# Ichnology of shallow sublittoral siliciclastics of the Burgschleinitz Formation (Lower Miocene, Eggenburgian) in the Alpine-Carpathian Foredeep (NE Austria)

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## Abstract

The marine shallow water sediments of the upper Eggenburgian (Lower Miocene, Lower Burdigalian) in northeastern Austria illustrate a unique, complex palaeogeographic situation. The transgressing Paratethys Sea in the Alpine-Carpathian Foredeep encroached on a morphologically highly structured crystalline area of the Bohemian Massif, forming several small islands and bays. These morphological depressions were filled with mostly immature sediments derived from the first cycle of weathering.

The Burgschleinitz Formation is characterized by an alternation of moderately to poorly sorted, coarse to fine sands with gravelly intercalations. Sedimentological and ichnological analyses allow the reconstruction of a wave- and storm-dominated littoral to shallow sublittoral environment in shallow bays sheltered by crystalline barrier islands. The marine sands of the outcrop “Burgschleinitz Kirchenbruch”, which is the type locality of the Burgschleinitz Formation, were deposited in a small bay open to the west and close to the nearby crystalline elevations.

In the Kirchenbruch quarry, at least 11 ichnotaxa were recognized, which is the highest diversity of trace fossils in the nearshore sediments of the Eggenburg Bay. In the middle part of the section the vertical trace fossil assemblage with *Ophiomorpha*, *Skolithos*, and *Arenicolites* suggests a colonization window; here, after a short regressive phase or stillstand, a stabilization of the sea floor related to new flooding can be assumed. This assemblage is indicative of the *Skolithos* ichnofacies, located in the upper shoreface. Upsection, the transition to the proximal *Cruziana* ichnofacies, which is typically positioned in the middle-lower shoreface, is indicated by *Thalassinoides*. In the muddy sands of the topmost Gauderndorf Formation, the lack of vertical trace fossils indicates the deepening during the proceeding Early Miocene (Eggenburgian) transgression.

Die marinen Flachwassersedimente des oberen Eggenburgium (Unteres Miozän, Unteres Burdigalium) im Nordosten von Österreich lassen eine einzigartige, komplexe paläogeographische Situation erkennen. Die Paratethys der Alpin-Karpatischen Vortiefe drang in ein morphologisch stark strukturiertes kristallines Gebiet der Böhmischen Masse ein, wobei zahlreiche kleine Inseln und Buchten entstanden. Die meist unreifen Sedimente wurden von den angrenzenden, tiefgründig verwitterten Kristallinrücken abgetragen.

Die Burgschleinitz-Formation ist durch den Wechsel von mäßig bis schlecht sortierten, grob- bis feinkörnigen Sanden mit kiesigen Einschaltungen gekennzeichnet. Sedimentologische und ichnologische Analysen ermöglichen die Rekonstruktion einer wellen- und sturmdominierten Küste. Litorale bis flach sublitorale Lebensräume in Buchten waren durch vorgelagerte kristalline Inseln geschützt. Die marinen Sande des Aufschlusses "Burgschleinitz Kirchenbruch", der Typlokalität der Burgschleinitz-Formation, wurden in einer kleinen, nach Westen offenen Bucht abgelagert, die von nahe gelegenen kristallinen Erhebungen umgeben war.

Im Kirchenbruch von Burgschleinitz konnte mit mindestens 11 Ichnotaxa die höchste Diversität an Spurenfossilien in den küstennahen Sedimenten der Eggenburger Bucht festgestellt werden. Im mittleren Teil des Aufschlusses weist eine vertikale Spurenfossil-Gemeinschaft mit *Ophiomorpha*, *Skolithos* und *Arenicolites* auf ein Besiedlungsfenster hin. Nach einer kurzen Regressions- oder Stillstandsphase kann eine Stabilisierung des Meeresbodens im Zusammenhang mit einer neuen Überflutung angenommen werden. Diese Situation ist für die *Skolithos*-Ichnofacies im oberen Sublitoral charakteristisch. Im Verlauf des Profils kann mit dem Auftreten von *Thalassinoides* der Übergang zur proximalen *Cruziana*-Ichnofacies, die typischerweise im mittleren bis unteren Sublitoral auftritt, festgestellt werden. Das Fehlen von vertikalen Spurenfossilien in den siltigen Sanden der zuoberst liegenden Gauderndorf-Formation weist auf einen steigenden Meeresspiegel im Zuge der frühmiozänen Transgression im Eggenburgium hin.

## 1. Introduction

Most ichnological analyses in Neogene shallow-marine siliciclastics refer to open shelf settings, where facies alternations show relatively clear trends (e.g., Pervesler et al., 2008b; Aguirre et al., 2010). Fewer studies have dealt with more complex settings, which are limited mostly to estuarine valley fills (e.g., Gibert and Martinell, 1998).

The Lower Miocene (Eggenburgian – Ottnangian, Lower Burdigalian) sediments in the surroundings of Eggenburg in northeastern Austria offer a unique, complex palaeogeographic situation. The transgressing Paratethys Sea encroached on a morphologically highly structured crystalline area of the Bohemian Massif, forming several small islands and bays. These morphological depressions were filled with mostly immature sediments produced by the first cycle of weathering.

This paper provides an ichnological characterization of Lower Miocene (upper Eggenburgian, Lower Burdigalian) sediments in the type section of the Burgschleinitz Formation, in Burgschleinitz Kirchenbruch, and in the type area of the widely known trace fossil *Thalassinoides*. The latter was described by Ehrenberg (1944; see also Ehrenberg, 1938) in the nearby, recently poorly exposed and abandoned sandpit Sieber (later called sandpit Hammerschmid). Some preliminary results have already been presented in a conference abstract (Pervesler et al., 2008a).

## 2. Geological setting

Upper Oligocene to Lower Miocene sediments are widespread along the southeastern border of the Bohemian Massif in Lower Austria. These terrestrial to marine sediments are erosional residuals of a former sedimentary cover on the pre-Oligocene

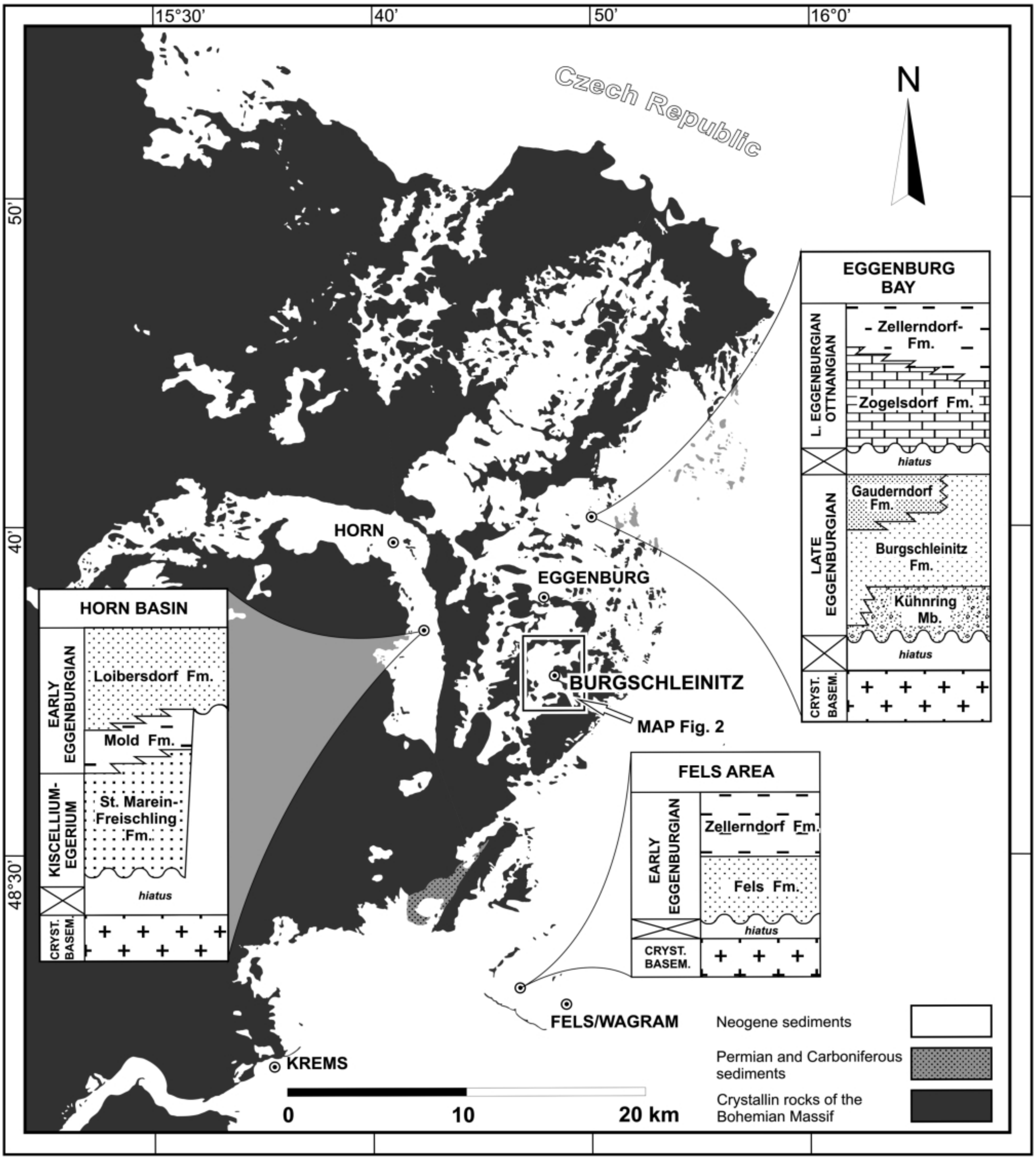



Figure 1: Neogene sediments at the southeastern margin of the Bohemian Massif in Austria and lithostratigraphic development in the Late Oligocene to Early Miocene in the Fels area, Horn Basin, and Eggenburg Bay (from Roetzel et al., 1999, modified).

basement relief. Neogene tectonics, which are active to the present, reactivated old fault systems within the crystalline basement, creating small basins and embayments such as the Horn Basin or the Eggenburg Bay (Fig. 1; e.g. Roštínský and Roetzel, 2005).

In the Eggenburg area these sediments can be differentiated into several lithostratigraphic units (Fig. 1; cf. Steininger and Roetzel, 1991; Roetzel et al., 1999; Piller et. al., 2007). From the Oligocene to the earliest Miocene (Egerian), the area was drained from west to east by the fluvial system of the St. Marein-Freischling Formation. These sediments, known from the Horn Basin and adjacent areas in the west, are poorly sorted gravel and sands, rich in feldspar and with silty intercalations (cf. Nehyba and Roetzel, 2010).

The southern margin of the Bohemian Massif was flooded during the Early Miocene marine transgression. Due to a complex palaeotopography, this transgressive development caused a heterochronous onset of the Eggenburgian sediments (Steininger, 1971; Roetzel et al., 1999; Piller et. al., 2007).

Marine flooding started in the Early Eggenburgian at the southern crystalline margin with nearshore sands of the Fels Formation, which further on were transgressively overlain by offshore pelites of the Zellerndorf Formation (Fig. 1). In the Horn Basin, the fluvial St. Marein-Freischling Formation was replaced by the estuarine Mold Formation. Subsequently, the advancing sea created a fully marine environment in the Horn Basin, where nearshore sands of the Loibersdorf Formation were deposited (cf. Fig. 1).

In the final step in the Late Eggenburgian, the sea level reached the eastern margin and the Eggenburg Bay. First, littoral sands and gravel of the Burgschleinitz Formation were deposited on the morphologically highly structured basement in that area. In estuaries close to small river mouths, the Kühnring Member was deposited. It is composed of poorly sorted silty sands and clays with oyster beds. In slightly deeper and calmer, fully marine areas, fine sands and silts with endobenthic molluscs of the Gauderndorf Formation were deposited, laterally interfingering with the Burgschleinitz Formation. Finally, during the proceeding transgression in the Eggenburg Bay, the coarse-grained facies of the Burgschleinitz Formation was topped by the Gauderndorf Formation (Fig. 1; Roetzel et al., 1999; Mandic and Steininger, 2003).

Interrupted by a distinct regression and erosion phase, a new transgression flooded the area in the Early Ottnangian. In the Eggenburg Bay, sandy shallow marine bioclastic limestones of the Zogelsdorf Formation were deposited above an erosional relief in upper Eggenburgian sediments (Harzhauser and Piller, 2007). Basinward, in deep-water areas in the east, pelitic sediments of the Zellerndorf Formation were deposited, interfingering with the carbonatic and siliciclastic-carbonatic lithofacies in the west. During the Ottnangian the sea prograded towards west and flooded former river valleys and depressions of the Bohemian Massif. In the Eggenburg Bay in this time the Zogelsdorf Formation was topped by the silty clays of the Zellerndorf Formation.

## 3. Characterization of the Burgschleinitz Formation

The Burgschleinitz Formation described in this paper is widespread in the Eggenburg Bay, where it typically transgresses directly on the crystalline basement of the Bohemian Massif. Locally at the base, poorly sorted silts, sands and gravel of the Kühnring Member (see above) are developed; they also laterally interfinger with the above formation.

The Burgschleinitz Formation is characterized by an alternation of immature, moderately to poorly sorted, coarse to fine sands with gravelly intercalations. In most cases the sands are several meters thick, but do not exceed 10 m.

The sediments are mainly deposited in a wave- and storm-dominated littoral to shallow sublittoral environment in shallow bays sheltered by crystalline barrier islands (Roetzel, 1990). In open marine sites, basal conglomerates with granitic boulders and cobbles are frequent. Generally, the lithofacies and biofacies of the Burgschleinitz Formation are very variable and heterogeneous, depending on multiple local factors including palaeorelief, water depth, and palaeocurrents. The deposition in littoral to shallow sublittoral areas is indicated by sedimentary structures such as even lamination, low to high angle cross-bedding, current ripple-bedding as well as palaeoenvironmentally indicative bivalves, gastropods, and trace fossils. Frequent shell layers or coarse grained, graded horizons, in some cases with remains of vertebrates, such as sea cows, are interpreted as tempestites (e.g. Pervesler et al., 1995).

The fully marine, thick-shelled and large-sized mollusc-fauna is dominated by littoral to shallow sublittoral forms including *Glycymeris fichteli*, *Isognomon rollei*, *Gigantopecten holgeri*, *Pecten pseudobeudanti*, *Ostrea lamellosa*, *Cordiopsis incrassata*, *Cordiopsis schafferi*, *Paphia benoisti*, *Lutraria sanna*, and *Protoma cathedralis* (see also Schaffer, 1910, 1912; Steininger, 1971; Mandic and Steininger, 2003). Additionally, remnants of vertebrates occur: fish teeth (sharks, rays, breams) and bones of dolphins (*Schizodelphis sulcatus*), whales, crocodiles (*Gavialosuchus eggenburgensis*), turtles, sea cows (*Metaxytherium krahuletzi*), and the anthracothere *Brachyodus onoideus* (Toula and Kail, 1885; Neumayr, 1888; Depéret, 1895; Abel, 1904; Schaffer, 1925; Brzobohatý and Schultz, 1971; Daxner-Höck, 1971; Steininger, 1971: p.134 ff., 146 ff., 154 ff.; Pervesler et al., 1995; Domning and Pervesler, 2001). Furthermore, ichnofossils are very frequent (see also Ehrenberg, 1938, 1944; Hohenegger and Pervesler, 1985).

The sediments of the Burgschleinitz Formation and the Kühnring Member are dated by their mammal fauna to the European land mammal Zone MN3 (basal Orleanian), which allows a direct correlation with the basal Burdigalian (Mein, 1989; Steininger et al., 1996; Steininger, 1999). Moreover, the Burgschleinitz Formation can be placed into the Late Eggenburgian and separated from the Early Eggenburgian Loibersdorf Formation by the presence of Burdigalian, Mediterranean-type pectinid species such as *Gigantopecten holgeri* and *Flexopecten palmatus*, combined with the absence of Paratethys endemic species and of the Early Eggenburgian index fossil

*Oopecten gigas* (Mandic and Steininger, 2003).

In the central Eggenburg Bay, the Burgschleinitz Formation is usually concordantly overlain by the fine-grained Gauderndorf Formation. The originally even to slightly undulating stratification of this fine silty sands is, in most cases, completely obliterated by the burrowing action of molluscs. The diverse, mostly thin-shelled, endobenthic molluscs are typical inhabitants of sandy mud-bottoms in slightly deeper, calmer, and sheltered sublittoral areas of the Eggenburg Bay. In parts of the bay where the Gauderndorf Formation is not developed, the Zogelsdorf Formation (Nebelsick, 1989a, b) mostly follows discordantly above.

In first descriptions, these sediments were combined with the “Schichten von Loibersdorf" in the Horn Basin (Suess, 1866; Abel, 1897, 1898). Fuchs (1900) then separately considered and designated the sands in the Eggenburg Bay as

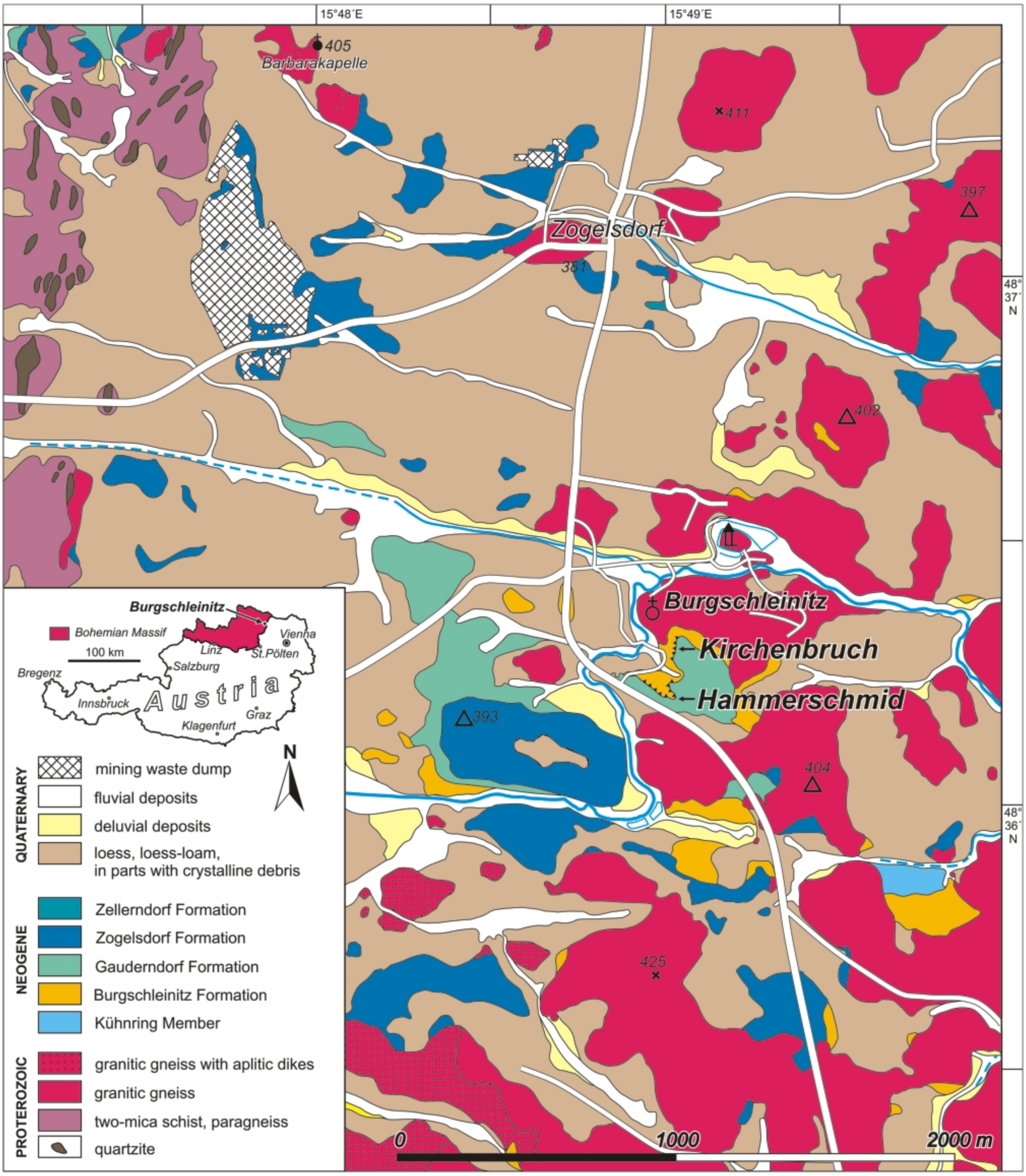



**Figure 2:** Geological map of the study area (R. Roetzel, 2003-2010, unpublished); distribution of the Burgschleinitz Formation; location of the Kirchenbruch quarry and the sandpit Hammerschmid (formerly Sieber).

"Liegend-Sande". Later, the "Liegendsande" together with the "Liegendtegel" were summarized as "Liegendschichten" (see also Schaffer, 1914). Steininger (1971) characterized the coarse sands from Burgschleinitz as "Grobsandentwicklung von Burgschleinitz" or generally as "Basale Grobsande" (Steininger, 1983). Finally, these sediments were designated as "Burgschleinitz-Formation" by Steininger and Roetzel (1991) and specified in Roetzel et al. (1999).

Informally, the abandoned sandpit "Kirchenbruch" 150 m SSE from the church of Burgschleinitz (N48°36'17''; E15°48'58'', Fig. 2) can be regarded as the type section for the Burgschleinitz Formation. In this outcrop the upper and lower boundaries are exposed.

## 4. The section Burgschleinitz Kirchenbruch

The outcrop Burgschleinitz-Kirchenbruch is situated close to a granite rise topped by the Romanesque church of Burgschleinitz. It was first mentioned by Cžjžek (1853, p. 31) and afterwards described by Schaffer (1914, p. 90 ff.), who distinguished five lithological units (a-e, Fig. 4a). Steininger (1971, p. 146 ff.) defined the outcrop Burgschleinitz Kirchenbruch as a faciostratotype locality of the Eggenburgian. Another more detailed characterization was given later by Roetzel et al. (1991a, b).

In the Kirchenbruch, the onlap of the upper Eggenburgian littoral sediments on the granitic basement is visible. The sands lie in a bay-like depression, surrounded by crystalline highs in the north, east and south, and opened towards the west (cf. Fig. 1, 2).

This paper distinguishes four lithological units (unit 1-4) in the Burgschleinitz Formation of the Kirchenbruch outcrop (see also Roetzel et al., 1991a, b), followed by the Gauderndorf Formation (unit 5) (Fig. 3a).

The transgressive sequence starts with well-rounded granite boulders, overgrown by barnacles, which cover the northward rising basement and are visible in the northern cellars (Fig. 3a, Fig. 4b).

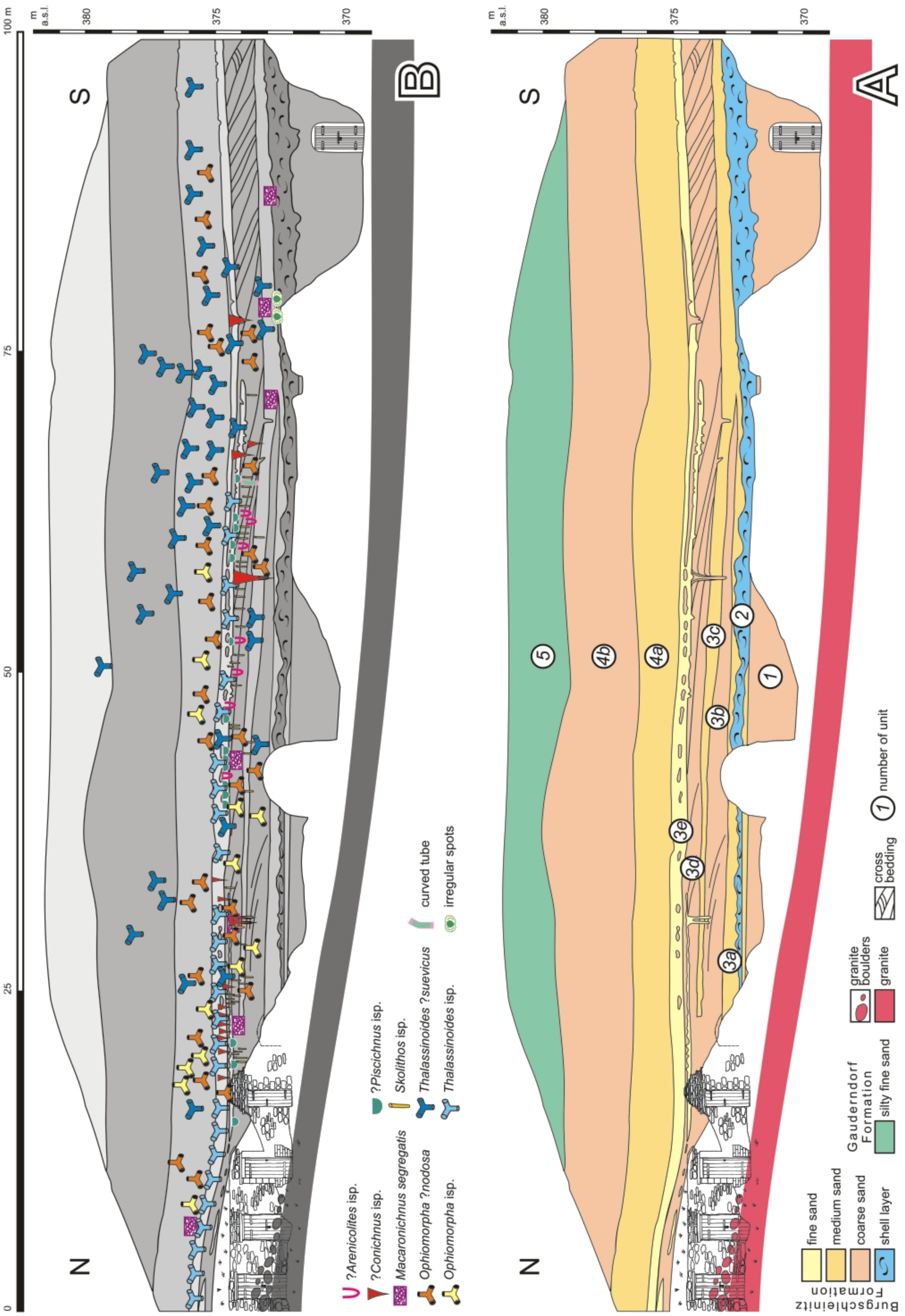
Unit 1. Above the south- to southwest dipping basement, a 3 m (formerly up to 5 m, see also Schaffer, 1914) thick horizon (Fig. 4f) of poorly sorted coarse to medium sands follows (unit 1 in Fig. 3a; see also Schaffer, 1914: unit e (Fig. 4a); Steininger, 1971: "Basaler Grobsand-Horizont"). The angular to subrounded sands are massive and show no sedimentary structures. They include pelitic clasts and fine gravel, which are increasing in concentration towards the crystalline high in the north. In the north, in the upper 20 cm, a transition from coarse sands to silty medium sands is visible. The immature sands are mainly composed of quartz (ca. 50%) and feldspar (ca. 20%); however, they also contain a relatively high amount of lithic components (ca.15%) such as granitic debris and polycrystalline quartz, along with mica (ca. 15%). The sediments occasionally contain single valves of *Venerupis haidingeri*, *Isognomon rollei*, *Lucina* sp., *Chama* sp., and thick-shelled, small ostreids, in some parts concentrated in layers. Schaffer (1914) and Steininger (1971) described ribs of the sea cow *Metaxytherium* in this unit.

Unit 2. This unit is an up to 1-m-thick shell layer that thins and fades out towards the granite rise (unit 2 in Fig. 3a; see also Schaffer, 1914: unit d (Fig. 4a); Steininger, 1971: "Molluskenschill-Horizont"). The coarse sandy to gravelly shell layer shows, at the base, a distinct erosive surface with up to 40-cm-deep scours and a wavy surface at the top (Figs. 4e-g). Towards the crystalline rise, the proportion of valves decrease and that of fine gravel of angular granitic fragments increases. In this layer, mainly isolated valves of calcitic and aragonitic, thick-shelled molluscs occur: *Glycymeris fichteli*, *G. menardi*, *Perna aquitanica*, *Atrina pectinata*, *Isognomon rollei*, *Venerupis basteroti*, *Pecten pseudobeudanti*, *Gigantopecten holgeri*, *Talochlamys multistriata*, *Plastomiltha multilamellata*, several big cardiids (*Bucardium* sp.), *Venus burdigalensis*, *Panopea* sp., *Thracia* sp., *Astrea* sp., cf. *Lucinoma* sp., several anomiids and several ostreids. These are accompanied by corals such as *Tabellastrea eggenburgensis* and *T. reussiana* along with barnacles. In the northern part the aragonite shells are completely dissolved.

Unit 3. This unit comprises a 2- to 2.5-m-thick succession of two coarse-grained, cross-stratified, elongated, and wedge-shaped sand bodies, alternating with fine-grained layers (subunits 3a-e in Fig. 3a; see also Schaffer, 1914: unit c (Fig. 4a); Steininger 1971: "Fossilarmer Quarzsand-Horizont"). Both coarse, maximum 1-m-thick cross-bedded sets (subunits 3b, 3d) consist of alternating angular, gravelly coarse and medium sand layers, evident especially in the north. The cross-beddings dip off the crystalline rise with low to high angle between 5 to 25° towards south to southwest. Below both cross-bedded sets, 30- to 60-cm-thick layers of medium- to fine-grained sands occur, which laterally combine in the south (subunits 3a, 3c). They show an increasing portion of coarse sand and gravel towards the north and are in places slightly cross-bedded in the south. On top of the upper cross-bedded set (subunit 3d), moderately sorted fine sands appear, which occasionally interfinger with the coarse sands below (subunit 3e). Some relics of these fine sands laterally interfingering with the upper cross-bedded set seem to be fine-grained topsets. Lens-shaped relics of coarse to medium sands with debris of barnacles in the fine-grained subunit 3e might represent isolated troughs of a ripple bedded layer.

Again, the immature sands are mainly composed of quartz (40-50%) and feldspar (plagioclase 10-30%, K-feldspar 5-15%), although they also contain lithic components (15-25%) and mica (up to 5%).

Intense bioturbation mostly starts from these fine-grained layers. Funnel-shaped trace fossils (*Conichnus* isp.) are accompanied by thin vertical burrows (*Skolithos* isp.), which penetrate deep into the underlying horizons (Fig. 5j). Horizontal, branched tunnels (*Thalassinoides* isp.) are restricted to the topmost fine sands (subunit 3e; Fig. 5a, b) and show increasing density towards the granite rise in the north, whereas they disappear towards the south. Additionally, Steininger (1971) de-



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3d
3e
4a
4b
5
Burgschleinitz Formation
fine sand
medium sand
coarse sand
shell layer
Gauderndorf Formation
silty fine sand
granite boulders
granite
cross bedding
number of unit
?Arenicolites isp.
?Conichnus isp.
Macaronichnus segregatis
Ophiomorpha ?nodosa
Ophiomorpha isp.
?Piscichnus isp.
Skolithos isp.
Thalassinoides ?suevicus
Thalassinoides isp.
curved tube
irregular spots

scribed remains of *Metaxytherium* and *Brachyodus* from unit 3.

Unit 4. The top of the Burgschleinitz Formation in this outcrop (Fig. 4c, e) is built up by a 4- to 4.5-m-thick, poorly sorted, coarse-grained, and fossiliferous horizon (subunits 4a-b in Fig. 3a; see also Schaffer, 1914: unit a-b (Fig. 4a); Steininger 1971: "Balaniden-Schill-Horizont" and "Horizont mit Kalksandsteinbänken"; in Steininger (1971, p.149) the layer with calcareous sandstones (subunit 4b) is falsely defined as an equivalent of the Zogelsdorf Formation).

The lower, 1.5- to 2-m-thick part (subunit 4a) consists of angular, medium to coarse sands with an upward as well as northward increasing portion of fine gravel. In the middle part of subunit 4a, the sands are concretionarily solidified to sandstone. The 2.5- to 3-m-thick upper part (subunit 4b) shows poorly sorted, silty and gravelly, coarse to medium sands with many nodular sandstone-concretions. The again immature sediments have a slightly lower portion of quartz (30-40%) and lithic components (12-20%) and a higher content of feldspar (35-50%) than the sands below.

In the lower subunit 4a, mainly barnacle debris (plates as well as scuta and terga) occurs; the amount of this material increases towards the crystalline rise. It is accompanied by valves of brachiopods (*Terebratula hoernesi*) and molluscs (*Ostrea edulis*, *Gigantopecten holgeri*, *Talochlamys multistriata*, *Glycymeris fichteli*, *Atrina* sp., *Thracia* sp., *Diplodonta* sp., mytilids, lucinids, and venerids). The higher part of this layer (subunit 4b), above an oyster horizon, additionally contains fragments of *Cordiopsis gigas*, *Isognomon rollei*, *Perna aquitanica*, *Turritella terebralis*, *Turritella* sp., *Panopea menardi*, *Pholadomya* sp., *Anomia epihippium*, *Hinites* sp., *Lutraria* sp., and *Diloma* sp. Again, barnacle fragments are very common.

Unit 4 is intensely bioturbated. *Ophiomorpha nodosa* (Fig. 5d, e) and *Thalassinoides* ?*suevicus* (Fig. 5f) are common trace fossils in this higher part of the Burschleinitz Formation. They are in some cases strongly weathered and show smooth burrow margins or an *Ophiomorpha* aspect imprinted into the substrate around, caused by the knobby outline of the burrow walls.

Unit 5. The top of the outcrop (Fig. 3a) contains fine-grained sediments of the Gauderndorf Formation (mentioned neither in Schaffer, 1914 nor in Steininger, 1971). The silty to clayey fine sands have lenses of granitic fine gravel and nodular concretions, typical for the Gauderndorf Formation. The sediments show an indistinct transition from the underlying coarse-grained Burgschleinitz Formation.

In the heavy mineral assemblages from the sediments of the section Kirchenbruch, besides opaque minerals, mostly tourmaline and zircon dominate. Especially in the basal unit 1 and the sediments of subunits 3a-d, only a few percent of metamorphic minerals, like garnet, staurolite, kyanite, and sillimanite, are present. Beginning with the fine sandy subunit 3e, an increasing portion of these metamorphic minerals, particularly garnet and staurolite, is visible. In unit 4 this trend continues, and in the Gauderndorf Formation (unit 5) garnet and staurolite are present in nearly the same amount as tourmaline and zircon.

About 150 m SSW of the Kirchenbruch is the abandoned sandpit Hammerschmid (former sandpit Sieber) (Fig. 2). This is the site from which Ehrenberg (1944; see also Ehrenberg, 1938) described the type specimen of the trace fossil *Thalassinoides*. In this now poorly exposed outcrop, a profile quite similar to the Kirchenbruch is visible. Nonetheless, variations in the grain size distribution are noticeable, reflecting the more distal position in the bay. *Thalassinoides*, described by Ehrenberg (1938, 1944), mainly derive from concretionary sandstones from the horizon equivalent to subunit 4a in the Kirchenbruch.

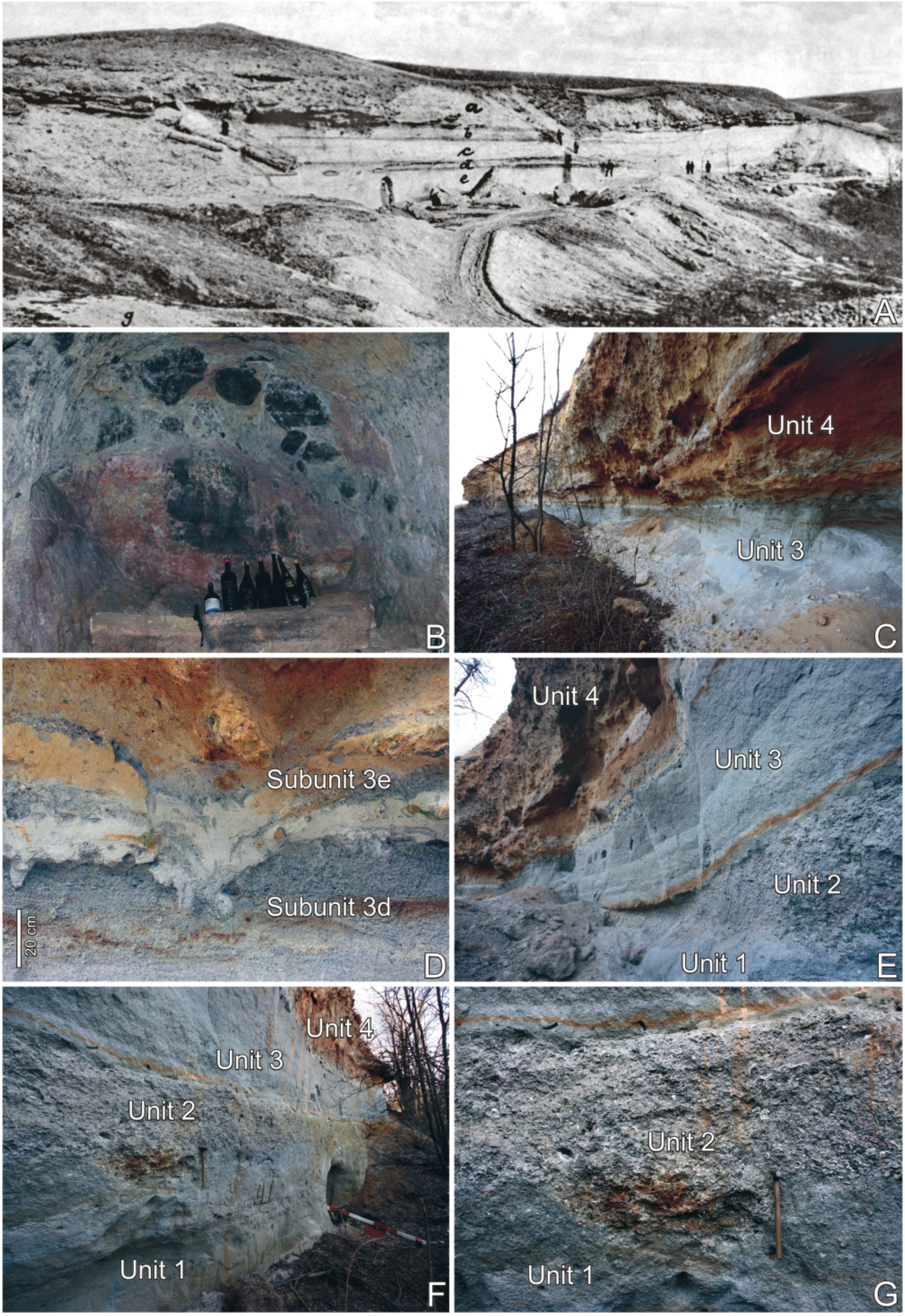
**Figure 3:** Cross section of the Kirchenbruch quarry. A: lithology of the section, B: distribution of trace fossils.

## 5. Synopsis of trace fossils

?*Arenicolites* isp. (Fig. 5j) is visible in the vertical section of sand beds as a simple unlined or thinly lined tube that is vertical in the upper-middle part and curved in the lower part. The tube – 2-7 mm in diameter and up to 210 mm deep – is filled with light-colored silty sand. Some tubes display a funnel-like widening at the top. One tube displays a basal, wide oblique part, pointing to a wide, asymmetric U-shaped burrow. This trace fossil is interpreted as a partly preserved *Arenicolites*, which is diagnosed as simple U-shaped cylindrical structures without spreite. *Arenicolites* is interpreted as a dwelling and feeding burrow of suspension-feeding annelids (e.g. Hakes, 1976) or small crustaceans (Goldring, 1962). It occurs in different environments, but is typical of shallow-marine settings (Crimes, 1977). For discussion of this ichnogenus see Fillion and Pickerill (1990) and Ekdale and Lewis (1991).

?*Conichnus* isp. (Figs. 5a, b) is a conical structure visible in cross sections. It tapers gradually from the top to the base and is filled with layered, fine- to medium-grained sand. The layers of filling are randomly steeply bent down. The upper part of the center is filled with sand that resembles a pouch in cross section. The apex is pointed or prolonged in an indistinct, thinly lined vertical tunnel, which is 7-8 mm wide. Cross sections of the burrow margins are straight. The structure usually is around 280 mm high and 115 mm wide at the top; extraordinary specimens can be more than 600 mm high and 500 mm wide (Fig. 4d). Fillings of *Thalassinoides* are deflected down near the margins of the cone, suggesting collapse of surrounding sediment due to transportation of sediment out of the cone. It cannot be excluded that some portions of ?*Conichnus* isp. are in fact collapse structures (Fig. 5h) in the upper part of *Ophiomorpha* isp., although the basal tunnel is distinctly thinner than in *Ophiomorpha* isp. or *O.* ?*nodosa*. *Conichnus* is considered to be a trace fossil produced by sea anemones, but their distinction from water escape structures is in some cases difficult (Buck and Goldring, 2003). The basal shaft in ?*Conichnus* isp. is an evidence of its organic origin.

*Macaronichnus segregatis* Clifton and Thompson, 1978 (Fig. 5c) is a cylindrical winding burrow, mostly horizontal and ob-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Unit 1
G

lique, filled with lighter sand of the same grain size as in the surroundings. It is 3-6 mm in diameter. The presence of this trace fossil is not obvious in many beds because of very poor preservation; nonetheless, on some damp, fresh surfaces of medium- to coarse-grained sands, poorly outlined, oval spots surrounded by darker material suggest bioturbation of this trace fossil. The opheliid polychaete *Euzonus* produces similar burrows and has been considered a modern analogue for the *Macaronichnus* tracemaker (Saunders, 1989; Pemberton et al., 2001, p. 126; Gingras et al., 2002; Nara and Seike, 2004; Seike, 2009). It feeds on epigranular microbial films deep within well-oxygenated foreshore and shoreface sands (Clifton and Thompson, 1978; Pemberton et al., 2001).

*Ophiomorpha* ?*nodosa* Lundgren, 1891 is a vertical or oblique, rarely branched tubular burrow with a distinct wall, which displays an even inner margin and rough outer margin. The wall, up to 2 mm thick, is built of muddy sand. The wall can be surrounded by a coarse-grained envelope. The burrows observed in this outcrop are up to 70 cm long, and their inner diameters measure 10-16 mm (Figs. 5d, e). The granular (knobby) exterior of the wall is rarely observed, but the overall character of the burrow is very similar to *O. nodosa. O. nodosa* is common in shallow-water settings. It is produced mostly by callianassid shrimps (Frey et al., 1978; Ekdale, 1992). It is most typical for the *Skolithos* ichnofacies (Frey and Seilacher, 1980; Pemberton et al., 2001), but also occurs in deeper shelf tempestites (Frey, 1990; Frey and Goldring, 1992).

*Ophiomorpha* isp. (Fig. 5g, h) occurs as long, vertical to oblique, rarely horizontal, up to 70-cm-long, straight to slightly curved, branched, walled tubes. The tube lumen is up to 32-34 mm in diameter. The wall is 3-4 mm thick. Some of the tubes terminate in the upper part with a funnel, which displays indistinct margins at least in the upper part. Laminas of sand in the funnel are wrapped down, dipping towards the shaft. Some of the funnels are sharply bounded in the lower, narrow part, where a sandy lining can be present. The funnel is filled from overlying layers in a “cone-in-cone” manner. The funnel probably resulted from a collapse of the upper part of the burrow (Fig. 5h). It cannot be excluded that some of ?*Conichnus* isp. represent such funnels, in which the continuation in the tube is not preserved.

?*Piscichnus* isp. (Fig. 5j) is a pouch-like structure with steeply inclined to vertical or even locally overhanging margins, slightly tapering downwards, with semicircular, gentle bottom. Commonly, one margin is steeper. It is up to 100 mm deep and up to 100-125 mm wide in the upper part. The filling comes from the overlying coarser sediment. *Piscichnus* is produced by rays feeding on bivalves (Gregory, 1991) and by other feeding fishes (Pearson et al., 2007).

**Figure 4:** Lithology of the Kirchenbruch quarry. A: historical view of the outcrop published in Schaffer (1914), B: granitic boulders exposed in the northern cellars, C: layers 3a-e (unit 3), 4a, b (unit 4) in the central part of the outcrop, D: large cone-shaped structure penetrating from subunit 3e down into 3d, E: units 1 to 4 in the southern part of the quarry, F: units 1 to 4 near the southern end of the outcrop, the shell layer (unit 2) shows a distinct erosive surface at the base with up to 40-cm-deep scours and a wavy surface at the top, G: detail of figure F showing erosive base of unit 2 with deep scours.

*Skolithos* isp. (Fig. 5j) is a cylindrical, vertical, straight or slightly winding, thinly lined burrow, 3-5 mm in diameter and up to 450 mm long. It is filled with light-colored silty sand. In the bed junction, coarse material is introduced from the higher bed to the lower bed around the burrow in a conical zone that is up to 30 mm wide at the top. *Skolithos* occurs in a broad variety of environments (Fillion and Pickerill, 1990, for review), but is most typical of shallow-water, high-energy settings. It is interpreted as dwelling and feeding burrows of annelids or phoronids (Alpert, 1974).

*Thalassinoides* ?*suevicus* (Rieth, 1932) is a burrow system composed of mostly horizontal, branched tunnels that are 35-60 mm wide. The larger forms show Y- and T-shaped branches, with enlargement of the branching points. Some of the tunnels are enlarged due to concretional overgrowth (Fig. 5f). *Thalassinoides* was produced by crustaceans, mostly decapods (Frey et al., 1984). For further discussion of this ichnogenus and its ichnotaxonomic problems see Fürsich (1973), Ekdale (1992) and Schlirf (2000).

*Thalassinoides* isp. (Fig. 5a, b) is a gallery composed of mostly horizontal, branched tunnels in a few levels connected by shafts. The tunnels lack walls, are elliptical in cross section, and 7-18 mm wide. T-shaped branches prevail. Most distances between branches range between 50 and 75 mm. The shafts are 20-30 mm long. The grain size, composition and/or color of the fillings differ from the surrounding rock. Galleries and shafts form a boxwork that extends vertically for about 15 cm.

Curved tubes (Fig. 5k) are incomplete, distinctly winding tubes observed in vertical section in subunit 3d starting from subunit 3e. These tubes are 4 mm in diameter, vertical in the lower part and oblique in the upper part. They are filled with light-colored silt and co-occur with *Skolithos* isp. and ?*Arenicolites* isp., which are preserved in the same way.

Irregular spots (Fig. 5l) visible in vertical cross sections are more or less oval, not uniform structures with diffuse margins, 15-20 mm in diameter, composed of lighter sand than in the surroundings. They very probably represent bioturbation structures.

A thick-lined tubular burrow (Fig. 5c) was observed in a horizontal cross section in subunit 3d. It is sub-circular in outline, 74 mm in diameter, with 22-mm-thick, light-colored sandy silt lining. The lumen, 31 mm in diameter, is filled with coarse sand.

Trace fossils are not rare in the Burgschleinitz Formation of the Eggenburg Bay. The most common ichnogenus in these nearshore deposits is *Ophiomorpha*, observable in several outcrops of the region (Hohenegger and Pervesler, 1985). Being the only remarkable trace fossil in this outcrop, *Thalassinoides* Ehrenberg (1944) was described from the sandpit Sieber (now Hammerschmid, cf. Fig. 2) a few steps SSW from the Kirchenbruch quarry. The latter, with at least 11 ichnotaxa, has the highest diversity of trace fossils in the Eggenburgian shallow-water sediments in this region.


Th
C
C
20 cm
A
Th
On
Unit 3e
50 cm
C
Unit 3d
C
B
M
10 cm
tb
C
10 cm
D
5 cm
E
BURGS.
KB2004
004
20 cm
F
20 cm
BURGS.
KB2004
007
G
20 cm
H
Pi
Sk
Ar
20 cm
J
5 cm
K
is
20 cm
L

In the section of Burgschleinitz Kirchenbruch the abundance as well as the distribution of ichnotaxa are very variable (cf. Fig. 3b).

In units 1 and 2 no bioturbation was observed. In contrast unit 3 shows the highest diversity of trace fossils of the section. This unit is subdivided into five subunits 3a-e with individual vertical and lateral distributions of trace fossils.

Subunit 3a contains no trace fossils. In the cross-bedded coarse sand horizon of subunit 3b *Ophiomorpha* ?*nodosa* and *O.* isp. occur between 23 and 42 m. Additionally a single cross section of *Thalassinoides* was found at 45 m.

In subunit 3c the cylindrical, winding, mostly horizontal to oblique *Macaronichnus segregatis*, filled with lighter sand, appears between 21 and 23 m, *Skolithos* isp. at 25.5 m, 29 m, 41 m, 44 m, 45 m, 60 m, and 61 m. *Ophiomorpha* ?*nodosa* occurs at 25 m and 58 m, ?*Conichnus* isp. penetrates from subunit 3d at 30 m and 57 m. Subunit 3c joins subunit 3a at around 70 m. *Macaronichnus segregatis* appears between 72 m and 87 m. Irregular spots at 78 m (Fig. 5l), more or less oval in vertical cross sections, not uniform with diffuse margins, are reminiscent of the irregular echinoid trace fossil *Bichordites* cross sections. *Thalassinoides suevicus* was found at 77 m and 82 m.

Subunit 3d is dominated by the vertical and U-shaped trace fossils *Skolithos* isp. and ?*Arenicolites* isp. *Skolithos* isp. (Fig. 5j) mostly starts from the boundary to the following fine-sand layer 3e. Concentrations of these vertical tubes were observed at approximately 25 m and between 46 and 65 m, single appearances at 33 and 71 m. ?*Arenicolites* isp. (Fig. 5j) appears from 50 to 62 m. ?*Piscichnus* isp. was found between 19 and 21 m, ?*Conichnus* isp. occurs at 30 m, 58 m, and 67 m. *Ophiomorpha* isp. is common between 25 and 54 m, *Ophiomorpha* ?*nodosa* between 50 and 77 m.

In subunit 3e *Thalassinoides suevicus* appears at 27 m (Fig. 5f), 38 m, 45 m, 69 m, and 75.5 m. Noticeable in this subunit is the dense boxwork of *Thalassinoides* isp. (Fig. 5a, b) over a range of 65 m (Fig. 3b, 0 to 65 m). Conspicuous *Conichnus* isp. funnels appear from 18 to 34 m, at 57.5 and 77 m. The frequent and characteristic trace fossil ?*Piscichnus* isp. is visible between 39 and 47 m as well as between 58 and 66 m (Fig. 5j).

**Figure 5:** Trace fossils of the Kirchenbruch quarry. A: ?*Conichnus* isp. (*C*) from subunit 3e close to the northern end of the outcrop, *Thalassinoides* isp. (*Th*) bent down following the funnel structures, B: *Conichnus* isp. (*C*) and steep, 70-cm-long *Ophiomorpha* ?*nodosa* (*On*) shaft in subunit 3e, dense boxwork of *Thalassinoides* isp. (*Th*) 50 cm above position of ?*Conichnus* isp. (*C*), C: *Macaronichnus segregatis* (*M*) in subunit 3d and thick-lined tubular burrow (tb), D: oblique *Ophiomorpha* ?*nodosa* tunnel in subunit 4a, E: cross section of *Ophiomorpha* ?*nodosa* tunnel in subunit 3e penetrating from subunit 4a, F: *Thalassinoides* ?*suevicus* from subunit 3e with concretionary overgrowth, G: *Ophiomorpha* isp. junction of shaft and three tunnels - subunit 4a, H: funnel-shaped collapse structure above *Ophiomorpha* isp. shaft - subunit 3d, J: subunit 3e with ?*Piscichnus* isp. (*Pi*), ?*Arenicolites* isp. (*Ar*) and *Skolithos* isp. (*Sk*) intruding into subunit 3d, K: curved tubes in subunit 3d, L: irregular spots (is) in subunit 3a.

Unit 4 is dominated by the crustacean burrows *Ophiomorpha* ?*nodosa*, *O.* isp. and *Thalassinoides* ?*suevicus*. Subunit 4a contains a high portion of *Ophiomorpha* ?*nodosa* and *O.* isp. in the northern part; *Thalassinoides* ?*suevicus* has only two occurrences. The southern part is characterized by a fading out of *O.* isp.. *O.* ?*nodosa* and *Thalassinoides* ?*suevicus* remain the dominating trace fossils in this part of the subunit. Finally in subunit 4b and also in unit 5 *Thalassinoides* ?*suevicus* is the only ichnofossil.

## 6. Discussion and interpretation

The sandy sediments of Burgschleinitz Kirchenbruch were deposited in a small marine bay open to the west and close to nearby crystalline elevations.

The massive, coarse to medium sands in the lowermost part of the section (unit 1) were deposited in the nearshore area and lack trace fossils. As shown by the light and heavy mineral spectra with typical minerals and components from the surrounding granites, these sediments were directly delivered from the weathered crystalline basement. The increase of coarse, lithic material towards the crystalline elevations also shows the input from these granite highs. At that time the sediment supply was high and the burrowing community was not well established. The coarse sediments probably also negatively influenced the burrowing benthos and hindered the preservation of their traces (Dashtgard et al., 2008).

From time to time the nearshore area was reworked by storms. In Burgschleinitz Kirchenbruch this is evident in the coarse sandy to gravelly shell layer of unit 2. It contains thick-shelled molluscs of the littoral and shows typical characteristics of tempestites with scour and fill structures at the erosional base and an undulatory top (see also Kidwell, 1991).

In the overlying unit 3, the cross-bedded subunits 3b and 3d show a downlapping progradation out of the bay towards the center of the basin, pointing to decreasing wave influence. Such cross-bedded units are common features in littoral to shallow sublittoral areas of the shoreface, and can be interpreted as beach bars. They contain rare *Ophiomorpha* ?*nodosa*, *Macaronichnus*, and *Thalassinoides*. A few *Skolithos* were found at the top of the fine-grained sand covering the first cross-bedded layer 3b. Other trace fossils present in this unit, though abundant, were produced after its deposition, thus reflecting subsequent environmental changes. Probably, very few tracemakers were able to colonize the migrating foresets.

The higher diversity and best preservation of trace fossils penetrating from the top of the upper cross-bedded subunit 3d is striking. Unit 3, showing progradation towards the center of the basin, can be considered as a regressive unit or a still-stand. The overlying layer of fine sand (subunit 3e) can be interpreted as evidence for a new marine flooding, which probably reduced the mobility of the sediment. Thus, the intense burrowing took place during a longer time interval of stabilization of the sea floor, when the colonization window (sensu Pollard et al., 1993) was long enough. The sea floor was stable due to the drop of accumulation rate and possible winnowing, enough to produce the *Thalassinoides* isp. boxwork in a stiff substrate (stiffground sensu Wetzel & Uchman, 1998) that allowed galleries without walls to be maintained. The presence of a *Thalassinoides* boxwork at the top of parasequences (e.g., Ghibaudo et al., 1996) and below sequence boundaries (e.g., Uchman and Pervesler, 2007) is common. The bed surface with ?*Piscichnus* and ?*Conichnus*, produced by feeding fish on the sea floor and by ?burrowing sea-anemones, respectively, suggests a long exposition of the stable sea floor. The *Thalassinoides* galleries are filled with coarse sands from the overlying bed. *Skolithos* and ?*Arenicolites* are filled with the fine sand. Further deposition of coarser sand and gradual destabilization of the sea floor resulted in colonization with *Ophiomorpha* ?*nodosa* and less frequently with *Ophiomorpha* isp. Commonly, the burrows collapsed in unstable sediment, as is shown by the conical structures in their upper part. The lateral distribution of trace fossils changes considerably in this portion of the section. *Skolithos*, ?*Arenicolites*, ?*Piscichnus*, and ?*Conichnus* seem to occur in patches. Patchy distribution of benthos is a well known phenomenon in biology (Valiela, 1995) but rarely visible in the fossil record, mainly due to obliteration caused by redeposition, or lateral migration and overlapping. Trace fossils, typically preserved *in situ*, show the original patchy distribution, frozen by subsequent environmental changes.

Higher up in the section in subunit 4a and 4b, landward and upward coarsening is evidence for a new, strongly advancing transgression. Non-erosion of the subjacent sediments points to a rapid sea level rise. The high content of barnacle-debris points to high abrasion of the nearby crystalline elevations. In contrast, the upward increasing input of heavy minerals from metamorphic areas (mainly mica schist and paragneiss of the Moravian Zone west of the Thaya granite) points to the expansion of flooded areas due to transgression. Poor sorting of the silty and gravelly sands additionally indicates deposition in the lower shoreface or transition zone, close to or below the mean fair-weather wave base, where wave activity was not strong enough to be effective. In this unit the trace fossil diversity decreases and preservation deteriorates. *Thalassinoides* ?*suevicus*, *Ophiomorpha* isp., and *O.* ?*nodosa*, are present but not abundant. The sediment supply was too high to enable the establishment of larger burrowing communities. The rock is partly cemented and strongly weathered, making observations in the higher part of the cliff difficult. Strong weathering prevents detailed observations of the overlying silty coarse-grained sand of subunit 4b, which contains at least *Thalassinoides* ?*suevicus*.

It is difficult to decide if the cross-bedded unit 3 represents a highstand system tract or not without a wider regional context. Until now, however, no evidence for a regressive phase or stillstand in that position within the Burgschleinitz Formation has been reported in other outcrops during mapping. Nevertheless, similar processes and their effects are expected in a regressive unit or stillstand such as the above. The application of ichnofacies considerably improves the interpretations. The vertical trace fossil assemblage (*Ophiomorpha*, *Skolithos*, *Arenicolites*) is indicative of the *Skolithos* ichnofacies, but the presence of *Thalassinoides* suggests a transition to the proximal *Cruziana* ichnofacies, which is typically placed in the middle-lower shoreface according to the models (e.g. Pemberton et al., 2001) applicable to open shelves. *Macaronichnus* is most abundant in the foreshore, but not limited to this zone. It can be present also in the *Cruziana* ichnofacies (see Pemberton et al., 2001; Bromley et al., 2009). However, the generally coarse sediments deposited in the protected bay, and the topographic proximity to the crystalline basement, suggest shallower depths for the lower part of the section. It would therefore correspond rather to the lower foreshore-upper shoreface. The disappearance of vertical trace fossils upsection and the deposition of muddy sands of the Gauderndorf Formation (unit 5) suggest a deepening related to the subsidence of overloaded crust of the foreland Molasse basin.

## 7. Conclusions

Sediments of the Burgschleinitz Formation mark the beginning of the Early Miocene (Late Eggenburgian) marine transgression in the Eggenburg Bay. In the type area of the Burgschleinitz Formation around Burgschleinitz, immature, moderately to poorly sorted, coarse- to fine-grained sands with gravelly intercalations were deposited in a small wave- and storm-dominated bay, open to the west, and close to adjoining crystalline elevations.

In the type section for the Burgschleinitz Formation – the Burgschleinitz Kirchenbruch – four lithological units can be distinguished; they are overlain by a fifth unit, the Gauderndorf Formation.

At least 11 ichnotaxa were recognized in the Burgschleinitz Formation of the Kirchenbruch quarry. This is the highest diversity of trace fossils in sediments of the Eggenburgian in this region.

In the lowermost part of the section, massive, coarse- to medium-grained, high-energy nearshore sands (unit 1), topped by a shelly coarse-grained tempestite (unit 2), show no evidence of trace fossils.

Most of the burrowing is concentrated in the middle, slightly finer part of the section (unit 3). Alternating coarse- to medium-grained cross-bedded sands with fine-sandy layers from upper shoreface areas point to a short regressive phase or a stillstand. The higher diversity and better preservation of trace fossils in the uppermost part suggests a colonization window, when stabilization of the sea floor was related to a new flooding. The vertical trace fossil assemblage (*Ophiomorpha*, *Skolithos*, *Arenicolites*) indicates the *Skolithos* ichnofacies.

Upsection, poorly sorted, coarse-grained, non-erosive sands with mollusc and barnacle debris (unit 4) point to a rapid sea level rise. *Thalassinoides* in the upper part of unit 3 and unit 4 suggests a transition to the proximal *Cruziana* ichnofacies, which is typically positioned in the middle-lower shoreface.

The disappearance of vertical trace fossils upsection in the topmost position of the silty Gauderndorf Formation (unit 5) generally correlates with the further deepening related to the proceeding of the Early Miocene (Eggenburgian) transgression.


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