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NEOTECTONICS OF POLAND: AN OVERWIEV OF ACTIVE FAULTING

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Abstract

Neotectonic studies in Poland concern mainly manifestations of those tectonic movements that have been active in Late Neogene and Quaternary times, as well as geodetically measured recent vertical and horizontal crustal motions. Among problems of particular interest, the following should be listed: periodicity of neotectonic (mostly Quaternary) activity, estimation of the parametres of the neotectonic stress field, amplitudes and rates of Quaternary and recent movements, development of neotectonic troughs and young faults, mutual relationships among photolineaments, geological structures and recent seismicity, as well as the role of tectonic reactivation of fault zones due to human activity. Neotectonic faults in Poland have developed in Neogene and Quaternary times due to reactivation of Laramian or older structures, or in the Quaternary due to reactivation of Neogene faults. The size of throw of Quaternary faults changes from 40–50 m and >100 m in the Sudetes and the Lublin Upland, to several – several tens of meters in the Carpathians. The average rate of faulting during Quaternary times has been 0.02 to 0.05 mm/yr, what enables one to include these structures into the domains of inactive or low-activity faults. A similar conclusion can be drawn from the results of repeated precise levellings and GPS campaigns. Strike-slip displacements have been postulated for some of these faults. Isolated faults in Central Poland have shown middle Quaternary thrusting of the order of 40–50 m, and some of the Outer Carpathian overthrusts tend to reveal young Quaternary activity, as indicated, *i.a.* by concentrations of fractured pebbles within the thrust zones. Episodes of increased intensity of faulting took place in the early Quaternary, in the Mazovian (Holsteinian) Interglacial, and during or shortly after the Odranian (Drenthe) glacial stage. Some of the faults have also been active in Holocene times. Recent seismic activity is often related to strike-slip faults, which in the Carpathians trend ENE–WSW and NE–SW, whereas outside the Carpathians they are oriented parallel to the margin of the East-European Platform and the Sudetic Marginal Fault. Future investigations should put more emphasis on palaeoseismotectonic phenomena and practical application of neotectonic research.

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Key words: neotectonics, active faulting, Poland

To the memory of Prof. Jerzy Liszkowski

NEOTECTONIC SUBDIVISION

From among different definitions of the neotectonic period (cf. Zuchiewicz 1995), for the purpose of this paper we have chosen that proposed by Şengör *et al.* (1985): ..."*the time that elapsed since the last major whole-scale tectonic reorganization*“. Extensive bibliography pertaining to the neotectonics of Poland can be found in Zuchiewicz (2003), whereas abridged reviews of manifestations of young tectonic movements are comprised in a few publications (*e.g.* Rühle 1973, Ostaficzuk 1995, Zuchiewicz 1995, 2002, Jarosiński 1999, 2005; and references therein). Beneath, we shall deal with some aspects of young faulting only, and particularly in areas situated outside the Alpine orogen, *i.e.* north of the Carpathians (Fig. 1).

A proposal of neotectonic-structural subdivision of Poland, presented by IGCP Project 346 *Neogeodynamica Baltica* (Karabanov, Schwab 1997) for the Baltic countries, includes the following 1st-order units (Fig. 2):

– Baltic-Belarus Syneclise, including both the areas subsiding since the onset of the Oligocene, and those originally subsided and then uplifted;

– Central-European Subsidence Zone, including the Odra Depression and West Baltic Step (subsided since the Oligocene), as well as the Pomeranian Depression and Central-European High;

– Central-European Zone of Uplift, including the Lusatian-Sudetic and Holy Cross blocks, as well as South-Polish – Podolian Uplift, uplifted since the Oligocene;

– Carpathian Foredeep, showing differentiated subsidence and uplift;

– Carpathians, showing differential uplift.

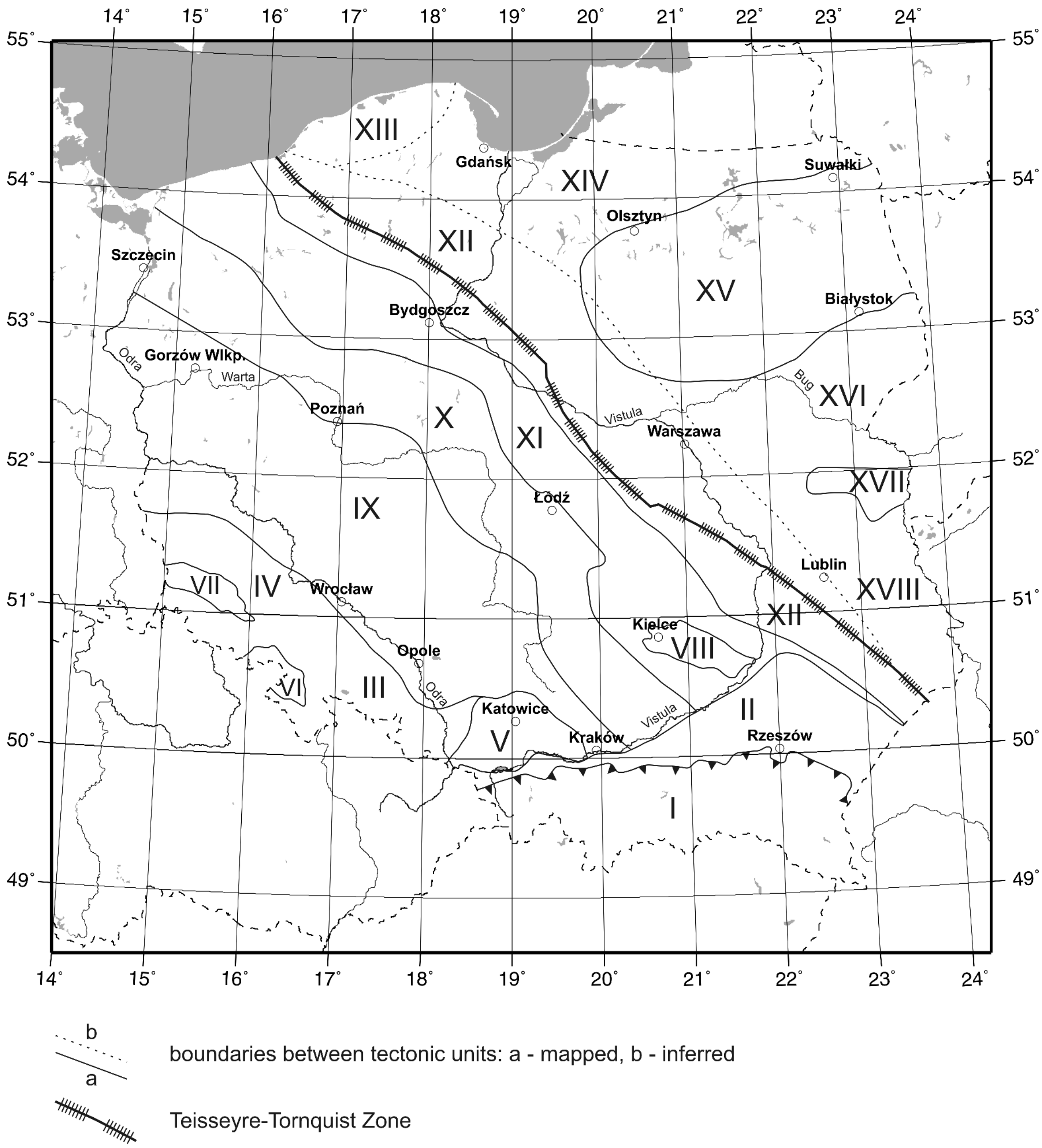


Fig. 1. Tectonic sketch-map of Poland (based on Znosko (ed.) 1998; modified). Areas of Alpine folding: I – Carpathians, II – Carpathian Foredeep. Areas of Palaeozoic folding. Caledonides and Variscides at the groundsurface or under thin sedimentary cover: III – East Sudetes, IV – West Sudetes and Fore-Sudetic Block, VIII – Holy Cross Mts. Variscan orogenic troughs: V – Upper Silesian Coal Basin, VI – Wałbrzych Coal Basin, VII – North-Sudetic Trough. Palaeozoic platform: IX – Fore-Sudetic Monocline and Silesian-Cracow Monocline, X – basins (from NW to SE): Szczecin, Mogilno-Łódź, Miechów, XI – Mid-Polish Anticlinorium (Kuyavian-Pomeranian Swell), XII – Marginal Depression. East-European Platform. Lowered parts of crystalline basement overlain by thick sedimentary cover: XII – Marginal Depression, XIII – Łeba High, XIV – Peribaltic Syneclise, XVI – Podlasie Low, XVIII – Bug Syneclise. Uplifted parts of crystalline basement overlain by thin sedimentary cover: XV – Mazury-Suwałki Anteclise, XVII – Sławatycze High (Horst).

The greatest geodynamic hazard, apart from the Carpathians, can be expected in the Central-European Zone of Uplift, and particularly in the Lusatian-Sudetic Block.

AMPLITUDES AND RATES OF QUATERNARY CRUSTAL MOVEMENTS

The amplitudes and spatial distribution of zones showing Quaternary tectonic mobility have been treated differently by different authors, depending on the time scale considered (cf. Zuchiewicz 1995, 2000). According to Rühle (1969, 1973), the amplitude of Quaternary uplift exceeded 100 m in NE Poland, as well as in southern Lublin Upland and Roztocze region, while subsidence tendencies (–50 to <–100 m) were confined to the lower Vistula River valley and NW Poland (Figs. 3, 4). Large thicknesses of Quaternary sediments (>200 m) within tectonic grabens and depressions in the Kuyavian-Pomeranian Swell and in the East-European Platform, however, indicate higher amplitudes of vertical movements (Rühle 1973, Baraniecka 1975, 1980). There-

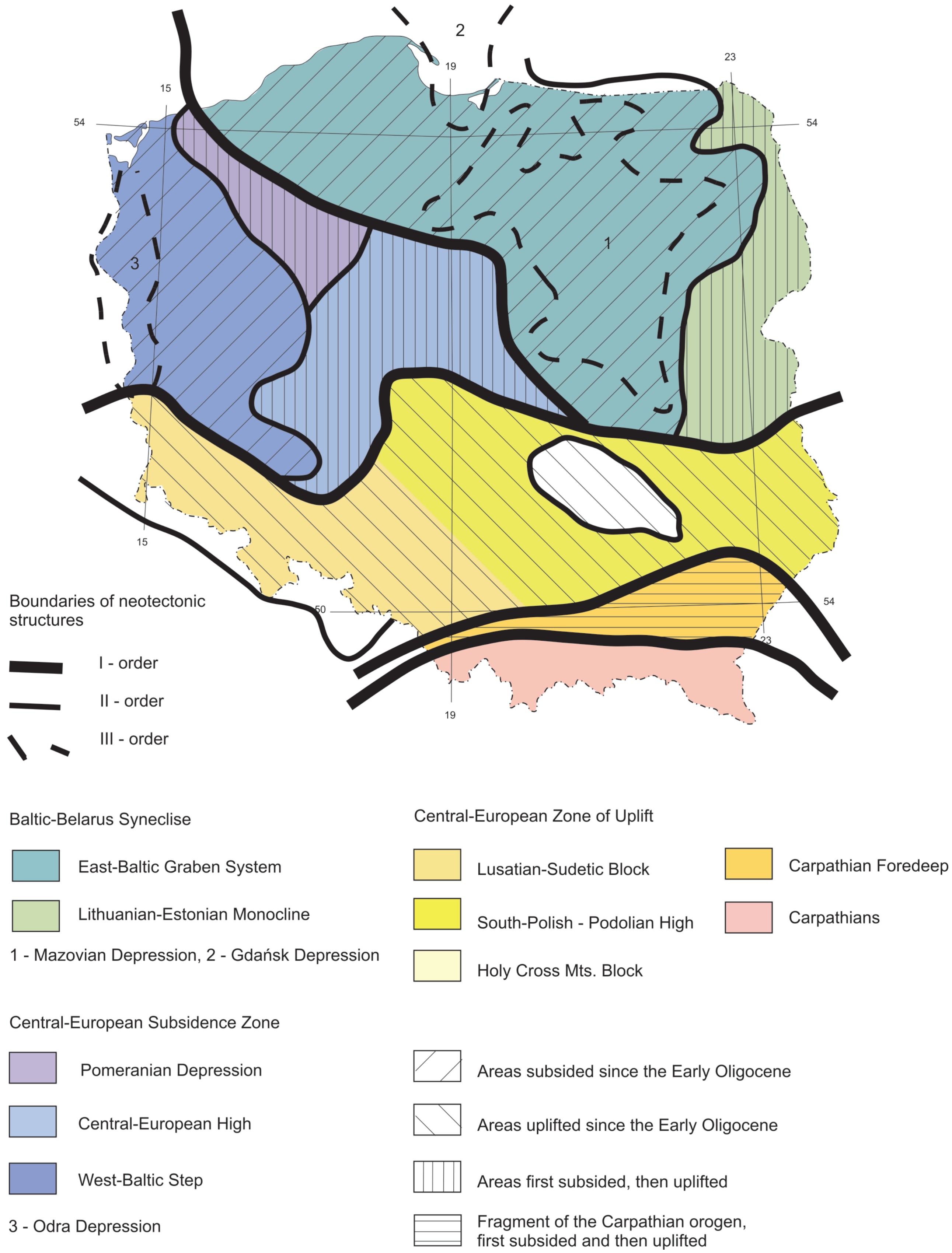


Fig. 2. Neotectonic-structural units (based on Karabanov, Schwab 1997; modified).

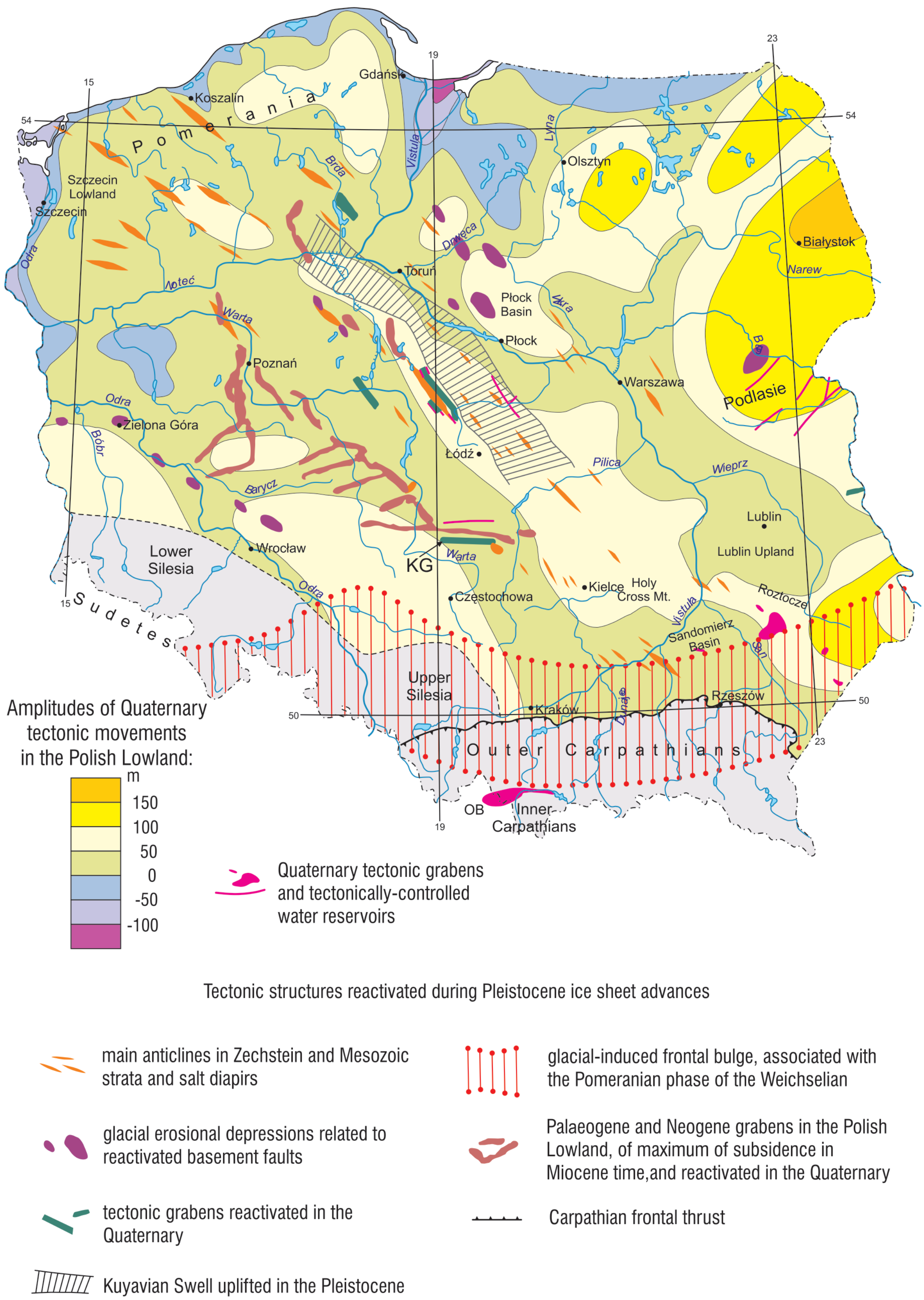
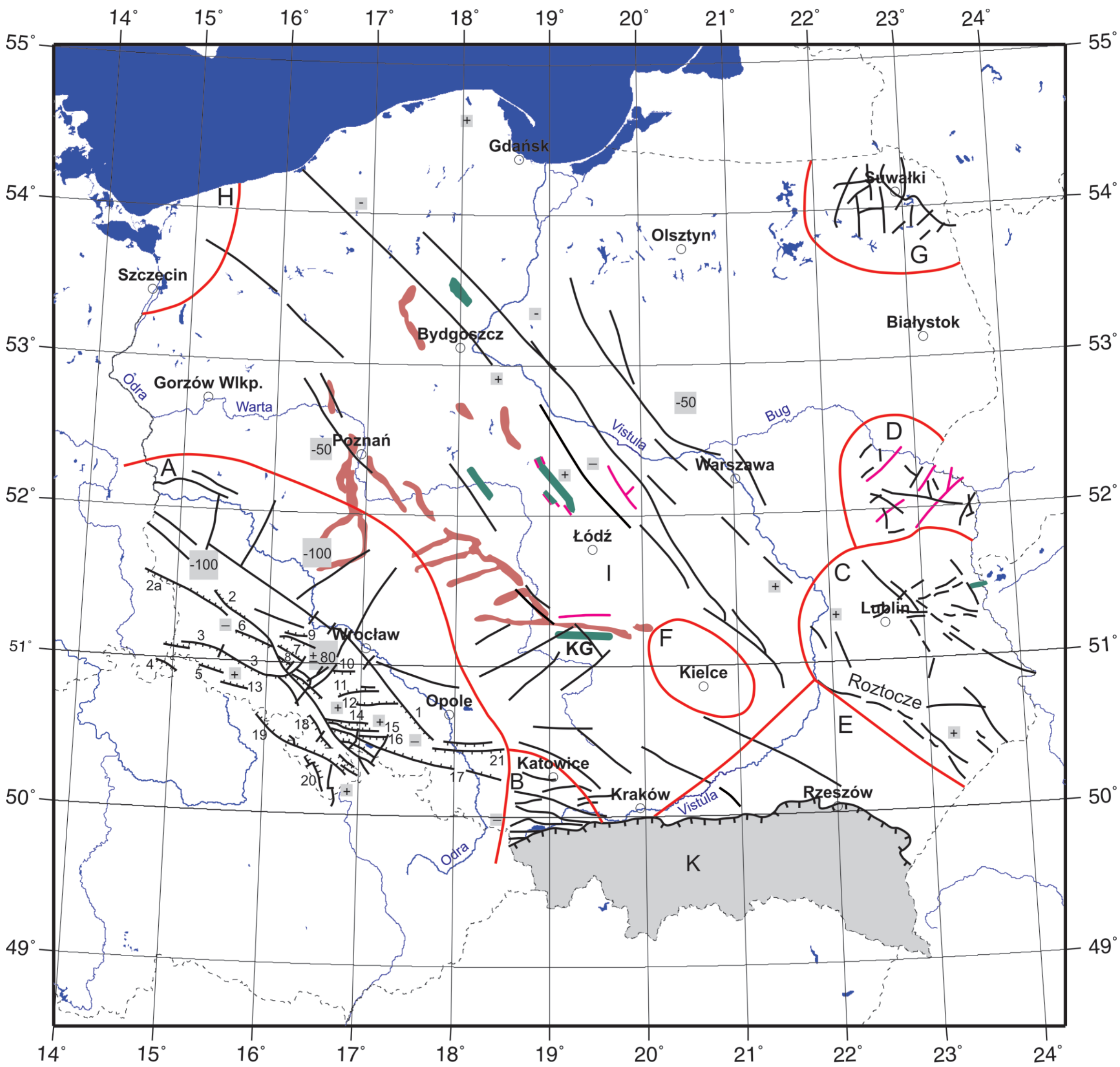


Fig. 3. Neotectonic map of Poland (based on different sources elaborated by Zuchiewicz 2000; modified). KG – Kleszczów Graben, OB – Orava Basin.



Quaternary tectonic grabens

Palaeogene and Neogene grabens reactivated in the Quaternary

grabens originated in Keuper time, showing maximum of subsidence in the Miocene, and reactivated in the Quaternary

Laramian and Neogene faults reactivated in the late Neogene and Quaternary, and Quaternary faults

Fig. 4. Young faults in Poland (based on: Kowalski, Liszkowski 1972, Rühle 1973, Liszkowski 1982, 1993, Henkiel 1984, 1993, Dyjor 1993, 1995, Baraniecka 1995, Dyjor *et al.* 1995, Krzyszkowski *et al.* 1995, Jura 1995, 1999, Ostaficzuk 1995, Nitychoruk 1996, Brzezińska-Wójcik 1999, Kasiński, Piwocki 1999, Ber 1999 and others; modified by Zuchiewicz 2000). Areas in which neotectonic faults were mapped: A – Lower Silesia, B – Upper Silesia, C – Lublin Upland and Roztocze region, D – Podlasie region, E – Sandomierz Basin, F – Holy Cross Mts., G – NE Poland (Suwałki area), H – NW Poland (including Szczecin Lowland), I – North-Polish Lowland and uplands of south-central Poland, K – Carpathians. Neotectonic faults in Lower Silesia: 1 – Middle Odra Fault Zone, 2 – Sudetic Marginal Fault (SMF), 3a – possible continuation of SMF, 3 – Intra-Sudetic fault, 4 – Zatoń fault, 5 – Rębiszów fault, 6 – Jerzmanowice fault, 7 – Głębinów fault, 8 – Bagieniec-Paszowice fault, 9 – Legnica-Chojnów fault, 10 – Sobótka fault, 11 – Strzelin fault, 12 – Przeworno fault, 13 – marginal Karkonosze fault, 14 – Ząbkowice Śląskie fault, 15 – Doboszowice fault, 16 – Pomianów Górny and Nysa faults, 17 – Biała Głuchołaska fault, 18–20 – faults associated with the Upper Nysa Kłodzka Graben, 21 – Toszek fault. –100 – tendencies of Quaternary vertical movements (in metres); KG – Kleszczów Graben.

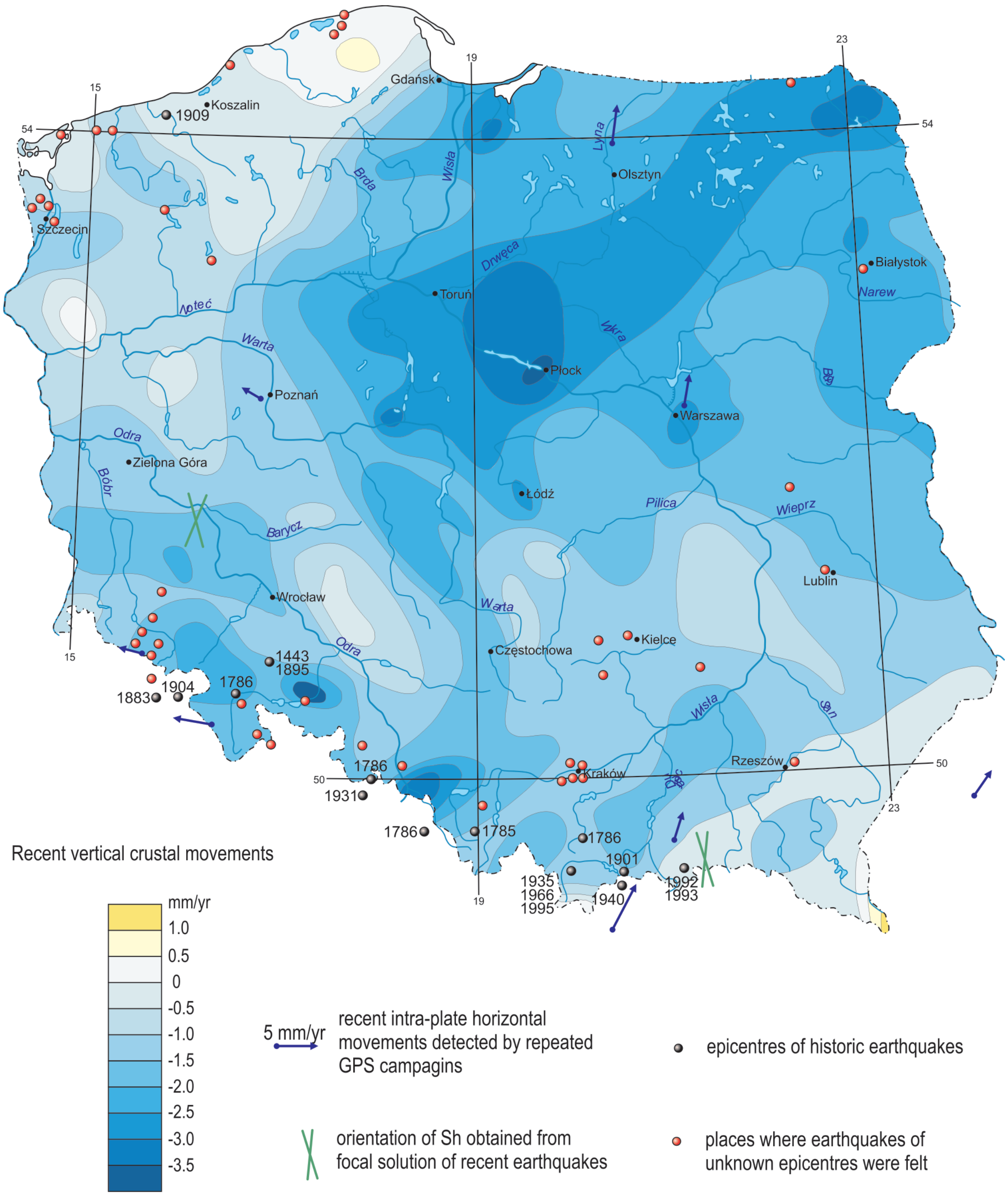


Fig. 5. Recent crustal movements and historical seismicity in Poland (based on Pagaczewski 1972, Wyrzykowski 1985, Hefty 1998, Jarosiński 1999, Zuchiewicz 2000).

fore, the average rates calculated for the entire Quaternary appear to be 0.04–0.06 and 0.08 mm/yr, respectively. The Quaternary neotectonic amplitudes during individual episodes of increased activity ranged from 15–20 m (subsidence in the Kleszczów Graben during the Pilica/Drenthe-Warthe Interglacial stage; cf. Brodzikowski 1987) and 20–30 m (uplift of the Roztocze region during the Mazovian/Holsteinian Interglacial; cf. Harasimiuk, Henkiel 1980) to 30–40 m (uplift of some portions of the Sudetes Mts., in the Mazovian/Holsteinian Interglacial; cf. Krzyszkowski *et al.* 1995) and 70–100 m (early Pleistocene uplift of some structures of the West Carpathians; cf. Zuchiewicz 1991). The rates of these movements in the Polish Outer Carpathians range from 0.02 to 2 mm/yr (Zuchiewicz 1991, Zuchiewicz *et al.* 2002).

In Northern Poland, episodes of increased neotectonic activity occurred at the end of Pliocene, in middle (1.45–1.35 Ma) and late Eopleistocene (1.15–1.00 Ma), and late Mesopleistocene (0.60–0.45 Ma) times (Mojski 1991). The subsidence of the Mazovian Depression and the Baltic Depression was interrupted by glacioisostatic uplift that followed every Scandinavian ice-sheet retreat, being combined with the reactivation of basement structures of the Kuyavian-Pomeranian Swell (Baraniecka 1975, Liszkowski 1993, Zuchiewicz 1995).

The latest version of the map of recent vertical crustal movements in Poland, based on repeated levelling (Wyrzykowski 1985), appears to indicate prevailing subsidence (usually between 0 and –3 mm/yr) all over the country, except for weakly uplifted parts of Pomerania and the SE portion of the Carpathians (Fig. 5). The strongest subsidence (<–3.5 mm/yr) is recorded in the Paczków Graben, Lower Silesia, upper Odra River valley, and Płock Basin (Figs. 4, 5). The results of repeated GPS campaigns are available for selected areas of Lower Silesia only (cf. Kontny 2003).

YOUNG FAULTS

Seismotectonic faults in Poland have developed in Neogene and Quaternary times due to reactivation of Laramian or older structures, or in the Quaternary due to reactivation of Neogene faults (Kowalski, Liszkowski 1972, Rühle 1973, Liszkowski 1982, 1993, Henkiel 1983, 1984, 1993, Dyjor 1983, 1993, 1995, Baraniecka 1995, Dyjor *et al.* 1995, Krzyszkowski *et al.* 1995, Jura 1995, 1999, Ostaficzuk 1995, Nitychoruk 1996, Brzezińska-Wójcik 1999, Kasiński, Piwocki 1999, Ber 1999, Zuchiewicz 2000, and others; see Fig. 4). The first group includes, *i.a.* faults bordering the lower Vistula River valley, the escarpment zone of the Roztocze region, SE Poland, and many fault zones in the Sudetes and Fore-Sudetic Block, SW Poland, of throws ranging from 100 m (Legnica - Chojnów fault) through 600 m (Paczków and Kędzierzyn grabens) to 800 m (Roztoka-Mokrzeszów graben). In NE Poland, manifestations of Quaternary reactivation of the Teisseyre-Tornquist zone and of faults perpendicular to it (NE–SW) have been encountered, owing to combined effects of the mid-Atlantic ridge-push and compression exerted by the Carpathians (Czarnecka 1993). Most of these faults coincide well with the photolineaments seen on satellite images and topolineaments identified on digital elevation models (Bażyński *et al.* 1984, Graniczny 1991, Ostaficzuk 1995, 1999).

The second group of faults includes those of Lower Silesia (Wrocław - Ozimek, Przeworno - Węgliniec, Sudetic Marginal Fault, a fault along the northern margin of the Karkonosze Mts.; Dyjor 1983, 1993, 1995, Migoń 1991) and Upper Silesia regions (*i.a.* a series of E–W trending faults showing recently downfaulted northern limbs, cf. Czarnecka 1988), the NW–SE, N–S, NE–SW, E–W, and ESE–WNW oriented faults of the Lublin Upland and Roztocze region (Harasimiuk, Henkiel 1984, Henkiel 1984, Buraczyński 1984), NNE–SSW and NE–SW oriented faults in the northern part of the Sandomierz Basin (Laskowska-Wysoczańska 1979, 1983), as well as several oblique-slip, strike-slip, and thrusts faults in the Carpathians (Zuchiewicz 1995, Zuchiewicz *et al.* 2002; and references therein).

In NW Poland (Kopczyńska-Lamparska 1979) and on the NW margin of the Holy Cross Mts. (Lindner 1978), Quaternary faulting proceeded in the Cromerian and Holsteinian interglacials, while on the NE margin of the Holy Cross Mts. it took place in the Warthe and Eemian stages (Kosmowska-Suffczyńska 1986). In the central part of the Holy Cross Mts. reactivation of Palaeozoic faults was noticeable in the early and middle Quaternary (Kowalski 1995). During the Middle-Polish (Saalian) glaciations and Eemian interglacial, intensive subsidence of some grabens in north-eastern (Kociszewska-Musiał 1978) and northern Poland (cf. Ostaficzuk 1981) became apparent. Grabens of throws up to 40–50 m originated in the Łódź Upland during Holsteinian times (cf. Zuchiewicz 1995). Recently initiated studies of fractured clasts in Quaternary fluvial series in the Carpathians (Tokarski, Świerczewska 2005, Tokarski *et al.* 2005b) point to reactivation of some map-scale thrusts.

The size of throw of Quaternary faults (Fig. 4) changed from 40–50 m to more than 100 m in the Sudetes, Lublin Upland, and Inner Carpathians, and from several to several tens of metres in the Outer Carpathians. The average rate of faulting during Quaternary times has been 0.02 to 0.05 mm/yr, what enables one to include these structures into the domains of inactive (D) or low-activity (C) faults (cf. Slemmons & Depolo 1986). Similar conclusions result from repeated levellings and GPS campaigns.

Strike-slip component has been suggested for some Quaternary faults, including the Sudetic Marginal Fault (Mastalerz, Wojewoda 1990, Tokarski *et al.* 2005a) or Janowice Fault in the Lublin Upland (Henkiel 1984). Solitary faults in Central Poland (Kleszczów Graben) represent Mid-Quaternary thrusts of displacements up to 40–50 m (cf. Hałuszczak 1999, Gotowała, Hałuszczak 2002).

Episodes of increased intensity of faulting took place in the early Quaternary, in the Mazovian (Holsteinian) Interglacial and during or shortly after the Odranian (Drenthe) glacial stage. Some of the faults have also been active in Holocene times (Karkonosze Mts., Roztocze region, Outer Carpathians).

The Quaternary faulting is reflected in increased thicknesses of young deposits on downthrown blocks (including stacks of colluvial-solifluction wedges; cf. Henkiel 1993), deformation of river terraces and alluvial fans, changes of the drainage pattern, clast fracturing, as well as in the formation of cracks within Pleistocene ice-sheets, controlling the preferred orientation of glacifluvial accumulation forms (*e.g.* Klajnert 1984).

Faults active in young Quaternary times are frequently accompanied by photolineaments, nearly 70% of which coincide with manifestations of historic and present-day seismicity (Graniczny 1991).

SEISMICITY

Historical seismic activity is often related to strike-slip faults, which in the Carpathians trend ENE–WSW and NE–SW (Bażyński *et al*. 1984, Graniczny 1991), whereas outside the Carpathians they are oriented parallel to the margin of the East-European Platform and the Sudetic Marginal Fault (Liszkowski 1982, Guterch, Lewandowska-Marciniak 2002; see also Fig. 5).

A detailed list of historical earthquakes recorded in Poland was presented by Pagaczewski (1972), Guterch and Lewandowska-Marciniak (1975, 2002), Prochazková *et al.* (1977, 1978) and Prochazková and Karnik (1978). In the years 1000–1970 AD, 89 earthquakes occurred, half of them in the Lower Silesia and usually along the Sudetic Marginal Fault. The recurrence interval for the Sudetes is 22 yrs, the maximum intensity of earthquakes attaining 8° MCS (Pagaczewski 1972). Within the Carpathians, earthquake foci usually cluster along the inner (southern) side of the Pieniny Klippen Belt and along some strike-slip and oblique-slip faults (Orava Basin in 1995 and 2004; Krynica area in 1992 and 1993); in other regions they occur sporadically. Seismic intensities of the Polish Carpathian earthquakes range from 4 to 7.5° MCS, whereas their magnitudes are between 3 and 5 (Orava Basin, on 30 Nov. 2004, Ml = 4.3, Ms = 4.4; cf. Guterch *et al.* 2005). The strongest earthquakes were reported in 1785-86 from the Žilina area (Slovak Western Carpathians, close to the Polish border). Focal depths reach up to 23 km, averaging at 10–12 km, although in the Orava Basin these are usually around 5–6 km. Cumulative magnitudes of the Carpathian earthquakes point to a close relationship between episodes of increased seismic energy release and climatic fluctuations of the Little Ice Age (cf. Zuchiewicz 1989).

The distribution of earthquake foci in Poland follows two principal directions: the "Sudetic" (NW–SE) and "Scandinavian" (NE–SW) ones, being parallel to the orientation of maximum shear stresses (cf. Liszkowski 1982).

Another question is the seismicity within areas of strong human impact, frequently related to reactivation of older faults due to subsurface and open-cast mining, as well as construction of artificial water reservoirs.

CASE STUDIES

As far as Quaternary faulting is concerned, the best studied regions are represented by the Lower Silesia, Kleszczów Graben, Lublin Upland, and Sandomierz Lowland within the Carpathian Foredeep (Fig. 4).

Lower Silesia

Neotectonic map of Lower Silesia, SW Poland, by Badura and Przybylski (2000) is the only detailed neotectonic map of a large fragment of Poland that shows distribution of faults either reactivated or formed in Neogene and Quaternary times (see simplified version of this map in Fig. 6). This map also portrays the distribution of young-Alpine folds and thrusts, exposures of young volcanics, distribution of hydrothermal and mineral waters, traces of young mineralization, and heat flow values.

From among faults reactivated in Quaternary times, the most important is the Sudetic Marginal Fault (SMF), nearly 300 km long, which marks the boundary between the uplifted Sudetes and stable and/or subsided Fore-Sudetic Block (cf. Dyjor 1995, Dyjor *et al.* 1995, Krzyszkowski *et al.* 1995, Badura *et al.* 2003, Kontny 2003). Its NW segment shows, apart from dip-slip, a minor sinistral component, while the SE segment is characterised by predominant dip-slip and, perhaps, insignificant dextral component. This problem will be solved owing to future detailed studies, including those of fractured pebbles in Pleistocene strata situated in the fault zone.

The SMF is considered to have been active in the Late Oligocene and reactivated later on, although it probably originated already during the Variscan orogeny. Quaternary activity of this structure has been a matter of debate. Some researchers suggested Quaternary uplift of the footwall ranging from 20–30 m to 60–80 m, and even 80–100 m, a large portion of it having been due to glacioisostatic rebound after the Saalian glaciation. Faulting of Quaternary terraces, rectilinearity of the fault scarp, possible seismotectonic deformations within Pleistocene alluvial fans, as well as historical seismicity, and contemporaneous, GPS-detected mobility, all testify to recent activity of this zone.

We have analysed the southeastern, nearly 100-km-long, portion of this fault. This portion of the SMF has been subdivided into seven segments showing slightly different orientation (N28°W to N55°W), geological setting, length (8.8–22.9 km), height of the fault and fault-line scarp (40–300 m), as well as the values of morphometric parametres of small catchment areas of streams that dissect the scarp. The latter parametres, particularly those characterising the elongation, relief, and average slope of individual catchment areas, together with abnormally small values of the valley floor width to valley height ratios, and mountain front sinuosity indices which are indicative of a nearly rectilinear trace of the mountain front, allow us to conclude about Quaternary uplift tendencies of the SMF footwall in the Sowie Mts. segment (cf. Badura *et al.* 2003).

The remaining faults reactivated in the Quaternary are clustered in the Sudetic Block, in the Karkonosze Mts., Izera Mts., Upper Nysa Kłodzka Graben, and in some portions of the Fore-Sudetic Block (Figs. 4, 6).

Kleszczów Graben

The Kleszczów Graben, Central Poland, 80 km long and 2–3 km wide, is situated in the Szczecin-Łódź-Miechów Synclinorium (Figs. 4, 7). This graben belongs to one of the most thoroughly studied Late Cenozoic structures of the Polish Lowlands (cf. Rühle *et al.* 1978, Krzyszkowski 1991, 1992, Hałuszczak 1999, Gotowała, Hałuszczak 2002). The graben is composed of a number of segments whose orientations in the eastern (WNW–ESE) and western (WSW–ENE) parts coincide with those of regional faults (Gotowała 1987, Gotowała, Hałuszczak 2002; see Fig. 7). The 250–600-m-thick Neogene–Quaternary infill is underlain by Jurassic and Cretaceous strata that became folded and faulted during the Early Palaeogene Laramian movements. The central portion of the graben is occupied by the open-cast brown coal mine "Bełchatów".

Within the Kleszczów Graben three structural stages were identified: the Valachian (folded and faulted Miocene strata), Bełchatów (strongly tectonized Pliocene and Lower and Middle Pleistocene strata), and upper (poorly deformed Odranian/Warthe through Holocene sediments) ones (cf. Krzyszkowski 1989, 1991). Differentiated subsidence occurred during the Augustovian Interglacial (Bavelian Complex), South-Polish (Elsterian) glaciations, Mazovian (Holsteinian) Interglacial, and – much more weaker – during the Warthe glacial stage (Krzyszkowski 1991), whereas main episodes of faulting took place at the turn of the Pliocene and Pleistocene, in the Mazovian Interglacial, and during the Warthe stage, in the so-called "Bełchatów phase" (Krzyszkowski 1991, Hałuszczak 1994). The amount of sub-

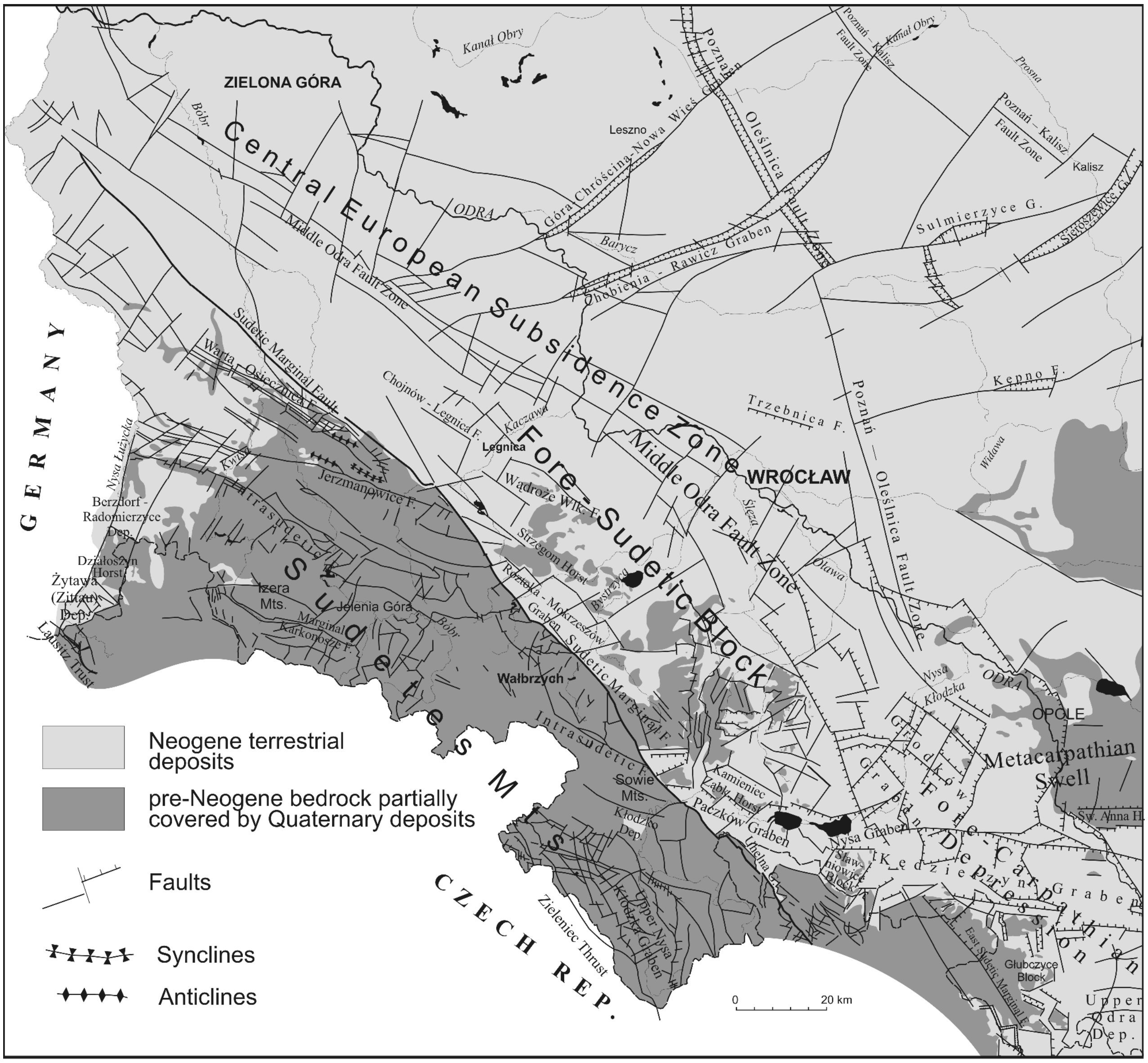


Fig. 6. Neotectonic map of Lower Silesia (based on Badura, Przybylski 2000; simplified), showing faults active in the Neogene and those active/reactivated in Quaternary times, as well as Laramian folds.

sidence between the Odranian (Drenthe) and Warthe stages attained 15–20 m (Brodzikowski 1987).

The Kleszczów Graben originated in Late Oligocene–Early Miocene times due to transtensional reactivation of basement faults, oriented WSW–ENE to NW–SE (Gotowała, Hałuszczak 2002). Later on, a series of WSW-striking pull-apart basins was formed, and in the Late Sarmatian–Early Pannonian, extensional reactivation of NE-orientated normal faults took over. Another episode occurred in the Late Neogene through Mid-Pleistocene, when dextral transpressional motions along reverse NW-striking faults took place (Fig. 7). The beginning of this stage (Late Miocene – South-Polish/Elsterian glaciation) was characterised by tectonic quiescence, while intensive faulting occurred at the end of the South-Polish (Elsterian) glaciation, resulting in the formation of NW-striking faults and folding of Cenozoic strata (see also: Krzyszkowski 1991, 1992, Hałuszczak 1994, Hałuszczak *et al.* 1995). It was probably at that time, when a NW-striking thrust-fault showing top to the NE displacement, in the northern part of the graben, was formed (Hałuszczak *et al.* 1995, Hałuszczak 1999). This episode terminated *ca*. 260 ka, shortly before the Warthe stage. The recent development of the Kleszczów Graben consists in reactivation of some of the pre-existing faults, partly due to mining exploitation, and also owing to present-day seismicity of magnitudes up to 4.6 and epicentres aligned parallel to one of the regional basement faults. Focal mechanisms of these earthquakes indicate oblique-slip kinematics (Gotowała, Hałuszczak 2002).

Lublin Upland

Cenozoic faulting in the Lublin Upland, SE Poland, post-dating Laramian movements, proceeded in the Early or Middle Eocene, Middle and Late Sarmatian, as well as in the Early Quaternary (*e.g*. Henkiel 1983, 1984, Harasimiuk,

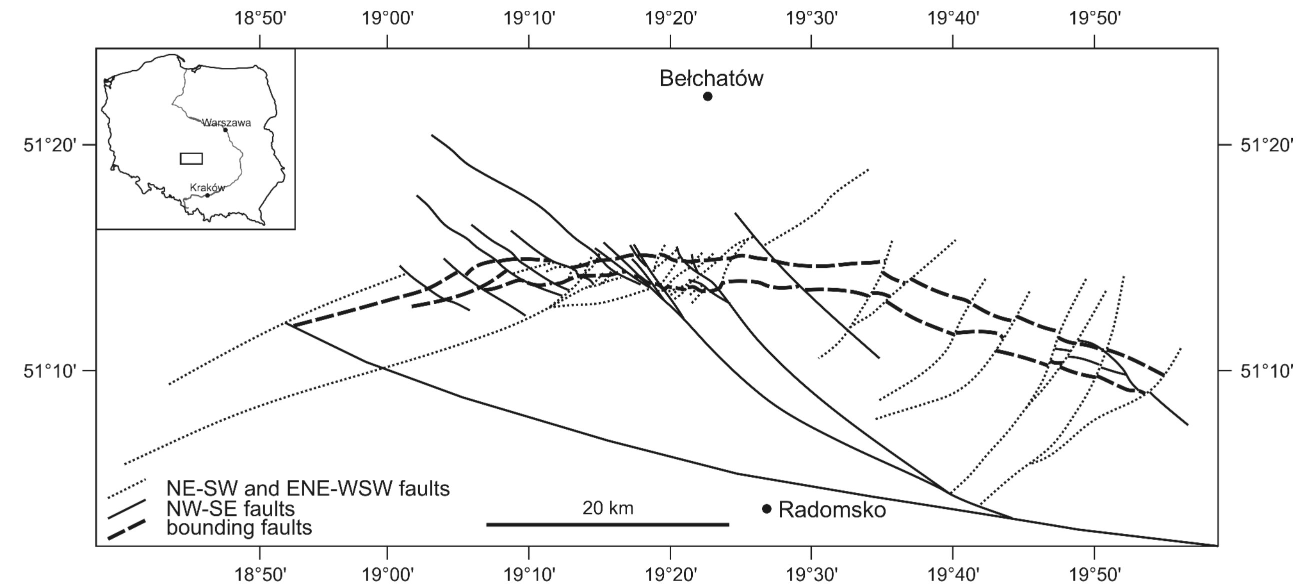


Fig. 7. Faults associated with the Kleszczów Graben (based on Gotowała, Hałuszczak 2002; simplified).

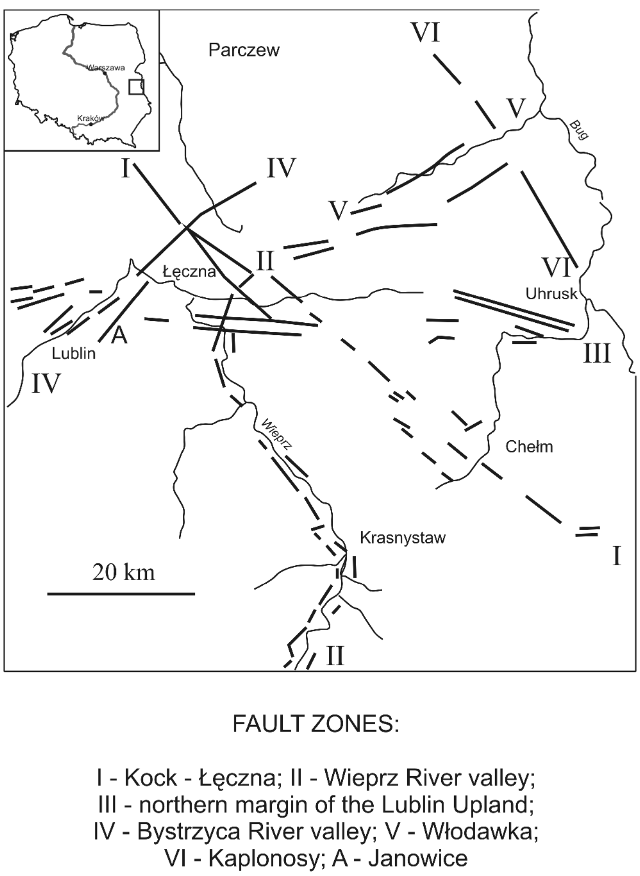


Fig. 8. Young fault zones in the Lublin Upland (based on Henkiel 1983, 1984; modified).

Henkiel 1984, Buraczyński 1997, Brzezińska-Wójcik 2002). The thickness of Quaternary sediments within tectonic grabens is between 50 and 120 m (Henkiel 1984). Another episode of faulting was confined to the Elsterian-2 glacial stage and the Mazovian (Holsteinian) Interglacial, when 20–30 m of subsidence occurred in some of the grabens (Harasimiuk, Henkiel 1981). The Middle and Late Pleistocene faulting was of considerably smaller amplitude.

The principal fault zones in the Lublin Upland include (Fig. 8): the dextral Kock-Łęczna fault (NW–SE); the Wieprz River valley fault zone (N–S), composed of alternating asymmetric grabens and half-grabens reactivated in Early Quaternary times; the Early Quaternary fault zone of the northern margin of the Lublin Upland (E–W), embracing the Mogielnica and Sobianowice grabens filled with more than 70 m thick Quaternary alluvium; the pre-Quaternary Bystrzyca River valley fault zone (NE–SW), composed of normal faults bounding narrow grabens and horsts; the Włodawka River fault zone; as well as the pre-Quaternary Kaplonosy fault (NNW–SSE).

The NW portion of the Lublin Upland bears the Janowice fault (NE–SW), considered by some authors as a Quaternary sinistral fault zone of up to 1 km offset (Henkiel 1983, 1984). The morphotectonic scarp at Dobre (NW–SE), Nałęczów Plateau, was interpreted as a seismotectonic normal fault, associated with a series of superimposed colluvial wedges, probably formed due to repeated palaeoseismic events (Henkiel 1993). The escarpment zone (NW–SE) of the Roztocze region became uplifted by 20–30 m following the South-Polish/Elsterian glaciations (*e.g.* Harasimiuk, Henkiel 1980, Laskowska-Wysoczańska 1984).

Carpathian Foredeep

The substratum of the Carpathian Foredeep between Kraków and Sandomierz, South Poland, is cut by several fault zones (Fig. 9). These include: a system of pre-Laramian, usually NE-trending strike-slip faults of the Kurdwanów-Zawichost zone (cf. Osmólski *et al.* 1978, Krysiak 2000), and a system of normal faults that bound Laramian horsts and grabens, oriented NW–SE. These structures became reactivated in Neogene and, possibly, also Quaternary times, as

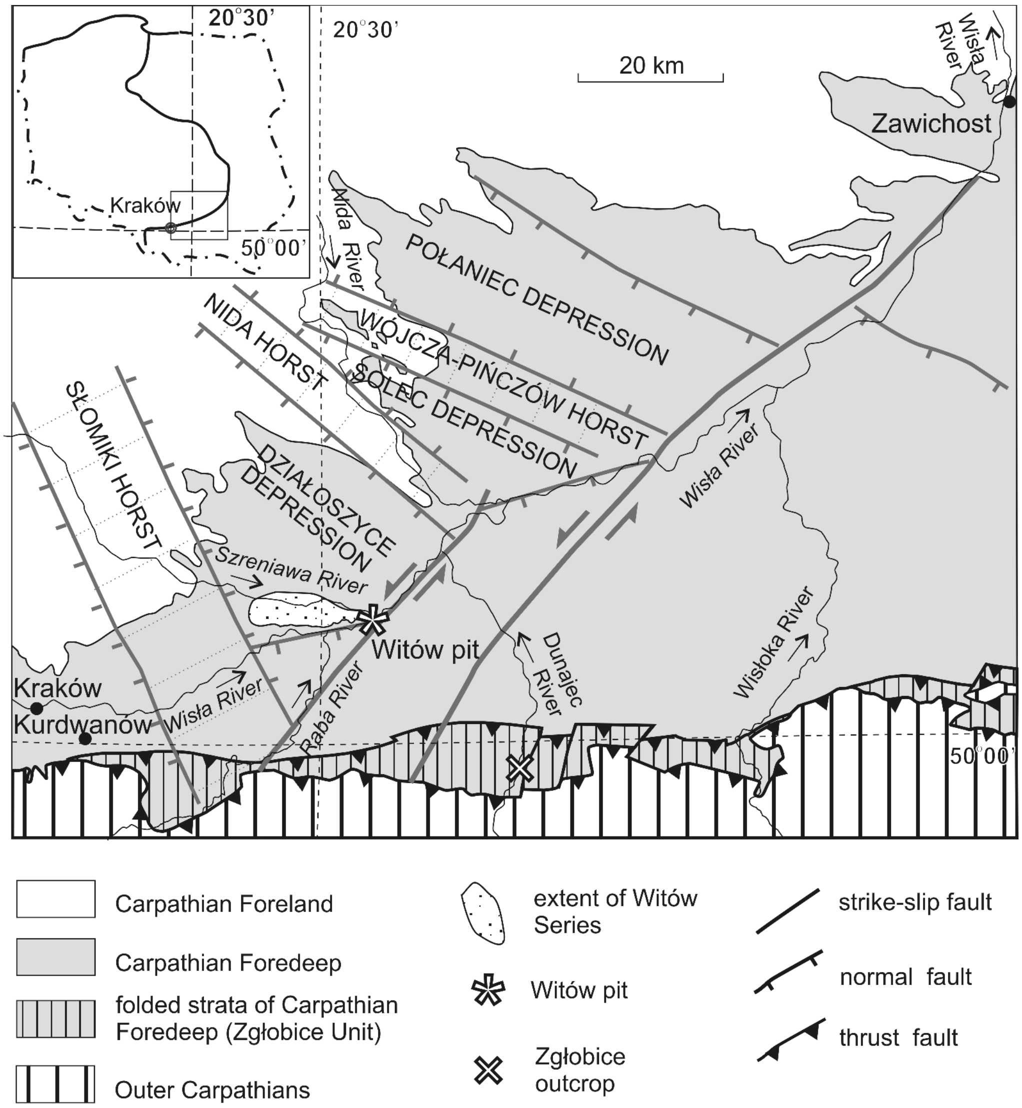


Fig. 9. Fault pattern in the medial Carpathian Foredeep (based on Krysiak 2000 and Rauch *et al.* 2006; modified).

shown by the results of structural studies of the Late Miocene fresh-water molasses of the Witów Series (cf. Brud *et al.* 2003). The molasses are cut by joints, and normal and strike-slip faults which were formed in two successive events: (1) a syn-depositional one, proceeding under NNW–SSE to N–S oriented horizontal compression, possibly coeval with reactivation of a NE-striking sinistral fault of the Kurdwanów-Zawichost Fault Zone in the basement; and (2) a post-depositional one, during N–S to NE–SW-oriented extension. In the first event, reactivation of the NE-striking sinistral fault led to formation of N–S-oriented joints, as well as NW-striking dextral, and NNW-trending normal faults. This event was probably contemporaneous with sinistral reactivation of some thrusts in the Western Outer Carpathians, induced by eastward-directed extrusion of crustal blocks in the Carpathian internides. In the second event, both W–E and NW–SE-oriented joints and WNW-striking normal faults were formed. The latter most probably originated due to reactivation of the Early Paleocene WNW- and NW-striking normal faults in the basement. Similar conclusions result from analyses of small-scale tectonic structures at other localities situated in the medial portion of the Carpathian Foredeep and in marginal slices of the Outer Carpathians (Rauch *et al.* 2006).

In the western part of the Carpathian Foredeep, the pre-Eemian uplift became replaced by subsequent subsidence associated with reactivation of normal faults (Niedziałkowska *et al.* 1985, Niedziałkowska, Szczepanek 1993-94).

Pliocene–Quaternary tectonic tendencies in the Polish segment of the Carpathian orogen are marked in Fig. 10. This area has been dominated in Quaternary times by reactivation of major thrust faults, principally due to NNE-oriented horizontal stresses; minor normal faulting being confined to intramontane basins and some portions of the Carpathian Foredeep (Zuchiewicz *et al.* 2002).

RECENT STRESS FIELD

Recent stress measurements indicate that the Carpathians are being exposed to tectonic push from the hinterland, which generates NNE-oriented compression in the eastern part of the Outer Carpathian fold-and-thrust belt (Jarosiński

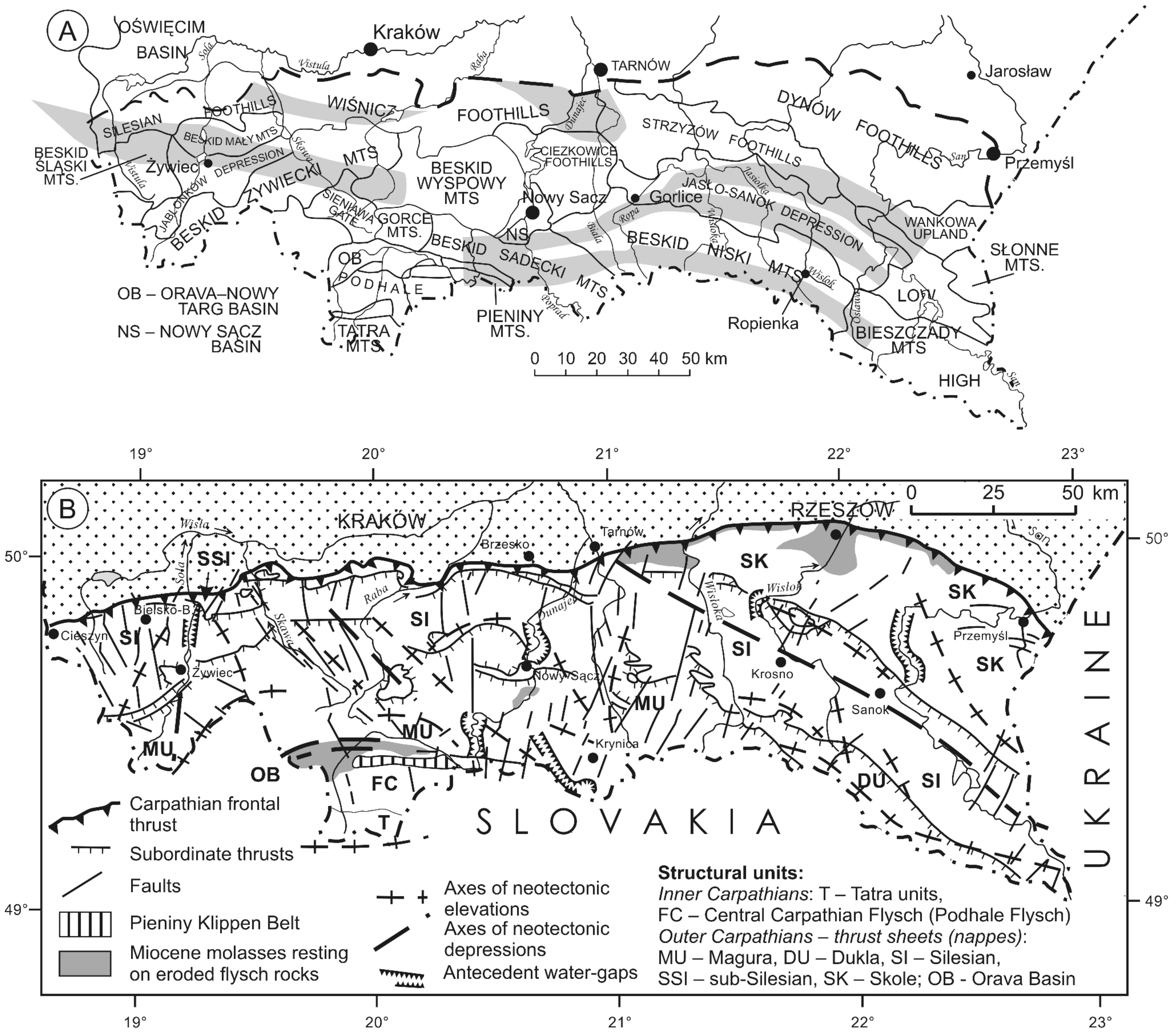


Fig. 10. Neotectonic sketch-map of the Polish Carpathians (based on Zuchiewicz *et al.* 2002): A – physiographic units and distribution of young uplifted zones, B – pattern of neotectonic elevations and depressions.

1999, 2005). This push is transmitted farther to the north along the marginal part of the East-European Platform (Fig. 11). Successive accommodation of this push is evidenced by systematic distortion of tectonic compression from NNE–SSW in the southern segment to NNW–SSE in the Baltic portion of the East-European Platform, where the Carpathian push is balanced with the North Atlantic ridge push. Within the Trans-European Suture Zone, frequent stress rotations between N–S and NW–SE in vertical borehole sections and among boreholes suggest a discrete strike-slip accommodation of the Carpathian push (Jarosiński 2005). A survey of natural and mining-induced tremors provides additional source of information about recent geodynamics (Guterch, Lewandowska-Marciniak 2002). For the inner part of the Outer Carpathians, *i.e.* close to the Pieniny Klippen Belt, either strike-slip or thrust fault stress regime is inferred for the nappes (Wiejacz 1994). The strike-slip stress regime was determined also for singular earthquakes in the Kleszczów Graben (Gotowała, Hałuszczak 2002) and the Kaliningrad district near the Polish border (Wiejacz 2004). Dominance of strike-slip fault stress regime was constrained by hydraulic fracturing tests in boreholes located in SE Poland, while in western Poland extensional stress regime with some amount of strike-slip component prevails (Jarosiński 2005).

FUTURE TASKS

Reliable estimation of geodynamic hazards in Poland will require integration of the existing, usually scattered, geological, geophysical, geomorphological, palaeoseismological, and geodetic data, combined with supplementation and verification of the characteristics of young tectonic structures and processes. Such an approach should enable for the construction of a new model of the neotectonic stress field in this part of Central Europe.

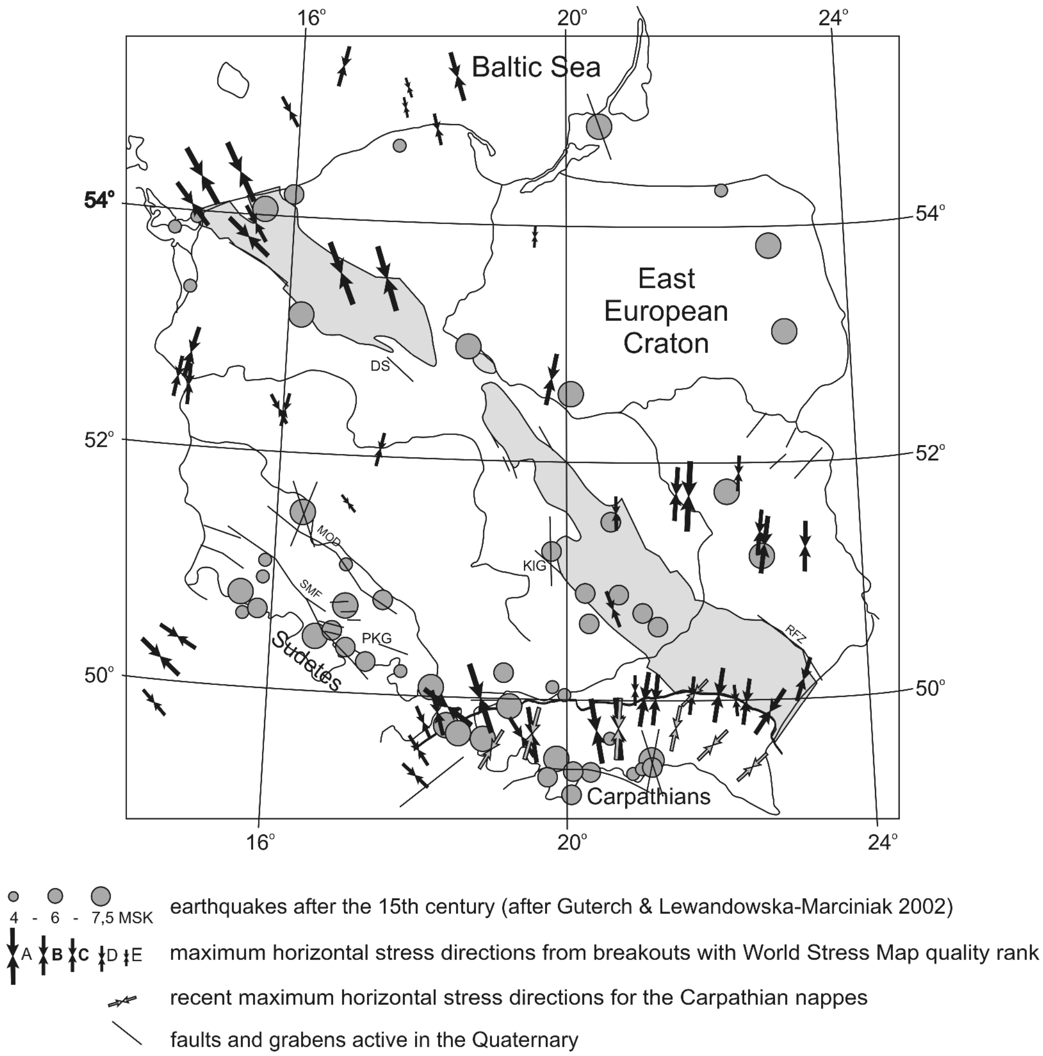


Fig. 11. Recent stress field in Poland (based on Zuchiewicz et al., 2006). Shaded area denotes the Mid-Polish Anticlinorium. Abbreviations: DS – Damasławek structure, KlG – Kleszczów Graben, RFZ – Roztocze marginal fault zone, MOD – Middle Odra Fault Zone, SMF – Sudetic Marginal Fault, PKG – Paczków Graben.

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