

## CAINOZOIC EVOLUTION OF LOWER SILESIA, SW POLAND: A NEW INTERPRETATION IN THE LIGHT OF SUB-CAINOZOIC AND SUB-QUATERNARY TOPOGRAPHY

Janusz BADURA <sup>1)</sup>\*, Bogusław PRZYBYLSKI <sup>1)</sup> and Witold ZUCHIEWICZ <sup>2)</sup>

<sup>1)</sup> Lower Silesian Branch, Polish Geological Institute, al. Jaworowa 19, 50-122 Wrocław, Poland

<sup>2)</sup> Institute of Geological Sciences, Jagiellonian University, ul. Oleandry 2A, 30-063 Kraków, Poland

\*Corresponding author's e-mail: janusz.badura@pgi.gov.pl

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### ABSTRACT

An analysis of the youngest tectonic movements by the use of either morphometric or instrumental techniques should take into account both exposed and buried fault zones. The sub-Cainozoic and sub-Quaternary surface maps presented in this study display buried palaeotopography whose interpretation proves helpful in identification of tectonic dislocations. Such a kind of analysis has been conducted for the area of Lower Silesia, including the Sudetes, Fore-Sudetic Block, and Fore-Sudetic Monocline. The maps have been constructed on the basis of well-bore data, vertical geoelectrical soundings, and detailed mapping of exposures of pre-Quaternary rocks. Well-bore data have been reinterpreted with a view to reconstruct the original depth to the top of the crystalline basement. Many archival borehole descriptions place the boundary between Tertiary strata and the Proterozoic-Palaeozoic substratum at the top of poorly weathered rocks, including regoliths of the crystalline substratum into the Tertiary cover. The presented maps portray for the first time the actual morphology of the sub-Cainozoic surface. A comparison between the sub-Cainozoic and sub-Quaternary surface maps enables us to document changes in tectonic mobility throughout Cainozoic times. An additional source of information is provided by the attached thickness maps of individual time-slices of the Cainozoic.

**KEYWORDS:** neotectonics, Cainozoic, sub-Cainozoic and sub-Quaternary surface maps, Lower Silesia, SW Poland

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### 1. INTRODUCTION

A preliminary overview of the existing archival data has shown that the state of recognition of sub-Cainozoic and sub-Quaternary topography in Lower Silesia is far from sufficient. Depending on individual author's preferences, the sub-Cainozoic morphology used to be presented as either erosional or formed due to young tectonic movements. Descriptions of numerous borehole logs are frequently misleading, usually due to erroneous age determination and/or inferred origin of the drilled rock complexes. Most of the authors have emphasized the duration of weathering processes, leaving aside the actual age of parent rocks. Another source of error consisted in the description of crushed borehole cores, so the boreholes drilled in regoliths resting upon granitoids or gneisses have frequently been interpreted as piercing sedimentary strata. That is why the top of crystalline basement has usually been determined as situated even 80 m lower than the actual one, and the hitherto made maps of sub-Cainozoic surface presented in fact the top of unweathered or high-resistivity basement. Increased topographic gradients on such maps have consequently been interpreted as fault zones. Basing solely on the existing archival

borehole descriptions, it is hardly possible to conclude about origin of the drilled rocks and the actual topography of the sub-Cainozoic surface in SW Poland. New maps presented in this study, taking into account the thickness of regolith covers, enable us to put forward another view on the origin of the sub-Neogene surface and the pattern of morphotectonic units.

### 2. STUDY AREA

The study area includes the Middle Sudetes Mts., the Fore-Sudetic Block without its NW part, a large portion of the Fore-Sudetic Monocline, and the Opole Trough filled with Cretaceous strata (Fig. 1). This region, encompassing an area of ca. 17,530 km<sup>2</sup>, is covered by five sheets of *The Geological Map of Poland, 1:200,000* (Wałbrzych, Wrocław, Nysa, Kłodzko, Jelenia Góra).

Figure 1 shows the extent of sub-Cainozoic bedrock units that has been redrawn from 1:200,000 *Geological Map of Poland*, whereupon geological boundaries have frequently been extrapolated from data coming from single well logs. The other maps used in our study show the outlines of individual map units taken from detailed stripped maps without

authors' extrapolation below the overlying sediments. Such extrapolation in the final form, presented in this study, has been processed with the help of the SURFER programme.

### 3. METHODS

The analysis of the sub-Quaternary and sub-Cainozoic surfaces is based on their digital elevation models, including data gathered by two of us (J. B., B. P.) from 11,455 borehole logs and geophysical surveys (Fig. 2). Archival wellbore data have been verified by testing their compatibility among neighbouring wells and with the existing 1:25,000 detailed geological maps. Spatial position (x, y, z) of well location has also been verified.

The most difficult and time-consuming task was to verify the existing maps of the sub-Cainozoic surface. The problem consisted in precise determination of the contact between Cainozoic sedimentary rocks and strongly chemically-weathered bedrock. The degree of weathering ranges from strongly decomposed or entirely kaolinised rocks to poorly-weathered ones. It has commonly been accepted in the existing literature that the most intense weathering was to proceed in Palaeogene and Early Miocene times. Therefore, top parts of strongly weathered crystalline rocks have been treated as sedimentary rocks and assigned a Tertiary age, without taking into account the presence of frequently preserved structures of the parent, crystalline rock. Geologists responsible for well log descriptions did not try to reconstruct the buried topography. Hence, our reinterpretation of archival data required verification of original well log charts, bearing the results of detailed geochemical determinations and electrical resistivity sounding data. In a few cases, verification process has been done basing on detailed geological maps whereupon, close to the exposures of granites, clayey sand and gravel occurrences have been described. In many cases, the gneiss waste covers have originally been described as sands, although they do contain clasts of schists. Such a kind of description signalled to us that the well must have pierced through crystalline rocks, and not younger sediments. Original colour descriptions have also been very helpful, since they indicated the presence of either micas or ferruginous compounds. Geochemical studies and the results of technological examinations have also been of some use to discriminate between the weathered bedrock and overlying sediment. For instance, a drastic increase in the nickel content marked the exposures of serpentinites, whereas the change of baking temperatures indicated the presence of ceramic clays. Electrical resistivity soundings provided information on the occurrence of waste covers which show slightly higher and lower resistivity values as compared to the low-resistivity Miocene sediments, and high-resistivity bedrock, respectively.

Lithological and stratigraphic descriptions of borehole logs have been analysed using archival reports by Grocholski and Drozdowski (1992), Kasiński et al. (1997), Przybylski (1998), Ihnatowicz and Czerski (1998), Badura (1999), reports related to brown coal, Ni-bearing ores, and magnesite prospection, as well as borehole and electric resistivity sounding data gathered by Badura et al. (2004). The top surface of sub-Cainozoic substratum in the Paczków Foothills, as well as the Strzelin and Niemcza Hills has been reconstructed basing on electric resistivity sounding data. Wellbore data have been supplemented by those derived from geophysical soundings (Wiński, 1990; Krawczyk and Tkaczyk, 1997). Gravity surveys from the Kędzierzyn Graben area have also been used to construct digital elevation model of the sub-Cainozoic surface, since the area in question has not been drilled extensively.

Palaeotopography of buried surfaces has been reconstructed basing on exposures of pre-Quaternary rocks which have been digitized from the sheets of the *Geological Map of Poland, 1:200,000*, and, for selected areas, from more detailed geological maps (1:50,000 or 1:25,000). Elevations of individual exposures have been adopted from the digital elevation model elaborated by A. Biel for Lower Silesia at the scale of 1:500,000 (Pawlak, 1997). As a result, a few times more data points have been obtained from bedrock exposures than from borehole logs or geophysical soundings. Altogether, 80,000 and 60,000 data points have been used for the construction of sub-Quaternary and sub-Cainozoic surface maps, respectively.

### 4. TECTONIC UNITS

The studied portion of Lower Silesia includes two Neogene structural-neotectonic units: the Central-European Zone of Uplift with the Lusatian-Sudetic Block, and the Central-European Subsidence Zone, including the West-Baltic Step and the Mid-Polish High (Zuchiewicz, 2000; Aizberg et al., 2001). Boundaries of these units coincide with fault zones marked in the sub-Cainozoic topography, and differ from those hitherto-used in neotectonic studies of Lower Silesia (cf. Oberc and Dyjor, 1969; Dyjor, 1975). A much more popular subdivision includes the Sudetes, Fore-Sudetic Block, Wrocław Monocline, Silesian-Cracow Monocline, and Opole Trough (Fig. 1).

#### 4.1. SUDETES

The physiographic and geological northern boundaries of the Sudetes are marked by the Sudetic Marginal Fault and the East-Sudetic Marginal Fault. The latter separates the Hrubý (High) and Nizký (Low) Jeseník Mts. in the SW and exposures of the Moravo-Silesian Block in the Głubczyce Plateau in the NE. In the west, the Sudetes are separated from the Lusatian Mts. by a series of Palaeogene-Neogene

troughs. Different character of the surfaces of erosional cutting in the Sudetes and Fore-Sudetic Block indicates that these two structures have been developing separately since the Permian. Deeper erosional dissection of crystalline rocks in the Fore-Sudetic Block, as well as abrupt termination of the Devonian, Carboniferous, and Permian exposures against the Sudetic Marginal Fault support this conclusion. It is commonly accepted that the Fore-Sudetic Block used to be more elevated than the Sudetes (Oberc, 1972; Cwojdziański and Żelaźniewicz, 1995).

The Fore-Sudetic Block became downthrown in the Late Oligocene and Miocene. The fault is most clearly marked between the Jeseník Mts. in the Czech Republic in the SE and Sichów area in the NW. The south-eastward continuation of the fault (Běla fault) is to be seen in the Eastern Sudetes which are separated from their foreland by a series of parallel faults that bound from the south the Paczków, Nysa, and Kędzierzyn Grabens. The northwestern continuation of the Sudetic Marginal Fault requires detailed studies. It is likely that the fault runs beneath Quaternary sediments between Sichów and Chojnów, although it can also be displaced by 4-5 km along a W-E fault between Sichów and Złotoryja. Northwestwards of Złotoryja, the fault again attains the NW-SE orientation.

Three prominent tectonic troughs occur in the Sudetes, including the so-called North-Sudetic and Middle-Sudetic Synclinoria, and the Upper Nysa Graben. These are old structures, whose present-day outline was shaped after the Late Cretaceous regression. Individual mountain ranges represent horsts. The horst-like character of the Bardo Mts. has already been described by Oberc (1972), and the role of normal faulting in shaping topography of the Stołowe (Table) Mts. has recently been pointed out by Latocha (2003).

#### 4.2. FORE-SUDETIC BLOCK

The Fore-Sudetic Block is a tectonic step, 80-km-wide, extending between the Sudetes and Fore-Sudetic Monocline. This structure has hitherto been interpreted as a Neogene tectonic unit whose top surface lacks the Permo-Mesozoic cover (Cwojdziański and Żelaźniewicz, 1995). Between Nowogród Biebrzański and Wrocław, the boundary of this block coincides with the Middle Odra fault zone, whereas its SE continuation is a matter of debate. It probably continues under the Upper Cretaceous strata of the Opole region. Basalts exposed in the Gracze and Ligota Tułowicka area, as well as the northern extent of Lower Carboniferous strata near Toszek probably mark the trace of this boundary.

The Fore-Sudetic Block is surrounded on the south and north by the Sudetes and Fore-Sudetic Monocline, respectively. The crystalline basement within each of these units slopes step-like to the north. The amount of throw between the Sudetes and Fore-

Sudetic Block ranges from 400 m and 1,000 m, that between the Fore-Sudetic Block and Fore-Sudetic Monocline being between 1,100, and 1,400 m.

The Fore-Sudetic Block can be subdivided into several minor tectonic structures. Close to the Sudetes, there occur deep tectonic grabens wherein the thickness of clastic sediments exceeds 660 m in the Mokreszów trough, 680 m in the Kędzierzyn Graben, and 300-400 m in the Paczków Graben. By contrast, the central part of the block is dominated by horsts that build isolated ("island") mountains in the present-day topography. These isolated hills have hitherto been considered erosional remnants; their tectonic control and modelling due to deep subsurface weathering being pointed out recently. Selective chemical weathering has led to formation of a characteristic etchplain-type landscape (Migoń, 1997a). Such a kind of topography is best preserved upon exposures of the Żulova granites, in the Bielawa Hills, and - buried under younger sediments - near Legnica.

The most elevated summit in the Fore-Sudetic Block is Ślęza Mt. (718 m a.s.l.), whose height measured from the base of sub-Cainozoic rock complex exceeds 900 m on the northern slope. The Strzegom and Niemcza-Strzelin Hills usually do not exceed 350 m a.s.l. Subcrops of the crystalline basement terminate abruptly north of Ślęza on a WNW-ESE-orientated fault (Fig. 1), well visible between Wądroże Wielkie and Przeworno. We propose to call this fault the Fore-Sudetic Marginal Fault. It is likely that the fault continues due ESE until the Głubczyce Plateau, wherein exposures of the Lower Carboniferous siltstones can be observed. The orientation of this fault is roughly parallel to the intra-Sudetic Fault. The Fore-Sudetic Marginal Fault displaces the northern part of the Fore-Sudetic Block by ca. 100 m or - counting from the top of the Strzegom and Strzelin Hills - 500 m.

The Fore-Sudetic Block is bordered on the east by the Opole Trough bearing Cretaceous strata (Badura and Przybylski, 1993), earlier considered a depression (Bossowski, 1974; Kotański and Radwański, 1977). In front of the Eastern Sudetes Mts., crystalline rocks of the Fore-Sudetic Block are overlain by the Upper Devonian and Lower Carboniferous greywackes and, locally, by Permian conglomerates. The crystalline basement slopes down to ca. 1,000 m near Biała, and even to more than 2,000 m farther eastwards.

The age of shaping of the Fore-Sudetic Block has usually been related to the age of deposition of clastic sediments overlying its surface, i.e. the Early Miocene. The Sudetic Marginal Fault was thought to have been reactivated in the same time. This reasoning did not take into account the tectonic setting of the Middle Odra fault zone where normal faulting occurred between the Late Triassic and Late Cretaceous. Transgressive Cenomanian strata rest unconformably upon Permo-Triassic, mostly

carbonate rocks, as well as on either crystalline basement or Devonian-Carboniferous greywackes and siltstones. Both the sub-Cenomanian and sub-Tertiary surfaces in the Middle Odra fault zone do not show any pronounced elevation differences, pointing to tectonic quiescence after the Early Cretaceous. The only exception is the Wrocław area, where tectonic activity lasted at least until the Middle Pleistocene. However, one cannot exclude a possibility that the onset of the activity of the Sudetic Marginal Fault should be placed in Mesozoic time, as indicated, for instance, by the age of some ore deposits, like gold-bearing ores that occur close to the Sudetic Marginal Fault in the Czech Republic (Skácel, 1989).

The Fore-Sudetic Block is composed of rock series that belong to different lithologic-tectonic units. The north-western and northern portions of the block are built up of the Kaczawa complex (Cwojdzński and Żelaźniewicz, 1995) which is eroded to deeper structural levels than its Sudetic counterpart. The Kaczawa complex disappears north of the Ślęza ophiolitic massif. The north-eastern part of the Fore-Sudetic Block, in turn, is composed of gneisses and schists of the Odra complex whose definition, however, is not clear. It cannot be excluded that these are Kaczawa complex rocks that underwent strong cataclasis in the Middle Odra fault zone. In the eastern part of the block, micaceous gneisses and gneisses of the Kamieniec complex occur, bearing intrusions of Carboniferous-Permian granites.

The central part of the Fore-Sudetic Block comprises granites of the Strzegom massif, ophiolites of the Ślęza massif, as well as rocks of the Sowie Mts. and the Niemcza zone. The Sowie Mts. and Kamieniec complexes continue into the Sudetes. Similarly to the Kaczawa complex, the amount of erosion was here much more greater and amounted to 5-10 km.

Rocks occurring on top of the Fore-Sudetic Block are strongly weathered. Most of the regoliths have been preserved under Miocene strata, rarely under Cenomanian rocks in the Opole Trough (Bossowski, 1974). These regoliths are a few to more than 100 m thick (Kural, 1979; Kościówko, 1982). The regolith profiles show gradual transition from poorly weathered host rock to totally kaolinized, structureless sediment. Macroscopic discrimination between strongly weathered bedrock and sedimentary kaolins is very difficult. Deeper parts of regolith profiles are represented by less weathered rocks bearing quartz, orthoclase, and kaolinised feldspars. Proceeding deeper, there occur unweathered, rounded rock fragments and angular blocks which, after subsequent denudation, build residual tors. The base of regolith profile is composed of disintegrated rock, although showing original structure. Top parts of regolith covers are usually white, rarely red or yellow, whereas deeper parts frequently show green, yellow or brown-red colours.

These regoliths are believed to have been formed upon a peneplain during the Palaeogene-Early Miocene. However, results of recent studies have shown that kaolin-dominated regoliths tend to form in regions of well-developed subsurface drainage, suitable for removal of the products of silicate and mica dissolution (Migoń, 1997b). Taking into account the originally greater extent of Mesozoic rocks in the Fore-Sudetic Block, their thickness amounting to some 400 m, time necessary for denudation, dominance of warm and humid climate, as well as the presence of strongly aggressive products of organic decay, one can suppose that the most suitable conditions for regolith formation occurred in the Jurassic, Early and Late Cretaceous (until the Cenomanian transgression), as well as in the Eocene and Early Oligocene. Regoliths formed during the remaining time intervals are relatively thin and show incomplete profiles where, instead of kaolins, mixed-layer clay minerals were developed. Recent attempts of dating kaolins in Bavaria and other parts of Europe point to Mesozoic age of a part of kaolin-dominated regoliths (Gilg, 2000; Migoń and Lidmar-Bergström, 2001).

During geological mapping of Lower Silesia, the weathered top parts of crystalline rocks have usually been assigned to the Tertiary, even though original rock structure was preserved. This resulted in erroneous determination of the actual top of sub-Cainozoic bedrock. All the existing maps of sub-Cainozoic substratum portray, in fact, the position of the weathering front (Grocholski and Kucharski, 1975; Cwojdzński and Jodłowski, 1978; Kural, 1979; Kościówko, 1982) or, when using electric resistivity sounding data, the top of high-resistivity bedrock. Such biased data served as a base for construction of sub-Cainozoic and neotectonic maps of Lower Silesia (Dyjur, 1975; Badura and Przybylski, 2000).

#### **4.3. FORE-SUDETIC MONOCLINE AND OPOLE TROUGH**

The southern margin of the Fore-Sudetic Monocline is marked by Cainozoic subcrops of the crystalline basement. The monocline is composed of two tectonic structures: the Wrocław Monocline and Silesian-Cracow Monocline. The Middle Triassic strata, granites and gneisses of the Fore-Sudetic Block, and greywackes and siltstones of Lower Carboniferous age are unconformably overlain by the Upper Cretaceous deposits, whose original extent was probably greater, encompassing the whole Sudetes and Fore-Sudetic Block. At present, these strata can only be found in the Opole region and within the Intra-Sudetic depressions. The structure of the Opole region has usually been referred to as a depression, principally due to monoclinical attitude of progressively younger strata on the basin margin. Cretaceous strata, however, are bounded on every side by normal faults which displace the Upper Cretaceous rocks by a few

tens to 200 m in respect to the surrounding areas (Badura and Przybylski, 1993; Przybylski and Badura, 2001).

##### 5. MAP OF SUB-CAINOZOIC SURFACE

The map of sub-Cainozoic surface (Fig. 3) has been constructed basing on well-bore data and the groundsurface distribution of sub-Cainozoic and sub-Quaternary bedrock. Reinterpretation of the position of in-situ weathered crystalline bedrock was possible for a part of wells only, similarly as discrimination between the Keuper and Poznań Formation clays in the NE part of the study area. The lack of information on the actual depth to the top of weathered bedrock artificially increases relief energy values of the buried topography. In the Świdnica area, for instance, these differences amount to 80 m. Interpretation of well logs drilled in weathered granites is particularly difficult. Abundant quartz grains and grain-like texture of the rock have led to erroneous descriptions of weathered granites as vari-grained sands. On the other hand, sands occurring close to granitic exposures invalidate discrimination between clastic sedimentary rocks and weathered granite. That is the reason why nearly all geologists have interpreted weathered crystalline rocks as Tertiary strata.

The sub-Cainozoic surface map features two main palaeoprovinces: a belt of Central-European highs, including the Sudetes, Fore-Sudetic Block, and Silesian Upland, as well as a more northerly situated belt of depressions, coinciding with the Central-European Subsidence Zone. The Sudetic Marginal Fault separates the Sudetes, showing mountaineous topography of relief energy (i.e., differences between the highest and lowest points) ranging between 500 and 800 m, and the upland-like Fore-Sudetic Block, of relief energy values not exceeding 500 m. The Fore-Sudetic Block passes eastwards into the Silesian Upland of poorly differentiated relief.

The sub-Cainozoic morphology of the Sudetes, except for the North-Sudetic Synclinorium and Kłodzko Depression, is very similar to the present-day topography of this area. Palaeotopography of the North-Sudetic and Intra-Sudetic Synclinoria has seriously been affected by tectonic subsidence whose rate used to be comparable with that of the Fore-Sudetic Block. The Kłodzko Depression is composed of radially-orientated grabens and valleys, sloping towards the basin centre. The top of the crystalline basement here is situated lower than that exposed in the Bardo water-gap. This observation is consistent with divergence observed along the long profile of the highest Quaternary terrace of the Nysa Kłodzka River, whose height above the river bed increases downstream from 35 to 55 m (Krzyszowski et al., 1998, 2000). A portion of the Sudetes Mts. situated between the Bóbr and Kaczawa River valleys is strongly lowered as compared to the remaining part which shows a typical mountaineous topography. The area in question is superimposed upon the North-

Sudetic Synclinorium built up of Permian, Triassic, and Upper Cretaceous strata. It cannot be excluded that subsidence of this structure has also been active in Neogene times. The amount of throw along the Sudetic Marginal Fault diminishes here to some 100 m.

The Sudetic mountain front displays a well-marked lowering upon exposures of the Kłodzko-Złoty Stok granites, and within the post-Permian Wolbromek Graben. A less pronounced lowering is to be seen in the Bolków Foothills.

The Sudetic Marginal Fault is very well portrayed in the topography, particularly along a 100-km-long segment extending between Kaczawa (Sichów) and Złoty Stok. The fault is segmented; individual segments showing slightly different orientations (Badura et al., 2003b,c). The fault trace is also displaced along parallel-orientated minor faults by 4-5 km near Świebodzice, and 2-3 km near Bardo. The height of the fault scarp, counted from the base of Cainozoic strata, changes from 400 m in its SE part, to 900 m at Mokrzeszów, and 100 m in the NW segment which is already buried by Quaternary sediments.

It is possible that the Sudetic Marginal Fault near Sichów and Złoty Stok either splays into different branches or is parallel-displaced by some 6 km due west. A short, W-E- orientated escarpment of the Sudetic mountain front occurring on the southern side of the Kaczawa River valley can be associated with a transversal, minor fault (Badura et al., 2003c; Wojewoda, 2003). The Sudetic Marginal Fault scarp gradually disappears NW of Złoty Stok. NW of Sichów, in turn, a small buried step occurs, exposing rocks of the Kaczawa Unit and isolated necks of Oligo-Miocene volcanoes. It cannot be excluded, therefore, that the main fault continues farther due NE towards Chojnów, where other Neogene basalts crop out.

The landscapes of the Fore-Sudetic Block include areas showing differentiated values of erosional dissection and separated from each other by tectonically-controlled structures. The entire block can be subdivided into the upland part, situated close to the Sudetes Mts., and the lowland one. Dense network of wells drilled near Legnica indicates that hilly landscapes of both the lowland and upland parts display comparable relief energy. Thick regolith covers point to the presence of an etchplain that became normal-faulted. The surface of the lower portion of the Fore-Sudetic Block gradually passes eastwards into the Fore-Sudetic Monocline, implying that the separating faults were inactive in Miocene times. It is only near Wrocław where top surfaces of these two structures show different elevations, probably due to continuous movements along the zone of the Permian East-Sudetic graben. In Late Miocene times, these movements were associated with normal faulting. Reactivation of this zone led to a shift of the Central European Subsidence Zone due SE. Intensified subsidence was responsible for the

formation of the Grodków Graben, situated between the Strzelin Hills and Silesian Upland, and disrupting a watershed of the Metacarpathian Swell. The graben was drained to the north by rivers flowing from the West Carpathians and Eastern Sudetes. Strong fluvial erosion at the incipient stage of formation of a new drainage pattern resulted in redeposition of microfauna, presently found throughout much of Lower Silesia and southern Wielkopolska (Great Polish Lowland) areas.

The Fore-Sudetic Block is cut by the Fore-Sudetic Marginal Fault whose footwall is dominated by isolated hills, whereas the hanging wall bears Cainozoic sediments up to 180 m thick. SE of the Strzelin Hills, the fault becomes blurred. The higher-elevated portion of the Fore-Sudetic Block is subdivided into minor horsts and troughs. Proceeding from the NW, the Legnica, Strzegom, Ślęza, Bielawa-Niemcza, and Strzelin horsts should be listed. The Strzegom horst is separated from the Sudetes by the deep Roztoka-Mokrzyszów Graben (Dyjur and Kuszell, 1977; Grocholski, 1977; Kural, 1979) which is divided by a transversal ridge (Figs. 2, 3). An analysis of archival borehole material from Mokrzyszów does not confirm earlier opinions about the presence of a thick series of tuffs that were to occur at a depth interval of 390-660 m. The alleged tuffs are in fact gravels and clayey sands shed by an high-energetic river. Abundant basalt gravels indicate that this river must have been flowing parallel to the Sudetic margin, from Jawor due SE.

The earlier distinguished Wądroże Wielkie horst should be linked with the Strzegom horst into one tectonic structure. The horst is bordered on the east by the Bystrzyca River valley, which is situated in a tectonic zone that originates on the margin of the Intra-Sudetic Depression and continues up to Wrocław. The Bystrzyca River valley can, however, be more shallow than shown on the map, since it truncates exposures of weathered granites, which could have been erroneously described as sands and gravels. Solution to this question lies in future drilling and electric resistivity soundings.

The Ślęza and Bielawa-Niemcza Hills horst can be subdivided into several smaller structures. Its central part is occupied by the Dzierżoniów Depression, whereas the eastern part is represented by the meridional Ślęza Graben. The horst of Bielawa-Niemcza Hills is separated from the Sudetes by the narrow Ostroszowice Graben whose bottom is covered by a thin veneer of Quaternary sediments. It is in this area where the base of the Sudetes is most elevated, pointing to either the highest rate of uplift of the Sowie Mts. and Bielawa Foothills, or preservation of a relict junction between the Metacarpathian Swell and the Sudetes.

The horsts of Niemcza and Strzelin Foothills are separated by a number of troughs that are drained by the Oława River. The largest troughs are to be seen

near Ziębice and Henryków-Ciepłowody. The Ziębice Graben was previously associated with that of Stoszowice, and called the Ząbkowice Śląskie Graben.

East of the Strzelin Hills, a narrow ridge linking the Fore-Sudetic Block and Silesian Upland is to be seen. This ridge represents a relict of the ancient main European watershed existing in this area until the Late Miocene, and separating the North Sea and Paratethys marine basins. Remains of large mammals found in Opole area point to important role played by this "bridge" in Middle Miocene times, during faunal migration from Asia to Western Europe through a land passage situated north of Paratethys and marine basins placed north of the Alps (cf. Głazek and Szykiewicz, 1986). The Fore-Sudetic Block and Silesian Upland used to form the Metacarpathian Swell which linked the Sudetes with the Holy Cross Mts. and Roztocze region. Marine Paratethyan sediments have been found in the Kędzierzyn and Nysa Grabens.

The East-Sudetic Boundary Fault, orientated NNW-SSE, is very well visible on the sub-Cainozoic surface map, separating the Nizký Jeseník Mts. and Głubczyce Plateau. The amount of throw is relatively small, between 50 and 80 m. The Głubczyce Plateau is a tectonic continuation of the Fore-Sudetic Block, although its surface is underlain by unmetamorphosed Lower Carboniferous greywackes and siltstones, and erosional remnants of Cenomanian sandstones and Turonian marls. The Głubczyce Plateau is bordered on the east by meridional faults that bound the Upper Odra River valley tectonic graben.

Along the Złoty Stok, Nysa, and Kędzierzyn line, the Fore-Sudetic Block is displaced by W-E striking troughs and grabens of Paczków, Łąka, and Nysa. The Kędzierzyn Graben separates the Silesian Upland from the Eastern Sudetes and Głubczyce Plateau. This structure is called sometimes the Paczków-Kędzierzyn Graben (Dyjur et al., 1978). These grabens are superimposed upon a single tectonic zone, although individual structures are slightly displaced versus each other. The largest is the Kędzierzyn Graben, first described by Stahl (1933) as a deep river valley. Subsidence of the Kędzierzyn Graben had already been active in Late Cretaceous time (Kotanski and Radwański, 1977), and the graben became reactivated at the end of the Early Miocene. Strong subsiding movements disappeared at the end of the Miocene. It cannot be excluded that in the Pliocene a short episode of tectonic inversion took place in the area. The distribution of Pliocene fluvial sediments throughout the Opole region appears to indicate tectonic quiescence in the youngest Tertiary. Depositional processes were only active between Grodków, Niemodlin and Opole.

The Kędzierzyn Graben disappears to the west between Nysa and Prudnik, being separated from the Nysa and Paczków Grabens by a meridional ridge which links exposures of the Moravo-Silesian Unit in

the Eastern Sudetes with similarly developed rocks underlying Upper Cretaceous strata SW of Opole. It cannot be excluded that the ridge was uplifted no sooner than after the peak of Badenian marine transgression. The structure coincides, in part, with a Late-Alpine horst already distinguished by Bossowski (1974), and called the Pakosławice Block.

Between the Fore-Sudetic Block and Eastern Sudetes Mts. (Figs. 2, 3), the Paczków Graben is situated, its outline being different in the eastern part from that suggested by Dyjor (1975, 1983, 1993, 1995) and Dyjor et al. (1978). The deepest part of the Paczków Graben is placed between Kamieniec Ząbkowicki and Paczków where the thickness of Neogene strata probably exceeds 400 m (Cwojdzński and Jodłowski, 1978; Skácel, 1989). Judging from the results of geoelectrical soundings, the thickness of unconsolidated sediments amounts to 600 m, although this figure can also include thickness of regolith covers upon crystalline bedrock (Cwojdzński and Jodłowski, 1978). Exposures of strongly weathered schists on the southern bank of the Otmuchów reservoir, 1-5 m below Holocene alluvium, mark the trace of a meridional ridge separating the Paczków and Nysa Grabens, orientated NNE-SSW. The latter extends from exposures of the Žulova granites in the Czech Republic, through Łąka and Radzikowice (Kościówko, 1982), up to Gielczyce. The Gielczyce Graben, however, has been considered by Kotański and Radwański (1977) as a part of the Kędzierzyn Graben. New wells and geophysical soundings are required to solve this question. Farther westwards, the Paczków Graben continues up to the Braszowice massif, separating the latter from the Bardo Mts. Close to Kamieniec Ząbkowicki, the Paczków Graben is joined by a narrow, meridional Ślęza Graben, extending from Jordanów area (Badura, 1999). This graben is superimposed upon an old tectonic unit, the Niemcza lineament. The strongest subsidence within the graben is to be seen at Przerzeczyn Zdrój spa, where sulphate waters occur.

The Stoszowice Graben is situated between the Bardo Mts., Braszowice massif, and Bielawa Hills. It is likely that the Miocene outflow from this basin proceeded through a narrow passage close to the Sudetic Marginal Fault. Neogene clastic sediments are here 80 m thick, and the original valley width did not exceed 300-400 m. Late Miocene complete filling of the valley led to formation of a different drainage pattern, the principal outflow occurring through the Ząbkowice Śląskie area, where "preglacial" fluvial sediments have been found (Badura et al., 1998a, b).

The map of thickness of Cainozoic strata (Fig. 4) clearly shows tectonic grabens and troughs. Differences in sediment thickness mark boundaries of individual horsts of the Fore-Sudetic Block, as well as deep troughs, like, for instance, the Grodków Graben whose formation controlled the evolution of drainage pattern in Late Neogene and Quaternary times.

## 6. MAP OF SUB-QUATERNARY SURFACE

The sub-Quaternary surface map features three prominent areas, namely the Sudetes, Fore-Sudetic region, and Silesian Lowland (Fig. 5). As far as tectonic subdivision is concerned, the Silesian Lowland is underlain by both the Fore-Sudetic Block and Wrocław Monocline. Boundaries of individual regions, showing different elevations of the top of sub-Tertiary bedrock, do not coincide with those between tectonic units shaped in the Late Cretaceous and Early Palaeogene.

The Sudetes are separated from the Fore-Sudetic Block by a morphotectonic scarp developed on the Sudetic Marginal Fault. The scarp is most elevated between Sichów near Złotoryja and the Złote/Rychlebské Mts. The results of studies of Quaternary fluvial terraces (Krzyszowski et al., 1998, 2000; Krzyszowski and Biernat, 1998; Migoń et al., 1998) and morphometric indices (Migoń, 1999; Ranošek, 2001; Badura et al., 2003a, b) point to young uplift of this zone. Elevation differences among terraces of the Nysa Kłodzka and Bystrzyca Rivers allow one to suppose that the Sudetic mountain front has been uplifted by 20 to 35 m after the Saalian (Odranian) glacial stage. Deformation pattern of younger terraces points to decreasing amplitude of subsequent uplift, from 5 m to 2 m.

Subsidence tendencies in the Kłodzko Depression, showing a concentric drainage pattern, is clearly marked on the maps (Figs. 5, 6). Basing on imprecise descriptions of hydrogeological wells, the thickness of Quaternary strata has been estimated here at some 70 m, whereas a comparison between wells drilled at the end of the 19th century (Walczak, 1957) and the position of Neogene strata exposed in the Kłodzko gravel-pit (Jahn et al., 1984; Krzyszowski et al., 1998) suggest that this thickness does not exceed 40 m.

Strong subsidence affecting the central part of the Kłodzko Depression appears to confirm Badura and Przybylski's (2004) hypothesis that fluvial gravels exposed at Kłodzko are much older than the overlying Late Pliocene silts (Jahn et al., 1984). This subsidence can also explain very high position of gravels that occur north of Łądek Zdrój at 70 m above river beds, and are overlain by a basaltic lava flow dated to the turn of the Late Miocene and Pliocene ( $5.46 \pm 0.23$  Ma; cf. Birkenmajer et al., 2002a). Hence, the rate of relative vertical displacement between the Kłodzko Depression and its eastern margin can be estimated at 0.01 mm/yr.

The Sudetic Marginal Fault between Złoty Stok and Sichów, along a 100-km-long segment, clearly marks the tectonic contact between the Sudetes and the downthrown Fore-Sudetic Block. The fault scarp can be subdivided into seven segments of slightly different orientation. The mountain front sinuosity value calculated for the entire scarp is 1.054, pointing to its relatively young age (Badura et al., 2003a, b).

Without Quaternary cover, elevation differences between the Sowie Mts. and mountain ranges situated due NW and SE are even greater. Such a picture is compatible with that resulting from morphotectonic analyses which point to strong uplift of the Sowie Mts.

The topography of the sub-Quaternary surface (Fig. 5) shows that the NW segment of the Sudetic Marginal Fault between Sichów and Złotoryja is displaced on a WNW-ESE-orientated fault by some 15 km. The base of the Sudetic mountain front is drained here by the Kaczawa River. NW of Złotoryja, the fault strikes again NW-SE. It is likely that the mountain front-related segment of the fault is not the Sudetic Marginal Fault proper, but represents one of parallel, subsidiary faults. NW of Sichów, a buried tectonically-controlled step is to be seen between Chojnów and the Legnica trough.

The Sudetes used to be in contact with the higher-uplifted, as mentioned in the previous chapter, Fore-Sudetic Block which is bounded on the north by the Fore-Sudetic Marginal Fault. This fault is more clearly marked on the sub-Quaternary surface map (Fig. 5) than on the sub-Cainozoic surface map (Fig. 3), probably due to greater number of data points. The strike of the fault is parallel to that of the southern segment of the Middle Odra fault zone between Chojnów and Grodków (Cwojdzński and Żelaźniewicz, 1995). Close to the Strzelin Hills, the fault is not so clearly marked. It is likely that it turns due SE, towards the East-Sudetic Marginal Fault, and later on strikes nearly parallel towards the Opole area. High elevation of the Odra and Nysa Kłodzka Rivers' interfluvium is associated with the Neogene Metacarpathian Swell. The lack of any depression between this interfluvium and the Eastern Sudetes indicates that the Kędzierzyn Graben either has not been active since the Pliocene or its western part has revealed a different sense of movement. Tectonic quiescence in the graben area is testified to by the course of the Osobłoga River which cuts obliquely this structure, showing no sign of eastward-directed deflection.

In the watershed of the Nysa Kłodzka and Odra Rivers, both NW-SE and NE-SW-orientated faults are to be noted (Badura and Przybylski, 1999b). The NW-SE-orientated faults coincide with cuestas mapped in the Silesian Upland.

The morphology of the remaining part of the Fore-Sudetic area resembles that shown by the older, sub-Cainozoic surface. Well-marked depressions are to be seen in the Nysa, Paczków, Stoszowice, Roztoka, Mokrzyszów, Ziębice, and Henryków Grabens. A rectangular trough, called the Wrocław Depression, can be traced near Wrocław (Różycki, 1968). Its outline points to tectonic origin, as shown on Figs. 5 and 6. Basing on elevation differences between the Gozdnicza Formation within the trough and upon its margins, Czerwonka and Krzyszkowski (1992) suggested a tectonic origin of the discussed depression. The southern margin of the trough

coincides with the Middle Odra fault zone that separates the Fore-Sudetic Monocline and the Fore-Sudetic Block.

The sub-Quaternary topography reveals deep subglacial furrows (Fig. 6) including, among others, a small Krzywa furrow WNW of Legnica, two furrows dissecting the brown coal deposit north of Legnica, the Bogdaszowice furrow SW of Wrocław, and the Oleśnica furrow in the NE. The outline of the latter two furrows has been reconstructed basing on the results of electric resistivity sounding (Krawczyk and Tkaczyk, 1997). It cannot be excluded that continuation of the Oleśnica furrow is to be found within the Wrocław Trough. The Krynka furrow occurs west of the Strzelin Hills, and another line of subglacial depressions becomes visible between Nysa and Grodków (Badura et al., 1998a).

## 7. DISCUSSION AND CONCLUSIONS

The palaeosurface cutting the Fore-Sudetic Block and Permo-Triassic rocks of the Fore-Sudetic Monocline had been shaped during a period of deep subsurface weathering before deposition of the Upper Cretaceous strata. It is probable that an etchplain-type surface originated in those times. After the retreat of the Late Cretaceous sea, erosional processes affected first the Upper Cretaceous marine deposits and later on the sub-Cretaceous surface, presently called the sub-Cainozoic surface, upon both the Fore-Sudetic Block and the Wrocław Monocline. During deposition of Tertiary strata, the boundary between these two units was poorly marked. In the Polkowice and Lubin areas, this surface became fossilized already in the Late Eocene. In Oligocene times, the Rupelian transgression (Dyjur, 1978) entered upon most of the area of the Fore-Sudetic Block and the monocline. The Oligocene fluvial sands and quartzites are preserved in the Kwisia River valley on the Upper Cretaceous rocks.

The Lower Miocene strata bearing the IVth (Dąbrowa) brown coal seam are exposed in the Fore-Sudetic Block and the Fore-Sudetic Monocline, north of Legnica (Piwocki, 1998). In the NW part of Lower Silesia, sandy-gravel sediments of the Rawicz Formation are to be observed (Piwocki and Ziemińska-Tworzydło, 1997), also called the Żary Series by Dyjur (1978). The Upper Miocene brackish deposits in the Kędzierzyn Graben rest upon the Upper Cretaceous strata (Odrzywolska-Bieńkowska, 1977), whereas in the remaining parts of the Fore-Sudetic Block and Fore-Sudetic Monocline, the deepest-situated depressions are filled with terrestrial deposits of late Early Miocene age (Kural, 1979; Kościółko, 1982). The younger lithostratigraphic members occupy consecutively larger areas of the Fore-Sudetic Block. The youngest Poznań Formation can be traced throughout the entire Fore-Sudetic Block, protruding in the west into the Sudetes along river valleys and tectonic troughs (Nosek, 1970; Kasiński et al., 2003).

A prolonged period of erosion lasting until the Late Oligocene and subsequent accumulation of progressively southward-increasing extent indicate a change in the stress field parameters in Lower Silesia at the turn of the Late Oligocene and Early Miocene. New tectonic structures were then formed whose boundaries do not coincide exactly with those of the Fore-Sudetic Block and Fore-Sudetic Monocline. The onset of a new tectonic regime was probably marked by the formation of intramontane troughs, rejuvenation of the Sudetic Marginal Fault, and incipient volcanism. The oldest volcanic rocks found in the Zittau Basin have been dated to 41.4 Ma (Panasiuk, 1986; Alibert et al., 1987), whereas in the Opole region, close to the Bielawa-Niemcza horst, and on the Sudetic Marginal Fault volcanic activity was active at the turn of the Late Oligocene and Early Miocene, between 30.85 and 18.54 Ma (Birkenmajer et al., 1977, 2002b; Birkenmajer and Pécskay, 2002).

A newly formed stress field led to the formation of the uplifted Sudetes block, Fore-Sudetic belt of depressions with the Roztoka, Mokrzeszów, and Paczków Grabens, as well as the Carpathian Foredeep including the Kędzierzyn Graben, a belt of uplifts associated with the western continuation of the Metacarthian Swell and, in the north, a zone of subsidence whose axis was tilted towards the North Sea basin. Such a stress field persisted until the end of the Middle Miocene.

Late Miocene reorientation of the stress field, induced by a push of the West Carpathians, led to the retreat of the Paratethys sea from the western part of the Carpathian Foredeep. Intensified subsidence in the present-day Odra River valley area and migration of its axis towards the south-east resulted in the disruption of the Metacarthian Swell near Grodków. It is likely that a similar stress field has been maintained until recent times with only minor modifications.

The presented analysis of maps of buried surfaces and hundreds of borehole logs has shown that the term "Fore-Sudetic Block" should be redefined. In Neogene times, this area was deformed together with the adjacent Fore-Sudetic Monocline and Opole Trough, forming new tectonic units that are arranged in an echelon versus older tectonic boundaries. The top surfaces of individual tectonic blocks are occupied by an etchplain, showing different state of preservation. At some places, fully-developed regolith sections are to be observed whereas at others poorly weathered rocks underlie gentle relief, composed of hills and basins formed due to selective, subsurface weathering. The entire area of the Fore-Sudetic Block displays an upland landscape, locally resembling that of low mountains, whose relief energy does not exceed 500 m.

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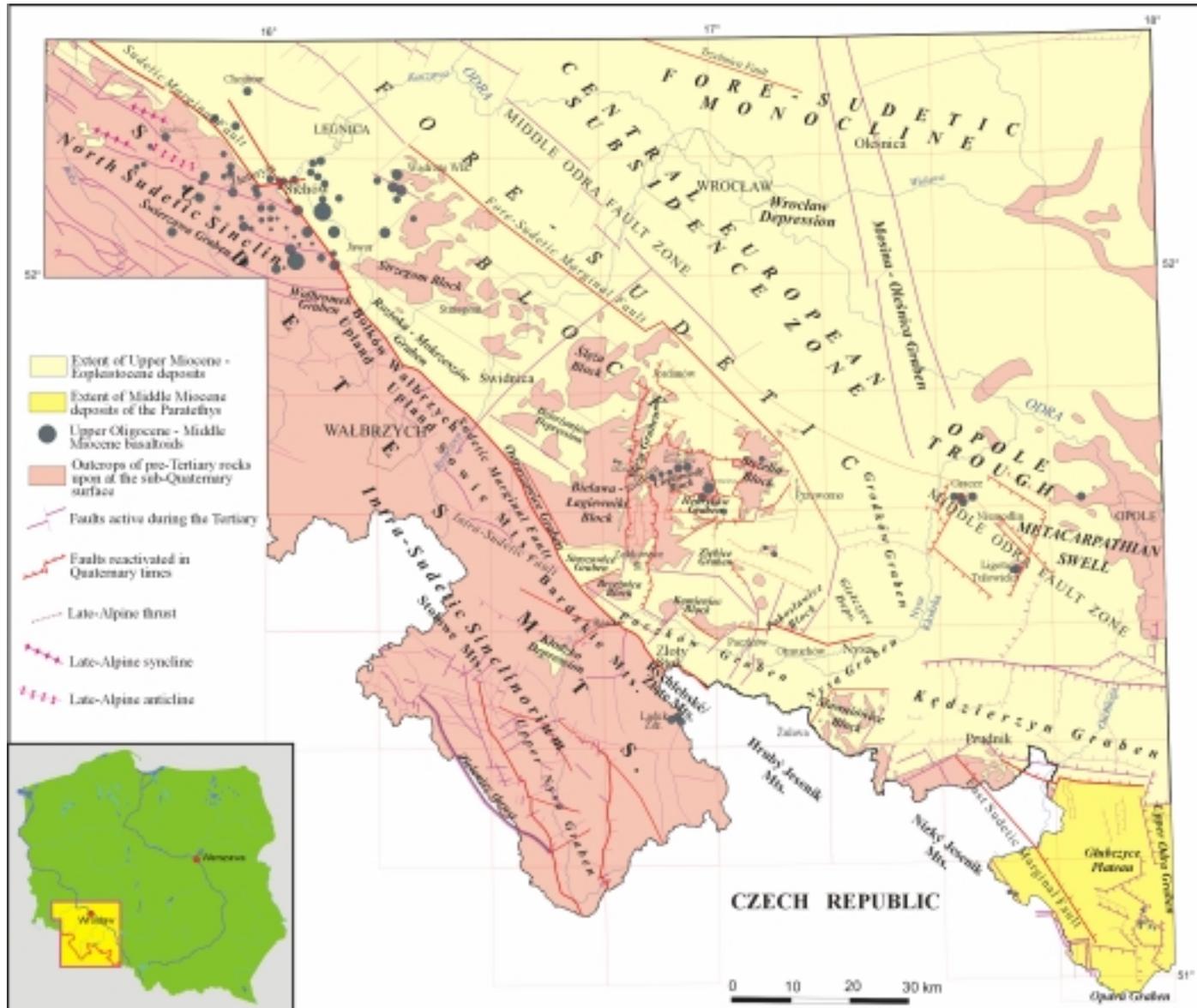
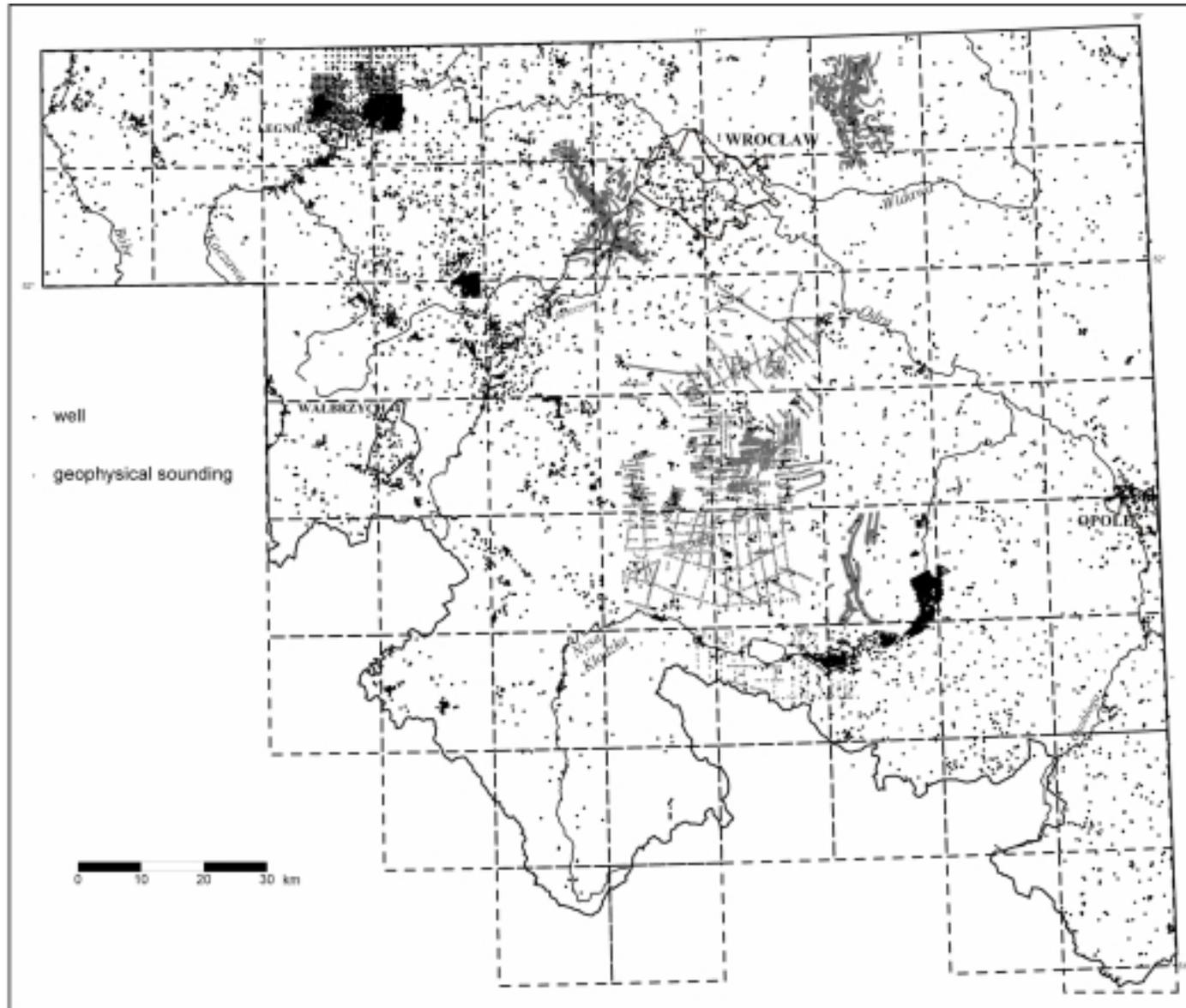
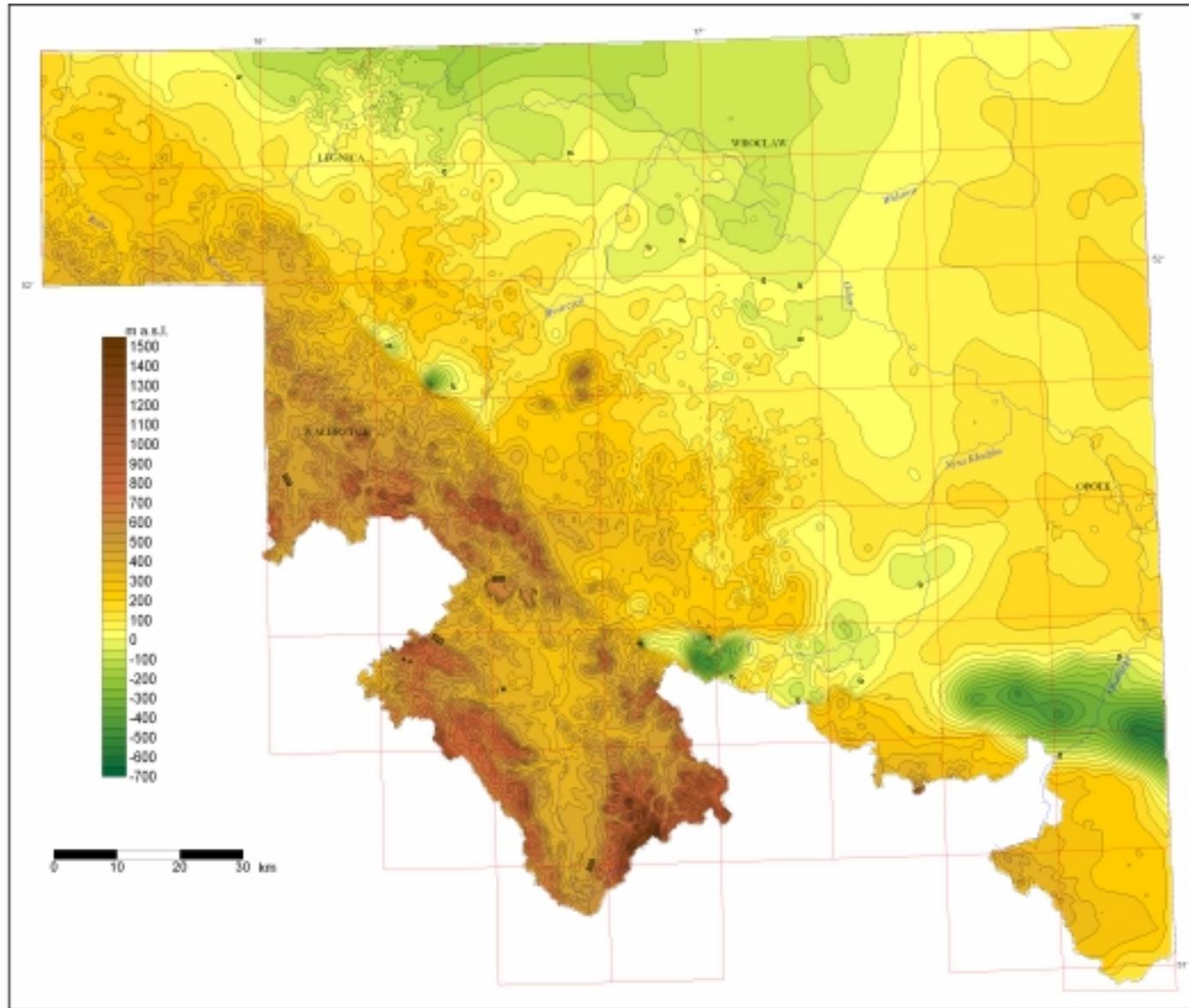


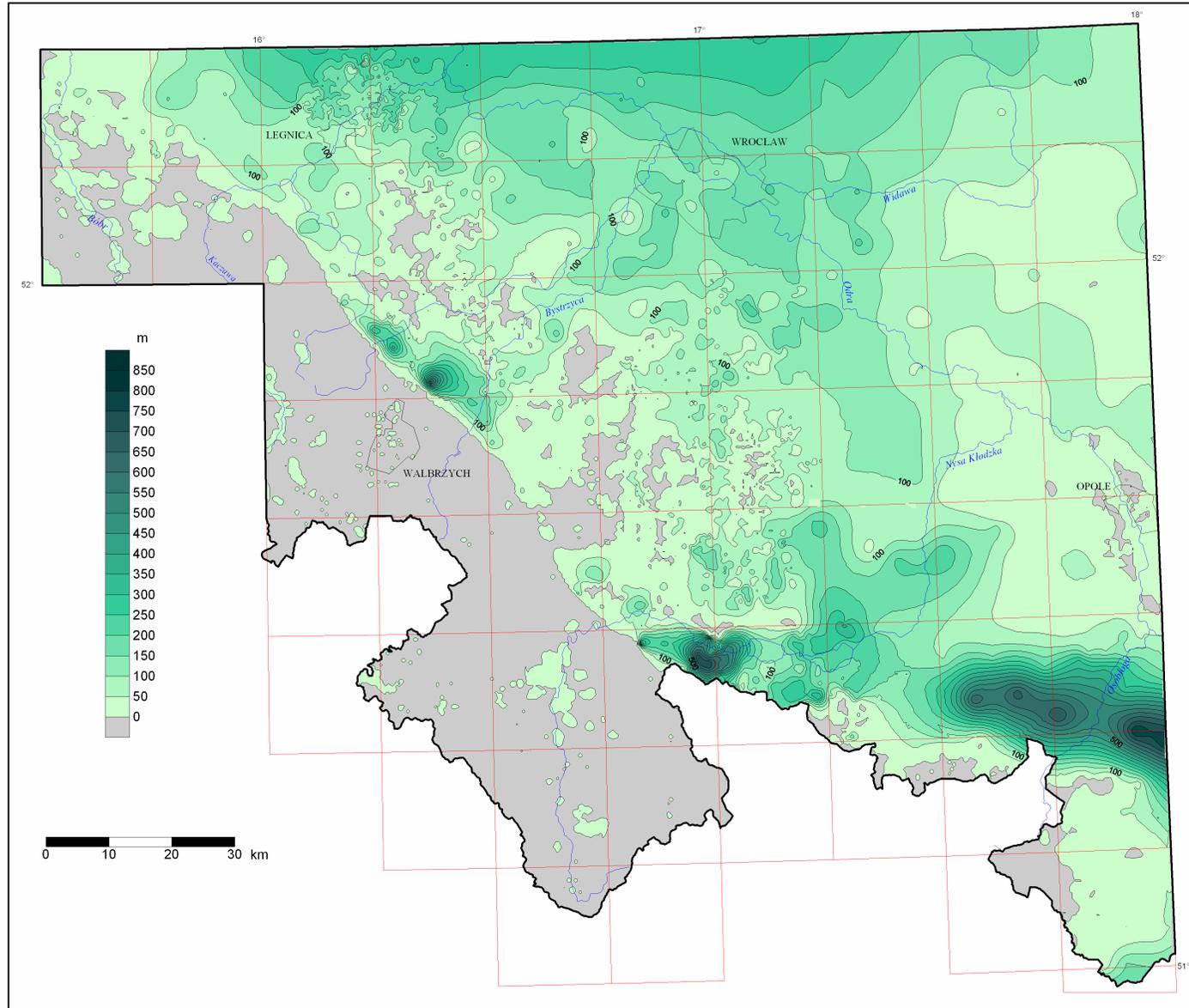
Fig. 1 Fault pattern and tectonic units in SW Poland



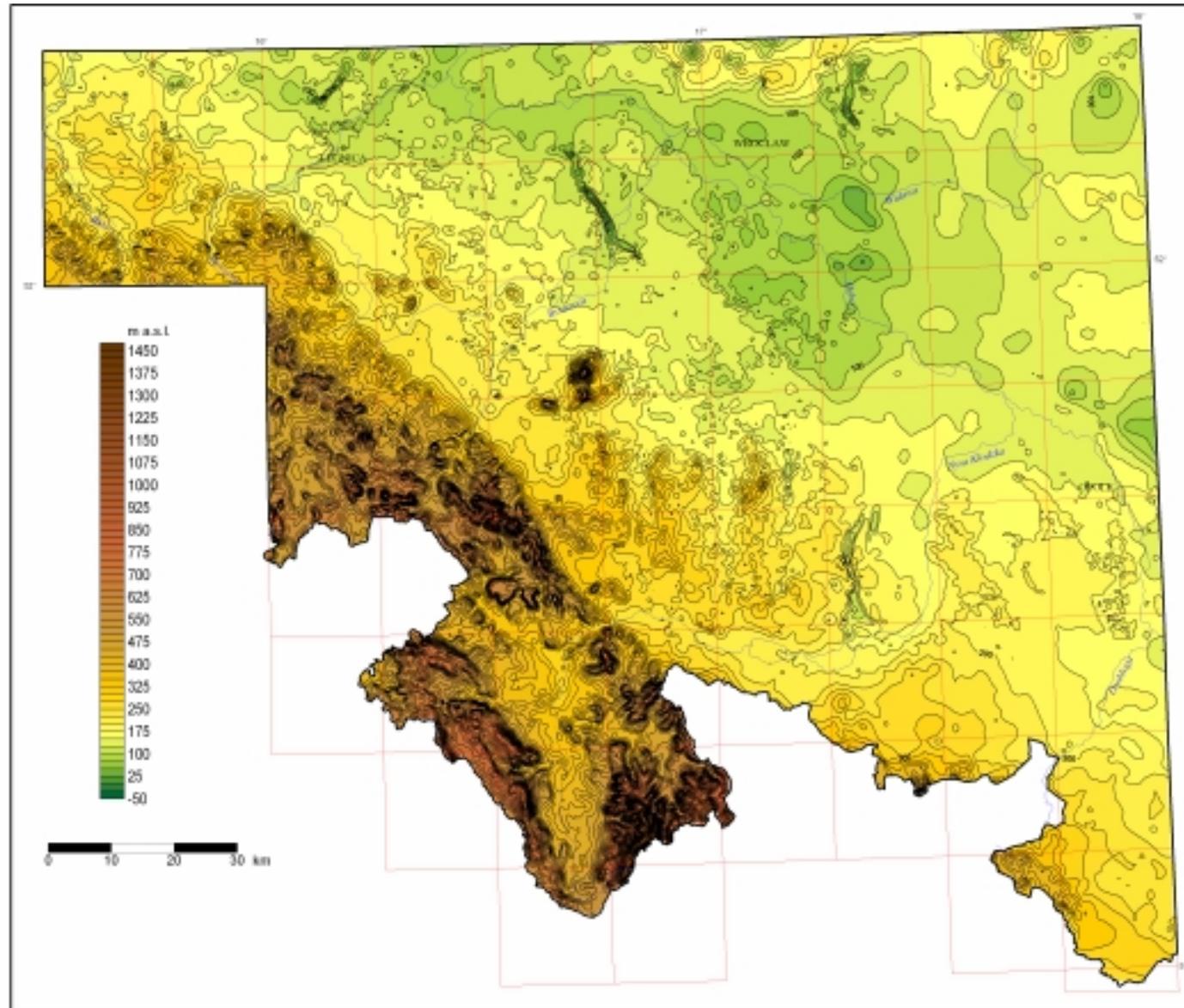
**Fig. 2** Map showing location of wells and geophysical sounding profiles used in this study



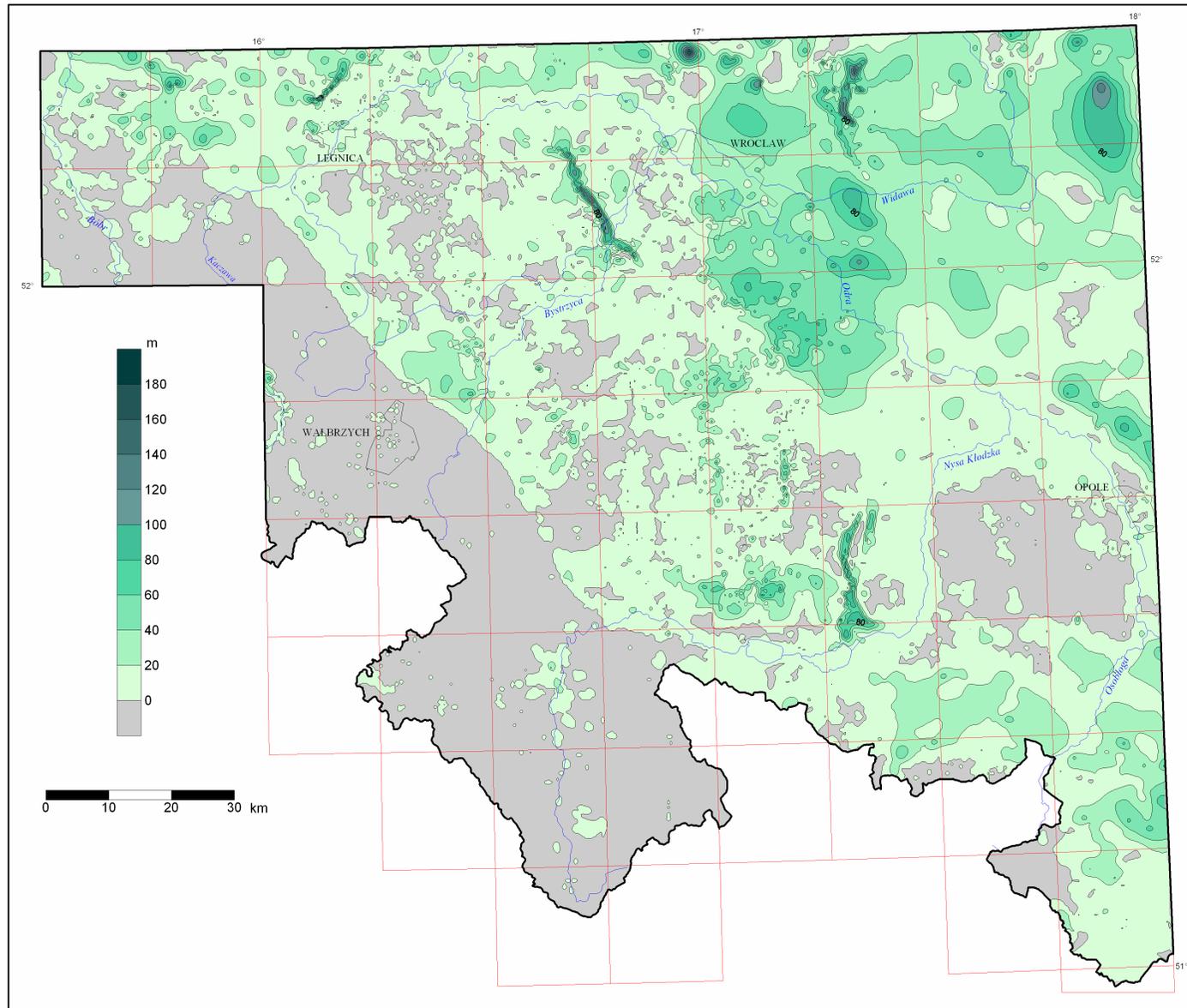
**Fig. 3** Topography of the sub-Cainozoic surface in SW Poland



**Fig. 4** Thickness of Cretaceous strata in SW Poland



**Fig. 5** Topography of the sub-Quaternary surface in SW Poland



**Fig. 6** Thickness of Quaternary sediments in SW Poland