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Lower Miocene olistostromes and giant-olistoliths: A new interpretation of the Eocene Waschberg Limestone occurrences and consequences for the structural composition of the southern Waschberg–Ždánice Unit in Lower Austria

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Abstract: The Waschberg–Ždánice Unit links the Alpine and Carpathian orogens. Its complex structural and sedimentary structures lack a modern interpretation, particularly in the Austrian part. In recent years, the southern end of the Waschberg–Ždánice Unit has been geologically mapped in detail. Nine large occurrences (km-size) of the Waschberg Limestone, particularly at Waschberg, Michelberg, Praunsberg, and at some unnamed places continue into and strike in line with the widespread olistostromes. They are consequently interpreted as giant-olistoliths and represent products of submarine mass transport processes contemporaneous with the adjacent olistostromes. Signs for large-scale imbricate structures (repetitive sequences) or interpretation as tectonic klippen were not found. Based on the detailed geological mapping, some previously unknown structural elements are introduced, such as Haselbach Wedge and "crunch-zone". The Waschberg Limestone itself is an allochthonous mixed sediment (high density debrites and turbidites) that contains shallow water benthic (e.g., *Nummulites*) and deep-water planktic foraminifera of different age. Formation and final deposition of the Waschberg Limestone included sedimentation of Ypresian larger foraminifera and other biogenic grains in an Ypresian/basal Lutetian basin, detachment and transport towards the north-west, mixture with crystalline basement fragments and Flysch components in an Egerian or basal Eggenburgian foredeep, exposure on unstable slopes of the thrust front, and finally mobilization and basinward transport of olistostromes and Waschberg Limestone giant olistoliths during the Eggenburgian. The formation of olistostromes and giant-olistoliths may be indicative for the increased velocity or higher intensity of the thrusting processes during the early Miocene.

Keywords: olistostromes, giant-olistoliths, Waschberg Limestone, Blocky Layers, Ždánice–Hustopeče Formation, lower Miocene, Eocene, Waschberg–Ždánice Unit.

Introduction

The so-called Waschberg Limestone (or Waschberg-Kalk in Austrian literature) has been investigated since the middle of the 19th century. The rocks were attractive because of their relative richness in *Nummulites* (large benthic foraminifera). They represent one of the northernmost mass-occurrences in Europe. Although known by scientists for a long time, no formal description of the formation exists until today. The origin of these deposits is still under discussion.

Figure 1 shows the southernmost tip of the Waschberg–Ždánice Unit. The prominent tops of the Waschberg and Michelberg are formed of Waschberg Limestone and were mined for local needs (e.g., gravel). The widespread cover with Pleistocene loess and gravel (Fig. 2) and the relatively small differences in altitude resulted in a small number of natural outcrops and a lack of longer sections. The lithostratigraphic units and main tectonic elements displayed in the geological section (Fig. 3) indicate the structural composition of the study area. Numerous pre-Pleistocene stratigraphic units were mapped (Table 1) and its structural relationships were analysed. The lower Miocene rock units of the Waschberg–Ždánice Unit are displayed schematically in Figure 4.

The focus of this contribution is to provide a new view on the origin of the Waschberg Limestone within the sedimentary context of the surrounding formations based on modern and older, re-interpreted field observations. Sub-marine mass transport and accumulation processes have played a role in the interpretation of the early Miocene formations for many decades, but were underestimated for large scale structures and Eocene rock bodies, such as the Waschberg Limestone occurrences. Detailed, high-resolution geological mapping allowed new insights into the sedimentation processes that took place during the early Miocene. As a consequence of this, the structural interpretation of the southern part of the Waschberg–Ždánice Unit (or nappe) has to be revised. In this contribution, an overview on previous structural and sedimentological concepts is given, the stratigraphic units related to the Waschberg Limestone and other Eocene Limestone units based on field mapping are described, the resulting sedimentary patterns and tectonic structures are analysed and the origin of the Waschberg Limestone is discussed.

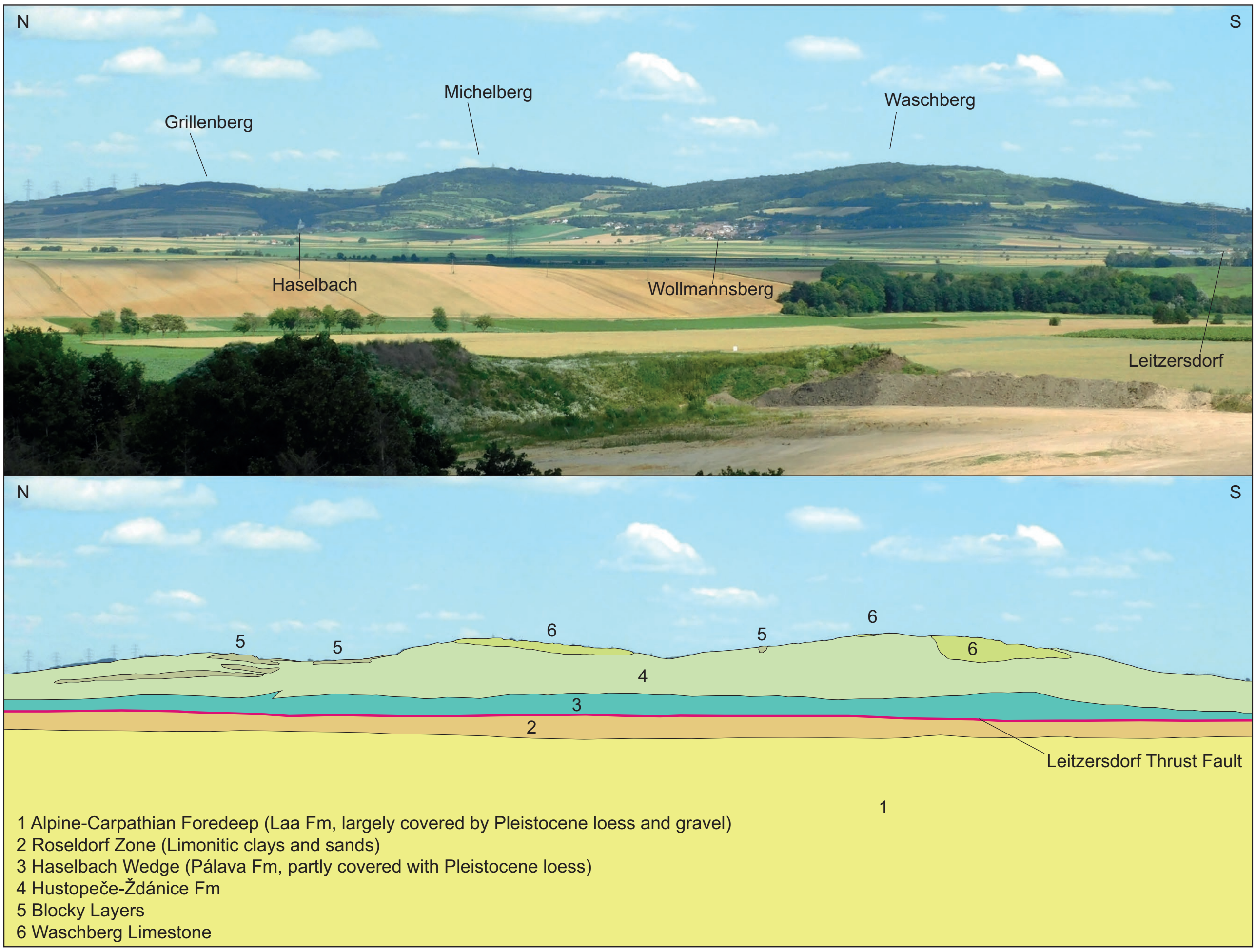

Fig. 1. Upper part: View from Senning to the east showing three prominent hills at the southern tip of the Waschberg–Ždánice Unit. Small differences in altitude, widespread soft rocks (marls) and Pleistocene loess cover result in a low number of outcrops and a lack of complete surface sections. Lower part: Occurring lithotectonic units in the same area.

Previous structural concepts for the southern part of the Waschberg–Ždánice Unit

König (1896), Abel (1899) and Götzinger (1913) explained the crystalline components in these rocks and the adjacent Blocky Layers by an elevation of a crystalline block (horst-structure) directly below or in the vicinity of the Waschberg Limestone occurrences. The first author to propose the imbricate structure and the overall allochthonous character of the Waschberg–Ždánice Unit was Kohn (1911). Based on mapping results, he proposed a seeming repetition of rock units and correlated the nummulitic limestones of Waschberg, Michelberg, and Praunsberg. Glaessner (1931, 1937) adopted the imbricate structure concept and enhanced it by adding more structural information. He distinguished five subzones separated by major thrust faults and used the term tectonic klippen for the various scraped-of pre-Miocene blocks. The imbricate structure became the standard concept until today and was adopted by many overview papers and map-explanations (e.g., Grill 1953; Götzinger et al. 1954; Grill 1962; Wessely et al. 2006). The Eocene Waschberg Limestone is assumed to form the basal layer of the hanging wall with the lower Miocene marls of the Ždánice–Hustopeče Formation (or Auspitzer Mergel), and on top was thrusted over the Ždánice–Hustopeče Formation footwall. Seifert (1980, 1982) interprets all Eocene occurrences as isolated rock bodies ripped-of from the original succession and always bordered by tectonic structures.

Previous sedimentary and paleo-environmental concepts

The Waschberg Limestone has a long history of geological and paleontological research. It was first mentioned by Boué (1830). In the beginning of the scientific research, descriptive reports on components and fossils dominated (Prinzinger 1852; Hauer 1858; Rzehak 1888, Bittner 1892; Paul & Bittner 1894). Already Hauer (1858) realized the close connection of the Eocene limestones (Waschberg Limestone, Hollingstein Limestone) with the occurrences of exotic crystalline blocks. The mixture of crystalline and Flysch boulders

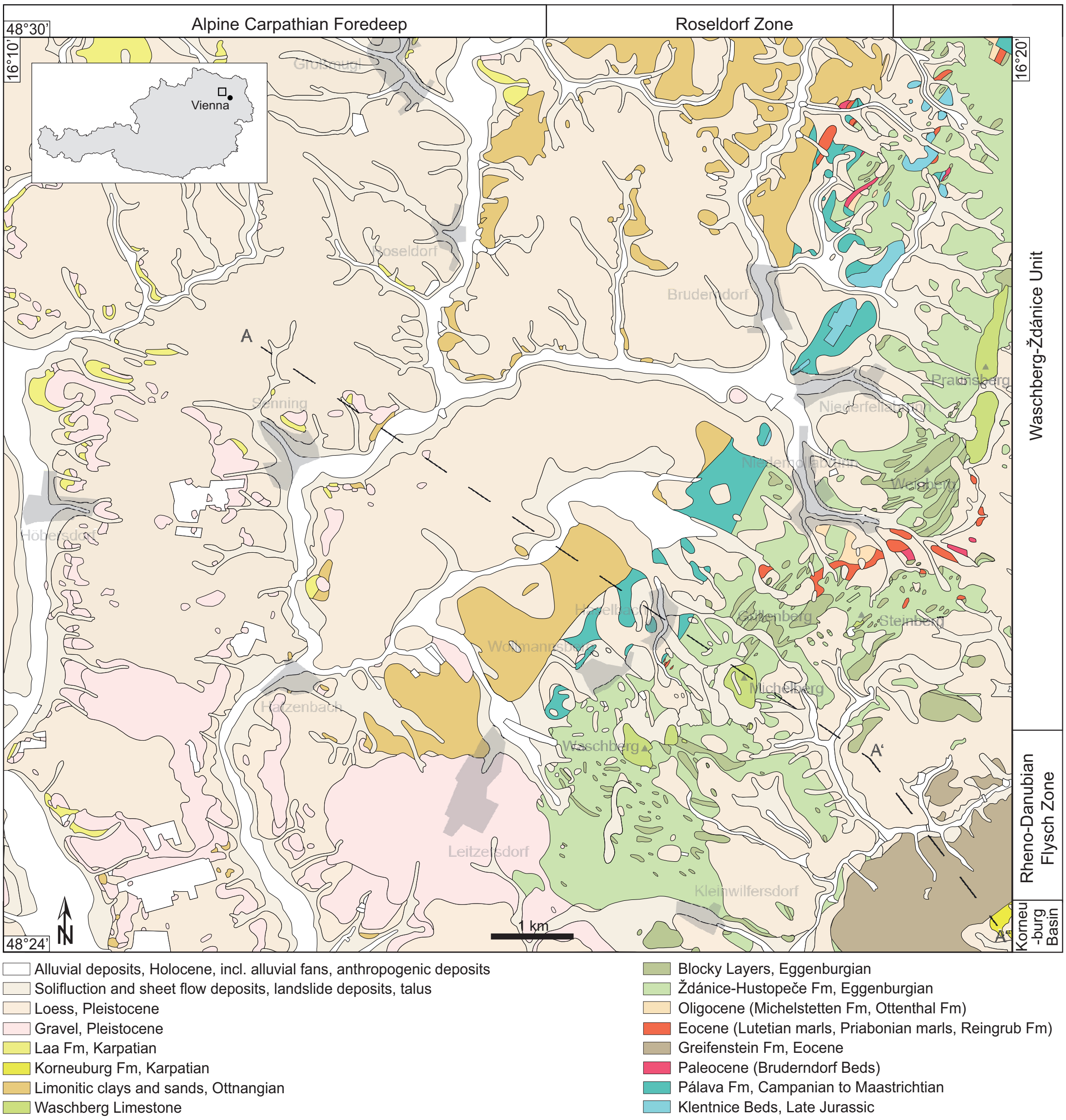

Fig. 2. Geological map of the southern part of the Waschberg–Ždánice Unit in Lower Austria. Insert shows location of study area within Austria. Stippled line with A–A'–A" shows position of section displayed in Figure 3.

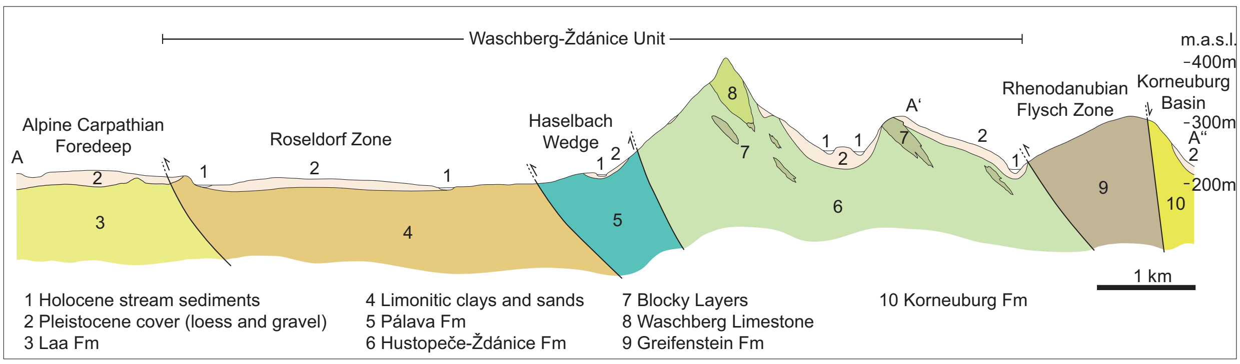

Fig. 3. Geological section through the Waschberg–Ždánice Unit and adjacent tectonic units. See Figure 2 for exact position. Altitude exaggeration 5×.

Table 1: Chart of formations studied in this contribution (without Pleistocene and Holocene sediments).

Stages	Formations
Karpatian	Korneuburg Fm., Laa Fm.
late Ottnangian	Limonitic clays and sands
Eggenburgian	Blocky Layers, Ždánice–Hustopeče Fm.
Egerian	Michelstetten Fm.
Kiscellian	Ottenthal Fm.
Priabonian	Reingtrub Fm., Hollingstein Limestone, Limestone with Mytilus levesquei
Ypresian to basal Lutetian	Waschberg Limestone
Selandian to Thanetian	Bruderndorf Beds
Campanian to Maastrichtian	Pálava Fm.
Tithonian	Klentnice Fm.

in the olistostromes and its different provenance was also known at that time. In the first half of the 20th century, the Blocky Layers were interpreted as a sign for the approaching Flysch front (Glaessner 1937). The adjacent Waschberg Limestones however were interpreted as *in situ* formations deposited during the Eocene period.

The frequent occurrences of "exotic" polymict crystalline components within the Waschberg Limestone was pointed out by many authors (e.g., Paul & Bittner 1894; Grill 1962). This lead Glaessner (1937) to the conclusion that the Waschberg Limestone was a "sediment of a crystalline beach". Seifert (1980) assumes crystalline barriers (island chain) at the shelf edge of the Bohemian Massif as the environment for the formation of the Waschberg Limestone. This is in line with former interpretations of shoreline areas of a crystalline hinterland for its depositional environment, meaning the combination of shallow water dwellers and crystalline components (e.g., Grill 1962).

Seifert (1980, 1982) acknowledged the possibility that some Waschberg Limestone occurrences are part of olistostromes. However, the imbricate structure concept for the Waschberg Limestone bodies was not challenged by sedimentation-related concepts until today.

Methodology

The recently finished detailed mapping in the southern Waschberg–Ždánice Unit (scale 1:10,000; sheet NM 33-12-13 Hollabrunn; Gebhardt & Ćorić 2014; Gebhardt 2016, 2018a, b, c) resulted in a vast amount of new field data, including already known and new outcrops, extensive areal distribution of rock units and also structural data (strike and dip directions). The field work was done within the scope of the general mapping program of the Geological Survey of Austria. Within this program, an area of about 38 km^2 with the stratigraphic units Ždánice–Hustopeče Formation, Blocky Layers, Waschberg Limestone, Hollingstein-Limestone, and Limestone with *Mytilus levesquei* was mapped and analysed litho- and biostratigraphically.

Facies interpretation of lithological units is based on the analysis of sedimentary structures, compositions and sequences as well as microfacies analysis of carbonates. Sedimentary structure and sequence interpretation follows Reineck & Singh (1980); Allen (1982); Tucker & Wright (1990); Einsele (1992); Stow et al. (1998); Viana et al. (1998), or Talling et al.

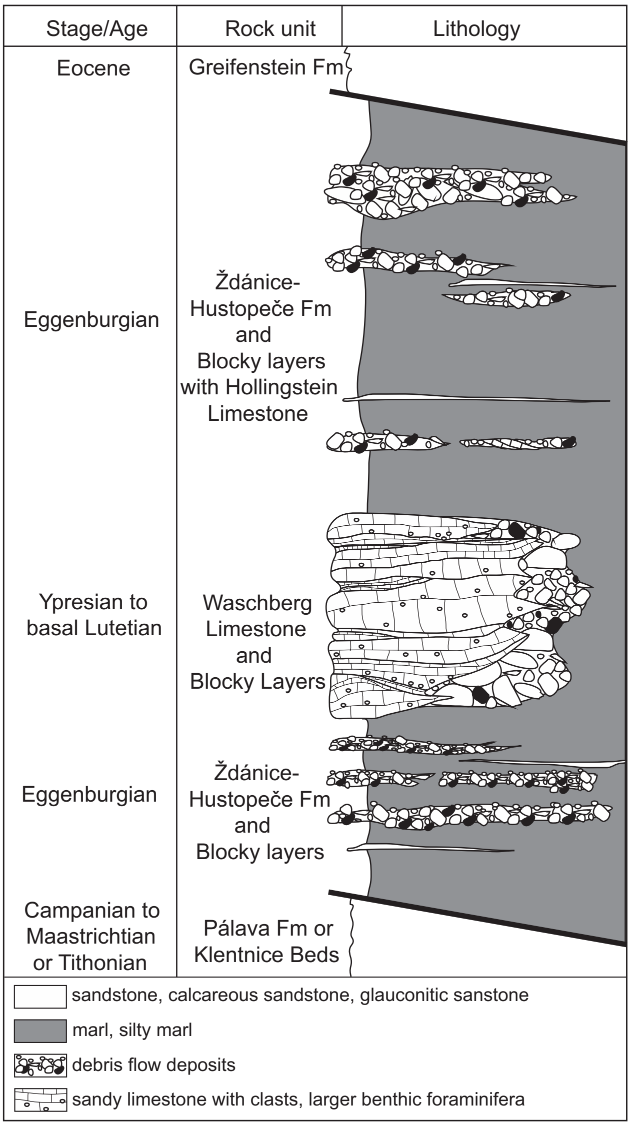

Fig. 4. Schematic lithological section of investigated lower Miocene rocks in the southern Waschberg–Ždánice Unit. Thrust faults mark lower and upper limits of the succession in most places.

(2012). Grain-size and composition estimates in the field were complemented by literature data (particularly Holzer & Küpper 1953; Grill 1953, Seifert 1980, 1982). Carbonate classification has been adopted from Wright (1992) and Flügel (2010).

Planktic and benthic foraminifera assemblage analyses were performed according to Van der Zwaan et al. (1990); Murray (1991); Luciani et al. (2010) with further references therein. Biostratigraphic data were adopted from previous studies on planktic foraminifera (Gebhardt & Ćorić 2014, applying the zonation of Berggren & Pearson 2006), calcareous nannofossils (Gebhardt & Ćorić 2014, applying the zonation of Martini 1971) and larger benthic foraminifera (Torres-Silva & Gebhardt 2015, applying the zonation of Serra-Kiel et al. 1998).

Table 2 shows the extensions of the 8 largest occurrences of Waschberg Limestone in the mapped area (see also Fig. 2 for overview). Smaller occurrences (metre to several 10s of metres, i.e., not mappable on the 1:10,000 scale) were not displayed separately. This concerns mostly crystalline blocks. The distribution of several rock units is presented in the geological map of the area (Fig. 2). Wherever possible, outcrops were measured and analysed for sedimentation processes and depositional environment. Figure 5 shows typical short sedimentary sections representing the lower Miocene rock units of the study area.

Results

Ždánice–Hustopeče Formation (Auspitzer Mergel, Schiefrige Tone und Tonmergel)

Description of rocks

This formation is the most extended in the Waschberg–Ždánice Unit and comprises layered dark grey to greenish-whitish silty shales with micaceous bedding planes, marls, thin (mm to cm-scale) and thick (dm-scale) sandstone layers. The Ždánice–Hustopeče Formation reaches thicknesses of 400 to 700 m in hydrocarbon drillings (Korneuburg 2, Wollmansberg, Götzinger et al. 1954; Grill 1962; Seifert 1982). Particularly in the southern parts, it encloses or intercalates with the Blocky Layers, indicating synchronous age of deposition. The investigated marl samples were dated as Eggenburgian (late Egerian to early Ottnangian) based on planktic and benthic foraminifera together with calcareous nannofossils of the NN2 to NN3 Zone (occurrence of *Helicosphaera ampliaperta*; Gebhardt & Ćorić 2014). Krhovský et al. (2001) assigned an identical age.

Interpretation of marl and sandstone facies

Thick sandstone layers show distinct grading (fining upward, Fig. 6C, D) and were interpreted as turbidites (e.g., Krhovský et al. 2001; Gebhardt & Ćorić 2014). Thin sandstone layers are fine grained and may represent more distal turbidites (fine grained turbidites) or contourites (Stow et al. 1998; Viana et al. 1998). The marls represent the originally muddy background sedimentation. Marls (and included Blocky Layers) were deposited in deep water (outer neritic to upper bathyal) based on the ratios of planktic to benthic foraminifera and foraminiferal assemblage composition (Gebhardt & Ćorić 2014). The deep-water facies continues into southern Moravia (Čtyroký 1993; Picha et al. 2006).

Blocky Layers (so-called Blockschichten, olistostromes)

Description of rocks

The Blocky Layers are distinct layers of chaotically oriented pebbles and blocks of cm to several metres in size within a sandy to silty matrix (Fig. 7). Internal size-grading of components has not been observed. The degree of roundness varies from angular to well rounded. The larger components contain dominantly Flysch-sandstones, pink granite, granodiorite, amphibolite, marble, Jurassic limestones, various gneisses, mica schists, and other crystalline rocks or quartz pebbles (see also Grill 1953; Holzer & Küpper 1953; Gebhardt & Ćorić 2014; Fig. 7A–E), but also Waschberg Limestone fragments were found at several places (Fig. 7F). The thickness of single layers varies from a few dm to several tens of metres. The layers may pinch out over small distances or interfinger with the under- and overlying marls of the Ždánice–Hustopeče Formation (Fig. 2). The matrix of the olistostromes may contain fragments of the Ždánice–Hustopeče Formation. Since the components are more resistant against erosion than the surrounding marls, the occurrences frequently form ridges or steeper slopes. The laying of two natural gas pipelines in 2011 (West-Austria-Gasleitung WAG II and Energieversorgung Niedeösterreich EVN) allowed for excellent insights into the internal structures of the Blocky Layers in the near surface underground (Fig. 7A, B, D; Posch-Trözmüller et al. 2013). The thickest stacks of Blocky Layers are located at the Grillenberg and at the Weinberg (Gebhardt 2018a, c; see Fig. 2). At Grillenberg, the Blocky Layers are also rather well exposed and dips can be measured directly within the intercalated sandy to marly layers. The calculated total thickness including the intercalated marls is about 600 m at both localities. The concentration of the olistostrome occurrences at certain localities through time indicates the stability of their sources (possibly feeder channels). A similar stack, but with less thick and extended Blocky Layers was found south of the Waschberg (Fig. 2).

Sedimentological interpretation of the Blocky Layers

Well exposed occurrences show no distinct grading (ungraded, see previous chapter for composition and grain size). Small and large intraclasts float within the sandy to silty matrix, sometimes with a higher concentration of larger clasts near the top of the beds (Figs. 5A, 7D). Densely packed

Table 2: Extensions (maximum lengths and widths) of giant-olistoliths occurring in the southern Waschberg–Ždánice Unit in Lower Austria. *longest width measured perpendicular to longest length.

No.	Location	Length	Width*	Lithology	Lat. (°N)	Long. (°E)
1	Waschberg	630 m	460 m	Waschberg Limestone	48°25'19"	16°16'21"
2	east of Waschberg	240 m	170 m	Waschberg Limestone	48°25'25"	16°16'38"
3	further east of Waschberg	70 m	40 m	Waschberg Limestone	48°25'22"	16°16'46"
4	Michelberg	570 m	420 m	Waschberg Limestone	48°25'48"	16°17'20"
5	south of Michelberg	80 m	50 m	Waschberg Limestone	48°25'29"	16°17'23"
6	Steinberg	160 m	60 m	Hollingstein Limestone	48°26'09"	16°18'32"
7	southern Praunsberg	910 m	300 m	Waschberg Limestone	48°27'28"	16°19'39"
8	nothern Praunsberg	1180 m	270 m	Waschberg Limestone	48°27'51"	16°19'44"

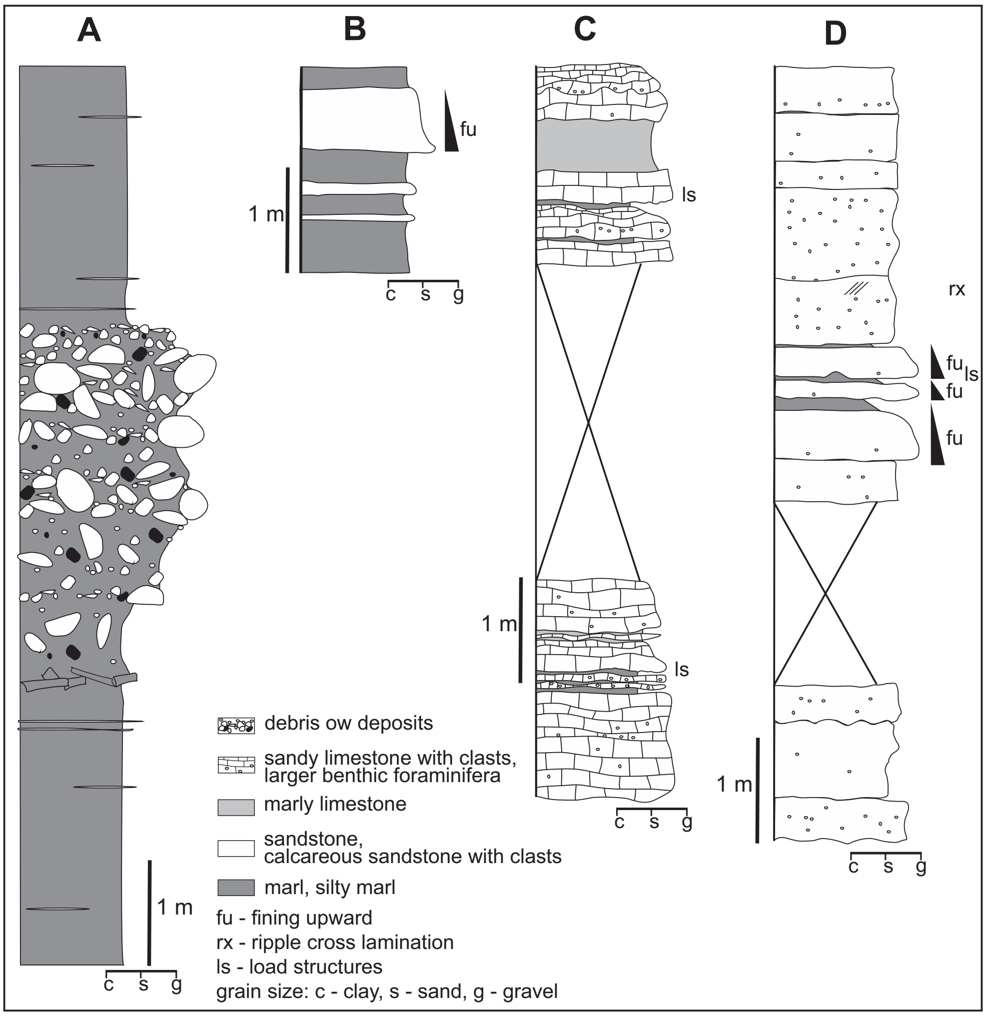

Fig. 5. Representative lithological sections from the study area. **A** — Blocky Layers within Hustopeče–Ždánice Formation, corresponds partly to Figure 7D. The marl and silty marl with thin sandstone layers continues ca. 20 m above and ca. 10 m underneath the debrite layer. **B** — Hustopeče–Ždánice Formation, corresponds to Figure 6C. **C** — Waschberg Limestone at Waschberg, corresponds to Figure 8A,B. **D** —Waschberg Limestone at northern Praunsberg, corresponds partly to Figure 8C.

conglomerates with poorly rounded components also occur (Fig. 7B). The maximum size of single clasts can reach several metres (Fig. 7A,E). A rather sharp upper boundary to the overlying marls of the Ždánice–Hustopeče Formation contrasts with an often poorly defined lower boundary with frequent ripped off marl clasts from the underlying marls in some cases. Structures and compositions of these deposits suggest an interpretation as submarine debris flow deposits, or olistostromes

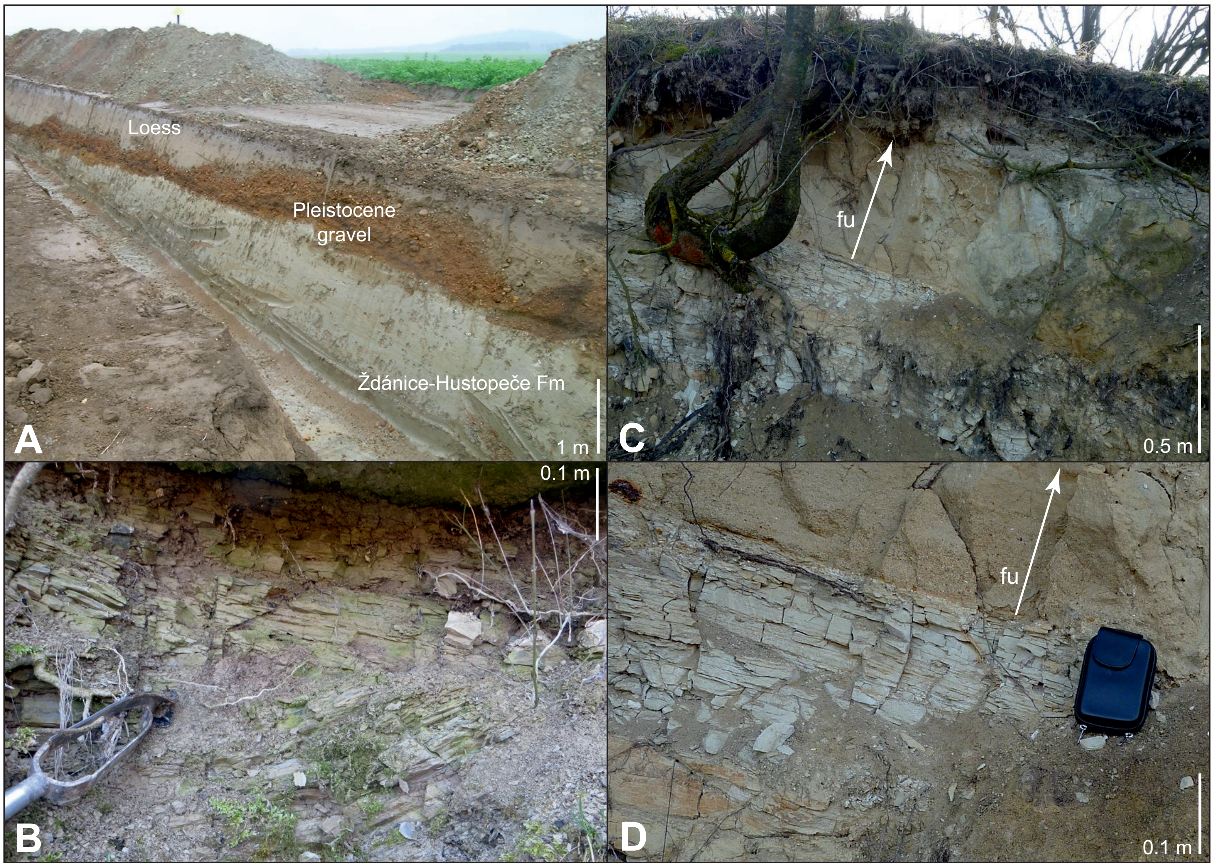

Fig. 6. Outcrop views of the Hustopeče–Ždánice Formation. **A** — Grey marls below Pleistocene cover (gravel, loess) in a natural gas pipeline trench south of the Waschberg (WAG). View towards NW, Waschberg in background, Photograph by G. Posch-Trözmüller. **B** — Southeastward dipping grey marls south of Niederhollabrunn, view towards S. **C** — Grey marls and fine to coarse graines sandstones between Niederhollabrunn and the Weinberg, strata dipping towards south-east, view towards SE, fining upward – fu. Photograph by M. Lotter. **D** — Detail of C, upper sandstone layer (fine to coarse sand) with distinct fining upward at base (turbidite), lower sandstone layer (silt to fine sand) with wavy and horizontal lamination. Photograph by M. Lotter.

(see also Gebhardt et al. 2008; Gebhardt 2018a,c). An interpretation as high density cohesive debris flows according to Talling et al. (2012) may be considered.

Waschberg Limestone

Description of rocks

Waschberg Limestone forms the most elevated parts in the southern Waschberg–Ždánice Unit (Fig. 1). The main occurrences are, from south to north, the Waschberg, the Michelberg, and the Praunsberg (Fig. 2). It is an informal rock unit that comprises detritic limestones and sandstones to conglomerates (Fig. 8) with sometimes high but strongly variable contents of larger benthic foraminifera (nummulitids, orthophragminids; Fig. 9; see also Torres-Silva & Gebhardt 2015), corallinacean algae, molluscs, coral fragments and other biogenic components. The originally grey rocks weather with yellowish to reddish-brownish colours. Most biogenic components are broken and only some complete molluscs, rhodoliths, or corals were found occasionally. Quartz, crystalline pebbles and fragments, and sands are very frequent and dominate the composition, particularly in the northern occurrences (Praunsberg; Fig 8C,D; see also Grill 1962; Gebhardt & Ćorić 2014; Gebhardt 2018c). The contents of crystalline components in thin sections are 5–15 % at the Waschberg, but reach 25 % at the Michelberg and 21 % at the Praunsberg (Seifert 1980). The amount of quartz grains is even higher. *Vice versa*, calcareous components are more frequent in the south (Waschberg, Michelberg). Minimum thicknesses are ca. 250 m at the Waschberg, ca. 150 m at the Michelberg, and at the Praunsberg, it is ca. 140 m (Seifert 1980; Gebhardt 2018c).

Biostratigraphy of the Waschberg Limestone

The rocks of all Waschberg Limestone occurrences have been dated as Ypresian to basal Lutetian by Torres-Silva & Gebhardt (2015) based on Larger Benthic Foraminifera (LBF, almost exclusively *Nummulites partschi*), and planktic foraminifera and calcareous nannofossils (Gebhardt & Ćorić 2014). The found assemblages indicate different ages for LBF (SBZ 10 to 11 of Serra-Kiel et al. 1998) compared with planktic foraminifera (Zones E7 to 11 of Berggren & Pearson 2006) and calcareous nannofossils (NP 14 to 16 of Martini 1971). The absolute ages of these biozones range from about 49 to 53 Ma for *Nummulites* and 40 to 49 Ma for planktic foraminifera and calcareous nannofossils (ages from Gradstein et al. 2012).

Fig. 7. Outcrop views and components of the Blocky layers (olistostromes). **A** — Large Amphibolite block (dark grey) and other components of the olistostrome in a natural gas pipeline trench (WAG) south of the Waschberg, view towards SW, dip to left side. Photograph by G. Posch-Trözmüller. **B** — Densely packed conglomeratic olistostrome layer (mainly rounded flysch-sandstone components) in a natural gas pipeline trench (WAG) south of the Waschberg, view towards NW, dip to right side. **C** — Rounded pinkish Granite block in sandy matrix, southern slope of Waschberg, view towards W. **D** — Weathered rounded and angular components of various sizes floating in a marly, silty to sandy matrix in a natural gas pipeline trench (EVN) south of the Waschberg, view towards N, dip to right side. Photograph by G. Posch-Trözmüller. **E** — Granite and Granodiorite blocks at the southern slope of the Waschberg, set free by washing away of the fine grained matrix, view towards NW. **F** — Waschberg Limestone block with numerous biogenetic components from the Grillenberg.

Fig. 8. Outcrop views of Waschberg Limestone at the Waschberg (A, B), view towards W and Praunsberg (C, D), view towards E. **A** — Nodular and massive calcareous beds and intercalated thin marl layer, asterisk indicates position of sample figured in Figure 9A. **B** — Calcareous, partly nodular beds and intercalated marl layers, asterisk indicates position of sample figured in Figure 9C. **C** — Sandy to gravelly calcareous beds with sedimentary structures typical for turbidites (fining upward – fu, ripple cross lamination – rx, load structure – ls). Photograph by M.Lotter. **D** — Coarse sand to gravelly massive bedded layers with prominent clasts (quartz pebbels – Qp,).

Depositional environment of the Waschberg Limestone

The Waschberg Limestone was interpreted as autochthonous and deposited in a shallow marine or even reef environment (e.g., Grill 1962; Seifert 1980). This interpretation was based on the dominance of shallow water dwellers, particularly *Nummulites* (and other larger benthic foraminifera; see Torres-Silva & Gebhardt 2015), corallinacean algae and corals in the component assemblages. Seifert (1980) assumes 10–50 m paleo-water depth for calcarenites of fore-reef depositional environments. However, Torres-Silva & Gebhardt (2015) point out that the co-occurrence of *Nummulites, Discocyclina* and *Orbitoclypeus* suggests deeper or more turbid waters. Gebhardt et al. (2013) deduced paleo-water depths of 70 to 200 m for similar assemblages from Helvetic Units of Bavaria (Adelholzen) based on existing schemes along depth gradients and planktic to benthic foraminifera ratios. The dominance of the sub-thermocline planktic foraminiferal genus *Subbotina* in the intercalated marls (Gebhardt & Ćorić 2014) also indicates greater depositional depths (Gebhardt et al. 2013 with further references therein). In addition to this, boundstones or framestones as classical reef indicators were not found. Merely, quartz-rich wackestones, packstones or grainstones were described (Seifert 1980; or packstones to arenitic rudstones in this contribution; Fig. 9). Sedimentary structures found in outcrops such as graded bedding (fining upward, a stack of three well developed sequences is shown in Figs. 5, 8C), load structures, or wavy lower surfaces (possible load or flute casts) point to turbiditic depositional systems and massive, largely ungraded beds with floating clasts indicate debrites or high density turbidites (Fig. 8A, B, D; compare e.g., Reineck & Singh 1980; Nichols 2009, or Talling et al. 2012). Cross lamination has been observed only at Praunsberg (Fig. 8C) and may be interpreted as (convolute) ripple cross lamination (Allen 1982;

Talling et al. 2012). Erosion of tops by subsequent events produces incomplete (Bouma-) cycles or massive beds and has been frequently described in the literature (e.g., Reineck & Singh 1980; Einsele 1992).

The marly layers between the thick debrite beds contain relatively high percentages of planktic foraminifera and therefore point to greater paleo-water depths (Fig. 8A,B; Van der Zwaan et al. 1990; Gebhardt & Ćorić 2014) and exclude deposition in shallow marine environments. Another important indicator is the significant age gap of several million years between the components (*Nummulites*) in the turbidites and debrites, and the pelagic background sediment (planktic foraminifera, calcareous nannofossils). Within the Waschberg Limestone occurrences, a south to north trend can be observed from more calcareous, biogenic grain-bearing, thick-layered, and so proximal debrites (debris-flows) to gravelly-sandy (quartz- and crystalline-rich), thin-layered, and therefore somewhat more distal turbidites (Fig. 8; see also Gebhardt & Ćorić 2014; Gebhardt 2018c). Thus, the Waschberg Limestone is an allochthonous mixed sediment, and its components were transported from different sources.

Hollingstein-Limestone and Limestone with Mytilus levesquei

Description and occurrence

A grey massive limestone with crystalline appearance was mined in the former limestone quarry at the Steinberg (or Hollingstein) north-east of the Michelberg (Fig. 10). The remaining outcrops show only adumbrated bedding structures (Gebhardt 2018a). The Hollingstein Limestone and the so-called Limestone with *Mytilus levesquei* (or Pfaffenholz Schichten, Niederhollabrunner Kalk, see Bachmayer 1961; Grill 1962; Seifert 1980) were interpreted as parts of the Priabonian Reingrub Formation by Krhovský et al. (2001). Seifert (1980) reported two occurrence of Limestone with *Mytilus levesquei* north-east of the Steinberg. The brownish-greyish Limestones with *Mytilus levesquei* (or Pfaffenholz-Schichten, Niederhollabrunner Kalk) can only be found today as debris within the Blocky Layers (Gebhardt 2018a). These outcrops are the only known occurrences of Hollingstein Limestone and Limestone with *Mytilus levesquei* in the southern Waschberg–Ždánice Unit.

Biostratigraphic ages

Glaessner (1937) reported some bivalves from the Steinberg which point to a late Eocene age. The Limestones with *Mytilus levesquei* were also dated as late Eocene (Krhovský et al. (2001).

Mapping results of Waschberg Limestone, Hollingstein Limestone, and Blocky Layer occurrences

The main occurrences of larger, and so mapable in 1:10,000 scale, Waschberg and Hollingstein Limestone occurrences are listed in Table 2 together with their maximal extensions. Their relation to the connected Blocky Layers can be seen in Figure 2 and are described below.

1. *Waschberg:* This is the southernmost large occurrence. The rock body strikes NW–SE and strata dip towards the SW. The south-eastern end continues with large rounded crystalline blocks of the Blocky Layers (Fig. 7E). Numerous smaller Blocky Layer deposits with the same strike direction were found south of the Waschberg.
2. *East of Waschberg:* This occurrence forms the peak of the hill east of the Waschberg as well as the north-western end of an extended Blocky Layer that contains Occurrence 3. Marls and sandstones of the Ždánice–Hustopeče Formation north-west of it strike NW–SE and dip towards the SW.
3. *Further east of Waschberg:* This small occurrence is nearly completely surrounded by Blocky Layers. The strike direction of the Blocky Layers is WNW–ESE. They form the crest of the elongated hill towards ESE and merge into Occurrence 2. Large rounded crystalline blocks of several metres length can be found alongside the dirt road south-west of the occurrence.
4. *Michelberg:* The ovate outcrop area of the Michelberg suggests an N–S strike direction that is intermediate between the southern occurrences (1–3) and the northern ones with their SSW–NNE strike directions. However, direct strike and dip measurements indicate southern to south-eastern dip directions (Seifert 1980; Gebhardt & Ćorić 2014) and suggest fragmentation and tilting of the block. At the northern and southern tips, the Waschberg Limestone continues into Blocky Layers or with the next Waschberg Limestone occurrence.
5. *South of Michelberg:* This small occurrence seems to float on top of a Blocky Layer olistostrome that is exposed in a temporary stream below. It may therefore be a fragment of the Michelberg block.
6. *Steinberg:* The remaining three blocks of Hollingstein Limestone in the abandoned quarry are located in the western, south-eastern and north-eastern margins of the pit. The direct contact or transition to the Block Layers is particularly well exposed at the north-eastern end. The place may serve as an excellent stop for field trips. The Blocky Layers continue several 100 metres in north-eastern as well as south-western directions and are paralleled by further Blocky Layers.
7. *Southern Praunsberg*: The southern (and northern) Praunsberg with its Waschberg Limestone occurrences strike perfectly in line with the several Blocky Layer levels in the south-west (Fig. 2). The Waschberg Limestone and Blocky layers strike SW–NE and sandstone layers within the Ždánice–Hustopeče Formation dip towards the SE (Fig. 6C,D).
8. *Northern Praunsberg:* This is the northern continuation of the southern Praunsberg and includes the highest point of the hill chain. Small mining pits provide good outcrops and indicate SE-ward dip of the sandy to gravelly turbidites and debrites (Fig. 8C,D). The ridge continues northward and is

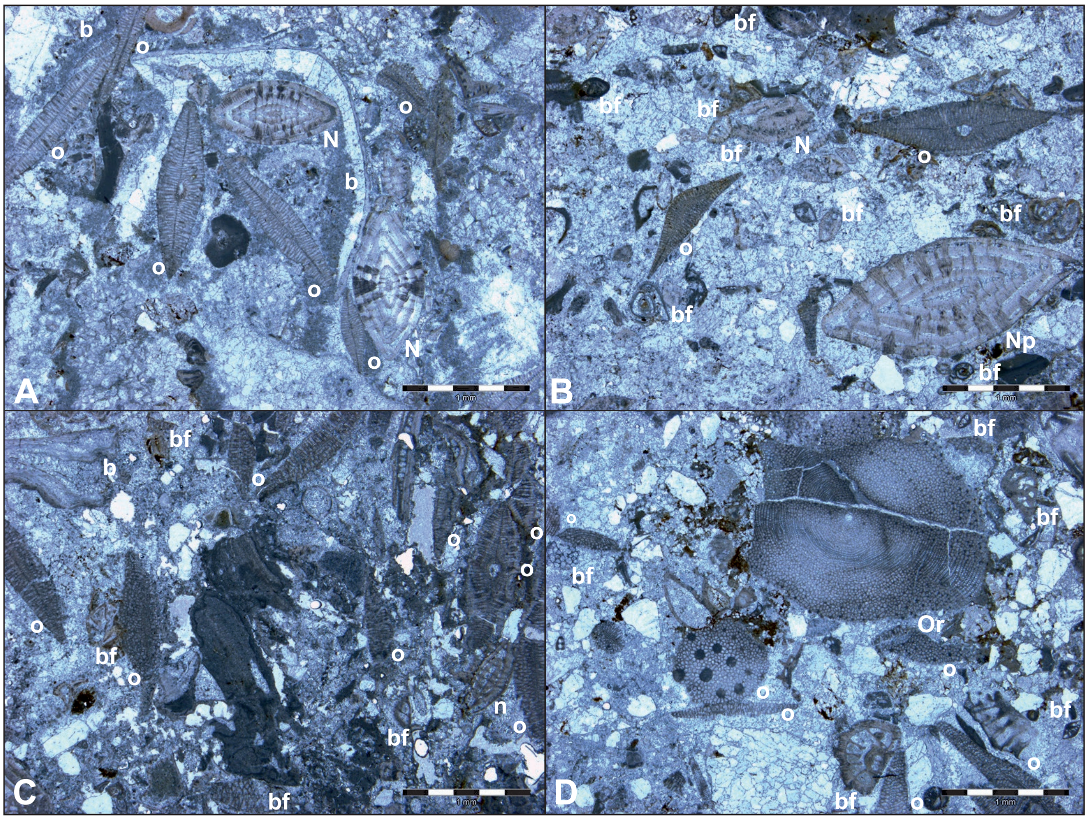

Fig. 9. Thin sections of Waschberg Limestone from Waschberg (A, C), Michelberg (B), east of Waschberg (D, No. 3 in Table 1). Length of scale bars 1.0 mm. **A** — Foraminiferal Rudstone with *Nummulites* sp., orthophragminids, fragments of bivalve and other calcareous shells, partly recrystallized. Sampling position shown in Figure 8A. **B** — Arenitic Rudstone with *Nummulites partschi*, orthophragminids, smaller benthic foraminifera and numerous angular sand grains (calcareous and siliclastic). **C** — Packstone to arenitic Rudstone with orthophragminids, bivalve fragments (oysters?), smaller benthic foraminifera and angular siliclastic sand grains. Sampling position shown in Figure 8B. **D** — Foraminifera bearing Quartzarenite or Orthophragminid (*Orbitoclypeus*) Rudstone with numerous angular to sub-rounded quartz grains, rock fragments and smaller benthic foraminifera. Key to labels: N – *Nummulites* sp., Np – *Nummulites partschi*, o – orthophragminids, Or – *Orbitoclypeus* sp., b – bivalve fragments, bf – smaller benthic foraminifera.

composed of Blocky Layers with an extremely high content of crystalline components (more than 90 % of the rocks found at the surface are amphibolitic, granitic or granodioritic). Waschberg Limestone components are very rare and highly weathered. An occurrence of sandy marls within the olistostrome was dated to the late Eocene (NP19; Seifert 1980).

The Waschberg Limestone and Hollingstein Limstone occurrences are described as strongly jointed and show numerous slickensides. This can be seen in the present outcrops in the field (Fig. 10) and was also reported by other authors (e.g., Grill 1953, 1962). These dilated joints indicate extensional strain or post-depositional movements of the sediments as in other prominent cases (e.g., by Lucente & Pini 2003; Festa et al. 2010).

The detailed field mapping showed that all Waschberg Limestone and Hollingstein Limestone occurrences (Table. 1) are always in direct contact with Blocky Layers (Fig. 2). Furthermore, the strike and dip directions of the occurrences are the same as those of the connected Blocky Layers (Fig. 2). In addition to this, fragments of Waschberg Limestone were found within the Blocky Layers at several places (e.g., Grillenberg, Fig. 7F, northern and southern ends of the Praunsberg hill chain).

Compressive structures such as folds or internal overthrusting were neither found during fieldwork nor reported in the literature. Repetitive sequences containing Waschberg Limestone that could point to imbricate structures were also not found during mapping (Fig. 2).

Large-scale tectonic structures

Figure 11 gives an overview on the main thrust faults, the cross faults and strike-slip movements as well as large tectonic wedges and small-scale fraction patterns in the recently mapped area. The Senning and Leitzersdorf Thrust Faults limit the Roseldorf-Zone, with the Senning Thrust Fault as western boundary of the Waschberg–Ždánice Unit to the autochthonous Alpine–Carpathian Foredeep. The Leitzersdorf Thrust Fault shows several lateral shifts of up to 500 m, for example, near Bruderndorf. East of the Leitzersdorf Thrust Fault, a large tectonic wedge (Haselbach Wedge) consisting of

Fig. 10. Outcrop views of the Hollingstein Limestone from the abandoned quarry at the Steinberg. **A** — North-western wall of quarry. **B** — North-eastern wall of quarry, transition (arrow points to boundary) from Hollingstein Limestone (lower part) to nodular limestone blocks and fragments of the Blocky Layers. Note the dilated joints (J) in both figures pointing to extensional strain during transport of the olistolith.

the Late Cretaceous Pálava Formation only, forms the transition to the thick sequence of the Hustopeče–Ždánice Formation which is intercalated by Blocky Layers and Waschberg Limestone (see also Fig. 3). North of Bruderndorf, a zone of small tectonic wedges with various rocks of Late Jurassic (Klentnice Beds) to early Miocene (Hustopeče–Ždánice Formation) ages forms the connection to the southern part. South-east of Niederhollabrunn, a ca. 2.5 km long and 1 km wide zone of Paleogene marly rocks ("crunch-zone") separates two blocks of Hustopeče–Ždánice Formation with intercalated Blocky Layers and Waschberg Limestone.

Discussion

Olistostromes and olistoliths

Olistostromes and mélanges are defined as mapable chaotic bodies of mixed rocks with a block-in-matrix fabric and are intimately linked to the structural and sedimentary processes attending their origin (Festa et al. 2010). They form significant components of collisional and accretionary orogenic belts. The terms olistostrome and olistolith (blocks included in, or floating on an olistostrome) were introduced by (Flores 1955) and Marchetti (1956). Richter (1976) suggested the term megolistolith for very large (house-size, several 10s of metres in diameter) olistoliths. Festa et al. (2010) give a comprehensive overview on the history of the mélange concept and describe many examples that substantiate their classification.

Richter (1976) distinguished several gravitational mass transport categories related to olistostromes and discussed their sedimentological (components, structures, dimensions) aspects and formation history. He distinguished between olistostromes (slide-bed), olistothrymma (slide-fragment), and olistoplaka (slide-plate) off which olistotrymma and olistoplaka are bound to specific tectonic situations and without any connections to olistostromes. Another classification based on lithological characters and particular tectonic situation under which the deposits evolved was published by Festa et al. (2010) in their paper on mélanges. They distinguish between sedimentary mélanges (including olistostromes and Wildflysch) and tectonic mélanges. They propose 6 major types and numerous sub-types, all based on their structural settings. The most common type is "type 6 – mélanges related to intracontinental deformation". The alpine term Wildflysch (large blocks and olistoliths derived from advancing nappe systems and emplaced into a foredeep) corresponds to the term "precursory olistostrome" as it describes identical phenomena (Festa et al. 2010).

Thicknesses of single olistostromes may vary between several dm and many 10s of metres, stacks of olistostromes can reach total thicknesses of more than 1 km (Richter 1976). The transport distances are in the range of many kilometres (12–40 km or more from examples of Richter 1976). During the transport process, even very large olistoliths may not be destroyed and deformations (due to drag or strain) occur only in their marginal parts.

Classfication and formation of the Waschberg and Hollingstein Limestone occurrences

The results presented here show many indications for an interpretation of the Waschberg and Hollingstein Limestone occurrences as olistoliths within an olistostrome dominated

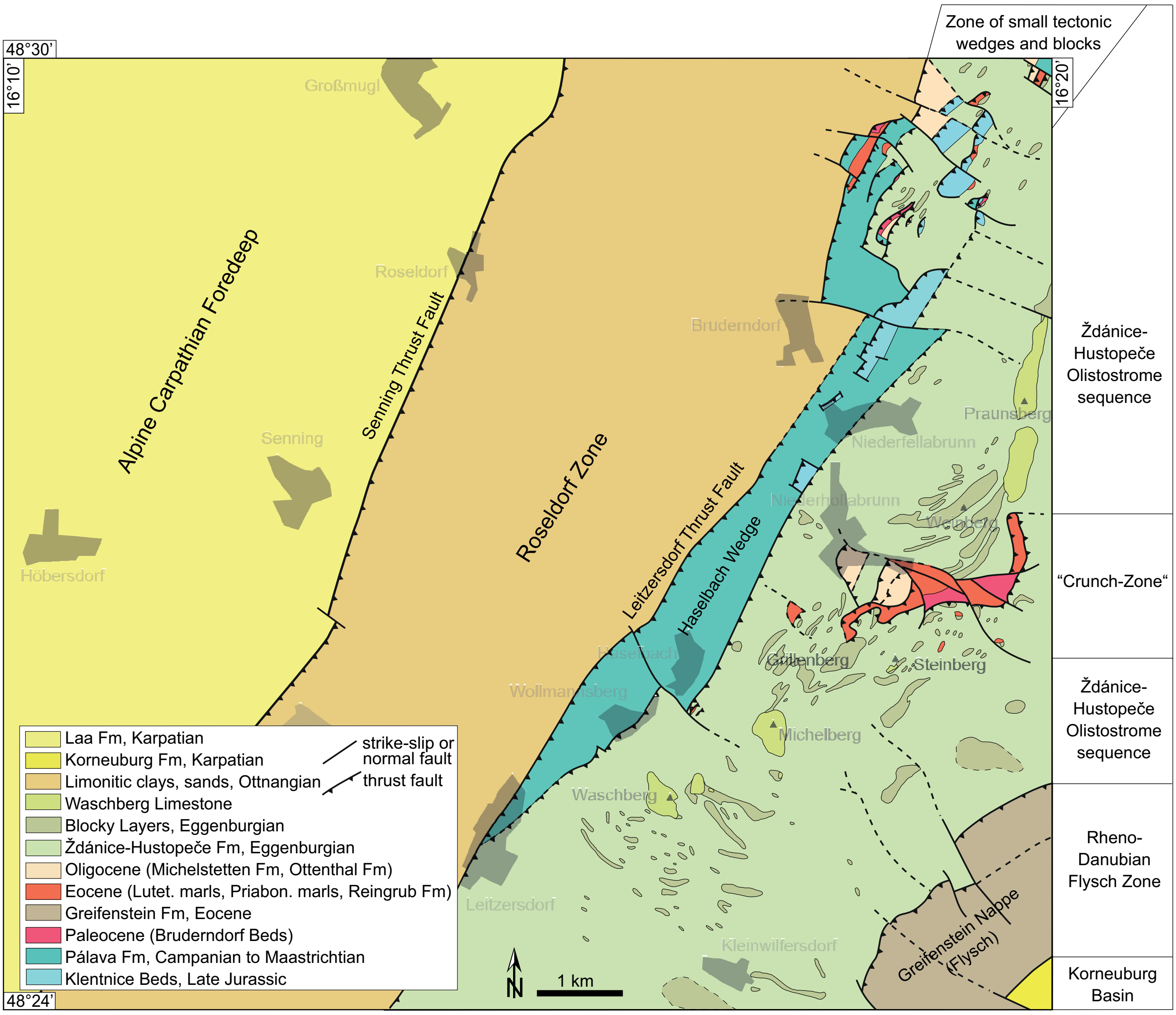

Fig. 11. New structural map of the southern part of the Waschberg–Ždánice Unit in Lower Austria based of recent field records (Gebhardt & Ćorić 2014; Gebhardt 2016, 2018a, b, c). Holocene and Pleistocene sediments removed. Stippled lines indicate assumed geological boundaries or faults.

sedimentary environment (Blocky Layers). Their dimensions are far larger than the usual olistoliths or even megolistoliths. They cover areas several km in length. By their dimensions, they can be compared with olistotrymma and olistoplaka of Richter (1976) but are in clear connection with or have even been deposited within the same sedimentation event of the surrounding olitostromes. Thus, the name giant-olistolith is preferred here. Blocks of several km size are well known from various passive margins and ocean floors, particularly generated by the failure of seamounts and submarine volcanoes (Festa et al. 2010 and several references therein). Also tectonic uplift of fore-arc and accretionary ridges produce giant-olistoliths, particularly known from the Polish and Ukrainian Outer Carpathians (e.g., Ślączka & Oszczypko 1987; Oszczypko et al. 2006; Ślączka et al. 2006; Cieszkowski et al. 2009, 2012; Okay & Altiner 2017).

The olistostromes and olistoliths occurring in the southern Waschberg–Ždánice Unit fit well into Festa et al. (2010) Type 6 – mélanges related to intracontinental deformation, in particular to sub-Type 6a – sub-nappe mélanges, and specially to sub-sub-Type 6a1 – precursory olistostromes. "These consist of classic olistostromes and Wildflysch commonly characterized by chaotic block bodies in a block-in-matrix fabric formed at the front of thrusts and/or nappe systems and deposited by cohesive debris flows and/or block avalanches in migrating foredeep basins" as it is exactly the case in the southern Waschberg–Ždánice Unit (see also chapter on search for equivalents). Also the almost clast-supported larger blocks or olistoliths and numerous exotic components point to this type. Festa et al. (2010) are certain that other varieties of chaotic rock bodies than the 6 types presented in their classification may be described. The combination of olistostromes with

Table 3: Lower Miocene olistostrome occurrences in the Alpine–Carpathian Foreland Basin and the Waschberg–Ždánice Unit of Lower Austria (compare Fig. 12). 1 Roetzel et al. 1999; 2 Schnabel et al. 2002; 3 Krenmayr 2003; 4 Wessely et al. 2006; 5 Gebhardt 2007; 6 Gebhardt et al. 2008; 7 Gebhardt 2008; 8 Gebhardt 2011a; 9 Gebhardt 2011b; 10 Gebhardt 2012; 11 Gebhardt & Ćorić 2014; 12 Roetzel et al. 2015; 13 Gebhardt 2016; 14 Gebhardt 2018a; 15 Gebhardt 2018c.

Occurrence	Rock unit	Location	Age	Reference	Lat. (°N)	Long. (°E)
A	Buchberg Conglomerate	Buchberg northeast of Neulengbach	Eggenburgian	2, 4, 5, 6, 7	48°12’50”	15°56’41”
B	Blocky Layers	southern Waschberg-Ždánice Unit	Eggenburgian	2, 4, 11, 13, 14, 15	48°26’12”	16°17’18”
C	Blocky Layers from Heuberg	Heuberg east of Siegersdorf	Eggenburgian	2, 6, 9, 12	48°15’07”	15°57’02”
D	Blocky Layers from Heuberg	south of Grabensee	Eggenburgian	2, 5	48°13’48”	15°55’53”
E	Blocky Sands of Königstätten	Königstetten	late Eggenburgian	2, 4, 10	48°17’44”	16°09’12”
F	Coarse conglomerates	southwest of Freundorf	Eggenburgian to early Ottnangian	8, 12	48°16’42”	16°02’53”
G	Mauer Formation	Dunkelsteinerwald near Melk	late Eggenburgian to early Ottnangian	2, 3, 4	48°13’44”	15°25’28”
H	Laa Formation	Göllersdorf	Karpatian	1, 2, 4, 15	48°30’02”	16°07’34”

a mainly sandy matrix and km-sized giant-olistoliths as in the southern Waschberg–Ždánice Unit may be such a case which is bound to a specific tectonic setting.

Controlling factors for the formation of olistostromes are various: earthquakes, oversteepening slope angles, or thrusting (Richter 1976; Cieszkowski et al. 2009, 2012; Festa et al. 2010; Ślączka et al. 2012). All of these processes effectively increase stresses in weakened sediments and trigger failures. Thrusting and subsequent oversteepening appear to be the most probable factors since the original stratification of the Waschberg Limestone occurrences is largely preserved.

Comparison of Blocky Layers and giant-olistoliths with examples of contemporaneous (Miocene) olistostromes

Scherba (1987) identified six stratigraphic levels that reflect regional formation of olistostromes during the Cenozoic of the circum-Mediterranean and Paratethys areas. Their formation is mainly related to nappe movements and reflects the regional intensity of these movements. For the Austrian part of the Alpine orogen, the end of the Oligocene and end of the lower Miocene levels are most prominent. However, the olistostrome occurrences in Lower Austria (Table 3) show that locally other periods of sedimentation were more active phases. A clustering of lower Miocene (Eggenburgian to Karpatian) occurrences north-west of Vienna is prominent (Fig. 12) and represents the regional focus of thrusting activity or at least mobilization of exposed rocks. One example from Siegersdorf, about 30 km south-west of the Waschberg (Fig. 12, location C) is described in detail (Blockschichten vom Heuberg; Hauer 1858; Schnabel et al. 2002; Gebhardt et al. 2008; Jochum et al 2009; Fig. 12, locations C, D). The olistostromes are dominated by crystalline components with tonalitic/granodioritic blocks of up to 3000 m^3. They have a sandy to silty matrix, and were deposited during the Eggenburgian (calcareous nannoplankton zone NN2). The large blocks were probably products of intense block faulting of nearby structural highs now below the Molasse sediments, or in the Bohemian Massif and later slid down gravitationally southward into the deeper basin. For the Blocky Layers in the southern Waschberg-Ždánice Unit, the surrounding Variscan basement however provides no magmatic suite with granites comparable to the components of the Blocky Layers (Wegner et al. 2013).

Debris flow deposits with nearly monomict composition (poorly sorted coarse conglomerates in sandy matrix and strongly dominated by Flysch-sandstones) were described from outcrops south-west of Freundorf south of the Danube River (Gebhardt 2008, 2009; Roetzel et al. 2015; Fig. 12, location F). These occurrences are locally restricted but are also embedded into thick Eggenburgian to early Ottnangian marl successions (so-called Robulus-Schlier) with sandstone intercalations. The so-called Blockschichten von Königstätten (Blocklayers of Königstätten; Fig. 12, location E), located between the Blockschichten vom Heuberg and the Waschberg Limestone, are in the same stratigraphic position. Within a sandy matrix, dm- to m-sized pebbles of crystalline and Flysch origin are frequent. Blocky layers interfinger with sandy layers and marls (so-called Robolus-Schlier; Götzinger et al. 1954; Plöchinger et al. 1974; Schnabel et al. 2002; Gebhardt 2012). All these sedimentation events apparently took place nearly synchronously, namely during the Eggenburgian regional stage. They therefore represent a period of tectonic activity that was likely related to the northward movement of the Alpine front.

Polycrystalline megabreccia of similar age are also described from the southern Dunkelsteiner Wald further to the west (Blockmuren von Mauer; Fuchs 1972; Krenmayr 2003; Fig. 12, location G). Olistostromes with olistoliths of several tens to hundreds of metres in diameter were described from the sub-surface of the Upper Austrian Molasse Basin close to the German border (de Ruig 2003). These occurrences were discovered by 3D-seismic surveys and are part of the Puchkirchen and Hall formations. Megaslides of up to 250 m

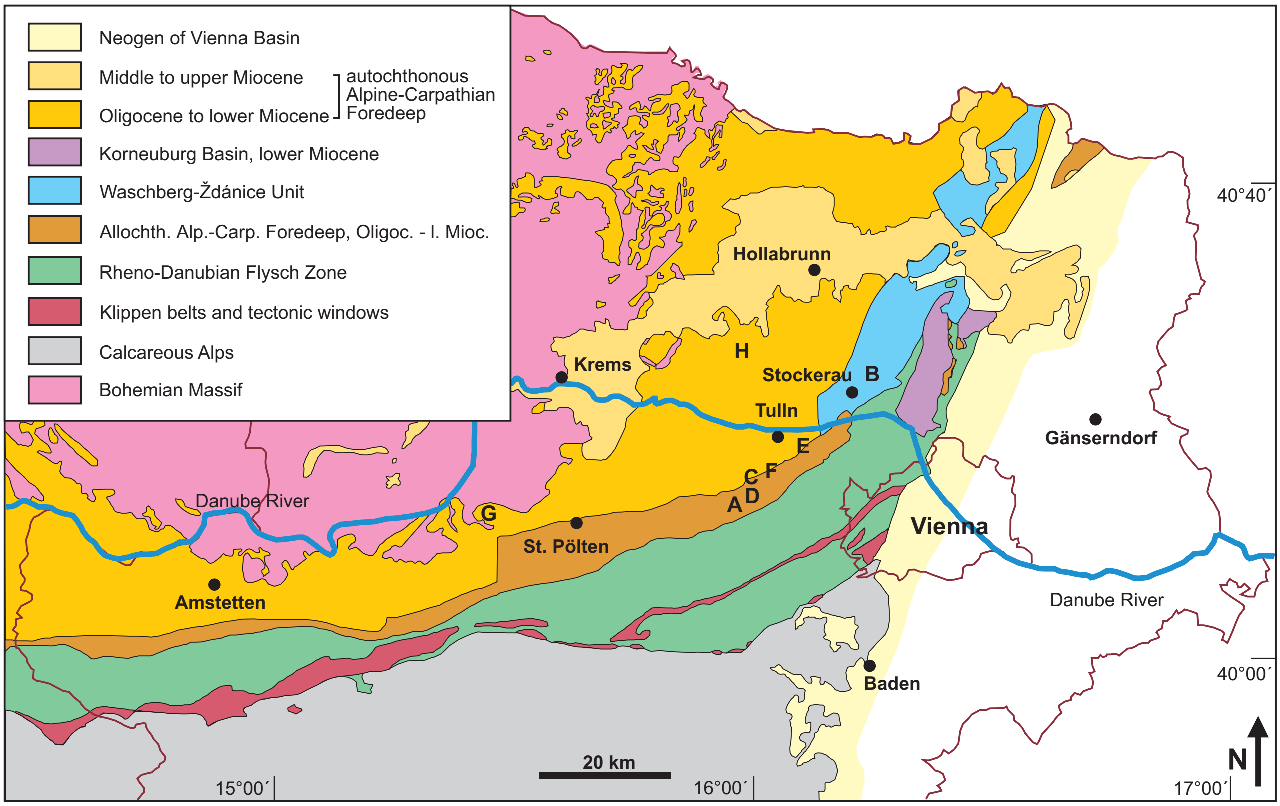

Fig. 12. Lower Miocene olistostrome occurrences (A to H corresponding to Table 3) in the Alpine–Carpathian Foreland Basin and the Waschberg–Ždánice Unit of Lower Austria. Geology based on Wessely et al. (2006), Waschberg–Ždánice Unit including Roseldorf-Zone, Pleistocene and Holocene sediments removed.

thickness that cover areas of several tens of square kilometres were also discovered. They were formed by gravitational collapse of the southern slope, probably triggered by tectonic movements of the Alpine front.

The so-called Buchberg Conglomerate consists nearly exclusively of unsorted gravel and of sandstone blocks in a sandy to marly matrix (Gebhardt et al. 2008; Fig. 12, location A), pointing to a single source in the Flysch Zone. The Karpatian debrites of Göllersdorf (Fig. 12, location H) show well rounded, matrix-supported gravel probably from a littoral environment and have their origin in the Waschberg–Ždánice Unit or in the Flysch-Zone. They form relatively thin sedimentary bodies and pinch out within a few tens of metres, and are interpreted as submarine channels (Roetzel et al. 1999).

At Strážovice in southern Moravia, the Ždánice–Hustopeče Formation contains conglomerates with components up to 1 m in diameter, including pebbles of nummulite limestone (Czech Geological Survey 1998a). These occurrences yielded rocks from various sources of Triassic to Paleogene age and were interpreted as olistostromes (Oppenheimer 1916; Soták 1986).

A detailed description of a middle Miocene large submarine slide in the northern Apennines was presented by Lucente & Pini (2003, Casaglia Monte della Colonna-body). Its thickness is more than 200 m and it covers more than 350 km^2. Due to the much better outcrop situations compared to the southern Waschberg–Ždánice Unit, internal deformation structures could be analysed and considered diagnostic for such gravitational mass wasting processes. In Lower Austria, however, only occasional and rather small outcrops occur due to intense weathering processes, vegetation cover, and extensive loess coverage. Regardless of the little information available from the Waschberg Limestone bodies directly, the dimensions and the integration of the several bodies into the olistostromes (Blocky Layers) make the Casaglia Monte della Colonna-body and the Waschberg Limestone occurrences and their formation processes comparable.

Search for equivalents of the Waschberg Limestone and its route to its present location

Unfortunately, surface parent rock occurrences of the Ypresian to basal Lutetian Waschberg Limestone are still unknown. Some authors proposed equivalents in the Moravian parts of the Waschberg–Ždánice Unit. Glaessner (1931); Pokorný (1947), and Čtyroký (1966) suggested the limestones of Holý vrch near Kurdějov (Němčice beds; conglomerates, sandstones, and sandy limestones with large *Nummulites*) as possible equivalents of the Waschberg Limestone. These beds in the surroundings of Hustopeče were already described by Hauer

(1858). The Hollingstein Limestone is seen as a stratigraphic equivalent of the Moutnice Limestone (dolomitic limestones; Čtyroký 1966). Exotic blocks of *Nummulites*- or *Discocyclina*-limestones were described from Oligocene strata near Bystřice nad Olší from the Subsilesian Zone in north-eastern Moravia (personal communication M. Bubík; Czech Geological Survey 1998b). However, the lack of original deposits is not unusual and many rocks are only known from such "exotic" olitholiths or even pebbles. For example, pre-existing ridges in the Outer Carpathians are indicated by olistoliths in flysch sediments since the ridges were overridden by an accretional prism (e.g., Picha et al. 2006; Cieszkowski et al. 2009).

Kováč et al. (2016, 2018) presented paleogeographic reconstructions for the Western Carpathians and developed a geotectonic model that allowed for accommodation space for the shallow water components (i.e., *Nummulites* and other sunlight-depending benthic organisms or rounded quartz pebbles from backstop uplifts) as well as deeper water indicators (e.g., planktic foraminifera; outer shelf to upper bathyal) of the Waschberg Limestone. These sediments were deposited in accretional wedge basins during the middle Eocene. A possible location may be around a structural high between the Magura Flysch Belt and the Buková Furrow at the position of the modern northern Vienna Basin. The nummulitic limestones of the Inner Carpathians (Picha et al. 2006) were probably too far away from the site of deposition to be the source of larger foraminifera and gravels for the Waschberg Limestones. During the Eggenburgian (lower Miocene), the deposition of the Ždánice-Hustopeče Formation took place in a trench in front of the growing Magura Belt accretionary wedge (Kováč et al. 2017).

The early Miocene development at the Alpine front in Lower Austria is characterized by "diachronic along-strike termination of foreland propagation thrusting with younger thrust ages and higher in-sequence thrust distances in the east" (Beidinger & Decker 2014), i.e., the Waschberg–Ždánice Unit. This twofold shift of the north-westward thrusting led to ca. 21 km more in-sequence thrusting in the east with a 4 my later termination during late Karpatian instead of early Eggenburgian times. Beidinger & Decker (2014) reconstructed a section that includes the Waschberg–Ždánice Unit. The Eggenburgian to Karpatian thrusting propagates with ca. 5.5 mm/yr from the floor thrust of the Flysch units into the foreland units about 1.5 My after the base of the Eggenburgian and after accommodating about 9 km of Eggenburgian thrusting. This scenario allows for some speculations on the formation and deposition of the olistostromes (Blocky layers) and the displacement of the Waschberg Limestone giant-olistoliths.

1. Ypresian larger foraminifera and other biogenic grains were deposited in a late Ypresian/basal Lutetian basin east or south-east of its modern position, possibly on top of the autochthonous Mesozoic formations below the modern Vienna Basin (Wessely et al. 2006). The Waschberg Limestone was then detached and moved to the north-west together with the propagating Flysch nappes.
2. Crystalline angular components scraped from basement or rounded components from the Egerian "Augensteinlandschaft" (pebbles) before the lateral extrusion of the Eastern Alps (Frisch et al. 1998; Kuhlemann et al. 2001) in the south, and sandstone/limestone blocks from the propagating Flysch nappes were collected in the Egerian or basal Eggenburgian foredeep.
3. Exposure of the Waschberg Limestone on unstable slopes of the thrust front led to mobilization and basinward transport of olistostromes and Waschberg Limestone giant olistoliths during the Eggenburgian, possibly triggered by earthquakes.
4. Continuation of thrusting until the late Karpatian. The formation of olistostromes and giant-olistoliths may be indicative for the velocity or higher intensity of the thrusting in the eastern sector compared to the west of Lower Austria with its thinner and less frequent olistostrome beds, smaller coverage and smaller olistolith dimensions.

New structural and sedimentary interpretation of the southern Waschberg–Ždánice Unit

All structural maps show a general SW–NE strike with a dip towards the SE (e.g., Grill 1962; Seifert 1980; Wessely et al. 2006) in the southern Waschberg–Ždánice Unit, except for the southernmost part, namely around the Waschberg itself with NW–SE-striking strata (Figs. 2, 3, 11; see also Grill et al. 1957). This was confirmed by the recent mapping (Gebhardt & Ćorić 2014). The block was apparently rotated clockwise by ca. 90° during the thrusting phase after deposition in the early Miocene. It was then moved to the north-west by a dextral strike-slip fault. The general SW–NE-strike pattern is not affected by the new results and interpretations presented here. Seifert (1980, 1982) further developed the hitherto existing interpretation and proposed a concept with two tectonic wedges of Ždánice–Hustopeče Formation divided by a thrust and expressed by the chain of Waschberg Limestone occurrences at the base of the footwall wedge. This concept is now disproved. Merely, the Ždánice–Hustopeče Formation, Blocky Layers and Waschberg Limestones form a thick (>1000 m) stack of sediments deposited during the Eggenburgian (possibly late Egerian to early Ottnangian).

Large (or giant-) olistoliths if set free by weathering or erosion from their surrounding younger beds can be taken for tectonic "klippen" (Picha et al. 2006; Festa et al. 2010). This happened in the past for some of the rocks of the southern Waschberg–Ždánice Unit. The Waschberg Limestone occurrences delt with in this contribution, however, never occur as isolated blocks but always connected to olistostromes. They may now be called "sedimentary klippen", for example, according to Richter (1976). Components of km-sized dimensions were not known for the authors of the imbricate structure concept (particularly Kohn 1911 or Glaessner 1937) at that time, also not the submarine processes that enabled the giant mass transports. The compilation study of Cieszkowski et al. (2009) shows that olistostromes are frequent in the Waschberg–

Ždánice Unit and the Subsilesian Unit of Moravia and in southern Poland, and that km-size giant olistoliths exist (e.g., the Štramberk-klippe), but they probably do not occur regularly. In the Pouzdřany Unit in front of the Waschberg–Ždánice Unit, no olistostromes were described in the literature (compare e.g., Picha et al. 2006), possibly because the original position of this unit is too far away from the Silesian Ridge to be reached by debrites from this potential source.

In the past, the Waschberg Limestone has been interpreted as an autochthonous sediment deposited in a shallow marine, or reef environment in the vicinity of the Bohemian Massif (e.g., Grill 1962; Seifert 1980, 1982). This was due to the co-occurrence of shallow water dwelling organisms and crystalline and quartz pebbles. This interpretation however neglects the deep-water indicators in the microfossil assemblages, the age difference between benthic (*Nummulites*) and planktic foraminifera, and in particular sedimentary structures typical for allochthonous sediments produced by debris flows and turbidites. In the context of the general thrusting activity in the alpine foreland during the Eocene, this new interpretation points to an already instable shelf or shallow water depositional area at that time. It also shows the proximity of sources for rather coarse crystalline components (e.g., gravel or conglomerates) which were mixed with the calcareous components. This took place in a relatively deep sedimentary basin of probably small size, at least small enough not to show up today in any known outcrop or below the Vienna Basin. The components of the so-called Waschberg Limestone were re-deposited twice: first in the basal Lutetian (middle Eocene) and second as giant olistoliths during the Eggenburgian (early Miocene).

This re-interpretation is in line with a paradigm change from purely tectonic explanations of large "exotic blocks" within rock sequences towards syn-sedimentary evolutions. Particularly the Subsilesian Units in southern Poland were revisited for the presence of large olistoliths that were previously interpreted as tectonic klippen (e.g., Cieszkowski et al. 2009; Ślączka et al. 2012)

As a result of this new interpretation of the Waschberg Limestone, the idea of the Waschberg Limestone as a marker (or base) for the boundary of two tectonic wedges (Seifert, 1980, 1982) becomes obsolete. However, the recent mapping also proved that the imbricate structure is real in the southern Waschberg–Ždánice Unit, particularly close to the Leitzersdorf Thrust Fault (Fig. 11).

Conclusions

In recent years, the southern end of the Waschberg–Ždánice Unit has been geologically mapped in detail. The resulting geological map (Fig. 2) and the geological section (Fig. 3) gave new insights into the stratigraphic and tectonic construction of the area under focus. The results question traditional concepts on its sedimentological and tectonic evolution. Fragments of Waschberg Limestone of varying size were found within olistostrome deposits. The nine large occurrences (km-sized) of the Waschberg Limestone, particularly at Waschberg, Michelberg, Praunsberg, and at some unnamed places continue into and strike in line with the widespread olistostromes. They are consequently interpreted as part of them and not as tectonic klippen. Compressive structures such as folds or internal overthrusting were neither found during fieldwork nor reported in the literature. Repetitive sequences that could point to imbricate structures were also not found. Instead, the Waschberg Limestone occurrences are interpreted as products of submarine mass transport processes contemporaneous with the embedding olistostromes (Blocky Layers). Because of the very large size of the rock bodies, the occurrences are named giant-olistoliths. The combined Ždánice–Hustopeče Formation, Blocky Layers and Waschberg Limestones form a thick (>1000 m) stack of sediments deposited during the Eggenburgian (possibly late Egerian to early Ottnangian). The olistostromes and olistoliths occurring in the southern Waschberg–Ždánice Unit fit well into Type 6 – mélanges related to intracontinental deformation, in particular to sub-Type 6a – sub-nappe mélanges, and especially to sub-sub-Type 6a1 – precursory olistostromes. The formation of olistostromes and giant-olistoliths may be indicative for the increased velocity or higher intensity of the thrusting processes during the early Miocene.

The Waschberg Limestone was formerly interpreted as autochthonous and deposited in a shallow marine or even reef environments. However, the high percentages of sub-thermocline planktic foraminifera in the intercalated marls indicates greater depositional depths. Furthermore, sedimentary structures found in outcrops such as graded bedding or massive, ungraded beds with floating clasts indicate debrites and turbiditic depositional systems. A significant age gap of several million years exists between the components (*Nummulites*) in the debrites and the pelagic background sediment (planktic foraminifera, calcareous nannofossils). Thus, the Waschberg Limestone is an allochthonous, mixed sediment and its components were transported in from different sources.

Successive steps to the present locations of the Waschberg Limestone and the other olistostrome components might be: Ypresian larger foraminifera and other biogenic grains were deposited in a late Ypresian/basal Lutetian basin east or southeast of its modern position. The Waschberg Limestone was then detached and moved to the north-west together with the propagating Flysch nappes. Crystalline components from the basement or the Egerian "Augensteinlandschaft", and sandstone/limestone blocks from the propagating Flysch nappes were collected in an Egerian or basal Eggenburgian foredeep. The Exposure of the Waschberg Limestone on unstable slopes of the thrust front led to mobilization and basinward transport of olistostromes and Waschberg Limestone giant olistoliths during the Eggenburgian. The thrusting continued until the late Karpatian.

The detailed geological mapping led to the identification of some previously unknown structural elements. The Leitzersdorf Thrust Fault shows lateral shifts of up to 500 m. East of the Leitzersdorf Thrust Fault, a large tectonic wedge (Haselbach Wedge) consists of the Late Cretaceous Pálava Formation only. South-east of Niederhollabrunn, a ca. 2.5 km long and 1 km wide zone of Paleogene marly rocks ("crunch-zone") separates two blocks of Hustopeče–Ždánice Formation with intercalated Blocky Layers and Waschberg Limestone.

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References

Abel O. 1899: Die Beziehungen des Klippengebietes zwischen Donau und Thaya zum alpin-karpatischen Gebirgssysteme. *Verhandlungen der Geologischen Reichsanstalt* 1899, 374–381.

Allen J.R.L. 1982: Sedimentary structures: their character and physical basis. Vol. 1. *Developments in Sedimentology* 30A, 1–593.

Bachmayer F. 1961: Bericht über Kartierungs- und Aufsammlungsergebnisse im Bereich der Waschbergzone auf Blatt Stockkerau (40). *Verhandlungen der Geologischen Bundesanstalt* 1961, A14–A17.

Beidinger A. & Decker K. 2014: Quantifying early Miocene in-sequence and out-of-sequence thrusting at the Alpine-Carpathian junction. *Tectonics* 33, 222–252. https://doi.org/10.1002/2012TC003250

Berggren W.A. & Pearson P.N. 2006: Tropical to subtropical planktonic foraminiferal zonation of the Eocene and Oligocene. In: Pearson P.N., Olsson R.K., Huber B.T., Hemleben C. & Berggren W.A. (Eds.): Atlas of Eocene planktonic foraminifera. *Cushman Foundation Special Publication* 41, 29–40.

Bittner A. 1892: Über zwei für die Nummulitenkalke von Stockerau neue Arten. *Verhandlungen der Geologischen Reichsanstalt* 1892, 241–242.

Boué A. 1830: Briefwechsel. Mittheilungen an den Geheimen Rath v. Leonhard gerichtet. *v. Leonhard's und Bronn's Jahrbuch für Mineralogie, Geognosie, Geologie und Petrefactenkunde* 1, 76–78.

Cieszkowski M., Golonka J., Krobicki M., Ślączka A., Oszczypko N., Waśkowska A. & Wendorff M. 2009: The Northern Carpathians plate tectonic evolutionary stages and origin of olistoliths and olistostromes. *Geodinamica Acta* 22, 101–126. https://doi.org/10.3166/ga.22.101-126

Cieszkowski M., Golonka J. & Waśkowska A. 2012: An olistolith interpretation for the Paleocene Szydlowiec Sandstones in the stratotype area (Outer Carpathians, Poland). *Austrian Journal of Earth Sciences* 105, 240–247.

Čtyroký P. 1966: Die eozäne Fauna der Moutnice-Kalke (Südmähren). *Sborník geologických věd, Paleontologie* 8, 71–104.

Čtyroký P. 1993: Das Tertiär der Böhmischen Masse in Südmähren. *Jahrbuch der Geologischen Bundesanstalt* 136, 707–713.

Czech Geological Survey 1998a: The database Significant Geological Localities of the Czech Republic: 1136 (online). *Czech Geological Survey*, Prague, 1998 (cit. 2020-05-26) Available from: http://locality.geology.cz/1136

Czech Geological Survey 1998b: The database Significant Geological Localities of the Czech Republic 669 (online). *Czech Geological Survey*, Prague, 1998 (cit. 2020-06-25). Available from: http://lokality.geology.cz/669

de Ruig M.J. 2003: Deep marine sedimentation and gas reservoir distribution in Upper Austria. *Oil Gas European Magazine* 2, 64–73.

Einsele G. 1992: Sedimentary basins. *Springer Verlag*, Berlin, 1–628.

Festa A., Pini G.A., Dilek Y. & Codegone G. 2010: Mélanges and mélange-forming processes: a historical overview and new concepts. *International Geology Review* 52, 1040–1105.

Flores G. 1955: Les résultats des études pour les recherches pétroliféres en Sicile: Discussion. *Proceedings of the 4th World Petroleum Congress, Rome Section* 1/A/2, 121–122.

Flügel E. 2010: Microfacies of carbonate rocks: analysis, interpretation and application. *Springer Verlag*, Berlin, 1–929.

Frisch W., Kuhlemann J., Dunkl I. & Brügel A. 1998: Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. *Tectonophysics* 297, 1–15. https://doi.org/10.1016/S0040-1951(98)00160-7

Fuchs W. 1972: Tertiär und Quartär am Südostrand des Dunkelsteiner Waldes. *Jahrbuch der Geologischen Bundesanstalt* 115, 205–245.

Gebhardt H. 2007: Bericht 2006 über geologische Aufnahmen im Neogen und Quartär auf Blatt 57 Neulengbach. *Jahrbuch der Geologischen Bundesanstalt* 147, 627–630.

Gebhardt H. 2008: Bericht 2007 über geologische Aufnahmen im Neogen und Quartär auf Blatt 57 Neulengbach. *Jahrbuch der Geologischen Bundesanstalt* 148, 233–236.

Gebhardt H. 2009: Bericht 2008 über geologische Aufnahmen im Tertiär auf den Blättern 39 Tulln und 57 Neulengbach. *Jahrbuch der Geologischen Bundesanstalt* 149, 513–515.

Gebhardt H. 2011a: Bericht 2009 über geologische Aufnahmen im Tertiär auf Blatt 39 Tulln. *Jahrbuch der Geologischen Bundesanstalt* 151, 94–96.

Gebhardt H. 2011b: Bericht 2010 über geologische Aufnahmen im Tertiär auf Blatt 39 Tulln. *Jahrbuch der Geologischen Bundesanstalt* 151, 96–99.

Gebhardt H. 2012: Bericht 2011 über geologische Aufnahmen im Tertiär auf Blatt 40 Stockerau. *Jahrbuch der Geologischen Bundesanstalt* 152, 229–231.

Gebhardt H. 2016: Bericht 2014 über geologische Aufnahmen im Paläogen/Neogen auf Blatt NM 33-12-13 Hollabrunn. *Jahrbuch der Geologischen Bundesanstalt* 156, 349–351.

Gebhardt H. 2018a: Bericht 2016 über geologische Aufnahmen im Paläogen/Neogen auf Blatt NM 33-12-13 Hollabrunn. *Jahrbuch der Geologischen Bundesanstalt* 158, 183–186.

Gebhardt H. 2018b: Bericht 2017 über geologische Aufnahmen im Paläogen/Neogen auf Blatt NM 33-12-13 Hollabrunn. *Jahrbuch der Geologischen Bundesanstalt* 158, 186–189.

Gebhardt H. 2018c: Bericht 2018 über geologische Aufnahmen im Paläogen/Neogen auf Blatt NM 33-12-13 Hollabrunn. *Jahrbuch der Geologischen Bundesanstalt* 158, 190–196.

Gebhardt H. & Ćorić S. 2014: Bericht 2012–2013 über geologische Aufnahmen im Paläogen/Neogen auf Blatt 5313 Hollabrunn Südost. *Jahrbuch der Geologischen Bundesanstalt* 154, 365–370.

Gebhardt H., Krenmayr H.-G., Ćorić S. & Roetzel R. 2008: Grobklastika in der allochthonen Vorlandmolasse am Ostende der Alpen. Field trip guidebook Pangeo 2008. *Journal of Alpine Geology* 49, 137–154.

Gebhardt H., Ćorić S., Darga R., Briguglio A., Schenk B., Werner W., Andersen N. & Sames B. 2013: Middle to Late Eocene paleo-

environmental changes in a marine transgressive sequence from the northern Tethyan margin (Adelholzen, Germany). *Austrian Journal of Earth Sciences* 106, 45–72.
Glaessner M. 1931: Geologische Studien in der äußeren Klippenzone. *Jahrbuch der Geologischen Bundesanstalt* 81, 1–23.
Glaessner M.F. 1937: Die alpine Randzone nördlich der Donau und ihre erdölgeologische Bedeutung. *Petroleum* 33, 1–8.
Götzinger G. 1913: Neue Beobachtungen zur Geologie des Waschbergs bei Stockerau. *Verhandlungen der Geologischen Reichsanstalt* 1913, 438–444.
Götzinger G., Grill R., Küpper H., Lichtenberger E. & Rosenberg G. 1954: Erläuterungen zur geologischen Karte der Umgebung von Wien. *Geologische Bundesanstalt*, Wien, 1–150.
Gradstein F.M., Ogg J.G., Schmitz M.D. & Ogg G.M. 2012: The Geological Time Scale 2012. *Elsevier*, Amsterdam, 1–1144. https://doi.org/10.1016/C2011-1-08249-8
Grill R. 1953: Der Flysch, die Waschbergzone und das Jungtertiär um Ernstbrunn (Niederösterreich). *Jahrbuch der Geologischen Bundesanstalt* 96, 65–116.
Grill R. 1962: Erläuterungen zur geologischen Karte der Umgebung von Korneuburg und Stockerau 1:50 000. *Geologische Bundesanstalt*, Wien, 1–52.
Grill R., Götzinger G. & Bachmnayer F. 1957: Geologische Karte der Umgebung von Korneuburg und Stockerau. *Geologische Bundesanstalt*, Wien.
Hauer F.R. v. 1858: Ueber die Eocengebilde im Erzherzogthume Oesterreich und in Salzburg. *Jahrbuch der k.k. geologischen Reichsanstalt* 9, 103–137.
Holzer H. & Küpper K. 1953: Geologische Beobachtungen am Hollingstein (Waschbergzug). *Verhandlungen der Geologischen Bundesanstalt* 1957, 146–150.
Jochum B., Gebhardt H., Krenmayr H.-G. & Ćorić S. 2009: The giant granodiorite block from Heuberg, Austria: geoelectric measurements of a submarine debris flow component and its genetic interpretation. *Geophysical Research Abstracts* 11, EGU2009-7339-5.
Kohn V. 1911: Geologische Beschreibung des Waschbergzuges. *Mitteilungen der Geologischen Gesellschaft in Wien* 4, 117–142.
König A. 1896: Die exotischen Gesteine vom Waschberg bei Stockerau. *Tschermak's mineralogische und petrographische Mitteilungen, Neue Folge* 15, 466–480.
Kováč M., Plašienka D., Soták J., Vojtko R., Oszczypko N., Less G., Ćosović V., Fügenschuh B. & Králiková S. 2016: Paleogene palaeoceanography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global and Planetary Change* 140, 9–27. https://doi.org/10.1016/j.gloplacha.2016.03.007
Kováč M., Márton E., Oszczypko N., Vojtko R., Hók J., Králiková S., Plašienka D., Klučiar T., Hudáčková N. & Oszczypko-Clowes M. 2017: Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global and Planetary Change* 155, 133–154. https://doi.org/10.1016/j.gloplacha.2017.07.004
Kováč M., Rybár S., Halásová E., Hudáčková N., Šarinová K., Šujan M., Baranyi V., Kováčová M., Ruman A., Klučiar T. & Zlinská A. 2018: Changes in Cenozoic depositional environment and sediment provenance in the Danube Basin. *Basin Research* 30, 97–131. https://doi.org/10.1111/bre.12244
Krenmayr H.-G. 2003: Bericht 2000 über geologische Aufnahmen im Tertiär und Quartär auf Blatt 55 Obergrafendorf. *Jahrbuch der Geologischen Bundesanstalt* 143, 351–353.
Krhovský J., Rögl F. & Hamršmíd B. 2001: Stratigraphic correlation of the late Eocene to early Miocene of the Waschberg Unit (Lower Austria) with the Ždánice and Pouzdřany Units (South Moravia). In: Piller W. & Rasser M.W. (Eds.): Paleogene of the Eastern Alps. *Österreichische Akademie der Wissenschaften,* Wien, *Schriftenreihe der Erdwissenschaftlichen Kommission* 14, 225–254.
Kuhlemann J., Frisch W. & Dunkl I. 2001: The Oligocene geologic and paleotopographic evolution of the Eastern Alps. In: Piller W. & Rasser M.W. (Eds.): Paleogene of the Eastern Alps. *Österreichische Akademie der Wissenschaften,* Wien, *Schriftenreihe der Erdwissenschaftlichen Kommission* 14, 129–152.
Lucente C.C. & Pini G.A. 2003: Anatomy and emplacement mechanisms of a large submarine slide within a Miocene foredeep in the northern Apennines, Italy: a field perspective. *American Journal of Science* 303, 565–602. https://doi.org/10.2475/ajs.303.7.565
Luciani V., Guisberti L., Agnini C., Fornaciari E., Rio D., Spofforth D.J.A. & Pälike H. 2010: Ecological and evolutionary response of Tethyan planktonic foraminifera to the middle Eocene climatic optimum (MECO) from the Alano section. *Palaeogeography, Palaeoclimatology, Palaeoecology* 292, 82–95. https://doi.org/10.1016/j.palaeo.2010.03.029
Marchetti M.P. 1956: The occurrence of slide and flowage materials (olistostromes) in the Tertiary series of Sicily. In: *Proceedings of the 20th International Geological Congress, Mexico*. Session 20, Sec. 5, I, 204–225.
Martini E. 1971: Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A. (Ed.): *Proceedings II Planktonic Conference* 2,739–785.
Murray J.W. 1991: Ecology and palaeoecology of benthic foraminifera. *Longman Scientific & Technical*, Harlow, 1–397.
Nichols G. 2009: Sedimentology and stratigraphy. *Wiley-Blackwell*, Chichester, 1–419.
Okay A. & Altiner D. 2017: Crustal scale Upper Cretaceous mass flows northwest of Ankara related to the destruction of the forearc. In: 10th International Symposium of the Cretaceous, Vienna. *Berichte der Geologischen Bundesanstalt* 120, 204.
Oppenheimer J. 1916: *Parahoplites Bigoureti* Seunes und *Lytoceras suptile* Oppel aus den Blockanhäufungen von Strazowitz bei Gaya. *Verhandlungen der geologischen Reichsanstalt* 1916, 259–262.
Oszczypko N., Krzywiec P., Popadyuk I. & Peryt T. 2006: Carpathian Foredeep Basin (Polanand and Ukraine): its sedimentary, structural, and geodynamic evolution. In: Golonka J. & Picha F.J. (Eds.): The Carpathians and their foreland: geology and hydrocarbon resources. *AAPG Memoir* 84, 293–350.
Paul C.M. & Bittner A. 1894: Erläuterungen zur geologischen Specialkarte der Umgebung von Wien (Colonne XIV, XV, XVI, Zone 12, 13 der Specialkarte der österr.-ungar. Monarchie im Massstabe von 1:75.000.) aufgenommen 1889/90 von Dionys Stur. *K.K. geologische Reichsanstalt*, Wien, 1–59.
Picha F.J., Stráník Z. & Krejčí O. 2006: Geology and hydrocarbon recources of the Outer Western Carpathians and their foreland, Czech Republic. In: Golonka J. & Picha F.J. (Eds.): The Carpathians and their foreland: geology and hydrocarbon resources. *AAPG Memoir* 84, 49–175.
Plöchinger B., Prey S. & Schnabel W. 1974: Der Wienerwald. *Sammlung Geologischer Führer* 59, 1–141.
Pokorný V. 1947: Contribution a l'étude de la géologie des environs de Hustopeče [Ke geologii okolí Hustopečí]. *Sborník Státniho geologického ústavu Československé Republiky* 14, 325–360.
Posch-Trözmüller G., Peresson M., Atzenhofer B., Bryda G., Ćorić S., Gebhardt H., Hobiger G., Linner M., Rabeder J., Roetzel R. Rupp C., Schuster R. & Zorn I. 2013: Geologische Bearbeitung kurzfristiger Aufschlüsse in Niederösterreich mit Schwerpunkt auf infrastrukturelle Bauten in schlecht aufgeschlossenen Regionen und auf rohstoffwissenschaftliche, umweltrelevante und grundlagenorientierte Auswertungen. Neue Bauaufschlüsse – neues Geowissen: Niederösterreich. Projekt NC 83, Final Report 2012. *Geologische Bundesanstalt*, Wien, 1–507.

Prinzinger H. 1852: Uebersicht der geologischen Verhältnisse des Viertels unter dem Manhardsberge in Österreich unter der Enns. *Jahrbuch der Geologischen Reichsanstalt* 3, 17–24.

Reineck H-E. & Singh I B. 1980: Depositional sedimentary environments. *Springer Verlag*, Berlin, 1–549.

Richter D. 1976: Olisthostrom, Olistholith, Olistothrymma und Olisthoplaka als Merkmale von Gleitungs- und Resedimentationsvorgängen infolge synsedimentärer tektogenetischer Bewegungen in Geosynklinalbereichen. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* 143, 304–344.

Roetzel R., Cícha I., Stojaspal F., Decker K., Wimmer-Frey I., Ottner F. & Papp H. 1999: C5 Göllersdorf – Ziegelei und Tonbergbau Wienerberger. In: Roetzel R. (Ed.): Arbeitstagung Geologische Bundesanstalt, Geologische Karten ÖK 9 Retz und ÖK 22 Hollabrunn, Geogenes Naturraumpotential der Bezirke Horn und Hollabrunn. *Geologische Bundesanstalt*, Wien, 335–341.

Roetzel R., Cícha I., Ćorić S., Gebhardt H., Havlíček P., Holácek O., Novák Z., Rudolský J. & Vachek M. 2015: Geologische Karte der Republik Österreich 1: 50 000, Blatt 39 Tulln. *Geologische Bundesanstalt*, Wien.

Rzehak A. 1888: Die Foraminiferen der Nummulitenschichten des Waschberges und Michelberges bei Stockerau in Niederösterreich. *Verhandlungen der Geologischen Reichsanstalt* 1888, 226–230.

Scherba I.G. 1987: Stages and phases of formations of Cenozoic olistostromes in the Alpine Fold Belt. In: Leonov Y.G. & Khain V.E. (Eds.): Global correlation of tectonic movements. *John Wiley and Sons*, New York, 49–82.

Schnabel W., Krenmayr H.-G., Mandl G.W., Nowotny A., Roetzel R. & Scharbert S. 2002: Geologische Karte von Niederösterreich 1:200.000. Legende und kurze Erläuterung. *Land Niederösterreich und Geologische Bundesanstalt*, Wien, 1–47.

Seifert P. 1980: Das Eozän der Waschbergzone (N.Ö.) und die angrenzenden Teile des Oberpaläozän und Unteroligozän: Stratigraphie, Mikrofazies, Paläogeographie und Tektonik. *Dissertation, Universität Wien*, 1–419.

Seifert P. 1982: Sedimentologie und Paläogeographie des Eozäns der Waschbergzone (Niederösterreich). *Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Österreich* 28, 133–176.

Serra-Kiel J., Hottinger L., Caus E., Drobne K., Ferràndez C., Jahuri A.K., Less G., Pavlovec R., Pignatti J., Samsó J.M., Schaub H., Sirel E., Strougo A., Tambareau Y., Tosquella J. & Zakrevskaya E. 1998: Larger foraminiferal biostratigraphy of the Tethyan Paleocene and Eocene. *Bulletin de la Societé géologique de France* 169, 281–299.

Ślączka A. & Oszczypko N. 1987: Olistostromes and overthrusting in the Polish Carpathians. *Annales Instituti Geologici Hungarici* 70, 287–292.

Ślączka A., Kruglov S., Golonka J., Oszczypko N. & Popadyuk I. 2006: Geology and hydrocarbon recources of the Outer Carpathians, Poland, Slovakia, aund Ukraine: general geology. In: Golonka J. & Picha F.J. (Eds.): The Carpathians and their foreland: geology and hydrocarbon recources. *AAPG Memoir* 84, 221–258.

Ślączka A., Renda P., Cieszkowski M., Golonka J. & Nigro F. 2012: Sedimentary basin evolution and olistolith formation: the case of Carpathian and Sicilian regions. *Tectonophysics* 568–569, 306–319. https://doi.org/10.1016/j.tecto.2012.03.018

Soták J. 1986: Stratigraphy and typology of the Upper Triassic in the outer units of the Western Carpathians (reconstruction from redeposites located in the area of the Silesian Cordillera). *Zemný Plyn, Nafta* 31, 1–53 (in Slovak).

Stow D.A.V., Faugères J.-C., Viana A. & Gonthier E. 1998: Fossil contourites: a critical review. *Sedimentary Geology* 115, 3–31. https://doi.org/10.1016/S0037-0738(97)00085-7

Talling P.J., Masson D.C., Sumner E.J. & Malgesini G. 2012. Subaqueous sediment density flows: Depositional processes and deposit types. *Sedimentology* 59, 1937–2003. https://doi.org/10.1111/j.1365-3091.2012.01353.x

Torres-Silva A.I. & Gebhardt H. 2015: Eocene larger benthic foraminifera (Nummulitids, Orthophragminids) from the Waschberg-Ždánice Unit, Lower Austria. *Jahrbuch der Geologischen Bundesanstalt* 155, 109–120.

Tucker M.E. & Wright V.P. 1990: Carbonate Sedimentology. *Blackwell Scientific Publications*, Oxford, 1–482.

Van der Zwaan D.J., Jorissen F.J. & de Stigter H C. 1990: The depth dependency of planktonic/benthic foraminiferal ratios: Constraints and applications. *Marine Geology* 95, 1–16.

Viana A.R., Faugères J.-C. & Stow D.A.V. 1998: Bottom-current-controlled sand deposits – a review of modern shallow- to deep-water environments. *Sedimentary Geology* 115, 53–80. https://doi.org/10.1016/S0037-0738(97)00087-0

Wegner W., Linner M., Schuster R. & Hobiger G. 2013: Composition of the Bohemian spur in the subsurface of the Eastern Alps: indications from exotic blocks. In: Gebhardt H. (Ed.): Arbeitstagung 2013, Geologie der Kartenblätter 55 Ober-Grafendorf und 56 St.Pölten. 23.-27.09.2013, Melk. *Geologische Bundesanstalt*, Wien, 136–137.

Wessely G., Gangl G., Gottschling P., Heinrich M., Hofmann T., Lenhardt W., Matura A., Pavuza R., Peresson H. & Sauer R. 2006: Niederösterreich. *Geologische Bundesanstalt*, Wien, 1–416.

Wright V.P. 1992: A revised classification of limestones. *Sedimentary Geology* 76, 177–185.