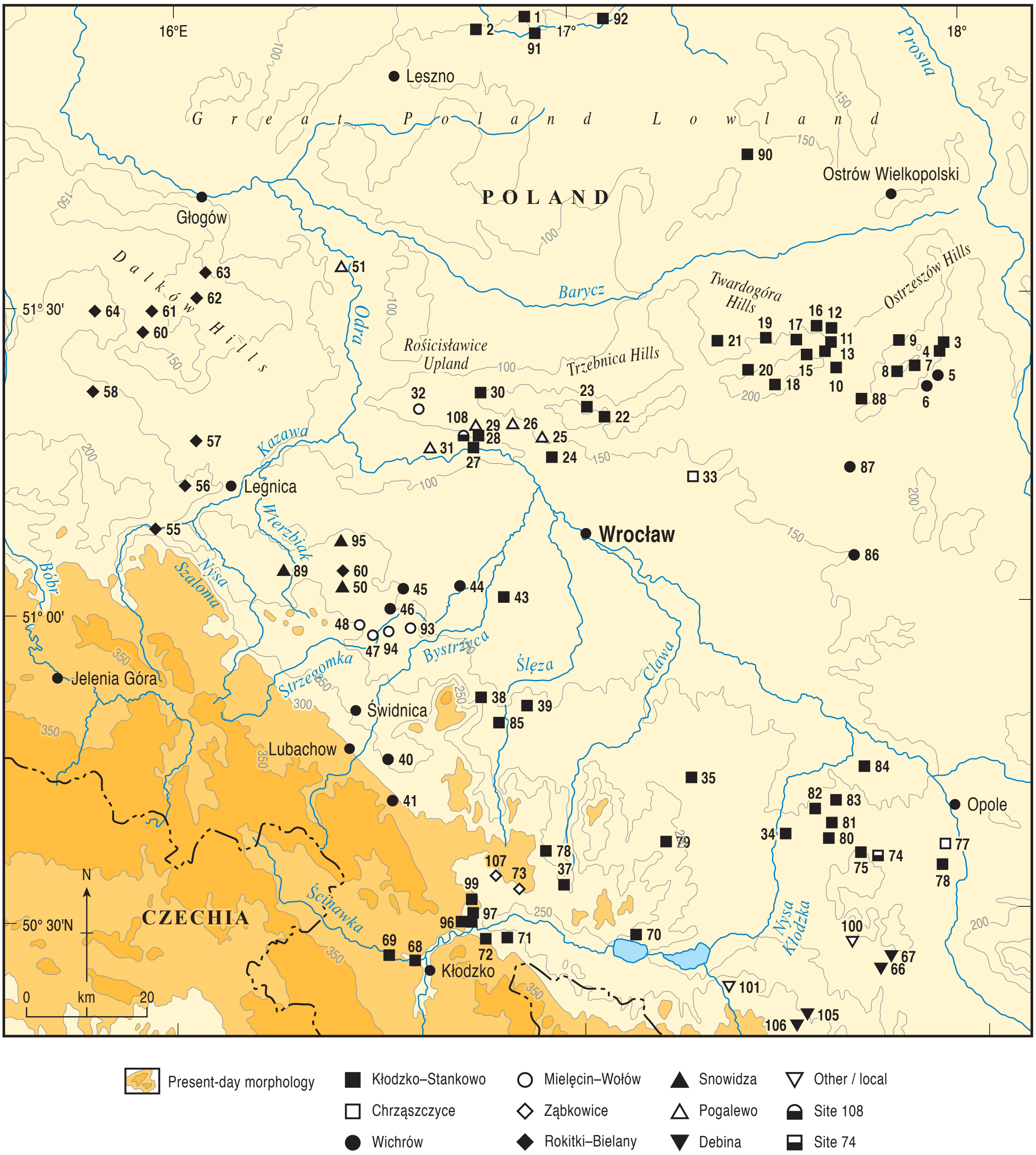


Figure 8

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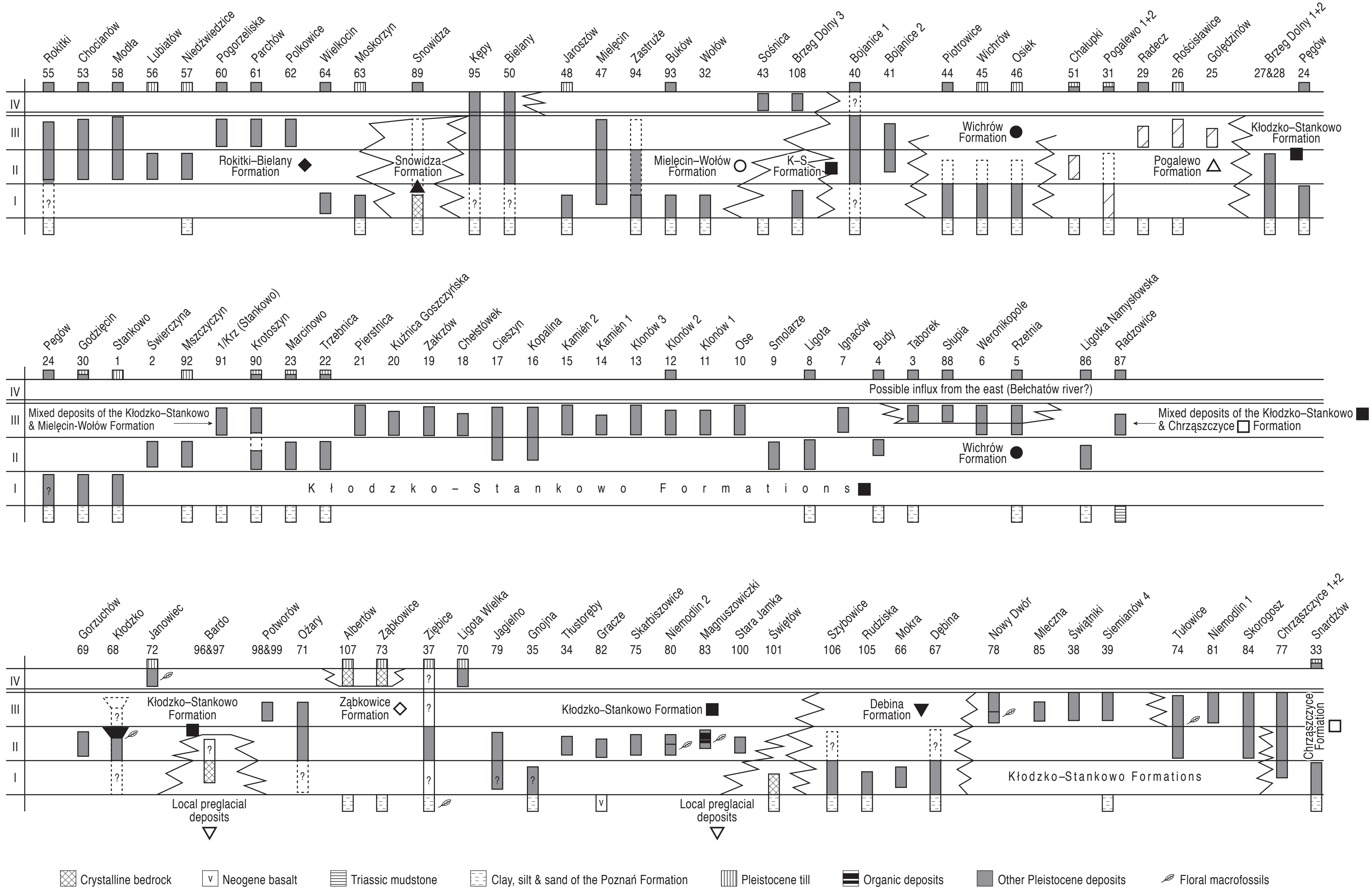

Figure 9 Click here to download Figure Figure 9.pdf

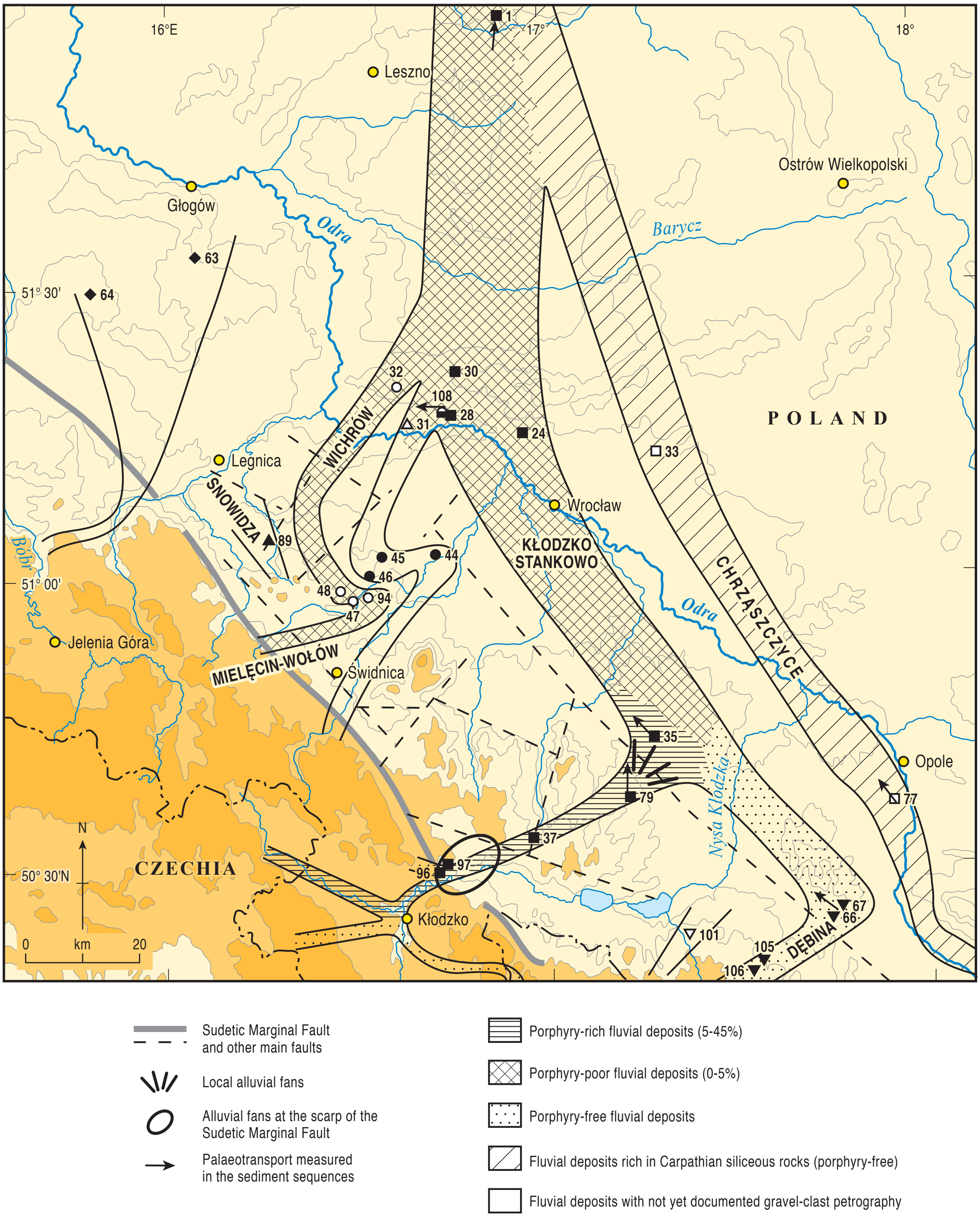

Figure 10

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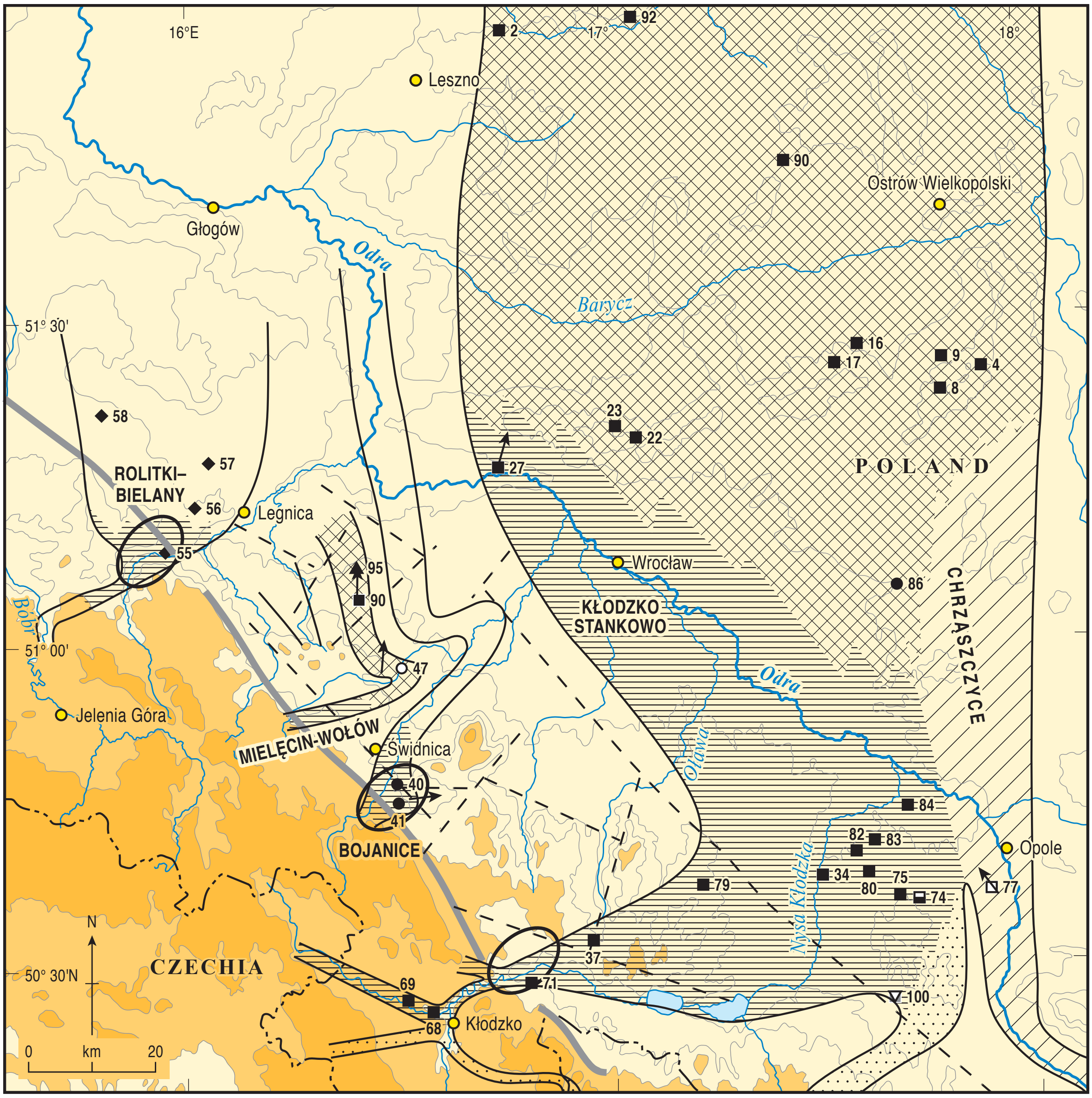

Figure 11 Click here to download Figure Figure 11.pdf

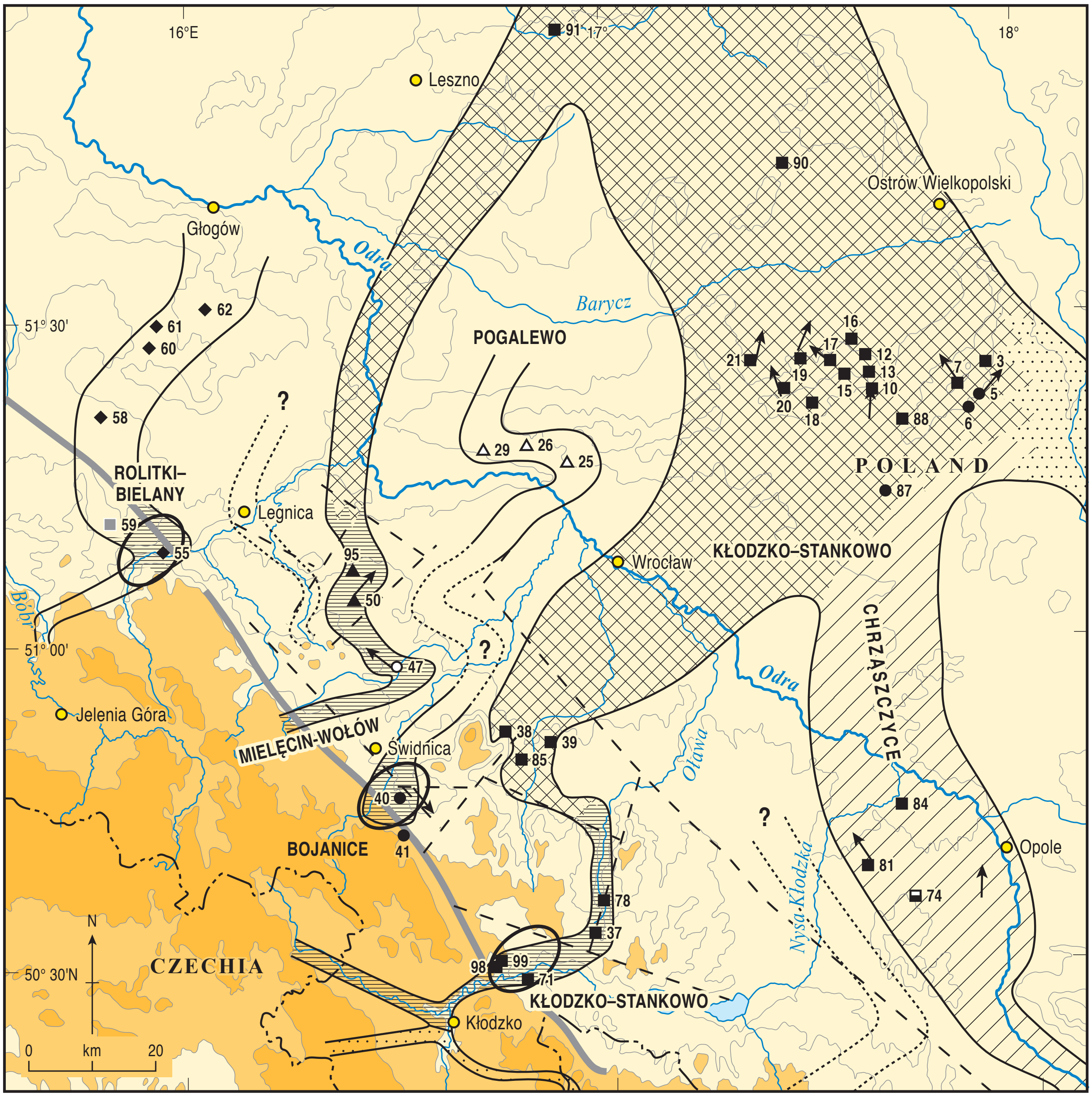

Figure 12

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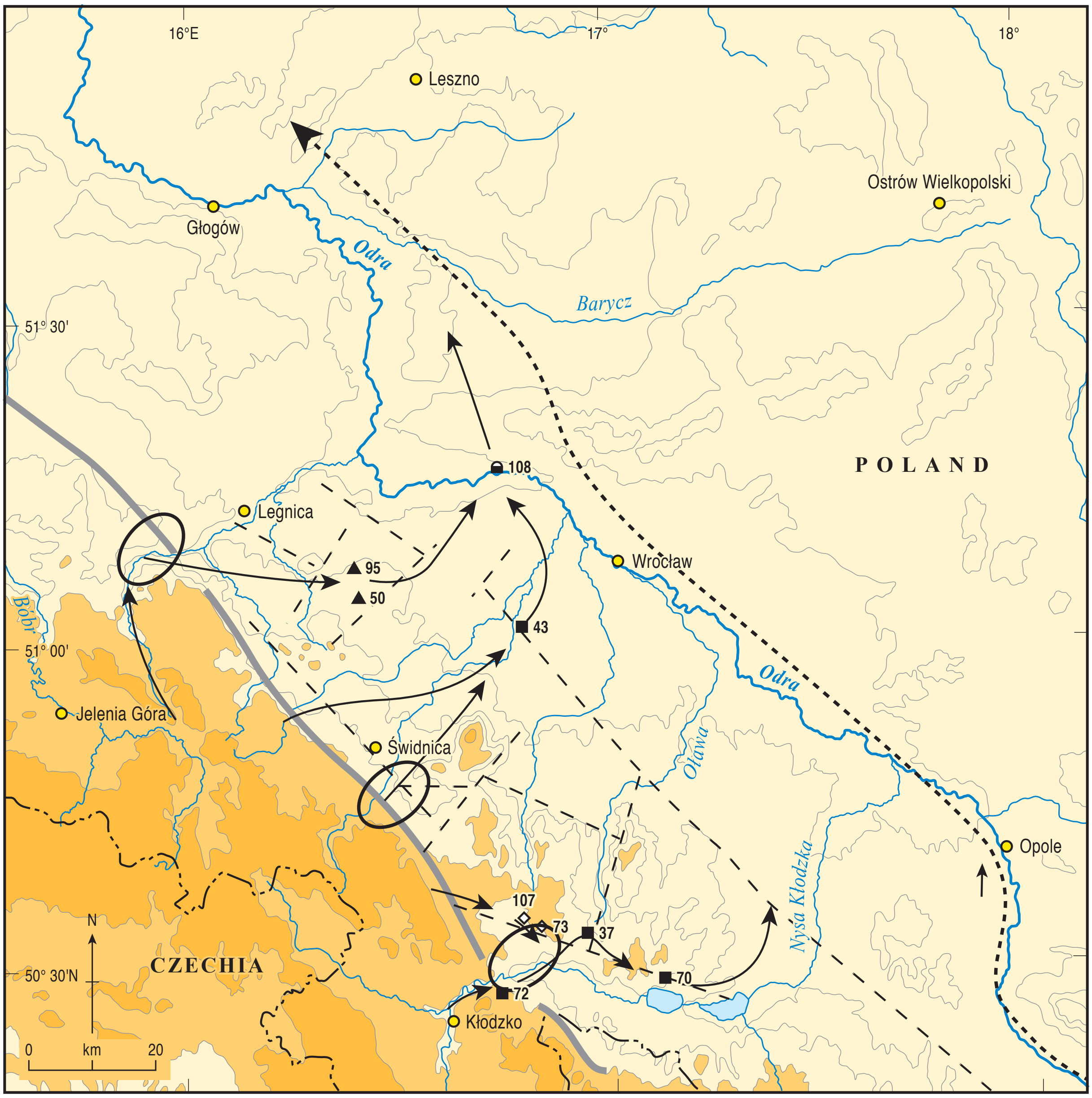
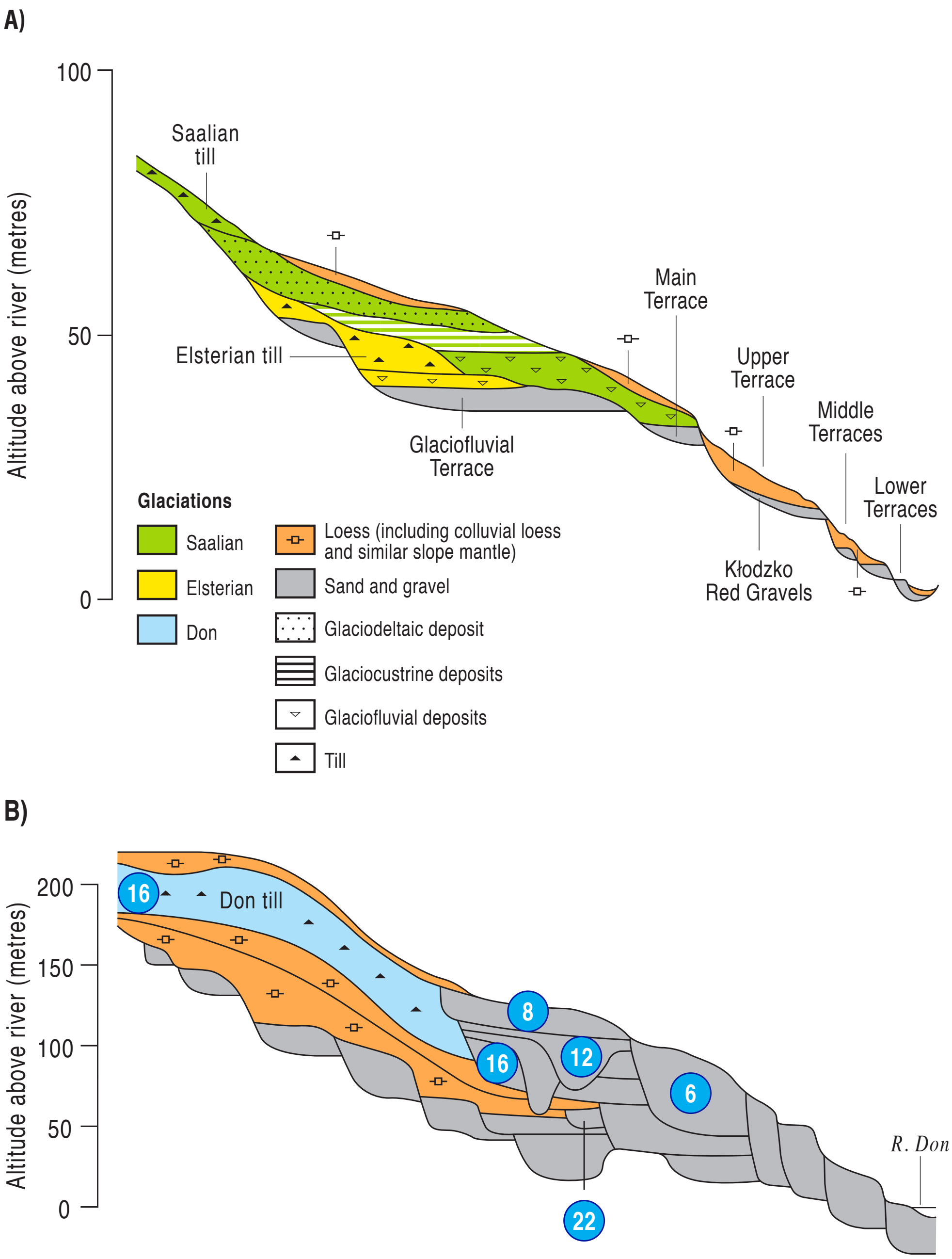


Figure 13 Click here to download Figure Figure 13.pdf



Supplementary material in support of the paper:

Drainage and landscape evolution in the Polish Sudeten Foreland in the context of European fluvial archives

by Dariusz Krzyszkowski, David R. Bridgland, Peter Allen, Rob Westaway, Lucyna Wachecka-Kotkowska, Jerzy A. Czerwonka

This material constitutes detailed information on selected localities, including sediment logs, section drawings, results from petrographic analyses, palaeocurrent measurement and height records.

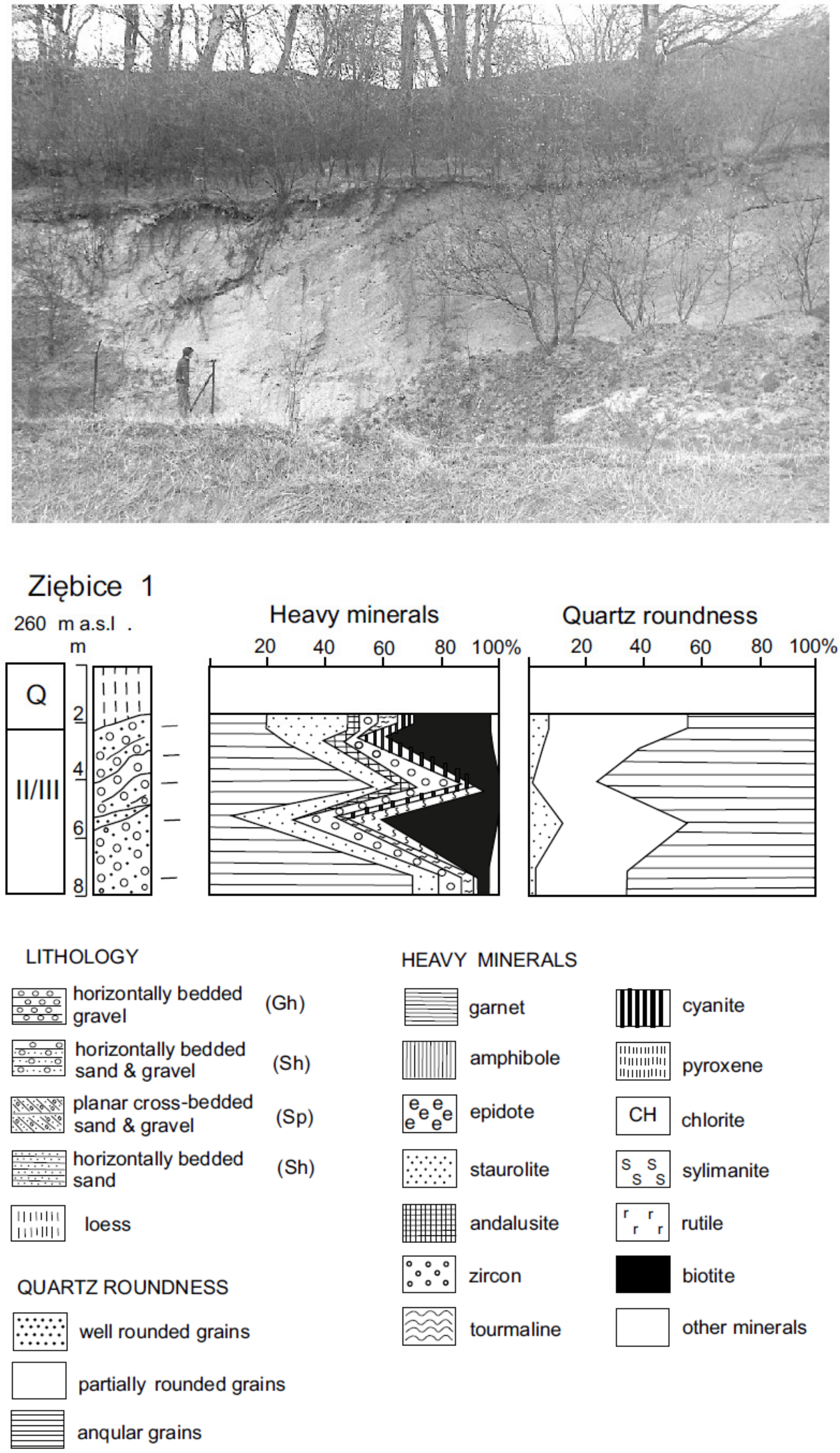


Fig. S1 – Ziębice [site 37], the locality in central Poland, formerly called Münsterberg, where fluvial 'white gravel' sediments, lacking Scandinavian material, were first described (Jentzsch and Berg, 1913; Frech, 1915; Lewiński, 1928, 1929; Zeuner, 1928). The site gives its name to the Ziębice Group (Czerwonka and Krzyszkowski, 2001). Photo by D. Krzyszkowski (1985).

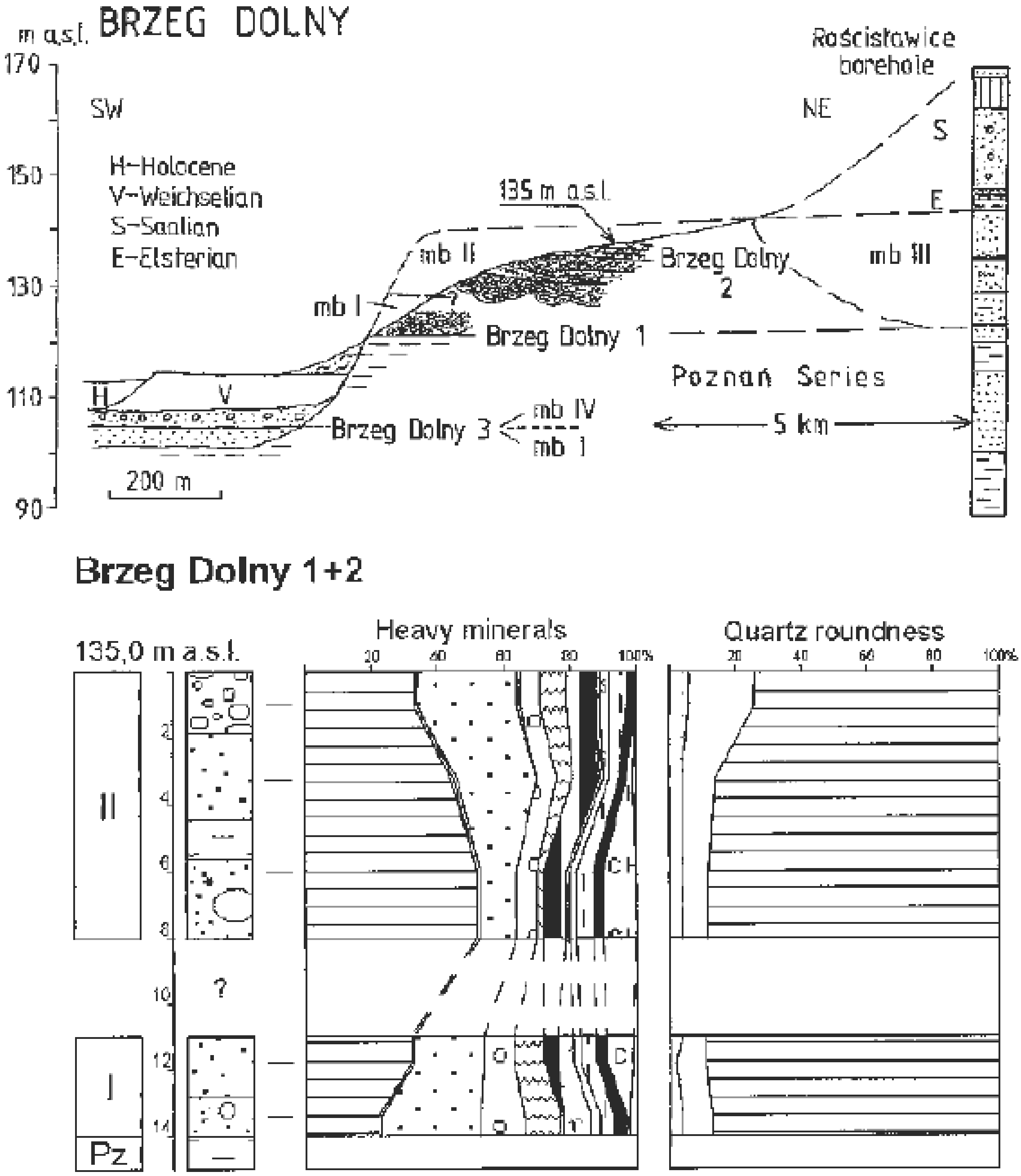


Fig. S2 – Brzeg Dolny [site 108]. Members I and II of the Kłodzko–Stankowo Formation, representing the palaeo-Nysa Kłodzka, with Member IV of the Mielęcin–Wołów Formation (Palaeo-Strzegomka) incised to a lower level.

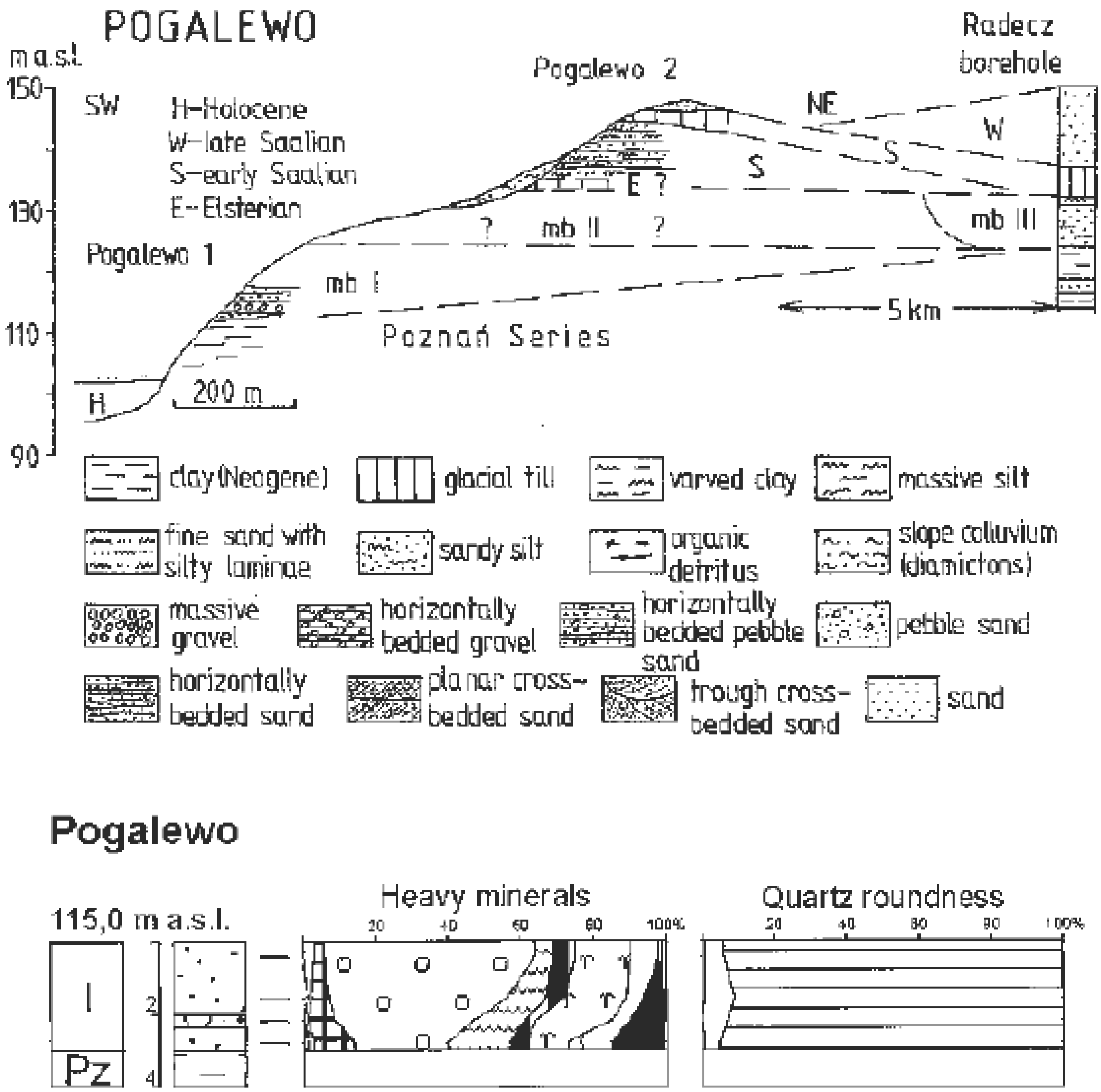


Fig. S3 – Pogalewo [site 31], the type locality of the Pogalewo Formation, representative of the Palaeo-Bystrzyca river. .

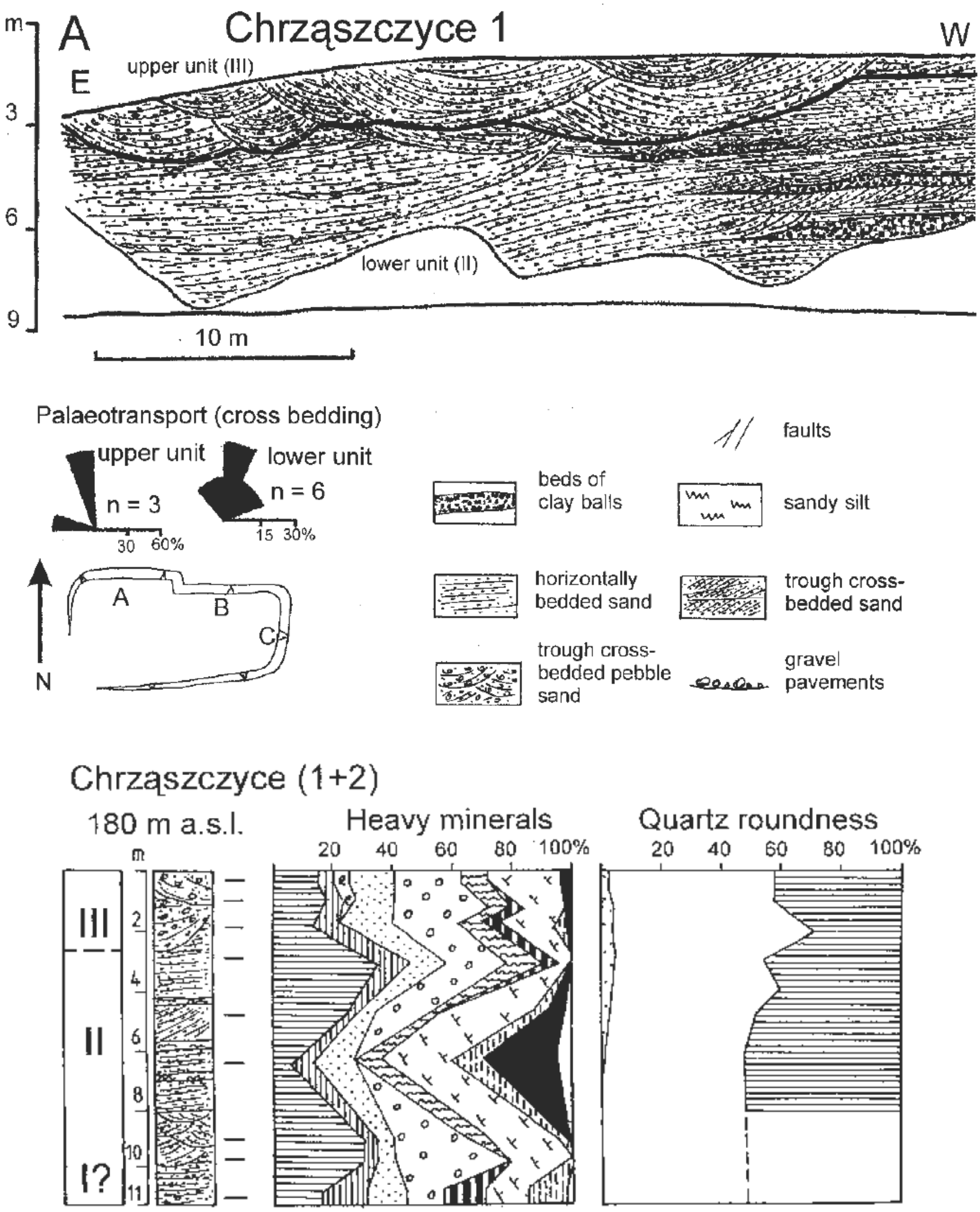


Fig. S4 – Chrząszczyce [site 77], type locality of the Chrząszczyce Formation, representative of the Palaeo-Odra river.

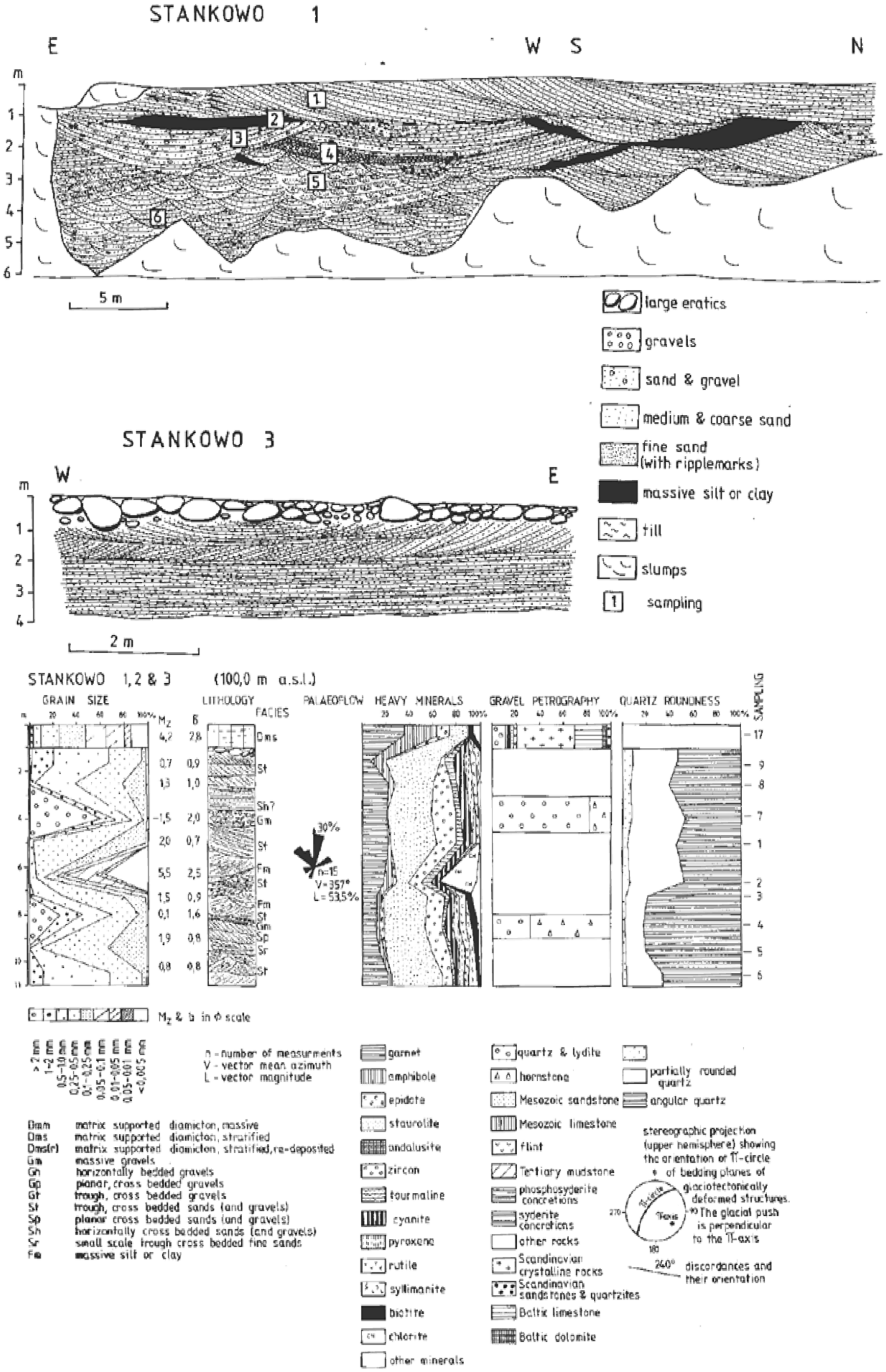
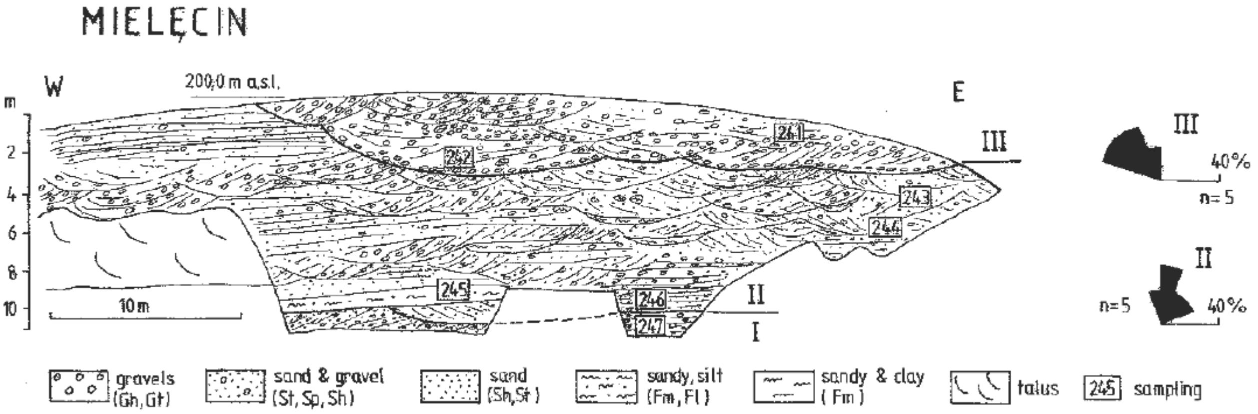


Fig. S5 – Stankowo [site 1], distal type locality of the Kłodzko–Stankowo Formation, near the northern margin of the study area. This represents the Palaeo-Nysa Kłodzka river.



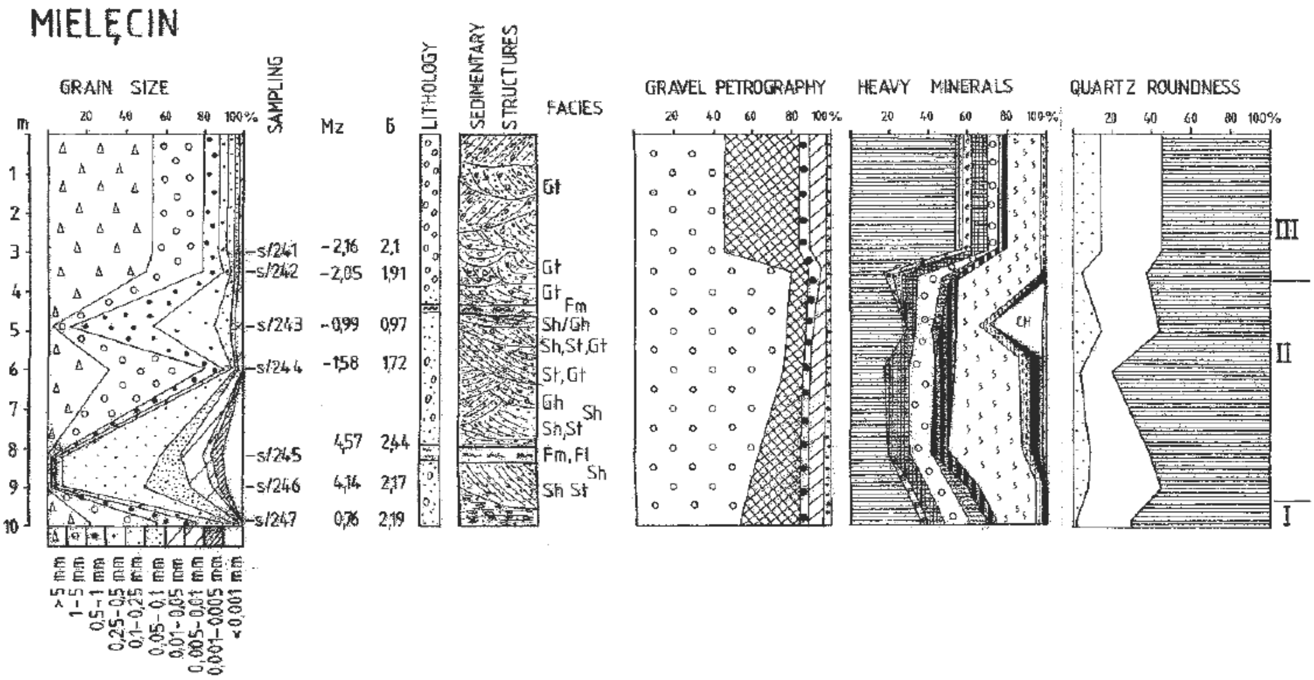


Fig. S6 – Mielecin [site 47], the proximal type locality of the Mielęcin–Wołów Formation, representative of the Palaeo-Strzegomka River.

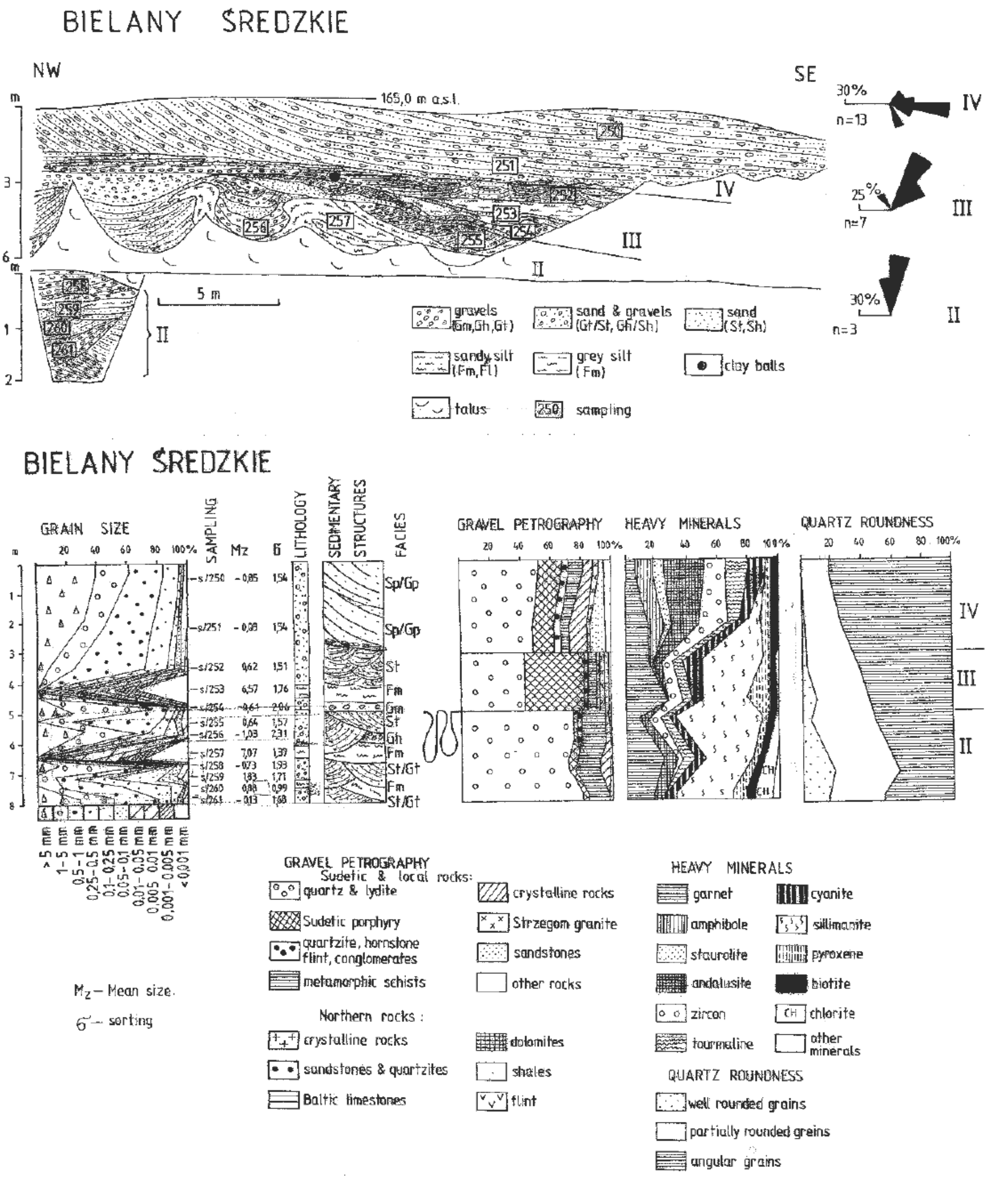


Fig. S7 – Bielany [site 50], distal type locality of the Rokitki–Bielany Formation, representing the Palaeo-Bóbr/Kaczawa .

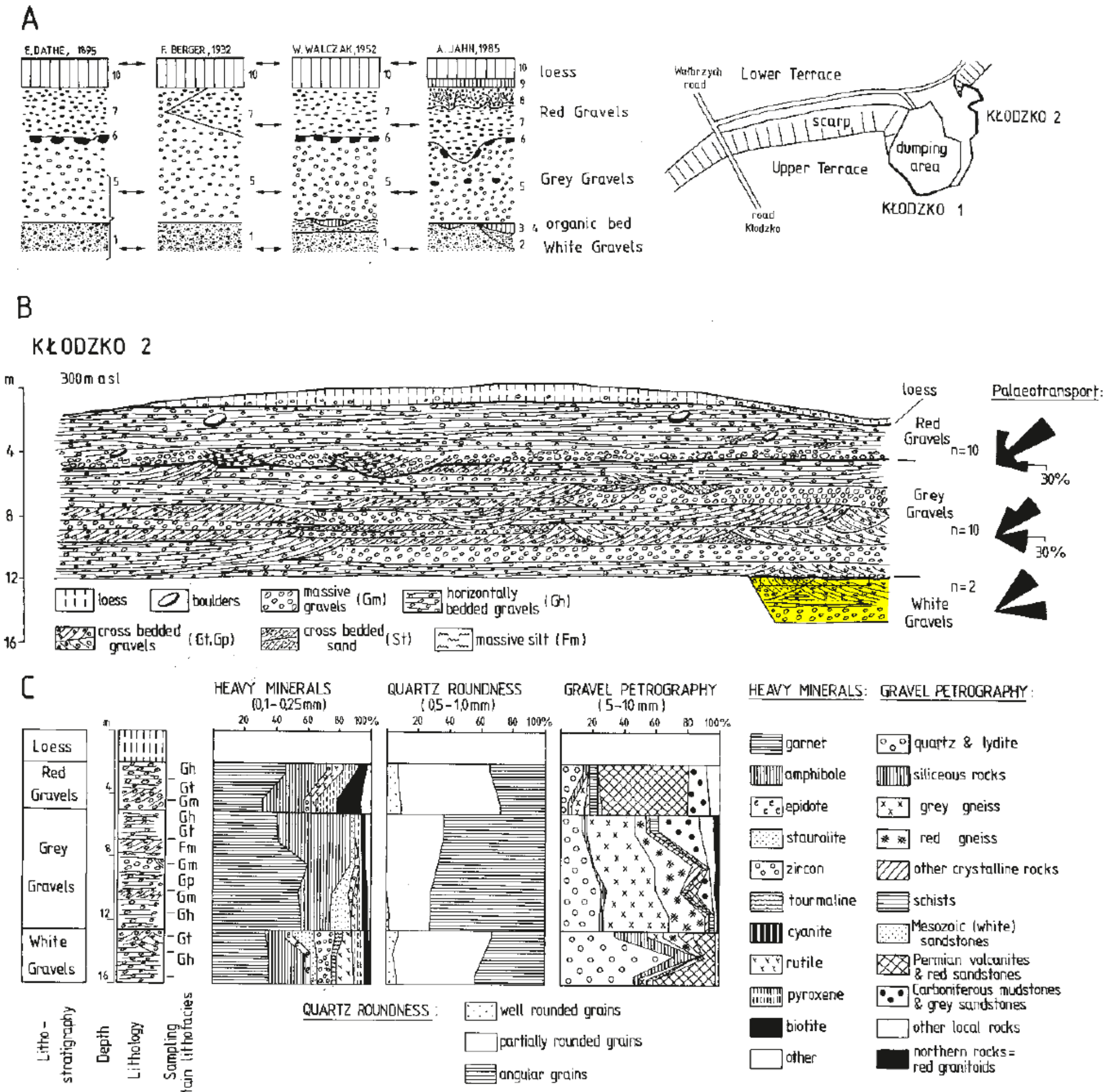


Fig. S8 – Kłodzko, proximal type locality of the Kłodzko–Stankowo Formation. Formation, representing the Palaeo-Nysa Kłodzka river.

Table S1 – Site data from Czerwonka and Krzyszkowski (2001)

number of site	site	stratigraphy	X	Y	top of the series	base of the series	comments
1	Stankowo 1	K-S; 1	36,312	57,570	99.0	-	
2	Swierczyna 2	K-S; 2	36,225	57,562	95.0	-	
3	Taborek	K-S; 3A	37,035	57,012	255.0	-	strongly deformed
4	Budy	K-S; 2	37,027	57,004	255.0	-	strongly deformed
5	Rzetnia	K-S; 3,3A	37,036	56,946	208.0	196.0	slightly deformed
6	Wernikopole	K-S; 3,3A	37,012	56,942	244.0	-	deformed
7	Ignaców	K-S; 3	36,989	56,972	250.0	-	deformed
8	Ligota	K-S; 2	36,958	56,967	215.0	-	deformed
9	Smolarze	K-S; 2	36,960	57,019	174.0	-	
10	Ose	K-S; 3	36,844	56,977	235.0	-	
11	Klonów 1	K-S; 3	36,835	57,006	175.0	-	deformed
12	Klonów 2	K-S; 3	36,835	57,010	186.0	-	strongly deformed
13	Klonów 3	K-S; 3	36,827	57,002	198.0	-	strongly deformed
14	Kamień 1	K-S; 3	36,796	57,003	180.0	-	deformed
15	Kamień 2	K-S; 3	36,800	56,993	185.0	-	deformed
16	Kopalina	K-S; 3-2	36,816	57,040	150.0	-	deformed
17	Cieszyn	K-S; 3-2	36,780	57,012	170.0	-	
18	Chełstówek	K-S; 3	36,743	56,947	235.0	-	deformed
19	Zakrzów	K-S; 3	36,729	57,022	137.0	-	
20	Kuźnica Goszcz.	K-S; 3	36,695	56,966	134.0	-	
21	Pierstnica	K-S; 3	36,646	57,015	170.0	-	
22	Trzebnica	K-S; 2	36,447	56,886	198.0	195.0	slightly deformed
23	Marcinowo	K-S; 2	36,413	56,901	180.0	-	strongly deformed
24	Pęgów	K-S; 1	36,360	56,810	130.0	-	
25	Golędzinów Ob/3	P; 3	36,338	56,847	143.0	-	borehole
26	Rościsławice Ob/6	P; 3	36,271	56,873	144.0	123.0	borehole
27	Brzeg Dolny 2	K-S; 2	36,224	56,844	135.0	-	
28	Brzeg Dolny 1	K-S; 1	36,222	56,846	124.0	121.0	
29	Radecz Bg/7	P; 3	36,203	56,867	132.5	125.0	borehole
30	Godzięcin Żm/2	K-S; 1	36,236	56,919	129.5	114.2	borehole; unexpectable heavy mineral content
31	Pogalewo 1	P; 1	36,152	56,813	115.0	112.0	
32	Wołów 1	M-W; 1	36,128	56,892	114.0	111.0	
33	Smardzów Ol/1	C; 1	36,608	56,774	72.0	64.5	borehole
34	Tłustoręby	K-S; 2	36,764	56,160	195.0	-	
35	Gnojna 2	K-S; 1	36,605	56,245	200.0	-	
36	Osinka 1	K-S; 3	36,448	56,085	253.0	-	weathered sediments only
37	Ziębice 1	K-S; 2	36,432	56,088	258.0	-	**holostratotype section**
38	Swiątniki	K-S; 3	36,362	56,389	149.0	124.0	
39	Siemianów 4	K-S; 3	36,334	56,380	170.0	-	strongly deformed
40	Bojanice 1	B; 4,3-2	36,062	56,284	290.0	-	strongly deformed
41	Bojanice 2	B; 3-2	36,064	56,282	290.0	-	deformed
42	Bystrzyca Dolna 1		36,037	56,335	255.0	-	profile not yet studied
43	Sośnica	M-W; 4	36,264	56,571	162.0	-	archival data only
44	Piotrowice Sr/3	W; 1	36,195	56,573	138.2	134.2	borehole
45	Wichrów Sr/1	W; 1	36,102	56,578	154.5	151.3	borehole
46	Osiek Sr/6	W; 1	36,080	56,542	166.5	160.0	borehole
47	Mielęcin	M-W; 3-1	36,052	56,503	200.0	-	
48	Jaroszów - Stanisław-S	M-W; 1	36,027	56,510	192.0	187.0	deformed
50	Bielany	M-W; R-B; 4-2	35,986	56,620	165.0	-	partly deformed
51	Chałupki Ru/2	P; 2	35,984	57,148	96.0	80.5	borehole
52	Kozów 1		35,875	56,674	175.0	-	profile not yet studied
53	Kozów 2		35,890	56,680	195.0	-	profile not yet studied
54	Wysocko		35,705	56,682	190.0	-	profile not yet studied
55	Rokitki	R-B; 3-2	35,664	56,682	195.8	-	
56	Lubiatów Lg/3	R-B; 2	35,718	56,766	131.0	-	borehole
57	Niedźwiedzice Lg/1	R-B; 2	35,740	56,841	101.0	83.0	borehole
58	Modła Ch/5	R-B; 3-2	35,560	56,920	127.5	95.0	borehole
59	Chocianów Ch/4	R-B; 3-2	35,577	56,741	110.5	83.0	borehole
60	Pogorzeliska Ch/3	R-B; 3	35,642	57,038	134.0	-	borehole; strongly deformed
61	Parchów Ch/2	R-B; 3	35,656	57,069	108.0	-	borehole; strongly deformed
62	Polkowice Gl/3	R-B; 3	35,738	57,099	190.0	-	borehole; strongly deformed
63	Moskorzyn Gl/1	R-B; 1	35,754	57,129	94.3	79.4	borehole; propably deformed

Table S1 (continued)

number of site	site	stratigraphy	X	Y	top of the series	base of the series	comments
64	Wielkocin Ch/1	R-B; 1	35,561	57,065	135.5	123.8	borehole; propably deformed
65	Lądek-Szary Kamień	K-S; 1	36,327	55,818	480.0	475.0	sediments covered by basalt lava
66	Mokra	D; 1	36,938	55,921	195.0	192.0	
67	Dębina	D; 1	36,943	55,932	190.0	186.0	
68	Klodzko 2	K-S; 2	36,165	55,934	288.0	-	organic deposits, dated
69	Gorzuchów	K-S; 2	36,119	55,961	304.0	-	weathered sediments only
70	Ligota Wielka 1+2	K-S; 4	36,498	55,981	2,790.0	-	deformed
71	Ożary	K-S; 2	36,293	55,982	280.0	-	
72	Janowiec	K-S; 4	36,257	55,983	273.0	-	organic deposits, dated
73	Ząbkowice	Z; 4	36,293	56,088	271.0	268.0	slightly deformed
74	Tułowice	K-S; C; 3-2	36,908	56,110	185.0	166.0	slightly deformed; floral macrofossils
75	Skarbiszowice	K-S; 2	36,893	56,126	196.0	-	
76	Chrząszczyce 1	C; 3-1	37,042	56,134	180.0	-	slightly deformed
77	Chrząszczyce 2	C; 2-1	37,042	56,134	180.0	-	
78	Nowy Dwór	K-S; 3	36,440	56,140	220.0	-	
79	Jagielno	K-S; 2-1	36,560	56,142	245.0	-	
80	Niemodlin 2	C; 2	36,838	56,165	180.0	-	
81	Niemodlin 1 -Wesele	C; 3	36,841	56,166	180.0	-	
82	Gracze	K-S; 2	36,812	56,200	170.0	165.0	sediments underlain by basalt lava
83	Magnuszowiczki	K-S; 2	36,847	56,216	160.0	-	floral macrofossils
84	Skorogoszcz	K-S; 3,2	36,900	56,275	161.0	-	
85	Mleczna	K-S; 3	36,308	56,354	171.5	-	
86	Ligotka Nam/1	K-S; 2	36,887	56,642	136.0	132.0	borehole
87	Radzowice Syc/2	K-S; 3	36,871	56,799	143.0	133.0	borehole; mixed series from K-S & C formations
88	Słupia	K-S; 3A	36,899	56,918	200.0	-	
89	Snowidza 1/6	S; 1(2,3)	35,890	56,610	171.0	149.0	borehole; profile not fully studied
90	Krotoszyn	K-S; 3,2	36,695	57,344	133.0	-	strongly deformed
91	Stankowo Krz/1	K-S; 3	36,317	57,566	95.0	85.0	borehole; mixed series from K-S & C formations
92	Mszczyczyn Gos/1	K-S; 2	36,442	57,586	104.0	101.0	borehole
93	Buków 1/3	M-W; 1	36,110	56,510	168.0	156.5	borehole
94	Zastruże 4/2	M-W; 1	36,062	56,520	167.0	140.2	borehole
95	Kępy 38/1	M-W; R-B; 4-2	35-980	56,660	155.0	124.0	borehole
96	Bardo 2	local; 1	36,244	56,002	300.0	290.0	borehole
97	Bardo 4	local; 1	36,244	56,002	300.0	290.0	borehole
98	Potworów 1	K-S; 3	36,248	56,008	295.0	285.0	borehole
99	Potworów 3	K-S; 3	36,248	56,008	300.0	290.0	borehole
100	Stara Jamka	K-S; 2	36,888	55,980	190.0	-	
101	Świętów	local; 1	36,680	55,869	270.0	260.0	
102	Czarnolas	K-S; 2	36,635	56,088	230.0	-	
103	Grabin	K-S; 2	36,769	56,110	203.0	-	
104	Roszkowice	K-S; 2	36,800	56,160	195.0	-	
105	Rudziczka	D; 1	36,799	55,865	265.0	250.0	borehole
106	Szybowice	D; 1	36,797	55,832	279.0	250.0	borehole
107	Albetów	Z; 4	36,262	56,088	283.0	-	deformed
108	Brzeg Dolny 3	K-S; M-W; 1,4	36,220	56,847	106.0	100.0	borehole; archival data only; membr IV - mixed series from M-W & R-B formations

D - Dębina Formation
K-S - Klodzko-Stankowo
C - Chrząszczyce
Z - Ząbkowice Formation
B - Bojanice Formation
W - Wichrów Formation
P - Pogalewo Formation
S - Snowidza Formation

M-W - Mielęcin - Wołów Formation
R-B - Rokitki - Bielany Formation
local - other, not specifically defined preglacjal deposits
1-4 - time units (members)
X - horizontal coordinate of site
Y - vertical coordinate of site
top of the series - "indicates the highest topographic position of sediment "in the studied site"
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