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Provenance and palaeogeographic evolution of Lower Miocene sediments in the eastern North Alpine Foreland Basin

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Abstract

Detrital heavy mineral analysis and sediment chemistry of Lower Miocene sediments of the Lower Austrian Northern Alpine Foreland Basin generally indicate provenance from metapelitic source rocks. The sediments of the Traisen Formation (Ottnangian) were primarily derived from Alpine sources such as the Austroalpine crystalline units of the Eastern Alps and reworked and eroded siliciclastics strata on top of the Northern Calcareous Alps and, in addition, low-grade metamorphic rocks of the Bohemian Massif. Ottnangian and Karpatian sediments in the subground of the northern Lower Austrian Molasse basin were mainly fed from the same southern sources, from low-grade metamorphic rocks of the Bohemian Massif and via resedimentation of Lower Miocene and Palaeogene of the Waschberg–Ždánice Unit and the Vienna Basin. A large-scale input of material from the Rhenodanubian Flysch Zone and of higher-grade metamorphic units and granites of the Bohemian Massif in the Lower Miocene Molasse basin can be ruled out. A compilation of well sections and heavy mineral data point to the existence of a partly emerged, N–S oriented ridge during the Egerian.

Keywords Miocene Central Paratethys · Garnet provenance · Heavy minerals · North Alpine Foreland Basin · Palaeogeography

1 Introduction

The Northern Alpine Foreland Basin (NAFB) is a large, peripheral sedimentary basin that extends from eastern France to the north-eastern part of Austria comprising mainly deposits of Eocene to Miocene times (Harzhauser and Rögl 2005; Piller et al. 2007). It was formed due to gravitational loading by the advancing Alpine orogenic wedge (Hinsch 2008; Sant et al. 2017). Over the last few years, a series of studies have been conducted dealing with different palaeographic, sedimentological and mineralogical aspects of the NAFB (e.g., Rögl 1998; Steininger and Wessely 1999; Kuhlemann and Kempf 2002; Harzhauser and Rögl 2005; Piller et al. 2007; Harzhauser and Piller 2007; Hinsch 2008; Grunert et al. 2010, 2012; Reichenbacher et al. 2013; Pippèrr and Reichenbacher 2017; Kováč 2017; Sant et al. 2017). There exist only a few detailed provenance studies with regard to sediments of the eastern part of the NAFB (Hamilton 1997) and sediments of the Vienna Basin (e.g., Stern and Wagreich 2013; Kovác et al. 2004).The main focus of this paper is to reconstruct the sediment provenance and to identify source areas of the eastern part of the NAFB during the early Miocene by comparative analyses of heavy minerals, including assemblage counts and detrital mineral chemistry and analyses of the bulk-rock geochemistry of the Burgidalian Traisen Formation in Lower Austria and coeval sediments in the subground of the basin.

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Single grain mineral studies primarily started off with the analyses of variations in major-element compositions of amphiboles (Mange-Rajetzky and Oberhänsli 1982), clinopyroxens (Cawood 1983), garnets (Morton 1985), tourmalines (Henry and Guidotti 1985) and chrome spinels (Pober and Faupl 1988). In recent years, the adoption of innovative analysis techniques (Mange and Morton 2007; von Eynatten and Dunkl 2012) for minerals like epidote (Spiegel et al. 2002), apatite (Morton and Yaxley 2007) and rutile (Zack et al. 2004; Meinhold et al. 2008; Triebold et al. 2012) allowed further insight in the provenance history of sedimentary rocks. A particular focal point of this work is the evaluation of the chemistry of Miocene garnets of the NAFB. Garnets derive from a wide variety of different source rocks that cover a large P–T–X range and are therefore well suited for reconstructing provenance and fingerprinting sediment transport systems (Morton 1985; von Eynatten and Dunkl 2012; Stutenbecker et al. 2017). A larger number of different garnet discrimination diagrams have been created that allow an interpretation of data in terms of provenance (Wright 1938; Teraoka et al. 1997; Grütter et al. 2004; Mange and Morton 2007; Aubrecht et al. 2009; Suggate and Hall 2013). A detailed review of garnet discrimination diagrams can be found in Krippner et al. (2014). Results of this present study are based on a new garnet discrimination plot (TETGAR) that will be briefly introduced in Sect. 3.

2 Geological and stratigraphical setting

Orogenic processes in the Alps during the Palaeocene and Eocene are a result of the collision of the Adriatic/Apulian and the European plate (Faupl and Wagreich 2000). The uplift of the Alpine orogen entailed the elimination of large parts of the Alpine Tethys Ocean (Handy et al. 2010). Due to crustal loading, uplift and growth of the Alpine mountain chain, a large-scale asymmetric depression of the European plate occurred, forming the prominent NAFB and creating the prerequisites for the deposition of massive sediment infill of up to 1 km in the foreland (Kuhlemann and Kempf 2002; Schuster and Stüwe 2010). North of the evolving orogen, the large but mostly shallow Paratethys Seaway was formed (Harzhauser and Rögl 2005; Piller et al. 2007). During Oligocene and Neogene times, relative sea-level changes caused marine transgressions and regressions and significant alterations of the palaeogeography of the Paratethys, leading to phases of faunal extinction and endemism (Piller et al. 2007). In contrast to the marine life of the Mediterranean Sea at that time, where diverse coral reefs could develop, the biota of the Paratethys yielded a relatively low diversity (Harzhauser and Rögl 2005). From ca. 20.5 Ma onwards (base of the Central Paratethys stage Eggenburgian), an extensive transgression onto the Bohemian Massif (Horner Basin, Eggenburg Bay, Bavaria) took place (Hilgen et al. 2012; see also Fig. 1). Sediments of the Burdigalian (Eggenburgian–Ottnangian of Central Paratethys regional stratigraphy) transgressive cycle are mainly shallow marine sands and offshore muds (Krenmayr 1999).

At the end of the Ottnangian a strong marine regression occurred in the NAFB (Rögl 1999; Harzhauser and Rögl 2005; Piller et al. 2007; Pippèrr and Reichenbacher 2017). Due to a less pronounced sea-level rise and the uplift of the southeastern part of the Bohemian Massif during the following transgressive cycle beginning at about 17.3 Ma (base of Karpatian regional stage), largely non-marine sedimentation took place in central Lower Austria during the Karpatian (Wessely 2006; Hilgen et al. 2012). The most recent definition of the upper Ottnangian lithostratigraphic units in the Austrian NAFB led to the establishment of the Traisen and Dietersdorf Formation which are summarized in the Pixendorf Group, based on outcrops south of the Danube (Gebhardt et al. 2013).

Burdigalian marine sediments (Ottnangian–Karpatian sediments (OKS]) of the eastern NAFB are mainly found in wells from areas north of the Danube up to the border to the Czech Republic (Aniwandter et al. 1990; Wessely 2006; see also Fig. 2).

2.1 Traisen Formation

The regression of the Lower Austrian Paratethys in the early Miocene is associated with the deposition of the Traisen Formation. The extent and thickness of these sediments in the Lower Austrian Paratethys varies considerably due to the filling of a palaeorelief (Gebhardt et al. 2013). The term Traisen Formation was introduced and defined by Gebhardt et al. (2013). It refers to the former *Oncophora* beds (Wessely 2006) located in an area around St. Pölten in the west, the Danube in the north and Judenau in the east (Fig. 2). The term *Oncophora* derives from the brackish water bivalve *Oncophora* (or *Rzehakia* in modern literature) which represents a characteristic macrofossil in these Ottnangian beds (Mandic and Coric 2007). Sand beds of several metres thickness alternate with clay layers, which are a few millimeters to centimeters thick. Sometimes coarser material can be observed, such as slump beds and rip-up clasts which are indicative of the synsedimentary erosion of older material. From a palaeontological point of view, a scarcity of nannofossils is a typical feature of the Traisen Formation.

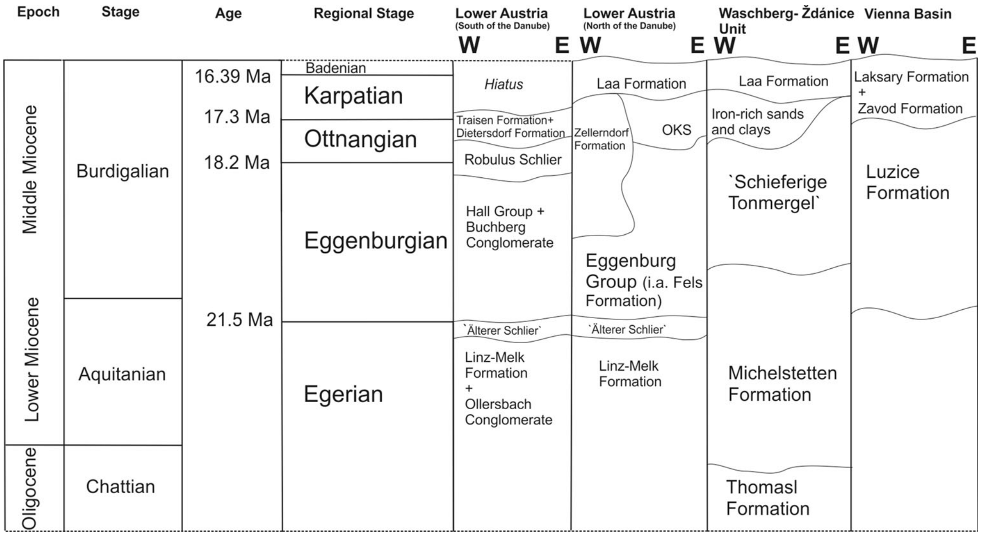


Fig. 1 Simplified stratigraphic table of the eastern part the NAFB for the Miocene (OKS = Ottnangian and Karpatian sediments in the subground of the northeastern part of the NAFB)

2.2 Dietersdorf Formation

Coarse sands and conglomerates with rock fragments up to 50 cm are the most frequent lithologies of the Dietersdorf Formation which extends over an area of approximately 12 × 3 km in the southeastern part of the Traisen Formation. Subordinate components are more finely grained sediments, e.g. sands and pelites. Due to its stratigraphic position, the Dietersdorf Formation is correlated to the late Ottnangian (Schnabel et al. 2002; Wessely 2006; Gebhardt et al. 2013). Based on the occurrence of flysch and carbonate components, an influence from Alpine units such as the Northern Calcareous Alps (NCA) and the Rhenodanubian Flysch Zone (RFZ) is evident (Schnabel et al. 2002; Gebhardt et al. 2013).

2.3 Iron-rich sands and clays

Iron-rich sands and clays ("Eisenschüssige Sande"; Schnabel et al. 2002) in the area west of the Waschberg–Ždánice Unit, north of the River Danube (Fig. 2), are grey to grey brown, weathered, mica-rich fine to medium sands and greyish, laminated clays and claystones with limonitic concretions. The original depositional area of these sediments was further to the east. They were thrust northwestward during the uplift of the Waschberg–Ždánice Unit (Rögl et al. 2009; Gebhardt et al. 2013). Heavy mineral studies revealed a predominance of garnet (~ 90%) and minor amounts of zircon, staurolite, rutile, apatite and epidotes (Novák and Stráník 1998). The typical occurrence of limonitic concretions in the iron-rich sands and clays does not correspond to the sedimentological characteristics of the Traisen Formation (Hamilton 1997; Gebhardt et al. 2013).

2.4 Ottnangian and Karpatian sediments in the subground of the northeastern NAFB (OKS)

West of the Waschberg–Ždánice Unit, Lower Miocene sediments (so called *Oncophora* beds in former literature, Brix and Schultz 1993) in the subsurface show characteristics of a deeper-water environment with sediment gravity flows, turbidites, muddy/sandy slumps, incomplete Bouma sequences and marine faunal assemblages (Aniwandter et al. 1990; Brix and Schultz 1993; Hamilton 1997; Kuffner 2001; Wessely 2006). OKS comprise alternating strata of fine sandstones, silts and laminated pelites with graded and convolute bedding.

In the course of this study, sediment of different wells (Wildendürnbach 4, Porrau 2, Altenmarkt im Thale, Laa 1, Kettlasbrunn 2, Mailberg 2, Moosbierbaum 1, Streithofen 1, Schaubing NÖ O3) in Lower Austria was analyzed. Lower Miocene sediments (Karpatian, Ottnangian, Eggenburgian) are found up to depths of about 1940 m in the well Laa 1. With regard to OKS, Hamilton (1997) suspected a major sediment input from the approaching NW-ward thrusting Waschberg–Ždánice Unit, whose main axis is oriented parallel to the south-eastern part of the Carpathian Foredeep (Beidinger and Decker 2014). A general increase in fish remnants, diatoms, radiolarian and echinoderms from south to north supports the view of a marine, deeper-water depositional environment for Lower Miocene sediments in northeastern Lower Austria, whereas a more marginal and brackish depositional environment prevailed during the sedimentation of the Traisen Formation in the south (Brix and Schultz 1993).

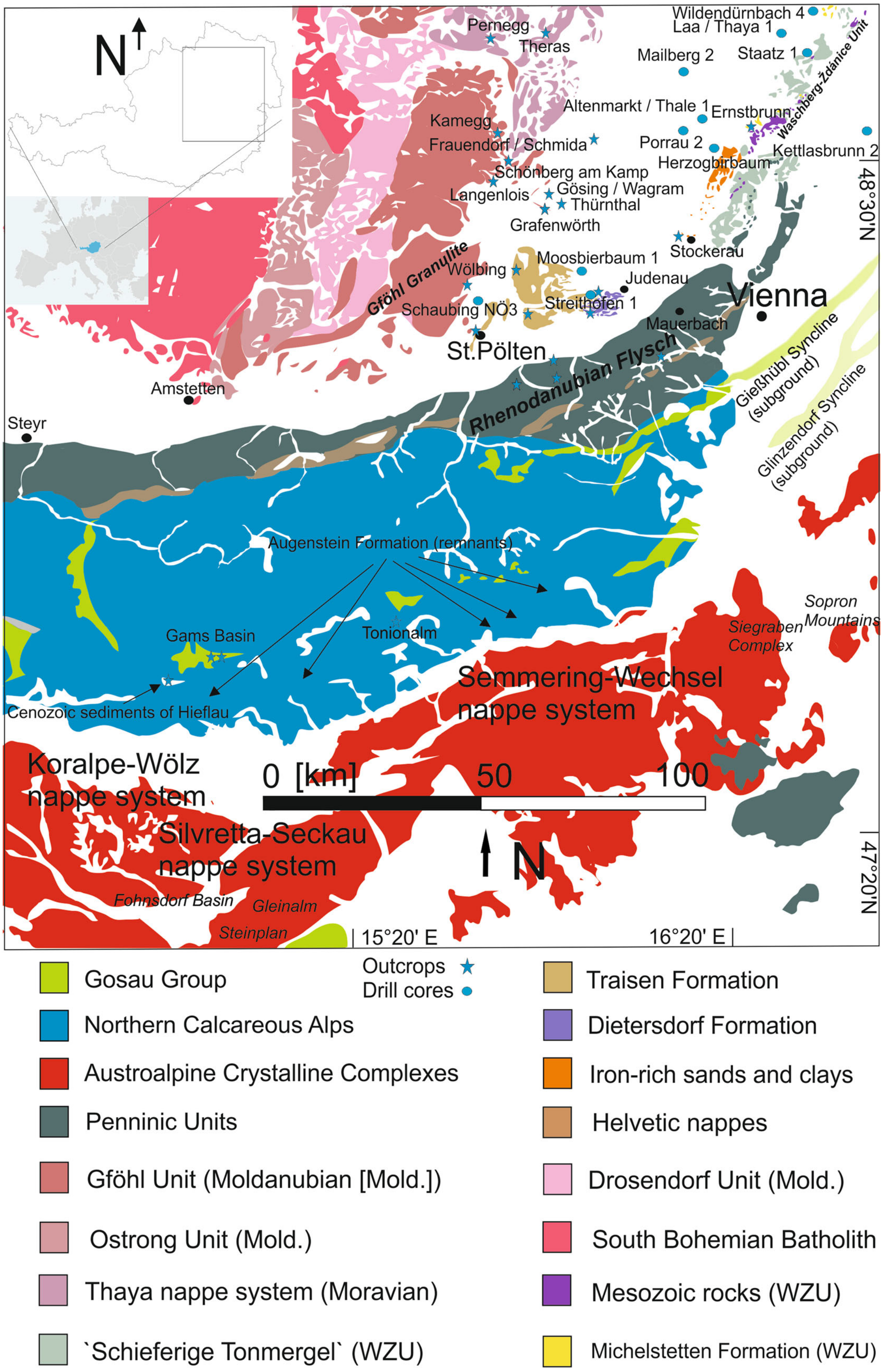


Fig. 2 Simplified geological map of Lower Austria and Northern Styria with outcrops. *WZU* Waschberg–Ždánice Unit

3 Methods

The preparation of heavy mineral concentrates from sand and sandstone samples involved crushing of the material (if needed) to coarse sands. Following immersion in acetic acid ($C_2H_4O_2$) to dissolve calcite cements, lasting 5 days; separation of the 0.063–0.4 mm fraction was carried out by sieving. The subsequent gravity separation was achieved by use of the heavy liquid tetrabromoethane (density 2.94 g/cm^3). The quality and quantity of the obtained heavy mineral fractions were analyzed using standardized polarized light microscopy. In order to guarantee statistical representativeness, about 200 grains per sample were counted.

Heavy minerals were embedded in carbon mounts and then extensively polished with a polishing disc for further investigation. Elemental analyses of carbon-coated minerals of the 0.063–0.4 mm sieve fraction were undertaken with a Cameca SX 100 electron microprobe analyzer (acceleration voltage of 15 kV) at the Department of Lithospheric Research, University of Vienna. Pulverized samples of the Traisen Formation, the Dietersdorf Formation, of adjacent lithologies and of OKS were analyzed at ACME Analytical Laboratories (Bureau Veritas, Vancouver, Ltd./ http://www.acmelab.com) by inductively-coupled plasma mass spectrometry (ICP-MS). Measurements of the whole rock chemistries were performed on 29 selected samples for eleven major oxides (SiO_2; Al_2O_3; Fe_2O_3; MgO; CaO; Na_2O; K_2O; TiO_2; P_2O_5; MnO; Cr_2O_3) and 47 minor and trace elements (Ni; Sc; Ba; Be; Co; Cs; Ga; Hf; Nb; Rb; Sn; Sr; Ta; Th; U; V; W; Zr; Y; La; Ce; Pr; Nd; Sm; Eu; Gd; Tb; Dy; Ho; Er; Tm; Yb; Lu; Mo; Cu; Pb; Zn; As; Cd; Sb; Bi; Ag; Au; Hg; Tl; Se; B). Absolute contents were determined by comparing the analytical results to those of prepared standards.

In order to overcome some limitations of conventional garnet discrimination diagrams, a new tetrahedral provenance plot, called TETGAR, has been developed (Knierzinger 2015). The TETGAR three-dimensional MATLAB plot is based on the four garnet end-members almandine (Alm), grossular (Gro), pyrope (Pyr) and spessartine (Spe) forming the vertices of a tetrahedron. Cartesian coordinates were recalculated from normalized end-member values. The three-dimensional impression of images given here is ensured by the use of a colorbar (z-axis) that corresponds to the spessartine content (high values = red; low values = blue).

Based on database of Suggate and Hall (2013) and additional EMPA-data (Brown 1969; Shimazki 1977; Manning 1983; Mann et al. 1991; Shenboa 1993; Paulick and Franz 2001; Willner et al. 2001; Ballevre et al. 2003; Makrygina and Suvorova 2011; Malvoisin et al. 2011; Antao 2013) the chemistry of more than 2600 garnets was evaluated and used to create various triangulated subfields that correspond to various subfields, which in turn correspond to different source types representing metamorphic facies conditions of metapelitic, metasomatic and metabasic rocks as well as felsic igneous rocks. The calculation of the space coordinates of the plotting points in the tetrahedron is accompanied by a normalization of data to 100%.

In order to compress the data volume, only garnets in the range of ($\pm$) one standard deviation (σ) of the arithmetic mean (μ) with regard to each end-member (almandine, pyrope, grossular and spessartine) were taken into account. Garnets with higher different (e.g., andradite, uvarovite) end-member components ($\geq$ 4%) were sorted out. Garnets from exceptional ores, migmatites, xenoliths, volcanic rocks, hornfelses, garnets with unclear or ambiguous attribution as well as redundant measurements were not quantitatively considered either (Fig. 3). A more detailed characterization of this plot and comparison with other garnet plots will be published elsewhere.

The MATLAB function ‘TETGAR’ can be found as supplementary material.

Additional internal OMV data of following wells have been incorporated into considerations: Wildendürnbach 1, Wildendünrbach 4, Porrau 1, Porrau 2, Altenmarkt im Thale 1, Laa 1, Kettlasbrunn 2, Mailberg 1, Mailberg 2, Moosbierbaum 1, Absdorf 2, Absdorf 4, Streihofen 1, Staatz 1, Herzogbirbaum 1, Goggendorf 1, Großharras 1, Hadres 1, Jettsdorf 1, Murstetten 1, Niederrußbach 1, Roggendorf 1, Rust 2, Stronegg 1 and Viehdorf 1.

4 Results

4.1 Whole rock chemistry

Typical SiO_2 contents of measured sandstones in the Traisen Formation range between ~ 60 to 71%. The scattergram (Fig. 3; modified from Herron 1988) of log (SiO_2/Al_2O_3) vs. log (Fe_2O_2/K_2O) illustrates different chemical compositions of the analyzed sands and pelites of the Traisen Formation, of the Dietersdorf Formation, of Wildendürnbach 4 (OKS) and adjacent lithological units. Sediments of the Traisen Formation exhibit very low carbonate contents. According to this diagram, analyzed sands of the Traisen Formation can generally be classified as wackes and litharenites. Coarser sands, scattered gravels and bigger rip-up clasts are more frequent in northwestern and central parts of the Traisen Foramtion. Slightly higher concentrations of Zr were found in the southeastern and in the northwestern part of the Traisen Formation.

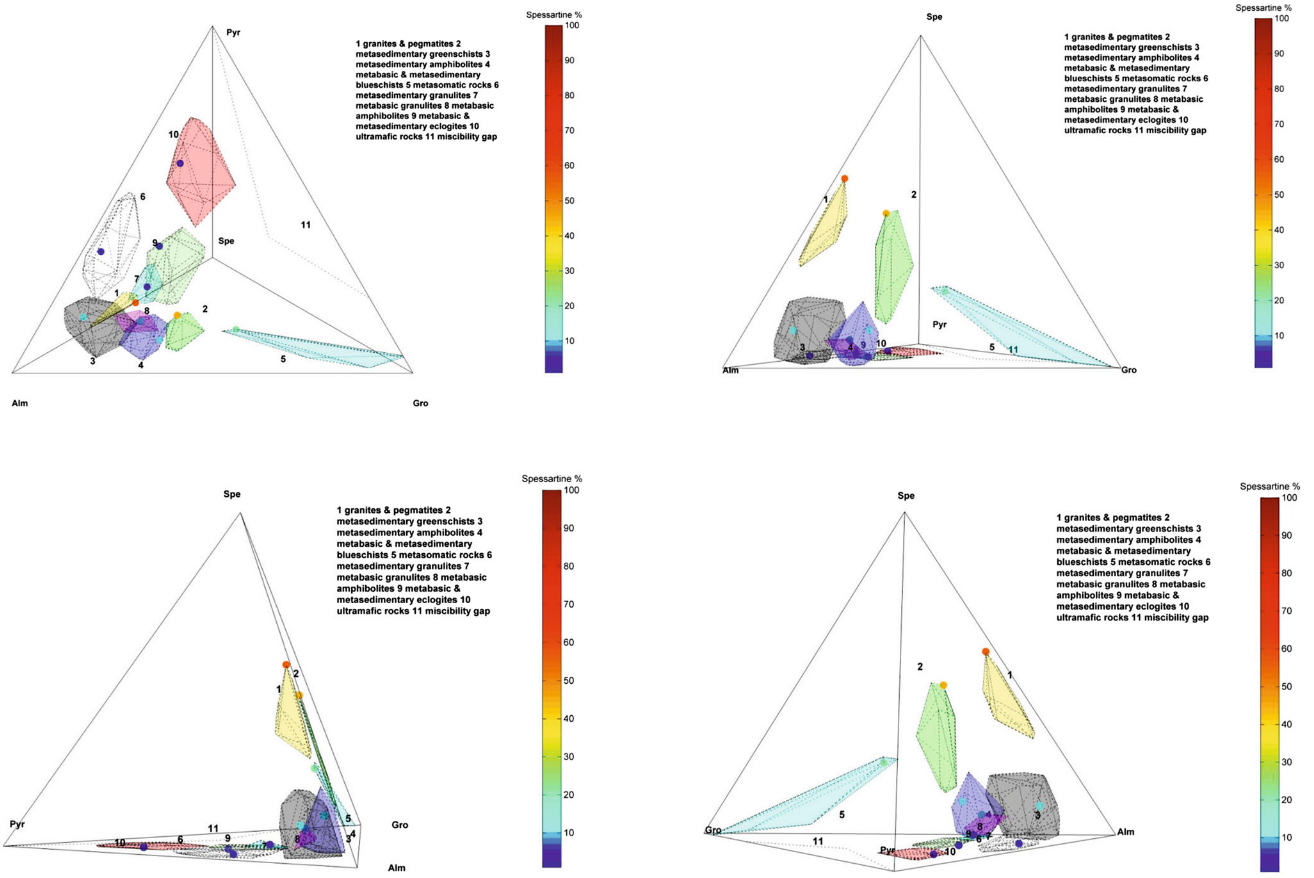


Fig. 3 TETGAR (top + front + side + back view with representative garnets for each subfield)

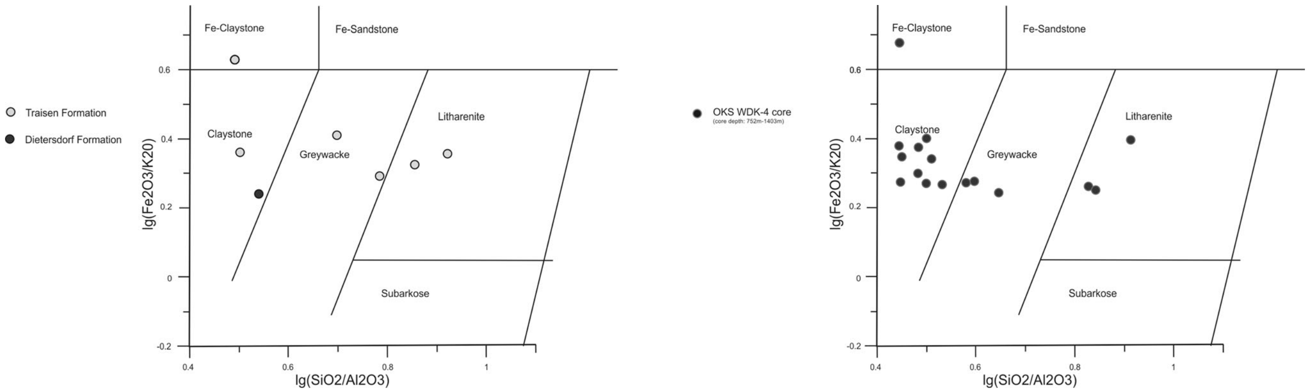


Fig. 4 Sandstone classification diagrams (Traisen Formation, Dietersdorf Formation and OKS). Modified from Herron (1988)

OKS predominantly consist of claystones (Fig. 4). Coarser, quartz-rich components were noticed along the margin of the Bohemian Massif in the west.

4.2 Heavy minerals and mineral chemistry

Heavy mineral analyses of samples from the Traisen Formation revealed high amounts of garnets (~ 65%) and relatively high amounts of epidotes/zoisites and amphiboles. Subordinate heavy minerals include tourmaline, rutile, staurolite, titanite, sillimanite, kyanite, apatite and zircon. With regard to epidotes/zoisites and amphiboles, a moderate depletion from west to east is noticeable. In the northern Traisen Formation, occasiconal findings of kyanite, sillimanite and Ca-amphiboles with higher Ti-contents (up to ~ 2.5%) were noted.

Although the heavy mineral spectra (also dominated by garnet) are broadly similar, in contrast to the Traisen

Formation, significant amounts of carbonates (calcite, rhodochrosite, magnesite, and dolomite) are characteristic of the Dietersdorf Formation.

The heavy mineral spectra of the analyzed drill cores in Lower Austria (OKS) are generally dominated by garnet (up to ~ 85%). A discrepancy between the heavy mineral spectra of the Traisen Formation and those of the OKS (Wildendürnbach 4, Laa 1, Staatz 1) is the rarity of amphiboles and epidotes/zoisites in OKS. Besides, slightly higher contents of staurolites, biotites and zircons were determined in OKS. Compared to other analyzed samples of OKS, slightly higher amounts of epidotes/zoisites and amphiboles were found in the Mailberg 2 and the Porrau 2 core. Deeper sections (1269 and 1329 m) of the Mailberg 2 core are characterized by different heavy mineral spectra (Fig. 5) and high-grade metamorphic garnets.

Analyses of amphiboles of the Moldanubian Zone of the Bohemian Massif (samples were taken from amphibolites at Kamegg and Grafenwörth, see Fig. 2) show relatively high TiO_2 contents (~ 1.5 to 2.5%), differing significantly from TiO_2 contents of ~ 0.4%. on average of amphiboles of the Traisen Formation and of OKS.

Heavy minerals of all analyzed locations (outcrops + drillings) predominantly appear in angular, sub-angular and sub-rounded forms. Rounded forms were barely detectable.

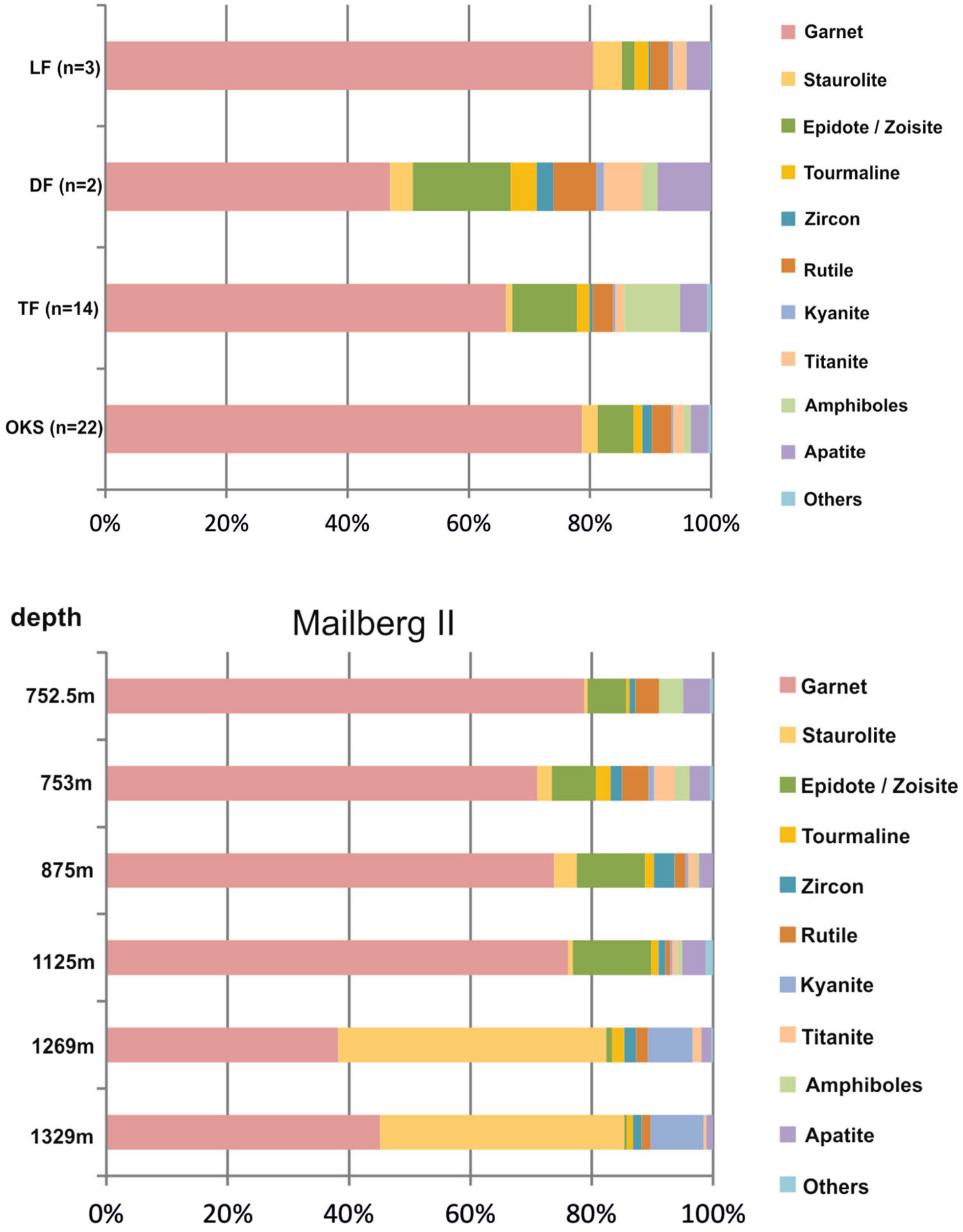


Fig. 5 Heavy mineral spectra OKS, Traisen Formation (TF), Dietersdorf Formation (DF) and Luzice Formation (LF) + heavy mineral spectrum Mailberg 2 core

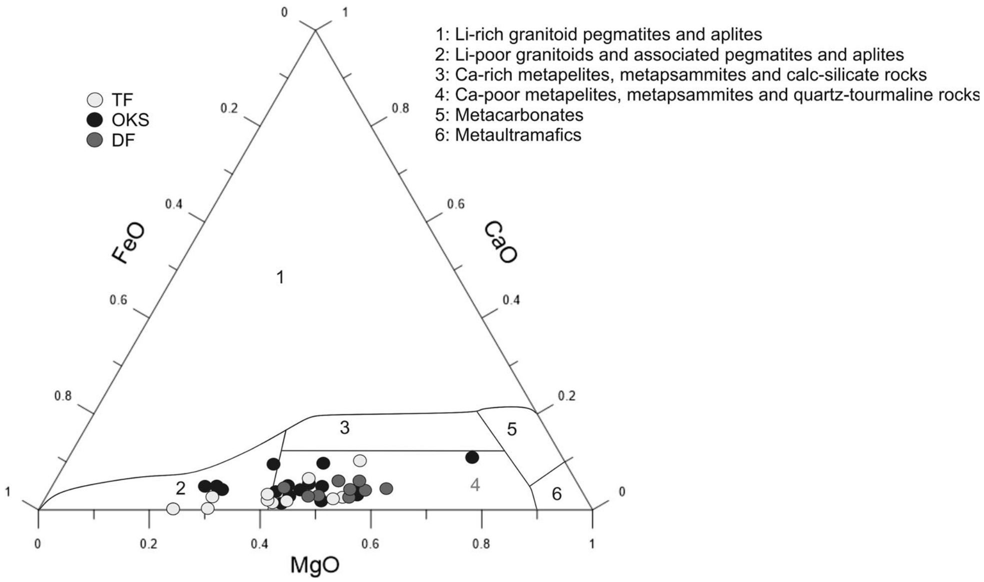


Fig. 6 Tourmaline discrimination diagram (Henry and Guidotti 1985). *TF* Traisen Formation, *DF* Dietersdorf Formation

According to the discrimination approach of Henry and Guidotti (1985), most tourmalines of the Traisen Formation, the Dietersdorf Formation and the OKS can be attributed to Ca-poor metapelites and calc-silicate rocks. The chemical compositions of tourmalines of the Traisen Formation and of OKS suggest granitoid rocks also (Fig. 6). A significant influence of meta-carbonates, meta-ultramafics and Li-rich rocks can be ruled out.

4.2.1 Garnet chemistry

The TETGAR plot implies a main attribution of the garnets of the Traisen Formation to metasedimentary amphibolites. While most of the measured garnets of the Traisen Formation exhibit grossular contents of $> 15\%$, some samples also show higher amounts of garnets with grossular contents of $< 12\%$. Higher amounts of these low-grossular almandines were found in the Streithofen core in the eastern part of the Traisen Formation and in sediments of the Laa Formation (outcrop Thürnthal) (see Fig. 2).

Garnets of the OKS, the iron-rich sands and clays, the Dietersdorf Formation and the Ottnangian Luzice Formation of the Vienna Basin (well Kettlasbrunn 2) are chemically similar to garnets of the Traisen Formation (mostly high-grossular almandines). Almandine garnets of the OKS tend to exhibit slightly lower grossular contents than garnets of the more southern Traisen Formation.

Considerable differences between Lower Miocene garnets of the eastern NAFB (see Figs. 7, 8) and high-grade metamorphic detrital garnets of Cretaceous–Palaeogene strata (Altlengbach Formation/RFZ, e.g., Egger et al. 2002) from the RFZ were found (see Fig. 9).

Following table provides an overview of chemical compositions of garnets of different lightological units in the NAFB and of adjacent areas:

Some pure grossular garnets were found in the northern part of the Traisen Formation. Almandines with higher

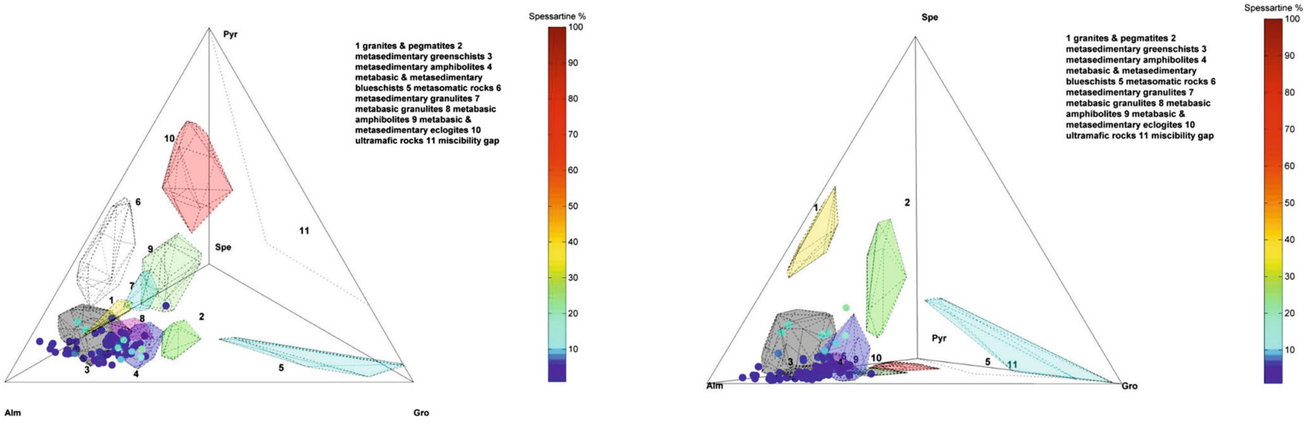


Fig. 7 Garnet chemistry Traisen Formation (TETGAR top + front view)

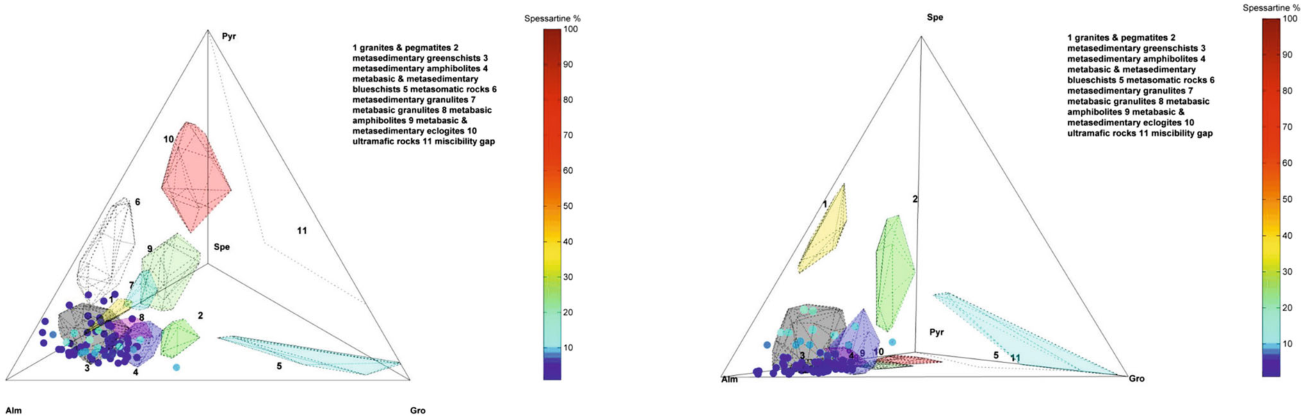


Fig. 8 Garnet chemistry OKS (TETGAR top + front view)

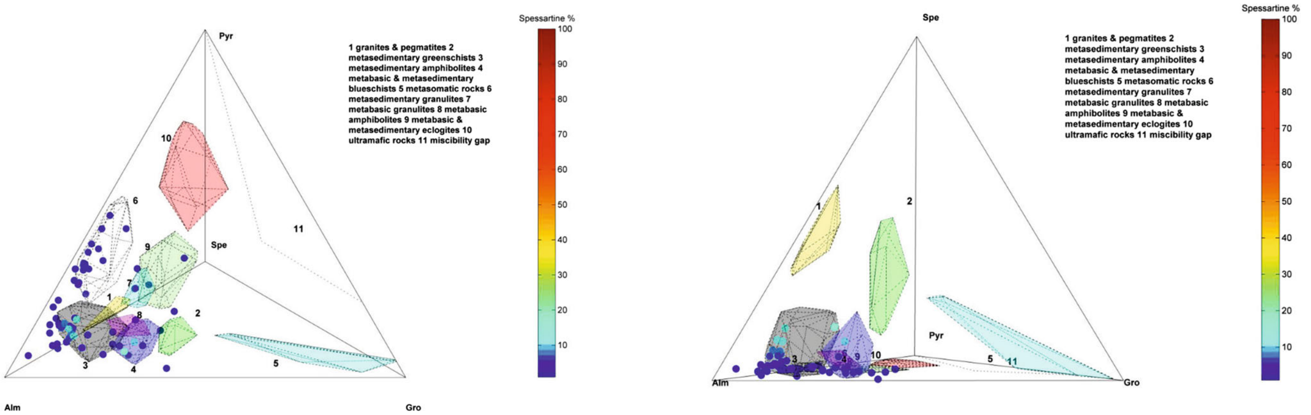


Fig. 9 Garnet chemistry Rhenodanubian Flysch (Altlengbach Formation) (TETGAR top + front view)

andradite contents were measured in samples of Moravian garnet-mica schists (outcrop Theras).

5 Discussion

5.1 Traisen Formation

The mineralogial composition of the Traisen Formation and the majority of the analyzed garnets of the Traisen Formation are in good correspondence with low to medium grade metapelitic source litholgogies of Austroalpine crystalline units of the Eastern Alps (Flügel 1975; Schuster and Frank 1999; Hölzel and Wagreich 2004; Wagreich and Strauss 2005; Wessely 2006; Gaidies et al. 2006; Raič et al. 2012; Bender 2014).Correspondences are also noted with garnets of Palaeocene sediments of the Gießhübl Formation (Gosau Group/NCA, see. Hofer 2013) and of Cretaceous to Eocene sediments of the Zwieselalm Formation (Gosau Group/NCA). Moreover, strong similarities to garnets of Alpine Cenozoic sediments in the area of Hieflau ('Hieflauer Tertiär'/NCA, see Wagreich et al. 1996) and similar siliciclastic sediments in the area of the Tonionalm (NCA) were found. The high degree of consistency between the garnet compositions of the Traisen Formation and monometamorphic garnet-mica schists of the Gleinalpe area is considered a strong argument for a significant input of Austroalpine crystalline source rocks from the Eastern Alps into the Burdigalian sediments of the Lower Austrian part of the NAFB. Monometamorphic garnet-mica schists in the Gleinalpe area were interpreted as an eastern continuation of the Radenthein Complex (Raič et al. 2012). The Radenthein Complex, which represents the uppermost part of the Koralpe–Wölz nappe system, witnessed an Eo-alpine (Cretaceous) thermal imprint. Extensive erosional, sedimentation and resedimentation processes of these monometamorphic lithologies during the Palaeogene are conceivable (Stern and Wagreich 2013) and thus explain similar compositions of garnets from Palaeocene Gosau-Group rocks and younger Neogene strata on top of the NCA.

Measured garnets of the Moldanubian crystalline basement in the well core Moosbierbaum 1 (paragneiss; depth 45 m) show similarities to the low-grossular almandines in

Table 1 End-member contents of garnets of the NAFB and of potential source rocks

Formation/lithology	Alm	Gro	Pyr	Spe	Source
Traisen Formation (NAFB)	67.9 (σ = 6.9)	18.9 (σ = 6.4)	8.6 (σ = 3.6)	4.4 (σ = 4.2)	This paper
Dietersdorf Formation (NAFB)	69.3 (σ = 10.0)	15.3 (σ = 10.5)	9.2 (σ = 5.8)	5.9 (σ = 5.6)	This paper
Ottnangian and Karpatian sediments in the subground of the northeastern part of the Lower Austrian NAFB	70.1 (σ = 6.7)	16.5 (σ = 7.2)	9.5 (σ = 4.7)	3.7 (σ = 4.1)	This paper
Iron-rich sands and clays (outcrop Stockerau/NAFB)	64.5 (σ = 9.7)	20.1 (σ = 5.4)	10.7 (σ = 7.8)	4.1 (σ = 3.4)	This paper
Laa Formation (outcrop Thuürnthal/ NAFB)	74.6 (σ = 6.4)	13.5 (σ = 7.6)	8.9 (σ = 4.2)	2.8 (σ = 3.1)	This paper
Linz–Melk Formation (outcrop Wölbing/ NAFB)	55.7 (σ = 17.6)	13.3 (σ = 12.2)	26.8 (σ = 15.2)	4.1 (σ = 12.2)	This paper
Linz–Melk Formation ? (well Mailberg 2 [depth 1329 m]/NAFB)	62.4 (σ = 12.1)	10.0 (σ = 12.2)	18.2 (σ = 14.0)	9.1 (σ = 10.3)	This paper
Fels Formation (outcrop Gosing am Wagram/NAFB)	64.8 (σ = 25.5)	13.2 (σ = 8.8)	9.7 (σ = 10.6)	12.1 (σ = 12.5)	This paper
Siliciclastic sediments Tonionalm (NCA)	68.4 (σ = 6.9)	19.3 (σ = 5.2)	8.9 (σ = 2.4)	3.2 (σ = 3.8)	This paper
Cenozoic sediments Hieflau (NCA)	66.1 (σ = 4.8)	20.9 (σ = 3.1)	8.1 (σ = 2.2)	4.6 (σ = 4.0)	This paper
Cretaceous–Eocene sediments of the Zwieselalm Formation (Gams Basin/ NCA)	66.6 (σ = 6.4)	18.1 (σ = 7.6)	9.0 (σ = 5.3)	6.1 (σ = 5.3)	This paper
Palaeocene sediments of the Gießhübl Formation (Gosau Group/Vienna Basin)	65.0 (σ = 4.9)	20.4 (σ = 3.7)	9.1 (σ = 2.8)	4.9 (σ = 4.7)	Hofer (2013)
Luzice Formation (well Kettlasbrunn 2/Vienna Basin)	67.2 (σ = 7.2)	18.9 (σ = 6.8)	9.6 (σ = 5.6)	4.0 (σ = 4.5)	This paper
Altlengbach Formation (Rhenodanubian Flysch Zone)	67.0 (σ = 10.5)	10.7 (σ = 9.3)	18.9 (σ = 11.4)	3.1 (σ = 3.4)	This paper
Garnet-mica schists Gleinalm (Koralpe–Wölz nappe system/Eastern Alps)	66.3 (σ = 2.2)	21 (σ = 7.1)	7.7 (σ = 6.7)	4.7 (σ = 2.5)	Raic et al. (2012)
Garnet-mica schists Steinplan area (Koralpe–Wölz nappe system/Eastern Alps)	68.9 (σ = 6.7)	19.7 (σ = 7.9)	9.9 (σ = 3.0)	1.4 (σ = 2.2)	Bender (2014)
Moldanubian mica-schists west of Langenlois (Bohemian Massif)	65.9 (σ = 4.6)	15.1 (σ = 4.8)	7.9 (σ = 1.4)	10.5 (σ = 3.1)	This paper
Moldanubian (?) garnet-mica schists (outcrop Frauendorf an der Schmida/ Bohemian Massif)	73.7 (σ = 6.6)	14.1 (σ = 4.5)	6.6 (σ = 2.2)	5.4 (σ = 4.7)	This paper
Moravian (?) greenschists (outcrop Schonberg am Kamp/Bohemian Massif)	65.7 (σ = 10.5)	7.3 (σ = 1.5)	7.3 (σ = 2.0)	19.5 (σ = 10.8)	This paper
Moravian garnet-mica schists (outcrop Pernegg (Pernegg Fomation)/Bohemian Massif)	79.9 (σ = 1.8)	10.1 (σ = 1.0)	8.1 (σ = 1.6)	1.6 (σ = 2.3)	This paper
Michelstetten Beds (outrcop Ernstbrunn/ WZU)	62.7 (σ = 12.2)	12.3 (σ = 8.1)	22.5 (σ = 12.4)	2.5 (σ = 2.0)	This paper

WZU Waschberg–Ždánice Unit

the Karpatian Laa Formation (Thürnthal outcrop). It should be emphasized that the vast majority of almandine garnets of the Moravian and Moldanubian units show significant lower grossular contents (< 15%) than typical Alpine metamorphic almandines (> 15%). Additional typical low-grossular almandines (see also Table 1) of different Moldanubian and Moravian rocks are reported by Zaydan and Scharbert (1983), Bernroider (1989) and Linner (1996). The reason for this difference is mainly to be found in high pressure conditions during the Alpine orogeny causing a stronger incorporation of Ca (Harangi et al. 2001; Suggate and Hall 2013; Krippner et al. 2014) in Alpine almandines.

The detection of pure grossular garnets in coarser-grained samples of the northern Traisen Formation is an indication for an influence of calc-silicate source rocks. A higher number of locally confined calc-silicate rocks are known from different units of the Moldanubian and Moravian (i.e., Drosendorf Unit, Pernegg Formation, Bites Unit) in the Bohemian Massif (Bernroider 1989; Schnabel et al. 2002; Wessely 2006). The presence of similar, already eroded lithologies at the southeastern margin of the Bohemian Massif in the Miocene is a reasonable assumption (Schnabel et al. 2002; Wessely 2006). At the same time, a sedimentary input from Moldanubian and Moravian metapelitic rocks (mica schists; paragneisses) into the Lower Miocene Paratethys seems certain, as indicated by coarser sediment material, low-grossular almandines and Ti–rich amphiboles in the northern Traisen Formation. Besides, analyses of Fe-rich tourmalines suggest a secondary influence from higher metamorphic Moldanubian units. A stronger influence from the Moldanubian in the northern part of the Traisen Formation is furthermore supported by the scattered presence of kyanites, sillimanites and bigger rip-up-clasts. Significant sedimentary input of the Gföhl Unit, the Ostrong Unit (both Moldanubian), igneous intrusive rocks of the Moravian and the Linz–Melk Formation (Egerian) can be ruled out.

A prominent influence of other higher metamorphic and more diverse crystalline units at the eastern margin of the Eastern Alps (e.g., Sieggraben Complex; Sopron Mountains; see Draganits 1998; Schuster et al. 2001; Kromel et al. 2011; Schuster et al. 2004) and of the zircon and tourmaline-rich sediments of the Augenstein Formation (Oligocene–Lower Miocene syntectonic strata on top of the NCA, see Frisch et al. 2002) can be excluded.

High-grade granulite garnets, typical for the RFZ, are almost completely absent (with some exceptions in the vicinity of the Gföhl granulite) in the Traisen Formation. A significant influence of the RFZ on early Miocene sedimentation in the central Lower Austrian Molasse basin can therefore be ruled out. However, higher concentrations of Zr in the southeastern part of the Traisen Formation can possibly be correlated with a minor influence of material from the zircon-rich RFZ, whereas higher concentrations of Zr in the northwestern part of the Traisen Formation (Traismauer) might be linked to zircon-bearing Moldanubian units (Niedermayr 1967; Schnabel et al. 2002; Nehyba and Roetzel 2010).

5.2 Dietersdorf Formation

The analyzed garnets of two sandstone samples of the Dietersdorf Formation indicate a primary attribution to low metamorphic rocks of the Austroalpine crystalline units of the Eastern Alps (i.e., Koralpe–Wölz nappe system, Silvretta–Seckau nappe system, Semmering–Wechsel nappe system). Unlike analyses of garnets of the Altlengbach Formation and other Flysch Units, no high-grade metamorphic garnets were found in the analyzed sample set. A frequent occurrence of flysch components in the Dietersdorf Formation, however, is mentioned by Schnabel et al. (2002) and by Gebhardt et al. (2013). This apparent contradiction is probably due to the high lithological inhomogeneity of the Dietersdorf Formation that also exhibits strong deviations in terms of the occurrence of heavy minerals in general and of certain carbonates such as rhodochrosite, magnesite and dolomite. In general, a major influence from the NCA and from Austroalpine crystalline units of the Eastern Alps seems certain.

5.3 Ottnangian and Karpatian sediments in the subground of the northeastern part of the NAFB (OKS)

Analyses of OKS in the drill core samples of Wildendürnbach 4, Laa 1, Mailberg 2, Porrau 2 and Altenmarkt/Thale revealed quite homogenous heavy mineral spectra that are dominated by almandine garnets. Different source rocks with respect to the Traisen Formation are indicated by slightly higher pyrope contents of the garnets, higher contents of staurolite, slightly higher contents of zircons and biotites and lower contents of epidotes/zoisites. Another discrepancy between the heavy mineral spectra of the Traisen Formation and those of OKS (Wildendürnbach 4, Laa 1, Staatz 1) is the rarity of amphiboles in OKS. The absence of amphiboles might be explained by intrastratal dissolution effects (Mange and Morton 2007). Comparisons with the heavy mineral spectra of near-surface samples of other cores (e.g., Staatz 1), however, indicate a primary lack of amphiboles in these sediments.

Similarly to the sediments of the Traisen Formation, chemical analyses of garnets and tourmalines of OKS suggest primarily metapelitic source rocks.

Considering coarser grain sizes in the area of Mailberg and Porrau, additional sedimentary input of material from the Moravian Zone into the early Miocene Paratethys is certain. Ti-rich Ca-amphiboles ($\sim$ 2% TiO_2) in Ottnangian/Karpatian sediments of the Mailberg 2 core can be attributed to amphibolites and paragneisses of the Bohemian Massif (Lieberman and Petrakakis 1991; Zeitlhofer 2009). Based on high amounts of high metamorphic garnets and congruent heavy mineral data, an association of deeper sections of the Mailberg 2 core ($\sim$ 1150 to 1450 m) with older sedimentary units of the Egerian Linz–Melk Formation (see Roetzel et al. 1983) seems reasonable. Strong similarities between the garnet chemistry of sediments of the Luzice Formation (Kettlasbrunn 2/Vienna Basin) and garnets of OKS and of the Traisen Formation suggest a similar Alpine provenance.

Ottnangian sediments in the Lower Austrian NAFB probably reach thicknesses up to more than 800 m

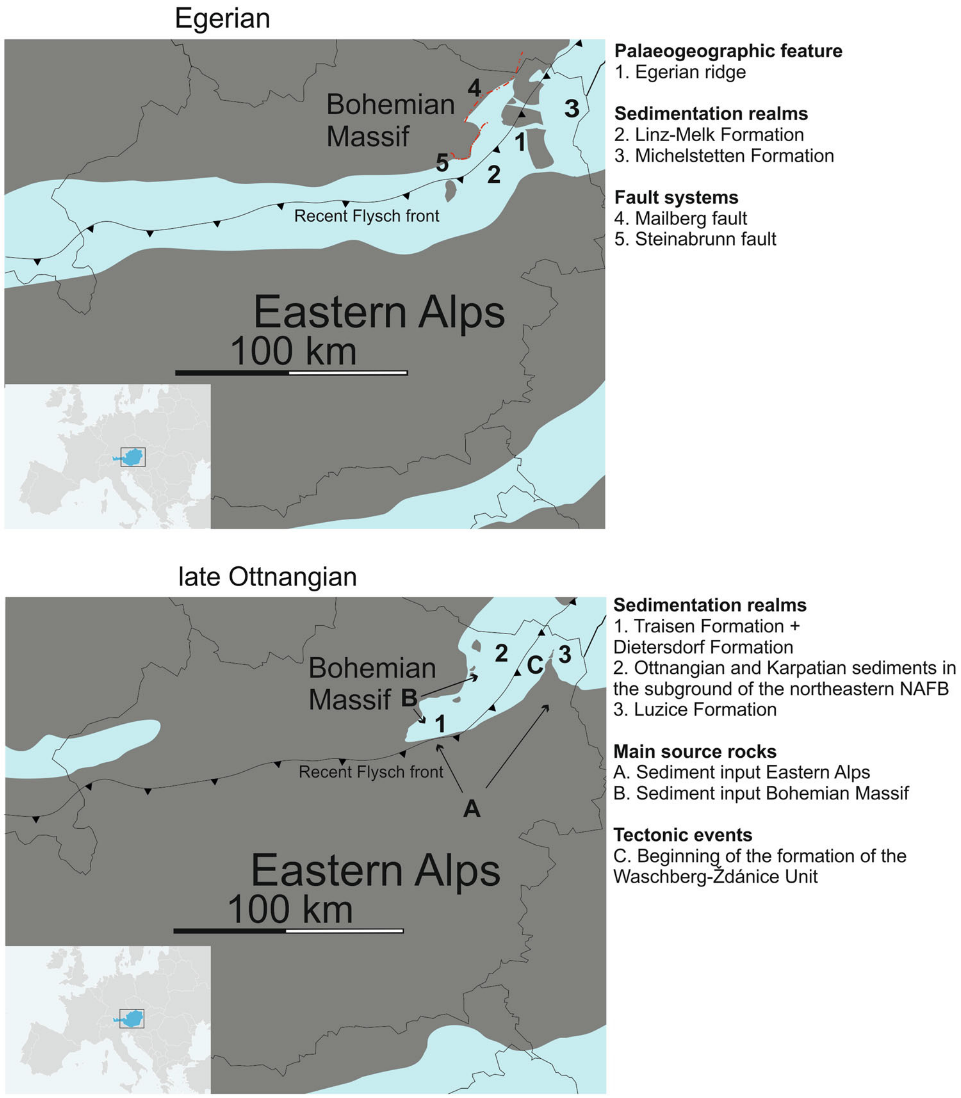


Fig. 10 Palaeogeographic sketch of the Central Paratethys in Lower Austria (Egerian + late Ottnangian)

(Herzogbirbaum core; see Kuffner 2001). Although sediment thicknesses vary considerably throughout the Lower Austrian NAFB and with regard to chronostratigraphic stages of the Miocene, high sediment accumulation rates of up to more than 1000 cm/ka during the late Ottnangian and the following Karpatian for the Paratethys in Lower Austria are assumed. Under the assumption of a relatively short sedimentation time of 0.5–0.8 Ma for the Traisen Formation (for Ottnangian timing see Hilgen et al. 2012), large catchment areas involving different lithologies in the Alps and high exhumation rates seem likely. Consequently, a sediment infill that was predominantly controlled by source rocks situated in the Bohemian Massif is considered improbable. This is further corroborated by chemical analyses of detrital minerals (see Sects. 4.2, 4.2.1). Higher andradite contents in almandines of Moravian garnet-mica schists in Theras (see also Libowitzky 1989) are not in accordance with garnets of the OKS either. However, a stronger sedimentary input in the area of Mailberg and Porrau from Moldanubian and Moravian metapelitic rocks (mica schists; paragneisses) compared to the Traisen Formation is indicated by lower grossular-almandines similar to low-pressure metapelitic rocks of the Moldanubian and the Moravian.

Similar to heavy mineral spectra of Lower Miocene sediments in the Lower Austrian NAFB, heavy mineral spectra of coeval sediments in the southern part of the Czech Republic along the Waschberg–Ždánice Unit are characterized by a dominance of garnets (Golonka and Picha 2006; Stráník et al. 2007) and low amounts of staurolites und rutiles. Detailed chemical analyses of these garnets have not been performed yet. Chemical analyses of almandine garnets of paragneisses in the southern part of the Malé Karpaty Mountains (westernmost core mountains of in the Western Carpathians) show very low grossular contents of $< 5\%$ (Dyda 1994). These kinds of garnets cannot be associated

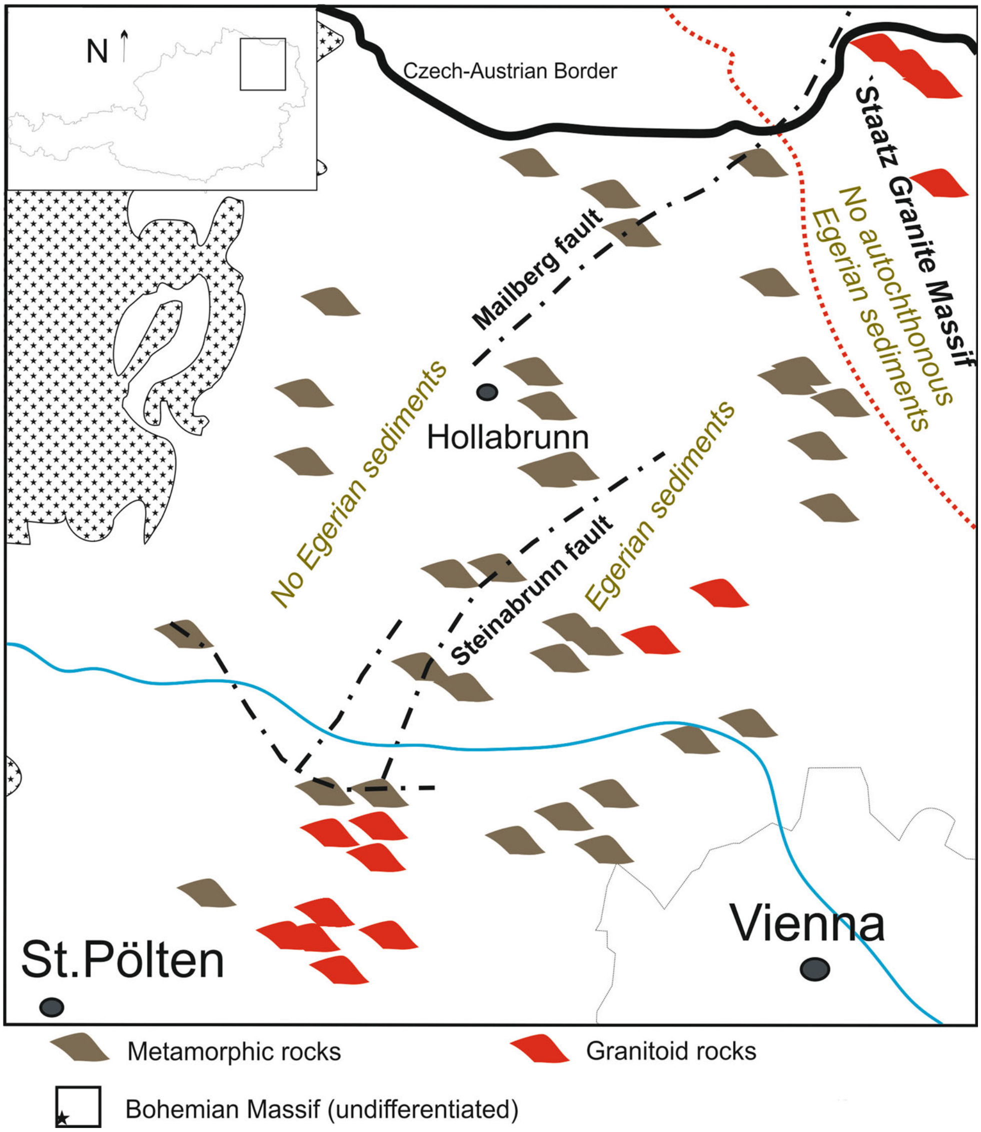


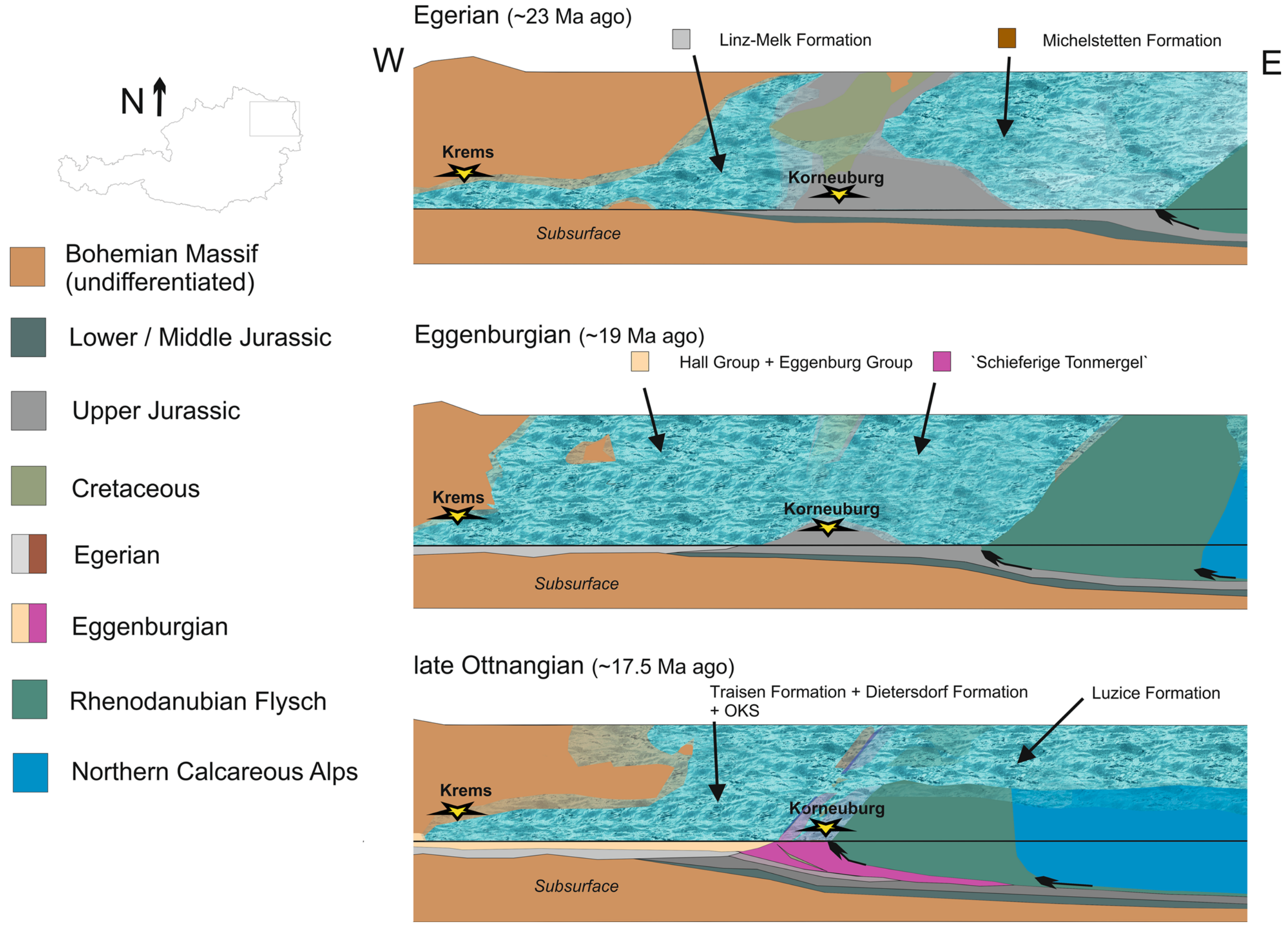
Fig. 11 Crystalline basement (subsurface) in Lower Austria (see also Dirnhofer 1996; Wessely 2006)

with garnets of OKS. Analyses of Permian sandstones in the northern part of the Malé Karpaty Mountains indicated a greater variability of sources rocks, including low-grade metapelites, contact-thermal metamorphic calcareous rock (high andradite contents), granulites and granites/pegmatites (Vd'ačný and Bačík 2015). A major sedimentological influence of these lithologies on the Lower Austrian NAFB during the Ottnangian is very unlikley.

6 Palaeogeography and provenance evolution

Missing Oligocene strata (see e.g., OMV cores Wildendürnbach 4, Staatz 1, Herzogbirbaum, Stronegg, Altenmarkt/Thale; Kapounek et al. 1967; Fuchs et al. 1980; Kuffner 2001) west of the Waschberg–Ždánice Unit are a strong indication for non-deposition during the Oligocene in the area of the Waschberg–Ždánice Unit, since no major tectonic processes have altered this area (Fuchs et al. 1980). The possibility of large-scale resedimentation processes of carbonate-free Egerian sediments, associated with the Linz–Melk Formation and originally deposited in the area of the present Waschberg–Ždánice Unit, must be excluded because higher amounts of high metamorphic garnets—typical for sediments of the Linz–Melk Formation—were only found in very small numbers in Ottnangian and Karpatian sediments in the NAFB.

We therefore infer a SW–NE trending ridge built by autochthonous Mesozoic rocks (see Wessely 2006) and some granite intercalations in the area of Wildendürnbach (see Brix and Fuchs 1984) that separated the depositional area of the carbonate-free Linz–Melk Formation in the west from sedimentation of the carbonate-rich


Egerian (~23 Ma ago)

Eggenburgian (~19 Ma ago)

late Ottnangian (~17.5 Ma ago)

Fig. 12 Palaeogeographic sections of the NAFB in Lower Austria (Egerian, Eggenburgian, Ottnangian) (dimensions are not to scale)

Michelstetten Formation (Fuchs et al. 1980; Schnabel et al. 2002) in the east. Today, autochthonous Mesozoic rocks are buried below the Alpine–Carpathian orogen, and only a minor part of these Jurassic and Cretaceous rocks are exposed on the surface due to thrusting of the WZU (Wessely 2006). In the Oligocene, however, larger parts of the autochthonous Mesozoic and also parts of the 'Staatz Granite Massif' were probably still at the surface (Brix and Fuchs 1984).

Based on these considerations, the existence of a continuous marine connection between parts of the Central Paratethys in Lower Austria and parts of the eastern Central Paratethys in Slovakia in the Egerian (see e.g., Rögl 1998; Steiner and Steininger 2005; Kováč et al. 2017) is questioned.

Whether this ridge represented a continuous separation from north to south or was divided into a series of smaller islands (see Fig. 10) cannot be inferred from the available data. The idea of an Egerian ridge ("Hagenberg Schwelle") was first formulated by Fuchs et al. (1980) and already indicated by Papp (1960). It is possible that a marine connection was completely (re)established in the late Egerian during the sedimentation of a marine fine-grained deeper water facies ("Älterer Schlier"; see e.g., Roetzel et al. 1983; Roetzel and Kurzweil 1986) in the NAFB.

The easternmost Egerian sediments buried under the RFZ in Lower Austria are known from Mauerbach (Wessely 2006). It is assumed that no Egerian sedimentation took place in the area of the easternmost reaches (east of Mauerbach) of the present RFZ in Lower Austria (see also Fuchs et al. 1980; Wachtel and Wessely 1981; Wessely 2006; Beidinger and Decker 2014).

The reason for a watershed formed by Mesozoic rocks in the area of the present WZU may lie in palaeo-fault activity in the NAFB. Parts of the southeastern Bohemian Massif may have subsided along fault systems like the Mailberg fault and the Steinabrunn fault (see also Pfleiderer et al. 2016). Taking into account internal OMV core data (see also Fuchs et al. 1980), it appears very likely that the southwestern parts of the Mailberg fault and of the Steinabrunn fault formed a geographical barrier to the Egerian Paratethys in the Lower Austrian NAFB. Varying erosion rates between areas east and west of the present Waschberg–Ždánice Unit might have already prevailed during

Mesozoic times due to different characteristics of the crystalline basement: while lithologies west of the Waschberg–Ždánice Unit are mainly comprised of schistose rocks, the crystalline basement in the area of the northern Waschberg–Ždánice Unit and in areas west of the Waschberg–Ždánice Unit consists of significant amounts of granite bedrock (Fig. 11). This might have promoted the formation of a/an (underwater) palaeo-ridge in the area of the present Waschberg–Ždánice Unit.

The original depositional area of sediments of the Waschberg–Ždánice Unit was further in the east (Wessely 2006). During the formation of the Waschberg–Ždánice Unit, these sediments were thrust onto the autochthonous Mesozoic and were later partly eroded and resedimented into the Miocene NAFB (Fig. 12). Micropaleaontological data of sediments in the NAFB suggests that these resedimentation processes might be correlated with higher amounts of reworked Cretaceous and Palaeogene material (personal communication Kallanxhi; Rögl and Nagymarosy 2004).

The deposition of sediments during the late Ottnangian/early Karpatian probably took place within a relatively short period of time and was controlled by sediment input from the east (resedimented sediments of the Waschberg–Ždánice Unit, Luzice Formation and Laksary Formation), from the west (mainly Moravian metasedimentary lithologies) and from the south (Traisen Formation).

According to Beidinger and Decker (2014), the extent of post-Eggenburgian foreland-propagating thrusting in the area of St. Pölten was limited. Considering this and the fact that almost no erosion products of the RFZ can be detected in the Traisen Formation, it is probable that most of the shortening, folding and uplift of the eastern RFZ took place after the sedimentation of the Traisen Formation (from Karpatian onwards).

7 Conclusions

Lower Miocene sediments of the Lower Austrian part of the NAFB were primarily derived from (1) Austroalpine crystalline units of the Eastern Alps and associated siliciclastic sediments on top of the Northern Calcareous Alps (shed by resedimentation in the course of the uplift of the NCA), (2) from low-grade Moravian and Moldanubian metamorphic rocks and (3) from resedimented Palaeogene and Miocene sediments of the Waschberg–Ždánice Unit. No significant influence of the RFZ, of Moldanubian and Moriavian granitoid rocks and of lithologies of the Malé Karpaty Mountains on the Traisen Formation and on OKS was found. A higher influence of erosional products of Moravian and Moldanubian lithologies is suspected for northwestern parts of the Traisen Formation and northwestern realms of OKS in the the Lower Austrian NAFB.

Exhumation and erosional processes of Austroalpine crystalline units of the Eastern Alps are also of fundamental importance for Lower Miocene sediment inputs east of the present Waschberg–Ždánice Unit. Resedimentation processes during the Ottnangian and Karpatian towards the west due to the uplift of the Waschberg–Ždánice Unit are indicated by higher rates of reworked Cretaceous and Palaeogene material and high sediment accumulation rates.

With respect to the Egerian palaeogeography, borehole data suggest a SW–NE trending, partly subaerial ridge of exposed Mesozoic rocks and intercalated granitoid rocks that separated the depositional area of the carbonate-free Linz–Melk Formation west of the present Waschberg–Ždánice Unit from sedimentation of the carbonate-rich Michelstetten Formation east of the present Waschberg–Ždánice Unit.

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