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Relics of the most distal part of the Neogene foreland basin in SW Moravia

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Abstract. The Nové Syrovice locality is the westernmost outcrop of Neogene marine deposits in SW Moravia. These Neogene sands are interpreted as shoreface-foreshore deposits. The sediments are mostly from local sources, although material from relatively distant ones has also been recognized. The origin of ferruginous sandstone clasts found within this deposit is connected to oxidizing processes during paleoweathering in a tropical or subtropical climate and to the presence of organic material. The exact stratigraphy (Eggenburgian, Lower Badenian?) of the deposits has not been determined, though paleoecological studies have resulted in data concerning the depth, dynamics, and salinity of the water, and indicate that the locality was well lit and aerated during deposition. Quartz rich gravels that overlie the Neogene marine sands in the vicinity probably represent younger fluvial deposits.

Key words: Neogene, foreland basin, passive margin, depositional environment, ferruginous sandstones

Introduction

Though the passive margins of foreland basins are seldom studied, such marginal/distal zones of deposition can reveal important information about the formation and depositional evolution of basins. Such information is important because of the complicated behaviour of the foreland bulges and thrust fronts associated with orogenic processes. Both Eastern Alpine and Western Carpathian tectonic processes affected the SW margin of the Bohemian Massif. Numerous occurrences of Miocene freshwater, brackish, and marine sediments overlie the crystalline basement of the Bohemian Massif in SW Moravia and southern and eastern Bohemia. These localities are several tens of kilometres away from the present extent of the Carpathian Foredeep and the Alpine Molasse Zone, the basins to which they are genetically related. Relics of these basin deposits exposed by denudation vary widely in geographic position, lithology, and stratigraphy. Their stratigraphic correlations are often complicated or unresolved.

A typical example of these relics is the occurrence of marine Neogene sands situated approximately 10 km SW of Moravské Budějovice, close to the village of Nové Syrovice – Augustov seclusion (Fig. 1). Previous studies of this locality have concentrated on several small roadside outcrops that allow the upper 2.5 metres of the sediment succession to be studied (Tejkal and Laštovička 1970, Matějovská et al. 1985, Hladilová and Nehyba 1992). The present paper considers new drill-core data, and a revised study of the outcrops and Neogene gravels in the vicinity.

Neogene sands

The deposits at the locality of Nové Syrovice are comprised predominantly of sands. The lithology of drill cores from these deposits is presented in Fig. 2. These Neogene sands have a distinct, sharp erosional base, and overlie the deeply weathered crystalline basement. Their total thickness has been determined at 8–9 m based on drilling (Matějovská et al. 1985). The thickness of the underlying clayey weathering products is about 1–2.5 m, which continues into progressively less weathered basement. The 30 m layer of brown and rusty brown clays described by Matějovská et al. (1985) as underlying the sands was not encountered.

Sedimentary structures are poorly preserved in the outcrops and drill cores. Horizontal (planar) lamination, sometimes resembling low-angle cross lamination, is the main recognizable structure. Small scale cross bedding and

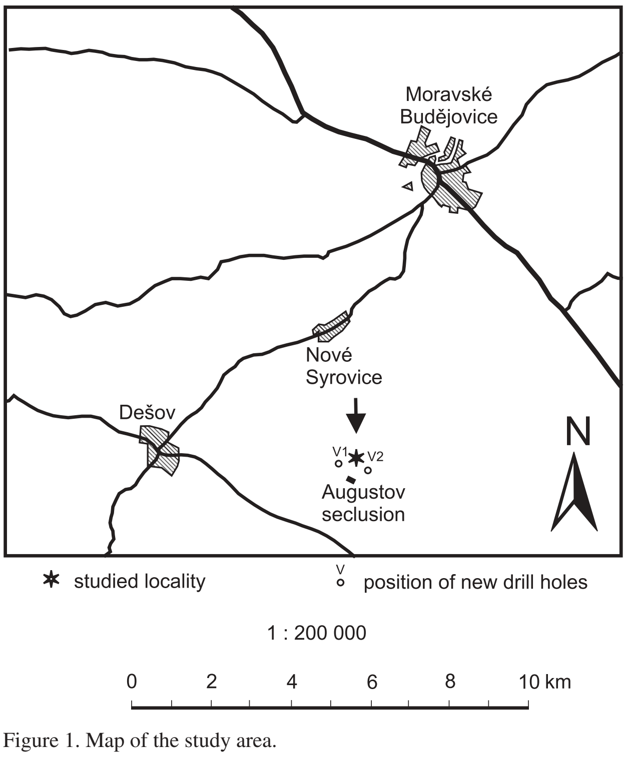

Figure 1. Map of the study area.

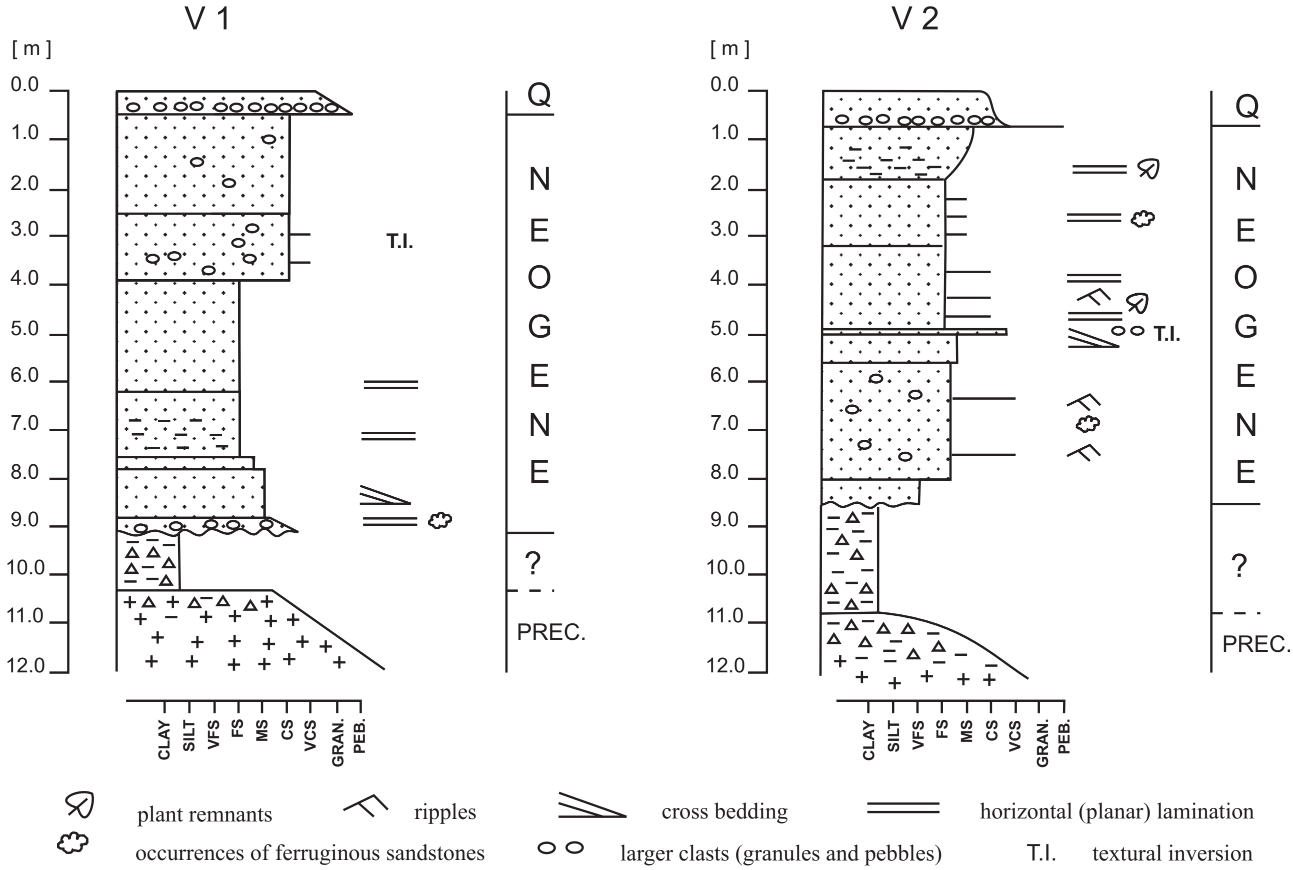

Figure 2. Drill cores from the Nové Syrovice locality.

subhorizontal strings of coarser clasts were also recognized within the profile. Subhorizontal, slightly irregular 5–7 cm thick beds of brown sand alternate with 30 cm thick beds of yellow sand and occurrences of ferruginous sandstones, reflecting intensive postdepositional processes. The drill-core sections reveal a general coarsening-upward trend. Though the remains of plants are rare, and reach only several mm in size, the evidence of biogenic activity in the form of trace fossils and burrows is present in the sands.

Nineteen samples were collected from various parts of the section (9 samples from outcrops, and 10 drill-core samples) for petrographical and textural studies. Most of the white-yellow, yellow, yellow-grey, brown-yellow, and light brown sands are of medium, medium-fine, or fine grain size, with only rare occurrences of coarse grains. The median (Md) grain size varies from 0.19 to 0.32 mm. They are predominantly moderately sorted (So 1.3–1.7). Poor and very poor sorting (So 2.0–5.1) is less common, and reflects the influx of a higher content of granules and small pebbles. The clay content of these deposits is generally low. Grain size distributions are symmetrical or positively skewed. The application of grain-size "genetic" diagrams (Passega and Byramjee 1969, Visher 1969, Passega 1977, Samsuddin 1986) suggests the deposition in high-energy conditions and the dominance of bedload transport (Hladilová and Nehyba 1992).

The granule and pebble content in most of the sands is less than 10%, and often less than 1%. Maximum clast sizes (P_{99}) vary between 0.7 to 8.0 mm, and are predominantly of quartz. Thin beds of fine sandy gravels, maximally a few cm thick, are present within the sands. The maximum diameter of the quartz pebbles is 2.4 cm. Quartz and gneiss/migmatite clasts dominate the coarse grain fraction, which also includes quartzose sandstone, graphitic quartzite, and feldspars. The proportion of metamorphic clasts decreases upwards within the profile, whereas that of quartz increases slightly towards the top. The clasts are usually subrounded and subangular, though both angular and well-rounded ones are also present. The degree of rounding generally increases towards the top of the profile. Several quartz varieties are observed in these deposits (white to milky white, grey, yellow). Corroded, cavernous surface textures, and remnants of kaolinized feldspar are also present. The occurrence of pure quartz crystals is rare.

Quartz grains comprise about 90% of the light minerals in the sand fraction. The grains have predominantly subangular and subrounded shapes. The transparent heavy mineral spectra (Table 1) reveal a relatively high content of superstable minerals (ZTR = zircon + tourmaline + rutile). The standard deviation values (thirteen samples in the 0.063–0.125 mm fraction) reflect relatively high differences in the proportions of some minerals (especially sillimanite, zircon). The proportion of sillimanite, apatite, and andalusite is slightly higher near the base of the profile, whereas that of the superstable minerals increases upwards in the profile.

Table 1. The transparent heavy mineral spectra

	Garnet	Tourm.	Kyanite	Staurol.	Rutile	Amph.	Zircone	Apatite	Sillim.	Sphene	Monazite	Zois.-Ep.	Andal.	Pyroxene	ZTR
Mean	9.7	12.7	2.7	3.8	11.4	1.5	27.9	1.7	12.3	2	3.6	2.3	2.4	0.4	52
St.deviat.	3.3	6.6	2	2.3	3.1	1.8	12	0.8	9.6	1	1.7	1.7	2.1	0.6	10.7

The results of heavy mineral studies can be compared with data from other Neogene deposits in the same area. Differences in their heavy mineral spectra can result from several processes (see Morton 1985). Detailed studies of selected minerals (such as the shape, colour, inner fabric, and degree of elongation of zircons) can provide additional data about the source rocks and also about the mutual relations between isolated deposits in SW Moravia (Hladilová and Nehyba 1992).

The zircons are elongated by an average value of 2.15. The relation between the elongation (EL) and the length (L) of the zircon grains is demonstrated in Fig. 3a. Several zircon populations were identified, which we believe to correspond to different sources based on the increased elongation of larger grains. The sources of these zircons were Moldanubian metamorphic and magmatic rocks (Niedermayer 1967, Finger and Haunschmid 1988). Increased elongation with increasing length, the presence of relatively smaller grains, and more pronounced elongation are typical of the zircons in the basal part of the profile. We interpret this to indicate that these zircons were derived from a local source of orthogneiss and/or migmatite. The zircon data from the upper part of the profile is more complex, involving larger grains and relatively lower degrees of elongation. This suggests that additional relatively distant zircon sources (i.e. paragneisses), and the mixing of the zircons from local and distant sources, contributed to the later layers of these deposits.

The Lower Badenian deposits at Hostim also reflect the various contributions from local and distant sources within the basal (terrestrial sediments) and upper (marine deposits) parts of the profile (Fig. 3b). Several sources (see Fig. 3c) can also be inferred for the Neogene fluvial sands described at Chvalatice (Nehyba 1991), though their provenance differs slightly from the marine sediments at Nové Syrovice. These two Neogene deposits are not paleogeographically or stratigraphically related to each other. Neogene fluvial deposits SW of Moravské Budějovice (Fig. 3d) also reflect different sources.

Interpretation

Rippled cross bedding passing upwards into planar lamination reflects a high degree of physical energy (Reading 1996). Erosion surfaces are represented by horizons of coarser clasts. The fact that these deposits are well-sorted, positively skewed, almost free of clay, of high textural and mineral maturity, and contain bioturbation structures allow them to be interpreted as shoreline sediments (foreshore, shoreface). The proximity of a low gradient coast is inferred. The deeply weathered crystalline basement was flooded, creating a transgressive surface at the base of

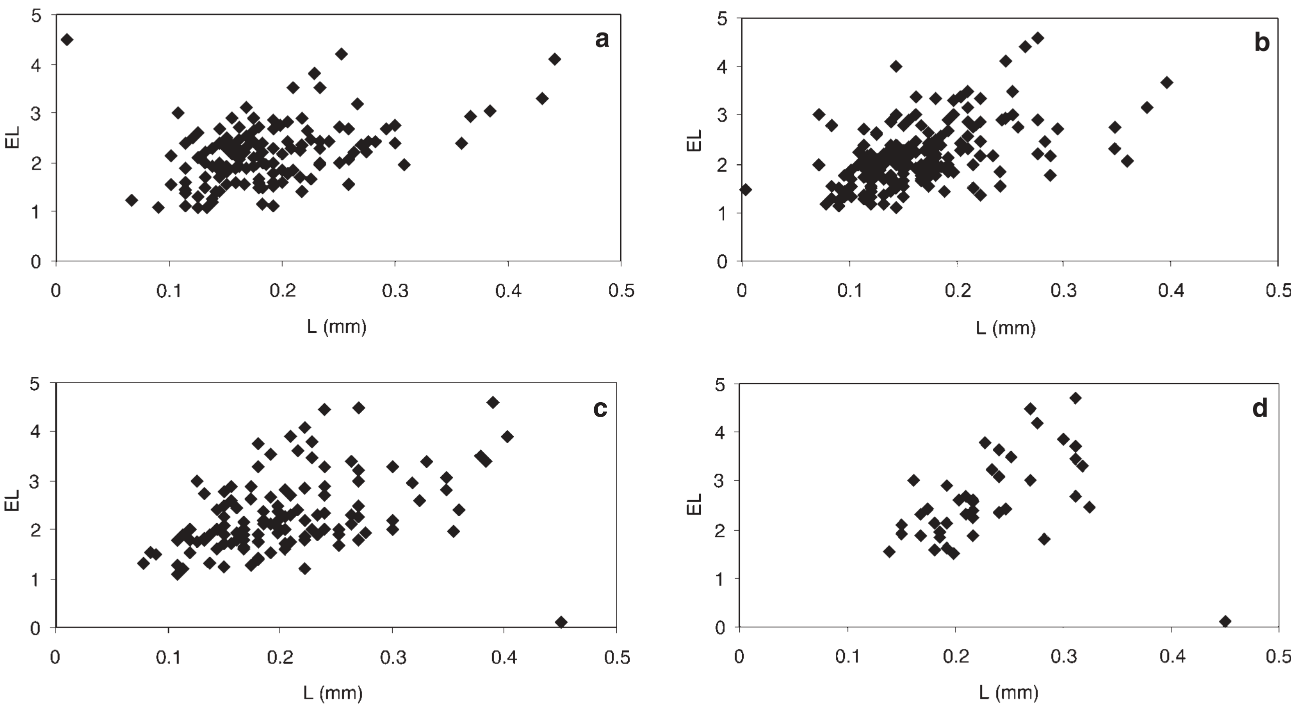

Figure 3. The relation between the elongation (EL) and the length (L) of zircon grains from various Neogene denudation relics. a – Nové Syrovice, b – Hostim, c – Chvalatice, d – Moravské Budějovice.

Figure 4. Morphologic types of ferruginous sandstones: a – characterized by the occurrence of pit-casts, b – characterized by borings or shafts produced by biogenic activity (trace fossils), c – generally isometric concretions characterized by absence of internal structures typically occur with fossil prints and high quartz clast contents, d – flat, platy concretions with various small conical and finger-shaped protrusions, and of highly varying diameter; the grains are sometimes finer and reveal internal laminar fabric.

these Neogene deposits. The sediment was derived predominantly from local sources, but contributions from relatively distant sources are also recognized. The relatively thin, retrogradational/transgressive succession is followed by a major progradational sequence. The prograding shoreline is taken as evidence that the rate of sedimentation at this site outweighed its dispersal. Highstand and transgressive areas can be inferred, though relatively active postdepositional processes have made a more precise interpretation almost impossible. Furthermore, the application of heavy minerals to the stratigraphy of the Neogene deposits of the Carpathian Foredeep (Krystek 1981) can be misleading at the marginal parts of the basin.

Ferruginous sandstones

The occurrence of ferruginous sandstone clasts (Fig. 4) with fossil contents is an important feature of the Neogene deposits under consideration. These clasts have been traditionally regarded as concretions (Nehyba and Fojt 2002). However, the morphology of these clasts reveals information about the various processes by which they formed (Seilacher 2001). Several morphologic types have been distinguished (Nehyba and Fojt 2002; see Fig. 4 of the present work), all of which occur together in one horizon close to the present surface. Quartz pebbles occur irregularly among these sandstone clasts. The role of erosion and the enrichment of the residuum in the coarsest fraction are evident. The drill-core profiles were found to contain this ferruginous sandstone only as granules.

Two processes leading to the formation of these sandstone clasts can be deduced. The first one involves the terrigenous weathering of the paleosurfaces as the dominant inorganic process. The second one involves the occurrence of organic matter (fossils and trace fossils) within them. The deposits from which these clasts were derived were initially highly calcareous marine sands, rich in shells and other fossils. This is confirmed by the relative abundance of internal and external moulds of shells in these sandstone clasts. Interaction with Fe-rich subsurface fluids led to the dissolution of the Ca and the precipitation of Fe minerals. These processes resulted in the preservation of fossils only in the ferruginous sandstones.

Chemical analyses and the study of polished thin sections have revealed that quartz grains are the dominant clastic component of this sandstone (Nehyba and Fojt 2002). These quartz grains are predominantly angular to subangular, and sometimes display corroded surface features. Grains of mica, feldspar, quartzose sandstone, metamorphic rocks (quartzite, phyllite), and magmatic rocks were found only rarely. The lithic grains tend to be more rounded than those of quartz. Limonite is the predominant matrix-forming Fe mineral. Magnetite, ilmenite, goethite,

Table 2. The fossil content of the ferruginous sandstones at the Nové Syrovice locality

Fossils	sampling (year)			stratigraphic range			
	1970	1991	2001	Egg.	Ott.	Karp.	Bad.
GASTROPODA							
Patella sp.	3	1	1	x	x	x	x
Turritella eryna eryna Orbigny	30	15	12		?		
Turritella eryna cf. *communiformis* Voorthuisen		1				?	
Hinia sp.		2		x	x	x	x
?*Dorsanum* sp.		1		x	x	x	x
Terebra cf. *basteroti* Nyst		1	2				
Gastropoda indet.	x	x	x				
BIVALVIA							
Barbatia cf. *clathrata* (Defrance)		2					
Arca sp.		1		x	x	x	x
Glycymeris cf. *fichteli* (Deshayes)		1					
Glycymeris pilosa cf. *deshayesi* (Mayer)		1					
Glycymeris sp.		5		x	x	x	x
Chlamys cf. *multistriata* (Poli)		5					
Chlamys cf. *malvinae* (Dubois)		1			?	?	
Chlamys cf. *macrotis* (Sowerby)		1					
Ostrea sp.		1	1	x	x	x	x
?*Cardita* sp.			1	x	x	x	x
Lucinoma borealis (Linnaeus)	1						
?*Cardium* sp.	1	3		x	x	x	x
Venus (Ventricoloidea) sp.	1	7		x	x	x	x
Venus sp.		5	1	x	x	x	x
Circomphalus cf. *cincta* (Eichwald)			7			?	
Periglypta sp.		1					
Chione basteroti cf. *taurinensis* (Sacco)		1					
Chione sp.	1	1		x	x	x	x
Dosinia cf. *exoleta* Linnaeus		1			?		
Pelecyora cf. *gigas* (Lamarck)	4		3				
Callista sp.		2	4	x	x	x	x
?*Tellina* sp.	4	1		x	x	x	x
Gastrana fragilis (Linnaeus)	1						
Gari sp.		1		x	x	x	x
?*Pharus* sp.		2		x	x	x	x
?*Lutraria* sp.	1			x	x	x	x
Panopea menardi Deshayes	3	1	1				
?*Gastrochaena* sp.			1	x	x	x	x
Corbula sp.			1	x	x	x	x
Bivalvia indet.	x	x	x				
ANTHOZOA (determination by J. Hladil)							
Heliastraea parva Chevalier		1					
Tarbellastraea abtitaxis Chevalier		1					
?Anthozoa indet.		1					
ECHINODERMATA							
Echinodermata indet.		2					
ICHNOFOSSILS (determination by Z. Novák)							
Ophiomorpha sp.			num.	x	x	x	x
Planolites sp.		num.	num.	x	x	x	x
Tubifexides moravicus Novák		num.	num.				

x – running species

pyrite, clay minerals, and plant remnants are very rare. The abundance of oxyhydroxide Fe minerals and the chemical composition of sandstones (Nehyba and Fojt 2002) allow us to connect their formation to paleoweathering (Makedonov and Predstečenskij 1988), probably in a tropical or subtropical climate. The relatively low Na, K, Ca, and Mg contents (see Nehyba and Fojt 2002) and high mineral maturity of these deposits would seem to indicate that they underwent leaching processes. The high porosity of these sands (well sorted, and with low mud content) can be favourable for oxidizing conditions.

The fossil content of the ferruginous sandstones (after Tejkal and Laštovička 1970, Hladilová and Nehyba 1992, and a new collection from 2001) is listed in Table 2. The new findings confirm earlier conclusions (Nehyba and Hladilová 1992) that the fossil fauna is indicative of water of 30‰ salinity, which corresponds to normal seawater without any freshwater influx. These sediments accumulated at a depth of 30 m, but in an environment somewhat protected from direct surf effects. Although the sea was well-lit and aerated, and the climate was warm, the water temperature varied within this shallow depth. As a vagile benthos-infauna predominates the fossil content, it follows that this fauna was active in the bioturbation of these sediments.

Most of the fauna has conspicuous Lower Miocene features, and is probably of Eggenburgian-?Ottnangian age. However, some younger elements found among the molluscs and corals suggest the possible redeposition of earlier fauna into younger sediments. The exact stratigraphic position of the Nové Syrovice sands remains unknown even after the latest study of fossils from the concretions collected in 2001.

The observation that the fauna seems to be paleoecologically homogeneous is of fundamental stratigraphical importance. This fact offers two possible interpretations:

a) Both the sediments and fossils from Nové Syrovice are probably of Lower Badenian age.

b) Older Miocene (Eggenburgian-?Ottnangian) sediments became redeposited at this locality during the Lower Badenian transgression, the depositional environment in Lower Miocene and in Lower Badenian having been of the same character.

These fossils seem to be comparable to those of the Burgschleinitz-Fels-Loibersdorf Formation (Lower Eggenburgian, zones NN2/NN3, N5, NGZ II) in Lower Austria (Roetzel et al. 1999). The rapid alternation between well- to moderately-sorted, coarse-, medium-, and fine-grained sands with gravel intercalations is typical in the latter formation. This grain size and sorting evidence combines with that of the sedimentary textures and structures to suggest deposition in an environment dominated by wave and storm action (shallow water facies in an eulittoral to shallow sublittoral environment). This facies interpretation is consistent with the abundant faunal and fossil traces. The molluscan fauna contains a large variety of species, with large forms being typical for bivalves and gastropods, such as turritellids, naticids, strombids, conids, arcids, glycymerids, mytilids, chlamysids, pectinids, ostreids, glossids, cardiids, pitariids, and panopeids. There is great similarity between the fossils found in Nové Syrovice (Table 2) and those known from the Austrian part of foreland basin (Roetzel et al. 1999).

Gravels

Individual quartz pebbles occur together with clasts of ferruginous sandstones. Numerous pebbles and cobbles (occasionally more than 10 cm in diameter) are distributed throughout the uppermost parts of the sediment succession. Though they overlie Neogene marine sands, the exact nature of their relationship with those sands has evaded determination. These gravels have been documented in an area of several km^2 from the locality considered in the present work. Quartz gravels interpreted as Neogene fluvial deposits have often been described in SW Moravia (Sýkora 1949, Jenček et al. 1983, Matějovská et al. 1985, Nehyba 1996). A more detailed study (Nehyba 1999) from the area around Moravské Budějovice has revealed that some gravels formed as a pebble lag on the surface due to the selective erosion of finer-grained particles from the underlying sandy fluvial deposits.

About 86% of the pebbles and cobbles in the gravels near Nové Syrovice are composed of quartz. Crystalline rocks (gneiss, migmatite, and quartzite) and feldspar comprise the remaining 14%. A variety of quartz has been recognized. The concentration of milky white and yellow-white quartz greatly surpasses the grey, light brown, and pink varieties. Petrographic studies have suggested that their sources were the Moldanubian crystalline rocks (migmatized gneisses, migmatites, quartzites, etc.).

The size, shape and roundness of 143 quartz pebbles were studied, with additional data obtained from gneiss and quartzite pebbles. The maximum clast diameters (A axis) are 10 cm for quartz, 9 cm for gneiss, and 6 cm for quartzite. The average diameter of the 10 largest quartz pebbles is 7.2 cm, while the average for all 143 quartz pebbles is 4 cm. The quartz pebbles are predominantly (37.1%) disc shaped (Zingg 1933), whereas elongated pebbles comprise 20.7%, spheroid pebbles 18.6%, and bladed pebbles 16.4%. The pebbles of metamorphic rocks are also predominantly of disc or bladed shapes. Evaluating the pebble shape distribution in accordance with the criteria of Sneed and Folk (1958) resulted in 24.5% bladed, 17.5% elongated, and 16.8% spheric-bladed pebbles, with the occurrence of other shapes amounting to less than 10% each.

The average OP index value is 0.87 (with a standard deviation of 5.92). High OP index values reflect the predominance of disc-shaped pebbles (Dobkins and Folk 1970), though the high standard deviation indicates a complex shape distribution. The average flatness index is 2.19 (with a standard deviation of 0.81), the average Krumbein sphericity value (Krumbein 1941) is 0.66 (standard deviation 0.1), and the average maximum projection sphericity

(Sneed and Folk 1958) is 0.64 (standard deviation 0.13). This data reflects the occurrence of flat pebbles with reduced C axes.

The average Krumbein visual roundness value (Krumbein 1941) is 0.39, while the average roundness value in accordance with the criteria of Wentworth is 271.2. Poorly rounded quartz pebbles comprise 20.3% of the total, while the well rounded constitute only 9.8%. The gneiss and quartzite pebbles are generally less rounded, with higher content of poorly rounded clasts. In general, the pebbles from our study area correspond to medium roundness (Dobkins and Folk 1970, Sneed and Folk 1958).

Interpretation

Depositional environment, the degree of transport, and the initial shape of the clasts are the principal factors influencing pebble shape and roundness. The higher influence of the initial shape of the clasts originating from metamorphic rocks is assumed in this case, as marine/shoreline pebbles and cobbles usually show better rounding and typical pebble shape segregation (Postma and Nemec 1990). The occurrence of quartz pebbles and cobbles within the preserved sedimentary profiles of marine deposits is relatively rare. These gravels seem to represent younger deposits, probably of a fluvial nature. Neogene marine deposits could only have served as a very limited, auxiliary source of pebbles. Understanding the gravels and quartz gravels of SW Moravia will require a more detailed study of all individual occurrences. The evolution of gravel beds in the broader area is often complicated by their relation to moldavite-bearing gravels.

Discussion

The Nové Syrovice locality is the westernmost outcrop of Neogene marine deposits in SW Moravia. It is considered to be the product of the forebulge depozone of the foreland basin system. The locality is stratigraphically comparable to Eggenburgian-Ottnangian and Lower Badenian deposits.

Most of the denudation relics in the area are believed to be Eggenburgian, Eggenburgian-Ottnangian, and Ottnangian in age, especially on the SE margins of the Bohemian Massif. Sandy deposits with various admixtures of gravel and clay dominate the composition of these deposits, though clays and gravels are also relatively frequent. Quartz pebbles often dominate the gravel fraction. Eggenburgian to Ottnangian relics have been identified isolated from and associated with younger deposits (Karpatian, Lower Badenian). Deposits that have been interpreted as representing marine (clastic coast) and brackish conditions based on paleontology are often located close to the continuous margins of the Carpathian Foredeep or Molasse Zone (in the broader surroundings of Šatov, Znojmo, Višňové, Ivančice, etc.), with which they are clearly related (Čtyroký and Batík 1983; Matějovská et al. 1987). Deposits in which direct paleontological evidence is absent (interpreted as representing alluvial, fluvial, deltaic, and perhaps also lacustrine environments) are also well known in SW Moravia. They are typified by their common lithologic character, heavy mineral spectra (showing the predominance of local sources), and sometimes by the occurrence of redeposited Cretaceous fossils.

Relics of Lower Badenian deposits have frequently been identified along the entire NW margin of the basin (Procházka 1895, 1899, Cicha and Dornič 1960, Hamršmíd 1984, Brzobohatý 1997, Hladilová et al. 1999, Petrová et al. 2001). Sandy deposits are the most common type in SW Moravia (Hostim, Dukovany, Ivančice), but clayey layers can also be relatively thick in the same region (Kralice nad Oslavou). The depositional environments of these localities were interpreted as a shorelines or shallow marine zones, developing from several metres of older weathering products or terrestrial sediments. The heavy mineral spectra of these deposits is dominated by garnet. Their relation to the upper part of the Lower Badenian deposits in the basin has been documented. Tectonic activity has strongly influenced both the position and the preservation of these relics.

Denudation relics are typically relatively thin, but can be regionally consistent and can contain important unconformities. Adjacent outcrops can vary significantly in stratigraphy.

Conclusions

The Neogene deposits at Nové Syrovice are the products of clastic coastal deposition (shoreface-foreshore deposits). They reflect transgression on a deeply weathered crystalline basement. The deposits were mostly derived from local sources, though material from more distant sources is also present. There is evidence for progradation along a low gradient shoreline.

The exact stratigraphy (Eggenburgian, Lower Badenian?) of the Miocene sands remains unresolved. Our paleoecological interpretation suggests that the salinity of the water in which this material was deposited was at least 30‰ to a depth of 30 m (a region somewhat protected from direct surf effects). This salinity corresponds to normal sea water without any influx of freshwater, but with sufficient lighting and aeration of the water in a warm climate. The majority of the fauna were active in the bioturbation of the sediments.

The origin of the ferruginous sandstones involved oxidizing conditions during paleoweathering processes (in a tropical or subtropical climate) close to the depositional surface. The role of organic material seems to have been important during the precipitation of Fe. Occurrences of ferruginous sandstone in a single horizon close to the surface demonstrates the significant role of erosion and denudation in shaping these deposits.

Quartz rich gravels within the vicinity of this locality represent younger deposits of a probable fluvial origin. Neogene marine deposits served only as an additional and limited source of pebbles.

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