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Provenance analyses of the Late Cretaceous – Palaeocene deposits of the Magura Basin (Polish Western Carpathians) – evidence from a study of the heavy minerals

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ABSTRACT:

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The Late Cretaceous-Palaeocene sequence of the Magura Nappe in Poland is underlain by the Albian-Cenomanian spotty marls at the base and overlapped by the Palaeocene/Early Eocene variegated shales at the top. The spotty marls are followed by variegated shales and then by turbiditic deposits. The upper boundary of the variegated shales is diachronous – older in the Rača zone (Santonian) and younger in the Krynica zone (Campanian/Maastrichtian). The turbiditic deposits of the marginal (northern) zone of the Magura Nappe display palaeocurrent directions from the NW in the western part and from the NE in the eastern part. In other parts of this unit palaeocurrent directions from the SE and E were observed. The northern source area of the Magura Basin is commonly connected with the Silesian Ridge, while the south-eastern one could be connected with an accreted fragment of the Inner Carpathians. The heavy mineral assemblages of the Magura Nappe are dominated by stable and ultrastable species. Chromian spinels occur additionally in the Krynica zone and to some extent in the Bystrica and Rača zones. Investigation of the chemical composition of the heavy minerals showed that that the southern source area was built of low- to medium-grade metamorphic rocks, as well as igneous rocks associated with ophiolite sequences. The chemical composition of minerals deriving from the NW indicates that they crystallized mainly in low- to high-grade metamorphic rocks and granitoids.

Key words: Heavy minerals, Source areas, Palaeogeography, Late Cretaceous – Palaeocene, Magura Basin.

INTRODUCTION

The Magura Nappe, the most prominent tectonic unit of the Outer Western Carpathians, is linked to the Rheno-Danubian flysch of the Eastern Alps (SCHNABEL 1992). The eastern termination of this unit is probably located in the Romanian Maramures (Eastern Carpathians, see BOMBITA & POP 1991; BOMBITA & *al.* 1992; AROLDI 2001). During overthrusting the Magura Nappe was detached from its substratum mainly along ductile Upper Cretaceous rocks (BIRKENMAJER 1986; OSZCZYPKO 1992). On the basis of facies differences of the Paleogene deposits, the Magura Nappe has been subdivided into four facies-tectonic zones (subunits): the Krynica, Bystrica, Rača and Siary (Text-fig. 1, see also KOSZARSKI *& al.* 1974). The Magura Nappe is flatly overthrust towards their foreland, composed of the Fore-Magura Group of units and the Silesian Unit. Towards

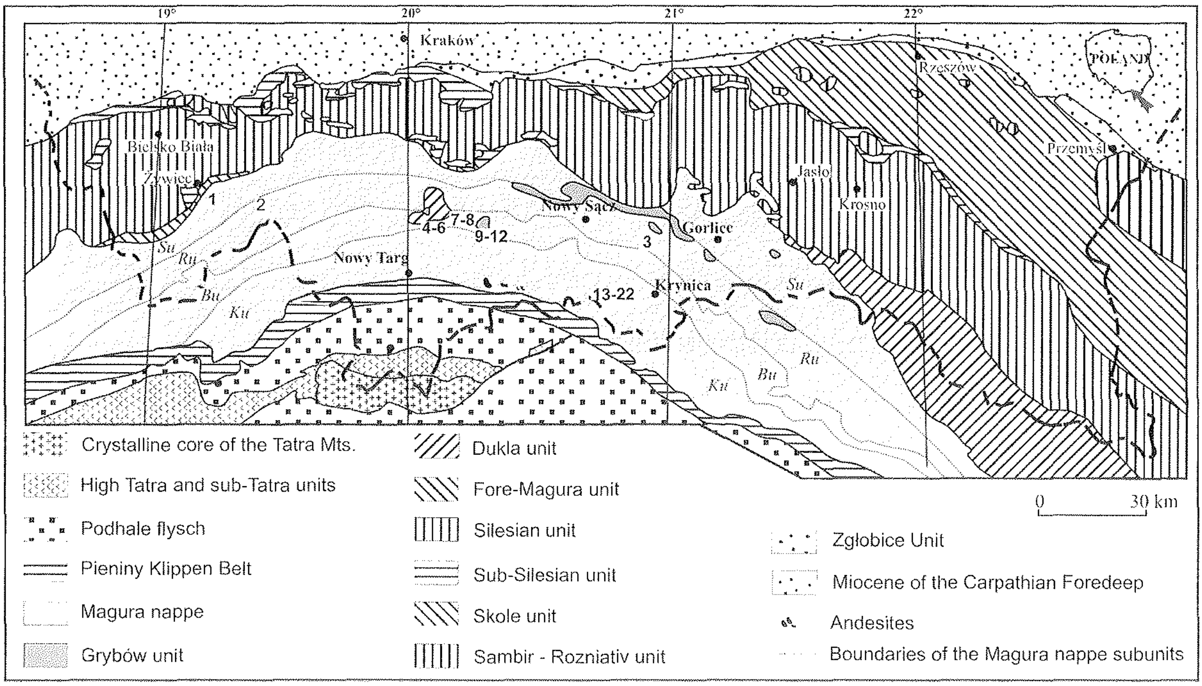


Fig. 1. Geological map of the Carpathians and localisation of the studied sections [after Żytko *& al.* (1989) and Lexa *& al.* (2000), supplemented and modified]. Symbols of locations are used in lithostratigraphic sections and in Table 1: 1 – Mutne (M), 2 – Stryszawa (ST), 3 – Grybów (G), 4 – Konina (KO), 5 – Koninki (KN), 6 – Poręba Wielka (PW), 7 – Półrzeczki (PŁ), 8 – Lubomierz (L), 9 – Przysłop (PRZ), 10 – Białe (B), 11 – Szczawa (SC), 12 – Zasadne (Z), 13 – Krościenko Łąkcica (KŁ), 14 – Krościenko Zawiasy (KZ), 15 – Sielski Stream (PS), 16 – Stary Stream (D), 17 – Szczawnica Zabaniszcze (SZ), 18 – Czarna Woda stream (CW), 19 – Życzanów (Ż), 20 – Wierchomla (W), 21 – Muszyna Złockie (SL), 22 – Jastrzębik (J), Su – Siary, Ru – Rača, Bu – Bystrica, and Ku – Krynica subunits

the south, the Magura Nappe is in tectonic contact with the Pieniny Klippen Belt (PKB) along a sub-vertical fault.

During the Late Cretaceous and Palaeogene, the Magura Nappe was supplied with clastic material from no longer preserved source areas situated at the northern and south-eastern margins of the basin. The Silesian Ridge (Cordillera) is commonly accepted as the northern source area (Książkiewicz 1962; Pescatore & Ślączka 1984), while the location of the south-eastern one is still debated (see Birkenmajer 1986, 1988; Oszczypko 1975, 1992, 1999; Sikora 1976; Marschalko 1975; Rakus *& al.* 1988; Mišik *& al.* 1991; Winkler & Ślączka 1994; Ellouz & Roca 1994; Golonka *& al.* 2000, 2003; Oszczypko *& al.* 2003; Poprawa *& al.* 2002; Nemčok *& al.* 2000).

In reconstruction of the palaeogeography of orogenic belts studies of heavy mineral assemblages and their chemical composition play an important role. The aim of our investigations was to analyse heavy mineral species to verify present palaeogeographic concepts of the Late Cretaceous – Palaeocene evolution of the Magura Basin, with particular emphasis on its source areas. An important new aspect of the investigations was the interpretation of the provenance of the main heavy mineral species separately on the basis of their chemical composition.

PREVIOUS WORK

Heavy minerals occurring in Upper Cretaceous-Palaeocene sandstones of the Magura Nappe have been a subject of interest for many years. Investigations concentrated on the western part of the nappe (Krysowska-Iwaszkiewicz & Unrug 1967) or dealt with single samples collected from the middle part. (Szczurowska 1985; Marek 1988; Winkler & Ślączka 1992, 1994). Most of the studies referred to the heavy mineral assemblages occurring in the Ropianka Formation, only a few of them dealt with the Jaworzynka and Jarmuta formations. Some samples taken from the Magura succession of the Pieniny Klippen Belt were studied by Łoziński (1956, 1966). Among the main components of the heavy mineral assemblages the authors listed found zircon, tourmaline, rutile and garnet. In the assemblages derived from the SE chromites were also recognised (Winkler & Ślączka 1992, 1994). On the basis of the heavy mineral composition these authors concluded that the north-western source area was of continental type and consisted mainly of granitoids and metamorphic schists, while the opposite, south-eastern source area, situated to the south of the PKB, was built of the above-mentioned rocks but also contained fragments of ophiolite sequences. In the late sixties of the 20th century KRYSTEK (1965) investigated heavy minerals from southern Moravia. All of the investigators treated and interpreted the provenance of heavy mineral spectrum as a whole. They did not investigate the chemical composition of the minerals. Only one of them studied the chemical composition of garnets occurring in the Szczawa area and found that the predominant end-member in them was almandine (MAREK 1988).

OTAVA *& al.* (1997, 1998) analysed detrital garnets from the following formations of the Rača Subunit of southern Moravia: Gault Flysch (Hauterivian–Albian), the Kaumberg Formation – an equivalent of the Malinowa Formation; and the Solan Formation – an equivalent of the Jaworzynka Formation. Garnets from the Jurassic deposits of the Czorsztyn Ridge of the PKB were studied by AUBRECHT & MÉRES (2000).

GEOLOGICAL SETTING

Detailed geological and sedimentological investigations were undertaken in three regions belonging to the Rača, Bystrica and Krynica subunits, all located in the middle part of the Magura Nappe (Text-fig. 1). The first one is situated in the Beskid Wyspowy Range (Text-figs 1-3), in the Łososina Valley (Półrzeczki section), around the hills of Jasień (1062 m) and Mogielica (1171 m). The second one is located in the northern part of the Gorce Range (Text-figs 1, 4), in the vicinity of the villages of Koninki, Poręba Wielka, Lubomierz, Szczawa and Zasadne. The third is located in the Beskid Sądecki Range between the rivers Dunajec and Poprad (Text-figs 1, 5). Additionally two sections (Text-figs 1, 2) were stud-

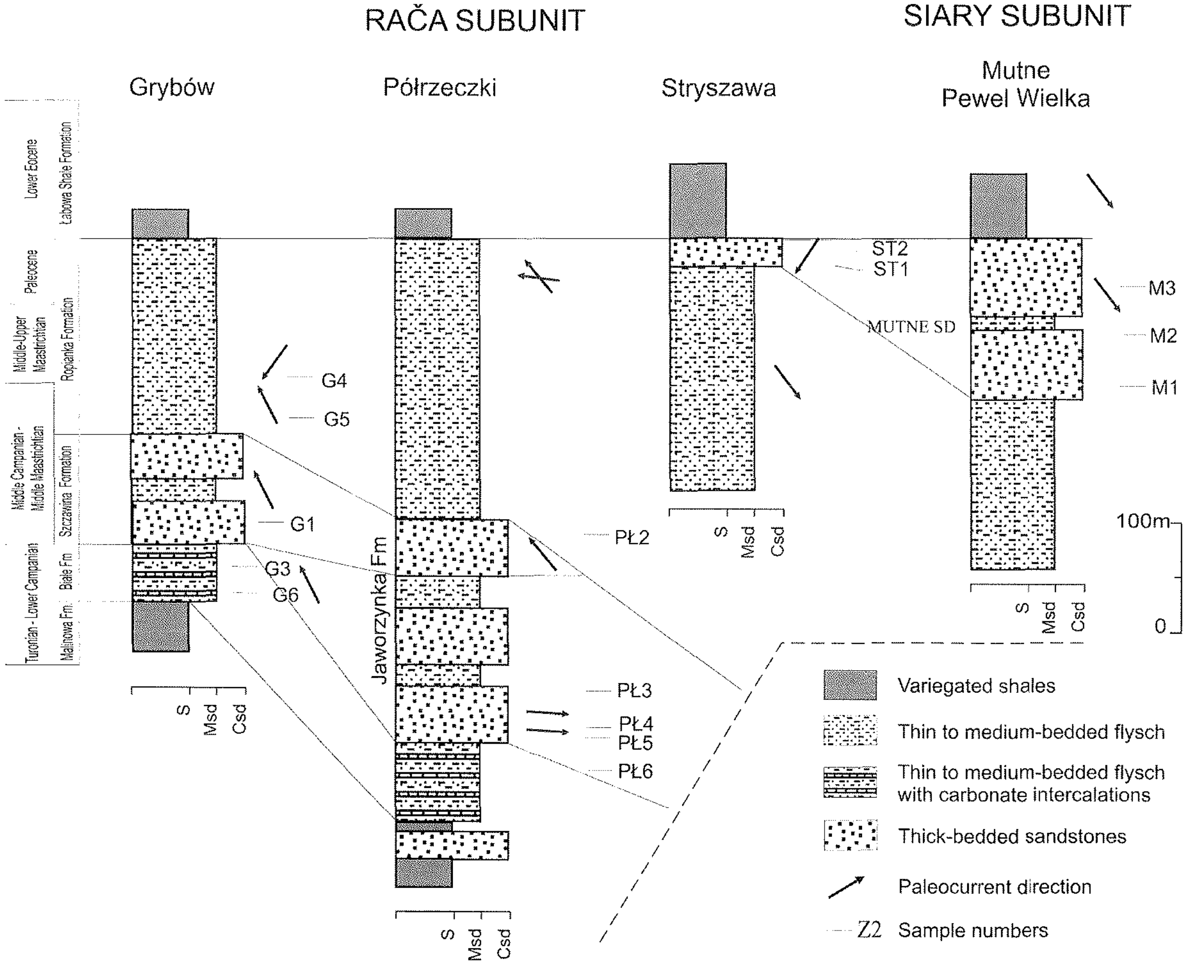


Fig.2. Lithostratigraphic sections of the Rača and Siary subunits. Abbreviations of grain fractions: S – silt, Msd – medium-grained sand, Csd – coarse-grained sand

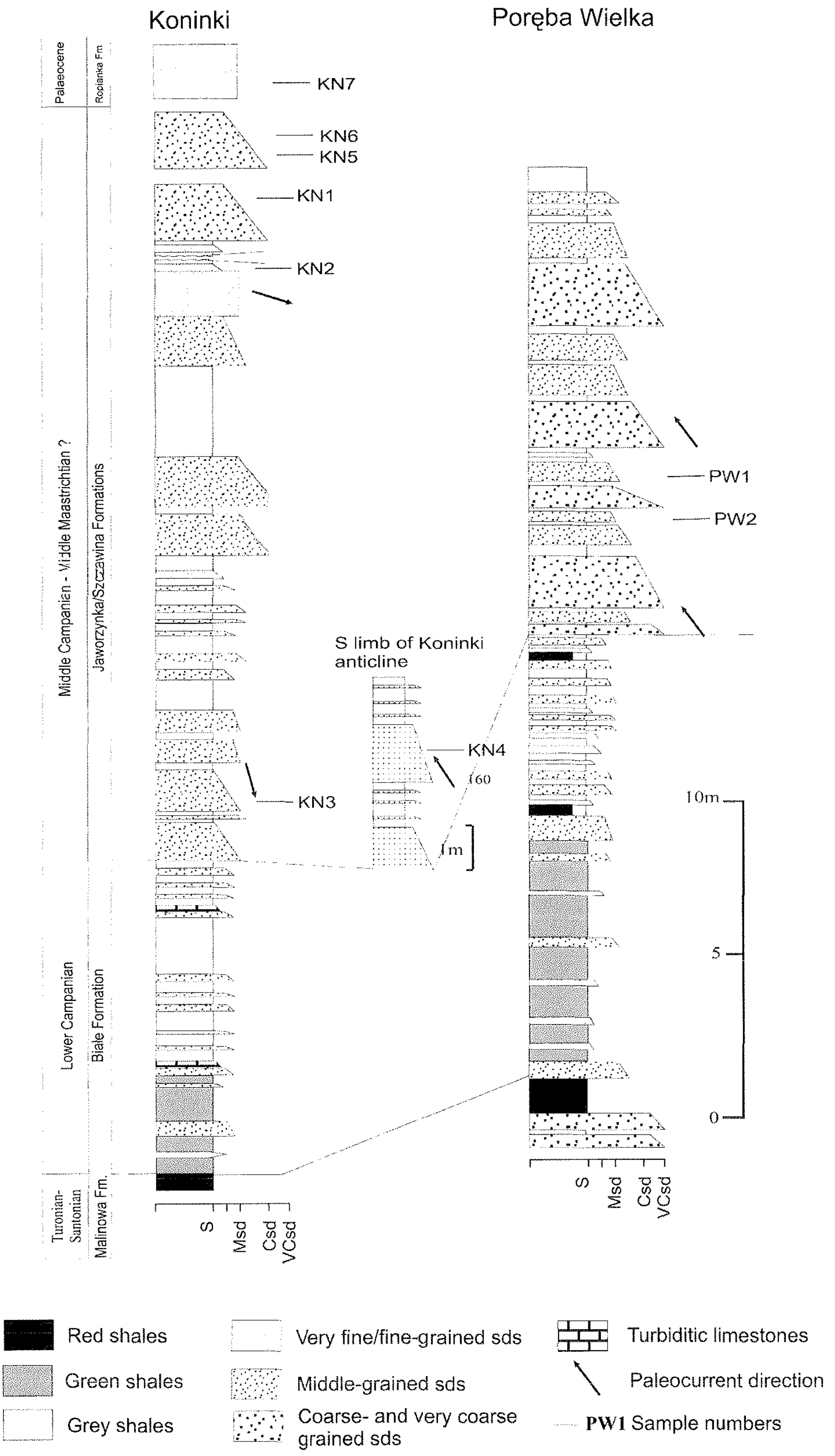


Fig. 3. Sedimentological logs of the Upper Cretaceous sequences of the Rača Subunit (Koninki – Poręba sections). Abbreviations of grain fractions: S – silt, Msd – medium-grained sand, Csd – coarse-grained sand, Vcsd – very coarse-grained sand

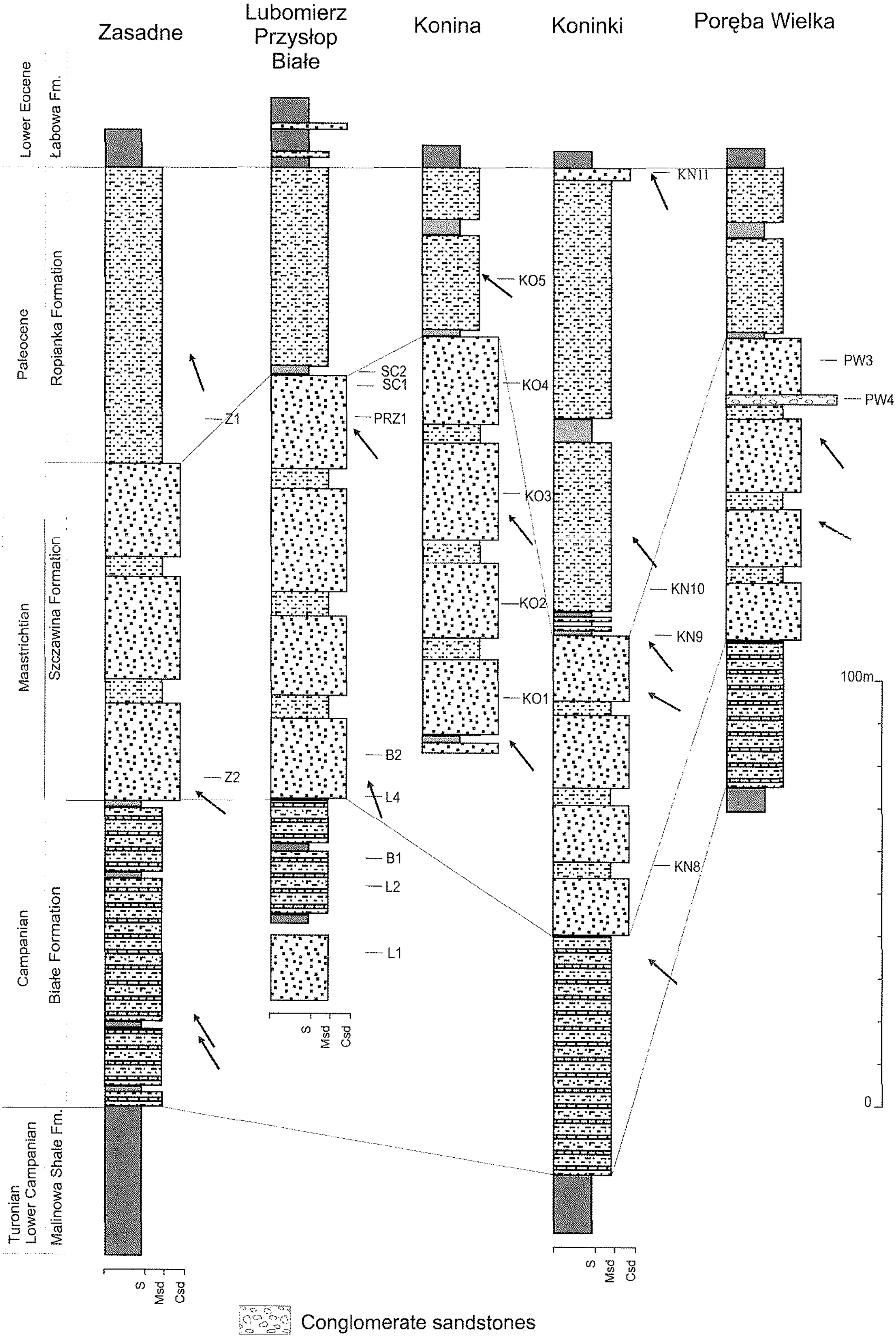


Fig. 4. Sedimentological logs of the Upper Cretaceous to Lower Eocene sections of the Bystrica Subunit. For other explanations see Fig. 2

ied in the area of Grybów (Rača subunit) and Sucha Beskidzka (Siary subunit).

The part of the Beskid Wyspowy Range investigated is built mainly of Upper Cretaceous-Lower/Middle Eocene strata of the Rača subunit, extending eastwards from the Mszana Dolna tectonic window and northwards from the Szczawa tectonic window (Text-figs 1-2) (ŚWIDERSKI 1953; BURTAN *& al.* 1978). This part of the Rača subunit is built up of several synclines, filled with the Eocene Magura Formation, and underlain by the Upper Cretaceous-Middle Eocene formations (Beskid Wyspowy thrust-sheet; see MASTELLA 1988).

The northern part of the Gorce Range studied forms the southern margin of the Mszana Dolna tectonic window, which belongs to both the Rača and Bystrica subunits of the frontal thrust of the Magura Nappe (Text-figs 1, 4) (BURTAN *& al.* 1976, 1978; OSZCZYPKO-CLOWES & OSZCZYPKO 2004). The Rača subunit occurs within the narrow (250-300 m), strongly tectonized thrust-sheet composed of Turonian–Palaeocene strata. The Bystrica subunit, thrust onto the Rača subunit, consists of Upper Cretaceous–Lower/Middle Eocene strata. This subunit is clearly visible in the feature-forming, W–E-trending belt of rounded hills (OSZCZYPKO *& al.* 1999).

Between the rivers Dunajec and Poprad (Text-figs 1, 5) we studied the Grajcarek unit (Szczawnica-Krościenko area), which is regarded as the Magura succession incorporated in the Pieniny Klippen Belt (BIRKENMAJER 1977) and the Krynica subunit (Krościenko, Życzanów and Muszyna – Złockie areas).

In the Grybów area the section studied belongs to the marginal part of the Rača subunit. The samples were

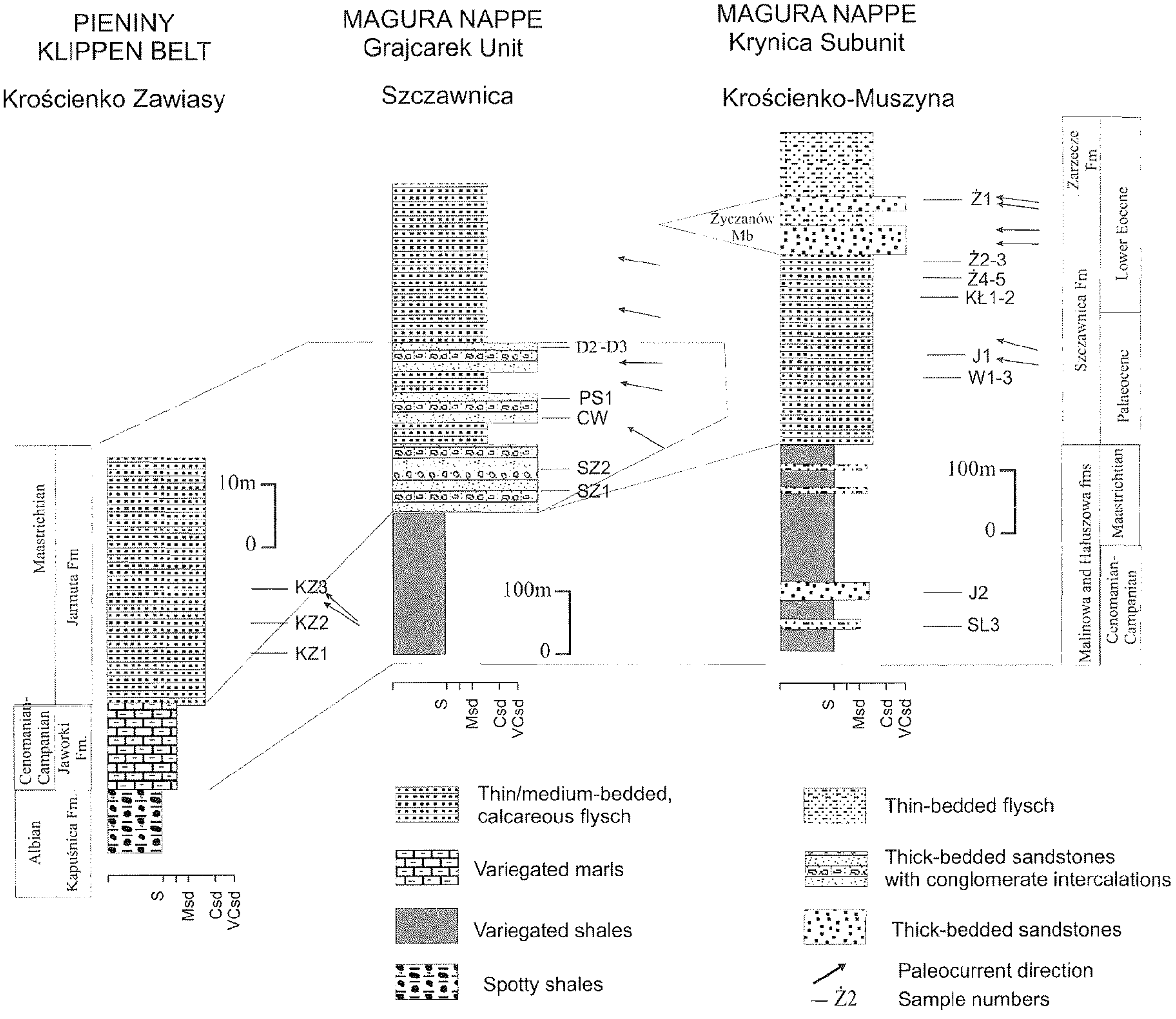


Fig. 5. Lithostratigraphic sections of the Upper Cretaceous to Eocene sections of the Pieniny Klippen Belt, Grajcarek Unit and Krynica Subunit of the Magura succession

taken from the Pławnik creek (SIKORA 1970) which cuts the narrow, north-verging, anticline. The core of the anticline is composed of the Malinowa Formation, while the flanks are formed from the Szczawina and Ropianka formations.

In the Sucha Beskidzka area the marginal part of the Magura Nappe, belonging to the Siary subunit was studied.

Lithostratigraphy

The Late Cretaceous–Palaeocene sequence of the Magura Nappe in Poland belongs to the Mogielica Group (OSZCZYPKO *& al.* 2005), which is underlain by the Albian – Cenomanian spotty marls (Jasień Formation) at the base and overlapped by the Palaeocene/Early Eocene variegated shales of the Łabowa Shale Formation at the top (Text-figs 2-4).

Malinowa Shale Formation and Hałuszowa Formation (Turonian – Maastrichtian)

The basal portion of the Late Cretaceous-Palaeocene sequence of the Magura Nappe is composed of the Malinowa Shale Formation (BIRKENMAJER & OSZCZYPKO 1989), which is represented by cherry and red coloured non calcareous shales occurring in the form of 30-50 cm layers intercalated by greyish-green shales, a few cm to 25 cm thick. It contains a few intercalations of thick-bedded, coarse- to medium-grained quartz-glauconite sandstones, laminated quartzitic mudstones and hornstones. The thickness of the Malinowa Formation ranges from few dozen metres in the Koninki area to more than 200 metres in the Muszyna and Szczawnica areas (Text-figs 2-5). In the Koninki and Półrzeczki sections, the Malinowa Formation belongs to the Turonian – Campanian, while in the Krynica subunit (Szczawnica-Muszyna area) the Hałuszowa Formation (Maastrichtian) is distinguished.

Białe Formation (Campanian – ?Maastrichtian)

The formation is composed of 3–5-cm thick, very fine calcareous sandstones, showing T_c and T_{cd} Bouma intervals (OSZCZYPKO *& al.* 1991). Sporadically 10-15 cm fine sandstones with $T_{bc+conv}$ intervals are observed. The greenish and yellowish marly shales, a few to a few dozen cm thick revealed very fine parallel lamination and usually are bioturbated. In the middle and upper part of the beds, a complex (a few metres thick) of thin- to thick-bedded sandstones and marls, with infrequent intercalations of red shales and red marls has been observed (OSZCZYPKO *& al.* 1991). The uppermost portion of the beds displays thin- to medium-bedded turbidites with numerous 5-7 up to 30 cm thick intercalations of turbiditic limestones (CIESZKOWSKI *& al.* 1989). These marls are rich in *Helminthoida* ichnospecies. The thickness of the beds ranges around 80 m (Text-figs 2-4). The Białe Formation was previously described as the Kanina beds.

Jaworzynka Formation (Campanian – Maastrichtian)

In the Półrzeczki area the Jaworzynka Formation is composed of thick-bedded, medium- to coarse-grained sandstones, with feldspars and admixture of glauconite and biotite. These greenish-grey, non-calcareous sandstones and fine conglomerates are dominated by quartz and metamorphic rock clasts with subordinate admixture of biotite and glauconite (Text-fig. 2). The sandstones are intercalated by greyish-green, non-calcareous shales. In the above-mentioned section the Jaworzynka Formation represents the Campanian to Maastrichtian (?) interval (BĄK & OSZCZYPKO 2001; OSZCZYPKO *& al.* 2005).

Szczawina Sandstone Formation (Maastrichtian – Palaeocene)

The type area of the formation is the marginal part of the Magura Nappe, S of Żywiec (SIKORA & ŻYTKO 1959), and the southern part of the Beskid Wyspowy Range (see OSZCZYPKO *& al.* 1991; MALATA *& al.* 1996; OSZCZYPKO *& al.* 2005). The thickness of the formation varies from 80 m in the Zasadne section to 350 m in the Mogielica and Krzysztonów sections (OSZCZYPKO *& al.*, 2005) (Text-figs 1, 3, 4).

In the Koninki-Półrzeczki-Szczawa area, the Szczawina Sandstone Formation is represented by thick-bedded grey-green sandstones with thin shale intercalations. The thickness of the sandstone beds varies from 0.5 to a few metres. The sandstones are coarse- to fine-grained, sometimes with granule admixtures. Conglomerate beds are locally common in the uppermost portion of the formation. The sandstones are composed of quartz, clasts of metamorphic rocks and feldspars cemented by carbonates. The characteristic feature of the formation is a large content of mica flakes, probably muscovite, but a small admixture of glauconite is also observed. The sandstones and conglomerate beds are separated by layers of green, black, sometimes red argillaceous shales with intercalations of thin- to medium-bedded sandstones. The basal portion of the formation, ca 25 m thick, is dominated by thin- to thick-bedded calcareous sandstones with intercalations of turbiditic limestones and marls, and sometimes with thin intercalations of red shales. This flysch passes upwards into thick-bedded sandstones (1.0-2.0 m thick) derived from the

SE, which reveal the $T_{abc+conv.}$ Bouma divisions. The sandstones are very coarse- to fine-grained, muscovitic, with carbonate cement. They are rich in shale clasts up to 15 cm in diameter, some of which are occasionally armoured. The sandstone beds are intercalated by rare dark grey shales up to a few dozen cm thick.

Ropianka Formation (?Maastrichtian – Palaeocene)

The Ropianka Formation represents the upper part of the Upper Cretaceous–Palaeocene sequence of the Magura Nappe (ŚLĄCZKA & MIZIOŁEK 1995). In the Półrzeczki area (Text-figs 1, 2) the Ropianka Formation is represented by thin- to medium-bedded turbidites with subordinate intercalations of thick-bedded (0.6-1.0 m), coarse- to medium-grained, parallel-laminated sandstones (T_{ab}). In this part of the sequence thin intercalation of red calcareous shales has been observed. The thin- to medium-bedded sandstone beds (5 to 35 cm thick) are mainly fine- to very fine-grained, calcareous, muscovitic, with parallel, cross and convolute lamination ($T_{bc+conv}$ Bouma intervals). The greenish-grey sandstones are intercalated with dark muscovite mudstones with coalified plant flakes and dark grey or blue, usually carbonate-free shales. In the upper part of the formation, intercalations of dark grey, medium-bedded and very fine-grained glauconite and biotite reach, non-calcareous sandstones are sometimes observed. Sporadic layers of turbiditic limestones and siderites have been found. The uppermost part of the formation (about 50-70 m thick) consists of a sequence of zebra-like thin-bedded turbidites (T_{cd}, T_d) with light grey mudstones and dark grey coloured sandstones. The mudstones are often bioturbated (spotty mudstones). In the Bystrica Subunit this part of the formation sometimes contains numerous thin intercalations of red shales (see the Zasadne, Szczawa and Koninki sections, Text-figs 1, 4). In the NW part of the Siary Subunit the uppermost part of the Ropianka Beds is replaced by the Mutne Sandstone Member (Palaeocene) (OSZCZYPKO *& al.* 2005). This member, displaying palaeotransport from both NW and NE, is composed of thick-bedded, amalgamated, pebbly sandstones and conglomerates up to 200 m thick (see also SIKORA & ŻYTKO 1959).

Jarmuta Formation (Maastrichtian – Palaeocene)

The Jarmuta Formation is known from the Grajcarek Unit, located along the tectonic boundary between the Pieniny Klippen Belt and the Krynica subunit of the Magura Nappe (Text-figs 1, 5). The formation, up to 500 m thick, is composed of thick- to medium-bedded, fine- to coarse-grained, calcareous, muscovitic sandstones alternating with grey marly shales (BIRKENMAJER 1977; BIRKENMAJER & OSZCZYPKO 1989). This formation contains thick beds of conglomerates and sedimentary breccias composed of Jurassic–Cretaceous sedimentary rocks and exotic crystalline and basic volcanic rocks (BIRKENMAJER 1977; BIRKENMAJER & WIESER 1990; MIŠIK *& al.* 1991). The (?)Maastrichtian – Middle Palaeocene Jarmuta Formation overlies and probably partly alternates with variegated shales of the Malinowa Formation (BIRKENMAJER & OSZCZYPKO 1989). Towards the north, the upper portion of this formation alternates with the Szczawnica Formation. In Krościenko-Zawiasy the Jarmuta Formation belongs to the Branisko type succession of the PKB. It is underlain there by variegated marls of the Jaworki Formation (Cenomanian – Campanian, see BIRKENMAJER 1985), which are an equivalent of the Malinowa Formation (Text-figs 1, 5).

Szczawnica Formation (Palaeocene – Lower Eocene)

The Szczawnica Formation (BIRKENMAJER & OSZCZYPKO 1989) represents a typical Palaeocene–Early Eocene lithofacies of the Krynica Subunit (Text-figs 1, 5). This formation is composed of thin-bedded flysch consisting of medium- to coarse-grained, calcareous sandstones with alternations of dark grey or bluish, mostly non-calcareous shales. Within the upper part of the Szczawnica Formation thick-bedded sandstones and conglomerates (Życzanow Member) were distinguished (OSZCZYPKO 1979; OSZCZYPKO & PORĘBSKI 1985; BIRKENMAJER & OSZCZYPKO 1989).

Palaeotransport directions

According to palaeotransport measurements, the Magura basin was supplied during the Cretaceous–Palaeocene from two opposite source areas located along the northern and south-eastern margins of the basin (Text-fig. 6, see also KSIĄŻKIEWICZ (1962). The palaeotransport from the northern source area was perpendicular or oblique to the Magura Basin axis, while the palaeotransport from the south-east was longitudinal and parallel to the axis of the basin, which was tilted towards the west (according to present-day geographical coordinates).

The coarse-grained Jaworzynka Formation, known as the biotite-glauconitic beds, occurring in the NW part of the Magura Nappe (Siary Subunit) and in the Fore-Magura scale, displays palaeotransport directions predominantly from the NW. The Mutne Sandstone Member (Palaeocene), which occupies very small areas in the marginal parts of the Magura Nappe, indicates

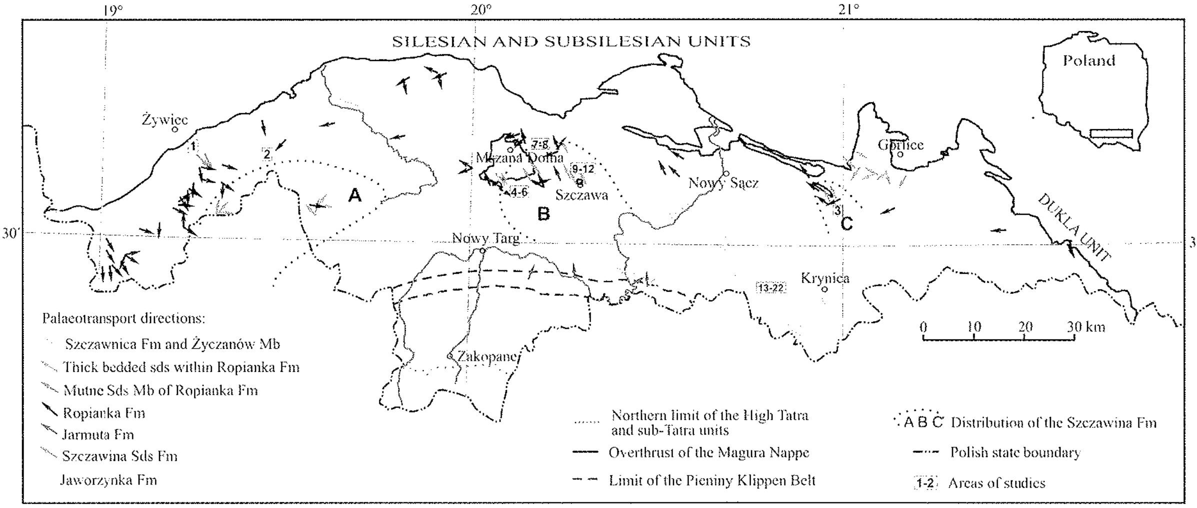


Fig. 6. Distribution of the palaeocurrent directions in Late Cretaceous–Palaeocene deposits of the Magura basin (based on KSIĄŻKIEWICZ 1962, supplemented). Symbols of locations as in Fig. 1

sediment supply from the NE and NW. Similar (from the NW) palaeotransport directions are shown by the Ropianka Formation to the west of the Raba River, whereas the thick-bedded sandstones of the Ropianka Formation near the Gorlice area were supplied from the NE.

The Szczawina Sandstone Formation occurs in three separate areas. In the Beskid Żywiecki Mts. (Rača Subunit) (Text-fig. 6, area A) the Senonian variegated shales and marls are overlain by the Szczawina Sandstone Formation, which displays palaeotransport from the SW (SIKORA & ŻYTKO 1959). Similar directions are shown by the Szczawina deposits between the Pilsko and Babia Góra peaks. In the Koninki and Półrzeczki sections (Rača Subunit, Text-fig. 6, area B) the Jaworzynka and Szczawina lithofacies showed palaeotransport from the NW and WSW respectively. In the Grybów area (Rača Subunit, see SIKORA 1970) (Text-fig. 6, area C), the Szczawina Formation (Santonian – Campanian) resembles the Białe Formation from the Koninki-Półrzeczki area. These sandstones show palaeotransport from the SE (170°) (Text-fig. 6). The Ropianka Formation (Maastrichtian–Palaeocene) to the east of the Skawa river shows palaeotransport from both the NE (Gorlice area) and SE (Grybów area).

Constant palaeotransport directions from the SE are shown by the Szczawina Formation of both the Bystrica and Krynica subunits, and the Jarmuta Formation of the Grajcarek Unit.

Sample collection

71 samples of Late Cretaceous–Palaeocene sandstones from 19 sections were collected for the heavy mineral study (SALATA 2003). Sampling was concentrated in the middle and southern parts of the Magura Nappe, where the Upper Cretaceous and Palaeocene deposits are best exposed.

Several lithostratigraphic units: the Malinowa, Białe, Jaworzynka, Szczawina and Ropianka formations, belong to the Bystrica and Rača subunits and are located (Text-fig. 1) in the Beskid Wyspowy and the Gorce ranges. In this area the following sections were sampled: Poręba Wielka-Koninki, Konina, Lubomierz, Przysłop, Szczawa and Zasadne (Text-figs 1, 3-4). Additional samples were collected in Sucha Beskidzka (Siary Subunit) and Grybów (Rača Subunit) (Text-figs 1, 2, 5).

The Malinowa and Szczawnica formations (Text-fig. 1, 5) were sampled in the Krościenko-Zawodzie, Życzanów, Wierchomla and Złockie sections (Krynica Subunit).

Sandstones of the Jarmuta Formation were sampled in the Szczawnica area in the following sections: Czarna Woda, Grajcarek, Stary, Sielski and Zabaniszcze. In the Krościenko-Zawiasy section, the Jarmuta sandstones belonging to the Branisko type succession of the PKB were also sampled (Text-figs 1, 5).

ANALYTICAL METHODS

Samples taken for the heavy mineral studies consisted of about 2 kilogram pieces of medium- to fine-grained sandstones. The samples were crushed, washed and sieved. For further investigations the 0.13-0.063 mm grain size was chosen as it represented the whole spectrum of heavy minerals occurring in the sandstones. The narrow size range is appropriate for fine-grained and well sorted sediments – it allows uniform observational conditions and helps to reduce the effect of hydraulic sorting (MORTON 1985; MANGE & MAURER 1992).

The heavy mineral fraction was separated using the magnetohydrostatic method in an aqueous solution of manganese chloride ($MnCl_2 \cdot 4H_2O$) with a concentration of 1240 kg/m^3 used as the heavy liquid (KUSIAK & PASZKOWSKI 1998). The separation was carried out at the current of 24-30Amps. The solution becomes a heavy liquid in the magnetic field thanks to the presence of paramagnetic Mn^{2+} ions (BROŻEK 1983). The method of separation is much quicker than standard gravity separations in heavy liquids although the process of division between light and heavy minerals looks similar.

Percentages of minerals were established by counting usually 200–300 non-opaque non-micaceous grains in each sample using the ribbon counting method (MANGE & MAURER 1992). Heavy mineral assemblages were studied using standard microscopic observations, scanning microscopy and cathodoluminescence. The chemical composition of the main mineral groups was analyzed in polished grain mounts using scanning electron microscopy (SEM) JEOL 5410 equipped with an energy dispersive spectrometer (EDS) Voyager 3100 (Noran) working at 20kV. The calculations were carried out according to the “standardless” procedure using standards from the software library supplied by the manufacturer. The cathodoluminescence of zircons was investigated using hot cathode equipment HC2-LM, Simon Neuser, Bochum, working at14kV and 10nA/mm, as well as using a Hitachi S-4700 (detector Gatan MiniCL) scanning electron microscope with field emission working at 25kV. The Fe^{3+} content in minerals was estimated on the basis of ideal mineral stoichiometry.

RESULTS

Heavy mineral composition

The percentages of the components of the heavy mineral assemblages analysed do not differ significantly. The ZTR index varies from 39.5 to 98.4%, which means that in almost all assemblages, minerals highly resistant to various factors of weathering, transport, deposition and diagenesis predominate. The lowest amounts of the ZTR index are characteristic only for samples where the concentration of garnets is high, especially in the Mutne Sandstones (Table 1).

To the dominant group belong: zircon (Text-fig. 7.1-7.3), tourmaline (Text-fig. 7.6-7.8) and rutile (Text-fig. 7.9-7.10). Of these, tourmaline is the most numerous mineral. In the Mutne Sandstones assemblages garnet predominates (31-60%) (Text-fig. 7.11-7.13). High amounts of garnet, exceeding 20%, were also found in single samples of the Ropianka Formation. In the other lithostratigraphic units, garnet is common, but in amounts usually not more than a few percent. For sediments derived from the SE the presence of chromian spinels is characteristic (Text-fig. 7.14-7.15). Apart from the minerals listed, apatite (usually up to 10%) (Text-fig. 7.16-7.17) and small amounts of brookite and traces of epidote group minerals, chloritoid and staurolite were also found (Text-fig. 7.18-7.20).

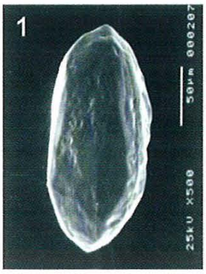
Taking into consideration the percentages of heavy minerals in the deposits investigated, three areas of their distribution connected with palaeotransport directions can be distinguished: 1) the north-western marginal part of the Magura Nappe (in the Siary Subunit), 2) the central part of the nappe (Rača and Bystrica subunits), and 3) the southern-marginal part of the unit (Krynica Subunit and the PKB). The first area is characterised by palaeocurrents from the NW and high concentrations of garnets. This is a particularly distinctive feature of the heavy mineral assemblages of the Mutne Sandstone Member (Table 1). For the third area, constant palaeocurrents from the SE and the presence of chromian spinels are typical (Jarmuta and Szczawnica formations). Chromian spinels were also noted in the central part of the nappe but only in the Białe Formation, while in other formations displaying the same palaeocurrents from the SE (Szczawina and Ropianka formations) they were either not found or were present only in traces. Apart from chromian spinels, the heavy mineral assemblages derived from the SE are enriched in tourmaline. The heavy mineral assemblages in the central part of the Magura Nappe are characterised usually by the most stable heavy mineral groups (zircon, tourmaline and rutile) and variable amounts of garnet.

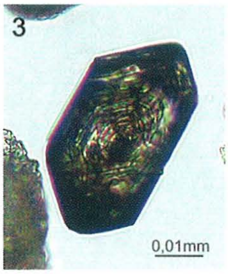
The usefulness of such poor heavy mineral assemblages, composed almost entirely of ultrastable and stable minerals, for interpreting the petrography of source regions is limited, and hence the interpretations were made mainly on the basis of the chemical composition of the main groups of the heavy minerals studied: tourmalines, garnets and chromian spinels.

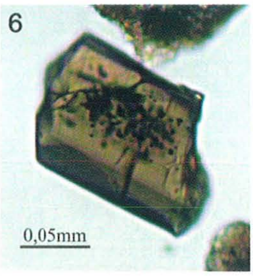
Table 1. Heavy mineral data for the studied Upper Cretaceous-Palaeocene sandstones: zrn = zircon; mnz = monazite; xe = xenotime; tur = tourmaline; rt = rutile; grt = garnet; chr = chrome spinel; ap = apatite; others = epidote group minerals+staurolite+brookite+chloritoid; ZTR = zrn+rt+tur, * Szczawina sandstone litotype, ** Szczawina – like sandstones with intercalations of variegated shales

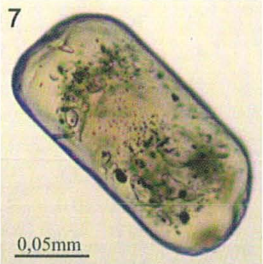
lithostratigraphic unit	sample No.	Palaeotransport	zrn+mnz+xe	tur	rt	grt	chr	ap	others	ZTR
Jaworzynka Fm	KN12	NW	30.8	29.5	17.5	17.0	0.3	2.9	2.0	77.8
Jaworzynka Fm	PŁ2*	SE	32.7	44.4	17.0	3.7	0.2	-	2.0	94.1
	PŁ3	NW	55.7	12.8	27.7	0.4	0.2	1.3	1.9	96.2
	PŁ4		21.3	18.5	21.1	2.4	-	26.6	10.1	60.9
	PŁ5		26.0	31.8	23.9	9.9	0.8	6.3	1.3	81.7
	PŁ6		58.3	11.5	7.2	10.4	0.2	6.2	6.2	77.0
Jaworzynka Fm ?	L1	?	49.2	24.6	14.7	2.5	2.5	0.3	6.2	88.5
Ropianka Fm	G4	NE	31.6	10.8	8.3	45.8	0.7	2.8	-	50.7
	G5	SE	12.5	51.7	11.8	14.7	6.1	3.2	-	76.0
	KN7		26.1	60.9	8.3	2.6	0.6	0.6	0.9	95.3
	KN10		18.3	47.3	28.5	3.4	-	0.8	1.7	94.1
	KN11		19.2	49.6	26.5	2.2	-	0.8	1.7	95.3
	KO5		31.7	28.3	15.3	20.1	-	4.3	0.3	75.3
	Z1		29.1	56.1	13.2	-	1.4	0.2	-	98.4
Mutne Sds Mb	M1	NW	20.0	5.7	13.8	60.3	0.1	-	0.1	39.5
	M2		31.9	6.4	18.9	42.5	0.2	-	0.1	57.2
	M3		24.2	14.5	29.1	31.2	0.1	0.9	-	67.8
	ST1	NE	17.8	11.9	24.9	45.0	0.2	0.2	-	54.6
	ST2		16.2	11.6	12.4	59.0	-	0.8	-	40.2
Malinowa Fm	J2	SE	30.8	31.1	16.9	17.3	0.3	3.6	-	78.8
	SL3 132-133		31.8	29.8	14.3	19.2	-	4.6	0.3	75.9
	SL3 136		33.8	21.0	15.2	24.8	0.2	5.0	-	70.0
Białe Fm	G3	SE	4.2	72.2	1.9	15.6	3.3	2.8	-	78.3
	G6		4.6	55.0	32.8	3.8	2.9	0.9	-	92.4
	L2		39.2	39.0	12.0	2.2	7.4	0.2	-	90.2
	B1		65.0	18.2	7.8	0.7	8.0	0.1	0.2	91.0
Szczawina Fm	L4	SE	14.2	37.0	24.0	22.0	0.2	2.3	0.3	75.2
	L5**		30.5	24.7	34.8	7.8	1.0	0.6	0.6	90.0
	L6**		35.2	42.2	10.4	10.0	1.2	1.0	-	87.8
	KN 1		29.6	41.1	15.9	2.5	-	10.5	0.4	86.6
	KN2	NW	19.9	53.2	11.9	9.3	-	2.9	2.8	85.0
	KN3		22.0	52.6	11.0	0.4	-	11.4	2.6	85.6
	KN4	SE	41.9	27.3	21.0	3.1	-	4.5	2.2	90.2
	KN5	-	46.4	28.9	15.4	0.0	-	7.1	2.2	90.7
	KN6	-	18.0	59.1	14.0	1.0	0.7	6.8	0.4	91.1
	KN8	SE	27.7	31.3	18.5	19.2	0.3	2.7	0.3	77.5
	KN9		22.4	40.3	17.4	15.3	1.0	2.7	0.9	80.1
	PW1		17.5	35.7	20.5	23.8	-	0.9	1.6	73.7
	PW2		28.9	38.0	18.6	2.5	-	9.8	2.2	85.5
	PW3		18.8	39.5	20.6	4.9	-	12.5	3.7	78.9
	PW4		11.7	58.9	20.5	4.4	0.1	1.7	2.7	91.1
	G1		19.2	52.3	12.5	7.7	-	7.7	0.6	84.0
	KO1		18.4	30.6	24.1	0.5	-	17.0	9.4	73.1
	KO2		26.1	35.4	19.3	3.2	-	12.6	3.4	80.8
	KO3		34.0	28.6	23.2	2.2	0.3	9.0	2.7	85.8
	KO4		18.1	35.5	9.9	28.1	-	6.2	2.2	63.5
	PRZ1		43.9	31.2	19.5	0.5	1.3	3.6	-	94.6
	B2		40.9	30.3	25.7	1.2	-	1.9	-	96.9
	SC1		23.2	42.2	17.2	12.2	-	4.5	0.7	82.6
	SC2		15.8	53.3	23.4	3.0	-	2.8	1.7	92.5
	Z2		10.1	67.7	8.0	7.2	-	1.7	5.3	85.8
Życzanów Mb	Ż1	SE	21.1	21.1	20.8	36.0	0.4	0.6	-	63.0
	Ż2		25.3	41.8	15.9	14.4	0.4	2.2	-	83.0
	Ż3		39.1	25.9	18.5	13.1	0.9	0.3	2.2	83.5

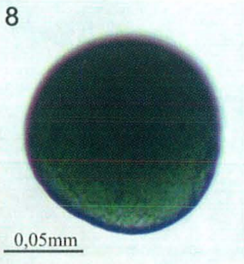
Szczawnica Fm	Ż4	SE	17.6	56.3	10.4	12.2	3.5	-	-	84.3
	Ż5		30.6	41.1	20.1	6.1	0.4	0.4	1.3	91.8
	W1		17.5	31.1	27.3	12.7	11.4	-	-	75.9
	W2		21.8	18.3	23.3	36.0	0.6	-	-	63.4
	W3		17.8	30.3	29.2	9.6	12.8	0.3	-	77.3
	KŁ1		30.1	51.9	9.4	1.5	4.7	2.1	0.3	91.4
	KŁ2		43.4	32.2	16.6	0.2	5.9	0.1	1.6	92.2
	J1		19.6	55.7	16.9	1.2	6.3	0.3	-	92.2
Jarmuta Fm (Grajcarek)	PS1	SE	45.7	25.7	13.6	10.5	1.6	2.4	0.5	85.0
	D2		16.3	48.6	13.2	17.4	3.7	0.6	0.2	78.1
	D3		35.0	33.1	8.1	11.4	3.6	8.8	-	76.2
	CW		44.2	18.0	13.8	14.8	8.2	0.5	0.5	76.0
	SZ1		48.4	25.1	14.8	0.9	9.1	1.7	-	88.3
	SZ2		20.6	41.6	6.8	23.5	1.5	5.6	0.4	69.0
Jarmuta Fm (PKB)	KZ 1	SE	35.3	36.3	17.4	3.7	2.3	0.9	4.1	89.0
	KZ2		26.0	60.6	9.2	0.6	2.7	0.9	-	95.8
	KZ3		38.1	47.2	10.0	2.2	1.8	0.6	0.1	95.3

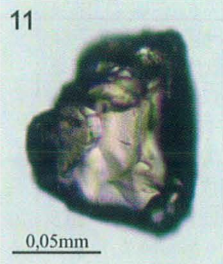


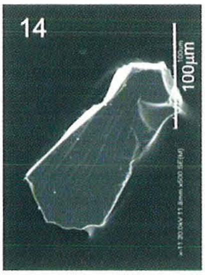


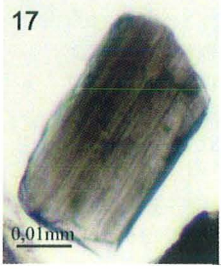


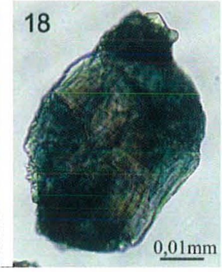


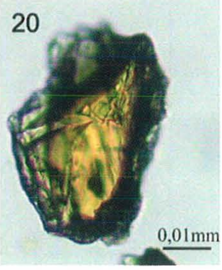












Chemical composition and features of the heavy minerals

Zircon

In the zircon population few types of this mineral could be distinguished:

a) Form in sediments: highly or moderately rounded grains and euhedral grains (Text-fig. 7.1-7.2). In almost all of the heavy mineral assemblages analysed highly or moderately rounded zircon grains prevail. In many samples they comprise up to 80 % of zircon populations.

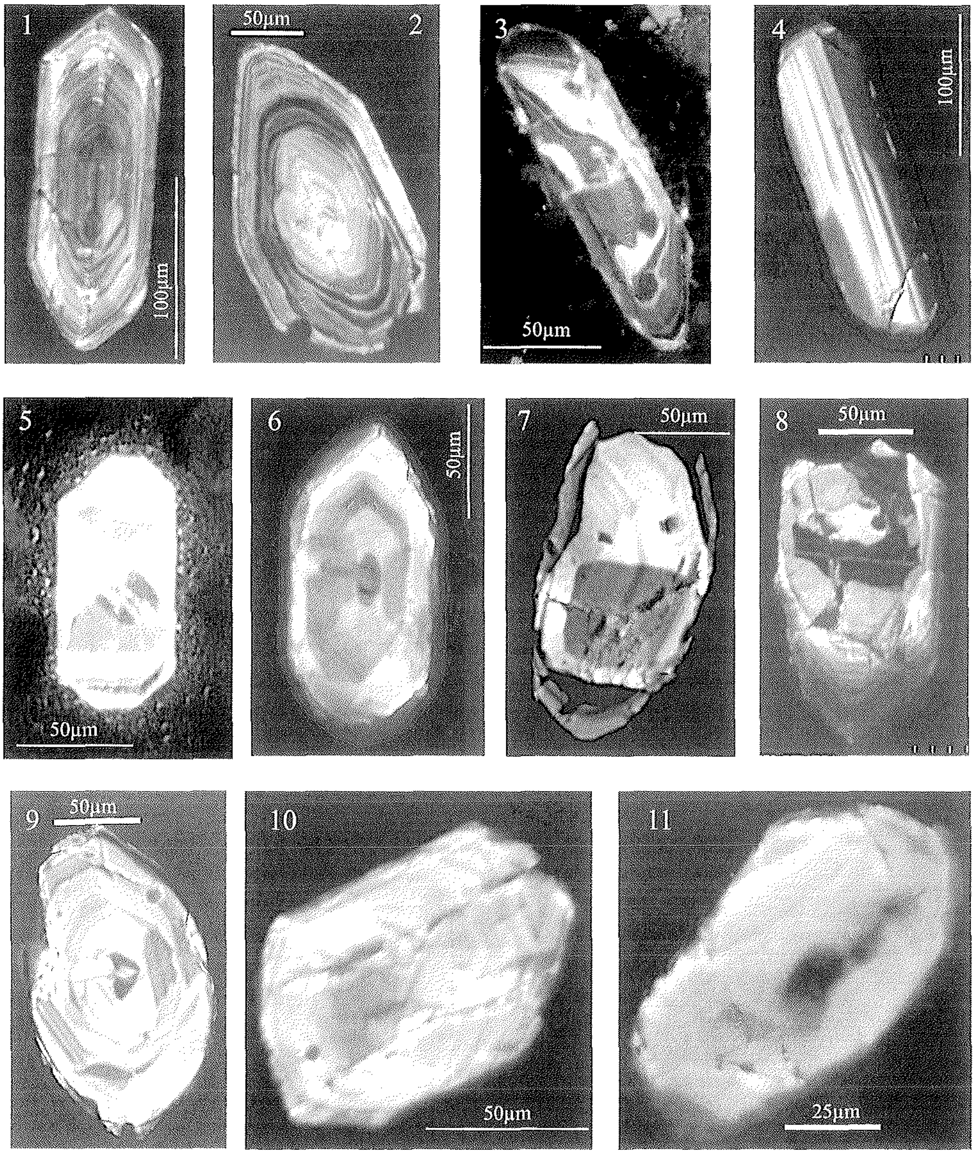


Fig. 8. CL and CL-SEM microphotographs of types of zoning in zircons. 1, 2 – oscillatory; 3 – convolute; 4 – parallel to Z axis; 5, 6 – sector zoning (hourglass type); 7, 8, 9 – sector zoning with shadows of primary zones; 10 – shadows of primary zones; 11 – azonal zircon: 1, 2, 9 – Malinowa Formation; 3 – Jaworzynka Formation; 4 – Życzanów Sandstone Member; 5, 8, 10 – Jarmuta Formation; 6, 11 – Ropianka Formation; 7 – Mutne Sandstone Member

Fig. 7. Heavy minerals occurring in the Upper Cretaceous-Palaeocene formations of the Magura Nappe: zircon: 1) highly rounded grain, 2) euhedral grain with numerous inclusions, 3) pinkish zircon with oscillatory internal zoning; 4) monazite; 5) xenotime; tourmaline: 6) un-rounded prismatic grain, 7) rounded prismatic grain, 8) rounded spherical grain; rutile: 9) elbowed reddish-brown rutile, 10) yellowish-orange grain; garnet: 11) macroscopic pink colour of garnet, 12) rounded colourless grain, 13) piece of pinkish grain; 14, 15) splinters of chromian spinels; 16, 17) apatite; 18) chloritoid; 19) brookite; 20) staurolite (1, 14 – SEM; 12 – stereomicroscope; other photos-transmitted light, PPL)(1, 2, 6, 7, 17 – Szczawina Formation; 3, 12, 20, 19 – Jaworzynka Formation; 4, 5, 9, 10, 11 – Mutne Sandstone Member; 8 – Ropianka Formation; 13 – Malinowa Formation; 14, 18 – Szczawnica Formation; 15, 16 – Jarmuta Formation)

b) Colour: the grains are mostly colourless, slightly yellowish, pinkish or reddish grains. In the red coloured grains zoning was often visible (Text-fig. 7.3).
c) Internal features: mostly numerous inclusions, rarely lacking inclusions. Among solid inclusions occurring in zircons mostly apatite and feldspars have been identified. Cathodoluminescence of the zircons has revealed that they are characterised by five types of internal zoning: 1) regular, oscillatory (with bright or dark core) (Text-fig. 8.1-8.2); 2) irregular, convolute (Text-fig. 8.3); 3) parallel to the Z axis (Text-fig. 8.4); 4) sector (Text-fig. 8.5-8.10); 5) zoning with cloudy or patchy metamorphic domains (Text-fig. 8.8-8.10). Besides, non-zonal zircons were found (Text-fig. 8.11).

Monazite and xenotime

In the Mutne Sandstone Member numerous grains of monazite, comprising about 10% of all grains, and single grains of xenotime were found. Single monazite grains were also observed in the Jaworzynka and Szczawnica formations. Monazites are usually present in the form of rounded grains, strongly resembling zircons (Text-fig. 7.4-7.5). The amounts of the monazite components from the Mutne sandstones vary over wide ranges: P_2O_5=29.78-45.06%, ThO_2=4.46-13.92%, La_2O_3=11.34-17.20%, Ce_2O_3=24.66-32.33%, Nd_2O_3=6.81-10.31%, Sm_2O_3=1.02-4.50%. In some grains SiO_2=0.15-4.41%, CaO=0.36-2.46% and ZrO_2=2.21-2.72% (amounts of oxides in wt %) were also present. The La/Nd ratio of the monazites oscillates around 1.3, only sporadically exceeding 2.0.

Tourmaline

The tourmalines studied occur usually as un-rounded prisms, rarely as moderately or highly (up to spherical) rounded prisms (Text-fig. 7.6-7.8). In the tourmaline population, in marked contrast to the zircon population, un-rounded grains predominate, usually comprising 75-90% of the population. Only in the Mutne Sandstones and the Ropianka Formation do the amounts of rounded and highly rounded tourmalines comprise up to 50% of the population.

Tourmalines display pleochroic colours from colourless or yellowish to dark brown or greenish-brown, but single grains of tourmaline with colour schemes in shades of blue and green were also found (Text-fig. 7.6-7.8). In the cross-sections of the prisms subtle colour zoning is often visible. Inside the crystals numerous solid inclusions of quartz, zircon and TiO_2 phases were identified. Among the tourmaline population some grains containing rounded tourmalines in their cores have been observed. The surface of the prismatic tourmaline grains is commonly covered with spots of opaque phases, while the surface of the spherical tourmaline grains is very smooth and “clean”.

The main elements in all the tourmalines analysed (from both source regions) are Si, Al, Fe, Mg and Na. Ti, Mn, Ca and K are additionally present. The amounts of the elements measured in the centres and rims of single crystals do not vary significantly (Table 2). The quantities of Ti and Ca do not exceed 0.10 apfu (atoms per formula unit), while Mn and K occur only in traces. The amounts of Mg are slightly higher then those of Fe. They mostly vary in the range 0.70-2.00 apfu and 0.50-1.70 apfu respectively. Lower or higher amounts of Mg and Fe than those given are rare. The proportions of the three main cations (Mg-Al-Fe) indicate that all the tourmalines belong to the schorl (Fe-end member)–dravite (Mg-end member) series, representing mostly compositions transitional between the two end members. Only a few grains, in all the tourmaline populations studied, displayed compositions close to foitite or Mg-foitite. The Mg/(Fe+Mg) ratios oscillate in the range 0.30-0.90 but in most of the tourmalines they are usually higher than 0.50 (Table 2).

Garnet

Garnets occur mostly as irregular fragments of grains; very rarely rounded ones may be found. Macroscopically the garnets are usually pink, seldom pinkish-orange. In polarised light they are mostly colourless, infrequently pinkish (Text-fig. 7.11-7.13). On the surface of the garnets, facet structures, developed probably under diagenetic conditions, are often visible (Morton 1985). In some of the garnets inclusions of quartz were found.

The main components of the garnets analysed comprise FeO, MgO, CaO and MnO, while TiO_2 occurs only in small amounts. Of all the oxides listed, FeO reaches the highest amounts in all the garnet populations, and hence almandine is the main end member. Almandine is accompanied by pyrope, spessartine, andradite and grossularite but there is a difference in the pyrope content between garnets derived from the northern and southern source areas (Table 3).

High MgO and thus high pyrope amounts are characteristic of garnets derived from the northern source region. Garnets with high pyrope contents ranging from 20-48 mol % comprise about 30 % of the garnet population in the Jaworzynka Formation and Mutne Sandstone Member, and up to 70 % in the Ropianka

Table 2 Summary of chemical analyses of detrital tourmalines

	Elements	Malinowa Fm	Białe Fm	Jaworzynka Fm	Szczawina Fm	Sandstones from red shales	Jarmuta Fm	Ropianka Fm	Mutne Sds Mb	Szczawnica Fm	Życzanów Mb
Rims of crystals	T										
	Si^{4+}	5.92-6.13	5.84-6.16	5.60-6.33	5.94-6.19	5.78-6.12	5.80-6.20	5.72-6.29	5.85-6.14	5.90-6.20	5.83-6.14
	Al^{3+}	0.00-0.01	0.00-0.16	0.00-0.40	0.00-0.06	0.00-0.22	0.00-0.20	0.00-0.28	0.00-0.15	0.00-0.10	0.00-0.17
	Z										
	Al^{3+}	5.91-6.30	5.70-6.54	5.56-6.57	5.70-6.39	5.53-6.35	5.70-6.23	5.80-6.78	5.93-6.47	5.84-6.33	5.20-6.32
	Mg^{2+}	0.00-0.02	0.00-0.26	0.00-0.74	0.00-0.43	0.00-0.47	0.00-0.48	0.00-0.20	0.00-0.07	0.00-0.16	0.00-0.51
	Y										
	Ti^{4+}	0.00-0.37	0.04-0.16	0.01-0.21	0.02-0.16	0.02-0.95	0.03-0.33	0.03-0.23	0.07-0.16	0.03-0.19	0.04-0.23
	Mg^{2+}	0.66-2.00	1.14-1.86	0.94-1.99	1.27-1.80	0.96-1.85	0.63-2.17	0.28-2.02	0.92-2.13	1.05-2.02	0.39-1.87
	Mn^{2+}	0.00-0.01	0.00-0.03	0.00-0.02	0.00-0.02	0.00-0.06	0.00-0.05	0.00-0.04	0.00-0.02	0.00-0.02	0.00-0.01
	Fe^{2+}	0.57-1.63	0.60-1.39	0.69-3.04	0.80-1.79	0.66-1.35	0.10-1.97	0.42-2.38	0.36-1.64	0.52-1.47	0.72-1.46
	X										
	Ca^{2+}	0.01-0.37	0.02-0.27	0.00-0.43	0.01-0.20	0.01-0.30	0.01-0.42	0.01-0.25	0.04-0.29	0.00-0.28	0.01-0.19
	Na^{+}	0.46-0.91	0.57-1.00	0.25-0.87	0.50-0.95	0.55-0.95	0.32-0.98	0.43-0.87	0.50-0.78	0.48-0.88	0.57-0.91
	K^{+}	0.00-0.01	0.00-0.01	0.00-0.27	0.00-0.01	0.00-0.01	0.00-0.01	0.00-0.03	0.00-0.02	0.00-0.02	0.00-0.01
	Mg/(Mg+Fe)	0.43-0.79	0.47-0.76	0.28-0.65	0.50-0.67	0.36-0.72	0.27-0.95	0.14-0.81	0.36-0.84	0.44-0.79	0.47-0.70
Centres of crystals	T										
	Si^{4+}	5.85-6.12	-	5.75-6.20	5.82-6.15	5.87-6.14	5.77-6.21	5.93-6.35	5.80-6.11	5.87-6.22	5.85-6.13
	Al^{3+}	0.00-0.15	-	0.00-0.25	0.00-0.18	0.00-0.13	0.00-0.23	0.00-0.07	0.00-0.20	0.00-0.13	0.00-0.04
	Z										
	Al^{3+}	6.11-6.32	-	5.64-6.34	5.45-6.39	5.58-6.35	5.70-6.20	5.82-6.76	5.80-6.47	5.68-6.58	5.48-6.42
	Mg^{2+}	0.00-0.88	-	0.00-0.30	0.00-0.55	0.00-0.42	0.00-0.49	0.00-0.18	0.00-0.20	0.00-0.32	0.00-0.34
	Y										
	Ti^{4+}	0.00-0.29	-	0.01-0.20	0.02-0.16	0.02-0.19	0.02-0.74	0.00-0.17	0.01-0.17	0.03-0.29	0.04-0.22
	Mg^{2+}	0.86-1.99	-	0.90-1.98	0.94-1.48	1.05-2.30	0.70-2.14	0.28-2.03	0.92-2.11	0.27-1.14	0.92-1.94
	Mn^{2+}	0.00-0.02	-	0.00-0.02	0.00-0.01	0.00-0.02	0.00-0.02	0.00-0.04	0.00-0.02	0.00-0.04	0.00-0.06
	Fe^{2+}	0.70-2.11	-	0.67-2.08	0.83-2.61	0.36-1.39	0.10-1.91	0.48-1.72	0.36-1.15	0.49-1.86	0.45-1.70
	X										
	Ca^{2+}	0.00-0.30	-	0.02-0.27	0.01-0.25	0.01-0.98	0.01-0.36	0.01-0.22	0.05-0.92	0.02-0.27	0.02-0.23
	Na^{+}	0.81-0.96	-	0.30-0.85	0.41-0.87	0.51-0.98	0.49-0.57	0.43-0.95	0.46-0.78	0.36-0.90	0.580.87
	K^{+}	0.00-0.01	-	0.00-0.26	0.00-0.06	0.00-0.02	0.00-0.02	0.00-0.02	0.00-0.02	0.00-0.02	0.00-0.01
	Mg/(Mg+Fe)	0.38-0.74	-	0.02-0.27	0.01-0.25	0.01-0.98	0.01-0.36	0.01-0.22	0.05-0.92	0.02-0.27	0.02-0.23

All analyses were calculated for 24.5 oxygen atoms; Elements in number of cations: as the real amount of B was impossible to establish it was calculated on the base of the ideal formula of tourmalines (3.00apfu); the total amount of Fe was calculated as FeO; T, Z, Y, X-cation positions in the tourmaline structure.

Table 3 Summary of chemical analyses of detrital garnets

	Malinowa Fm	Białe Fm	Jaworzynka Fm	Szczawina Fm	Sandstones from red shales	Jarmuta Fm	Ropianka Fm	Mutne Sds Mb	Szczawnica Fm	Życzanów Mb
Al_2O_3	19.49-21.51	19.65-22.06	19.90-21.83	19.41-21.18	20.08-21.75	19.12-21.20	20.34-22.25	19.65-22.61	19.91-21.10	19.92-21.52
SiO_2	34.89-37.77	34.60-38.83	34.04-39.61	35.26-37.28	35.76-38.26	36.30-37.93	36.14-39.75	35.14-40.02	34.46-37.36	35.57-37.70
TiO_2	0.00-0.39	0.00-0.20	0.00-0.08	0.00-0.48	0.00-0.26	0.00-0.47	0.00-0.63	0.00-0.18	0.00-0.36	0.00-0.17
FeO	19.99-40.54	21.25-35.48	27.60-39.98	28.90-39.37	28.53-40.36	27.05-39.47	12.45-39.18	12.57-38.79	22.98-39.31	28.94-40.56
MgO	0.35-6.86	0.65-9.11	2.22-9.39	0.72-4.19	1.06-7.42	0.41-5.82	1.05-12.79	0.89-11.76	0.45-9.04	0.58-6.67
MnO	0.13-6.57	0.34-10.73	0.33-5.94	0.31-8.36	0.17-5.21	0.27-11.02	0.22-28.17	0.22-19.12	0.16-15.55	0.20-10.10
CaO	0.23-6.21	0.52-12.49	0.57-3.02	0.53-9.01	0.41-5.40	0.66-8.42	0.27-12.98	0.52-19.90	0.45-8.68	0.48-5.93
Si^{4+}	5.80-6.04	5.72-6.09	5.67-6.09	5.83-6.03	5.88-6.01	5.82-6.04	5.8-6.01	5.69-5.95	5.85-5.97	5.85-5.96
Al^{3+}	3.84-4.05	3.53-4.11	3.85-3.95	3.81-4.02	3.89-4.03	3.72-4.06	3.70-4.04	3.68-4.02	3.87-3.98	3.87-4.03
Fe^{3+}*	0.04-0.31	0.00-0.76	0.05-0.20	0.00-0.32	0.00-0.22	0.00-0.35	0.02-0.46	0.09-0.12	0.06-0.26	0.08-0.27
Ti^{4+}	0.00-0.05	0.00-0.02	0.00-0.01	0.00-0.06	0.00-0.07	0.00-0.06	0.00-0.08	0.51	0.00-0.04	0.02
Fe^{2+}	2.59-5.43	3.36-4.61	3.49-5.02	3.80-5.41	3.67-5.45	3.50-5.21	1.39-5.16	1.44-5.15	2.95-5.26	3.73-5.42
Mg^{2+}	0.09-1.61	0.16-2.09	0.55-2.15	0.17-1.01	0.26-1.72	0.10-1.38	0.03-3.96	0.27-2.55	0.12-1.22	0.14-1.57
Mn^{2+}	0.02-2.99	0.03-1.50	0.04-0.82	0.04-1.16	0.02-0.72	0.04-1.56	0.05-2.06	0.03-2.64	0.02-2.15	0.03-1.41
Ca^{2+}	0.04-1.08	0.09-2.17	0.10-0.51	0.06-1.55	0.07-0.94	0.12-1.49	0.11-1.25	0.09-1.36	0.08-1.58	0.09-1.04
prp	1-26	3-35	9-36	3-17	4-28	2-23	4-48	4-43	2-20	2-26
alm	43-89	56-76	59-85	63-90	61-90	57-85	49-80	23-84	48-86	61-88
sps	1-48	1-25	1-13	1-19	1-12	1-25	0-8	0-64	1-35	0-23
and	0-8	1-19	1-10	0-8	0-5	0-9	1-5	0-12	0-6	2-7
grs	0-15	1-28	0-6	0-24	0-14	0-21	0-16	0-31	0-21	0-13

Oxides in wt %. Elements in number of cations. All calculations were based on 24 oxygen atoms.

* The amount of Fe^{3+} was approximately established as the supplement to sum of trivalent cations in the ideal stoichiometric formula of garnets.

Formation. The amount of pyrope tends to increase towards younger lithostratigraphic units: it is higher in the garnets from the Mutne Sandstones (Palaeocene) and the Ropianka Formation (Palaeocene) than in garnets from the Jaworzynka Formation (Campanian – Maastrichtian). Spessartine amounts ranging from 20-63 mol % (8 % of garnet grains) and grossularite ranging from 20-31 mol % (4 % of garnet grains) were found only in the Mutne Sandstone Member. In the Jaworzynka and Malinowa formations, the spessartine, grossularite and andradite contents do not exceed 15 mol %.

In garnets derived from the southern source region almandine predominates. Pyrope contents reaching 26 mol % were found only in single grains. Spessartine attains higher values (up to 48 mol %), but also only in single grains. In addition, no change of chemical composition in the garnets with time was observed (Table 3; see also SALATA 2004).

Chromian spinel

Spinel grains are reddish brown but this is visible only in thin grains, whereas the thick ones are transparent only at their edges. The spinels are present mostly in the form of un-rounded platy angular fragments or splinters (Text-fig. 7.14-7.15).

The chromian spinels belong to a solid solution designated by $FeCr_2O_4$-$FeAl_2O_4$-$MgCr_2O_4$-$MgAl_2O_4$. Compositional zoning and chemical variability as well as admixtures of other phases have not been found in the minerals. A single grain from the Szczawina Sandstones contained an inclusion of olivine $Fo_{92.1}$.

In the majority of spinel grains $Cr_2O_3 > Al_2O_3$, but single grains of chromian spinels with the chemical composition of chromites have been found in the Jarmuta and Szczawnica formations. The values of both the Cr/(Cr+Al) and $Fe^{2+}/(Mg+Fe^{2+})$ ratios show a variation in a broad range from over 0.20 to over 0.80. The estimated Fe^{3+} content is low and ranges from 0.00 to 0.93apfu, while the Fe^{2+} amount ranges from about 2.50 to over 6.00. Therefore the Fe^{2+}/Fe^{3+} ratio in the spinels is high and exceeds 3.00. Only single grains from the Szczawnica Formation had a value lower than 3.00. The content of TiO_2 in most grains is lower than 0.3 wt %; only two spinels from the Jarmuta Formation and three grains from the Szczawnica Formation had values higher than this (Table 4). Other oxides like MnO_2, V_2O_5, CaO and ZnO occur in amounts not reaching 1.0 wt % (Table 4).

	Białe Fm	Szczawina Fm	Jarmuta Fm	Szczawnica Fm
Al_2O_3	9.72-45.88	18.12-30.11	7.08-47.31	5.72-39.67
Cr_2O_3	22.91-57.99	39.94-59.98	6.26-62.13	26.64-67.26
V_2O_5	0.12-0.40	0.16-0.38	<0.01-0.46	<0.01-0.49
TiO_2	<0.01-0.14	<0.01-0.32	<0.01-0.45	<0.01-2.22
MgO	6.83-18.57	9.51-13.27	0.40-16.09	3.08-16.80
FeO	10.87-24.63	<0.01-20.13	2.85-29.31	14.07-30.29
MnO	<0.01-0.45	<0.01-0.49	<0.01-0.65	<0.01-0.94
CaO	<0.01-0.16	-	<0.01-0.23	<0.01-0.31
ZnO	<0.01-0.30	-	<0.01-0.65	<0.01-1.25
Al^{3+}	3.12-11.69	5.40-8.38	2.33-12.25	1.92-10.59
Cr^{3+}	3.97-12.47	7.52-11.13	2.28-13.73	4.98-14.58
Fe^{3+} *	<0.01-0.66	<0.01-0.30	<0.01-0.88	<0.01-0.93
V^{5+}	<0.01-0.07	0.03-0.06	<0.01-0.54	0.02-0.09
Ti^{4+}	<0.01-0.03	<0.01-0.06	<0.01-0.19	<0.01-0.43
Mg^{2+}	2.77-5.99	3.69-4.72	0.11-5.28	1.30-7.80
Fe^{2+}	1.66-5.19	<0.01-4.16	2.57-6.32	2.36-6.10
Mn^{2+}	<0.01-0.10	<0.01-0.06	<0.01-0.14	<0.01-0.23
Ca^{2+}	<0.01-0.04	-	<0.01-0.06	<0.01-0.12
Zn^{2+}	<0.01-0.06	-	<0.01-0.13	<0.01-0.26

Oxides in wt %. Elements in number of cations. All calculations were based on 32 oxygen atoms.

* The amount of Fe^{3+} was approximately established as the supplement to sum of trivalent cations in the ideal stoichiometric formula of chromian spinels.

Table 4 Summary of chemical analyses of detrital chromian spinels

DISCUSSION

Provenance of the heavy minerals

Zircon

The variety of external and internal features of the zircons, especially roundness and types of zoning, indicates that the zircon population is definitely not uniform and suggests a complex history.

The rare euhedral zircons were most probably transported directly from the primary source rocks, while the rounded ones are probably older, underwent recycling and may derive from sedimentary as well as metasedimentary rocks occurring in the source areas.

Oscillatory and, sometimes, convolute zoning are usually characteristic of zircons crystallising in igneous rocks (VAVRA 1990, 1993, 1994; PIDGEON 1992; HOSKIN 2000; RUBATTO & GEBAUER 2000). Patchy, cloudy domains with relicts of regular zoning in some zircon grains indicate that they underwent alteration under high grade metamorphic conditions (VAN BREEMEN *& al.* 1987; PIDGEON 1992; VAVRA *& al.* 1996).

Monazite and xenotime

Monazite and xenotime are mainly components of granites, pegmatites and syenites. Xenotime may also form in quartz-mica gneisses (DEER *& al.* 1963, 1992; MANGE & MAURER 1992). A low La/Nd ratio in the monazites, oscillating around 1.3, suggests their origin from granitoid type rocks (FLEISCHER & ALTSCHULER 1969 *fide* MORTON 1995).

Tourmaline

The predominance of un-rounded grains in the tourmaline populations suggests their derivation from a primary source, while the minority rounded grains may derive, similarly to zircons, from sedimentary or metasedimentary rocks. The high concentration of rounded (even spherical) tourmalines in the Mutne Sandstones and Ropianka Formation may be the effect of long or intensive transport in a high-energy water environment.

There is almost no difference in the chemical composition of the tourmalines derived from the SE and NW. As mentioned above, the predominant part of the tourmaline population represents a transitional composition between schorl and dravite.

Tourmalines belonging to the schorl–dravite series may crystallise in granitoids (usually the schorl type) as well as in metamorphic rocks (dravite type). However, the chemical composition of the tourmalines, especially the fact that the $Mg/(Mg+Fe_{tot})$ ratio values are mostly higher than 0.40 (Table 2), indicates that most of them formed under metamorphic conditions (HENRY & DUTROV 1992, 1996). Only a few grains in each tourmaline population displayed chemistry reflecting their derivation from igneous rocks of granitoid type (HENRY & DUTROV 1992, 1996). Points discriminated by the main cations: Al, Mg and Fe, plot mainly in the fields of various types of metapelites and metapsammites, only a small number of points plot in the areas of granitoids and associated rocks (Text-fig. 9) (HENRY & GUIDOTTI 1985; HENRY & DUTROV 1992, 1996). The lack of a clear difference in the chemistry of the centres and rims of the tourmaline crystals suggests stable conditions throughout their growth.

Garnet

Garnets with the predominant almandine end member may crystallize under different conditions, from granitoid melts to metamorphic alterations up to granulite facies. Interpretation of their provenance is therefore difficult. Nevertheless, considering the fact that most of the tourmalines studied derived from metamorphic rocks we may assume that the garnet populations occurring with tourmalines in the heavy mineral assemblages derived from the same genetic rock-type. Since determination of mineral phases coexisting in paragenesis with garnets is impossible, the P-T conditions obtaining during garnet growth cannot be known in detail. However, taking into consideration the fact that garnets rich in Fe develop mainly during barrowian type metamorphism, we can assume that the source rocks could have been garnet-mica schists, gneisses and/or amphibolites. For garnets forming under high-grade metamorphic conditions an increase of the pyrope end member is characteristic (MIYASHIRO 1953, 1975; STURT 1962; NANDI 1967; MIYASHIRO & SHIDO 1973). Therefore, garnets with pyrope amounts higher than 20% or 30% may derive from rocks of granulite facies. Such garnets are especially frequent in assemblages transported from the NW or NE. According to the determination diagram of MIYASHIRO & KUCULU (in ANTIPIN 1977), most of the garnets derived from the SE were formed under metamorphic conditions of the epidote-amphibolite and garnet-amphibolite facies (Text-fig. 10). Therefore, their parent rocks could have been the above-mentioned amphibolites, gneisses and garnet-mica schists. As noted above, the pyrope content of the garnets coming from the opposite source region increases towards younger lithostratigraphic units (Text-fig. 10). As the sequence of clastic material is usually in reverse order to that of the

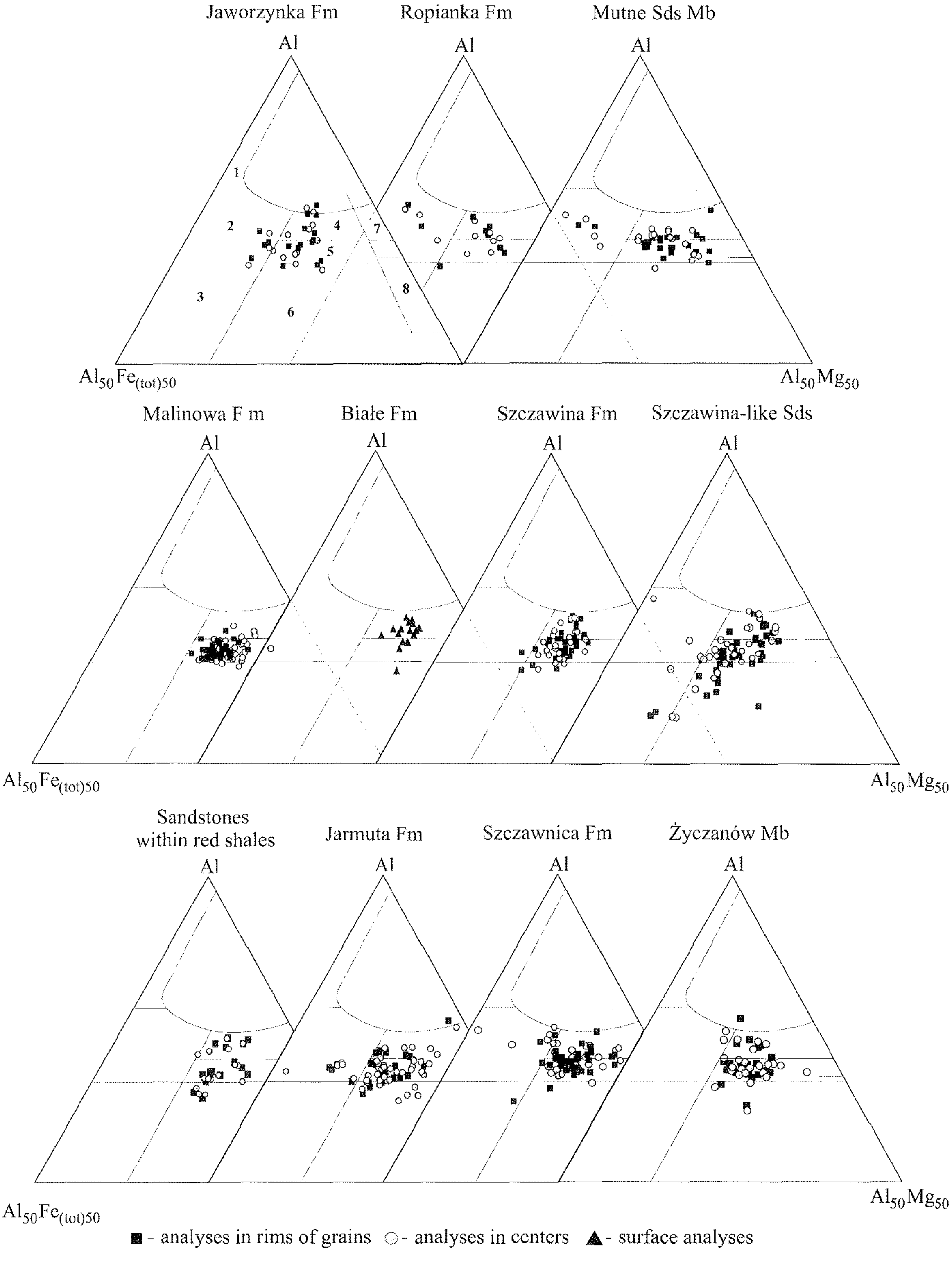


Fig. 9. Provenance of tourmalines from the investigated lithostratigraphic units in Al-Fe(tot)-Mg diagrams (numbering of fields as in the triangle for the Jaworzynka Formation: 1) Li – rich granitoid pegmatites and aplites, 2) Li – poor granitoids and associated pegmatites and aplites, 3) Fe^{3+}-rich quartz tourmaline rocks (hydrothermally altered granites), 4) Metapelites and metapsammites coexisting with an Al – saturating phase, 5) Metapelites and metapsammites not coexisting with an Al – saturating phase, 6) Fe^{3+} – rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites, 7) Low – Ca metaultramafics and Cr, V – rich metasediments, 8) Metacarbonates and meta-pyroxenites (Henry & Guidotti 1985)

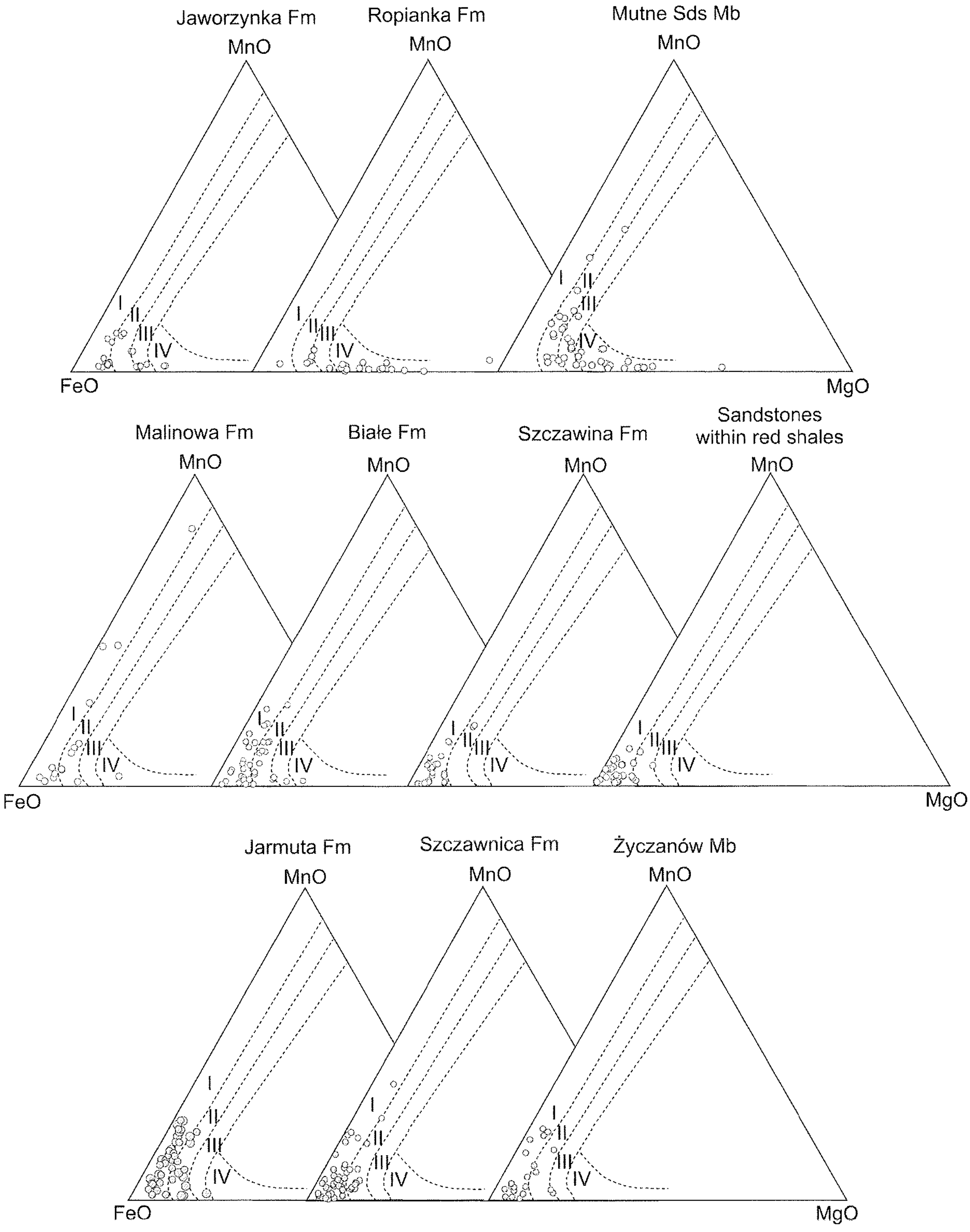


Fig. 10. Chemical composition of the detrital garnets from the sampled lithostratigraphic units. Individual fields represent various metamorphic zones: I – garnets from greenschists and epidote-amphibolite facies, II – garnets from epidote-amphibolite facies and low-temperature subfacies of garnet-amphibolite facies, III – garnets from amphibolite facies, IV – garnets from granulite facies (according to MIYASHIRO & KUCULU in ANTIPIN 1977)

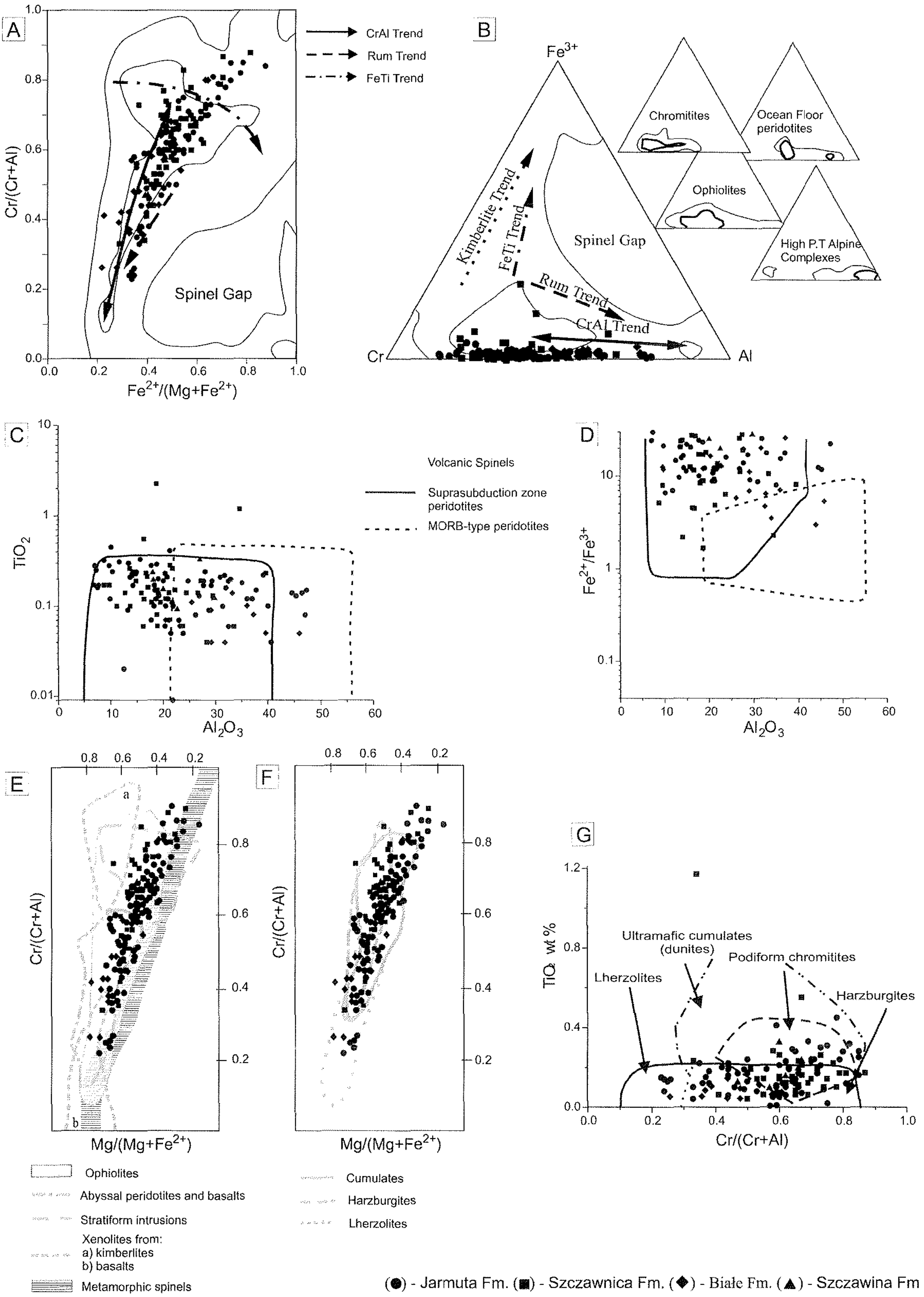


Fig. 11. Provenance of the analysed chromian spinels (A, B – Barnes & Roeder 2001; C, D – Kamenetsky & *al.* 2001; E, F – Dick & Bullen 1984; G – Pober & Faupl 1988)

parent rocks in the source area, such a change in garnet composition reflects a gradual change in rock types from high grade-metamorphic ones, up to medium-grade rock types in the upper part of the host massif (SALATA 2004).

Chromian spinel

The low amounts of Fe^{3+}, the broadly variable amounts of Al and Cr, and the Cr/(Cr+Al) and $Fe^{2+}/(Mg+Fe^{2+})$ values all indicate that the spinels represent the Cr-Al trend (BARNES & ROEDER 2001) (Text-fig. 11A, B). Such a sloping trend is representative of plutonic ultramafic and mafic bodies including Alpine-type peridotites, ophiolites and ocean floor peridotites. The spinels do not display such low Al and high Cr compositions as the high P-T Alpine peridotites and hence seem not to be derived from such rock-types, albeit ophiolites and ocean floor peridotites cannot be excluded (Text-fig. 11B). The enclosure of the TiO_2 *vs* Al_2O_3 as well as Fe^{2+}/Fe^{3+} *vs* Al_2O_3 data in the field representing the composition of the suprasubduction zone also suggests a mantle origin for the spinels (KAMENETSKY & *al* 2001). Only three grains from the Szczawnica Formation display features of volcanic spinels ($TiO_2>0.3$ wt % and $Fe^{2+}/Fe^{3+}<3$) (Text-fig. 11C, D).

The ranges of the Cr/(Cr+Al) and the Mg/(Mg+Fe) ratios allow the source of the spinels to be interpreted as an ophiolite sequence (DICK & BULLEN 1984; POBER & FAUPL 1988; HAGGERTY 1991) (Text-fig. 11E). The chemistry of the spinels agrees with that of spinels occurring in Cr-rich ultramafic cumulates, lherzolites and harzburgites (Text-fig. 11F, G). The fields representing the composition of the rocks overlap on the discrimination diagrams and therefore the exact determination of the parental source is difficult. Nevertheless, we can suppose that the grains represent a mixture of spinels originating from different parts of the obducted ophiolite. This interpretation of the provenance of the Cr-spinels is supported by the composition of the olivine inclusion found in one of the spinels, which suggested its provenance from ultramafic bodies (MALPAS & STRONG 1975).

PALAEOGEOGRAPHY OF THE MAGURA BASIN

During the Cenomanian–Turonian a period of slow and uniform sedimentation prevailed in almost all of the Outer Carpathian Basins (ŚLĄCZKA & KAMIŃSKI 1998; OSZCZYPKO 1992, 1999, 2004) (with the exception of the western part of the Silesian and the southern part of the Skole subbasins). This period was characterised by very low rates of sedimentation (0.5-5 m/my). At the end of the Cenomanian, radiolarian shales followed by red clays with intercalations of basinal turbidites were deposited below the CCD (OSZCZYPKO 1999). Oxic conditions prevailed, and the appearance of red and green shales like the Malinowa Formation in the Magura Basin (BIRKENMAJER & OSZCZYPKO 1989) is typical. In the northern and middle part of the Magura Basin (Text-fig. 12) this type of sedimentation persisted up to the Campanian, whereas in the Krynica zone it persisted until the Maastrichtian (OSZCZYPKO 2001). The rate of sedimentation of the variegated shales varies between 15 to 25 m/my. The basinal variegated shales of the Magura Basin were bounded to the south and north by slope deposits represented by pelagic variegated marls (Scaglia rossa type). The southern slope of the basin consisted of the Czorsztyn succession of the PKB (Jaworki Formation, BIRKENMAJER 2001). The northern slope of the Magura Basin could have been composed of the Late Cretaceous Fore-Magura Marls and shales (see KOSZARSKI 1985). The south-eastern prolongation of these marls is probably represented by the Puchov Marls of the Marmarosh Klippen (Vezany Unit, see OSZCZYPKO 2004). This opinion corresponds well with ŻYTKO's (1999) idea of the correlation of the Rača, Bystrica and Krynica lithofacies zones of the Magura Nappe in the Western Carpathians with the Trans-Carpathian Palaeogene Flysch (Petrova Monastyrec), Botiza and Wild Flysch of the Ukraine and Romanian Carpathians respectively (SMIRNOV 1973; AROLDI 2001).

During the Late Campanian/Palaeocene time, a considerable reorganisation of the Magura Basin took place (Text-fig. 13). At the very beginning (Campanian) this was connected with inversion of the Silesian Ridge (POPRAWA & *al.* 2002) at the northern margin of the Magura Basin and finally (Maastrichtian–Palaeocene) by the collision of the Inner Carpathian block with the Czorsztyn Ridge (OSZCZYPKO 2004). It was accompanied by deposition of the Upper Senonian–Palaeocene flysch. The rate of sedimentation varied between 50 and 75 m/my. In the NW and NE segment of the Magura Nappe in Poland (Siary Subunit), which was supplied from the Silesian Ridge, flysch deposition started with the Jaworzynka Formation at the turn of the Santonian, and was followed during the Maastrichtian–Palaeocene by deposition of the Mutne Member of the Ropianka Formation with complexes of thick bedded sandstones.

The start of flysch deposition in the Bystrica Subunit (Koninki-Półrzeczki-Szczawa area) took place during the Campanian. This coarsening- and thickening-upwards turbidite sequence begins with few dozen metres of distal flysch deposits with intercalations of turbiditic limestones (Białe Formation – Campanian), which grade upwards into a thick complex of thick-bedded sandstones and conglomerates (Szczawina Sandstone Formation-Maastrichtian –

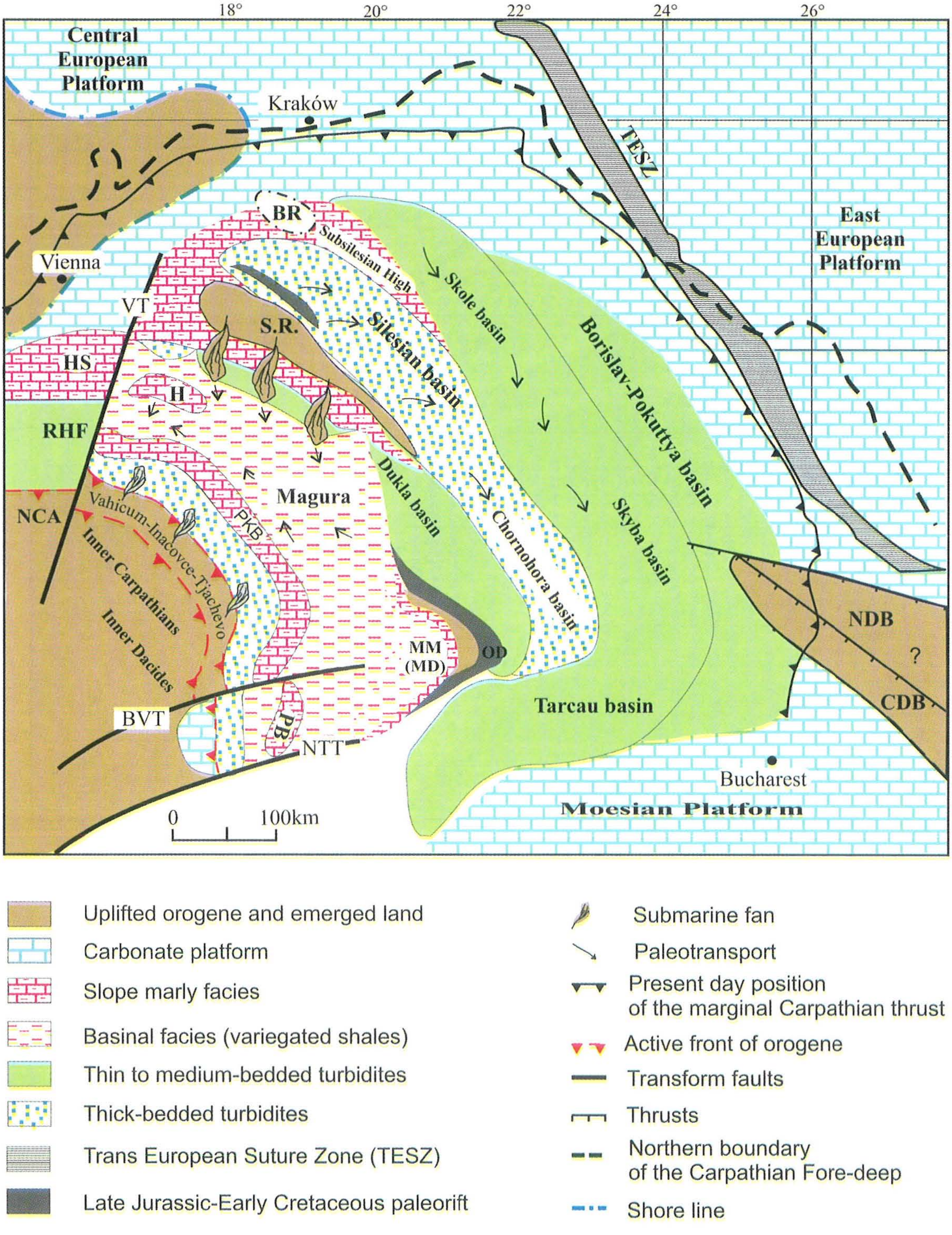


Fig. 12. Late Campanian palaeogeographic and palinspastic map of the Outer Carpathian sedimentary area (partly after Ellouz & Roca 1994; Aroldi 2001). Abbreviations: BR – Baška Ridge, VT – Vienna transform fault, HS – Helvetic shelf, RHF – Rheno-Danubian Flysch, NCA – Northern Calcareous Alps, SR – Silesian Ridge, H – Hluck submerged ridge, PKB – Pieniny Klippen Belt, MM (MD)-Marmarosh Massif (Median Dacides), OD – Outer Dacides, BVT – Bohdan-Voda transform fault, PB – Poiana Botizi submerged ridge, NTT – North Transylvanian transform fault, NDB – North-Dobrudja Belt, CDB – Central-Dobrudja Belt, TESZ – Trans-European Suture Zone

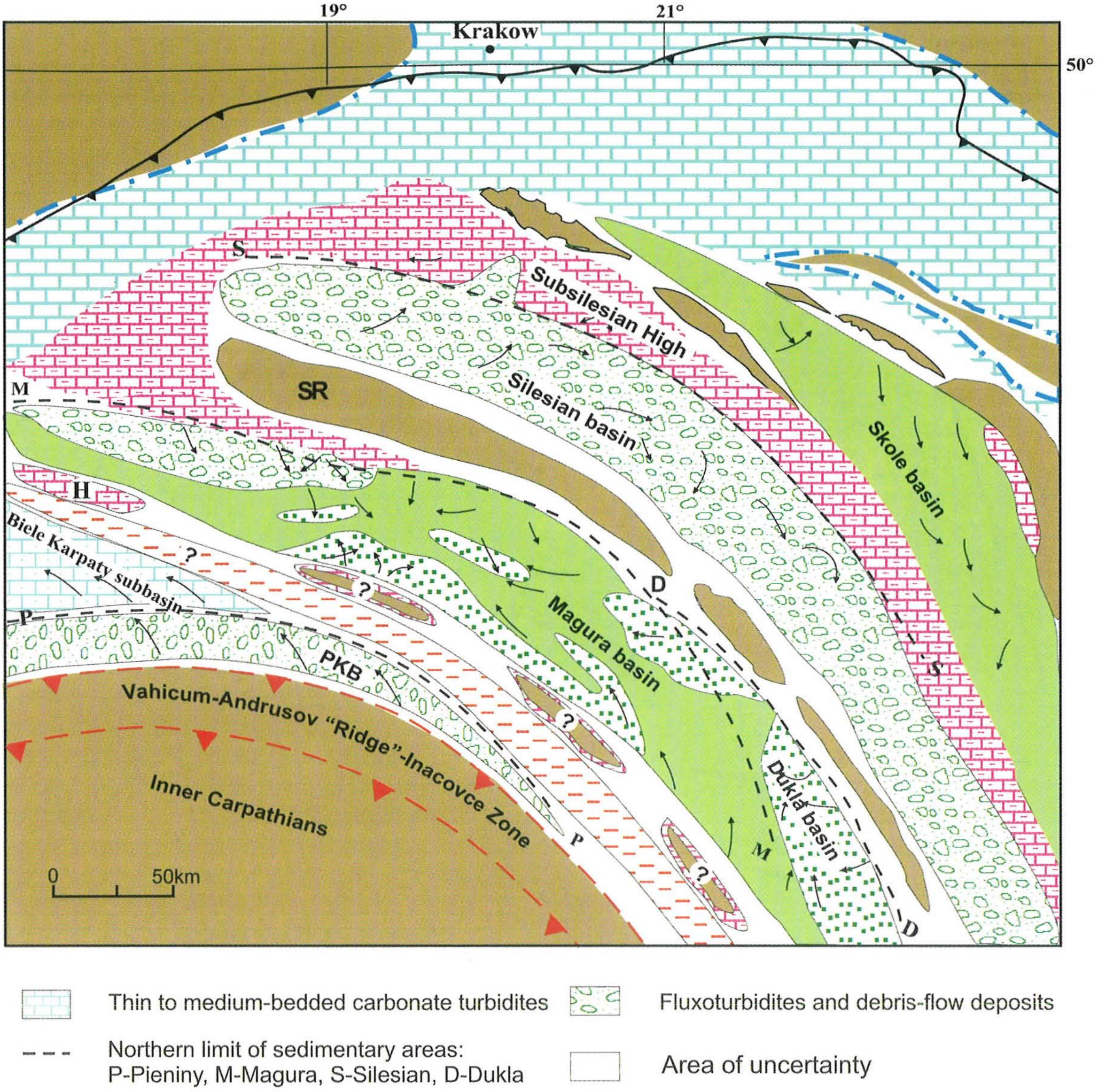


Fig. 13. Maastrichtian palaeogeographic and palinspastic map of the Outer Carpathian sedimentary area (partly after KSIĄŻKIEWICZ 1962). For abbreviations see Fig. 12

Palaeocene). The upper part of this sequence, which displays fining- and thinning-upward trends, belongs to the Ropianka Formation (Palaeocene), which finally passes into variegated shales of the Łabowa Formation (Lower Eocene). All the Upper Cretaceous – Palaeocene deposits of the Bystrica Unit display palaeotrasnport directions from the S and SE.

In the Muszyna area (Krynica Subunit), the transition from the uppermost part of the Malinowa Formation (Maastrichtian) to the Szczawnica Formation (Palaeocene) is marked by the development of green shales with sporadic intercalations of medium-bedded, fine-grained quartzitic sandstones.

In the Grajcarek Unit of the PKB the flysch deposits start with the coarse-clastic Jarmuta Formation (Maastrichtian – Palaeocene) which passes upwards and northwards (Krynica Subunit) into calcareous flysch of the Szczawnica Formation (Palaeocene–Early Eocene).

POSITION AND CHARACTER OF SOURCE AREAS

During the Late Cretaceous/Palaeogene the Magura Basin was supplied from two opposite directions located on the NW/NE and SE sides of the basin.

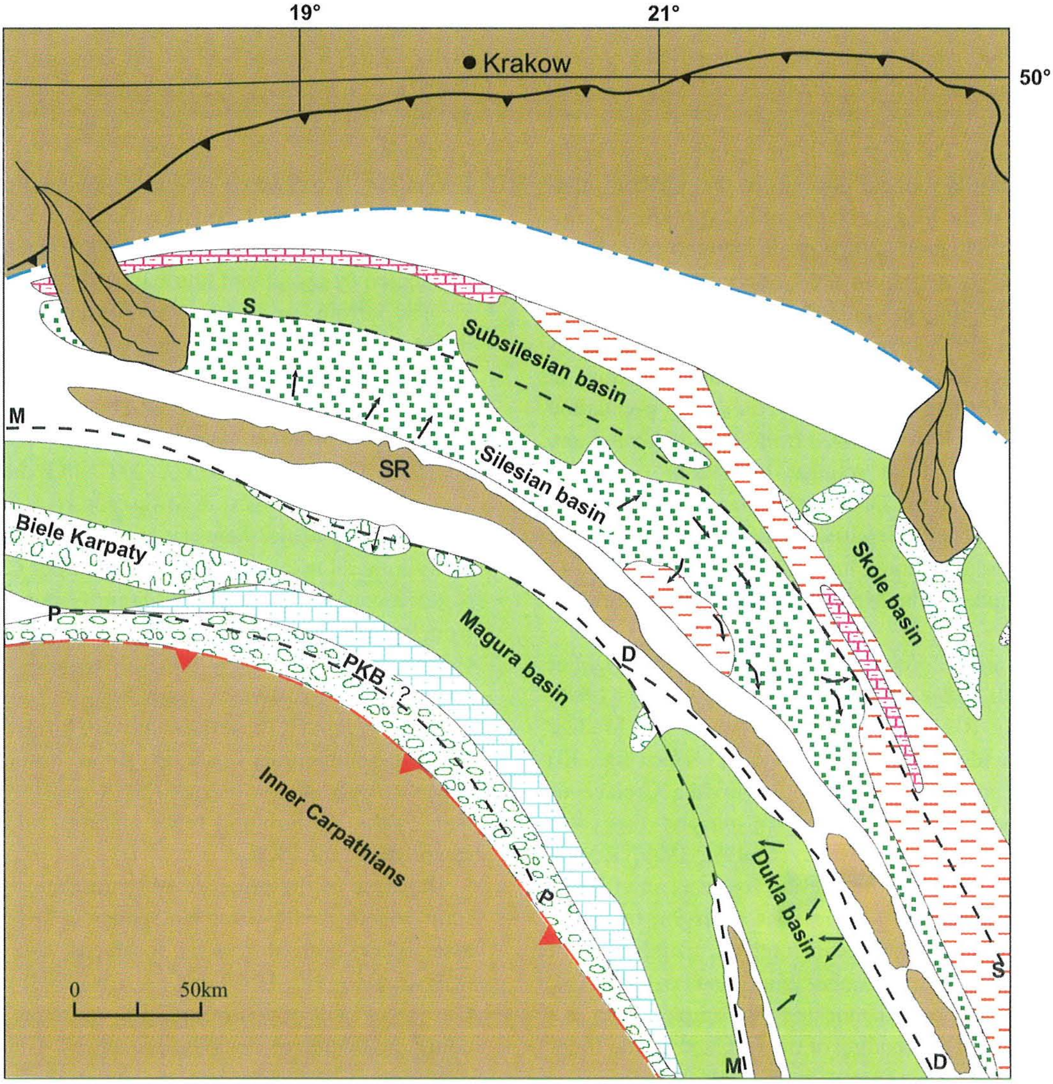


Fig. 14. Palaeocene palaeogegraphic and palinspastic map of the Outer Carpathian sedimentary area (partly after KSIĄŻKIEWICZ 1962). For abbreviations see Fig. 12

The northern source area is commonly correlated with the Silesian Ridge, being mostly active from the Late Senonian through Early Oligocene (Text-figs 11-14, see also KSIĄŻKIEWICZ 1962). The Silesian Ridge is interpreted as a 50-100 km wide "crystalline ribbon continent" (SOTAK 1990). Towards the south the ridge passed into a narrow shelf and a slope occupied by the Fore-Magura basin with pelagic sedimentation.

The geological structure of the Silesian Ridge was reconstructed on the basis of exotic pebbles and heavy mineral studies. According to KRYSTEK (1965), KRYSOWSKA-IWASZKIEWICZ & UNRUG (1967), WIESER (1970), BURTAN & *al.* (1984), ELIAŠ & ELIAŠOVA (1984), WINKLER & ŚLĄCZKA (1992, 1994) the Silesian ridge was built of barrowian-type metamorphic rocks (phyllites, schists, gneisses, granulites) and quartzites, felsic igneous rocks and sedimentary rocks (mainly limestones). Provenance analyses based on the heavy minerals confirms the theory that such rocks were included in the above-mentioned source region but also yield additional information. The chemical composition of the garnets and tourmalines, the variability in the zircon population and the high roundness of the zircon grains indicate that almost all of them originated from metamorphic rocks, and that such rocks covered a large part of the ridge. It contradicts the idea of KRYSOWSKA-IWASZKIEWICZ & UNRUG (1967) who connected the tourmalines and zircons chiefly with granitoids and, to a lesser extent, with metamorphic rocks. Moreover, closer inspection of the "zircon" population as well as chemical analyses revealed the presence of significant amounts of monazite and xenotime, which had not been recognised previously. Their presence in the assemblages and their chemistry confirm the existence of granitoid-type rocks in the Silesian Ridge. The increase in the pyrope content in the garnets towards younger deposits in the northern marginal parts of the Magura Nappe reflects progressive erosion and exhumation of high-grade metamorphic rocks.

Detrital garnets from the Cretaceous sediments of the Magura Group in southern Moravia were studied by OTAVA *& al.* (1997, 1998). The composition of the garnets is similar to that of garnets from the Silesian Ridge in Poland. According to the authors, the garnet population from the Gault Flysch derived from the Moldanubikum, whereas garnets from younger formations originated from the Kulm of the Drahany Highland.

The data from the garnet analyses suggest that the Silesian Cordillera could have had a similar structure to the rocks building the Moldanubikum and the Moravian Variscides.

There are different opinions regarding the origin of the Silesian Ridge. According to SANDULESCU (1988), the Silesian Ridge was a prolongation of the Median Outer Dacides (Marmarosh Massif) (Text-fig. 10) deformed and uplifted during the middle Cretaceous collision with the Outer Dacide terrane (see also ROYDEN & BALDI 1988; OSZCZYPKO 1992, 1999). ROURE *& al.* (1993) regarded the Silesian Ridge as an effect of the Late Cretaceous – Palaeocene inversion tectonics, which affected the European foreland, mainly west of the Tornquist–Teisseyre mobile zone (also POPRAWA *& al.* 2002). It was probably connected with simple shears as a consequence of the loading of the foreland by the Inner Carpathians nappes (DERCOURT *& al.* 1990).

The position of the southern source area(s) is still debated (Text-fig. 12-14). This source area was uplifted during the Maastrichtian – Palaeocene, being most active during the Eocene. The exotic rocks from the Jarmuta and, in part, the Szczawnica formations are rich in fragments and pebbles of the crystalline and sedimentary rocks of the basement (BIRKENMAJER 1988; BIRKENMAJER & WIESER 1990); Triassic quartzites, red shales, limestones and dolomites, Lower Jurassic to Aptian shallow-water and pelagic rocks (mainly limestones), and volcanic and pyroclastic rocks of the Late Jurassic (?)– Late Cretaceous subduction-related magmatism. These rocks reveal a strong connection with the so called "exotic" Andrusov Ridge (BIRKENMAJER 1986, 1988), which was uplifted during the Late Cretaceous accretion of the Central Western Carpathian units wedge with the Pieniny Klippen Belt (Oravic ribbon continent) terrane (PLASIENKA 2002; KOVAČ & PLASIENKA 2002). The same provenance of material is shown by the Javorina Formation (Late Campanian – Maastrichtian) of the Biele Karpaty Unit of the Magura Nappe (W Slovakia, see POTFAJ 1993; ŠVABENICKA *& al.* 1997). The Javorina Formation, which shows similarity both to the Szczawina Sandstones as well as to the Jarmuta Formation, is composed of quartz, metamorphic rocks and large amount of carbonate rocks (up to 45%), mainly dolomites, derived from the S. The heavy minerals are dominated by garnet and tourmaline (POTFAJ 1993).

The Jarmuta and Szczawnica formations have similar heavy mineral assemblages to those of the formations in the Rača and Bystrica subunits but, in contrast, they are additionally characterised by the relatively high content of chromian spinels (see also WINKLER & ŚLĄCZKA 1992, 1994; SALATA 2003 and this paper). According to WAGREICH & MARSCHALKO (1995), there are close similarities between the chromian spinels in heavy mineral associations from the Upper Cretaceous – Palaeocene of the Brezova-Manin Group and those from the Gosau Group of the Northern Calcareous Alps (NCA). The same heavy mineral assemblages of the Jarmuta and Szczawnica formations of the Magura Nappe suggest that these deposits were formed in a continuous sedimentary area in slope basins of the Adriatic/Austroalpine margin (NCA and their equivalents in the Western and Inner Dacides) and accreted fragments of the PKB.

Because of the presence of tourmaline, zircon and rutile together with chromian spinels in heavy mineral assemblages derived from the south-east area WINKLER & ŚLĄCZKA (1992, 1994) and SALATA (2003) concluded that it was built of continental-type rocks but also contained fragments of ophiolite sequences. The chemical composition of the garnets and tourmalines indicates that they crystallised under low- to medium-grade metamorphic conditions and that therefore the metamorphic rocks building the south-eastern source area were mainly phyllites, schists, gneisses and/or amphibolites. Only single grains of tourmalines originated from granitoid type rocks. This idea is supported by the fact that such rocks were found among exotic pebbles coming from the same SE direction. The chemistry of the chromian spinels implies that the listed rock-types co-existed with ultramafic harzburgites, lherzolites and cumulates, indicating the active character of the source area.

In the Middle Jurassic deposits of the PKB, AUBRECHT & MÉRES (2000) noted pyrope-almandine garnets and stated that their origin was connected with granulites and eclogites of the Moldanubikum. Such a garnet composition does not correspond to the almandine-dominated garnets from the Jarmuta and Szczawina formations which derived from the SE area in the Inner Carpathians.

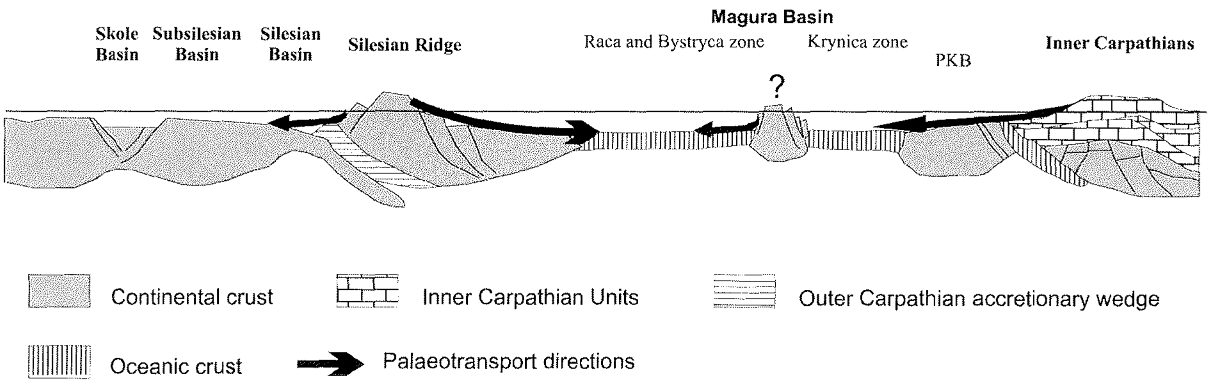


Fig. 15. The Late Cretaceous–Palaeocene palinspastic model of the Northern Carpathians. (based on OSZCZYPKO 1999, supplemented)

The Maastrichtian–Palaeocene Szczawina Sandstones of the Bystrica and Rača subunits (Text-fig. 13) of the Magura Nappe, dominated by monocrystalline quartz grains and feldspars, have different compositions of exotic pebbles (crystalline rock fragments and small amount of carbonates) and only traces of chromian spinels in the heavy mineral assemblages. This suggests weaker (distal) relationships with the active Austroalpine margin (WAGREICH & MARSCHSALKO 1995) or the presence of a small local intrabasinal ridge which supplied the Szczawina sandstones with clastic material (Text-fig. 15). During the Maastrichtian – Palaeocene an additional source of clastic material could have appeared on the boundary between the Krynica and Bystrica facies zones (Text-figs 13, 15). The existence of the source was very short. In the Late Palaeocene and Eocene the source disappeared and unifying of facies took place again.

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