Geological Quarterly, 2024, 68: 2
DOI: http://dx.doi.org/10.7306/gq.1725

The Pomerania Gravity Low at the East European Craton margin – a granitic batholith or a Paleoproterozoic impact structure?

Marek NARKIEWICZ[1, *] and Zdzisław PETECKI[1]

[1] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland, ORCID: 0000-0003-1962-0253 [MN], 0000-0002-9615-0390 [ZP]

Narkiewicz, M., Petecki, Z., 2024. The Pomerania Gravity Low at the East European Craton margin – a granitic batholith or a Paleoproterozoic impact structure? Geological Quarterly, 68: 2; https://doi.org/10.7306/gq.1725

Associate Editor: Jacek Szczepański

The Pomerania Gravity Low is a regular large-amplitude, oval anomaly of disputable origin located at the East European Craton margin. In the past it has been interpreted as a Proterozoic crustal keel or an Early Paleozoic/Permian-Mesozoic depocentre. The origin of the anomaly has been reconsidered based on a reinterpretation of previous potential fields, seismic and magnetotelluric data and recent gravimetric modelling results. New alternative interpretations are proposed and discussed, namely a felsic intrusion related to the Transscandinavian Igneous Belt and a large impact structure dating to ~1.6–1.8 Ga. The data assembled, together with regional comparisons, make the impact origin seem more probable. Nevertheless, prolonged erosion, deep burial and a metamorphic overprint hamper testing of this hypothesis, e.g., through finding impact ejecta or shock-affected minerals.

Key words: gravity anomaly, East European Craton, magnetic anomaly, magnetotellurics, gravity modelling.

INTRODUCTION

The Pomerania Gravity Low (PGL) at the SW margin of the East European Craton (EEC) is an oval anomaly with a maximum amplitude of –60 mGal, its longer dimension attaining ~200 km. Explaining its origin may shed light on important questions of European geology including the nature of the Teisseyre-Tornquist Zone (TTZ) at the craton margin (Narkiewicz et al., 2015) and the southward extent of the Paleoproterozoic Transscandinavian Igneous Belt (Bogdanova et al., 2015). Causes for the anomaly are still debatable, including lateral differences in rock-density distribution (Grabowska et al., 1992; Królikowski and Petecki, 1995; Królikowski et al., 1998), crustal thickening (Fajklewicz, 1964; Królikowski and Petecki, 2002; Petecki, 2002; Mazur et al., 2015) or a combination of both of these factors (Grabowska et al., 1998). Geological explanations have inferred the presence of a deep Phanerozoic depocentre (Grabowska et al., 1998) or a crustal keel connected with the Meso-Neoproterozoic Teisseyre- Tornquist suture (Mazur et al., 2015, 2016).

Here, we review available data and gravity modelling results, particularly regarding the recent modelling output (Petecki, 2019) which help constrain possible explanations of the PGL. We show that a review of the potential fields, seismic and magnetotelluric data casts doubt on current geological hypotheses related to the anomaly. Hence, new alternative genetic models are proposed, namely a felsic intrusive body and a large impact structure, both of Paleoproterozoic age. Such explanations of old buried structures are never straightforward, particularly so in the case of impact phenomena whose original topography is long gone, and where the rock record has been removed and/or is inaccessible (Pesonen, 1996). Nevertheless, arguments, mainly geophysical, will be presented in support of both hypotheses to discuss their pros and cons, and which may eventually provide a convincing solution.

REGIONAL BACKGROUND

The PGL is located at the south-western margin of the East European Platform (EEP) within a Fennoscandian part of the EEC basement (Fig. 1). In the south-west it is bordered by TTZ which corresponds to a major discontinuity in the lithospheric structure of the European Plate (Ernst et al., 2008; Wilde-Piórko et al., 2010). Its crustal expression has been documented by the results of deep refraction seismic studies (Guterch and Grad, 2006). It can be traced as a prominent magnetic-anomaly gradient separating uniformly low magnetic susceptibility values in the SW from a complex pattern of generally higher values in the EEP area (recently summarized by Narkiewicz and Petecki, 2017, 2019). The basement of the Paleozoic Platform between the TTZ and the inner Variscan

* Corresponding author: e-mail: MarekJNarkiewicz@gmail.com

Received: June 20, 2023; accepted: December 2, 2023; first published online: March 26, 2024

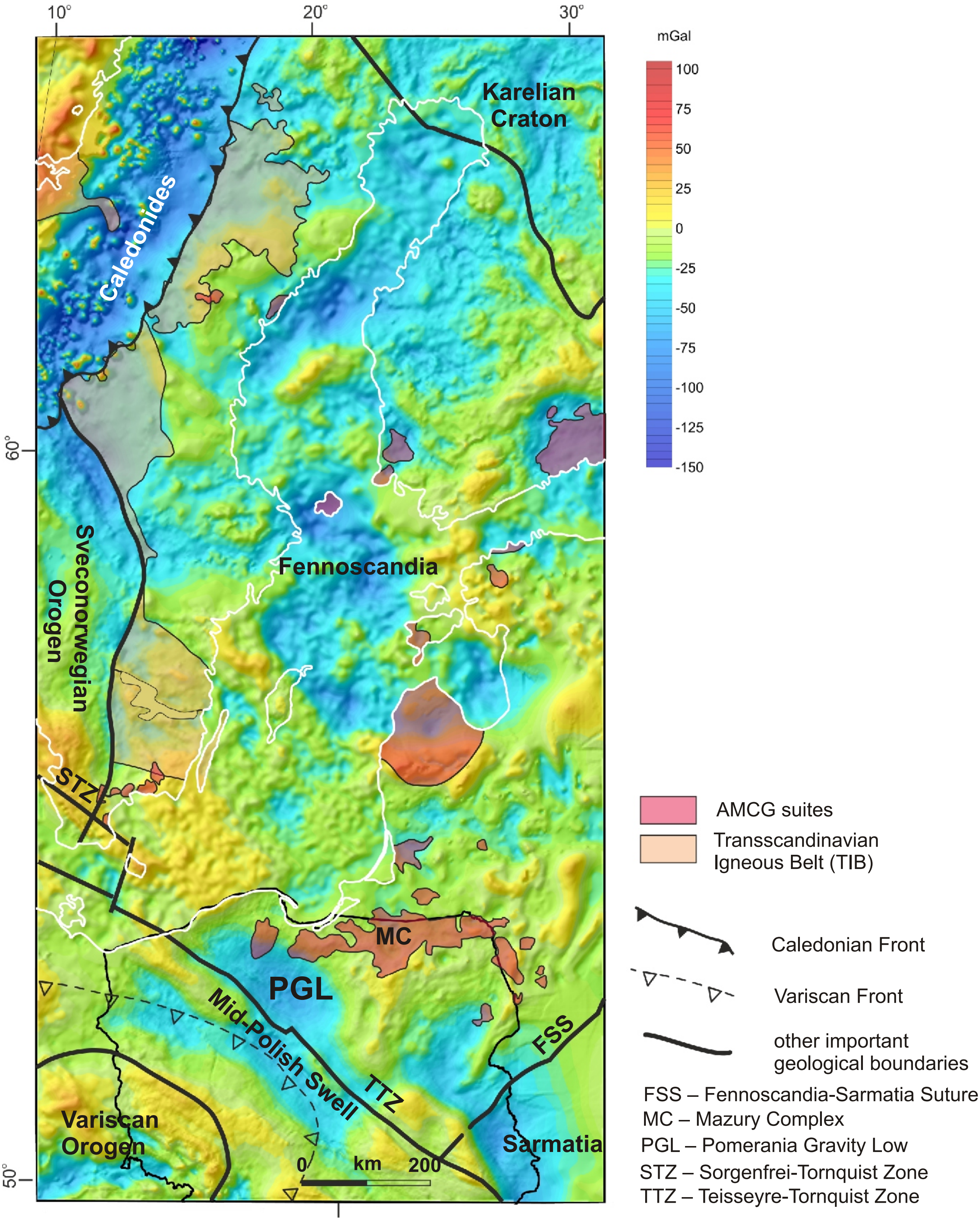

Fig. 1. Location of the Pomerania Gravity Low within the geological framework of western Fennoscandia (after Krzemińska et al., 2021) on the background of a Bouguer gravity anomaly map

AMCG – anorthosite-mangerite-charnockite-granite intrusions

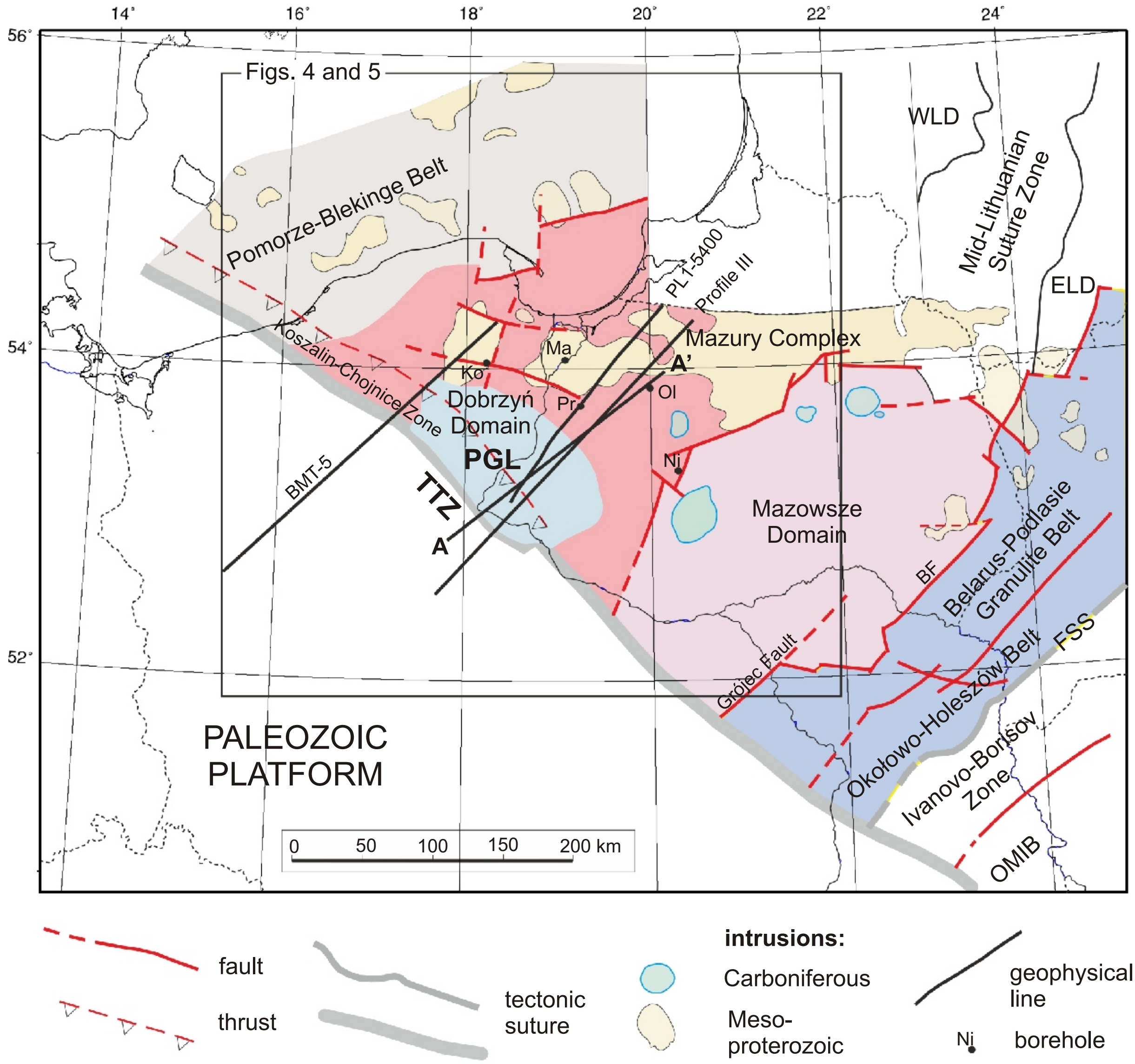

Fig. 2. Map of the Polish part of the crystalline East European Platform basement (after Krzemińska et al., 2017, simplified) showing the Pomeranian Gravity Low (contoured along the 40 mGal isoline), and location of the geophysical lines analyzed and borehole sections cited in the text

A–A' – the line of gravimetric modelling (Petecki, 2019); BF – Białystok Fault; ELD – East Lithuanian Domain; FSS – Fennoscandia-Sarmatia Suture; OMIB – Osnitsk-Mikashevichi Igneous Belt; TTZ – Teisseyre-Tornquist Zone (after Narkiewicz et al., 2015); WLD – West Lithuanian Domain; abbreviation of borehole names: Ko – Kościerzyna IG 1, Ma – Malbork IG 1, Ni – Nidzica IG 1, Ol – Olsztyn IG 2, Pr – Prabuty IG 1

Orogen (Fig. 1) is composed of Caledonian terranes of Gondwanan and Baltican origin (Dadlez et al., 2005; Narkiewicz and Petecki, 2017). In the study area, the TTZ and an adjoining narrow strip of the EEP are overridden by deformed Lower Paleozoic strata forming a fold-and-thrust complex referred to as the Koszalin-Chojnice Zone (Fig. 2; Dadlez, 1978; Dadlez et al., 1994).

The Paleozoic Platform cover includes Devonian and Carboniferous deposits, partly overlain by an external Variscan fold-and-thrust belt (Narkiewicz, 2020). During the late Permian to Mesozoic a pronounced depocentre, the Mid-Polish Trough, developed along the TTZ. Alpine compression around the Cretaceous-Paleogene boundary led to inversion of the depocentre and formation of an elongated antiform, the Mid-Polish Swell. This structure is clearly visible as a chain of positive gravimetric anomalies parallel to, and south-west of, the TTZ (Fig. 1). The compression affected also the EEC margin, mainly the pre-existing Koszalin-Chojnice Zone, causing inversion of previously formed narrow Mesozoic grabens and formation of narrow antiforms, such as the Chojnice Anticline (Fig. 3; Dadlez et al., 1998; Dadlez, 2001).

The EEP cover in northern Poland comprises Ediacaran to Cenozoic, mostly flat-lying strata gradually thickening from <0.5 km in the east to ~9 km near the cratonic edge (Kubicki and Ryka, 1982; Znosko, 1998). The cratonic basement shows a general pattern of SW–NE trending tectonic domains related to Svecofennian crustal accretion progressing from the Sarmatia-Fennoscandia Suture north-westwards (Fig. 2; Krzemińska et al., 2017). The PGL is associated with the Dobrzyń Domain which, based on scarce borehole data, is composed mostly of synorogenic I-type granites, and biotite and garnet-sillimanite-biotite paragneisses, locally migmatized,

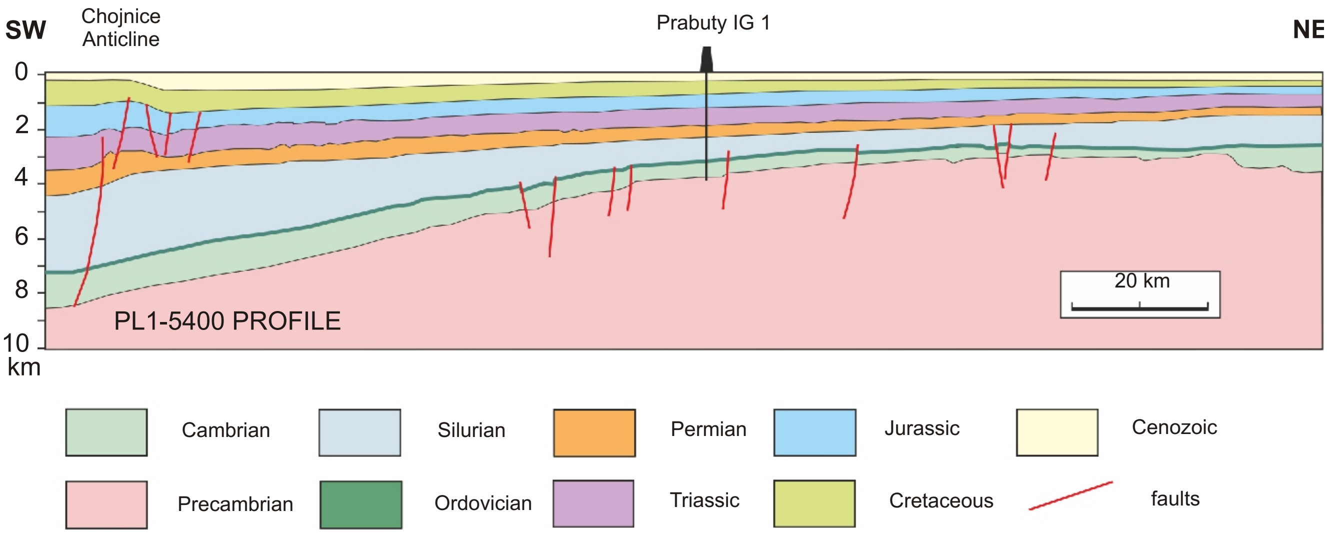

Fig. 3. Cross-section along the reflection seismic PL1-5400 profile showing the geometry of the platform cover in the study area (after Mazur et al., 2015, modified)

Note location of the Prabuty IG 1 borehole

with ages ranging from 1.82 to 1.76 Ga. The Dobrzyń Domain adjoins the Mazowsze Domain (1.84–1.80 Ga) in the south-east, the latter comprising mainly para- and ortho-gneisses and S-type granitoids as well as volcanic and plutonic rocks metamorphosed to amphibolite and greenschist facies. In the NW the Dobrzyń Domain is bordered by the Pomorze-Blekinge Belt (1.79–1.74 Ga) composed mainly of synorogenic granodiorites, quartz-monzonites and granites. This belt is characterized by occurrence of oval positive magnetic anomalies striking WSW–ENE (Krzemińska et al., 2017).

Superimposed on the Paleoproterozoic belts are two generations of anorthosite-mangerite-charnockite-granite (AMCG) intrusions. The older generation (1.54–1.49 Ga) comprises subcrops of the Mazury Complex stretching E-W for more than 300 km across the Dobrzyń and, in part, the Mazowsze domains (Fig. 2). Smaller intrusions, <50 km in diameter, are known from the Mazowsze Domain and the Belarus-Podlasie Granulite Belt. The younger AMCG intrusions (1.48–1.45 Ga) are scattered in the Pomorze-Blekinge Belt. Their irregular subcrops attain various dimensions, usually <100 km (Krzemińska et al., 2017). On potential field maps the AMCG suites correspond to positive and negative anomalies of variable amplitude. Distinct magnetic anomalies are related to the different groups of intrusive rocks. For example, locally strong negative magnetic anomalies are related to the Mesoproterozoic anorthosite massifs of Kętrzyn and Suwałki (Petecki and Rosowiecka, 2017). The latter consists also of gabbro-norite, gabbro and diorite, hosting Fe–Ti–V ore deposits (Petecki and Wiszniewska, 2021) with positive magnetic and gravity anomalies. Positive magnetic and gravity anomalies also coincide with monzodiorite and granodiorite intrusions.

Of subordinate regional importance are small granitic intrusions, ~1.5 Ga in age but clearly post-dating the AMCG plutonism in NE Poland. A further igneous phase in the study area is known from the Mississippian. Small plutons are represented by semicircular to elliptical subcrops ranging in size from a few kilometres to ~40 km. They are composed of various alkaline rocks, mainly syenites and gabbros, subordinately alkaline ultramafites, whose crystallization age is estimated at 354 to 338 Ma (Demaiffe et al., 2013; Krzemińska et al., 2017). Their development was associated with extensional processes in the Variscan Foreland of central and eastern Europe (Narkiewicz, 2020).

PREVIOUS WORK

The PGL anomaly in N Poland, also known as the Lower Vistula River depression, is one of the most pronounced negative gravity anomalies in Poland with a minimum value of ~62 mGal (Królikowski and Petecki, 1995). The origin of the PGL anomaly has been the subject of various hypotheses and many analyzes using 2D gravity modelling and gravity stripping. Fajklewicz (1964) suggested that the anomaly is connected with the Moho topography. Other authors argued that the PGL is due to the superimposed gravity effects of the Moho topography and the lower-density upper part of the sedimentary cover (Grabowska et al., 1998). Still other authors have suggested that this anomaly may be caused by low-density rocks in the crystalline EEC basement (Młynarski et al., 1982; Grobelny and Królikowski, 1988; Grabowska and Raczyńska, 1991; Grabowska et al., 1992; Królikowski and Petecki, 1995; Królikowski et al., 1998).

Earlier gravity models along profiles crossing the TTZ in northwest Poland (Królikowski and Petecki, 1997, 2002; Petecki 2002, 2008) demonstrated a low-density uppermost mantle and a wide zone of crustal thickening in the area of the PGL. More recently, Mazur et al. (2015) carried out 2-D/2.5-D gravity and magnetic modelling along two NE–SW trending reflection seismic lines, including the PL1-5400 line running across the PGL (Fig. 2) and discussed below in a more detail. Based on the modelling results they ascribed the PGL to a ~20 km-wide crustal keel and a Moho step which, according to their interpretation, is associated with a modified course of the TTZ. This concept sparked further discussion (Narkiewicz and Petecki, 2016, 2017; Mazur et al., 2016).

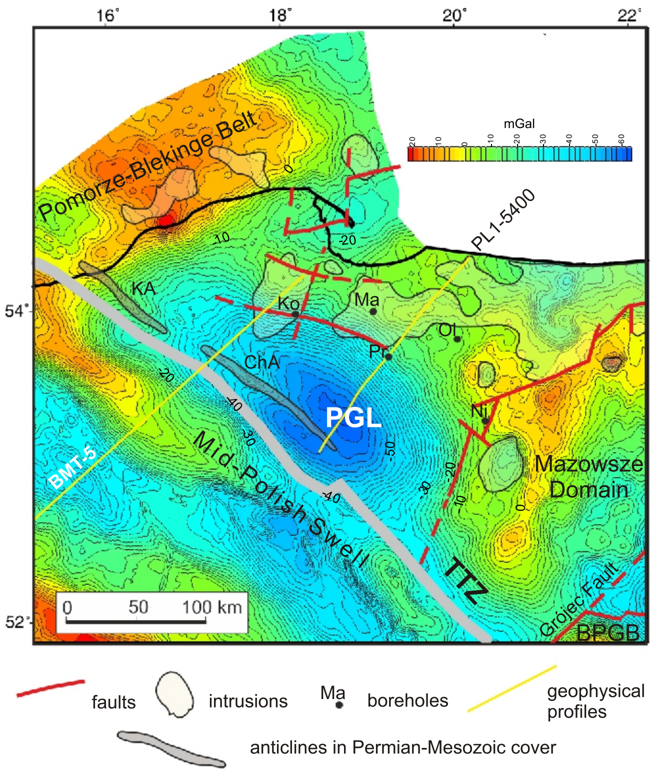

Fig. 4. Bouguer gravity anomaly map of the PGL and adjoining areas within the geological framework of the East European cratonic crust (after Krzemińska et al., 2017) and showing location of geophysical profiles and borehole sections discussed in the text

BPGB – Belarus-Podlasie Granulite Belt, ChA – Chojnice Anticline; KA – Koszalin Anticline; for other explanations see Figure 2

GEOPHYSICAL DATA

GRAVITY ANOMALIES

The Bouguer anomaly maps (Figs. 1 and 4) show the oval shape of the Pomerania Gravity Low, truncated by TTZ in the south-west. The longer axis of the anomaly is perpendicular to the NE-SW trending Paleoproterozoic terranes of the EEC and oblique to the E-W trend of the Mazury Complex intrusive rocks. The magnitude of PGL attains –60 mGal, contrasting with lower-amplitude anomalies of the adjoining part of the EEC.

In the area south-west of the TTZ, the anomalies reflect the NW–SE striking pattern of deformation of the Permian-Mesozoic cover – the Mid-Polish Swell (Dadlez et al., 1995). Such a trend is also shown by elongated positive anomalies superimposed on the PGL, related to the tectonic Koszalin-Chojnice Zone (Fig. 2). These subordinate features correspond to the narrow Koszalin and Chojnice anticlines developed in the Mesozoic cover during the late Cretaceous to early Paleogene interval (Fig. 4).

The oval outline of the outer PGL perimeter on the EEC side is flanked by a discontinuous belt ("ring") of elevated gravity. The largest contrast is seen to the E and NE, and this may be partly related to the superimposed magmatic intrusions of Carboniferous and Mesoproterozoic age, respectively. To the NE the prominent positive anomalies are caused by Mg-diorites to granites of the Pomerania-Blekinge Belt of volcanic arc affinity (Krzemińska et al., 2021).

MAGNETIC ANOMALIES

The magnetic anomaly pattern (Fig. 5) reflects two contrasting crustal domains. The Paleozoic Platform to the SW of the TTZ displays uniformly low values of magnetic field anomalies in the range –100 to –300 nT. The EEC is characterized by an irregular pattern of large-amplitude magnetic highs and lows. Positive anomalies whose maxima attain 500–900 nT are mostly related to the AMCG intrusive rocks of the Mazury Complex north of the PGL and to the younger generation of AMCG plutonism in the Pomorze-Blekinge Belt. The elongated, NNE–SSW oriented positive anomalies east of PGL are related to granitoids of the Mazowsze Domain (Krzemińska et al., 2017). Part of the PGL corresponding to the maximum gravity low shows an irregular pattern of local magnetic highs of moderate amplitude up to 200 nT, adjoining the uniform low values typical of the Paleozoic Platform to the SW. The highs are surrounded by a magnetic low (<0 nT) pattern to the east and north while in the north-west they appear to be overprinted by positive anomalies of the Mazury Complex.

SEISMIC DATA

The central part of PGL is transected by the high-resolution reflection seismic line PL1-5400 acquired in the framework of the ION Geophysical PolandSPAN^{TM} regional programme (Mazur et al., 2015). The cross-section along this line (Fig. 3) shows an interpretation of the EEC platform cover according to the authors cited. The north-eastern part is characterized by a regular layer-cake geometry of the successive Phanerozoic systems. The thickness of the Paleozoic, particularly Silurian,

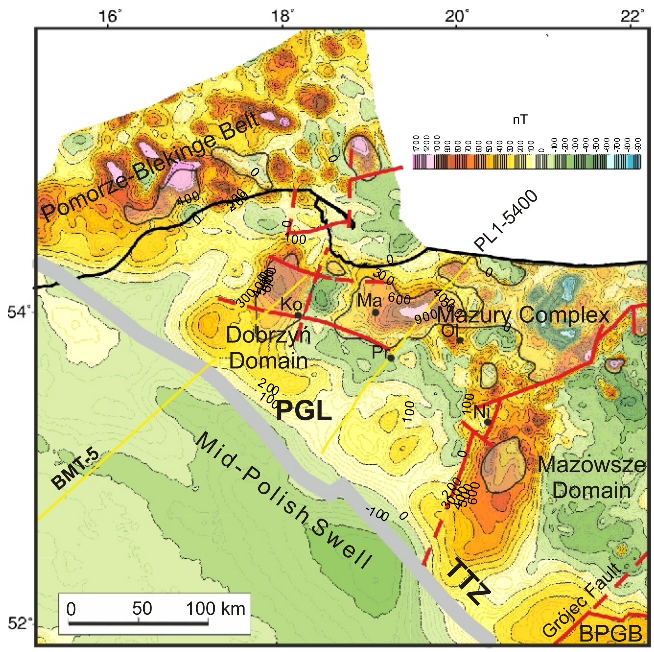

Fig. 5. Reduced-to-the-pole total intensity magnetic anomaly map of the PGL

For other explanations see Figure 4

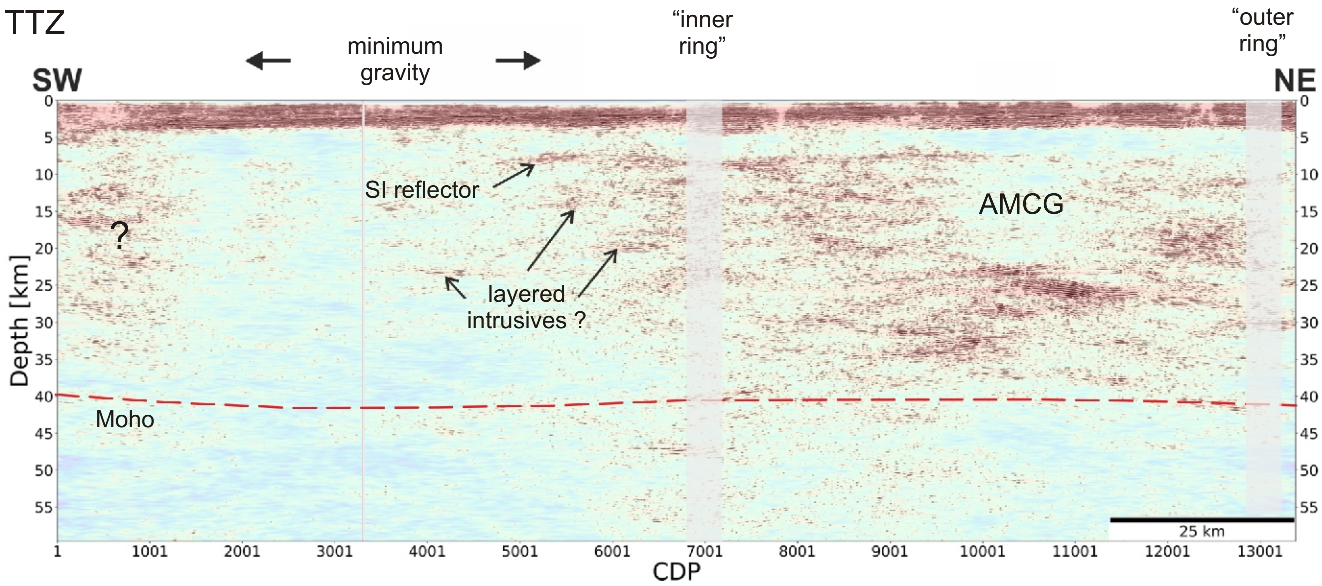

Fig. 6. Reflection seismic PL1-5400 profile (after Mężyk et al., 2019, modified and reinterpreted) crossing the central part of the PGL (see Fig. 2 for location), Moho after Majdański (2012)

Vertical "inner" and "outer ring" lines mark the inner and outer limits of positive gravity and magnetic anomalies encircling the PGL; the SI reflector (Mężyk et al., 2019) probably represents layered Carboniferous intrusive rocks

strata, gradually increases south-westwards. A considerable thickness increase of the Mesozoic strata is seen near the SW termination of the cross-section marking the NE flank of the Mid-Polish Trough. The Permian-Mesozoic cover is here faulted and folded, forming the Chojnice Anticline.

The extended correlation reprocessing of the PL1-5400 seismic data by Mężyk et al. (2019) allowed these authors to extend the nominal record length of the original data to depths covering the entire crust and part of the underlying mantle (Fig. 6). The resulting data revealed a complex pattern of crustal and sub-Moho reflectivity in the PGL area. Most of the subhorizontal to gently inclined reflective patterns were interpreted by the authors cited as shear zones formed in the convergent setting of a Paleoproterozoic orogen. The central part of the Mazury AMCG Complex lacks such deformational structures, showing an almost transparent image. Notably, the crystalline crust corresponding to the central part of the PGL is also relatively transparent, in contrast to both its flanks. The "SI reflector" (Mężyk et al., 2019) protruding towards the SW at a depth of ~10 km (Fig. 6) was interpreted as representing Mesoproterozoic or Carboniferous layered intrusive rocks, a plausible explanation also for other horizontal reflectors in this sector. The reflection-seismic Moho in the PGL area is poorly defined, in contrast to its NE flank. An irregular reflectivity pattern in the SW-most part of the profile may be related to the Paleoproterozoic orogenic fabric mentioned above or, alternatively, may result from younger tectonic and igneous processes along the TTZ (Narkiewicz and Petecki, 2019).

MAGNETOTELLURICS

Earlier results of deep electromagnetic soundings in the study area (Ernst et al., 2008) demonstrated that the TTZ coincides, at upper mantle levels, with a boundary between the highly resistive EEC and more conductive Paleozoic Platform. By contrast, the Paleozoic Platform crust shows a generally more complex conductivity pattern than the EEC crust, the latter displaying a variable but overall higher resistivity. Nevertheless, the difference between the electrical crustal properties between the geological regions was not clearly resolved by deep magnetotelluric investigations (Jóźwiak, 2013).

The distribution of electric parameters in the crust is clearer in the shallow (down to 30 km) magnetotelluric survey conducted along the BMT-5 Profile crossing the NW part of the PGL (Stefaniuk et al., 2008, unpublished report). This profile coincides with the POLONAISE'97 P2 deep refraction seismic profile (Guterch and Grad, 2006) which enables comparisons with a deep crustal structure deduced from the P-wave velocity distribution (Fig. 7). The uppermost, 3–8 km-thick conductive layer corresponds roughly to low-velocity Meso-Cenozoic strata. The deeper resistivity pattern seems to be generally consistent with the crustal blocks defined by Narkiewicz and Petecki (2017) in northern Poland. In particular, both the Pomeranian Suture and TTZ appear to coincide with lateral resistivity gradients. The TTZ is marked by a nearly vertical, 15–20 km-wide zone of higher resistivity extending to a depth of ~20 km. To the NE this zone borders the flank of a bowl-shaped zone of moderate resistivity attaining 30–50 Ohm*m. This reaches a depth of 20–25 km and thus is located entirely in the middle-upper crystalline crust. Its substrate as well as its NE flank are characterized by less conductive crust, with resistivities up to 300–400 Ohm*m. The conductive zone broadly corresponds to the PGL although its lowermost part appears to be slightly displaced NE-wards relative to the gravity minimum (Fig. 7). There is a minor low-resistivity "body" at 230 km of the profile (LRB in Fig. 7), which is difficult to interpret in terms of the regional geology (perhaps a small mafic intrusion or mineralization?).

The MT survey by Oryński et al. (2019) included Profile III, stretching NE–SW ~20 km to the east and parallel to the PL1-5400 profile (Fig. 2). The interpretation of this profile, extending down to 20 km depth, also shows a conductive zone roughly coincident with the central part of the PGL, although its bowl-shaped outline is less clear. Its more resistive SW flank

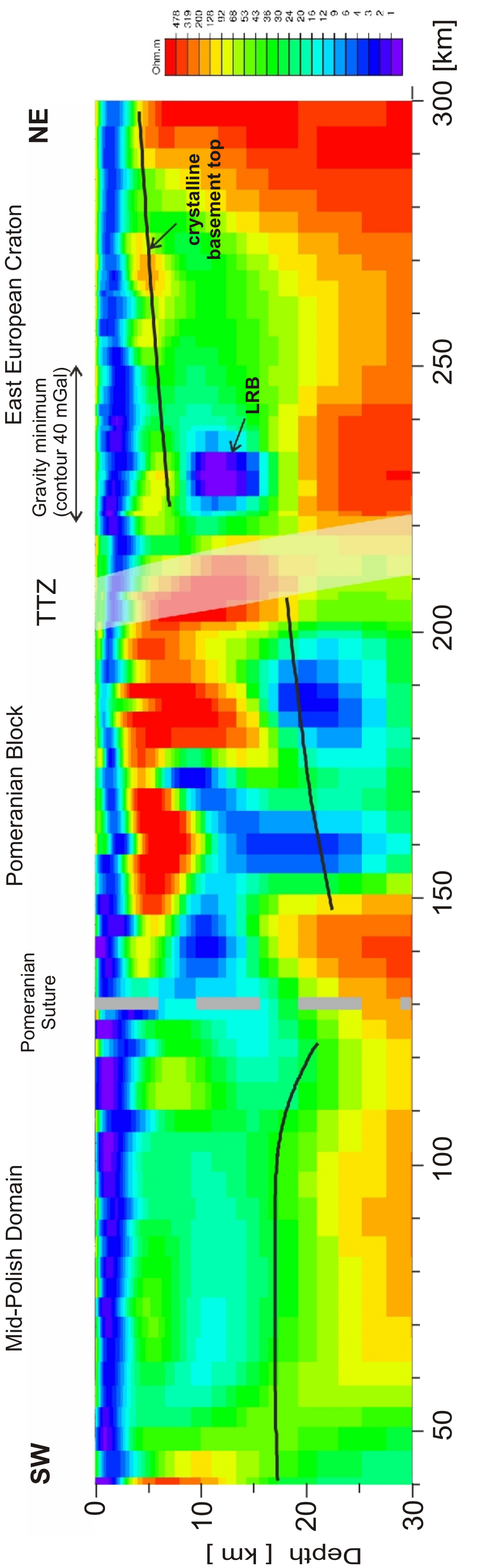

Fig. 7. Magnetotelluric cross-section BMT-5 (after Stefaniuk et al., 2008, unpubl.) with the geological interpretation of the present authors (partly after Narkiewicz and Petecki, 2017)

Bold black lines mark the crystalline basement top from refraction seismic data along the POLONAISE P2 profile (Guterch and Grad, 2006); LRB – low resistivity "body" (see the text)

extending from the depth of 8 km downwards is nevertheless much wider than the TTZ interpreted in the BMT-5 Profile. The NE flank, comprising the less-conductive depth interval from ~4 km to ~18 km, seems to correspond to a zone of reflective patterns interpreted as a Paleoproterozoic orogenic fabric with superimposed intrusive rocks (Mężyk et al., 2019).

IDEAL BODY ANALYSIS OF THE PGL ANOMALY

The source of the PGL anomaly was examined using Parker's ideal body theory (Parker, 1974, 1975) and a linear programming technique (Huestis and Ander, 1983). The procedure consisted of inverting a residual gravity anomaly along the profile transecting the PGL in the NE–SW direction. It is based on finding the extreme density solution with the smallest possible maximum density contrast that can explain the anomaly within a given misfit in a specified region of solution confinement (Petecki, 2019).

A series of optimizations were performed modifying either the depth to the top or the thickness of the region of solution confinement (Petecki, 2019). Considering that the residual PGL anomaly has negative values, the absolute data values were used to satisfy the non-negative condition required by the inversion algorithm (Huestis and Ander, 1983).

A misfit of 0.25 mGal was assumed for the gravity values used in the calculations. The region of confinement was partitioned into rectangular cells whose horizontal and vertical dimensions along the profile were 5 and 2 km, respectively, while their lateral extent was ±50 km in the direction perpendicular to the profile.

The set of solutions of the ideal body inversion, shown as trade-off diagrams (Fig. 8), defines the allowed ranges of parameters of feasible solutions for the source of the PGL. All solutions lying within concave zones of the trade-off curves shown in Figure 8 are consistent with the constraints imposed in the inversion procedure. The ideal body inversions also show that the depth to the body top cannot exceed 15 km (Fig. 8A).

From the ideal body analysis, the maximum possible source top depth or minimum thickness of the source (when the top depth is fixed) can be found for any assumed density contrast. Some constraints on the latter come from a few deep boreholes near the PGL (Fig. 2), which sampled the topmost part of a granite, granitoid or AMCG suite, of average densities 2.66–2.71 g/cm^3, and a gneiss of average density 2.79 g/cm^3 encountered in the Olsztyn IG 2 borehole (Petecki, 2019).

Petecki (2019), analyzing the results of the ideal body inversion of the PGL anomaly together with other geophysical and geological constraints from previous studies, concluded that the source of the PGL anomaly is in the upper and middle crystalline crust. According to the density data cited above, a value of –0.2 g/cm^3 may be assumed as a geologically plausible maximum density contrast related to the potential crystalline basement source of the PGL. Accordingly, the top of the source body can be no deeper than 11.5 km (Fig. 6), and the body can be no thinner than 7 km, when the source is confined below 8 km depth (Fig. 6).

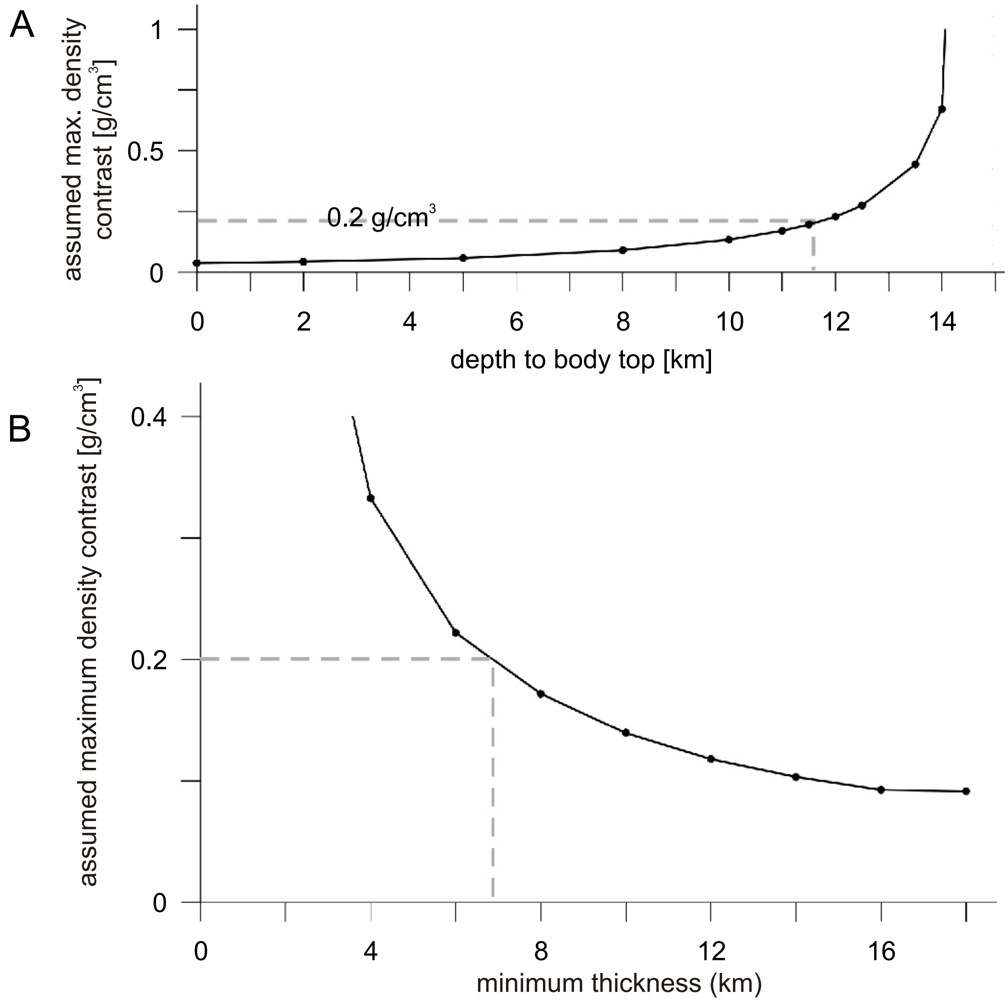

Fig. 8. Gravity modelling results based on the ideal body concept (Petecki, 2019)

See the text for methodological background. **A** – trade-off curve for assumed maximum density contrast versus the depth-to-top of the ideal body having its bottom not limited by a depth constraint (solid line and dots). The maximum depth is 11.5 km assuming a maximum density contrast of 0.2 g/cm^3. **B** – trade-off curve for assumed maximum density contrast versus minimum thickness of the ideal body, where its top is 8 km below the surface (solid line and dots). The minimum thickness is 7 km, assuming a maximum density contrast of 0.2 g/cm^3

INTERPRETATION

PREMISES AND CONSTRAINTS

The results of the modelling summarized above (Petecki, 2019) constrain the depth of a PGL source to the interval of the lower-middle crystalline crust ranging from the basement top (~8 km depth) down to ~15 km or more. These constraints are based on a geologically plausible density contrast responsible for the anomaly, not exceeding -0.2 g/cm^3. It should be stressed that with the assumption of a shallower source, corresponding to the 4 km-thick Lower Paleozoic, the greatest negative density contrast is ~ –0.3 g/cm^3 (Petecki, 2019). Such a contrast appears geologically implausible, however, as shales and siltstones constituting the bulk of the respective strata are characterized by a relatively high mean density of 2.65 g/cm^3 (Petecki, 2019). Furthermore, the possible gravity effect of the Lower Paleozoic depocentre (Grabowska et al., 1998) is questionable given that the layer-cake platform cover above the basement top dips at a low angle to the SW (Fig. 3). Moreover, the earlier modelling results of Grobelny and Królikowski (1988) and Petecki (2008) exclude Permian–Cenozoic strata as a source for the PGL anomaly.

The above constraints are consistent with the earlier results of 3-D gravimetric stripping, pointing to a possible greater significance of "light" crystalline basement rocks relative to platform sedimentary strata (Grobelny and Królikowski, 1988; Królikowski and Petecki, 1997; Królikowski et al., 1998). Nevertheless, interpretations relating the PGL to thickening of the lower crust (Królikowski and Petecki, 2002; Petecki, 2002; Mazur et al., 2015, 2016) also appear inconsistent with the recent modelling outcome (Petecki, 2019). Moreover, the presence of a crustal keel proposed by Mazur et al. (2015) is not supported by the deep seismic refraction and reflection results (Majdański, 2012; Mężyk et al., 2019). In their discussion, Narkiewicz and Petecki (2016) questioned the concept of a crustal keel, considering it as a modelling artifact not supported by any factual data. They stressed that the modelling procedure included poorly substantiated assumptions such as oversimplified crustal structure, i.a. neglecting the existence of a distinct discontinuity related to the TTZ. Other drawbacks included the poorly constrained rock-density distribution resulting in biased modelling input. The reply by Mazur et al. (2016) did not dispel the doubts raised by the present authors (see their further comments in Narkiewicz and Petecki, 2017).

The regular oval shape of PGL, oriented perpendicular to the NE–SW strike of the Paleoproterozoic terranes (Krzemińska et al., 2017), speaks against a relationship to the Svecofennian accretionary processes in the Dobrzyń Domain. Thus, the possible interpretation of the anomaly as e.g., an orogenic root composed of felsic metasedimentary rocks, seems scarcely possible. Such an explanation was put forward for the elongated Bouguer anomaly lows in the Moldanubian Zone, paralleling the Variscan orogenic structures of the Bohemian Massif (Guy et al., 2011).

Regardless of the geological cause (-s) of the PGL anomaly, its age may be constrained using some indirect geological premises and a regional context. The lower age limit is defined by the age of the Dobrzyń Domain terranes (1.82–1.76 Ga) constituting the PGL substrate (Krzemińska et al., 2017). The upper limit is set by the emplacement of the AMCG intrusive rocks, particularly those related to the Mazury Complex, 1.54–1.49 Ga in age (Krzemińska et al., 2017). This conclusion seems substantiated in view of the apparent overprinting of the PGL margin by the gravity and magnetic effects of the Mesoproterozoic intrusions (Figs. 4 and 5). Thus, it may be assumed that the geological source of the PGL came into existence during the Statherian Period (~1.6–1.8 Ga).

The above considerations lead to the conclusion that the previous geological explanations of the PGL do not satisfy the geological evidence, and in particular, the geophysical data and modelling results discussed above. Thus, other possible genetic models should be considered, which are consistent with, or at least not contradictory to, the constraints presented.

ALTERNATIVE INTERPRETATIONS

The density contrast of ca. –0.2 g/cm^3 explaining the Pomeranian anomaly may be related to a low-density felsic body flanked by denser metamorphic rocks. Such interpretation is supported by the occurrence of Paleoproterozoic granites in the Dobrzyń Domain and the presence of a gneiss encountered in the Olsztyn IG 2 borehole (see sections on regional background and ideal body analysis). In general, the concept of a granitic massif below the EEC platform cover is compatible with the modelling results although these do not constrain the 3-D geometry of such a causative body (Petecki, 2019).

The hypothetical pluton may have formed a part of the Transscandinavian Igneous Belt (TIB). The age of its early phase, TIB-1, is estimated as 1.76–1.81 Ga (Högdahl et al., eds., 2004) roughly corresponding to the age of the Dobrzyń Domain. According to Bogdanova et al. (2015) the belt may continue southwards to northern Poland. The hypothetical TIB-1 intrusive rocks in the PGL area would be separated from the southernmost outcrops of the TIB rocks in south Sweden by the distinct Pomorze-Blekinge Domain (Krzemińska et al., 2017, 2021). The basement of Pomerania and the adjoining Baltic Sea to the NW of the Dobrzyń Domain differs from typical TIB-1 rocks in displaying pervasive deformation and is thus similar to the deformed Blekinge bedrock in SE Sweden (Krzemińska et al., 2021). The isolated occurrence of this hypothetical PGL-related TIB batholith is in accordance with the discontinuous nature of the TIB outcrops in Scandinavia (Fig. 1). Moreover, the TIB granites are characterized by densities of the order of 2.66–2.69 g/cm^3 (Pascal et al., 2007), compatible with the "light" source of the PGL. The overall lack of seismic reflectivity (Fig. 6) may be related to the presence of a batholith with a seismically homogeneous structure. According to Juhojuntti and Juhlin (1998) the middle to lower crust displays a notably weak reflectivity associated with the TIB, in contrast to an adjoining more reflective Svecofennian crust.

Alternatively, the regular oval pattern of the gravimetric PGL anomaly may be suggestive of a large Paleoproterozoic impact structure superimposed on the Svecofennian crustal orogenic fabric. In this case, the original circular anomaly outline typical of impact structures (Pilkington and Grieve, 1992) may have been obliterated given the long interval post-dating the impact (Pesonen, 1996). In particular, the PGL displays an oval to semicircular shape apparently truncated by TTZ in the NE. Thus, it seems plausible that tectonic processes connected with the TTZ development and evolution (Narkiewicz et al., 2015) may have modified the originally circular outline of the structure (Fig. 4). If the extent of the gravity low gives an estimate of the crater diameter, the latter may correspond to ~200 km, comparable to the Chicxculub, Vredefort and Sudbury structures (Grieve et al., 2008; Osinski et al., 2022). The anomaly observed attains –60 mGal whereas the residual anomaly, after removing the regional background, is –47 mGal (Petecki, 2019). This value exceeds 30–35 mGal regarded as a general maximum for large structures, although a crystalline target may produce larger anomaly. The anomaly may result from a density contrast between impact-fractured and unaffected target rocks, which, for a crystalline basement, is on average 0.18 g/cm^3 (Pilkington and Grieve, 1992: tab. 1), and thus close to the density contrast suggested by scarce borehole data and the modelling outcome. In the PGL example this effect may have been enhanced by the "light" granitic lithology of the target.

The central part of PGL corresponds in the magnetic anomaly map (Fig. 5) to an area of variable but overall rather low magnetic susceptibility – a feature characteristic of most impact craters (e.g., Muundjua et al., 2007; Gilder et al., 2018). Nevertheless, the pattern is less clear than in the gravity map, partly due to overprint by Mesoproterozoic and Carboniferous intrusive rocks.

The seismic reflectivity pattern of the crust in the PGL area (Fig. 6) may result from a large projectile disrupting the original crustal orogenic fabric. Brecciation and fracturing caused by an impact lead to incoherent reflections, particularly in the central part of a structure (Therriault et al., 2002). Termination of crustal reflectivity towards the centre of an impact structure was observed e.g. in the case of the Vredefort and Siljan structures (Henkel and Reimold, 1998; Juhlin and Pedersen, 1987). This was interpreted as transition to "plastic crust" resulting from shock compression.

The increased electric conductivity (Fig. 7) is consistent with a large impact structure (Masero et al., 1997). In the case of the Siljan impact, the enhanced conductivity documented by a MT survey was interpreted as a consequence of fluid migration through the fractured bedrock (Zhang et al., 1988).

DISCUSSION

The SmÍland-Värmland granitoids of the southern TIB termination in Sweden display an E–W to ESE–WNW structural strike as well as internally complex, irregular structure (Gorbatschev, 2004: fig. 3). Moreover, their mapped gravity expression is more irregular than the oval NW–SE trending geom-

Table 1

Comparison of two alternative interpretations of the PGL with respect to their compatibility with various attributes discussed in the text

Attribute	TIB intrusion	Impact structure
Regional setting	–	+/–
Geometry (map)	–	+
Modelled depth	+	+
Gravity anomaly pattern	+	+/–
Magnetic anomaly pattern	–	+/–
Modelled density contrast (~0.2 g/cm^3)	+	+
Seismic reflectivity pattern	–	+
Magnetotelluric data (resistivity pattern)	+/–	+

(–) incompatible; (+/–) neutral; (+) compatible

etry of the PGL (Fig. 1). Also, the TIB granitoids show increased magnetic susceptibility (Juhojuntti et al., 2001) which is observed only in the outer part of the area of the PGL anomaly. In Pomerania, the reflection seismic results indicate a transparent crust down to Moho boundary, displaying merely localised reflections attributable to Mesoproterozoic and/or Mississippian intrusive rocks (Fig. 6). Such a pattern differs from the seismic records of the TIB intrusive rocks, characterised by weak reflectivity in the middle to upper crust (Juhojuntti and Juhlin, 1998).

By contrast with the felsic TIB intrusion hypothesis, the impact structure concept is better supported by the regular geometry of the negative gravity anomaly. When compared to the largest-diameter terrestrial impact structures, the hypothetical Pomeranian one differs in displaying an apparently uniform internal structure, without several circular anomalies characterizing large multi-ring craters (Grieve et al., 2008). Also, a central dome of uplifted target rocks is not clear, particularly in the gravity anomaly pattern. Moderate positive magnetic anomalies corresponding to the central part of the PGL (Fig. 5) may represent a weak expression of the structural central high (Henkel and Reimold, 2002), but such a possibility remains hypothetical. The magnetic properties may be partly obscured by post-impact phenomena, such as thermal remagnetization and metalliferous hydrothermal mineralization (Henkel and Reimold, 1998).

A geophysical record of a central dome and peak-ring is not always convincingly documented in geophysical studies of large impact structures. For example, the well-preserved Popigai Crater with a diameter of ~100 km, 35.7 Ma in age, displays an annular gravity high ~45 km in diameter connected with the peak ring but at the same time the structure shows a central gravity low suggesting the lack of a central uplift (Pilkington et al., 2002). According to Masaitis et al. (2019) the central depression with insignificant central uplift is filled with thick low-density brecciated material. Alternatively, Pilkington et al. (2002) explained the apparent lack of a central gravity high by a uniform distribution of bedrock density related to a uniform crustal lithology. Such lateral density contrasts are present e.g. in the Chicxculub Crater showing a central gravity high related to the basement uplift.

An unclear expression of the internal features of a hypothetical impact structure in potential field patterns may result also from deep erosion coupled with a thick post-impact sedimentary cover. The time interval postdating the PGL formation in the Statherian was dominated by uplift and erosion of the EEC basement, lasting for ~1 Ga until the Ediacaran. The magnitude of denudation may have been comparable to that of the Vredefort structure in which 8–10 km of estimated erosion removed ejecta and crater-fill, exposing a deep substructure (Therriault et al., 1993; Osinski et al., 2022). As a result, the structure lacks expression of the peak ring found in other large structures such as Chicxculub (Osinski et al., 2022) Apart from the erosional removal, any direct evidence of the impact in the basement rocks may have been obscured by the widespread metamorphic episode associated with the AMCG magmatism (Krzemińska et al., 2017).

Based on the geophysical observations and modelling results, the impact hypothesis seems to explain the origin of the PGL anomaly better than do other genetic concepts, including that of a felsic TIB intrusion (Table 1). Nevertheless, it is clear that an approach based principally on remote sensing, although important in finding and studying impact structures, cannot allow their unquestioned identification (French and Koeberl, 2010). Such identification will depend on future discoveries of direct evidence of shock-metamorphic features, impact breccia or distal ejecta (Reimold, 2007; French and Koeberl, 2010; Osinski et al., 2022).

CONCLUSIONS

The results of geophysical investigations and gravity modelling contradict hypotheses stressing the significance of a thick platform cover and/or crustal keel of the East European Craton for the Pomeranian Gravity Low formation. These results point to the middle-upper crystalline crust as a source of the PGL. Moreover, regional premises constrain the age of PGL to the Statherian Period (1.8–1.6 Ga), postdating the Paleoproterozoic accretion in NE Poland but pre-dating the emplacement of the Mesoproterozoic AMCG intrusives.

Two new alternative interpretations of PGL are proposed and discussed: (1) a large felsic intrusion forming a southern extension of the Trans-Scandinavian Igneous Belt, and (2) an impact structure, ~200 km in diameter, partly obliterated by prolonged denudation, Mesoproterozoic intrusions and metamorphism, and Ediacaran-Phanerozoic tectonism.

In the light of the result discussed and regional comparisons the “impact model” seems to be more compatible with geological and geophysical PGL attributes (Table 1). Nevertheless, conclusive evidence for such an impact may be provided only by deep boreholes probing diagnostic structures in the crystalline basement, such as shock-metamorphic features or impact breccia.

Acknowledgements. The financial support was provided by the statutory funds of the PGI-NRI (project 62.9012.2202.00.0). We are grateful to the reviewers, M. Stefaniuk (Kraków) and M. Bielik (Bratislava), as well as to J. Szczepański, the editor of Geological Quarterly, for their constructive comments which led to improvement of the manuscript.

REFERENCES

Bogdanova, S., Gorbatschev, R., Skridlaite, G., Soesoo, A., Taran, L., Kurlovich, D., 2015. Trans-Baltic Palaeoproterozoic correlations towards the reconstruction of supercontinent Columbia/Nuna. Precambrian Research, **259**: 5–33; https://doi.org/10.1016/j.precamres.2014.11.023

Dadlez, R., 1978. Sub-Permian rock complexes in the Koszalin–Chojnice Zone (in Polish with English summary). Geological Quarterly, **22** (2): 269–301.

Dadlez, R., 2001. Mid-Polish Trough – Geological Cross-sections (1:200 000). Państwowy Instytut Geologiczny, Warszawa.

Dadlez, R., Kowalczewski, Z., Znosko, J., 1994. Some key problems of the pre-Permian Tectonics of Poland. Geological Quarterly, **38** (2): 169–190.

Dadlez, R., Narkiewicz, M., Stephenson, R.A., Visser, M.T.M., van Wees J.D., 1995. Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. Tectonophysics, **252**: 179–195; https://doi.org/10.1016/0040-1951(95)00104-2

Dadlez, R., Marek, S., Pokorski, J., 1998. Paleogeographic Atlas of Epicontinental Permian and Mesozoic in Poland (1:2 500 000). Państwowy Instytut Geologiczny, Warszawa.

Dadlez, R., Grad, M., Guterch, A., 2005. Crustal structure below the Polish Basin: Is it composed of proximal terranes derived from Baltica? Tectonophysics, **411**: 111–28; https://doi.org/10.1016/j.tecto.2005.09.004

Demaiffe, D., Wiszniewska, J., Krzemińska, E., Williams, I.S., Stein, H., Brassines, S., Ohnenstetter, D., Deloule, E., 2013. A hidden alkaline and carbonatite province of Early Carboniferous age in Northeast Poland: Zircon U-Pb and pyrrhotite Re-Os geochronology. Journal of Geology, **121**: 91–104; https://doi.org/10.1086/668674

Ernst, T., Brasse, H., Cerv, V., Hoffmann, N., Jankowski, J., Jozwiak, W., Kreutzmann A., Neska, A., Palshin, N., Pedersen, L.B., Smirnov, M., Sokolova, E., Varentsov, I. M., 2008. Electromagnetic images of the deep structure of the Trans-European Suture Zone beneath Polish Pomerania. Geophysical Research Letters, **35**: L15307; https://doi.org/10.1029/2008GL034610

Fajklewicz, Z., 1964. Depth of the Mohorovičić discontinuity in Poland (in Polish). Technika Poszukiwań, **10**: 6–11.

French, B.M., Koeberl, Ch., 2010. The convincing identification of terrestrial meteorite impact structures: what works, what doesn't, and why. Earth-Science Reviews, **98**: 123–170; https://doi.org/10.1016/j.earscirev.2009.10.009

Gilder, S., Pohl, J., Eitel, M., 2018. Magnetic signatures of terrestrial meteorite impact craters: A summary. In: Magnetic fields in the solar system (eds. H. Luhr, J. Wicht, S. Gilder and M. Holschneider): 357-382. Springer, Cham; https://doi:10.1007/978-3-319-64292-5_13

Gorbatschev, R., 2004. The Transscandinavian Igneous Belt – introduction and background. Geological Survey of Finland, Special Paper, **37**: 9–15.

Grabowska, T., Raczyńska, M., 1991. Structure of the Earth crust in the Polish Lowland in the light of gravimetric modelling. Publications of the Institute of Geophysics, Polish Academy of Science, **A-19**: 85–110.

Grabowska, T., Raczyńska, M., Dolnicki, J., 1992. Interpretation of gravity anomalies along the Eu-3 Geotransect in Poland. Acta Geophysica Polonica, **40**: 159–173.

Grabowska, T., Bojdys, G., Dolnicki, J., 1998. Three-dimensional density model of the Earth's crust and the upper mantle for the area of Poland. Journal of Geodynamics, **25**: 5–24; https://doi.org/10.1016/S0264-3707(97)00001-X

Grieve, R.A.F., Reimold, U., Morgan, J., Riller, U., Pilkington, M., 2008. Observations and interpretations at Vredefort, Sudbury, and Chicxulub: toward an empirical model of terrestrial impact basin formation. Meteorics and Planetary Science, **43**: 855–882; https://doi.org/10.1111/j.1945-5100.2008.tb01086.x

Grobelny, A., Królikowski, C., 1988. Gravimetric anomalies caused by sub-Permian sediments in northwestern Poland (in Polish with English summary). Geological Quarterly, **32** (3/4): 611–634.

Guterch, A., Grad, M., 2006. Lithospheric structure of the TESZ in Poland based on modern seismic experiments. Geological Quarterly, **50** (1): 23–32.

Guy, A., Edel, J.-B., Schulmann, K., Tomek, Č., Lexa, O., 2011. A geophysical model of the Variscan orogenic root (Bohemian Massif): Implications for modern collisional orogens. Lithos, **124**: 144–157; https://doi.org/10.1016/j.lithos.2010.08.008

Henkel, H., Reimold, W.U., 1998. Integrated geophysical modelling of a giant, complex impact structure: anatomy of the Vredefort Structure, South Africa. Tectonophysics, **287**: 1–20; https://doi.org/10.1016/S0040-1951(98)80058-9

Henkel, H., Reimold, W.U., 2002. Magnetic model of the central uplift of the Vredefort impact structure, South Africa. Journal of Applied Geophysics, **51**: 43–62; https://doi.org/10.1016/S0926-9851(02)00214-8

Högdahl, K., Andersson, U.B., Eklund, O. (eds.), 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. Geological Survey of Finland, Special Paper, **37**.

Huestis, S.P., Ander, E., 1983. IDB2 – a Fortran program for computing extremal bounds in gravity data interpretation. Geophysics, **47**: 999–1010.

Jóźwiak, W., 2013. Electromagnetic study of lithospheric structure in the marginal zone of East European Craton in NW Poland. Acta Geophysica, **61**: 1101–1129; https://doi.org/10.2478/s11600-013-0127-z

Juhlin, C., Pedersen, L. B., 1987. Reflection seismic investigations of the Siljan impact structure, Sweden. Journal of Geophysical Research: Solid Earth, **92**(B13): 14113–14122; https://doi.org/10.1029/JB092iB13p14113

Juhojuntti, N., Juhlin, C., 1998. Seismic lower crustal reflectivity and signal penetration in the Siljan Ring area, Central Sweden. Tectonophysics, **288**: 17–30; https://doi.org/10.1016/S0040-1951(97)00279-5

Juhojuntti, N., Juhlin, C., Dyrelius, D., 2001. Crustal reflectivity underneath the Central Scandinavian Caledonides. Tectonophysics, **334**: 191–210; https://doi.org/10.1016/S0040-1951(00)00292-4

Królikowski, C., Petecki, Z., 1995. Gravimetric Atlas of Poland. Polish Geological Institute, Warszawa.

Królikowski, C., Petecki, Z., 1997. Crustal structure at the Trans-European Suture Zone in northwest Poland based on gravity data. Geological Magazine, **134:** 661–667; https://doi.org/10.1017/S0016756897007395

Królikowski, C., Petecki, Z., 2002. Lithospheric structure across the Trans-European Suture Zone in NW Poland based on gravity data interpretation. Geological Quarterly, **46** (3): 235–245.

Królikowski, C., Petecki, Z., Żółtowski, Z., 1998. Main structural units in the Polish part of the East-European Platform in the light of gravimetric data (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **386**: 5–58.

Krzemińska, E., Krzemiński, L., Petecki, Z., Wiszniewska, J., Salwa, S., Żaba, J., Gaidzik, K., Williams, I.S., Rosowiecka, O., Taran, L., Johansson, Å., Pécskay, Z., Demaiffe, D., Grabowski, J., Zieliński, G., 2017. Geological Map of Crystalline Basement in the Polish part of the East European Platform 1:1 000 000. Państwowy Instytut Geologiczny, Warszawa.

Krzemińska, E., Johansson, Å.E., Krzemiński, L., Wiszniewska, J., Williams, I.S., Petecki, Z., Salwa, S., 2021. Basement correlation across the southernmost Baltic Sea: Geochemical and geochronological evidence from onshore and offshore deep drill cores, northern Poland. Precambrian Research, **362**: 106300; https://doi.org/10.1016/j.precamres.2021.106300

Kubicki, S., Ryka., W. (eds.), 1982. Geological Atlas of Crystalline Basement in Polish Part of East-European Platform. Państwowy Instytut Geologiczny, Warszawa.

Majdański, M., 2012. The structure of the crust in TESZ area by kriging interpolation, Acta Geophysica, **60**: 59–75; https://doi.org/10.2478/s11600-011-0058-5

Masaitis, V.L., Mashchak, M.S., Naumov, M.V., 2019. Main geological features of the impact structure. In: Popigai impact structure and its diamond-bearing rocks (ed. V.L. Masaitis): 1–17. Springer, Cham, Switzerland; https://doi.org/10.1007/978-3-319-77988-1_1

Masero, W., Fischer, G., Schnegg, P.A., 1997. Electrical conductivity and crustal deformation from magnetotelluric results in the region of the Araguainha impact, Brazil. Physics of the Earth and Planetary Interiors, **101**: 271–289; https://doi.org/10.1016/S0031-9201(96)03267-0

Mazur, S., Mikołajczak, M., Krzywiec, P., Malinowski, M., Buffenmyer, V., Lewandowski, M., 2015. Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica? Tectonics, **34**: 2465–2477; https://doi:10.1002/2015TC003934

Mazur, S., Mikołajczak, M., Krzywiec, P., Malinowski, M., Buffenmyer, V., Lewandowski, M., 2016. Reply to Comment by M. Narkiewicz and Z. Petecki on "Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica?" Tectonics, **35**: 1600–1607; https://doi:10.1002/2015TC003934

Mężyk, M., Malinowski, M., Mazur, S., 2019. Imaging East European Craton margin in Northern Poland using extended-correlation processing applied to regional reflection seismic profiles. Solid Earth, **10**: 683–696; https://doi.org/10.5194/se-10-683-2019

Młynarski, S., Bachan, W., Dąbrowska, B., Jankowski, H., Kaniewska, E., Karaczun, K., Kozera, A., Marek, S., Skorupa, J., Żelichowski, A.M., Żytko, K., 1982. Geophysical-geological interpretations along the profiles of Lubin-Prabuty, Przedbórz-Żebrak, Baligród-Dubienka (in Polish with English summary). Biuletyn Instytutu Geologicznego, **333**: 5–60.

Muundjua, M., Hart, R. J., Gilder, S. A., Carporzen, L., Galdeano, A., 2007. Magnetic imaging of the Vredefort impact crater, South Africa. Earth and Planetary Science Letters, **261**: 456–468; https://doi.org/10.1016/j.epsl.2007.07.044

Narkiewicz M., 2020 – The Variscan foreland in Poland revisited: new data and new concepts. Geological Quarterly, **64** (2): 377–401; https://dx.doi.org/10.7306/gq.1511

Narkiewicz, M., Petecki, Z., 2016. Comment on "Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica ?" by Mazur et al. Tectonics, **35**: 1595–1599; https://doi:10.1002/2016TC004127

Narkiewicz, M., Petecki, Z., 2017. Basement structure of the Paleozoic Platform in Poland. Geological Quarterly, **61** (4): 502–520; https://doi.org/10.7306/gq.1356

Narkiewicz, M., Petecki, Z., 2019. Teisseyre-Tornquist Zone – evolving approches and new data (in Polish with English abstract). Przegląd Geologiczny, **67**: 837–848; https://doi.org/10.7306/2019.48

Narkiewicz, M., Maksym, A., Malinowski, M., Grad, M., Guterch, A., Petecki, Z., Probulski, J., Janik, T., Majdański, M., Środa, P., Czuba, W., Gaczyński, E., Jankowski, L., 2015. Transcurrent nature of the Teisseyre-Tornquist Zone in Central Europe - results of the POLCRUST-01 deep reflection seismic profile. International Journal of Earth Sciences, **104**: 775–796; https://doi.org/10.1007/s00531-014-1116-4

Oryński, S., Klityński W., Neska A., Ślęzak, K., 2019. Deep lithospheric structure beneath the Polish part of the East European Craton as a result of magnetotelluric surveys. Studia Geophysica et Geodaetica, **63**: 273–289; https://doi.org/10.1007/s11200-017-1264-7

Osinski, G.R., Grieve, R.A., Ferrière, L., Losiak, A., Pickersgill, A., Cavosie, A.J., Hibbard, S.M., Hill, P.J.A., Bermudez, J.J., Marion, C.L., Newman, J.D., Simpson, S.L., 2022. Impact Earth: a review of the terrestrial impact record. Earth-Science Reviews, **232**: 104112; https://doi.org/10.1016/j.earscirev.2022.104112

Parker, R.L., 1974. Best bounds on density and depth from gravity data. Geophysics, **39**: 644–649.

Parker, R.L., 1975. The theory of ideal bodies for gravity interpretation. Geophysical Journal of the Royal Astronomical Society, **42**: 315–334.

Pascal, C., Ebbing, J., Skilbrei, J.R., 2007. Interplay between the Scandes and the Trans-Scandinavian Igneous Belt: integrated thermo-rheological and potential field modelling of the Central Scandes profile. Norwegian Journal of Geology, **87**: 3–12.

Pesonen, L.J., 1996. The impact cratering record of Fennoscandia. Earth, Moon, and Planets, **72**: 377–393; https://doi.org/10.1007/BF00117542

Petecki, Z., 2002. Gravity and magnetic modeling along LT-7 profile (in Polish). Przegląd Geologiczny, **50**: 630–633.

Petecki, Z., 2008. Magnetic basement in the Pomeranian segment of the Trans-European Suture Zone (NW Poland) (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **191**: 5–72.

Petecki, Z., 2019. Ideal body analysis of the Pomerania Gravity Low (northern Poland). Geological Quarterly, **63** (3): 558-567; http://dx.doi.org/10.7306/gq.1485

Petecki, Z., Rosowiecka, O., 2017. A new magnetic anomaly map of Poland and its contribution to the recognition of crystalline basement rocks. Geological Quarterly, **61** (4): 934–945; http://dx.doi.org/10.7306/gq.1383

Petecki, Z., Wiszniewska, J., 2021. Internal structure of the buried Suwałki Anorthosite Massif (East European Craton, NE Poland) based on borehole, magnetic and gravity data combined with new petrological results. Geological Quarterly, **65**: 4; http://dx.doi.org/10.7306/gq.1574

Pilkington, M., Grieve, R.A.F., 1992. The geophysical signature of terrestrial impact craters. Reviews in Geophysics, **30**: 161–181; https://doi.org/10.1029/92RG00192

Pilkington, M., Pesonen, L.J., Grieve, R.A.F., Masaitis, V.L., 2002. Geophysics and petrophysics of the Popigai impact structure, Siberia. In: Impact in Precambrian shields (eds. J. Plado and L.J. Pesonen): 87–107. Springer, Berlin-Heidelberg.

Reimold, W.U., 2007. The Impact Crater Bandwagon (Some problems with the terrestrial impact cratering record). Meteoritics and Planetary Science, **42**: 1467–1472.

Stefaniuk, M., Wojdyła, M., Petecki, Z. Pokorski, J., 2008. Dokumentacja badań geofizycznych. Temat: Budowa geologiczna pokrywy osadowej i podłoża krystalicznego segmentu pomorskiego bruzdy śródpolskiej na podstawie kompleksowych badań geofizycznych (profilowań magnetotellurycznych). Etap I: 2007–2008 (in Polish). Unpubl. documentation of geophysical surveys, National Geological Archives. Polish Geological Institute-National Research Institute. Warsaw. Document no. CBDG 949963.

Therriault, A.M., Grieve R.A.F., Pilkington M., 2002. The recognition of terrestrial impact structures. Bulletin of the Czech Geological Survey, **77**: 253–263.

Therriault, A.M., Reid, A.M., Reimold, W.U., 1993. Origin of the Vredefort structure, South Africa: Impact model, Lunar and Planetary Science XXIV, p. 1421–1422, In Lunar and Planetary Inst., Twenty-Fourth Lunar and Planetary Science Conference. Part 3: N-Z p 1421-1422 (SEE N94-20636 05-91).

Wilde-Piórko, M., Świeczak, M., Grad, M., Majdański, M., 2010. Integrated seismic model of the crust and upper mantle of the Trans-European Suture zone between the Precambrian craton and Phanerozoic terranes in central Europe. Tectonophysics, **481**: 108–115; https://doi.org/10.1016/j.tecto.2009.05.002

Zhang, P., Rasmussen, T.M., Pedersen, L.B., 1988. Electric resistivity structure of the Siljan impact region. Journal of Geophysical Research, **93**: 6485–6501; https://doi.org/10.1029/JB093iB06p06485

Znosko, J., 1998. Tectonic Atlas of Poland. Państwowy Instytut Geologiczny, Warszawa.