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The Upper Oligocene–Lower Miocene Krosno lithofacies in the Carpathian Flysch Belt (Czech Republic): sedimentology, provenance and magnetic fabrics

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Abstract: The Krosno lithofacies is the Upper Oligocene–Lower Miocene synorogenic sequence that terminates the flysch sedimentation in the orogenic system of the Western Carpathians. Its deposition replaced the hypoxic sedimentation of the underlying Oligocene Menilite Formation. This change in deposition was connected with the Helvetian Neoalpine orogeny which iniciated the fundamental rearangement in the orogenic belt, gradual isolation of foreland basins and creation of the "Protoparatethys". The differences in deformation between the Krosno lithofacies and the underlying Upper Cretaceous to Eocene strata are recorded in all tectonofacial units of the Outer (Menilite-Krosno) Group of thrust sheets. Moreover, a trend towards increase of ductile deformation from the outer to the inner margin of the Flysch Belt is evident. The investigation of translucent heavy minerals produced evidence of different spectra between the Krosno lithofacies and underlying strata of individual tectonofacial units. The spatial distribution of the Krosno lithofacies and the transport of clastic material from the SE indicate the deposition of a submarine fan that prograded to the NW.

Key words: Upper Oligocene–Lower Miocene, Carpathians, Flysch Belt, Krosno lithofacies, tectonics, paleogeography, sedimentology, heavy minerals, magnetic anisotropy.

Introduction

The Krosno lithofacies consisting of Upper Oligocene to Lower Miocene synorogenic sediments crowns the flysch deposition in the Western Carpathian Flysch Belt. It reflects the integrated effects of the Helvetian Neoalpine orogeny and eustatic changes in the Oligocene. This lithofacies characterizes, together with the Menilite Formation, the Outer (Menilite-Krosno) Group of thrust sheets of the Flysch Belt. In the Magura Group of thrust sheets this lithofacies described from eastern Slovakia and Poland by Świdziński (1961) as the Malcov Formation was not studied.

The purpose of the present paper is to characterize the Krosno lithofacies and its underlying sediments from the point of view of lithology, petrology, sedimentology, paleogeography and ductile deformation interpreted in terms of plate tectonics. The obtained results follow up the biostratigraphic study (Švábenická et al. 2007), which indicates the gradual onset of the Krosno lithofacies from the internal to external zones of the Outer Group of thrust sheets.

Geological setting

The Upper Oligocene–Lower Miocene Krosno lithofacies represents the youngest flysch sequence of the Outer (Menilite-Krosno) Group of thrust sheets in the Flysch Belt of the Western Carpathians. In the territory of the Czech Republic this lithofacies is developed in the Krosno, Ždánice-Hustopeče and Křepice Formations within the stratigraphic range Late Oligocene–Early Miocene. The Krosno lithofacies in the Outer Group of thrust sheets usually overlies the Menilite Formation originated in the hypoxic environment which dominated in the northern part of Tethys during the Early Oligocene (Table 1). The relation of the Lower Miocene Šakvice Marl to the underlying Krosno lithofacies in the Ždánice and Pouzdřany Units in South Moravia is not clear (Cicha & Pícha 1964; Molčíková & Stráník 1987; Krhovský et al. 1995).

The diachronous onset of the Krosno lithofacies based on the occurrence of the marker Jasło Limestone in different lithostratigraphic units (Menilite, Krosno and Malcov Formations) was supported by Koszarski & Żytko (1959), Jucha (1969) and Haczewski (1989) in the Polish and Slovak Flysch Carpathians. In the Czech Republic only incomplete information exists from this point of view about the age of the Krosno lithofacies (Bubík 1987; Bubík & Švábenická 2000; Stráník & Švábenická 2004).

Material

Not only the profiles containing boundary strata of the Krosno lithofacies and Menilite Formation but also indi-

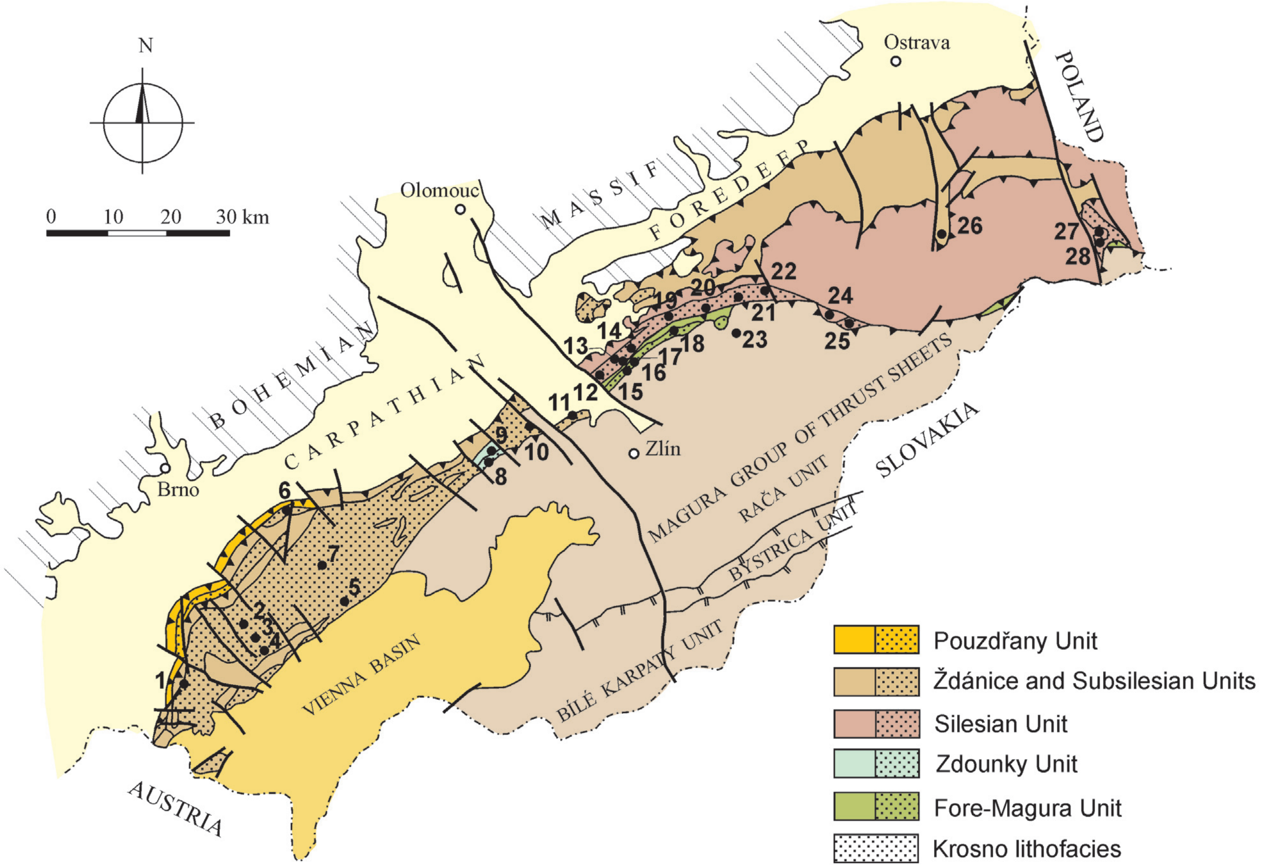

Fig. 1. Extent of the Krosno lithofacies of the Carpathian Flysch Belt in the Czech Republic. **1** — Dolní Věstonice, **2** — Boleradice, **3** — Němčičky, **4** — Velké Pavlovice, **5** — Stavěšice, **6** — Slavkov, **7** — Ždánice, **8** — Divoky, **9** — Milovice, **10** — Těšnovice, **11** — Kurovice, **12** — Holešov, **13** — Jankovice, **14** — Tučapy, **15** — Chomýž, **16** — Brusné, **17** — Brusné lom, **18** — Slavkov, **19** — Lhota u Kelče, **20** — Komárno, **21** — Police, **22** — Juřinka, **23** — Hostýn, **24** — Hažová, **25** — Prostřední Bečva, **26** — Ženklava, **27** — Jablunkov, **28** — Jablunkov (Vitališov).

vidual samples from boreholes, excavations, and natural outcrops were chosen for the study of lithology, petrology, sedimentology and ductile deformation (Fig. 1).

Most of the localities were sampled in the Ždánice Unit together with the Subsilesian Unit (about 30 localities). Significantly less of the localities were investigated in the Silesian Unit (about 10 localities) and in the Zdounky and Fore-Magura Unit (about 5 localities).

Lithology and lithostratigraphy

In the Ždánice Unit (incl. the Čejč–Zaječí Zone) and in the Waschberg Zone (Pavlovské vrchy Hills), the Krosno lithofacies is represented by the Ždánice-Hustopeče Formation. The flysch character of this formation is indicated by rhythmic alternation of sandstones, siltstones and grey calcareous shales with subordinate bodies of conglomer-

Table 1: Lithostratigraphy of the Outer (Menilite-Krosno) Group of thrust sheets of the Flysch Belt (Western Carpathians).

NW — SE

		POUZDŘANY UNIT	ŽDÁNICE - SUBSILESIAN UNIT	ZDOUNKY UNIT	SILESIAN UNIT	FORE-MAGURA UNIT
NEOGENE	↑					
	Eggenburgian	Křepice Fm	Ždánice - Hustopeče Fm	Upper division		
	Aquitanian	Boudky Marl			Krosno Formation	
PALEOGENE	Oligocene	Uherčice Fm	Menilite Fm	?	Menilite Formation	
		Pouzdřany Marl				
	Eocene		Němčice and Frýdlant Fms		Rožnov Fm	Submenilite Fm
	Paleocene		↓	Lower division	↓	
CRETAC.	Upper / Late			↓		
	↓					

ates. The proportion of sandstones and shales varies both vertically and horizontally from predominantly shaly to predominantly sandy facies. Based on these changes the pelitic, psammite-pelitic and psammitic facies were distinguished (Cicha et al. 1964). The maximal extent of the formation is known from southeast Moravia. A Krosno lithofacies with planar laminated sandstones was distinguished in the vicinity of Kroměříž and named by Menčík et al. (1954) as the Těšnovice development.

The pelitic facies of the Ždánice-Hustopeče Formation, originally termed the Hustopeče Marls (Rzehak 1881), is characterized by complete predominance of calcareous layered claystones and marls with sporadic thin intercalations and laminas of sandstones and siltstones (Fig. 2.1). The facies presents some similarities in lithology and microbiostratigraphy to the overlying Šakvice Marl (Cicha et al. 1975) of Eggenburgian age. This facies of Eggenburgian age (Švábenická et al. 2007) is widespread in the northwestern margin of the Ždánice Unit south of Slavkov u Brna.

The psammite-pelitic facies of the Ždánice-Hustopeče Formation is characterized by rhythmic alternation of sandstones, siltstones and layered calcareous shales (Fig. 3.1). The cycles usually begin with sandstone at the bottom and gradually pass upwards through siltstones into shales at the top. The thickness of cycles varies from decimeter to several meters. The accumulation of cycles of the same thicknesses gives rise to a sequence of thin, medium- and thick-bedded rhythmites. In the middle rhythmic flysch of the disused quarry near Boleradice village thin intercalations of Zagórz Limestone, described by Haczewski (1984) in Poland, were observed (Fig. 3.2).

The psammitic facies of the Ždánice-Hustopeče Formation, originally termed the Ždánice Sandstone (Steinitzer in Paul 1890), is formed of thick bedded massive fine- to coarse-grained calcareous sandstone of low lithification. Some irregular bodies of conglomerates (usually debrisflows) occur. Thin intercalations of mudstones are very rare. The psammitic facies has a large extension in the SE

Fig. 2. **1** — Pelitic facies of the Ždánice-Hustopeče Formation, Ždánice Unit locality Vážany u Slavkova. **2** — Flute-casts of the Ždánice-Hustopeče Formation, Ždánice Unit, locality Boleradice (disused quarry).

Fig. 3. **1** — Psammite-pelitic facies of the Ždánice-Hustopeče Formation, Ždánice Unit, locality Boleradice (disused quarry). **2** — Nannofossil Zagórz Limestone of the Ždánice-Hustopeče Formation, Ždánice Unit, locality Boleradice (disused quarry).

part of the Ždánice Unit and in the lower part of the Ždánice-Hustopeče Formation (based on the log of deep wells). The total thickness of Ždánice-Hustopeče Formation is estimated to be 1250 m.

The Krosno lithofacies of the Zdounky Unit possess a slightly specific lithology characterized by algal sandstones with *Lithothamnium* sp. Chmelík (1970) described these Oligocene sediments as the Upper division and the underlying Upper Cretaceous to Eocene strata as the Lower division of the Zdounky Unit. The Lower division manifests some lithological similarities with its stratigraphic equivalents in the Ždánice Unit. The Menilite Formation was not observed.

In the Silesian and Fore-Magura Units the Krosno lithofacies is represented by the Krosno Formation (Tietze 1889) which is very similar in lithology to the Krosno lithofacies of the Ždánice Unit. Only the facial differentiation, especially the pelitic facies, is not so distinctly developed. The underlying Menilite Formation in the Silesian and Fore-Magura Units contains some layers of the fine to coarse sandstones (Kliwa Sandstone). The Submenilite Formation, recently renamed to the Rožnov Formation (Eliáš 2001), is characterized by similar lithology to the Němčice Formation of the Ždánice Unit. In its lower part the lenticular bodies of sandstones and conglomerates occur. The thickness of the Rožnov Formation is estimated to be 600–800 m. The facies with slump bodies of tilloid conglomerates (debris flows) in the Pre-Magura Unit was termed the Chvalčov Member by Pesl & Hanzlíková (1983).

In the Pouzdřany Unit, we consider the Křepice Formation of Aquitanian to Eggenburgian age (Cicha et al. 1965) overlying the Boudky Marl, to belong to the Krosno lithofacies. The Křepice Formation consists of fine- to medium-grained slightly lithificated sandstones, siltstones and layered shales. Their layers are centimeter to several meters thick, rhythmically alternate and forming a sequence a few hundred meters thick.

The presence of the Krosno lithofacies in the Subsilesian Unit is a subject of discussion. Earlier, the Menilite Formation was considered to be a youngest member of the Subsilesian Unit. Recently, Eliáš (1998) put the sediments in the source tributary of Sedlnice stream near Ženklava village into the Krosno lithofacies and termed them the Ženklava Formation. Roth et al. (1973) assigned these sediments to the Frýdlant Formation (new name introduced by Eliáš 1993 for the earlier Submenilite Formation). Studies of petrology (see in this paper) and the microbiostratigrafic study by Švábenická & Bubík (pers. com.) do not confirm Eliáš's observations.

Petrology and mineralogy

The sandstones of the Krosno lithofacies were sampled for thin sections, the translucent heavy mineral assemblages and the geochemical analyses of detrital garnet. In order to evaluate the change of provenance, comparative samples from the underlying strata were collected and analysed.

Thin section petrology

The sandstones of the Krosno lithofacies possess according to the thin section study a fairly consistent petrologic composition. The sharp to half-rounded quartz clasts, forming about 20 % of the rock, prevail over the often sericitized feldspars. Muscovite and chloritized biotite, assorted into parallel structure, locally create up to 15 % of the rock. The calcite grains are probably both of clastic and authigenic origin. The rock fragments are present in the amount of 7 % and include volcanic glass, gneiss, phyllite and vulcanite. The carbonate matrix is of basal character and often corrodes the feldspar and quartz grains. There are generally badly visible clasts of fossils in the rock.

Heavy minerals

Translucent heavy mineral assemblages (further only THMA) were studied and correlated at several dozen localities along the whole area of investigation (see Fig. 1).

There are three groups of assemblages distinguished within the sandstone samples belonging to the Krosno lithofacies and the underlying strata. The first group should be defined as a garnetic assemblage, the second one as a tourmaline-garnetic assemblage and the third group as a polymict assemblage of varied composition (Fig. 4).

Garnetic assemblage

The garnet amount is mostly higher than 85 %, further minerals as the apatite, tourmaline, zircon, rutile and staurolite are present in the amounts between 1–10 %.

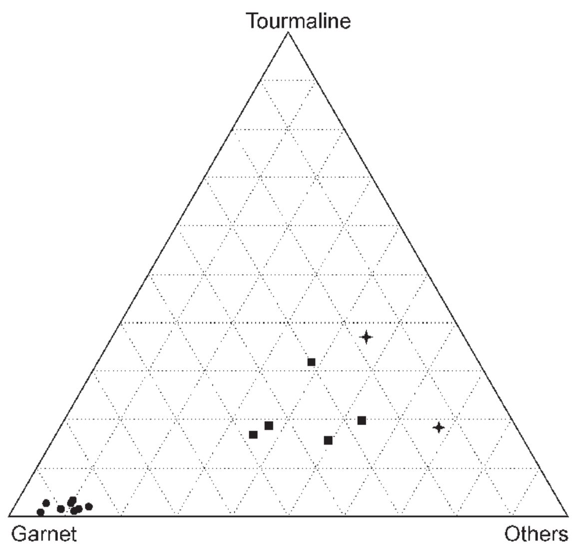

Fig. 4. Comparison of the translucent heavy mineral assemblages of sandstones. **Dot** — garnetic assemblage of the Krosno lithofacies of the Silesian and Ždánice Units, **square** — tourmaline-garnetic assemblage of the Krosno lithofacies of the Zdounky and Fore-Magura Units, **cross** — polymict assemblage of the strata underlying the Krosno lithofacies of the Outer Group of thrust sheets.

The garnetic THMA was investigated with all analysed sandstone samples from Krosno Formation of the Silesian Unit. There are only two garnetic THMA from the six analysed sandstones of the Ždánice-Hustopeče Formation. The other four sandstone samples with different composition of THMA were found in the pelitic facies of the Ždánice-Hustopeče Formation extended along the external margin of the Ždánice Unit. Nevertheless, the garnetic THMA is characteristic of the Ždánice-Hustopeče Formation as demonstrated by the data (150 sandstone analyses) presented by Pícha (1973) from this formation of the Ždánice Unit.

Tourmaline-garnetic assemblage

The tourmaline amounts are usually in tens of %, in several cases higher than those of garnet. Other minerals such as staurolite, apatite, rutile, zircon and hornblende are present in variable unstable amounts.

The tourmaline-garnetic THMA characterizes generally the Krosno lithofacies of the Fore-Magura and Zdounky Units. This THMA was found also in two samples belonging to the Těšnovice development, whose tectono-facial appurtenance is not clear. The identical THMA was described from the Těšnovice development by Pícha (1973).

Polymict assemblage

The assemblages of the sandstones underlying the Krosno lithofacies are of varied composition. This THMA presents a high amount of the tourmaline, garnet and staurolit. The substantial diversity in amount of other haevy minerals may be influenced by provenance from different tectono-facial units. A similar THMA was determined in the sandstones near Ženklava, mistaken by Eliáš (1998) for the Krosno lithofacies.

A special subgroup with some typical and unifying features was identified in the Menilite Formation of the Fore-Magura Unit. It is characterized by high ratio of oval to idiomorphic zircons (6:1) and high amounts of rutile.

Correlation and provenance

There are significant differences in THMA not only between the Krosno lithofacies and the underlying strata but also between the individual tectono-facial units. These differences are connected with the changes in deposition and in the source areas. The changes reflect the Helvetian orogeny during the Oligocene. Most probably the differences in THMA are controlled by different provenance, because of change in the ratios of ultrastable minerals. The primary source of translucent heavy minerals was undoubtedly rich in high temperature and high-pressure metamorphites (gneiss, granulite). Most probably the garnets were redeposited from the uplifted Magura Flysch.

Detrital garnet geochemistry

The sandstones of the Krosno lithofacies in the Silesian Unit were analysed and the results were compared with earlier analysed sandstones of the Magura Group of thrust sheets. The obtained results alow us to comment on certain overlaps and/or analogies in the composition of the detrital garnet assemblages (estimated as 30–40 %) of the sandstones of the Krosno Formation (Oligocene–Miocene) of the Silesian Unit and selected sandstones of the Soláň Formation (Upper Cretaceous–Paleocene) of the Rača Unit of the Magura Group of thrust sheets (Fig. 5A,B). The detrital garnets common in the sandstones of both units have high almandine contents (65–85 %), low spessartine

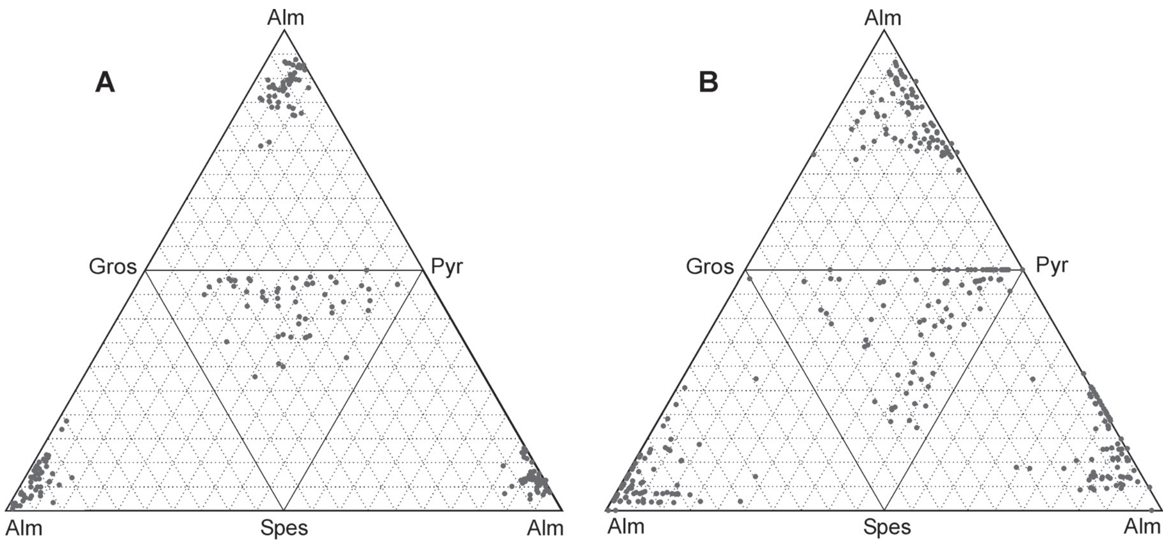

Fig. 5. Comparison of the detrital garnet geochemistry between: **A** — sandstone of the Krosno Formation, Silesian Unit, locality Lhota u Kelče (19 — see Fig. 1) and **B** — sandstone of the Soláň Formation, Rača Unit, Magura Group of thrust sheets, locality Hostýn (quarry, 23 — see Fig. 1). The diagram was constructed by "opening" the walls of a tetrahedron where the tops represent almandine, grossulare, spessartine and pyrope end members.

(1–8 %) and similar stable amounts of pyrope and grossulare (5–20 %).

The coincident composition of detrital garnet in the sandstones of the Krosno and Soláň Formations indicates the redeposition of detritus from the Proto-Magura Group of thrust sheets into basins of the Krosno lithofacies.

Sedimentology

The Krosno lithofacies can be characterized in all tectono-facial units from the point of view of sedimentology as synorogenic deepwater flysch sediments. The transport and deposition of these sediments is produced mainly by gravity flows. The dominant sediment support mechanisms of gravity flows are fluid turbulence, escaping pore fluid, dispersive pressure, matrix strength and density. These mechanisms characterize the turbidity and contourity currents from which turbidites and contourites originate. The most significant features of turbidites and contourites are the sole markings, size grading, plane, ripple-cross and convolute laminations. The size grading which usually is not present in the contourites, is regarded as a diagnostic feature to distinguish them from turbidites. The vertical succession of these features was framed into an ideal sequence (interval Ta-e — Bouma 1962, or division S_{1-3}, Tt and Td-e — Lowe 1982). According to Shanmugam (2000) the massive sandstones can be applied universally for either turbidites, contourites, or sandy debris flows usually found in the Ta-c interval of the flysch sediments.

The sedimentological study of the Krosno lithofacies was pursued only in the Ždánice Unit, where this lithofacies (Ždánice-Hustopeče Formation) could be examined in a lot of artificial outcrops and boreholes from the 1960s to 1990s.

The Ždánice-Hustopeče Formation was studied in detail in the disused quarry at the NW border of the Boleradice village, where a sequence of thin-bedded turbidites in thicknesses of ca. 12.5 m is exposed (see Fig. 3.1). This sequence consists of rhythmic alternance of fine- to medium-coarse calcareous sandstones, siltstones and grey brownish and greenish wheathered calcareous shales. The layers of sandstones usually up to 15 cm, sporadically maximum 40 cm thick slightly predominate over the shales of the same thicknesses. The turbidity sequences usually begin with interval Tb and Tc (thin layers). On the base of sandstone layers rare flute-casts (Fig. 2.2), load-casts and ichnofossils occur. The grade bedding is little pronounced. The Bouma's interval Tc has very frequent parallel and ripple-cross laminations. Conversely the convolute lamination is rare. The flute-casts and ripple-cross-lamination (9 measurements) indicate the direction of paleocurrents from SSE (within the extent 290 to 26°). The studied sequence represents distal turbidites deposited under low flow regime conditions from the lobes of the lower submarine fan. The Zagórz Limestone may be regarded as the nannofosil pelagite of the turbidity sequence (Te) originated during the maximum decrease in the strength of the turbidity current over the calcite compensation depth (CCD) level.

The facies analysis of the Ždánice Unit based on the geological mapping and well-log indicates that the psammite-pelitic facies is the most extended facies of the Ždánice-Hustopeče Formation. The psammitic facies more commonly found in the rear of the Ždánice Unit is characterized by a lot of typical features of turbidity currents such as Bouma's interval Ta, graded bedding, slump and slide structures, erosion and others. It contains numerous conglomerate bodies interpreted as debris flows. The sediments of psammitic facies represent the base-of-slope deposits more commonly found in the middle and upper fan abutting the continental slope. They may be regarded as proximal turbidites. In contrast, the pelitic facies was observed mainly in the external margin of the Ždánice Unit. In comparison with proximal psammitic facies its sediments were deposited far from source area. The relatively abundant microfossils and total predominance of calcareous shales indicate the deposition in open sea under very low flow regime conditions. The distribution of the facies of the Ždánice-Hustopeče Formation indicates a depositional environment of prograding and overlapping submarine fan which gradually filled the basin. This assumption coincides with the northwestward trending of paleocurrents markings not only on the locality Boleradice and numerous measurements in the whole of Ždánice Unit, but also with episodic measurements in the Krosno lithofacies of the Silesian and Fore-Magura Units. These indicators as well as the massive redeposition of microfossils from the older flysch sequences into the Krosno lithofacies and the pebbles of the Zlín Formation and of the Variscan granitoids observed in the debris-flows of the Ždánice-Hustopeče Formation near Velké Pavlovice suggest, that the clastic material originates both from internal basinal source and the Carpathian thrust belt (Stráník et al. 1982; Hanžl et al. 1998). This assumption is compatible with the result of the study of the garnet geochemistry (see in this paper) which indicates the possibility of sources in the uplifted Magura Flysch.

Magnetic fabric and ductile deformation

For investigating the anisotropy of magnetic susceptibility (AMS), oriented specimens (10 to 15 pieces per locality), were sampled in 176 localities of the western (Moravian and Slovak) sector of the Flysch Belt in the framework of various research projects. The results were partially published elsewhere (Hrouda & Stráník 1985; Hrouda & Potfaj 1993; Hrouda et al. in preparation) and serve for overall characterization of the AMS of the western sector of the Flysch Belt. In order to characterize the AMS of the Krosno lithofacies, special oriented sampling was done for the purpose of the present paper. In all the samplings, psammites (mostly sandstones) were taken, because they are more sensitive to the initial deformation than siltstones and pelites. The latter show relatively strong depositional/compactional magnetic fabric and its change into a deformational one needs more intense deformation than in the case of psammites.

The anisotropy of magnetic susceptibility (AMS) of oriented specimens was measured by the KLY-2 and KLY-3S Kappabridges (Jelínek 1973, 1980; Jelínek & Pokorný 1997) and computed using the ANISO 11-14 and SUSAR programs (Jelínek 1977, 1996).

The results of AMS measurements are summarized in terms of P, T, and f parameters, being presented in the box-and-whisker plots (Tukey 1977; McGill et al. 1978). The P and T parameters are defined as follows:

$$P = k_1/k_3,$$
$$T = 2\,ln(k_2/k_3)/ln(k_1/k_3) - 1,$$

where $k_1 \geq k_2 \geq k_3$ are the principal susceptibilities. The P parameter, called the degree of AMS, indicates the intensity of the preferred orientation of magnetic minerals in a rock and the T parameter (Jelínek 1981) indicates the shape of the susceptibility ellipsoids; it varies from −1 (perfectly linear magnetic fabric) through 0 (transition between linear and planar magnetic fabric) to +1 (perfectly planar magnetic fabric). The f parameter is the angle between the magnetic foliation and bedding.

The mean bulk susceptibility of the sandstones investigated is very low, being in the order of 10^{-5} [SI] and in the very beginning of the order of 10^{-4}. The magnetic minerals, as revealed by investigation of temperature variation of susceptibility, are represented by a mixture of paramagnetic minerals and magnetite, the former prevailing. There are no systematic differences among tectono-facial and lithostratigraphic units.

The AMS in sedimentary rocks provides information on the deposition and compaction processes. In addition, in sedimentary rocks that underwent ductile deformation, which is the frequent case of accretionary prisms, it can serve as a sensitive indicator of progressive ductile deformation. In natural sedimentary rocks unaffected by later deformation, the magnetic foliation is always oriented near the bedding, while the magnetic lineation is mostly roughly parallel to the near-bottom water current directions determined using sedimentological techniques. Less frequently, the magnetic lineation may be perpendicular to the current direction, which is typical of the flysch sediments of the lowermost *A* member of the Bouma sequence. The degree of AMS is relatively low and the AMS ellipsoid is in general oblate (Stage I in Fig. 6a).

During the processes of diagenesis and early ductile deformation, the originally sedimentary magnetic fabric may be slightly modified. If the ductile deformation is represented by vertical shortening due to the loading by the weight of overlying strata, the degree of AMS and the oblateness of the AMS ellipsoid increase, while the magnetic foliation and lineation retain their orientations. If the ductile deformation is represented by the bedding parallel shortening or by the bedding parallel simple shear or by both, the degree of AMS initially decreases and only later increases when the deformation is strong enough to overcome the initial vertical compaction. The magnetic fabric becomes initially more planar and only later is it more triaxial or even linear. The magnetic lineation deviates gradually from the direction of flow towards that of maximum strain, often creating a bimodal pattern. The magnetic foliation remains initially near the bedding, after a stronger strain it deviates from it, creating a girdle in magnetic foliation poles that is perpendicular to the magnetic lineation (Stages II and III in Fig. 6a).

The AMS of the Flysch Belt was investigated extensively in the past and the results were presented by Hrouda & Stráník (1985), Hrouda & Potfaj (1993) and Hrouda et al. (in preparation). They can be summarized as follows.

The magnetic fabrics in the Flysch Belt show both sedimentary and deformational features. The relatively low degree of AMS, planar magnetic fabric, small angle between magnetic foliation and bedding in the majority of specimens, and small angle between magnetic lineation and current direction (if measured) may indicate the sedimentary origin of the magnetic fabric. On the other hand, the predominantly prolate magnetic fabric and moderate to very large angle between magnetic foliation and bedding (in many specimens magnetic foliation is almost perpendicular to bedding) or the existence of a girdle pattern in the magnetic foliation poles no doubt indicate deformational effects on the magnetic fabric. Consequently, the magnetic fabric can be regarded in general as composite, that is composed of the deformational magnetic fabric superimposed on the sedimentary magnetic fabric. This superimposition has a character of overprinting of variable degree, sometimes none or very weak, sometimes relatively strong, but never obliteration.

The weakest tectonic deformation is indicated in the Ždánice Unit whose mean degree of AMS is the highest of all the thrust sheets investigated, the magnetic fabric is mostly planar, and the magnetic foliation/bedding angle is the smallest. In the Silesian Unit, the indications of the tectonic deformation are stronger, but not very much. It is comparable to the Bílé Karpaty and Oravská Magura Units of the Magura Group of thrust sheets. In the innermost tectonic structure (the Fore-Magura Unit) the effect of tectonic deformation on the magnetic fabric is the strongest, so strong that the magnetic foliation in numerous specimens was reoriented from the position parallel to the bedding into the position perpendicular to the bedding. The same degree of deformation characterizes the Rača and Bystrica Units of the Magura Group of thrust sheets. The above relationship demonstrates the box-and-whisker plots of the degree of AMS in individual units of the western sector of the Flysch Belt (Fig. 6b). The degree of AMS, though rather variable in all units, is relatively high in the marginal units indicating mostly sedimentary magnetic fabrics (the Ždánice and Silesian Units in the west and the Bílé Karpaty and Oravská Magura Units in the east), while it is relatively low in the central Fore-Magura, Rača, and Bystrica Units, indicating non-coaxial superposition of the deformational magnetic fabric on the sedimentary one.

The AMS is able to indicate differences in the ductile deformation not only between the tectono-facial units, but also between the strata within these units. From this point

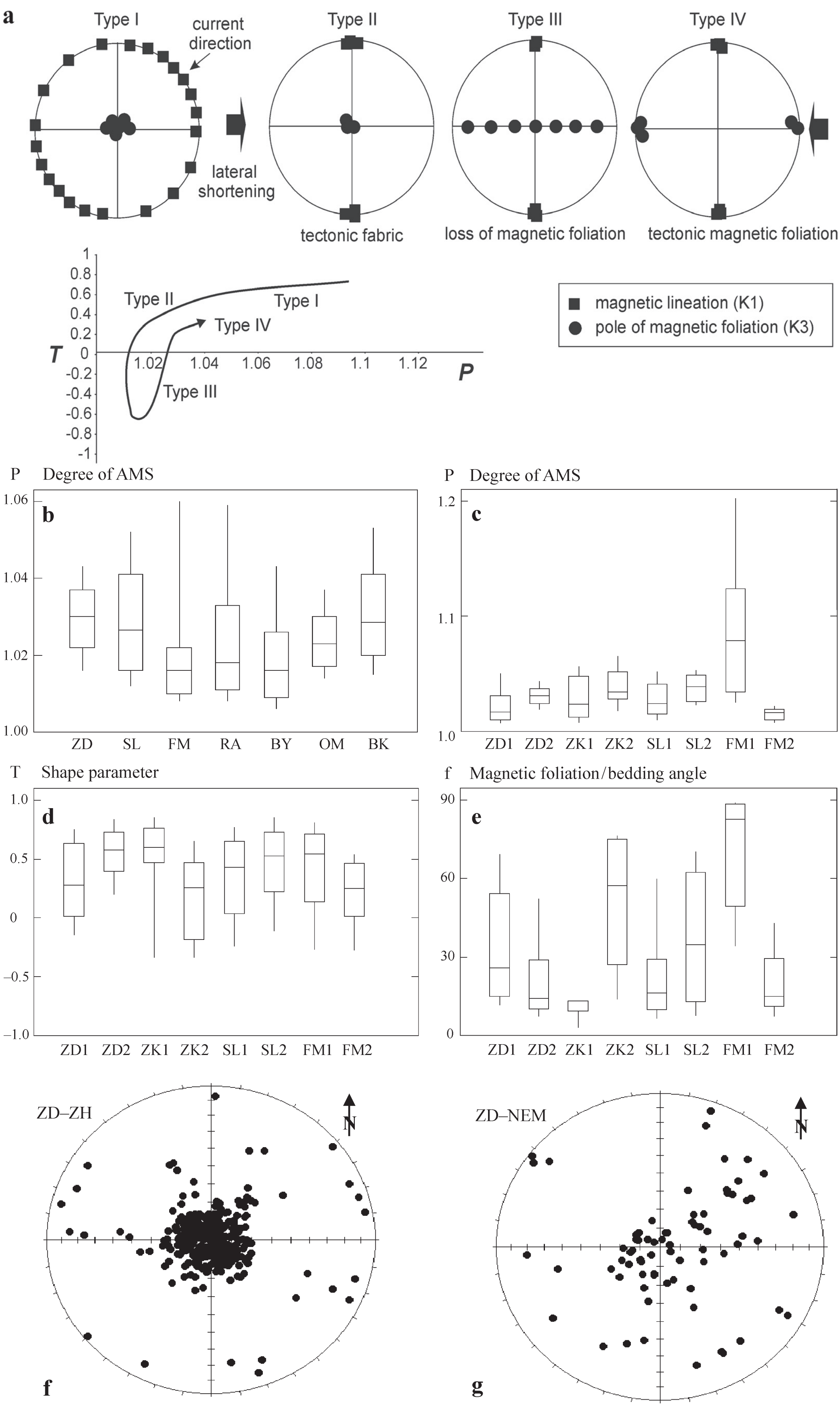
a
Type I
current direction
lateral shortening
Type II
tectonic fabric
Type III
loss of magnetic foliation
Type IV
tectonic magnetic foliation
T
P
Type II
Type I
Type IV
Type III
magnetic lineation (K1)
pole of magnetic foliation (K3)
P Degree of AMS
b
ZD SL FM RA BY OM BK
P Degree of AMS
c
ZD1 ZD2 ZK1 ZK2 SL1 SL2 FM1 FM2
T Shape parameter
d
ZD1 ZD2 ZK1 ZK2 SL1 SL2 FM1 FM2
f Magnetic foliation/bedding angle
e
ZD1 ZD2 ZK1 ZK2 SL1 SL2 FM1 FM2
ZD–ZH
N
f
ZD–NEM
N
g

Fig. 6. ▶

of view, the relationship between the Krosno lithofacies and the underlying formations is particularly important, because it can indicate changes in the arrangement of plates in the vicinity of the Paleogene/Neogene boundary. This relationship can be best studied in the Ždánice Unit, where the Ždánice-Hustopeče Formation was extensively investigated by Hrouda & Stráník (1985) and the underlying Němčice Formation was investigated for the present paper. The degree of AMS is clearly higher in the Ždánice-Hustopeče Formation than in the underlying Němčice Formation (Fig. 6c). Similarly, the magnetic fabric shape is more planar in the former formation than in the latter (Fig. 6d). The magnetic foliation/bedding angle is on the other hand much larger in the Němčice Formation than in the Ždánice-Hustopeče Formation (Fig. 6e–g). All these parameters indicate that the Ždánice-Hustopeče Formation suffered very low ductile deformation if any, while the ductile deformation of the underlying Němčice Formation was clearly stronger, even though also weak absolutely.

In the Zdounky Unit, the degree of AMS is clearly higher in the Upper division, than in the Lower division (see Fig. 6c). The shape parameter, indicating the magnetic fabric shape, shows relatively planar magnetic fabrics in the Lower division and very variable, but less planar, magnetic fabrics on average in the Upper division (see Fig. 6b). The magnetic foliation/bedding angle is low in the Lower division, while it is very variable and large in average in the Upper division (see Fig. 6c). This magnetic fabric is not easy to interpret from the point of view of ductile deformation. The degree of AMS indicates stronger ductile deformation in the Lower division, whereas the shape parameter and magnetic foliation/bedding angle indicate stronger ductile deformation in the Upper division.

In the Silesian Unit, the degree of AMS is clearly higher in the Krosno Formation than in the underlying Rožnov Formation (see Fig. 6c). The magnetic fabric shapes are similar in both the formations, being very slightly more planar in the former formation than in the latter (see Fig. 6d). The magnetic foliation/bedding angle is very variable and relatively large on average in the Krosno Formation, while it is moderately variable and small on average in the underlying Rožnov Formation (see Fig. 6e). The degree of AMS and the shape parameter indicate weaker ductile deformation in the Krosno Formation, while the magnetic foliation/bedding angle indicate the weaker deformation in the underlying Rožnov Formation.

In the Fore-Magura Unit, the degree of AMS shows very low variability and very low mean value in the Krosno (Chvalčov) Formation, while in the underlying Submenilite and Menilite Formations it is extremely variable and very high on average (much higher than in all the formations investigated in this study (see Fig. 6c). The magnetic fabric is relatively planar in the Submenilite and Menilite Formations, while in the Krosno (Chvalčov) Formation it is much less planar (see Fig. 6d). The magnetic foliation/bedding angle is very variable and very large on average in the Submenilite and Menilite Formations, while it is moderately variable and small on average in the Krosno (Chvalčov) Formation — see Fig. 6e). The magnetic fabric in the Fore-Magura Unit is no doubt deformational in origin, the intensity of ductile deformation being much higher in the underlying formations than in the the Krosno (Chvalčov) Formation.

The above differences in ductile deformation, even though not always unambiguous, but evident, between the Krosno lithofacies and the underlying formations may indicate changes in the tectonic setting of the plates in the terminal stages of closing the Flysch Belt basins. The relatively strong ductile deformation in the latter formations may result from motions connected with subduction, while much weaker ductile deformations in the former formations may indicate the situation when subduction terminated and started to be transformed into the beginning of collision. The rocks of the Krosno lithofacies were evidently deposited on the slopes of the European plate, fed also from the Magura Flysch likely underplated to the southern West Carpathian plate. After deposition, the whole body was slightly thrust over the Carpathian Foredeep without suffering observable ductile deformation.

Fig. 6. Characteristics of the AMS in sandstones of the western sector of the Flysch Belt of the Western Carpathians. **a** — Schematic development of the AMS in progressively weakly deformed rocks of the accretionary prisms (adapted from Aubourg et al. 2004) **b** — Box-and-whisker plot of the degree of AMS in individual units of the western sector of the Flysch Belt. In the plot the mean value is represented by the median being the central line in the central box. The central box covers the middle 50 % of the data values, between the lower and upper quartiles. The "whiskers" extend out to extremes (minimum and maximum values), but only to those points that are within 1.5 times the interquartile range. ZD — Ždánice thrust sheet, SL — Silesia thrust sheet, FM — Fore-Magura thrust sheet, RA — Rača thrust sheet, BY — Bystrica thrust sheet, OM — Oravská Magura thrust sheet, BK — Bílé Karpaty thrust sheet. **c** — Box-and-whisker plot of the degree of AMS in the Krosno lithofacies and in the underlying formations in selected units of the Flysch Belt. ZD1 — the Němčice Formation in the Ždánice Unit, ZD2 — the Ždánice-Hustopeče Formation in the Ždánice Unit, ZK1 — the Lower division in the Zdounky Unit, ZK2 — the Upper division in the Zdounky Unit, SL1 — the Rožnov and Menilite Formations in the Silesian Unit, SL2 — the Krosno Formation in the Silesian Unit, FM1 — the Submenilite Formation in the Fore-Magura Unit, FM2 — the Krosno (Chvalčov) Formation in the Fore-Magura Unit. **d** — Box-and-whisker plot of the shape parameter in the Krosno Formation and in underlying formation in selected units of the Flysch Belt. For legened see fig. 6c. **e** — Box-and-whisker plot of the magnetic foliation/bedding angle in the Krosno Formation and in the underlying formation in selected units of the Flysch Belt. For legend see fig. 6c. **f** — Orientations of magnetic foliation poles in the Ždánice-Hustopeče Formation of the Ždánice Unit after simple tectonic correction (rotation of bedding about bedding strike into horizontal position). Equal-area projection on the lower hemisphere. **g** — Orientations of magnetic foliation poles in the Němčice Formation of the Ždánice Unit after simple tectonic correction. Equal-area projection on the lower hemisphere.

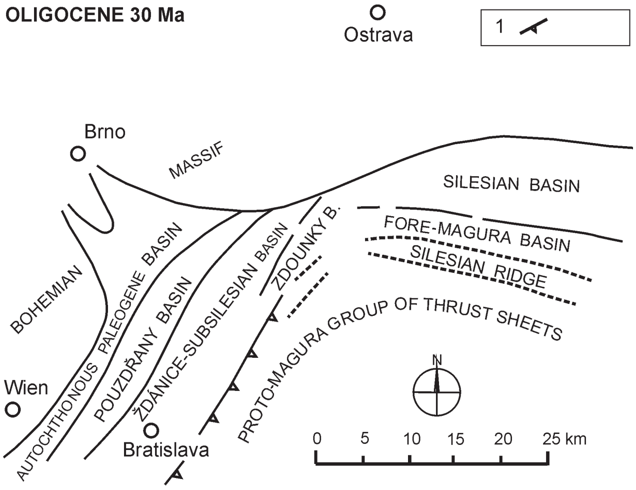

Fig. 7. Palinspastic sketch of the Outer Western Carpathians in the Oligocene (30 Ma). **1** — front of the Proto-Magura Group of thrust sheets.

Regional correlation and attribution to major tectonic and depositional events

The Upper Oligocene to Lower Miocene sediments represented by Krosno lithofacies of the Carpathian Flysch Belt are defficient of diagnostic paleontological data. Their age, facies determination and regional correlation, therefore, depend also on the lithology and the overall tectonostratigraphic setting. In order to better integrate this lithofacies into the broader Alpine-Carpathian system we relate them to principal depositional and tectonic events. The Krosno lithofacies is a typical synorogenic flysch sequence being deposited in a complex system of foreland basin formed on the mobile European platform margin in the Late Oligocene. Its deposition reflects the important environmental changes which took place on the north margin of Tethys in the Oligocene. The Krosno flysch-type sedimentation is marked by a very high influx of detrital material especially from the orogenic belt, large thickness of deposits and distinct facial changes. It replaced the hypoxic sedimentation of the underlying Menilite Formation. These changes in deposition are related to the Helvetian orogeny in the Oligocene. The foreland basins on the downbended margin of the platform and the rearrangement of the orogenic belt shown by the study of heavy minerals and ductile deformation are also connected with the Helvetian movements. The flexural downbending of the platform margin is most likely related to the loading of the progressing Carpathian thrust sheets. A similar interpretation of the downbending of the subducting European plate was presented in the Western Alps by Ziegler (1987, 1988).

The Krosno lithofacies has a large extent in the Alpine-Carpathian orogenic belt. The sediments of similar lithofacies are known from Eastern Carpathians in Poland, Ukraine and Romania. The strata in the tectonic window of the Eastern Alps near Rogatsboden in Austria and the Purkirchen Beds (Bachmann & Müller 1991) of the Bavarian Molasse show some similarities.

Conclusions

The Krosno lithofacies is a synorogenic sequence that terminates the flysch sedimentation in the Upper Oligocene up to Lower Miocene in the Outer Group of thrust sheets of the Flysch Belt in the Alpine-Carpathian orogenic system.

The spatial distribution of the individual developments of the Krosno lithofacies within the Ždánice Unit and the transport of the material from the SE in all tectono-facial units indicate the depositon from a submarine fan that prograded to the NW and gradually filled in newly established foreland basins.

Different spectra of translucent heavy minerals were found in the Krosno lithofacies and the underlying strata of individual tectono-facial units. The provenance of the clastic material (pebbles of the Zlín Formation in the conglomerates of the Ždánice-Hustopeče Formation) from the Proto-Magura Group of thrust sheets coincides with identical geochemical composition of garnets from sandstones of the Krosno Formation in the Silesian Unit and those from the Soláň Formation in the Magura Group of thrust sheets (see Fig. 5A–B). According to these results we suggest that the Proto-Magura Group of thrust sheets was folded, emerged and supplied the material into the basins of the Outer Group of thrust sheets where the sedimentation of the Krosno lithofacies continued (Fig. 7). The differences in the tectonic deformation recorded by the AMS between the Krosno lithofacies and the underlying formations, originally found in the Ždánice Unit, were recently indicated in all tectono-facial units of the Outer Group of thrust sheets. In addition, a trend was observed in increasing of the ductile deformation from the outer towards the inner margin of the Outer Group of thrust sheets (see Fig. 6c–e). The differences in deformation are ascribed to the Helvetian Neoalpine orogeny in the Oligocene that initiated the changes in sedimentation in the foreland basins and the rearrangement of the orogenic zone. In terms of plate tectonics this orogeny represents the stage of closing subduction and starting collision.

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