Annales Societatis Geologorum Poloniae (2007), vol. 77: 69–92.

GEOLOGY OF KRYNICA SPA, WESTERN OUTER CARPATHIANS, POLAND

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Oszczypko, N. & Zuchiewicz, W., 2007. Geology of Krynica Spa, Western Outer Carpathians, Poland. *Annales Societatis Geologorum Poloniae*, 77: 69–92.

Abstract: Krynica Spa is situated in the southern part of the Magura Nappe, at the boundary between the Bystrica and Krynica subunits. The Bystrica succession is composed of the Middle to Upper Eocene strata of the Magura Formation, while the Krynica succession is built up of the Palaeocene through Middle Eocene strata that belong to the Szczawnica, Zarzecze and Magura formations. The Bystrica and Krynica subunits contact along a sub-vertical, NE-dipping fault. In the study area, several NE-trending transversal faults cut both the Bystrica and Krynica subunits into several blocks. The Krynica area is seismically active, as shown by the most recent, moderate-intensity earthquakes which occurred in 1992–1993, of epicentres situated NE of Krynica Spa. The region is rich in natural mineral water springs which are confined to a tectonic block bounded by the Tylicz and Krynica faults.

Key words: lithostratigraphy, structure, deep basement, mineral waters, Magura Nappe, Outer Carpathians, Poland.

Manuscript received 26 October 2006, accepted 8 March 2007

INTRODUCTION

Krynica Spa is the biggest health-resort in Poland, rich in natural mineral waters of different hydrochemical types. In 1997–1999, this area was a subject of integrated hydrogeological and geological studies conducted in the framework of a project financed by the State Committee for Scientific Research (*Komitet Badań Naukowych*) and National Fund of Environmental Protection and Water Management (*Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej*) (Ciężkowski *et al.*, 1999). Realisation of this project involved, i.a. new geological mapping at the scale of 1:10,000 of the Kryniczanka River drainage basin, ca. 50 sq. km large. The first results of these studies were published by Zuchiewicz (1998b) and Oszczypko *et al.* (1999b).

The aim of this paper is to present final results of our research, including detailed geological maps, geological cross-sections, and interpretation of small-scale tectonic structures, with special emphasis on the geological structure of the Krynica area and its relation to the deep basement of that part of the Polish Western Carpathians.

PREVIOUS WORKS

The history of geological investigations in the Krynica Spa area has been strongly connected with the development of the spa itself. Preliminary geological investigations in this region were carried out by Walter and Dunikowski (1883), Paul (1884), and Uhlig (1888).

In 1896, within the framework of the *Geological Atlas of Galicia* project, the Muszyna sheet (Szajnocha, 1896) was published. Since 1903, geological research in Krynica was carried out by Zuber (1916, 1918), who also initiated drilling of a deep borehole for the prospection of mineral waters. This borehole (now Zuber I) discovered a new, hitherto unknown, type of mineral waters and gave an insight into the deep structure of the region. In the early 1920s, Nowak (1924) prepared the first detailed geological map of Krynica. The map portrayed two tectonic units of different lithostratigraphic successions. The northern unit was named "Parautochtonous", whereas the southern one – "Krynica Thrust Sheet". The boundary between these units was located along the southern slope of the Parkowa Góra Mt. Nowak (1924) also initiated drilling of another deep borehole, i.e. Zuber II.

In 1933–1953, the Krynica area was mapped at the scale of 1: 25,000 by H. Świdziński. His map has served as a basis for prospection and documentation of mineral waters in Krynica Spa for a long time. The results of Świdziński's studies were published in 1939, 1953, and 1954, and became summarized in 1972 in the paper "*Geology and mineral waters of Krynica*". Following Nowak's (1924) ideas, Świdziński (1972) distinguished in the Magura Nappe of the Krynica area two facies-tectonic zones, namely the Nowy Sącz and Krynica ones, and described their stratigraphy and tectonics. He also put forward novel hypotheses on the origin of mineral waters and distribution of CO_2 in this region, and proposed drilling of the following deep boreholes: Zuber III, Zuber IV, B-1, and B-2. Papers by Węcławik (1969a, b) on the geology of Magura Nappe in the Tylicz and Mochnaczka areas were very important for a better understanding of the geology of Krynica region.

New ideas on the relationship between the Krynica and Bystrica zones in the Krynica area were presented by Oszczypko (1979), who, during the following years, published several papers on the stratigraphy of the Bystrica and Krynica zones (cf. Birkenmajer & Oszczypko, 1989; Oszczypko, 1991, Oszczypko *et al.*, 1990, 1999b). These led to a revision of previous views on the stratigraphy of the oldest deposits of the Krynica Zone which became the youngest strata of the Bystrica Zone. These findings had a pronounced influence on tectonic interpretations.

In 1995, the Muszyna sheet of the *Detailed Geological Map of Poland* (1: 50,000) by Chrząstowski *et al.* (1995) was published. In 1997–1999, the area of Krynica Spa was a subject of an integrated hydrogeological and geological study conducted in the framework of the Project KBN/NFOŚGW (Zuchiewicz, 1998b; Ciężkowski *et al.*, 1999; Oszczypko *et al.*, 1999b).

GEOLOGICAL SETTING

Krynica Spa is situated in the southeastern part of the Magura Nappe, at the boundary of the Bystrica and Krynica facies zones (Fig. 1).

Lithostratigraphy

Bystrica Zone

The NE part of the study area belongs to the Bystrica Zone (Fig. 2; see Świdziński, 1972). This region, a few kilometres wide, is composed of several NW–SE trending hills that extend from Szalone (828.8 m a.s.l.), through Huzary (846.4 m a.s.l.), Parkowa (718.8 m a.s.l.), Hawrylakówka (779.6 m a.s.l.), up to Jaworzynka (898.7 m a.s.l.). This belt is built up of the Maszkowice, Mniszek and Poprad members of the Magura Formation.

The *Maszkowice Member* crops out in a few small quarries located on the right bank of the Palenica Stream (Figs 2, 3). The biggest exposures are situated ca. 100 m eastwards of the Tylicz Pass. In this place, thick-bedded (60–120 cm), fine to very coarse-grained, poorly sorted, muscovitic sandstones bearing calcareous-muddy cement are exposed in overturned position. These sandstones, grey-blue in colour, display Bouma's Tabc intervals. The sandstones contain numerous clasts of mudstones, up to 15 cm in diameter, and pass upwards into strongly bioturbated mudstones, rich in the mica flakes and coalified plant debris. The bottom surfaces of sandstones display groves and flute casts indicating palaeocurrent direction towards the NW (N70–60°W). The sandstones are intercalated by soft, dark-grey turbiditic marlstones (5 do 20 cm thick) or sandy/muddy couplets, up to 1 m thick. In an exposure located in the Pułaski Street, the fining and thinning upward sequences with amalgamated sandstones, up to 6 m thick, are visible. Thick to very thick-bedded (50–200 cm), clast-rich granule conglomerates, and amalgamated sandstones occur there. These strata display coarsening and thickening upwards sequences, typical of the channel-lobe turbidite system. The Maszkowice Member contains rare packets, up to few metres thick, of the Łącko-type marls (Świdziński, 1972). These sandstones were pierced down to 406 m by numerous boreholes drilled for mineral waters along the Palenica Stream valley and Pułaski Park (Świdziński, 1972). Unfortunately, the core material was sampled only from the borehole B-2 (Fig. 4), situated on the southern slope of the Parkowa Hill. In this borehole, the top of the Maszkowice Member was reached at a depth of 180 m in an overturned position. Below, down to a final depth of 350 m, thin-bedded flysch strata of the Mniszek Member, formerly described as Beloveža beds (see Świdziński, 1972), have been found. In the Krynica area, the thickness of the Maszkowice Member reaches 700–800 m (Fig. 3; Oszczypko *et al.*, 1990; Oszczypko, 1991; Chrząstowski *et al.*, 1993). This member belongs to the Middle Eocene calcareous nannoplankton zone NP16/17 (see Oszczypko-Clowes, in Oszczypko *et al.*, 1999b).

The *Mniszek Member* is composed of thin-bedded strata bearing intercalations of variegated shales (Oszczypko, 1979; Oszczypko *et al.*, 1990, 1999b), which occur on the southern slope of the Parkowa Hill and were pierced by Zuber's (I–IV) and B-2 boreholes (Figs 2, 4). These beds were originally described by Świdziński (1972) as the Beloveža beds. Superposition of the Mniszek Member over the Maszkowice Member was documented by the position of sole marks, as well as Middle Eocene assemblages bearing *Reticulophragmium amplectens*, found by Prof. S. Geroch in boreholes Zuber III and B-2 (see Świdziński, 1972). The basal portion of the Mniszek Member is composed of two packets of red shales, intercalated by a few metres thick packet of thick-bedded sandstones and conglomerates, pierced by Zuber III borehole at depths of 0 to 132 m (Świdziński, 1972). In this borehole, above the second level of red shales occurring in a stratigraphically higher position, thin-bedded, fine-grained sandstones and dark-grey noncalcareous shales were found. In Zuber III borehole (Fig. 4), at a depth interval of 204.3–234.6 m, another, probably the uppermost intercalation of red shales covered by quartzitic conglomerates and thick-bedded sandstones was drilled. The total thickness of the Mniszek Member in this borehole

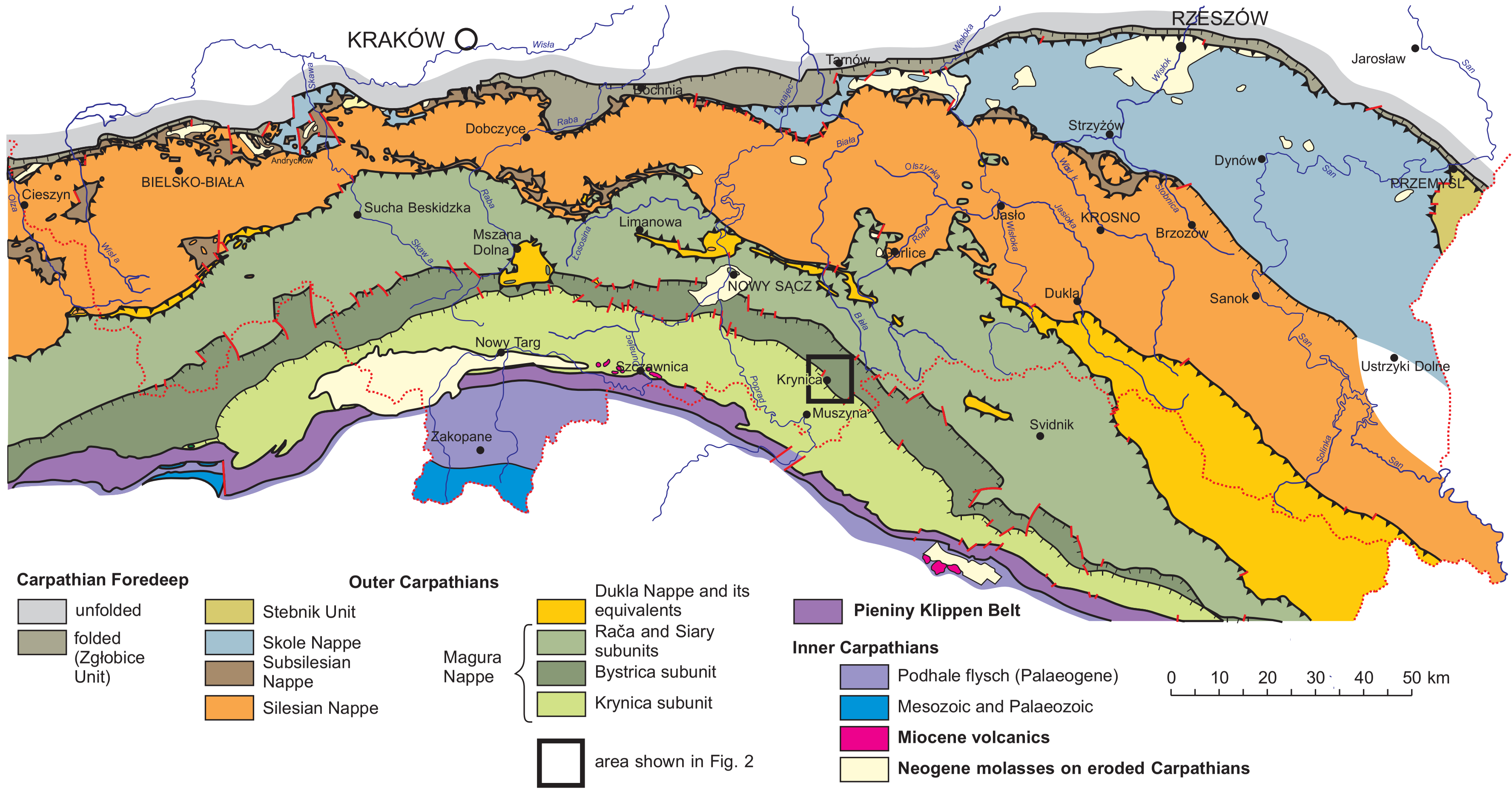

Fig. 1. Geological sketch-map of the Polish Carpathians (based on Żytko *et al.*, 1989; modified)

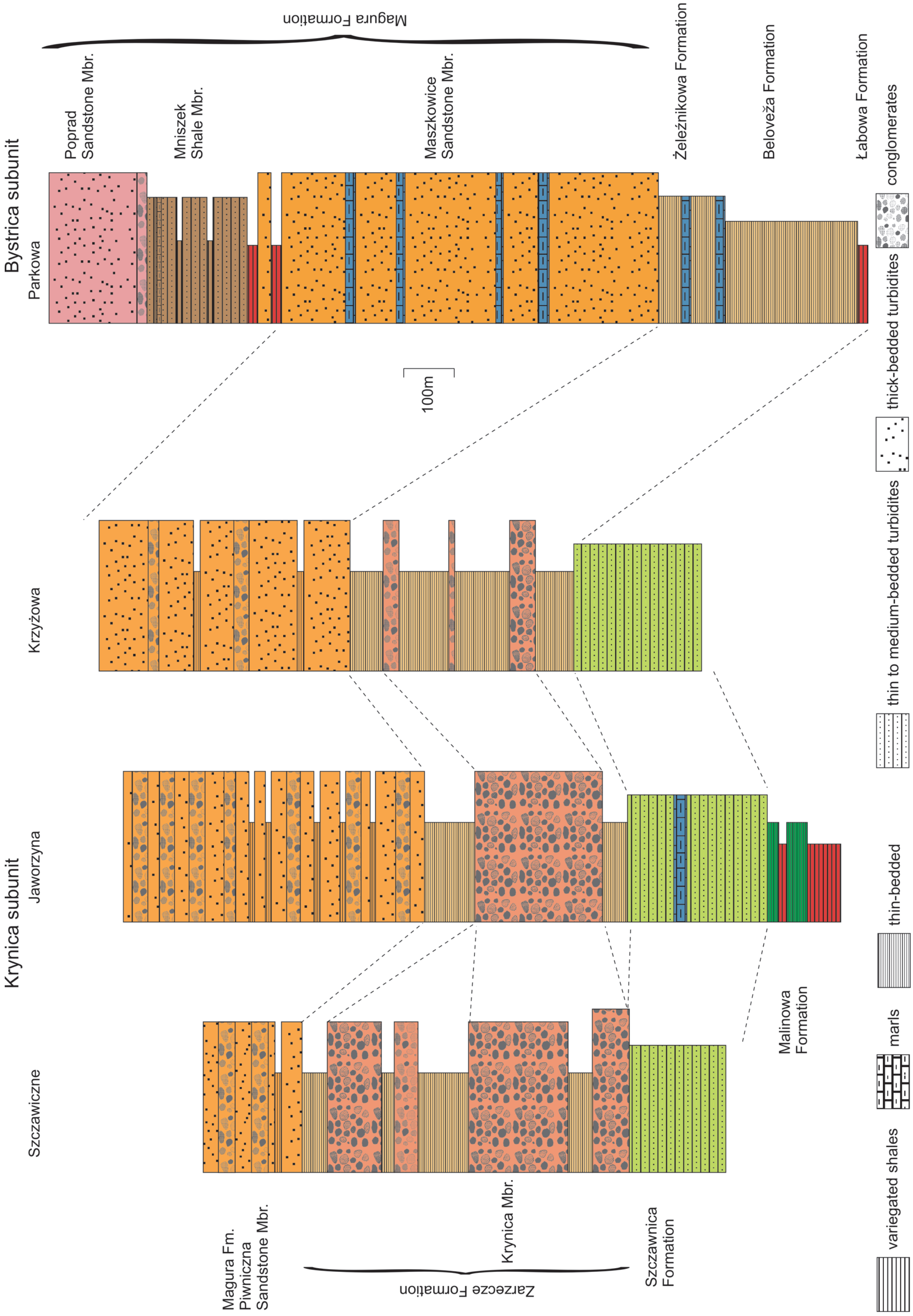

Fig. 3. Lithostratigraphic logs of the Magura Nappe in the Krynica area

is up to 250 m (Fig. 3). Conglomerates were also found (Dulski, 1967) in borehole Zuber IV at depths of 0–280 m (Fig. 4). At the top of these conglomerates, a few metres thick packet of yellow-green mudstones, resembling the Łącko marls, was identified. Thin-bedded turbidites of the Mniszek Member have also been found in B-2 borehole (depth interval 180–350.7 m; see Świdziński, 1972). The Mniszek Member passes progressively, in an overturned position, into the Poprad Member of the Magura Formation. In boreholes: Zuber I (interval 599–720 m), Zuber II (609–727 m), Zuber III (503–762 m), and Zuber IV (200–297 m), thin-bedded turbidites are completely replaced by thick-bedded sandstones (Dulski, 1967; Świdziński, 1972). In the stratigraphically lowermost horizon of the variegated shales in Zuber III and B-2 boreholes, the Middle Eocene agglutinated assemblages with *Reticulophragmium amplectens* (Grzybowski) were found. Similar foraminiferal assemblages were also found in borehole B-2 (Świdziński, 1972) within variegated shales (depth interval 204.3–346.6m) and thin-bedded flysch (at ca. 250 m), as well as in variegated shales in the Pod Skocznią brook (see Malata; in Oszczypko *et al.*, 1999b). Basing on the presence of NP18 calcareous nannoplankton zone in the top part of the Mniszek Member (Oszczypko, 1991; Dudziak, 1991), the age of this member can be considered as not older than the Late Eocene.

Poprad Member. The strata of this member are known only from boreholes. The lowermost portions of all Zuber's boreholes (Zuber I: 720–948.5 m; Z II: 727–789.7 m; Z III: 762–983 m; Z IV: 280–803.2 m; Fig. 4) represent unknown sandstones, which have been named the "Zuber sandstones" (Dulski, 1967; Świdziński, 1972), of minimum thickness 200–250 m. Judging from clast samples derived from boreholes Z III and Z IV (Fig. 2), these are medium to coarse-grained sandstones which bear intercalations of green-brown shales and are rich in coalified flakes. The thickness of shale-mudstone intercalations is up to a few tens of metres. The age of these sandstones was not determined, but taking into account their position over the Mniszek Member, it can be regarded as the Late Eocene. In this case, these sandstones should be correlated with the Poprad Member of the Magura Formation of the Bystrica Subunit (Oszczypko, 1979; 1991; Oszczypko *et al.*, 1990, 1999b; Oszczypko-Clowes, 2001).

Krynica Zone

In the study area, the Krynica Subunit is composed of the Szczawnica, Zarzecze, and Magura formations (Fig. 2). All these lithostratigraphic units were defined by Birkenmajer and Oszczypko (1989).

The base of the *Szczawnica Formation* is exposed in the Jastrzębik and Złockie sections, situated a few kilometres west of Krynica (Oszczypko *et al.*, 1990). In these sections, variegated shales of the Malinowa Shale Formation (Turonian–Campanian) pass upwards into at least 100-m-thick complex of thin-bedded, non calcareous, dark-grey flysch strata bearing sporadic intercalations of reds shales (Fig. 3). The strata resemble the Hałuszowa Formation, and are probably of the Maastrichtian–Early Palaeocene age (see Oszczypko *et al.*, 1990). Thin-to medium bedded calcareous flysch of the Szczawnica Formation, at least 300 m thick (Fig. 3), occurs higher up in the section. In the Krynica area, this formation was first described by Oszczypko *et al.* (1999b). These deposits are exposed in the middle segment of the Czarny Potok Stream, close to the lower ski station "Jaworzyna", in the SW part of Słotwina village, as well as in the middle reach of the Szczawiczne and Źródlany streams. In older publications, these strata were assigned to either the lower Hieroglyphic beds (Nowak, 1924), Beloveža beds (Świdziński, 1972), or Zarzecze beds (Chrząstowski *et al.*, 1993). The best exposures of the Szczawnica Formation are situated in the middle reach of the Szczawiczne Stream (Fig. 2). This section displays thin (5–7 cm) to medium-bedded (25–30 cm), fine to medium-grained, calcareous, grey-bluish sandstones with parallel and ripple cross lamination (Tbc, and sometimes Tbcd Bouma's intervals). Thick-bedded, coarse-grained (Tabc) sandstones are observed in places. In the Czarny Potok and Szczawiczne Stream sections, the uppermost part of the Szczawnica Formation is represented by very thin-bedded (2–5 cm), fine-grained sandstones (Tcd), intercalated with bluish, poorly calcareous shales. In the Czarny Potok Stream, 50 m NW of the lower ski station, a packet of dark, 1 m thick soft marls was identified (Oszczypko *et al.*, 1999b). The boundary between the Szczawnica and Zarzecze formations is not characteristic, and can be located roughly at the base of the first packet of the Krynica conglomerates (e.g., Szczawiczne section) or at the boundary between the Szczawnica and Zarzecze lithofacies (Czarny Potok Stream). The Szczawnica Formation is relatively strongly tectonized, and bears frequent calcite veins. According to foraminifera and calcareous nannoplankton determinations, the age of the Szczawnica Formation was estimated as the Late Palaeocene–Early Eocene (Oszczypko *et al.*, 1999b).

The Szczawnica Formation is succeeded by the *Zarzecze Formation*, composed of thin-bedded turbidites. The total thickness of the formation is 400–650 m. Fine to medium-grained, calcareous sandstones display Tbc, and rarely Tbc+conv Bouma's intervals. The formation consists of thin-bedded, bluish-grey calcareous sandstones, alternating with dark-grey mudstones and marly claystones. Claystones are green when weathered, whereas sandstones tend to obtain rusty colour. The sandstone soles show currents marks, which indicate palaeotransport towards the NW. Trace fossil assemblages bearing *Paleodictyon* have been observed in this formation (Nowak, 1924; Oszczypko *et al.*, 1999b). The Zarzecze flysch strata contain one to few metres thick packets of thick-bedded sandstones, pebbly sandstones, and gravelstones belonging to the *Krynica Sandstone Member*, the thickness of which ranges from 10 to 250 m (Figs 2, 3). Sporadically, there also occur thick beds of pebbly mudstones with exotic material, which is dominated by milky quartz, accompanied by metamorphic, plutonic and volcanic rocks, and rare pebbles of Mesozoic carbonates (Oszczypko, 1975; Oszczypko *et al.*, 2004). The exotic conglomerates build up the Koci Zamek Hill in Słotwina.

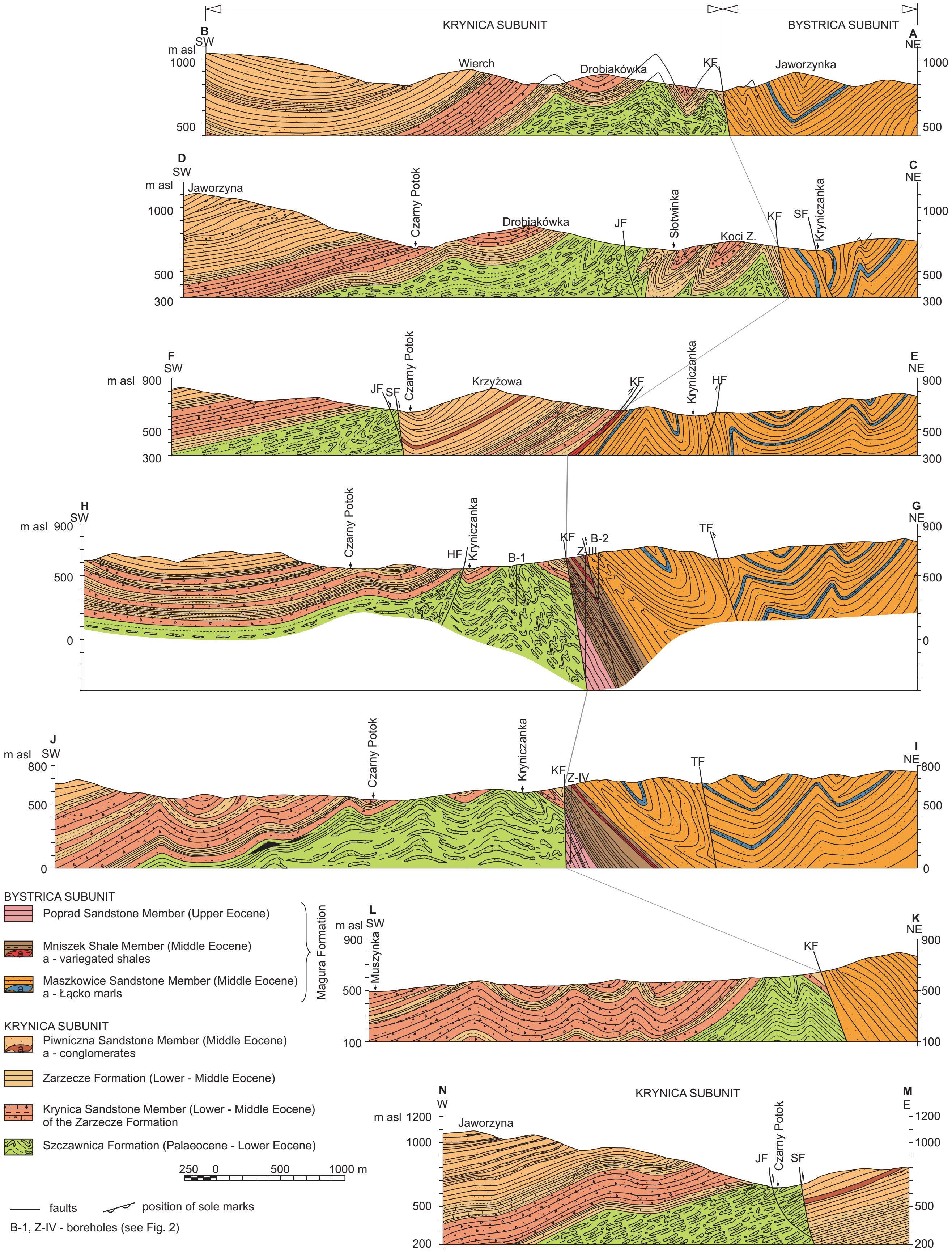

Fig. 4. Geological cross-sections

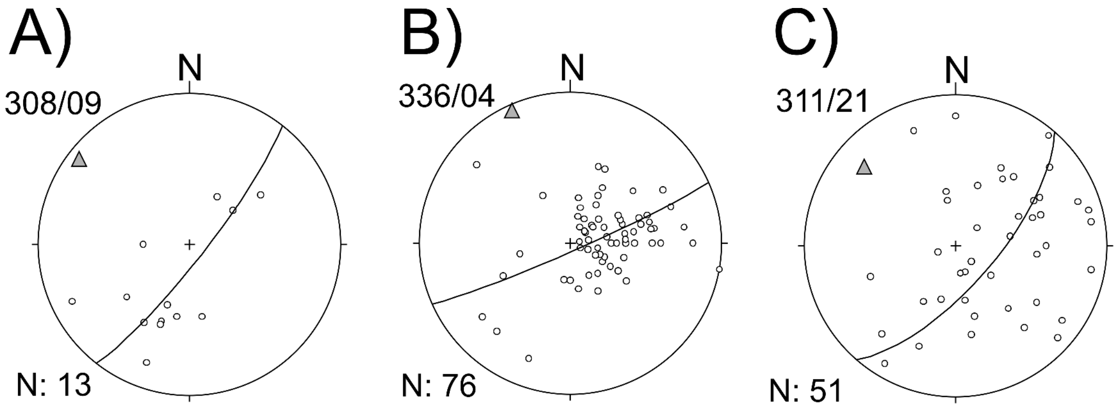

Fig. 5. Bedding attitude in the Krynica area. π-diagrams and orientation of map-scale folds in: **A** – Bystrica subunit (NW part of the Kryniczanka drainage basin); Krynica subunit: **B** – NW part of the Kryniczanka drainage basin, **C** – SE part of the Kryniczanka drainage basin. Lower hemisphere plot

The Krynica sandstones and conglomerates, 250 m thick, were identified on the slope of the Jaworzyna Krynicka Mountain (Fig. 2). In the Szczawiczne Stream, the Krynica Sandstone Member revealed palaeotransport towards the NE. This lithophacies displays features of channel deposits. Calcareous nanoplankton determinations suggest an Early to Middle Eocene age (Oszczypko-Clowes; in Oszczypko *et al.*, 1999b).

In the study area, the youngest deposits of the Krynica subunit belong to the *Piwniczna Sandstone Member* of the *Magura Formation*. These strata build the Góra Krzyżowa, Jaworzyna Krynicka, and Krynica Wieś synclines. These are thick-bedded, medium to coarse-grained muscovitic sandstones which bear intercalations of thin-bedded sandstones and non-calcareous siltstones. The thickness of these intercalations ranges from a few decimetres to a few metres. Thick-bedded, poorly sorted sandstones are composed of quartz, feldspars, muscovite, and lithoclasts of metamorphic, plutonic, volcanic, and sedimentary rocks. The sandstone cement varies from calcareus to argillaceous. These sandstones are harder than those of the Krynica Sandstone Member. This member contains sometimes packets of fine conglomerates and pebble sandstones. The thickness of the member attains 500 m and 600 m, in the Góra Krzyżowa and Jaworzyna Krynicka synclines, respectively (Fig. 3).

In the Żegiestów area, the Piwniczna Sandstone Member is covered by variegated shales of the *Mniszek Member* (Oszczypko *et al.*, 1990; Chrząstowski *et al.*, 1993). The Piwniczna Sandstone Member is mainly of the Middle Eocene age (Bromowicz & Uchman, 1992, Oszczypko-Clowes, 2001). In the Milik quarry, in the uppermost part of this member, calcareous nannoplankton belonging to NP18 Zone (early part of the Late Eocene) has been found (Dudziak; in Oszczypko *et al.*, 1990).

Structure

Since the pioneer geological study of Nowak (1924), the Krynica area has been assigned to the Bystrica and Krynica tectonic subunits of the Magura Nappe. These subunits coincide, to a large extent, with the corresponding facies zones established by Świdziński (1972) as the Sącz (Bystrica) and Krynica zones (see Oszczypko, 1979; Birkenmajer & Oszczypko, 1989).

Krynica subunit. This subunit is characterised by the presence of NW–SE trending narrow anticlines and broad synclines, built up of the Piwniczna Sandstone Member. The cores of anticlines are usually composed of the Zarzecze Formation, while the Szczawnica Formation occurs only in marginal, more elevated folds. Compared to the Zarzecze Formation, the Szczawnica Fm. is strongly deformed, and reveals numerous shear zones, boudinage, and joints, the latter being filled with calcite veins up to ten centimetres thick. To the east of the Kryniczanka Stream, the Krynica subunit is composed of several narrow anticlines, built up of the Zarzecze Formation, and flat synclines that are filled with the Krynica Sandstone Member (Figs 2, 4). Two broad synclines of Krzyżowa-Palenica and Jaworzyna Krynicka-Przysłop, filled with thick-bedded sandstones of the Piwniczna Sandstone Member, occur to the west of the Kryniczanka Stream. These synclines display well developed northern limbs, composed of thin-bedded flysch of the Zarzecze Formation, and reduced southern limbs. Axes of map-scale folds plunge gently (at 4°) towards N24°W in the NW part, and at 21° towards N49°W in the SE part of the area (Fig. 5B, C).

The *Bystrica subunit* occurs in the northern part of the study area and is represented by a broad, sometimes secondary folded synclinal zone, called the Szalone-Huzary-Hawrylakówka-Jaworzynka syncline (Fig. 2). This zone is characterised by north-deeping axial surface (Figs 2, 4; cf. Nowak, 1924; Świdziński, 1972). Sub-vertical thrust sheets are common in the Bystrica subunit. Both the northern limbs of anticlines and southern limbs of synclines are tectonically reduced and usually overturned. Axes of map-scale folds plunge here at 9° towards N52°W (Fig. 5A).

The relationship between the Krynica and Bystrica subunits in the Krynica area drew attention of numerous geologists for a long time. Following Nowak's (1924) interpretation, the Krynica thrust sheet (Krynica "Skiba") was thrust onto the northern "Parautochtonous" unit, and then refolded. According to Świdziński (1972), the studied subunits are bounded by a steep, north-deeping fault, called the Krynica Fault (KF). Both Nowak (1924) and Świdziński (1972) regarded variegated shales occurring on the southern slope of the Góra Parkowa Hill as the oldest strata of the Krynica succession. Subsequent studies by Oszczypko (1979, 1991) and Oszczypko *et al.* (1999b) documented that the variegated shales (Mniszek Shale Member) belong to the Bystrica succession and are younger than the Maszkowice Sandstone Member of the Magura Formation. As a result of this interpretation, the Krynica Fault (KF) became placed between the Mniszek Shale Member of the Bystrica subunit and Szczawnica or Zarzecze formations of the Krynica subunit (Figs 2, 4). This is an inverse, subvertical fault that strikes immediately north of the Zuber's boreholes line. Another inverse fault, parallel to the previous one, was documented in borehole B-2 (Fig. 4; cf. Świdziński, 1972). The Tylicz Fault (TF, see Świdziński, 1972) is probably of the same origin, although its possible normal character requires consideration (cf. Fistek & Węcławik, 1990). Our investigations enabled a precise location of the NE–SW trending Słotwina Fault (SF), described by Świdziński (1972) (Figs 2, 4). In Słotwina area, this fault replaces the contact of the Bystrica and Krynica subunits. Towards the south, the fault separates synclinal blocks of Jaworzyna Krynicka, and Góra Krzyżowa and Krynica Wieś. Between the Słotwina and Czarny Potok Stream, another fault (Jaworzynka Fault – JF) was mapped. This fault joins the Słotwina Fault (SF) in the Czarny Potok Stream (Fig. 2). Two other oblique-slip faults, paralell to the Słotwina Fault (SF), were recognised in the SE part of the studied area. The more western Góra Parkowa Fault (GPF) is situated between Zuber III and Zuber IV boreholes (cf. Świdziński, 1972), while the Powroźnik Fault (PF) is located a few hundred metres SE of the GPF. It seems likely, therefore, that the study area includes graben and half-graben structures. During this study, the Drobiakówka Fault (DF) was identified in the upper reach of the Czarny Potok Stream. This is a normal fault which divides the Jaworzyna and Przysłop blocks. A minor, NNE–SSW trending, fault was documented in an excavation for the ski path in the Czarny Potok Stream valley (Oszczypko *et al.*, 1999b), whereas the NW–SE trending Hawrylakówka Fault (HF) was recognised in the NE part of the studied area.

Small-scale tectonic structures

Small-scale tectonic structures, particularly joints, were studied at 11 stations (Fig. 6) situated within the Krynica (6 stations) and Bystrica (5 stations) subunits of the Magura Nappe. Their choice was mainly controlled by the quality of available exposures. The Krynica subunit is represented by stations located upon exposures of thick-bedded sandstones of the Krynica Member (Zarzecze Fm.) of Early through Middle Eocene age (5) and the Piwniczna Sandstone Member (Magura Fm.) of Early Eocene age (1). In the Bystrica subunit, in turn, only exposures of thick-bedded Maszkowice Member (Magura Fm.) of Middle Eocene age have been taken into account (5 stations).

The results were presented on lower hemisphere stereographic plots and rose-diagrams drawn using the STEREO computer programme, and later rotated into horizontal position of the host strata. The resulting picture displays two to three sets of kathetal transversal joints, and one to two kathetal longitudinal joints, in respect to the strike of map-scale folds.

The cross-fold joints include two sets of diagonal (D_1 and D_2) joints and a single set of cross-fold joints (T), whose orientation is parallel to the acute bisector between the diagonal joint sets. The diagonal joints are characterised by smooth and flat surfaces, their intersection with bedding surfaces is rectilinear; they also frequently pass into Riedel-type fractures that show a tendency to dextral (D_1) and sinistral (D_2) displacement, respectively. Some of these joints pass into en echelon orientated fractures that are filled with either calcite or dismembered host rock material, and whose acute bisector is perpendicular to the strike of map-scale folds. The D_1 joints abut against the D_2 joint surfaces, and vice versa. The two sets intersect one another at 45–80° (mainly 60–70°) in the Krynica subunit, and 45–80° (mainly 50–60°) in the Bystrica subunit. The lowest figures are to be observed at stations WOJ and PIS (45°); the highest ones – at ZAD, WO1, and PAT (80°; cf. Fig. 6). Orientation of the D_1 set in the Krynica subunit changes from N85°E to N5°W (at station WOJ being N50°E), whereas in the Bystrica subunit these figures are between N15°W to N5°E, except for station ZEB (N45°E). Analogous values for the D_2 set are: N35°W to N75°E (station WOJ – N95°E) in the Krynica subunit, and N55–95°E in the Bystrica subunit. Joints of the T set display uneven, rough, undulated surfaces, and the traces of their intersection with bedding surfaces are usually curvilinear. These joints are frequently lined with thin calcite veins. Their orientation is subparallel to that of the acute bisector between the D_1 and D_2 joints, being aligned: N55°W to N35°E (at station WOJ – N75°E) in the Krynica subunit, and N5°W to N45°E (at station ZEB – N75°E) in the Bystrica subunit. The latter set does not occur at DKM (Piwniczna Sandstone Member), and at station PIS (Maszkowice Member) it is the only representative of the transversal joints.

Longitudinal joints are roughly parallel (L) or subparallel (20–30°; L') to the axes of map-scale folds. At some stations, only L sets have been encountered (CAP, ZAD, WO1, PIS), or longitudinal joints do not occur at all (WOJ). These are mostly non-systematic joints of insignificant lateral continuity, and abutting at the transversal joint surfaces. Calcite mineralisation is a rare feature. Orientation of the joints in question changes from N75°E to N35°W (at station CAP – N10°E) in the Krynica subunit, and from N85°E to N15°W in the Bystrica subunit.

Discussion

Morphological properties and cross-cutting relationships indicate that the diagonal (D_1 and D_2) joints are coeval and represent a conjugate system of shear or (station

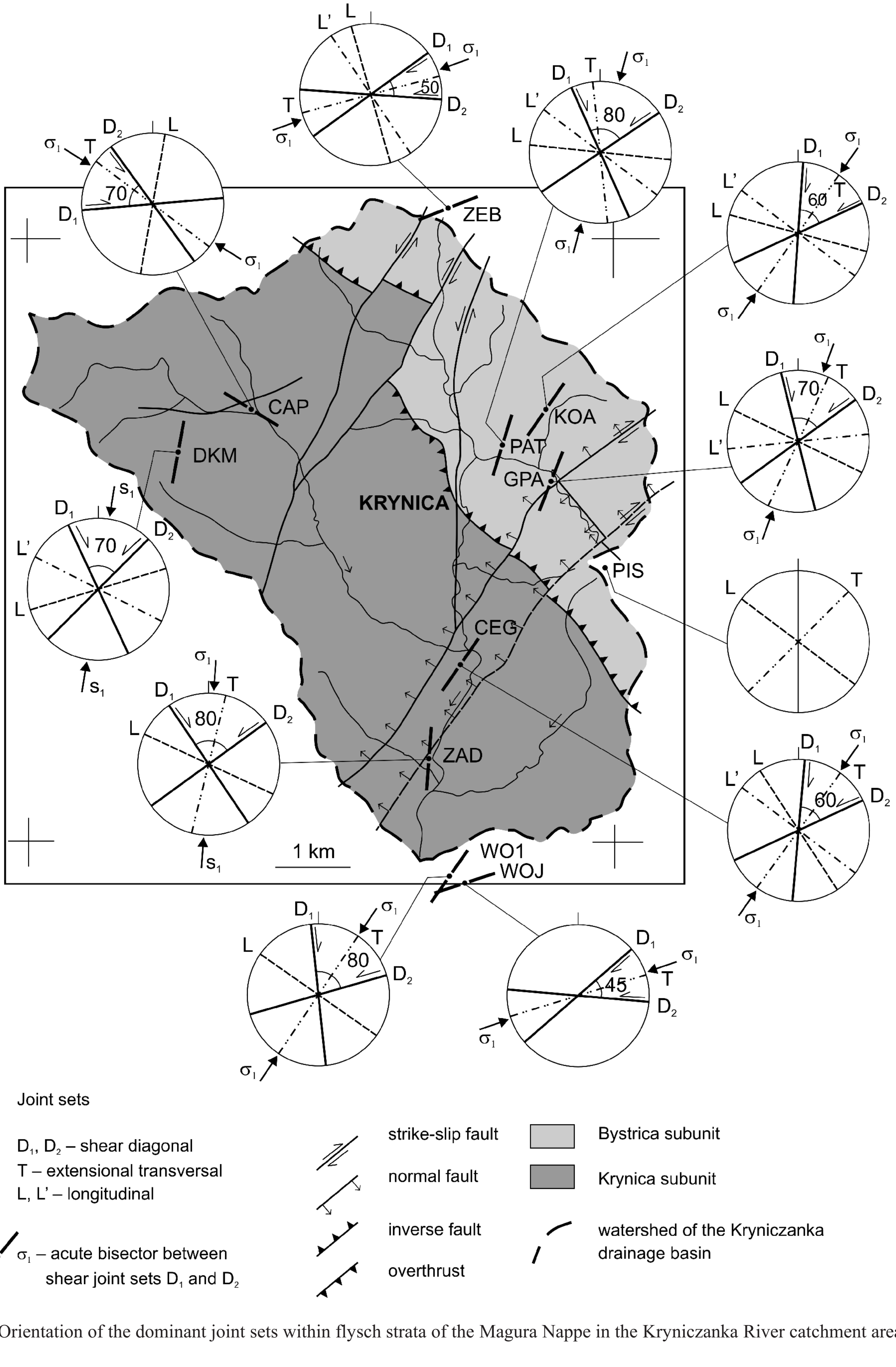

Fig. 6. Orientation of the dominant joint sets within flysch strata of the Magura Nappe in the Kryniczanka River catchment area

WOJ) hybrid joints that originated relatively early, before complete induration of primarily horizontal host strata, i.e., during the incipient stage of map-scale folding. Stations ZAD, WO1, and PAT, however, raise some doubts, since the above joint sets intersect one another at 80°. Dominant orientations of the D_1 and D_2 sets in the study area are widely scattered and different from average values recorded in the middle and eastern portions of the Magura Nappe (i.e., N20°W and N40°E, respectively). The acute bisector between two sets of shear joints (D), parallel to the maximum stress axis σ_1, was horizontal at the time of joint formation, being indicative of strike-slip motions (cf. Mastella *et al.*, 1997; Świerczewska & Tokarski, 1998; and references therein). Orientation of σ_1 in the Krynica subunit falls into the N10–35°E interval, except at stations CAP and WOJ. A similar situation is to be noted in the Bystrica subunit (N5°W to N35°E), except for station ZEB. All the above stations, like ZAD (Fig. 6), are situated close to the fault zones whose mobility could have led to re-orientation of the primary position of the map-scale folds. Dominant orientation of σ_1 for shear joints within Tertiary strata of the middle and eastern portions of the Magura Nappe is N10°E and N20°E, respectively (Zuchiewicz, 1998a).

Morphological properties of the T joints point to their extensional origin, whereas their perpendicular arrangement versus the axes of map-scale folds, like that of the acute bisector between the two sets of diagonal (D) joints, indicates that all these joint sets are roughly coeval. On the other hand, the longitudinal (L) joints appear to postdate transversal joints and their origin has probably been associated with extension induced by undulation of the map-scale folds. These joints (L) maintain more or less stable orientation as opposed to that of both the transversal and diagonal joints. This orientation is compatible with that shown by the L joints in the eastern portion of the Magura Nappe (cf. also Oszczypko & Zuchiewicz, 2000).

STRUCTURAL EVOLUTION OF THE SOUTHERN PORTION OF THE MAGURA NAPPE

The Krynica area, as a part of the Outer Carpathian orogenic belt, has undergone a very complex geological history. The Outer Carpathian basins developed between the colliding European continent and intra-oceanic arcs of the northern periphery of the Tehtys Ocean. Throughout the pre-orogenic and syn-orogenic evolution of the Outer Carpathian basins, the following prominent periods can be established: Middle Jurassic–Early Cretaceous basin opening and post-rift subsidence, Late Cretaceous–Palaeocene inversion, Palaeocene through Middle Eocene subsidence, and Late Eocene–Early Miocene synorogenic closing of the basins (Oszczypko, 2004). The important driving forces of the tectonic subsidence were syn-and post-rift thermal processes, as well as the emplacement of nappe loads related to the subduction processes. Like other orogenic belts, the Outer Carpathians were progressively folded towards the continental margin. This process was initiated at the end of the Palaeocene at the Pieniny Klippen Belt/Magura Basin boundary and completed during the Early Burdigalian.

The following palaeotectonic scenario can be proposed for the southern part of the Magura Nappe, wherein Krynica Spa is located:

1) In the Late Eocene (before deposition of the Malcov Formation), the Krynica subunit became apparently overthrust upon the Bystrica (Nowy Sącz) subunit.

2) During the Middle Burdigalian (Eggenburgian), the Magura basin fill was folded and formed the Magura Nappe (Oszczypko, 1997; Oszczypko *et al.*, 1999a).

3) The Krynica Fault (KF), presently observed at the boundary between the Krynica and Bystrica (Nowy Sącz) subunits, originated during the subsequent Late Burdigalian folding of the Outer Carpathians (Oszczypko, 1997).

4) The Mid-Badenian faulting, preceding deposition of Miocene strata within the Nowy Sącz Basin (Oszczypko *et al.*, 1992), resulted in formation of extensional, NE-striking faults.

DEEP BASEMENT STRUCTURE OF KRYNICA AREA

Krynica Spa is situated in the southern part of the Magura Nappe (Fig. 7), at the contact between the Bystrica and Krynica subunits, some 20 km north of the Pieniny Klippen Belt. The Magura Nappe, which is the largest and innermost nappe of the Outer Carpathians, represents an Oligocene–Early Miocene accretionary prism that is flatly thrust over the Early-Middle Miocene accretionary prism of the Moldavides (Oszczypko, 1997, 1998). The basal thrust of this nappe near Krynica is probably situated at a depth of ca. 5 km b.s.l. (Oszczypko & Zuber, 2002). The Moldavidic accretionary prism includes structural units of the Fore-Magura group (Grybów, Dukla, and Fore-Magura units), as well as the Silesian, Subsilesian, Skole (Fig. 1) and, in Ukraine, Borislav-Pokuttya nappes. The Outer (flysch) Carpathians are thrust upon Lower and Middle Miocene strata of the Carpathian Foredeep. In front of the Carpathian frontal thrust, a narrow zone of folded Miocene strata occurs (Stebnik and Zgłobice units) which is thrust over autochthonous Miocene deposits of the foredeep. The basal Carpathian thrust has been well recognised by numerous deep boreholes in a belt ca. 20–30 km wide. Between the Dunajec and Biała Dunajcowa rivers, this surface is fairly regular and gently south-dipping. Extrapolation of this surface farther southwards (Oszczypko & Tomaś, 1985; Żytko *et al.*, 1989) allows one to suppose that near Krynica Spa it occurs at a depth of ca. 8 km b.s.l.

Rocks of the Epivariscan Platform and its Permo-Mesozoic cover build up the basement of the Carpathian Foredeep and the Polish segment of the Outer Carpathians (Oszczypko, 1997, 1998). The basement structure was formed during a Late Alpine continental collision. Numerous boreholes drilled in the marginal part of the Carpathians pierced through autochthonous Miocene strata of the Carpathian

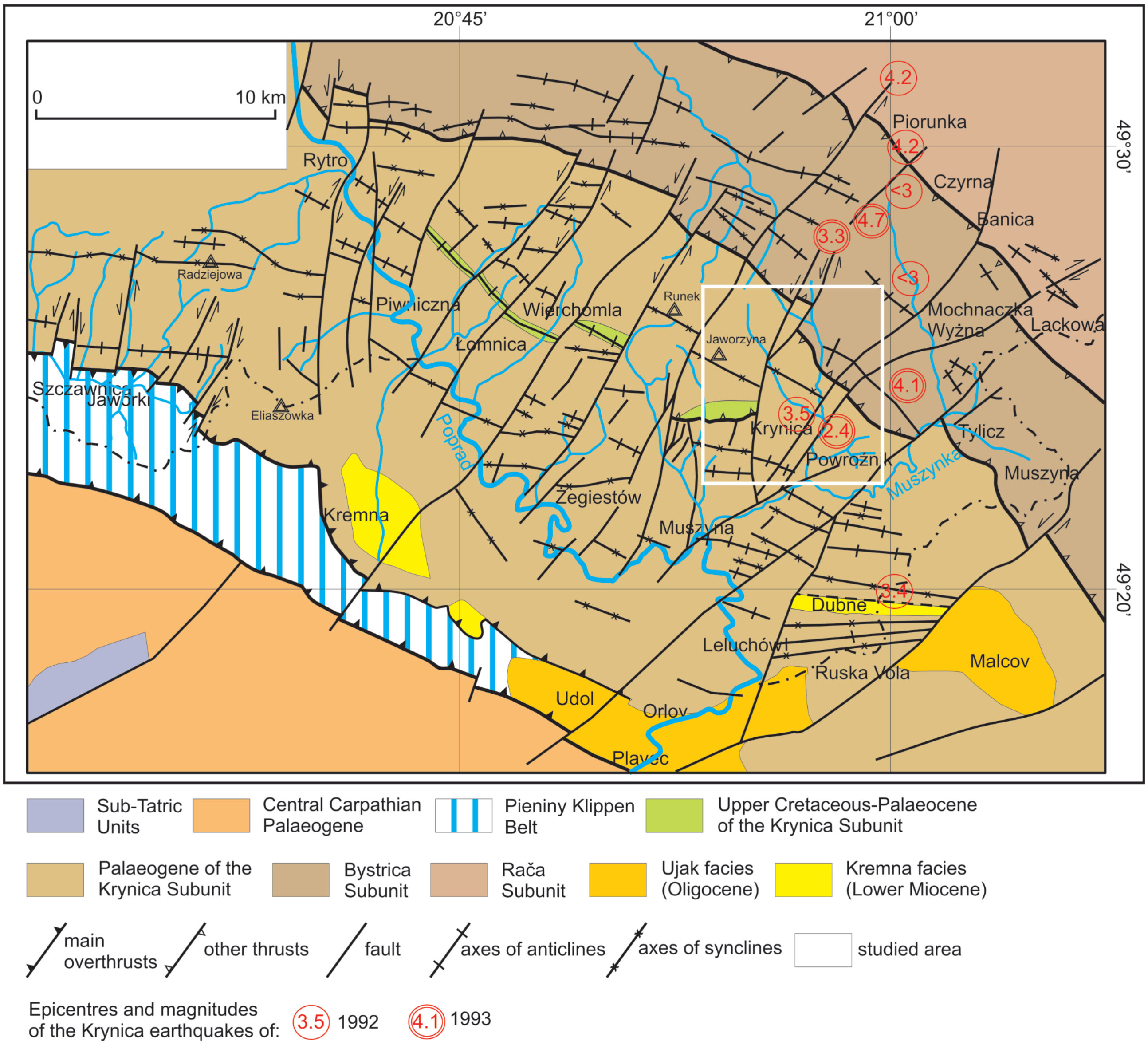

Fig. 7. Tectonic sketch map of the SE part of the Beskid Sądecki Range and NW part of the Lubovnianska Pohorkatina Range (based on sheets of the Detailed Geological Map of Poland, 1: 50,000; as well as Nemčok, 1990 and Oszczypko *et al.*, 2005)

Foredeep, occurring below the Carpathian overthrust. These strata are from a few hundred to 2,000 m thick. Few boreholes, however, found no Miocene deposits at all. As far as the drilled portion of the Carpathians is concerned, the depth to the platform basement is between a few hundred metres to more than 7 km (cf. Kuźmina 1 borehole; Oszczypko, 1997, 1998). Magnetotelluric soundings conducted in the Outer Carpathians revealed a high-resistivity horizon which is correlated with the top of the crystalline basement (Ryłko & Tomaś, 1995; Żytko, 1997). Depths to the magnetotelluric basement range from 3–5 km in marginal parts of the Outer Carpathians, through 15–20 km within basement depression, to 8–12 km in the elevated southern zone. The axis of magnetotelluric depression is situated immediately north of Krynica Spa at depths between 15 and 20 km, while farther south, near Muszyna, it rises to a depth of 10–12 km (cf. Ryłko & Tomaś, 1995; Żytko, 1997; Oszczypko & Zuber, 2002). This axis is roughly coincident with the trace of the regional gravity low. Geomagnetic soundings have indicated that the Krynica area is also crossed by the line of zero values of Wiese vectors, which is apparently associated with a low-resistivity medium of high electric conductivity, overlying the high-resistivity horizon. The low-resistivity horizon (3–7 Ωm) near Krynica is 1.5–2.0 km thick (Żytko, 1997). According to numerous authors, this line marks a suture at the boundary between ALCAPA and North-European Plate (see, for instance: Żytko, 1997; Šefara *et al.*, 1998). This hypothesis has been confirmed by seismic soundings conducted in Western Slovakia. The origin of low-resistivity medium in the Carpathian basement is not fully understood. Some authors underline the role played by ultramylonitisation and graphitisation processes (Żytko, 1997), while others point to importance of highly mineralised solutions produced during dehydration of clayey rocks (Chen & Chen, 1998) and/or bituminous shales (Šefara *et al.*, 1998). All these factors lead to a decrease of the coefficient of friction, and to formation of crustal instabilities or discontinuities that are favourable to seismic activity. The crustal thickness near Krynica is about 35 km (Šefara *et al.*, 1998).

HEAT FLOW

The Polish segment of the Western Carpathians displays a poorly differentiated geothermal field and generally low values of surficial heat flow. A heat flow map by Šefara *et al.* (1998) shows values of 50–60 mWm^{-2} in the Carpathian Foredeep, and slightly higher ones (60 mWm^{-2}) in the flysch Carpathians and Podhale Basin. These values tend to increase in the Krynica region to 70 mWm^{-2}, and particularly SE of Krynica, where at the boundary between the Pieniny Klippen Belt and Magura Nappe heat flow values are 80–90 mWm^{-2}.

Close to Krynica, reliable geothermal measurements were conducted at several boreholes. Borehole Bańska IG-1 near Nowy Targ revealed an increase in temperature from 16° C at the groundsurface to 127°C at a depth of 4,750 m, resulting in geothermal gradient of 23.37°C/km, i.e. 42.793 m/1°C. Comparable figures were recorded in boreholes: Maruszyna IG-1 (19.4°C/km), Obidowa IG-1 (21.0°C/km), and Poręba Wielka IG-1 (22.7°C/km; A. Tomaś, *pers. comm. 1990*).

The Hanušovce-1 borehole, 6,003 m deep, was drilled in eastern Slovakia, some 60 km SE of Krynica, at the contact between the Pieniny Klippen Belt and Magura Nappe. Measurements conducted in the depth interval of 10 to 5,440 m in this borehole helped to determine geothermal gradient at 34.27 m/1°C, i.e. 29.18°C/km (Leško *et al.*, 1985). Segment measurements indicated 37.96 m/1°C (26.34°C/km) for depths 100–2,700 m, and 31.74 m/1°C (31.51°C /km) for the interval of 2,700–5,874 m. Another borehole in eastern Slovakia (Smilno-1; 5,700 m deep) is situated within the Magura Nappe, some 30 km east of Krynica, its geothermal gradient being from 31.25 to 38.25 m/1°C (26.14–32.0°C/km) (Leško *et al.*, 1987). Extrapolation of these data to a depth of 20 km helped to reconstruct the pattern of isotherms at the Bochnia-Krynica cross-section. At this depth, temperatures range between 400°C near Bochnia to 500°C close to Krynica.

RECENT SEISMICITY

Earthquakes in the Krynica area have been recorded for a long time (cf. Pagaczewski, 1972). The last manifestations of seismic activity date back to 1992–1993 years (Wiejacz, 1994; Dębski *et al.*, 1997).

Basing on instrumental data recorded by more than ten seismic stations in Central Europe and also macroseismic observations, it was possible to precisely locate epicentres of the last earthquakes (Fig. 7). According to instrumental data, most of the epicentres were situated NE of Krynica, i.e. close to Czyrna (B, D, H, I; cf. Table 1), north of Piorunka (E), and NE of Mochnaczka (C). Two epicentres occurred at Tylicz (A, J), and solitary ones were observed at Muszynka (G), Krynica (F), and close to the mouth of the Czarny Potok Stream (Fig. 7). The results of macroseismic observations, in turn, place the epicentres farther east, i.e. at Banica village (March 1, 1993) and on the southern slope of the Lackowa Góra Mt. (June 29, 1992), at the Polish-Slovak boundary. Focal depths were between 2 and 6 km, except for two quakes whose foci were located deeper in the upper crust (A, H; 14–19 km). The strongest earthquakes (June 28, 29, and 30,1992) revealed magnitudes of 4.1, 4.2, and 3.4, respectively; whereas the March 1, 1993 earthquake showed a magnitude of 4.7. The MSK-60 ten-grade scale intensities of the earthquakes of March 29, 1992 and March 1, 1993 were 5 and 7, respectively. The pattern of isoseismal lines of June 29, 1992 earthquake was aligned NW–SE, while that of March 1, 1993 earthquake was NE–SW.

Fault plane solutions were calculated by Dębski *et al.* (1997) for earthquakes A, D, E, and H. Event A was associated with a normal fault, showing a minor strike-slip component (nodal plane A: N78°E, 50°SE), while event D can be related to a reverse fault, also showing a minor strike-slip component (nodal plane A: N110°W, 51°NW). In the latter case, the inferred fault plane strike is parallel to the Pieniny Klippen Belt (Dębski *et al.*,1997). Focal solution for event E is comparable to that of event D. Event H was apparently associated with a deep-seated strike-slip fault (nodal plane A: N31°W, 61°NE). Focal solutions obtained for events A, D, E, and H are different, although pointing to a N–S-orientated maximum compression, which is compatible with that recorded by breakouts recorded in Tarnawa 1 and Rajbrot 2 boreholes, situated north of Krynica (Jarosiński, 1998). Another interpretation was proposed by Wiejacz (1994), who related 29 June, 1992 and March 1, 1993 earthquakes to a maximum compression aligned NNW–SSE to NW–SE, and concluded about strike-slip character of displacement.

Instrumentally determined epicentres clustered along transversal faults that strike NE–SW (Fig. 7). Three epicentres near Czyrna (B, H, I), showing magnitudes, respectively: 3, 3.3, and 4.2, are related to the Słotwina Fault, while earthquakes in Krynica (F) and north of Mochnaczka (C) should be confined to the Krynica Fault. Event E can be associated with the Andrzejówka-Roztoka Wielka Fault (M = 4.2), whereas A, D, and J events may have been related to transversal faults striking NW–SE. Epicentres A and J were situated in a close proximity to the Tylicz Fault (DT), and nodal plane B of event A was parallel to the strike of this fault, its mechanism being a normal one. On the other hand, the mechanism of event D was related to a reverse fault striking along the contact between the Bystrica and Rača subunits. Macroseismically determined epicentres clustered along the PowroŞnik Fault (March 1, 1993) and at the continuation of the Tylicz Fault (June 29, 1992).

According to Prochazková *et al.* (1994) and Labak and

Table 1

List of 1992-1993 earthquakes in Krynica Spa (after Dębski *et al.*, 1997)

Earthquake	Date	Hour, minute	Latitude	Longitude	Magnitude	Focal depth (km)
A	28.05. 1992	23:18	49° 02'	21° 02'	4.1 (F)[1]	(14-19) (i)[4]
B	28.05. 1992	23:22	49° 29'	21° 05'	<3 (F)	
C	28.05. 1992	23:28	49° 27'	21° 08'	<3 (F)	
D	29.05. 1992	00:29	49° 30'	21° 07'	4.2 (M)[2]	(2-6) (i) (3) (m)[5]
E	29.05. 1992	00:35	49° 32'	21° 05'	4.2 (A)[3]	(4-5) (i)
F	29.05. 1992	06:05	49° 24'	20° 57'	3.5 (A)	
G	30.05. 1992	23:34	49° 20'	21° 01'	3.4 (A)	
H	1.03. 1993	07:42	49° 29'	21° 04'	4.7 (M)	>19(i) (3) (m)
I	1.03. 1993	08:22	49° 28,	20° 58,	3.3 (A)	
J	1.03. 1993	18:42	49° 24'	21° 01'	2.4 (A)	

[1] F - foreshock, [2] M – main shock, [3] A - aftershock, [4] i – instrumental data, [5] m – macroseismic data

Brouček (1996), the West Carpathians are dominated by shallow earthquakes, the focal depths of which in the Slovak part do not exceed 15–17 km, i.e. coinciding with the lower boundary of the brittle upper crust (Šefara *et al.*, 1998). The thickness of the latter was determined by Bielik and Antal (2006) at 25 to 35 km along the 2T seismic profile. Lankreijer *et al.* (1999) have shown that a brittle layer of high strength (200–240 MPa) is related to the upper, 20 km thick, crust, whereas the lower crust in this area is up to 10 km thick and shows low strength values (up to 40 MPa). Subtracting 3 to 9 km thick low-strength sedimentary series from the thickness of the brittle layer would suggest that earthquakes could be generated in a relatively thin (10–20 km) brittle crust.

As far as the seismicity of Krynica Spa is concerned, previous earthquakes of December 17, 1857 and May 6, 1909 revealed intensities comparable to those of 1992 earthquakes (Wiejacz, 1994). Judging from Prochazková *et al.*'s (1994) map, as well as 1992–1993 earthquakes, one should expect events not exceeding grade 7 of the MSK-60 scale, of recurrence interval ranging between 50 and 100 years, for this area. According to Wiejacz (1994), the latest earthquakes in Krynica Spa do not pose threat to mineral water resources in this region. The only danger would be provided by earthquakes situated in the closest proximity to individual intakes of mineral waters.

SURFICIAL SEDIMENTS AND CONTEMPORARY GEOLOGICAL PROCESSES

Geomorphological studies and detailed mapping of Quaternary sediments were performed in the years 1997–1998. The hitherto-conducted research in this domain includes: general maps of Quaternary sediments (Świdziński, 1972; Chrząstowski *et al.*, 1995; Zuchiewicz, 1998b), analyses of selected landslides (Z. Alexandrowicz & S. W. Alexandrowicz, 1992; Margielewski, 1995a, b; 1997a, b, 1998; S. W. Alexandrowicz, 1996; S. W. Alexandrowicz & Z. Alexandrowicz, 1999), as well as unpublished geological-engineering reports (i.a., Ślebodziński *et al.*, 1975; Lipiec-Petryna, 1979; Fistek & Szarszewska, 1987).

Geomorphological setting

The Kryniczanka river catchment area is situated at the boundary between the Beskid Sądecki, Beskid Niski, and Čerchov Mountains (Starkel, 1991). The northern part of this catchment is characterised by topography typical of poorly rejuvenated watershed areas, of relief 150–200 m, whereas the south-western part displays properties of a transitional area between foothills and low mountains, showing relief of 200 to 250 m. The Czarny Potok Stream partial catchment, in turn, displays topography of low and middle mountains, of relief energy values not exceeding 500 m.

The dominant landforms are broad and rounded, rarely – upon exposures of thick-bedded Krynica sandstones and conglomerates – narrow and rounded ridges, orientated NW–SE, similarly to the predominant bedrock structures. Short (up to 500 m long) ridges, orientated W–E and N–S, are to be found in the central part of the catchment, particularly at the Kryniczanka and Czarny Potok rivers' interfluve. The summits are usually dome-like, rarely haystack-type or – upon exposures of the Krynica conglomerates – cone-like. Ridge-top flattenings are delimited by structural-denudational breaks. Most of these flat surfaces are either structurally- or lithologically-controlled, being cut into shales or thin-bedded flysch strata. Flat ridge segments represent either planation surfaces (Kram, 1966; Starkel 1972;

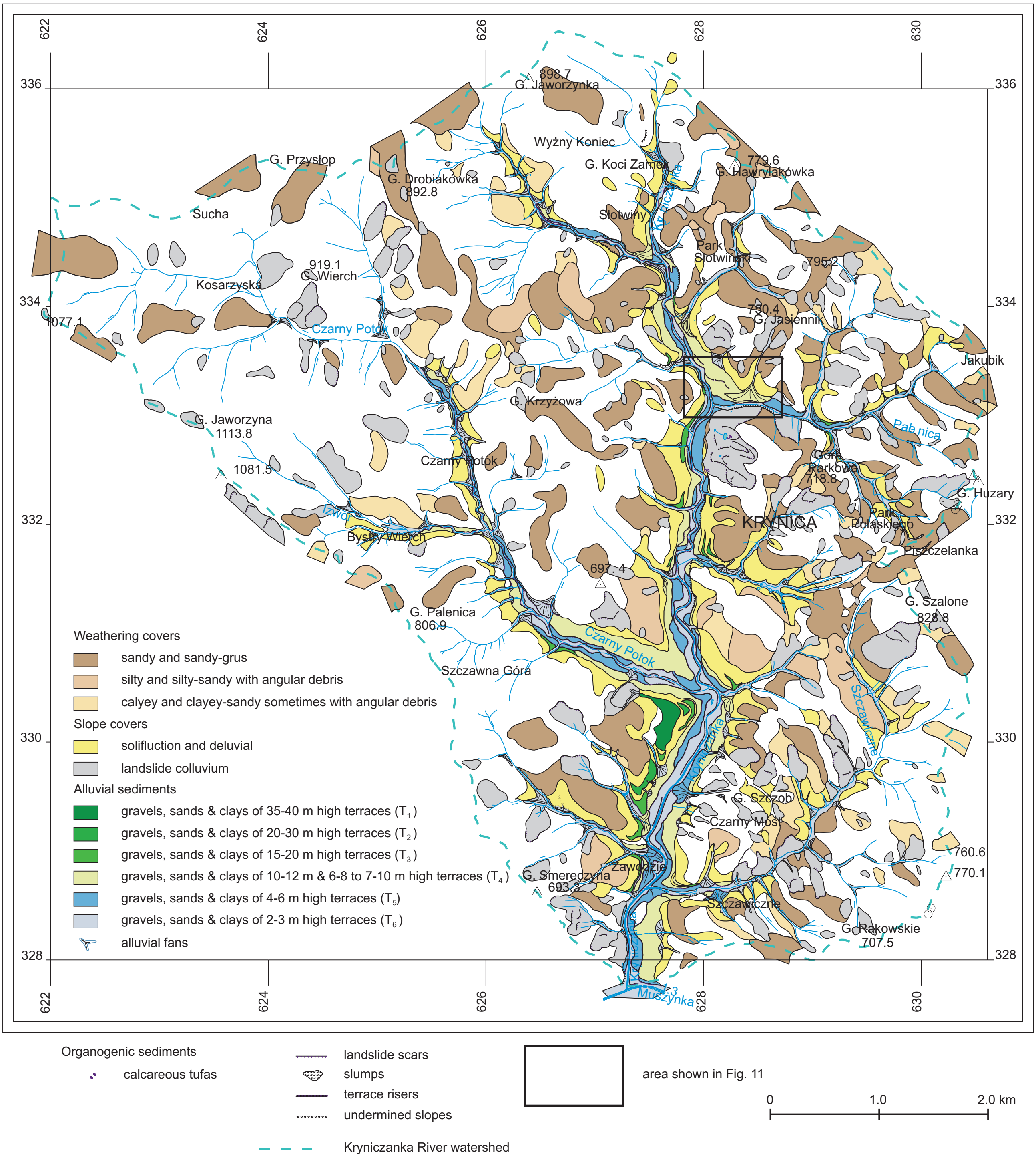

Fig. 8. Map of Quaternary sediments in the Kryniczanka River catchment area

Zuchiewicz, 1984) or rather structural-denudational landforms. They rise upon recent valley floors at ca. 400 m ("Beskidy level"?; Jaworzyna Krynicka Range), 200–230 m ("intramontane level"), 100–150 m ("foothills level"), as well as 80–85 m and 50–60 m (Early Quaternary "riverside level"). Lower-situated straths (35–45 m, 20–25 m) are probably of Middle and Late Quaternary age (cf. Zuchiewicz, 1998b).

The slopes usually have convex-concave, rarely concave profiles, are relatively short and, in the upper part of the Czarny Potok Stream valley, steep. Slopes of the western side of the Kryniczanka River valley are up to 1 km long in the lower course of the river. They display concave or convex-concave profiles, and pass into slope-base glacis-like surfaces mantled by a thin veneer of slopewash and solifluction-slopewash sediments. Slopes on the opposite valley side are shorter and more steep. Ridges and slopes occurring SE of the Jaworzyna Krynicka massif display isolated tors, 4–7 m high, built up of the very thick-bedded Krynica sandstones.

The drainage pattern is of trellis and dendritic type, and in the upper part of the Czarny Potok Stream catchment also of rectangular type, following both the strike of faults and exposures of bedrock strata of variable resistance to erosion. Long valley segments usually run subsequently in respect to the bedrock structures; short valley reaches being either obsequent or resequent. The permanently drained valleys are both V-shaped and flat-bottomed (Kryniczanka, Słotwinka, middle and lower course of Czarny Potok Stream, lower courses of Czerwony and Szczawiczny streams), the latter showing a sequence of a few strath and cut-and-fill terraces. The episodically drained valleys are represented by gullies and dellen, usually not very deep.

Steep slopes of deeply-cut V-shaped valleys in the NW portion of the study area are occupied by rocky landslides, the sizes of which rarely exceed 150 x 100–200 m (Fig. 8). These landslides cluster on the left-hand side of a left tributary of the Czarny Potok Stream (Drobiakówka Mt.), on the SE slope of a ridge extending to the east of the Jaworzyna Krynicka Mt., on southern slopes of the Wierch Mt., as well as SE of the Szczawna Góra Mt. Their occurrence is usually confined to the contact between the thick-bedded Krynica sandstones and conglomerates and thin-bedded turbidites of the Zarzecze and/or Szczawnica formations. The largest landslides, both obsequent and composite ones, accompany fault zones on the western slope of the Parkowa Góra Mt. (700 x 500 m), NE slope of the Parkowa Góra Mt. (250 x 300 m), as well as the Jastrzębia Góra Mt. slope (250 x 300 m). The first landslide is situated shortly north of the Krynica Fault, the remaining two are placed on the Tylicz Fault zone. These landforms display differentiated topography, show several generations of landslide scars up to 30 m high, as well as numerous minor ridges, grooves, and depressions that are either dry or water-filled. The Parkowa Góra Mt. landslide has been developing in several stages since the Late Vistulian time (cf. Z. Alexandrowicz & S. W. Alexandrowicz, 1992). Minor landforms are represented by landslumps and landslips occurring within headwater segments of the Czerwony Potok and Źródlany Potok streams, close to Zuber III well, within Źródlane living quarter, and on either side of the middle and upper reaches of the Szczawiczne Stream valley. Smaller landslips, resulting from lateral fluvial erosion, accompany left-hand valley sides of the Źródlany, Palenica, and Czarny Potok stream valleys, whereas minor slumps are ubiquitous upon exposures of thin-bedded and shaly flysch strata. These are usually composite, rarely consequent and obsequent landforms.

Most of the landslides are stabilised landforms. Recently active landslides are located in Krynica Spa (above “Lwigród” resort), within headwater segments of the Źródlany and Czerwony streams, in the middle and upper reaches of the Szczawiczne Stream, as well as upon slopes of the right-hand side of the Kryniczanka River valley in its downstream reach.

Quaternary sediments

Quaternary sediments are represented by regoliths, slope deposits, alluvia of the Middle-Late Pleistocene through Holocene age, and organogenic (calcareous tufas) sediments (Figs 2, 8). Their thickness is usually between 0.5 m and a few metres, except for some solifluction and slopewash sediments, as well as alluvia in the lower courses of the Kryniczanka and Czarny Potok streams, the thickness of which reaches up to 10–15 m.

Weathering covers, 0.3–7 m (averaging 0.5–4 m) thick, are ubiquitous upon interfluves and upper parts of slopes. Their composition is strongly dependent on the lithology of the bedrock. Covers composed exclusively of boulders and grus are relative rare; they accompany exposures of the Krynica conglomerates and thick-bedded Magura sandstones, particularly in the Jaworzyna Krynicka massif. On the contrary, sandy covers and sands bearing angular sandstone clasts, 15–20 cm in diameter (up to 0.5 m), are ubiquitous upon thick-bedded sandstones and conglomerates, both in the Jaworzyna Krynicka massif and at the Kryniczanka and Czarny Potok rivers' interfluve, as well as in the northern part of the catchment area. Silts and silty sands bearing angular debris are infrequent, and restricted to exposures of the Maszkowice Sandstone Member, like clayey and clayey-sandy covers that tend to develop upon thin-bedded turbidites and shales, particularly in the central portion of the study area. The amount of debris changes from 5 to 40% (10–20% on the average), whereas the amount of clay does not exceed 40%, averaging 20–30%.

Slope deposits include landslide colluvia and solifluction-slopewash sediments. Landslide colluvium is usually composed of sandy, sandy-clayey and clayey loams bearing angular debris and, at places, chaotically orientated boulders up to 1 m in diameter (usually 20–30 cm across). Minor landslumps and landslips are built up of loams bearing small-size debris. Landslide colluvia are from a few to a dozen or so metres thick.

Landslide phases recorded in the catchment area (Z. Alexandrowicz & S. W. Alexandrowicz, 1992) and the nearby Jaworzyna Krynicka massif (Margielewski, 1995a, 1997a,b) were largely coeval with wet phases of the Holocene (S. W. Alexandrowicz, 1996). The Parkowa Góra landslide, studied in detail by Z. Alexandrowicz and S. W. Alexandrowicz (1992), originated around 8,430 years BP, being later reactivated before 2,690 years BP, and in the latest Holocene (S. W. Alexandrowicz & Z. Alexandrowicz, 1999).

Solifluction and slopewash sediments are 7–15 m (av. 3 m) thick. These covers accompany lower, concave parts of slopes in the Słotwinka Stream catchment, as well as in the lower courses of the Czarny Potok and Kryniczanka rivers, frequently interfingering with alluvium of the Middle-Polish and Vistulian terraces. Slopewash sediments, 2.5–4 m thick, are well exposed on the right-hand side of the Kryniczanka River valley in Krynica Spa and in a brickyard situated south of the mouth of the Czarny Potok Stream (Fig. 8). These are vari-grained sands, usually medium to

Table 2

Terraces in the Kryniczanka River valley (in metres; elevation of straths given in brackets)

T	Upper reach	Middle reach	Lower reach A	Lower reach B	Lower reach C
		80 50–55	60–65	100 80–85	85–90 60
T1		37–38	36–40/33–35	40–42/30	42–46
T2		25–30/20	21-26		26–35/24–26
T3		14–15 (12.5)	14–17 (10)/15	20–21	20-23
T4	10 (5) 5–6	10–12 6–8	11–12 (3.5) 8-9	12–14 (9.5) 6–8/9–10 (4.5–7)	8–9/11–12 (7) 7–10
T5	4	4–5	4–6	5–6/4–5	6–7/4–5
T6	2–2.5	2–3	2–3	2-3	2.5–3/1.5–2.5

Upper reach: headwaters – mouth of the Słotwinka Stream, middle reach: mouth of the Słotwinka Stream – mouth of a right-hand tributary near Zielona Street, lower reach: A – mouth of a right-hand tributary near Zielona Street – mouth of the Czarny Potok Stream, B – mouth of the Czarny Potok Stream – right-hand tributary at Zawodzie, Krynica-Wieś, C – right-hand tributary at Zawodzie, Krynica-Wieś – mouth of the Muszynka River at Powroźnik; 100 m – foothills level; 80–85 m, 50–60 m – fragments of the riverside level; T_1–T_4 – Pleistocene terrace steps; T_5– T_6 – Holocene terrace steps

fine-grained, showing indistinct parallel, wavy or lenticular lamination. Upon exposures of the Krynica conglomerates, these sands bear a minor admixture of fine gravel, 0.5–2 cm in diameter. These sediments overlie thin solifluction deposits as well as Late Pleistocene alluvium. The solifluction covers proper are represented by 0.5–3 m (up to 10–11 m) thick sandy, sandy-clayey, rarely sandy-silty loams, rusty or light-brown in colour, bearing angular sandstone clasts, 0.5–3 to 5–15 cm in diameter, that are aligned parallel to the slope. Poor preservation of exposures makes detailed identification of solifluction processes impossible; one can only infer that the Vistulian (late Pleniglacial?) sheet solifluction and outcrop curvature processes must have been predominant.

Fluvial sediments, 0.5 to 8–10 (av. 2–3) m thick, build Late Pleistocene and Holocene terraces and alluvial fans (Figs 2, 8–11). These are mostly channel lag sediments, composed of fine- and medium-grained gravels, poorly and very poorly rounded and poorly sorted, that are overlain by thin sands and silty sands of the overbank facies in the lower reach of the Kryniczanka River valley. The thickness of individual terrace covers rarely exceeds a few metres, reaching up to 10–12 m within alluvial fans of major tributaries.

Morphostratigraphy of fluvial terraces

The above-discussed sediments build a number of erosion-accumulational and cut-and-fill terraces, whose complete sequence can be studied in the Kryniczanka River valley (Figs 2, 9–11; Table 2).

T_1 – 35–40 m terrace

In the middle and lower courses of the Kryniczanka River valley, the T_1 terrace is 37–38 m to 40–42 m high, whereas in the upper course the coeval straths are elevated at 36–40 m to 42–46 m above the river bed. At Krynica Spa, poorly preserved gravel series is to be found at 35 m, and the greatest thickness of alluvium (7–12 m) has been encountered close to a brickyard situated downstream of the Czarny Potok and Kryniczanka rivers' confluence. These are variably weathered clasts, 2–3 cm to 15–16 cm in diameter, poorly and very poorly rounded and poorly sorted, densely packed in fine gravel (0.5–1 cm across) and coarse- to medium-grained loamy sand, that interfinger in the near-slope parts with sandy loams bearing angular debris, and are overlain by 3-m-thick slopewash sands and loams.

T_2 – 20–30 m terrace

These are poorly preserved straths, overlain at places by a thin veneer of weathered fluvial gravels. Relative elevations tend to change from 21–25 m in the upper and middle reaches to 25–35 m in the lower course of the Kryniczanka River valley.

T_3 – 15–20 m terrace

The terrace surface is a little bit lower than the T_2 terrace, although forming a separate step overlain by 2–2.5 to 4–7 m thick fluvial series. Close to the mouth of the Kryniczanka River, isolated straths have been preserved at some 20–23 m above river bed. Individual straths of this terrace change from 12.5–10 m in the middle river course to 7–7.5 m in the lower one. At Krynica-Wieś, 4–7 m thick weathered gravels, poorly rounded and poorly sorted, 4–20 cm (av. 6–8 cm) in diameter, packed within fine (0.5–2 cm) gravel and loamy sand, are exposed. They are overlain by sandy loams with angular debris.

Fig. 9. Location of cross-sections through Quaternary sediments of the Kryniczanka River valley

T_4 – 10–12 m terrace

This landform occupies the largest surface among bottom terraces in the Kryniczanka River valley. It is composed of two separate steps, 10–12 m and 6–8 to 7–10 m high, that are frequently overlain by alluvial fan sediments. The straths rise from 5 m in the upper reach, through 3.5–4.5 m at Krynica-Wieś, to some 2 m in the lower reach. The terrace surface gradually passes into gently inclined slopes that are covered by solifluction-slopewash sediments. These terrace steps do also occur in lower courses of the Kryniczanka's main tributaries, namely: the Słotwiński, Palenica, Czarny Potok, and Szczawiczne streams (Figs 2, 8–11). It is likely that these fluvial sediments originated during the last glacial stage (Vistulian) and represent, respectively, either early and late Pleniglacial, or late Pleniglacial and Late Glacial (?) time intervals.

T_5 – 4–6 m terrace

These are mostly cut-and-fill terraces that form 5–6 m and 4 m high steps in the upper reaches, 4–5 m and 5–6 m in the middle reach, and 4–6 m in the lower reaches. The alluvium is predominantly composed of gravels and cobbles of the channel lag facies.

T_6 – 2–3 m terrace

These are also cut-and-fill terraces that build steps of

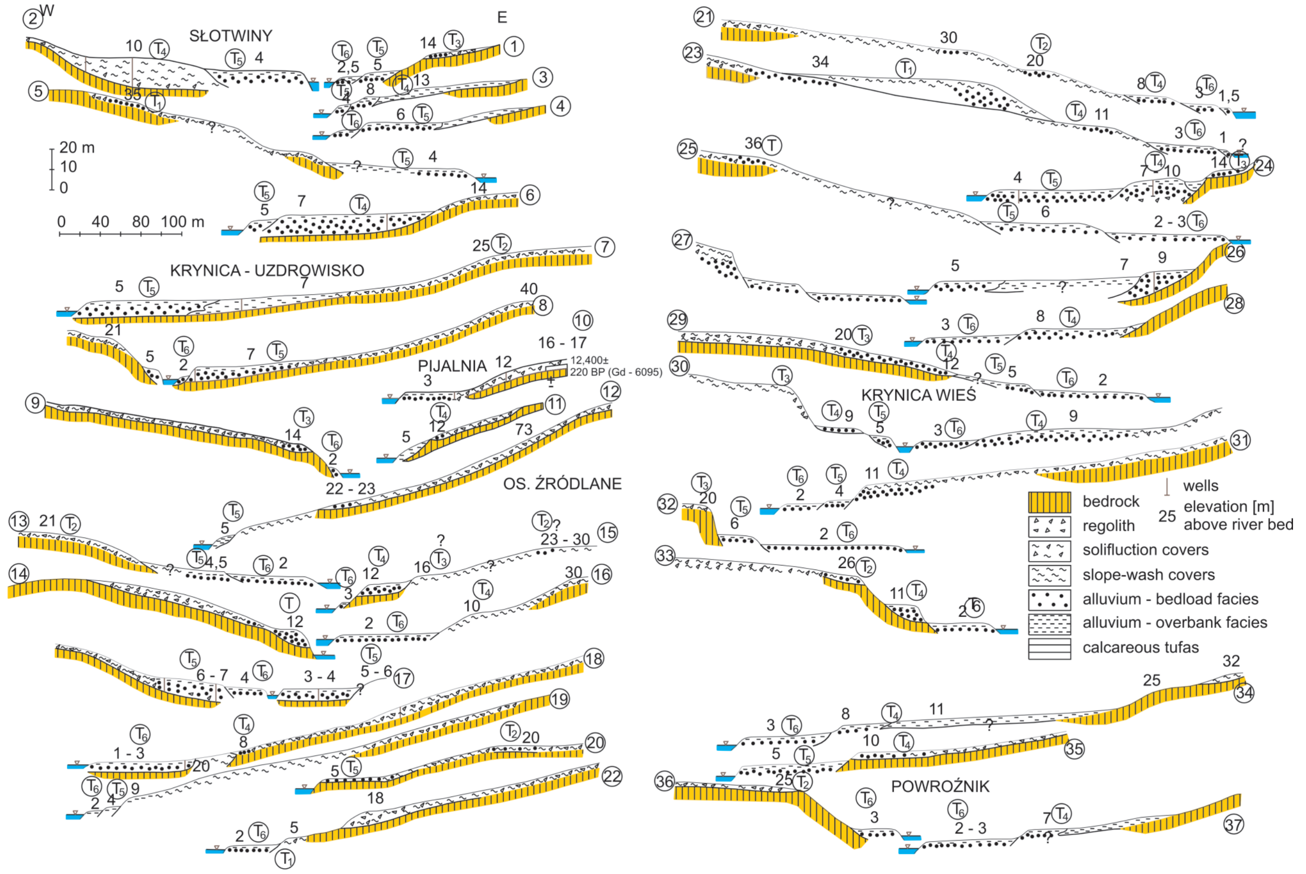

Fig. 10. Cross-sections through Quaternary sediments of the Kryniczanka River valley

relatively small width and rising 2–2.5 m, 2–3 m or 1.5–2.5 m above river beds. Such landforms are ubiquitous in the Kryniczanka River valley and its major tributaries.

Fluvial sediments which are coeval with the T_4 to T_6 terrace covers are to be observed in the main Kryniczanka's tributary valleys. Older terraces are represented in larger valleys by straths or erosional breaks of slope. The Słotwinka Stream valley, in the northern part of the study area, bears a sequence of straths and erosional breaks 30–35 m, 15–20 m to 20–25 m, and 10–12 m to 8 m high, erosional-accumulational terraces that rise 5–6 m to 6–8 m (T_4), and 4–5 m to 5–6 m (T_5?), as well as cut-and-fill terraces: 2–3 m and 1.5–2 m (T_6). At the mouth of the Czarny Potok Stream, the largest right-hand tributary of the Kryniczanka River, beneath straths rising at 32–42 m, one can observed erosional-accumulational: T_1 (20–32 m), T_2 (19 m), T_3 (17 m, straths at 7 m), and cut-and-fill terraces: T_4 (7.5–8 m to 9.5–12 m and 5–7 m), T_5 (5–5.5 m to 4 m and 3–3.5 m), and T_6 (2–3 m), along with 10-m-broad gravel-covered floodplains. The Vistulian terrace covers are composed of gravels 3–8 cm in diameter, densely packed in loamy, vari-grained sand. Late Pleistocene dellen, filled with solifluction sediments, have been dissected in Holocene times by some 7–11 m, whereas alluvium infilling such scours rarely exceeds 3 m in thickness.

Organogenic sediments are represented by calcareous tufas and organogenic silts and peat infilling landslide depressions. Calcareous tufas have been found in the middle reach of the Czerwony Potok Stream valley, in SW part of the Parkowa Góra landslide, as well as in the northern portion of that landslide to the east of Łabędzi Staw pond (Figs 2, 8). These are near-spring tufas that have been formed both recently (Czerwony Stream), and during several stages since the close of the Vistulian (Parkowa Góra landslide). In the latter case (Z. Alexandrowicz & S. W. Alexandrowicz, 1992), calcareous tufas rich in gastropods were mainly formed at the end of the Vistulian, in the Early Holocene, during the Atlantic phase, and in historical times under conditions of, respectively, sparsely forested, forested, and anthropogenically forested slopes. Calcareous silts underlying calcareous tufa in the SW part of the landslide have been radiocarbon-dated to 12,400 ± 200 yrs BP (Gd-6095), whereas calcareous tufas at the Łabędzi Staw pond gave an age of 2,690 ± 110 yrs BP (Gd-2787). Tufas occurring in the SW part of the landslide are overlain by allochthonous peat bearing fallen tree trunks and branches that have been dated to 8,430 ± 90 yrs BP (Gd-5567; cf. Z. Alexandrowicz & S. W. Alexandrowicz, 1992).

Discussion

The age of alluvial sediments is difficult to constrain due to the lack of datable material. Nevertheless, taking into account morphostratigraphic criteria, and particularly mutual relationships between alluvium and solifluction depos-

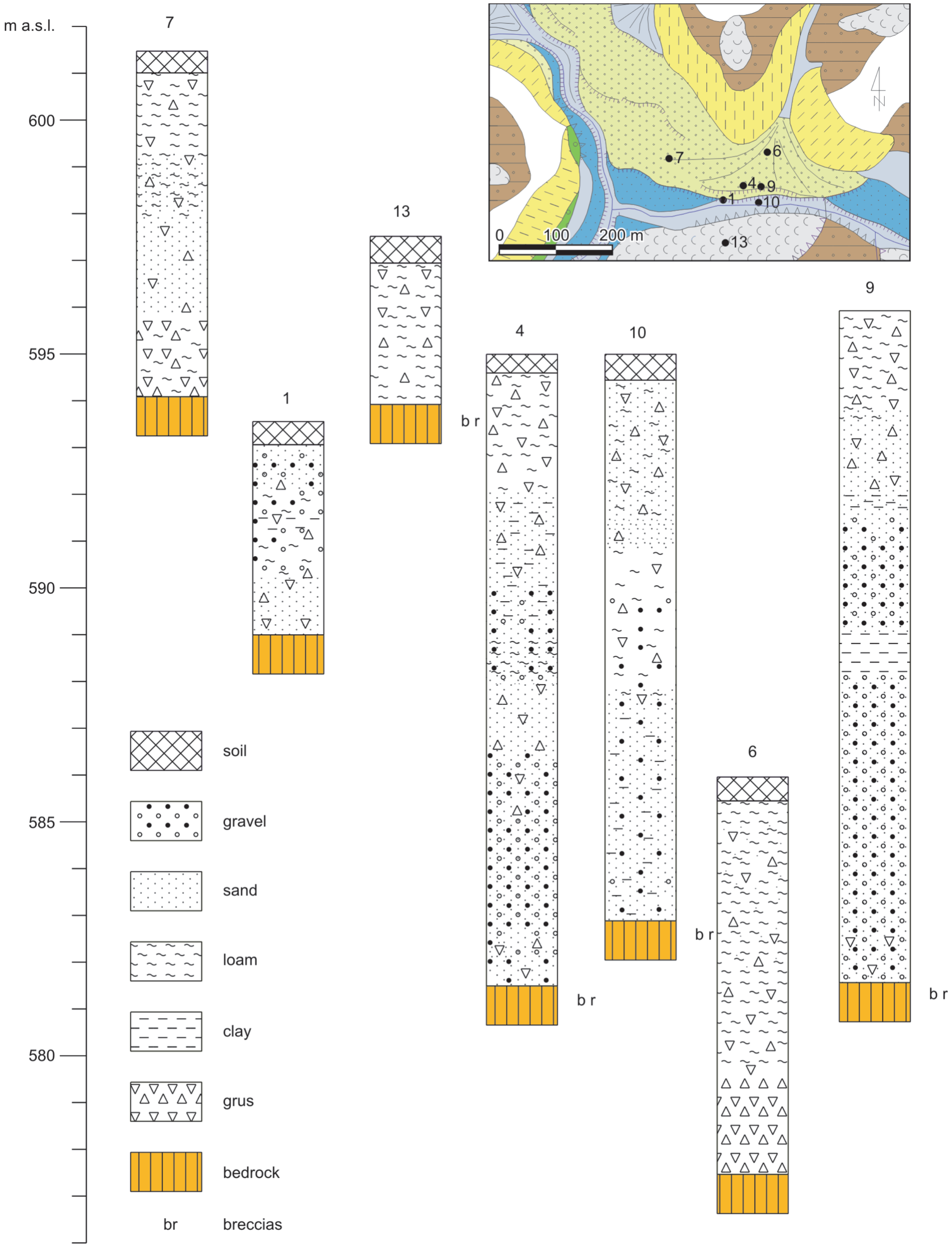

Fig. 11. Lithology of Quaternary sediments exemplified by terraces and alluvial fans at the confluence of the Palenica and Kryniczanka rivers at Krynica Spa (borehole data based on Fistek & Szarszewska, 1987). See Figs 2 and 8 for location

its whose interfingering in the near-slope bases testifies to a "glacial" age of an alluvial series (cf. Klimaszewski, 1971; Starkel, 1971), terraces T_5 and T_6 together with coeval alluvial fans can easily be assigned a Holocene age, whereas the T_4 terrace steps should be considered as formed in Vistulian (Weichselian) times. The age of older terrace covers can be interpreted either as: (a) Sanian (Elsterian?) – T_1, Odranian (Drenthe) – T_2, and Wartanian (Warthe) – T_3; or (b) Odranian – T_1 and T_2, and Wartanian – T_3. The first option appears to be a more plausible one.

MINERAL WATERS

The Krynica area is very rich in natural mineral waters (Świdziński, 1972). The belt of mineral water springs extends between Tylicz and Krynica, and then continues through Powroźnik-Jastrzębik-Złockie to the Poprad River valley between Muszyna-Milik and Żegiestów Spa (Fig. 7). The occurrence of carbonated waters in Krynica is strongly controlled by geological structure of this area. Mineral springs are usually associated with anticlinal hinges, wherein either Szczawnica or Zarzecze formations crop out. These springs are also commonly close to some of the fault zones, first of all the Krynica (KF) and Tylicz (TF) faults. The western boundary of the mineral springs area is marked by the Słotwina (SF) and Jaworzynka (JF) faults. In the Palenica Stream valley, mineral waters flow out from the Maszkowice Sandstone Member, while in the Źródlany Stream valley they originate from the Szczawnica Formation. On the southern periphery of Krynica Spa, mineral waters occur in the Szczawiczne Stream valley (Fig. 7), wherein springs are related to the Krynica Member, which shows the best collector properties among strata composing the Magura Nappe in this region. The Krynica Sandstone Member is composed of thick-bedded conglomerates and coarse- to medium-grained sandstones of clayey-marly cement, which are very poorly compact close to the groundsurface. The sandstones occur within shale-sandstone complexes of the Zarzecze lithofacies, and tend to form 10 m to 250 m thick bodies. In map view, this member is most widespread in the lower course of the Kryniczanka River, i.e. within the Szczawiczne Stream catchment and at Zawodzie.

The number of mineral springs and wells exploiting mineral waters amounts to 32 in Krynica Spa (Ciężkowski & Kozłowski, 1999). According to Świdziński (1972), the debit of springs varies from 4, 5 l/min (spr. Józef) to 46 l/min (spr. Główny). These waters belong to the bicarbonate type, showing differentiated composition of the main cations (Na^+, Ca^{2+}, Mg^{2+}). These waters, saturated by carbon dioxide and showing mineralisation of at least 1000 mg/dm^3, are called in Polish "szczawa" [*schtchava*] (Świdziński, 1972).Their totals of dissolved solids (TDS) vary between 1.0 (0.65) g/dm^3 and 28.14 g/dm^3 (Ciężkowski & Kozłowski, 1999). The maximum content of free CO_2 (2.7–2.9 g/dm^3) was determined in the Główny [*Main*] and Słotwinka springs, respectively (Świdziński, 1972). On the surface, a decrease in dissolved CO_2 resulted in precipitation of red and brown, colloidal hydroxides (ochre). Among mineral waters of Krynica Spa, Ciężkowski and Kozłowski (1999) distinguished seven hydrochemical types, three of them being most frequent: HCO_3-Ca (0.5–5.1 g/dm^3 TDS); HCO_3- Mg (3.2–10.2 g/dm^3 TDS), and HCO_3-Na (21.2–29.4 g/dm^3 TDS). Waters of the first two types are of meteoric origin. These waters, discharging from springs and withdrawn from wells up to 200 m deep, contain tritium (Oszczypko & Zuber, 2002). Mineral waters of more shallow circulation display tritium ages ranging from 9 to 50 years (Zuber *et al.*, 1999). The last type, known only from four deep wells (Zuber I–IV; depth interval 670–919 m) and showing increased Cl^- and Mg^{2+} contents, are called "Zuber" waters, commemorating the name of their discoverer, Prof. Rudolf Zuber (see Świdziński, 1972; Oszczypko & Zuber, 2002).

Oszczypko and Zuber (2002) concluded that the Cl^--δ^2H relationship of the "Zuber-type" waters is typical of dehydration waters, and that the former should be regarded as resulting from mixing between meteoric and diagenetic waters. The available heat flow and deep basement structure data allow one to safely conclude that the origin of carbon dioxide and "Zuber-type" mineral waters could be related to dehydration and decarbonatisation of the basal part of the Outer Carpathian flysch cover and the strata of the platform basement.

GEOLOGICAL ASPECTS OF THE ORIGIN OF CARBON DIOXIDE IN MINERAL WATERS IN KRYNICA SPA

The origin of carbon dioxide in mineral waters of the southern portion of the Magura Nappe was studied for a long time. In 1938, Jan Nowak concluded that the occurrence of CO_2 is associated with the southern periphery of the Carpathian petroleum province, and its origin results from final oxidation of hydrocarbons. A completely different view was expressed by Świdziński (1972) who associated the origin of carbon dioxide with manifestations of Tertiary volcanism. A possibility of metamorphic origin of CO_2 was already suggested by Borysławski *et al.* (1980), but genuine progress in solving this question was provided by isotopic studies (Leśniak, 1998; and papers cited therein), which unequivocally pointed out that the Poprad region is dominated by CO_2 produced due to thermal destruction of carbonate and siliceous rocks.

The origin of CO_2 in this area cannot be fully explained without detailed reconstruction of Miocene orogenesis of the Western Carpathians. Notwithstanding numerous doubts, it is commonly accepted that the Outer Carpathian accretionary prism was finally shaped in the mid-late Miocene, due to continental collision between the North-European plate and ALCAPA and Tisza-Dacia microplates (Birkenmajer, 1986; Oszczypko, 1998). This collision was accompanied by calc-alkaline (andesitic) volcanism. In the Polish Carpathians, the occurrence of andesites is restricted to a narrow zone extending between Czorsztyn and Szczawnica, within the Grajcarek Unit of the Pieniny Klippen Belt, and the southern portion of the Krynica subunit of the Magura Nappe (Birkenmajer, 1992). Andesitic intrusions disappear to the east of Szczawnica and re-appear 70 km farther eastward, near Prešov in eastern Slovakia. The youngest generation of andesites near Czorsztyn was dated to the Sarmatian (12.5–10.8 Ma; cf. Birkenmajer, 1992, Birkenmajer & Pécskay, 1999, 2000). Following this date, the final episode of thrusting of the Carpathians upon Carpathian Foredeep strata took place, its amplitude attaining at least 30 km (Oszczypko, 1998). One can suppose, therefore, that andesitic dykes near Czorsztyn and Szczawnica are cut off their feeding vents; what explains the lack of CO_2 exhalations in this area (Rajchel *et al.*, 1999).

Deep basement structure and pressure-temperature conditions of the Carpathians are important to solve the question of the origin of carbon dioxide in the Krynica area (Fig. 7). Interpreting geothermal gradients recorded in boreholes Smilno-1 and Hanušovce-1, one can reconstruct temperatures of deeper parts of the crust in that region. Taking into account average gradient of 29.18°C/km recorded in Hanušovce-1 (Leško *et al.*, 1985), it is possible to determine a constant increase in temperature with depth in the following way: up to 146°C per 5 km, 292°C per 10 km, and 584°C per 20 km. A similar procedure can be applied when calculating pressures. Accepting, after Bojdys and Lemberger (1986), that specific density of the upper crust in this area amounts to 2.7 t/m^3, one can obtain the following pressure values: 135 MPa per 5 km, 270 MPa per 10 km, and 540 MPa per 20 km. These parametres unequivocally suggest that in the Krynica region the basal part of the flysch cover and underlying platform basement rocks, i.e. Palaeogene–Miocene siliciclastic strata and Palaeozoic–Mesozoic carbonates, became subjected to temperatures and pressures which are characteristic of shallow and intermediate metamorphic zones. According to Mason (1990), such zones are characterised by processes leading to emanation of CO_2 at 101.3 kPa, namely: hydration and decarbonatisation at temperatures of 185–190°C, dehydration and decarbonatisation at 240–305°C, and decarbonatisation at 310–410°C. These reactions tend to be accompanied by formation of new minerals, like: talc, tremolite, diopside, forsterite, periclase, and wollastonite. As far as the Krynica area is concerned, the origin of both CO_2 and mineral waters of the "Zuber-type" is probably associated with metamorphic phenomena (Zuber & Grabczak, 1987). One can infer that such processes proceed at a depth of ca. 10 km, at temperatures ranging between 240° and 305°C (Fig. 7).

Magnetotelluric studies conducted by Chen and Chen (1998) in the Taiwan foldbelt indicated that dehydration processes lead to emanation of fluids and the formation of a low-resistivity zone. This zone occurs in Taiwan at depths between 10 and 20 km, being probably situated at the boundary between the brittle and ductile crust, i.e. at the top of the aseismic zone. The dehydration zone is here associated with the greenschist-zeolite facies occurring in the zone of collision between the Eurasian and Philippine plates.

Near Krynica, in turn, the low-resistivity horizon occurs at a depth of 17–20 km (Oszczypko & Zuber, 2002), probably in the zone of collision between the North-European and ALCAPA plates (cf. Żytko, 1997). It can be concluded that the origin of carbon dioxide and "Zuber-type" mineral waters in the Krynica area could have been related to dehydration and decarbonatisation of basal parts of the Carpathian flysch cover and the underlying platform bedrock.

FINAL REMARKS

New detailed geological mapping was performed in Krynica Spa, situated in the south-eastern part of the Magura Nappe at the boundary between the Bystrica and Krynica subunits. The Bystrica succession is composed of the Middle to Upper Eocene strata of the Magura Formation, while the Krynica succession is built up of the Palaeocene through Middle Eocene strata that belong to the Szczawnica, Zarzecze and Magura formations. The Bystrica and Krynica subunits contact along a vertical or sub-vertical, NE-dipping fault, formed during the Late Burdigalian. In the study area, several NE-trending faults cut both the Bystrica and Krynica subunits into several blocks. These faults probably resulted from an episode of the mid-Badenian faulting.

Main valleys of this region bear six fluvial terraces, the oldest of which date back to the Sanian (Elsterian) stage. Episodes of increased deposition of landslide colluvia have largely been coeval with wet phases of the Holocene, the oldest landslides dating from the Vistulian Late Glacial.

The Krynica area is a seismically active one, as shown by the most recent, moderate-intensity earthquakes which occurred in 1992–1993, of epicentres situated NE of Krynica Spa. Future earthquakes in this region should not exceed intensity 7 of the MSK-60 scale, their recurrence interval ranging between 50 and 100 years.

The region is rich in natural mineral water springs which are confined to a tectonic block bounded by the Tylicz and Krynica faults. These waters bear abundant carbon dioxide, the origin of which can be related to dehydration and decarbonatisation of the base of the Outer Carpathian flysch cover and underlying bedrock.

Acknowledgements

Helpful comments by M. Cieszkowski and A. Wójcik on the first draft of this paper, and patient and tedious editorial work by J. Golonka are highly appreciated. We also thank A. Świąder, MSc., and Dr. M. Oszczypko-Clowes for their help in preparing computer-generated artwork.

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Streszczenie

BUDOWA GEOLOGICZNA KRYNICY-ZDROJU

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Uzdrowisko Krynica jest usytuowane w południowo-wschodniej części płaszczowiny magurskiej na styku podjednostki (bystrzyckiej) i krynickiej (Fig. 1). W badanej przez nas zlewni Kryniczanki utwory strefy bystrzyckiej występują jedynie fragmentarycznie, w NE części obszaru badań. Do strefy bystrzyckiej (sądeckiej) należą wyłącznie utwory formacji magurskiej wieku środkowo-późnoeoceńskiego, o łącznej miąższości stratygraficznej 1150– 1250 m. Są to: ogniwo z Maszkowic (piaskowce gruboławicowe z przeławiceniami margli łąckich), ogniwo łupków z Mniszka (łupki pstre i cienkoławicowy flisz) oraz ogniwo piaskowców popradzkich ("piaskowce zuberowskie"). Strefa krynicka reprezentowana jest przez paleoceńsko-środkowo-eoceńskie utwory formacji szczawnickiej (cienko- i średnioławicowy flisz), zarzeckiej (cienkoławicowy flisz z ogniwem piaskowców krynickich) oraz magurskiej (piaskowce gruboławicowe). Niepełna miąższość utworów strefy krynickiej wynosi co najmniej 1300 m. Podjednostki bystrzycka (sądecka) oraz krynicka kontaktują ze sobą wzdłuż pionowego lub niemal pionowego, zapadającego na NE uskoku, zwanego "dyslokacją krynicką". Uskoki poprzeczne o przebiegu NE–SW dzielą obie podjednostki na kilka bloków. Między Czarnym Potokiem a Słotwinami wąski półrów tektoniczny towarzyszy uskokowi słotwińskiemu. W okolicach Krynicy notowane były w latach 1992–1993 wstrząsy sejsmiczne. Epicentra tych wstrząsów grupują się wzdłuż uskoków poprzecznych o orientacji NW–SW oraz dyslokacji krynickiej.