The vicinity of Graz: Upper Silurian to upper Carboniferous of the Graz Palaeozoic, upper Cretaceous of the Kainach Gosau and middle Miocene of Gratkorn

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Abstract

The city of Graz is dominated by mountains belonging to the Graz Palaeozoic, a thrusted series of Silurian to upper Carboniferous sediments. Some parts, like the Rannach Facies are slightly metamorphosed. The western part of the Graz Palaeozoic is partly covered by upper Cretaceous sediments of the Kainach Gosau, comprising alluvial sediments at the northern margin of the basin grading into deep marine fan depositions of the centre. In the southern and southeastern parts the Graz Palaeozoic is covered by Neogene sediments of the Styrian Basin. These sediments are dominated by fluvial and limnic deposits of middle to late Miocene age. Marine intercalations are rare, which renders correlations to more distal parts of the Styrian Basin challenging. The fossil site Gratkorn yields one of the most diverse and best studied vertebrate faunas of late middle Miocene age in Central Europe.

1. Introduction

The mountains that surround the city of Graz belong to the *Graz Palaeozoic* (GP), a thrust complex of Silurian to upper Carboniferous sediments capped by upper Cretaceous *Gosau* clastics. In the west, north and east the GP exhibits tectonic contacts to basal Austroalpine metamorphic complexes. To the south and southeast the GP is covered by Neogene sediments of the Styrian Basin.

Internally the GP consists of several facies nappes. The *Rannach Facies*, in the uppermost tectonic position, indicates a sedimentation area changing from a passive continental margin with intra-plate volcanism to shelf and platform geometries during Silurian to Devonian time. During early to middle Devonian time deposition changed from near-shore facies to open platform environments, during the late Devonian and Carboniferous the carbonate platform was drowned and pelagic limestones were deposited. Basal nappes of the GP are made up of late Silurian to early Devonian sequences that were subjected to metamorphic overprint under upper greenschist to exceptionally occurring amphibolite facies metamorphic conditions. Meggen-type lead/zinc-barite Sedex mineralizations occur in some upper Silurian–lower Devonian volcaniclastic sequences.

In its western sector the Graz Palaeozoic is sealed by upper Cretaceous (upper Santonian–Maastrichtian sediments of the *Kainach Gosau* (KG). The facies inventory of the *KG* comprises proximal alluvial sediments at the northern margin of the basin grading into deep marine fan depositions of the centre. Bituminous marls at the eastern margin represent a lacustrine environment which was temporarily affected by marine flooding.

Neogene sediments in the vicinity of Graz comprise largely fluvial and limnic deposits of middle to late Miocene age. Marine intercalations are rare, which renders correlations to more distal parts of the Styrian Basin challenging. The fossil site Gratkorn yields one of the most diverse and best studied vertebrate faunas of late middle Miocene age in Central Europe. Due to its origin from a rapidly accumulated floodplain palaeosol, time-averaging is low and the taphocoenose reflects well the original vertebrate community. As the Gratkorn site is dated independently from vertebrate biochronology, it is a very important benchmark for a vertebrate-based, continental biostratigraphy of the Central Paratethyan realm, and probably beyond.

The excursion focuses on the stratigraphy and facies architecture of the slightly metamorphosed *Rannach Facies* at the upper structural level of the GP thrust complex, marginal marine sequences of the KG and terrestrial deposits at the Gratkorn vertebrate locality.

2. Overview of the Graz Palaeozoic, the Cretaceous Kainach Gosau and the Styrian Neogene Basin

2.1. Graz Palaeozoic

In the Eastern Alps the Palaeozoics belong to the Upper Austroalpine Nappe System (SCHMID et al., 2004) in which non metamorphosed Palaeozoic sequences were primarily superposed unconformably by late Palaeozoic to Eocene stratigraphic sequences of the Calcareous Alps. The nappe structure of the Upper Austroalpine System was triggered by the closure of the Meliata Ocean during early Cretaceous and sealed by late Cretaceous to Eocene overstep sequences (Gosau Group). Later, during the indentation of the Apulian

Plate to the north and the southward subduction of the Penninic units under the Apulian Plate, the Upper Austroalpine Nappe System was thrusted into the uppermost tectonic position of the Eastern Alps. Contemporaneous with the Apulian indentation uplift of the Penninic Tauern Window and other core complexes triggered lateral ex-trusion of the eastern parts of the Eastern Alps within the Alpine-Carpathian-Pannonian unit to the east (RATSCHBACHER et al., 1991; NEUBAUER et al., 2000). Today lowgrade and non metamorphosed Palaeozoic successions are irregularly distributed in Austria (Fig. 1). Two major regions of Palaeozoic domains can be distinguished which are separated by the Periadriatic Fault, the most prominent Alpine fault system: the Eastern Alps with the Greywacke Zone, the Gurktal Nappe, the Graz Palaeozoic (GP), some isolated domains in south Styria and Burgenland and the Southern Alps with famous fossiliferous Palaeozoic sequences in the Carnic Alps and the southern Karawanken Mountains (SCHÖNLAUB & HEINISCH, 1993; HUBMANN et al., 2014).

Fig. 1. Austria and its disconnected Palaeozoic units (shaded areas). Major Palaeozoic domains in Austria belong to the Eastern Alps (Graz Palaeozoic, Greywacke Zone, Gurktal Nappe, South Burgenland) and the Southern Alps (Carnic Alps, South Karawanken Mts.).

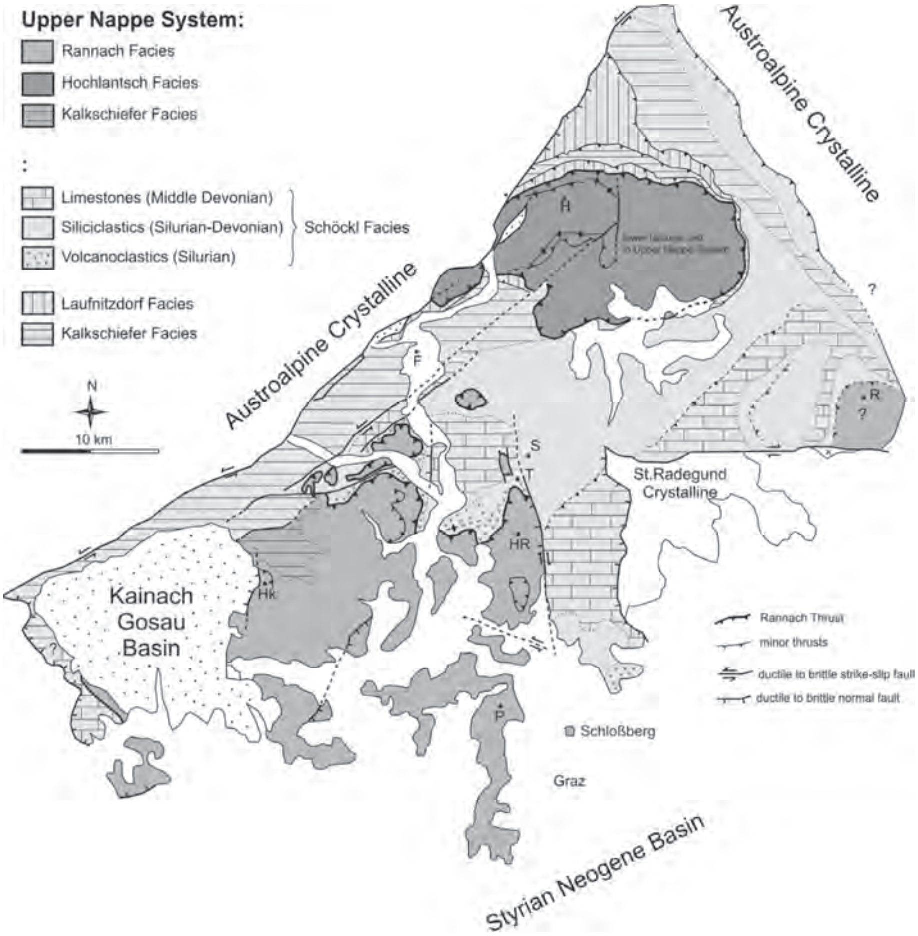

Fig. 2. The Graz Palaeozoic, its framing and internally organisation in nappe groups (modified after GASSER et al., 2009). H = Hochlantsch, Hk = Höllererkogel, HR = Hohe Rannach, P = Plabutsch, R = Raasberg, S = Semriach, T = Taschen (modified after GASSER et al., 2010).

The GP comprises an outcropping area of approximately 1,250 km^2 tectonically resting on metamorphic basement. Metamorphic units in the northwest, west, northeast and southeast belong to the Upper Austroalpine Silvretta-Seckau and Koralpe-Wölz Nappe Systems (SCHMID et al., 2004). The boundary between metamorphic units and the GP is formed by distinct thrust planes and a significant NE–SW striking sinistral wrench corridor at the northwestern border (Fig. 2). The nappes of the GP are unconformably overlain by the upper Cretaceous Kainach Group („Kainach Gosau"; EBNER & RANTITSCH, 2000) in the west and by Neogene sediments of the Styrian Basin in the south (EBNER & SACHSENHOFER, 1991, 1995; GROSS et al., 2007a). SW of Rothleiten upper Cretaceous conglomerates are also included along the sinistral wrench corridor between the GP and the Austroalpine metamorphic units.

The succession of the GP (?Silurian–upper Carboniferous) belongs to the "classical" non to only low grade metamorphic fossiliferous Austroalpine Palaeozoic units. The Eo-Alpine (Cretaceous) internal structure is composed of a Lower and an Upper Nappe System (GASSER et al., 2009, 2010). Each of them is differentiated into individual facies domains which reflect basal pre-Devonian volcanoclastics and a pronounced platfom to basinal facies geometry during the Devonian. The excursion focuses to the most famous and best investigated Rannach Facies of the Upper Nappe System. The sequence of the Rannach Facies begins with a volcanoclastic influenced environment (Reinerspitz Group; ?Ludlow–Lochkovian) followed by a Lochkovian to Frasnian carbonate shallow water environment (Rannach Group) which interfingers with basinal calcareous schists ("Kalkschiefer-Fazies"). During Frasnian the facies changed to a pelagic environment (Forstkogel Group) which continued until the Serpukhovian and is followed by limestones and slates of the Dult Group (Bashkirian). The concordant marine sequence which persists to the Bashkirian is interrupted by some erosion events.

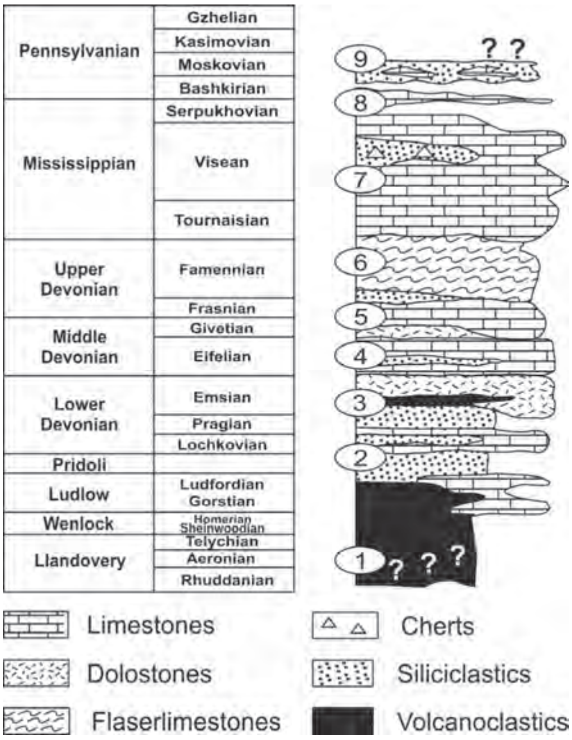

Fig. 3. Stratigraphic column of the Rannach Nappe indicating main lithologies.
Kötschberg Group: 1. Kehr Fm., Kötschberg Fm.
Rannach Group: 2. Parmasegg Fm., 3. Flösserkogel Fm., Bameder Fm; 4. Plabutsch Fm., 5. Kollerkogel Fm.
Forstkogel Group: 6. Steinberg Fm., 7. Sanzenkogel Fm.
Dult Group: 8. Höchkogel Fm., 9. Hahngraben Fm. (after EBNER & HUBMANN, 2012).

The architecture of the Rannach Facies is controlled by the specific tectonic and sedimentological history of the Noric Composite Terrane (FRISCH & NEUBAUER, 1989) and global environmental trends (sea level fluctuations, climatic changes etc.). The primary basement as well as the beginning of sedimentation in the Rannach Facies is still unknown (Fig. 3). Nevertheless, the Reinerspitz Group (FLÜGEL, 2000) forms the stratigraphic footwall in which alkaline basic volcanism (Kehr Fm.; >100 m; upper Ludlow in its upper parts; FLÜGEL, 2000) and fine clastic and pelagic carbonate sedimentation (Kötschberg Fm.; up to 30 m; FLÜGEL, 2000) reflect the evolution at passive margins of the separating terrane. Carbonate lenses/layers with fossils (conodonts, orthoceratides, brachiopods) indicate a Ludlow–Lochkovian age of the Kötschberg Fm.

Some massive basic volcanics (diabase) at top of the Kehr Fm. (Haritzgraben, Eggenfeld) with lava flows, block lavas, lapilli and ash tuffs derive from volcanic islands with volcanic activity in shallow water and subaerial domains. Trace element analysis reveals weak alkaline affinities of the basaltic volcanics formed in an intracontinental rifting basin (FRITZ & NEUBAUER, 1988). Due to the morphology of the island, the superposition is heterochronous. On the slope (e.g., Eggenfeld) a several metres thick alternation of bedded dark fossil rich dolomite and fine grained tuffite (Ludlow–Lochkovian; EBNER, 1976a; PLODOWSKI, 1976; HIDEN, 1996; HISTON et al., 2010) developed, whereas the top of the volcano (Haritzgraben) was still covered by dolomites of the basal Flösserkogel Fm. (Pragian).

During Pragian to lower Emsian times, intertidal to shallow subtidal deposits developed on a carbonate ramp which were comprised to the Parmasegg Fm. (FRITZ, 1991).

From the lower Devonian, probably in causal connection with a gradual movement of the plate to which the depositional area of the GP belonged into lower latitudes (FRITZ & NEUBAUER, 1988; FENNINGER et al., 1997), increase of carbonate production is obvious. Thick successions of coarse-grained sandstones with layers of diabase tuff were deposited in a shallow marine, near-shore environment (Flösserkogel Fm., Heuberg Mb.).

Due to different lithological characteristics, FENNINGER & HOLZER (1978) distinguished four facial types which were considered as members by FLÜGEL (2000). In general, the Flösserkogel Fm. comprises different kinds of dolostones, silt- to sandstones and subordinated dolomitic limestones which are interpreted as depositions of a supra- to shallow subtidal, barrier-surrounded lagoon, or tidal flats (FENNINGER & HOLZER, 1978). Near Graz the lower parts of the succession are interpreted as sand bars whereas the upper parts which are separated by volcanic tuffs contain meadows of the spaghetti-like stromatoporoid *Amphipora* (HUBMANN et al., 2006; HUBMANN & SUTTNER, 2007). Although conodonts are very rare they point to a (lower?) Emsian age (cf. EBNER et al., 2000).

A highly fossiliferous sequence dominated by dark marly bioclastic limestones overlies or rather interfingers the Flösserkogel Fm. This sequence, called Plabutsch Fm., exhibits in the lower parts especially at the boundary to the underlying Flösserkogel Fm. yellow to brownish shales occasionally blotched with moulds of chonetid brachiopods. In the upper parts of the formation intercalations of red marls and marly limestones are common phenomena.

Among the organisms typical "reefbuilders" are common (HUBMANN, 1993, 2003) in all sectional sites. Nevertheless, there is no evidence in the field of a "true reef"; rather coral-stromatoporoid-carpets and lagoonal sediments are the dominant features. Environmental investigations indicate deposition on a differentiated and slightly inclined carbonate platform (HUBMANN, 1993). The following features support the assumption that sedimentary conditions were unfavourable for reef formation: the rarity of in situ organisms, the intermittent high supply of clayey sediments (marl-limestone intercalations) and high supply of lime mud, temporary influx of high amounts of continental phytoclasts, storm impacts (several tempestite sequences within the profiles) and especially their effects on the biocoenosis (HUBMANN, 1995).

This phase of the Plabutsch Fm. is terminated by a repetition of tidal flat deposits similar to the Flösserkogel Fm. and obviously caused by an eustatic sea level fall.

Transgression resulted in a sequence with sharp (bio)facial contrasts between patch-reefs and monotonous mudstones of Givetian age (Rannach Facies: Kollerkogel Fm., Hochlantsch Facies: Tyrnaueralm Fm., Zachenspitz Fm.) in the Upper Nappe System. Grey dolomites with biolaminations, light bluish limestones (mostly mudstones), locally bioclastic limestones with chert nodules which are interpreted to have developed in major parts in an open platform setting are comprised to the Kollerkogel Fm. According to FLÜGEL (2000) four members in the Kollerkogel Fm. are discernible: Gaisbergsattel Mb. (dark grey biolaminated dolostones; about 20 m), the basal part of the formation representing tidal flat deposits and sediments of a restricted lagoon, Kanzel Mb. (light grey to bluish limestones; mostly mudstones; up to 100 m), Platzlkogel Mb. (grey limestones with locally developed biohermal structures; about 75 m), Platzl Mb. (grey limestones intercalated with carbonatic argillaceous shales; about 50 m; reaches up to the upper Devonian). In contrast to the Kanzel Mb. which is very poor in conodonts the conodont fauna of the Platzlkogel Mb. is much richer. The *Polygnathus*-*Icriodus* ratio indicates a higher energetic open platform environment (EBNER, 1998).

During uppermost Givetian to lower Frasnian the sedimentation of shallow platform carbonates was replaced by variegated micritic cephalopod limestones (Forstkogel Group) which continued until the Serpukhovian (Fig. 4). The thickness of this pelagic group reaches in maximum 100 m. In the eastern parts of the Rannach Facies it is reduced to ~30 m by an intraformational stratigraphic gap across the Devonian–Carboniferous boundary caused by karstification (EBNER, 1978, 1980a, b). Colour (grey–yellowish brown–reddish–violet) and lithology (thin to thick bedded, flaser- to nodular marly limestones) are strongly changing. By means of conodonts the Forstkogel Group can be subdivided in the upper Devonian Steinberg Fm. and the Carboniferous Sanzenkogel Fm. Locally, the Givetian parts of the Steinberg Fm. are separated as the 20–30 m thick Höllererkogel Mb. (EBNER, 1978, 1980a, b, 1985; EBNER et al., 1979, 2000; NÖSSING, 1974, 1975; SURENIAN, 1978; BUCHROITHNER et al., 1979). Marker beds within the Upper Sanzenkogel Fm. are the Trolp Phosphorite Bed (up to 40 cm thick shale and lydite with phosphorite nodules) in the western and the Hart Lydite Bed (250 cm lydite; EBNER, 1978; BOSIC, 1998, 1999; FLÜGEL, 2000) in the eastern parts of the Rannach Facies.

All known conodont zones from the *varcus* Zone (latest Givetian) until the Serpukhovian *Gnathodus bilineatis bollandensis* Zone were proved in the Forstkogel Group (FLÜGEL & ZIEGLER, 1957; NÖSSING, 1975; EBNER, 1977a; SURENIAN, 1978; BUCHROITHNER et al., 1979; BOSIC, 1998, 1999).

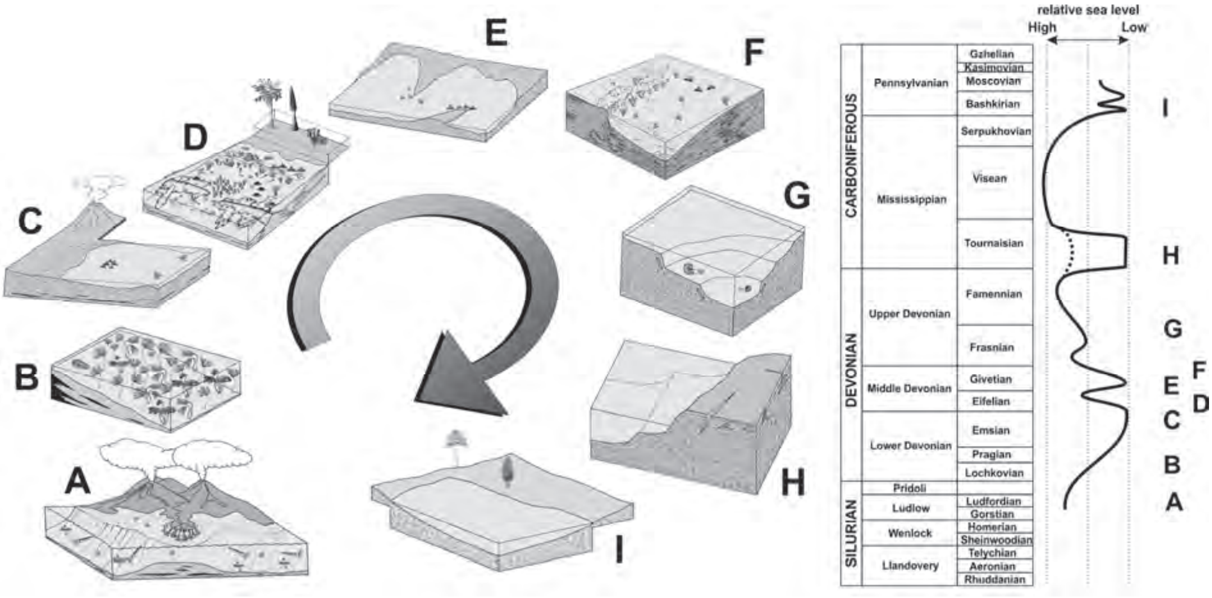

Fig. 4. Cartoon of the depositional environments of the Rannach Facies.
A. Kötschberg Fm., B. Parmasegg Fm., C. Flösserkogel Fm., D. Plabutsch Fm., E. Gaisbergsattel Mb., F. Kanzel Mb., G. Steinberg Fm., H. Sanzenkogel Fm., I. Höchkogel and Hahngraben Fms.
Note the relative sea-level curve through time estimated from sedimentological and palaeontological data (modified after EBNER et al., 2000).

Generally continuous sequences across the Devonian–Carboniferous boundary occur in the western parts of the Rannach Facies. In the east this level is dominated by erosional gaps which increase in their stratigraphic extent towards the east. In maximum the erosion phase includes the time span from early Famennian to early Visean. Therefore, the strongly condensed and only 220 cm thick Lower Sanzenkogel Fm. (Tournaisian, *Siphonodella sulcata–Scaliognathus anchoralis* Zone) occurs only in the western domains.

Since no evidence for a facial change is traceable, it is assumed that the considered area remained in an off-shore shelf position. Thus, to explain the conodont mixed faunas the depositional environment must have been affected by synsedimentary tectonics and/or sea level fluctuations causing a shallowing of the sea with local desiccation followed by rapid deepening within the latest Tournaisian to early Visean time interval. The western domain with continuous sections remained always in marine, pelagic positions. Sedimentation of shales, lydites and phosporites (Trolp Phosphorite Bed) may indicate upwelling zones at the margin of the outer shelf just at the beginning the Carboniferous transgression (EBNER et al., 2000).

Tentatively the bathymetric path of the Forstkogel Group was interpreted from Mn contents (BUCHROITHNER et al., 1979; EBNER & PROCHASKA, 1989; EBNER et al., 2000). These data, calibrated with Mn contents of 400–1750 ppm for Palaeozoic cephalopod limestones (BUGGISCH, 1972; LÜTKE, 1976), suggest a depth of 60–300 m for the formation of phosphorite and cephalopod limestones in the GP (NÖSSING, 1974). Additionally increasing Mn contents indicate an environmental deepening. During the upper Devonian the western domains represent deeper and more open shelf conditions. A deepening trend until the early Famennian *crepida* Zone was followed by shallowing until to the *styriacus* Zone. The generic composition of the conodont biofacies of the *styriacus* Zone indicates „shallow to moderate deep water on the continental shelf" (SANDBERG, 1976). The decreasing and low level Mn contents of the western domains reflect the uplift/shallowing of the eastern parts culminating in subaerial erosion and karstification. During late Tournaisian increasing Mn contents reflect the transgression of the Upper Sanzenkogel Fm. and a deepening of the environment in which lydite formation may indicate the deepest parts in both areas. Possibly the crossing of the bathymetric paths in the eastern and western domains after the phosphorite event indicates diverse synsedimentary tectonics of the two blocks. Decreasing Mn contents at top of the Sanzenkogel Fm. coincides with another erosion event between the Forstkogel and Dult Groups.

The Dult Group (EBNER, 1978; FLÜGEL, 2000) began after an erosion gap at top of the Sanzenkogel Fm. (EBNER, 1976b, 1977a, b, 1978, 1998; EBNER et al., 2000; FLÜGEL, 2000). At its basal part the Höchkogel Fm. consists of dark coloured limestones (Hartbauer Mb.) which are interfingering/superposed with/by an alternation of shales with black limestones. The latter sometimes contain birdseye-structures (Schrausbauer Mb.) indicating a shallow water deposition. At top of the Dult Group approximately 50 m thick black slates, sometimes with intercalations of silt- and sandstone with fine phytoclastic materials are comprised to the Hahngraben Fm.

The Höchkogel Fm. is dated by conodonts of the *Declinognathodus-Idiognathoioides* group as lower Bashkirian (EBNER, 1977, 1980a; ZHI-HAO & YU-PING, 2002). The boundary between the pelagic Forstkogel Group and shallow marine Dult Group is formed by an erosion surface. Locally at the very base of the Hartbauer Mb. 20 cm thick fine-grained limestone breccias contain mixed conodont faunas with autochthonous elements of the lower Bashkirian and reworked conodonts (Visean–Serpukhovian) from the Upper Sanzenkogel Fm. At one site the entire Upper Sanzenkogel Fm. was eroded, thus affecting a direct superposition of upper Devonian limestone (*velifer* Zone) by the Bashkirian Hartbauer Mb. (EBNER, 1978, 1980a).

2.2. Kainach Gosau

The depositional environment of Kainach Gosau (KG) originated as an extensional basin during the late Cretaceous (late Santonian to Maastrichtian). Subsidence of the basin is explained by synchronous uplift of the Gleinalm dome (see also Fig. 2) in a sinistral wrench corridor (EBNER & RANTITSCH, 2000; BODROGI et al., 1994, cum lit.). On three sides, in the west, north and east, the KG is bordered by Devonian limestones and dolomites the GP. In its southern and southeastern part the KG is overlain by middle Miocene limnic-fluvial sediments. Contact with the Gleinalm crystalline is nowhere given. The basal face is formed by a pre-upper Cretaceous karst topography on mainly lower to middle Devonian successions of the GP.

The inventory of deposits comprises proximal alluvial conglomerates, marine fan sediments, and bituminous marls of a restricted lacustrine environment. Alluvial fan sediments are exposed in the northern sector of the basin in the area of Geistthal. These sediments, mostly coarse-grained conglomerates, grade into deep marine fan deposits characterised by more fine-grained clastics (sand/siltstones, clays) located in the centre of the basin. Bituminous marls and marly limestones are known from the eastern margin the basin. In the southeast of the basin hydraulic limestones, marls, calcareous marls and bioclastic limestones occur. Four lithostratigraphic units can be distinguished:

(1) Geistthal Fm. (EBNER & RANTITSCH, 2000): The basal sequence comprises several 100 metres of intensively red coloured conglomerates mainly exposed at the northern margin of the basin (GRÄF, 1975; SCHIRNIK, 1995). The clasts (up to 100 cm in diameter) are dominated by reworked limestones and dolostones, subordinate alkaline volcanics, shales/slates and sandstones of the GP. Interestingly some “exotic” pebbles indicate a northern alpine provenance (e.g., Dachstein Limestone, Hierlatz Lst., Tressenstein/Plassen Lst., radiolarian cherts) whereas others indicate a southern alpine origin (Silurian cephalopod limestones, red sandstones of the Gröden Formation, fusulinid limestone) (cf. GRÄF, 1975; FLÜGEL, 1983; GOLLNER et al., 1987; SCHIRNIK, 1995; EBNER & RANTITSCH, 2000; BOJAR et al., 2001). Upper parts of the formation may locally contain snail shells of *Trochactaeon* which point to a late Santonian to early Campanian age (GRÄF, 1975).

(2) St. Pankrazen Fm. (EBNER & RANTITSCH, 2000): Bituminous marls reach up to 50 metres in thickness at the eastern margin of the basin (Platzlkogel–St. Pankrazen area). A subdivision in three members were proposed by EBNER & RANTITSCH (2000): (A) Conglomerate member: up to 2 m thick monomict conglomerates, transgressively overlying the Palaeozoic basement. (B) Limestone member: marly gastropod limestones with crustacean coprolites (FENNINGER & HUBMANN, 1994). (C) Bituminous marl member: Bituminous, calcareous clay to siltstones, up to 50 metres in thickness, with allochthonous (terrigenous) vitrinites and autochthonous (lacustrine) alginites and liptodetrinites as main constituents of the organic matter (SACHSENHOFER et al., 1995; RUSSEGGER et al., 1998).

(3) Afling Fm. (EBNER & RANTITSCH, 2000): This formation comprises about 1.000 to 1.200 m thick grey-brown clay-, silt- and sandstones with locally intercalated by conglomerate layers. Some sections in the northern and western basin point to proximal turbiditic conditions.

(4) St. Bartholomä Fm. (EBNER & RANTITSCH, 2000): In an “adjacent basin“ around the village St. Bartholomä the Afling Fm. is overlain by approximately 250 m thick grey to yellow marls.

Sometimes these ‘hydraulic marls’ (“Zementmergel”) contain in some layers clasts of rudist bivalves. Microfossils point to a late Santonian to early Campanian age (BODROGI et al., 1994).

2.3. Styrian Basin

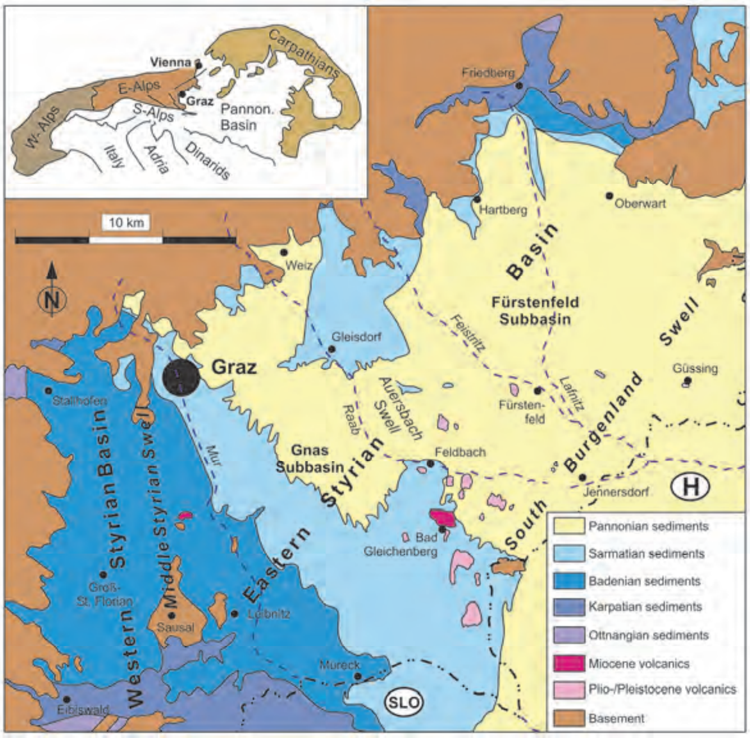

Fig. 5. Geological sketch of the Styrian Basin.

The Styrian Basin is located at the SE margin of the Alps and belongs to the Pannonian Basin System (Fig. 5). Its N, W and SW border is build up by metamorphic Austroalpine units and the Graz Palaeozoic. In the NE the Güns Mountains (Pennic unit) forms its boundary. Towards the E the South Burgenland Swell separates the Styrian Basin from the Western Pannonian Basin. The Styrian Basin is approximately 100 km long, 60 km wide and basin filling reaches a maximum thick-ness of up to 4000 m. The Middle Styrian Swell (Sausal Mountain range) divides it into a Western and an Eastern Styrian Basin. Additionally, subordinate swells and basement spurs cause a complex differentiation in several subbasins and bays.

The basin filling (synrift phase) started in early Miocene times (Ottnangian) with limnic–fluvial sediments in central basin areas (“Limnic Series”) as well as with alluvial fan, fluvial to deltaic deposits at the basin margins (Radl Fm., “Lower Eibiswald Beds”, Köflach-Voitsberg Fm.; Fig. 6). In the Karpatian enhanced subsidence as well as a sea level rise led to the deposition of several hundred metres thick offshore mud- and siltstones (“Kreuzkrumpl Fm.” resp. “Styrian Schlier”), which interfinger to the basin margins with mass flow, fluvial fan and deltaic sediments (e.g., Sinnersdorf Fm., “Conglomerate-rich Group”). Extensional tectonics were accompanied by volcanic activity (“Gleichenberg Volcanics”), which continued until the early Badenian. Around the early/middle Miocene boundary, a global sea level fall and tectonic movements caused block tilting as well as a major unconformity (“Styrian Tectonic Phase”). In the early Badenian (onset of the postrift phase), the marine environments reached its largest extend. While sedimentation of fine clastics (“Marl, Silt/Sand”) prevailed in central basin position, variegated mixed-siliciclastic-carbonatic systems became established on morphologic highs (Kreuzberg Fm., Weissenegg Fm, Tauchen Fm.). Lagoonal deposits dominate the central Western Styrian Basin (“Florian Beds”), including basaltic intrusions (“Weitendorf Volcanics”) at the transition to the Eastern Styrian Basin. After a marked regression at the Badenian/Sarmatian boundary, late middle Miocene sedimentation is characterised by pelitic sediments (Rollsdorf Fm.) or bryozoan-serpulid biocontructions (Grafenberg Fm.). A regressive event (“Carinthian Phase”) caused basin ward progradation

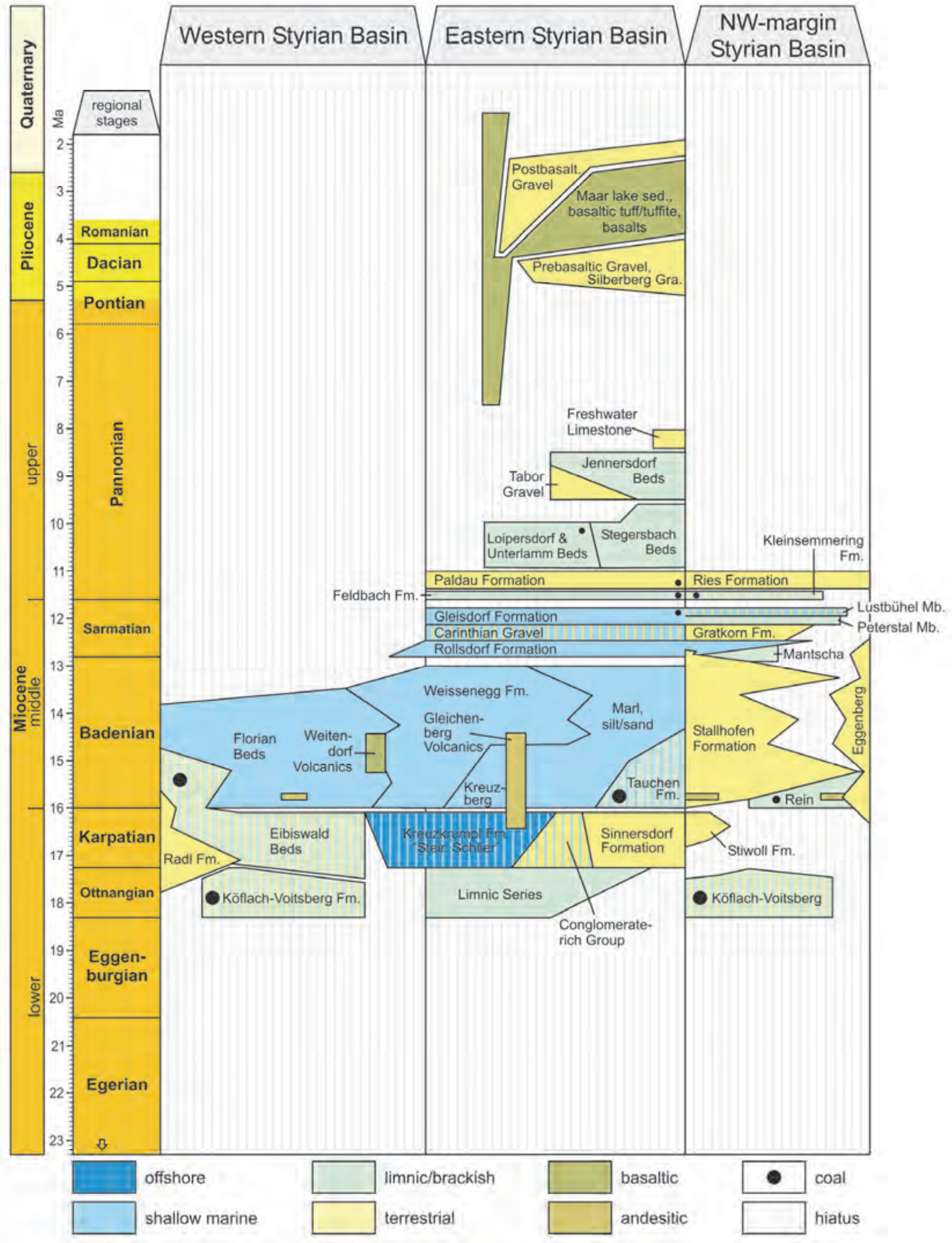

Fig. 6. Lithostratigraphic units of the Styrian Basin and correlation with Neogene Formations at the NW-margin of the Styrian Basin (after GROSS, 2015).

of fluvial environments (“Carinthian Gravel”, Gratkorn Fm.), followed by cyclic successions of siliciclastics and carbonates (e.g., silt/sand/oolites; Gleisdorf Fm.). The separation of the Central Paratethys Sea around the middle/late Miocene boundary is accompanied by significant erosion and the evolution of Lake Pannon. Repeated alternations of limnic–deltaic–fluvial or even terrestrial environments determined sedimentation in Pannonian times (Feldbach Fm., Paldau Fm., “Loipersdorf and Unterlamm Beds”, “Stegersbach Beds”, “Tabor Gravel”, “Jennersdorf Beds”, “Freshwater Limestone”). Subsequent basin inversion caused considerable erosion and a hiatus ranging up to the Pliocene. Fluvial clastics are observed below or adjacent ("Prebasaltic Gravel, Silberberg Gravel") as well as on top ("Postbasaltic Gravel") of variegated alkali basaltic volcanics of Plio-/Pleistocene age.

Except the works of WINKLER-HERMADEN (e.g., 1957), especially the paper of KOLLMANN (1965), the studies of KRÖLL et al. (1988), EBNER & SACHSENHOFER (1991, 1995) and SACHSENHOFER et al. (1997) offer detailed data about the basement and basin filling. GROSS et al. (2007a) provide a more recent compilation; SCHREILECHNER & SACHSENHOFER (2007) present a sequence stratigraphic framework.

3. The Field Trip

3.1. Stop 1 – Plabutsch–Fürstenstand

Topic: Introduction to the geology of the vicinity of Graz.

Locality: Fürstenstand, 4.5 km WNW Hauptplatz Graz, 47°05'25"N/15°23'6"E.

Description: After the incorporation of some municipalities in the year 1938 the hill Plabutsch with 754 m altitude became the highest elevation of the city Graz. The derivation of the name "Plabutsch" is not clarified. Possibly Celtic roots of „pla" indicate the meaning of iron smelt.

At the summit of the Plabutsch a little observation tower called "Fürstenstand" is located more than 400 metres higher than the centre of Graz and therefore provides a magnificent view over Graz and a panoramic view over the hilly landscape of the surrounding countryside, fair weather provided. The most important geologic units recognisable from here are illustrated in Fig. 7.

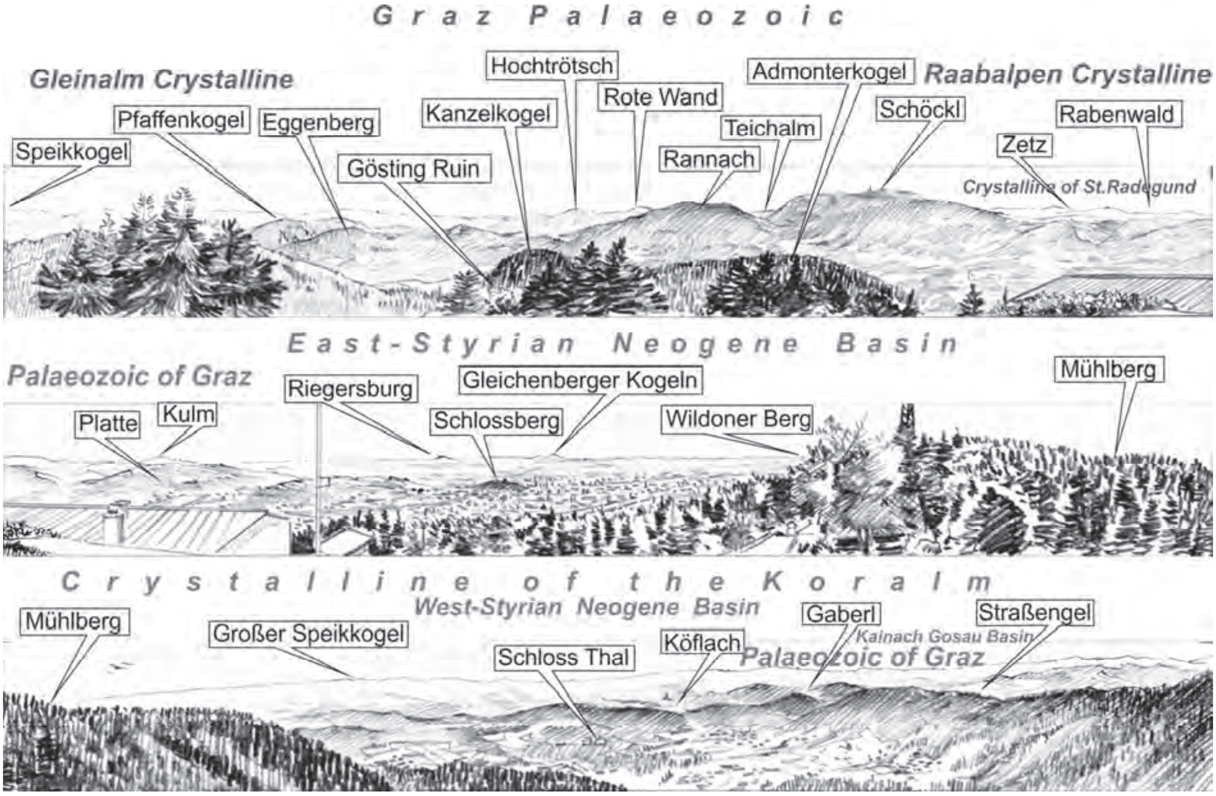

Fig. 7. Panoramic view from the "Fürstenstand". Main geologic units indicated. Drawing by Fritz Messner.

Already ROLLE (1856: 238) reported from the crest of the Plabutsch lots of fossils (i.e., rugosans, tabulates, stromatoporoids, crinoids, "bivalves") occurring in dark grey limestones and assumed a reef structure. Since these limestones were used as building stones, the walls of the observation tower give an instructive insight into the organic composition of the environment (Fig. 8).

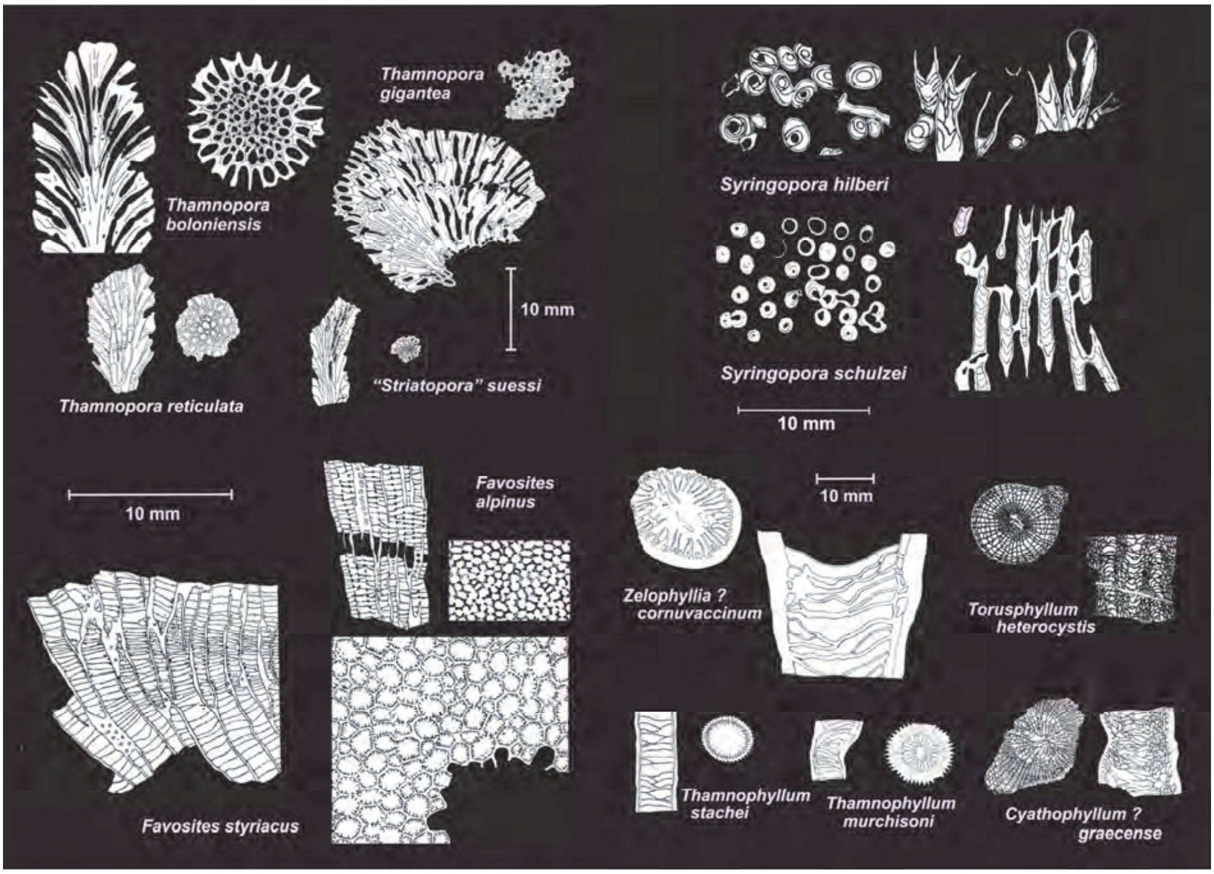

Fig. 8. Sectional images of the most important coral taxa of the Plabutsch Fm. as they can be seen in the building stones at the Fürstenwarte (after EBNER et al., 2000).

One and a half decade before Rolle, Franz Unger (1800–1870), a famous palaeobotanist at the Joanneum in Graz, published in 1843 taxonomic determinations of the following corals and stromatoporoids (UNGER, 1843): *Gorgonia infundibuliformis* GOLDF., *Stromatopora concentrica* GOLDF., *Heliopora interstincta* Bronn (*Astraea porosa* GOLDF.), *Cyathophyllum explanatum* GOLDF., *Cyathophyllum turbinatum* GOLDF., *Cyathophyllum hexagonum* GOLDF., *Cyathophyllum caespitosum* GOLDF., *Calamopora polymorpha* a. var. *tuberosa* GOLDF., *Calamopora polymorpha* b. var. *ramoso - divaricata* GOLDF., *Calamopora spongites* a. var. *tuberosa* GOLDF. and *Calamopora spongites* b. var. *ramose* GOLDF.
Today this listing of taxa is only of historical value. Nevertheless honour is due to Unger having presented the first faunal list of Devonian fossils in Austria. The crest area of the Plabutsch from where the fossils originate is therefore the first area outside Great Britain and Germany where sediments were assigned to the Devonian system. Note that the Devonian period was established by Murchison and Sedgwick only 4 years before in 1839!
References: EBNER & HUBMANN (2012), HUBMANN et al. (2003).

3.2. Stop 2 – Forest road Attems

Topic: Fossiliferous shallow marine succession; type locality of the Plabutsch Formation; type locality of the udoteacean taxon *Pseudolitanaia graecensis*.
Locality: Forest road "Attems" at the southern slope of Frauenkogel, 47°05'18"N/15°22'05"E.
Lithostratigraphy: Plabutsch Formation (type section).
Biostratigraphy: –
Chronostratigraphic age: Eifelian; locally the sequence may range from upper Emsian to lower Givetian.
Description: Along the road variegated dolostones of the Flösserkogel Formation, marly shales and marly limestones (Gaisbergsattel Member) and dark grey marly bioclastic limestones of the Plabutsch Formation are exposed.

The outcrop along the road starts with whitish sandy dolostones of the Flösserkogel Fm. (Emsian) which passes into laminated dolomitic limestones (tidal flat deposits) in the uppermost part of the formation.

Separated by a fault brownish to yellow marly shales with moulds of chonetid brachiopods and very rare trilobites (*Maladaia* sp.) on bedding planes follow. At the base of this succession the shale is intercalated by marly limestone-beds less than 10 cm in thickness. The yellow to reddish-brown limestones are densely packed brachiopod or Eridostraca shell accumulations. Some brachiopod shells were used by auloporid tabulates (*Aulostegites* sp.) as substrate for anchorage. Partly the ostracods (unidentifiable smooth valved individuals) and eridostracs (*Eridoconcha papillosa* and *Cryptophyllus* sp.) are silicified in contrast to other fossil remains. The succession described reaches up to 8 to 10 metres in thickness and is assigned to the Gaisberg Bed of the Plabutsch Fm. (HUBMANN, 2003). The uppermost part of the Gaisberg Bed is characterised by the settlement of mound shaped favositid tabulates (*Favosites styriacus*) with diameters of colonies up to 80 cm. The occurrence of corals coincides with a rapid lithological change from orange marls and marly limestones to greyish blue limestone beds.

The first few metres of these limestones are dominated by a stromatoporoid-coral faunal association which passes into a coral-brachiopod biofacies. This community includes *Favosites*, *Thamnophyllum*, *Thamnopora*, *Zelophyllia* and other corals. Approximately at the middle part of the unit this community is replaced by a biofacies which is dominated by calcareous green algae (e.g., *Pseudopalaeoporella*, *Pseudolitanaia*; HUBMANN, 1990) and thamnoporids.

In the upper part of the Plabutsch Fm. thick valved brachiopods which are assigned to *Zdimir* cf. *hercynicus* occur. Together with „*Striatopora*" and *Thamnopora* they compose the brachiopod-coral biofacies (Fig. 9).

Within the entire sequence along forest road Attems, conodonts are sparsely distributed. Mainly icriodontids were found which suggest an Emsian–Eifelian age for the lower part of the Plabutsch Fm. (SUTTNER & BERKYOVÁ, 2009). Despite a very rich fauna (Fig. 10) the age of this formation remains problematic, because distinctive age-constraining fossils are rare (HUBMANN & MESSNER, 2005). Generally the faunal association indicates an uppermost Emsian to lowermost Givetian age.

References: EBNER & HUBMANN (2012), HUBMANN (1993, 2003), HUBMANN et al. (2003), HUBMANN & MESSNER (2005).

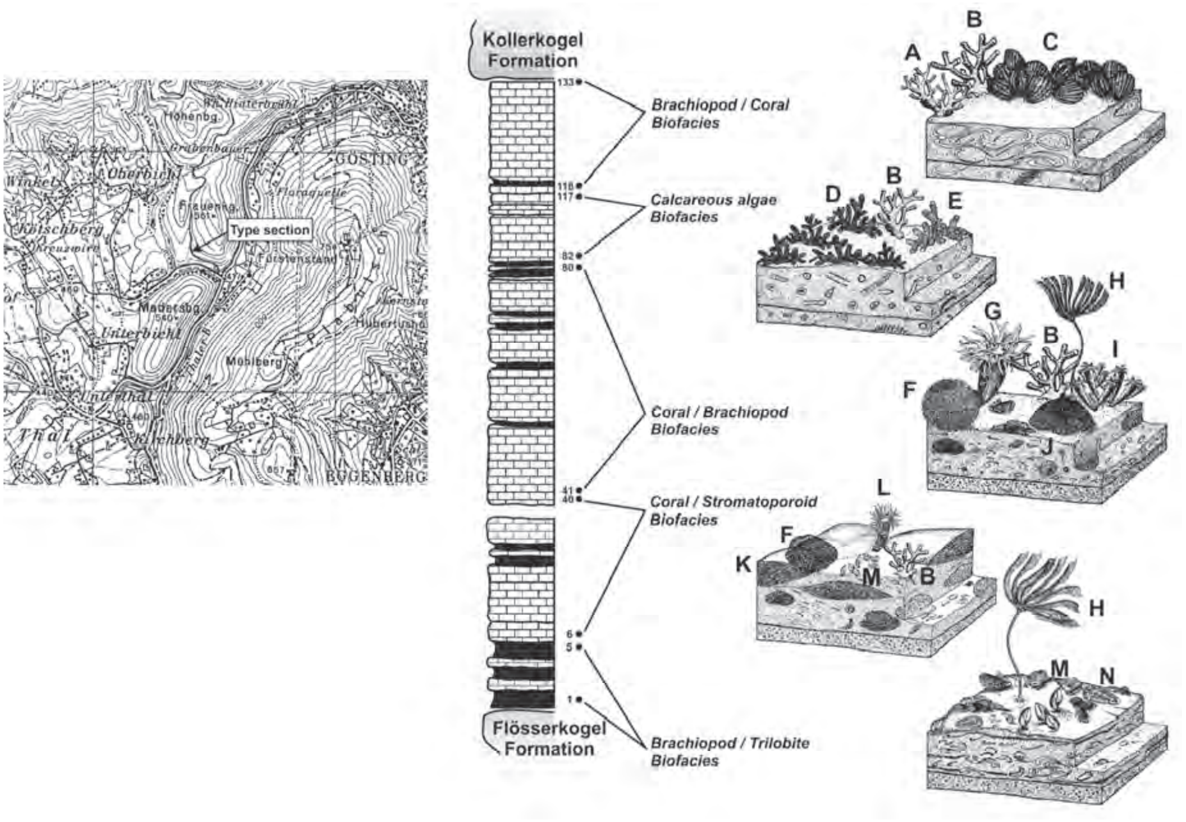

Fig. 9. Forest road Attems. Section of the Plabutsch Fm. subdivided into 5 biofacial sections: a: Siliciclastic Brachiopod-Trilobite-Biofacies ("Chonetenschiefer" = Gaisberg Bed) with: *Chonetes* sp., *Maladaia* sp., and crinoids; b: Coral-Stromatoporoid-Biofacies with: *Actinostroma* sp., *Thamnophyllum stachei*, *Thamnophyllum murchisoni*, *Favosites styriacus*, *Thamnopora* sp., *Striatopora* sp., *Pachycanalicula barrandei*, *Heliolites* cf. *peneckei*, Crinoids; c: Coral-Brachiopod-Biofacies with *Thamnophyllum stachei*, *Thamnophyllum murchisoni*, *Thamnopora reticulata* ?, *Thamnopora* sp., *Striatopora* (?) *suessi*, *Favosites* sp., *Chonetes* sp., "Spiriferids", Crinoids; d: Algae-Biofacies with *Pseudopalaeoporella lummatonensis*, *Pseudolitanaia graecensis*; e: Brachiopod-Coral-Biofacies with: *Zdimir* cf. *hercynicus*, *Thamnopora* cf. *reticulata*, *Striatopora* (?) *suessi* (modified from HUBMANN, 2003).

3.3. Stop 3 – Quarry Trolp/Forstkogel

Topic: Devonian–Carboniferous boundary; type locality of Lower Sanzenkogel Formation; type locality of the conodont taxon *Polygnathus styriacus*.

Locality: Abandoned quarry "Trolp", 47°04'7"N/15°19'18"E.

Lithostratigraphy: Steinberg Formation and Lower Sanzenkogel Formation (type section).

Biostratigraphy: *Bispathodus costatus* Zone to the *Gnathodus typicus* Zone.

Chronostratigraphic age: Famennian/Tournaisian boundary.

Description: The abandoned quarry exhibits an overturned stratigraphic sequence of the upper parts of the Steinberg Formation (Frasnian–Famennian) and the Lower Sanzenkogel Fm.; it is the type locality of the Famennian conodont taxon *Polygnathus styriacus*.

In the eastern face of the quarry an overturned section from the latest Devonian *Bispathodus costatus* Zone to the *Gnathodus typicus* Zone is exposed. This section includes the site which was discussed as a favourite for the international Devonian–Carboniferous boundary stratotype (SANDBERG et al., 1983; ZIEGLER & SANDBERG, 1984), the type section of the 220 cm Tournaisian Lower Sanzenkogel Fm. and a 20 cm thick horizon with shale, lydite and

Fig. 10. Typical fossils of the Plabutsch Formation. 1) *Thamnophyllum stachei* PENECKE, 1894, x 1,5; 2) *Thamnophyllum murchisoni* PENECKE, 1894, x 1,5; 3) Fragment of a calyx of *Tryplasma devonica* (PENECKE, 1894), x 1,5; 4) Fragment of a calyx of *Zelophyllia cornuvaccinum* (PENECKE, 1894), x 0,75; 5) *Disphyllum caespitosum* (GOLDFUSS, 1826), x 1,5; 6) *Pachycanalicula barrandei* (PENECKE, 1887), x 1,5; 7) *Thamnopora reticulata* (BLAINVILLE, 1830), x 2,2; 8) *Thamnopora vermicularis* (M'COY, 1850), x 2,2; 9) „*Striatopora*“ *suessi* PENECKE, 1894, x 2,2; 10) *Thamnopora boloniensis* (GOSSELET, 1877), x 2,2; 11) *Favosites styriacus* PENECKE, 1894, x 1,5; 12) *Atrypa reticularis* LINNE, x 1,5; 13) *Zeapora gracilis* PENECKE, 1894, x 3. All specimens are from the private collection of Fritz Messner.

phosphorite nodules (Trolp Phosphorite Bed) at the bottom of the Upper Sanzenkogel Fm. (Figs. 11, 12).

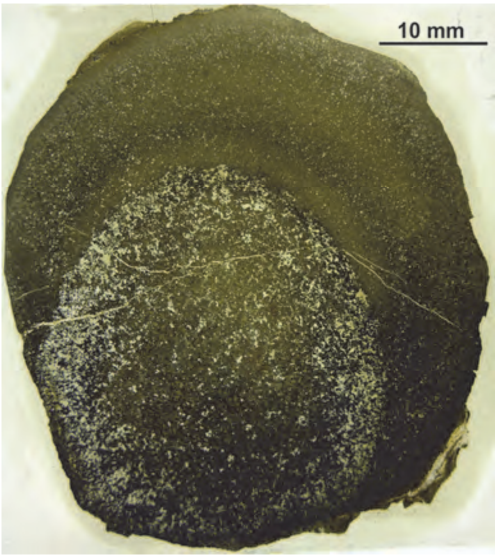

Fig. 11. Thin section of a phosphorite nodule with radiolarians from the Trolp Phosphorite Bed.

The sparsity of macrofossils and siphonodellid conodonts excluded this section as international boundary stratotype. In the section (Fig. 13) the beginning of the Carboniferous is indicated by the first occurrence of *Protognathodus kuehni. Siphonodella sulcata* as the international index conodont for the base of the Carboniferous was not yet found in the lowermost 20 cm of the Lower Sanzenkogel Fm. (EBNER, 1980; SANDBERG et al., 1983; ZIEGLER & SANDBERG, 1984; KAISER, 2005).

The boundary section is part of a 220 cm intensively investigated (conodonts, microfacies, stable isotope geochemistry) section (KAISER, 2005). The light-grey to ochre, sometimes nodular and flaser-bedded marly cephalopod limestones are rich in conodonts (CAI ~4.5) and represent a complete succession from the latest Famennian *Siphonodella praesulcata* to the Tournaisian *Siphonodella sulcata* Zone. At top of bed 9 there is a lithological change in form of a 1 cm thick argillaceous layer followed by thin bedded (~1–2 cm) marly limestones (mud- and wackestones) above which the base of the Carboniferous was recognised by the occurrence of *Protognathodus kuehni*. Due to the poor conodont fauna the marly bed is correlated with the main extinction phase of the Hangenberg event at top of the middle *Siphonodella praesulcata* Zone. This level is characterised by a positive $\delta^{13}C$ isotope excursion which coincides also with a main extinction phase during the deposition of the Hangenberg black shale in Germany and indicates a global perturbation of the carbon cycle during a period of warm seawater (KAISER, 2005).

Fig. 12. Type section of the Tournaisian Lower Sanzenkogel Fm. and the 20 cm thick horizon with shale, lydite and phosphrite nodules (Trolp Posphorite Bed) at the bottom of the Upper Sanzenkogel Fm.

The Tournaisian Trolp-Phosphorite Bed at the base of the Upper Sanzenkogel Fm. includes lydite with fragments of radiolarians (EBNER & HUBMANN, 2012). It indicates the deepening of the environment resulting in the formation of phosphorite nodules along upwelling zones of the Carboniferous shelf margin (EBNER et al., 2000).

References: NÖSSING (1974), EBNER (1980), EBNER et al. (2000), EBNER & HUBMANN (2012), KAISER (2005).

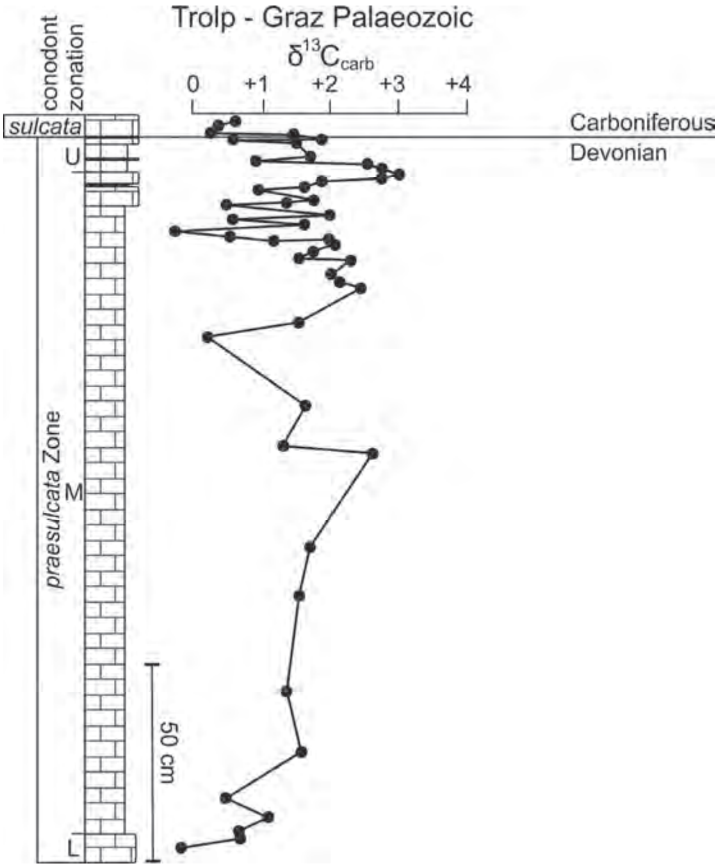

Fig. 13. Detail section across the Devonian–Carboniferous boundary (Steinberg Fm.–Lower Sanzenkogel Fm.) in the Trolp Quarry with the range of the conodonts and $\delta^{13}C_{carb}$ values (KAISER, 2005). Note the isotopic excursion in bed 10 and 11 and that in nature the section is inverted.

3.4. Stop 4 – Eastern slope of Höllererkogel (as an alternative to Stop 2 – Forest road Attems)

Topic: Shallow marine succession, very rich in tabulate and rugose corals and stromatoporoids.
Locality: Forest road at the eastern slope of Höllererkogel, 47°09'20"N/15°12'28"E.
Lithostratigraphy: Plabutsch Formation.
Biostratigraphy: –
Chronostratigraphic age: Eifelian; locally the sequence may range from upper Emsian to lower Givetian.
Description: The recently exposed section through the Plabutsch Formation along a forest path at Höllererkogel (near St. Pankrazen; W-Styria) provides an outstanding insight into a sequence of bioclastic limestones very rich in fossils.

In the course of forestry work a new profile through the upper portions of the Plabutsch Fm. was exposed which is built of mostly thick beds of dark grey-blue limestones. These beds (up to 60 to 80 cm) often result in layers strongly enriched fossil detritus. Corals or branches of coral respectively are often enriched suggesting that they did not have wide transport (Fig. 14). Presumably they derive from a thamnoporid coral carpet, which was destroyed by storm events.

References: EBNER & HUBMANN (2012), HUBMANN (1993, 2003), HUBMANN et al. (2003), HUBMANN & MESSNER (2005).

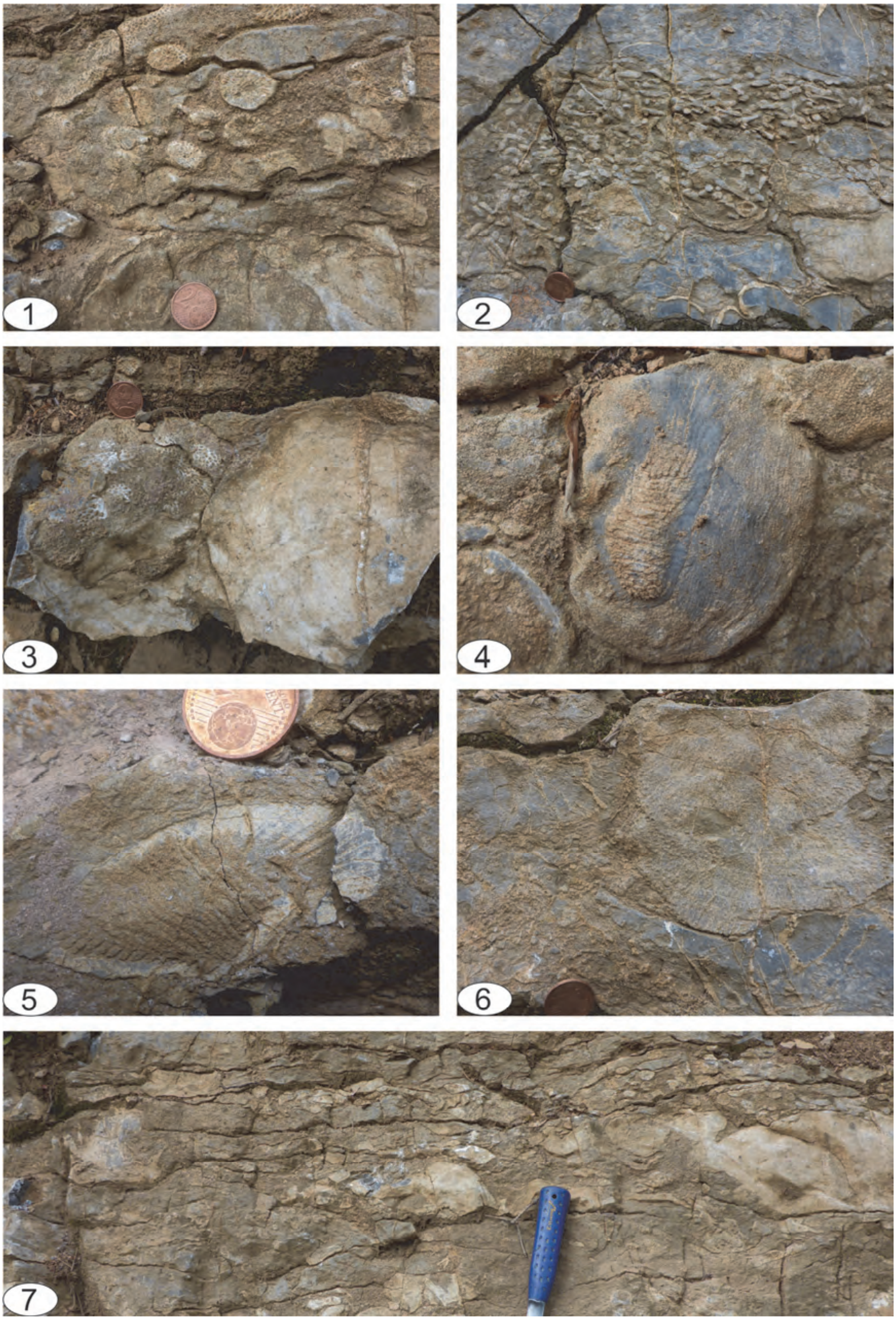

Fig. 14. Plabutsch Fm. at Höllererkogel. Details of weathered surfaces normal to bedding. Two cent coin for scale. 1) Cross sections of several branches of *Thamnopora boloniensis*; 2) Storm generated layer with densely packed of *Thamnopora reticulate*; 3) *Thamnopora boloniensis* and massive stromatoporoid (probably *Actinostroma*); 4) *Thamnophyllum* sp. in oblique longitudinal section incrusted by a stromatoporoid; 5) Oblique cross section of *Zelophyllia cornuvaccinum*; 6) Overturned heliolitid coral (? *Pachycanalicula barrandei*); 7) Vertical view on a bed (hammer shaft for scale).

3.5. Stop 5 – Farmstead Linshalmer (Geistthal)

Topic: Upper Cretaceous bituminous marls (“oil source rock”) and uplifted block of lower Devonian dolomites (“oil reservoir rock”).
Locality: “Linshalm road”, a small side road of state road L315 to Geistthal, 47°10'30''N/15°10'29''E.
Lithostratigraphy: St. Pankrazen Formation.
Biostratigraphy: –
Chronostratigraphic age: Upper Santonian to lower Campanian and Emsian.
Description: Dark brown bituminous marlstones with rare occurrences of very small gastropods and fish scales crop out along a road to the farmstead Linshalmer. According to RUSSEGGER et al. (1998) these marlstones were deposited in a temporary highly productive bituminous marl lake which was situated in near distance to the marine Gosau basin thus occasionally suffering alternatively from terrigenous influence and marine disturbances.
Approximately 100 metres to the north lower Devonian dolomites (Flösserkogel Fm. of the GP) are exposed at the road L315 to Geistthal. Bitumen on open joint planes of the dolomites indicate that these dolomites served as “oil reservoir rock” for bitumen emigrating from the bituminous marls (Fig. 15).
References: BOJAR et al. (2001), EBNER & RANTITSCH (2000), RUSSEGGER et al. (1998).

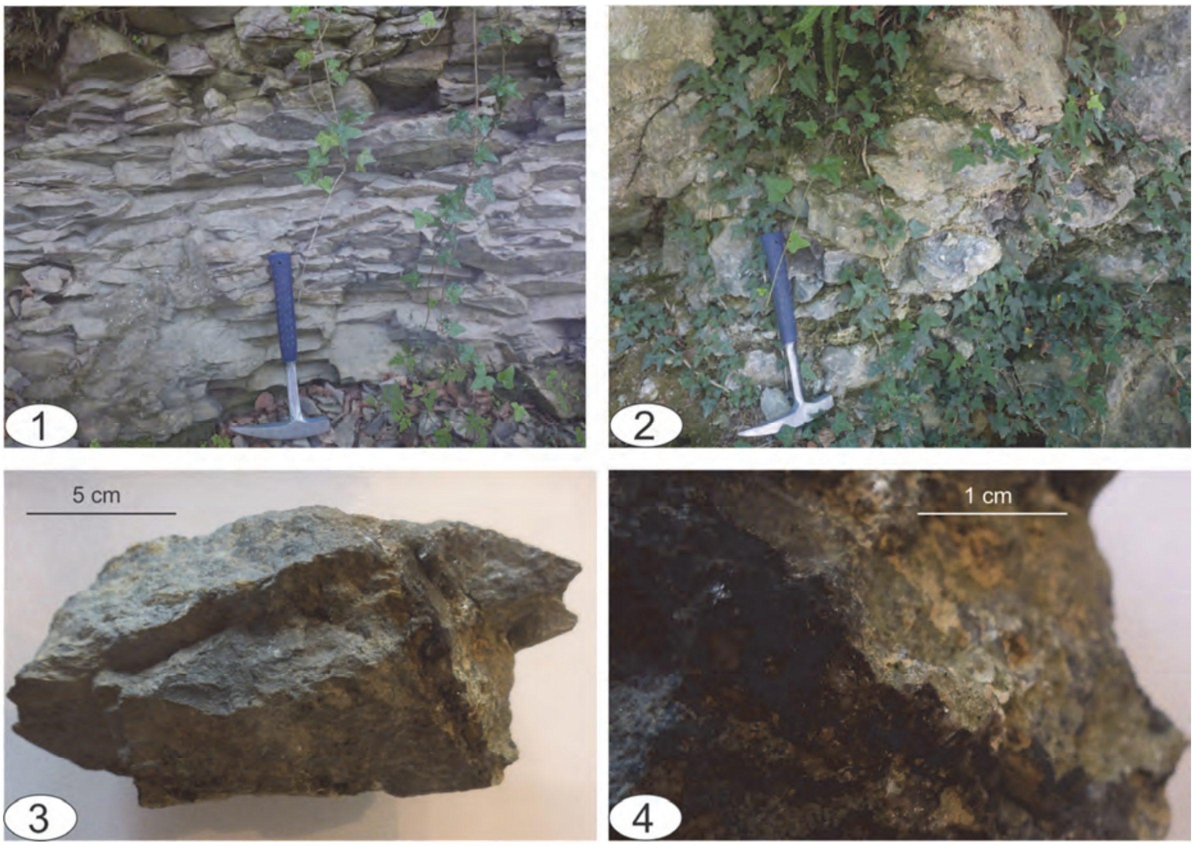

Fig. 15. 1) Dark brown bituminous marlstones of the St. Pankrazen Fm. at Linshalm road. Hammer for scale; 2) Lower Devonian dolomites (Flösserkogel Fm.) at road L315 to Geistthal; 3) Hand rock sample of the Devonian dolomite with bitumen on open joint plane; 4) Detail of 3).

3.6. Stop 6a – Geistthal

Topic: Basal sequence of the Kainach Gosau (lower part).
Locality: Road junction Almgrabenweg/Muralterweg northwest of Geistthal, 47°10'41"N/15°09'38"E.
Lithostratigraphy: Geistthal Formation.
Biostratigraphy: –
Chronostratigraphic age: Upper Santonian to lower Campanian.
Description: Polymict conglomerates in red (haematitic) matrix alternating with red siltstones (alluvial fan) (Fig. 16, 1–2).
References: SCHIRNIK (1995).

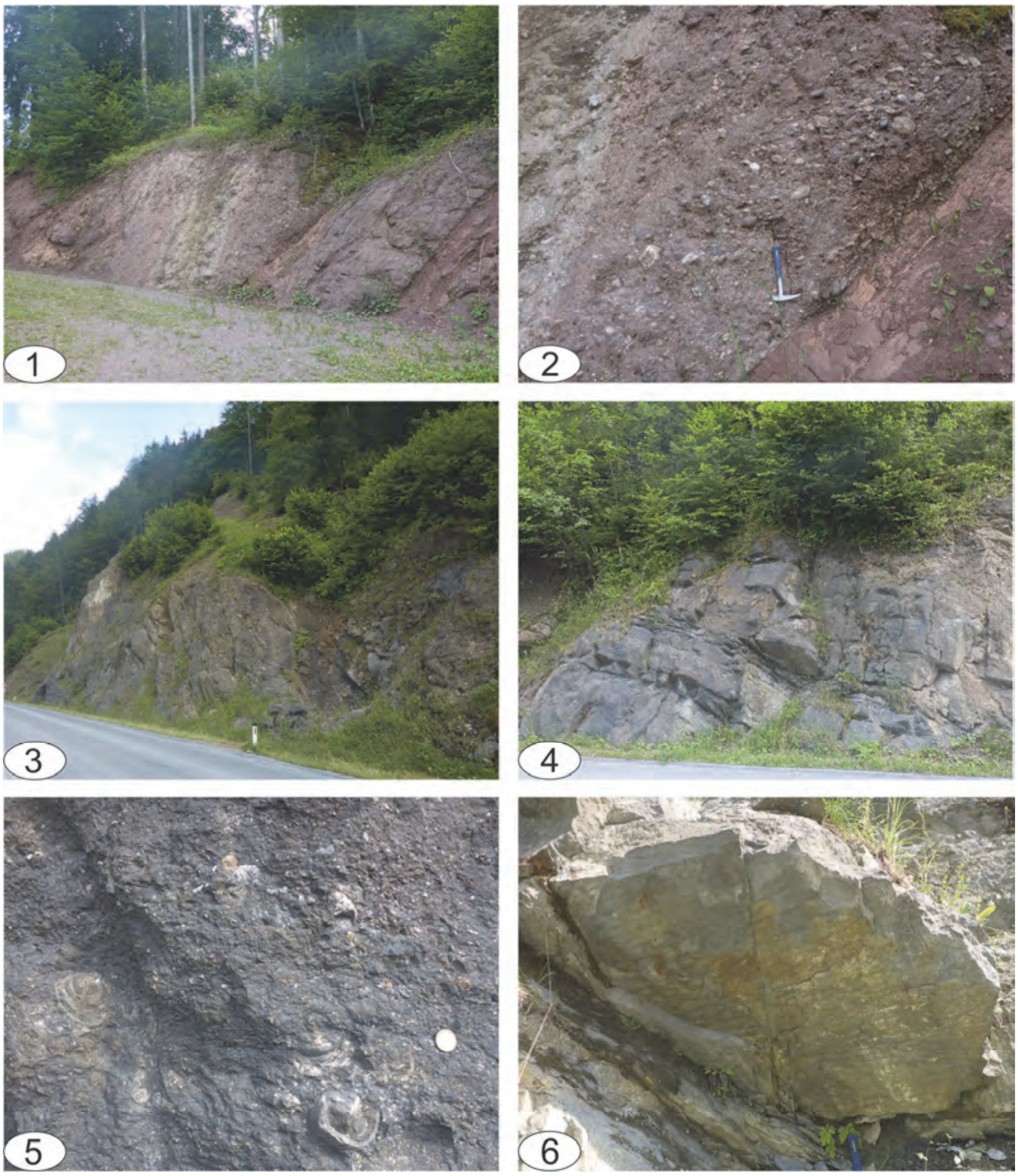

Fig. 16. Lower Geistthal Fm. at Geistthal (1–2) and upper Geistthal Fm. at Gallmannsegg.
1) Basal succession of the Geistthal Formation at Almgrabenweg/Muralterweg northwest of Geistthal; 2) Polymict conglomerate with red (haematitic) matrix. Hammer for scale (Detail of 1); 3) Section through conglomerate-sandstone alternation of the upper Geistthal Fm. along Gallmannsegg road; 4) Upper part of the section containing snail shells of 5) Some *Trochactaeon* shells in life position. One Euro coin for scale; 6) Symmetrical ripple marks on the lower surface of a sandstone bed.

3.7. Stop 6b – Gallmannsegg

Topic: Basal sequence of the Kainach Gosau (upper part).
Locality: Road junction Gallmannsegg Hauptstraße/Gschmurgraben, Gallmannsegg, 47°09'28"N/15°05'47"E.
Lithostratigraphy: Geistthal Formation.
Biostratigraphy: –
Chronostratigraphic age: Upper Santonian to lower Campanian.
Description: Polymict conglomerates with various limestone pebbles and black lydites alternating with dark grey sandstones. In the upper part of the outcrop thick-walled snail shells of *Trochactaeon* (Ø up to 10 cm) occur indicating an aquatic (brackish) depositional environment. Sandstones show symmetrical ripple marks (Fig. 16, 3–6).
References: SCHIRNIK (1995).

3.8. Stop 7 – Gratkorn Clay Pit

Topic: Late middle Miocene vertebrate site; palaeosol; limnic sedimentation.
Locality: Gratkorn Clay Pit, ~0.7 km E Gratkorn (~10 km NNW Graz), 47°08’14”N/15°20’56”E.
Lithostratigraphy: Gratkorn Formation and Gleisdorf Formation (Peterstal Member).
Biostratigraphy: Mammal Neogene zones MN 7+8; indirectly *Elphidium hauerinum*–*Porosononion granosum* foraminifera Zone.
Chronostratigraphic age: Upper Serravallian (upper Sarmatian *sensu* regional Central Paratethyan stages).
Description: The Gratkorn pit is situated in the eastern part of the Gratkorn Basin, which belongs to a series of embayments along the northern margin of the Styrian Basin (Fig. 17). Sedimentation in the Styrian Basin as well as in its satellite basins was – beside tectonics – strongly affected by short-term sea level changes of the Central Paratethys. This enabled the development of a detailed sequence stratigraphic concept in addition to a comprehensive aquatic biota-based biostratigraphy (e.g., KOLLMANN, 1965; HARZHAUSER & PILLER, 2004; SCHREILECHNER & SACHSENHOFER, 2007). However, in marginal basin areas, where alluvial to lacustrine deposition predominates, stratigraphic tie points are scarce. Especially, at the northern and north-eastern fringe of the Styrian Basin (including the Gratkorn Basin) these hardly exposed sediments are (index)fossil-poor and radiometrically datable volcanoclastic intercalations are unknown. Nevertheless, a correlation with the high-resolution stratigraphic framework of the open Styrian Basin could be established during the last years (GROSS et al., 2007b; HARZHAUSER et al., 2008; GROSS, 2015; Figs. 6, 18).

3.8.1. Litho-, bio- and chronostratigraphy

In the eastern Gratkorn Basin, more than 20–30 m thick, polymict coarse gravels/conglomerates with sandy or pelitic matrix form the lowermost part of the exposed basin fill. Occasionally, horizontally or cross-bedded fine–medium grained gravels and sands are intercalated; locally, palaeosol formation is observed (e.g., Gratkorn pit). These strata are termed Gratkorn Formation and are interpreted as deposits of a braided river system, partly influenced by distal alluvial fans.

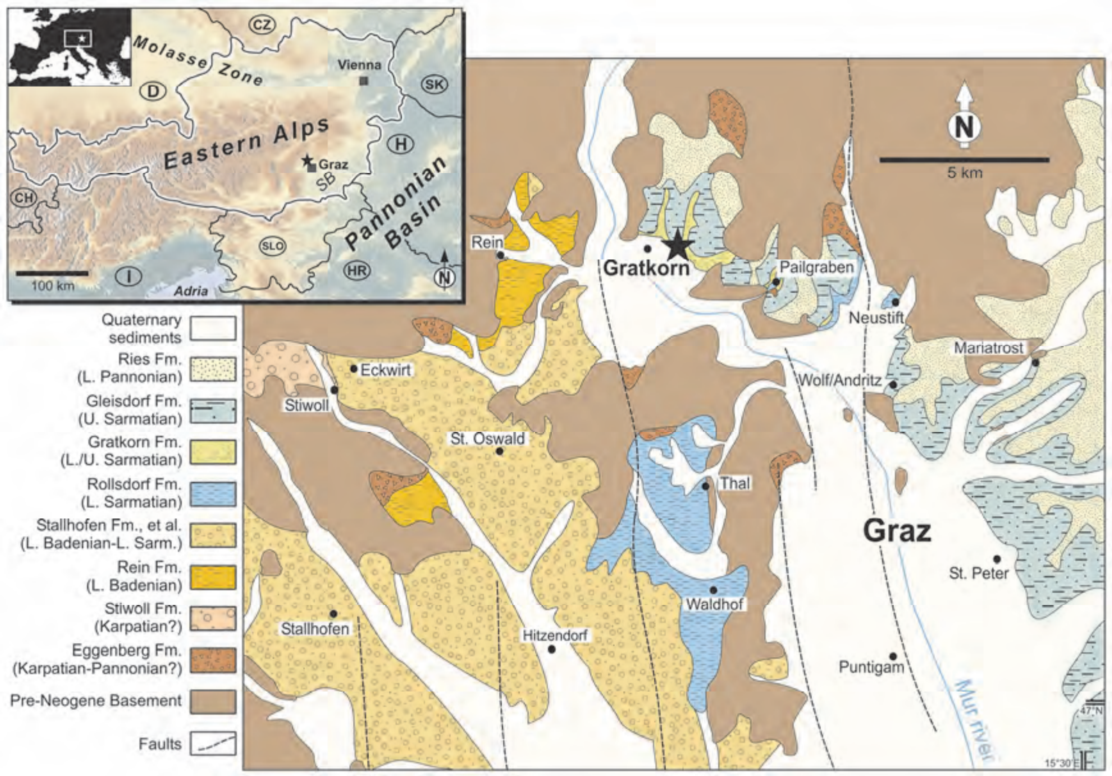

Fig. 17. Location of the Gratkorn clay pit (L. = lower; U. = upper; after GROSS et al., 2014).

The Gratkorn Fm. is overlain by up to 25 m thick, massive or laminated, frequently plant-bearing, largely limnic pelites (Peterstal Member/Gleisdorf Formation; e.g., clay deposit at the Gratkorn site). Alternations of gravel–sand–pelite follow above (Lustbühel Member/Gleisdorf Fm.), which are topped by fluvial gravels/conglomerates with rare sandy and pelitic intercalations (Ries Formation; lower upper Miocene/Pannonian; for a recent compilation of the lithostratigraphic framework see GROSS, 2015).

The Gratkorn Fm. can be traced out into the Styrian Basin, where it is underlain by marginal marine, lower Sarmatian sediments (Rollsdorf Formation; *Elphidium reginum–Elphidium hauerinum* Zone; GROSS et al., 2007b). Index fossils are missing in the overlying Peterstal Mb., however, in the area of Graz, the Lustbühel Mb. contains rare marginal marine faunas as well as thin oolitic layers, indicative for a late Sarmatian age (*Porosononion* Zone; GROSS et al., 2007b).

The position of the Gratkorn Fm. between biostratigraphically dated underlying lower Sarmatian strata (Rollsdorf Fm.) and upper Sarmatian hanging wall sediments (Gleisdorf Fm.) relates its deposition to the so-called “Carinthian Phase” at the end of the early Sarmatian (e.g., GROSS et al., 2007b, 2011; Fig. 18). During that phase a wide-ranging sea level fall is recorded in the Vienna Basin as well as in the adjacent Pannonian Basin and Austrian Molasse Zone (e.g., HARZHAUSER & PILLER, 2004; STRAUSS et al., 2006; SCHREILECHNER & SACHSENHOFER, 2007; KOVÁČ et al., 2008). This enables a correlation of the Gratkorn Fm. with the sequence stratigraphic concept of the Styrian Basin. LIRER et al. (2009) proposed an age of about 12.2. Ma for the early/late Sarmatian boundary. As for the limnic pelites of the Peterstal Mb./Gleisdorf Fm. normal magnetic polarity is recorded at the Gratkorn pit, a correlation to Chron C5An.1n (12.174–12.049 Ma after HILGEN et al., 2012) is possible. Hence, the vertebrate-bearing palaeosol of the Gratkorn pit is assumed to have formed around the early/late Sarmatian boundary, about 12.2–12.0 Ma (GROSS et al., 2011).

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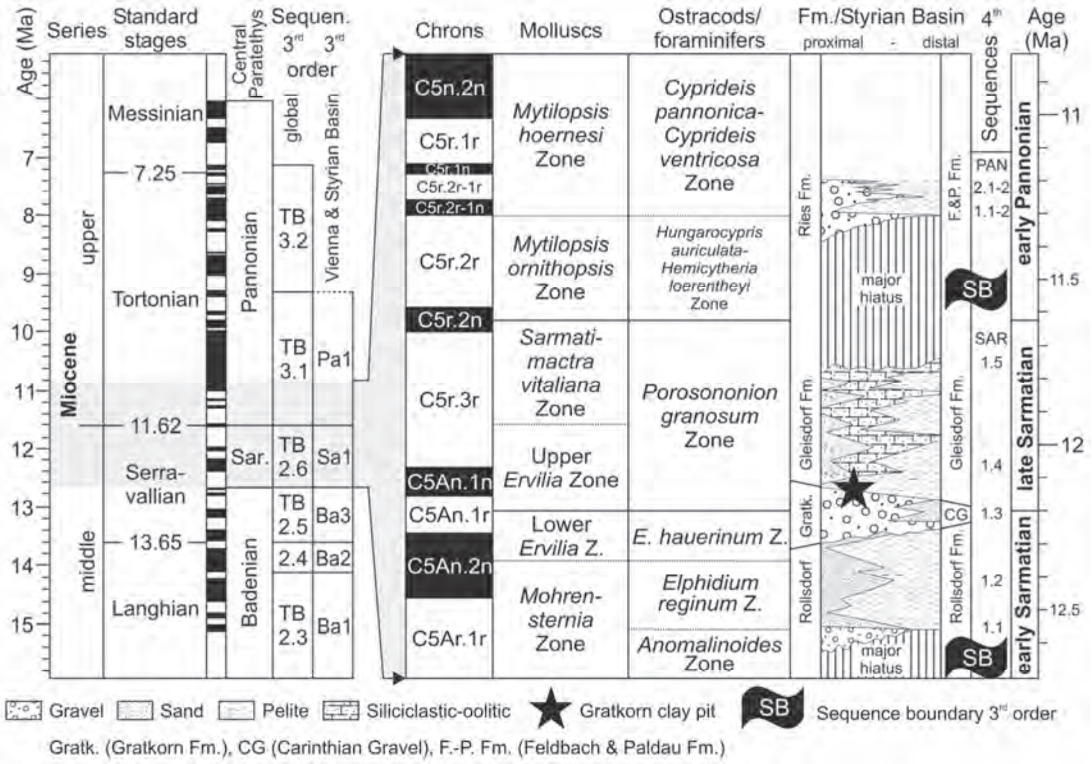

Fig. 18. Stratigraphic position of the Gratkorn site (after GROSS et al., 2011, 2014).

3.8.2. Section and facies interpretation of Gratkorn

At the Gratkorn pit calcareous pelites are exploited for cement production (Fig. 19). The vertebrate-bearing palaeosol represents the mining floor. The sediments below working level could be studied in prospecting holes only (Figs. 20, 21a).

The basal gravels (1) are interpreted as gravel bar deposits of a braided river system, topped by sandy and silty fine sand layers (2, 3) of flash floods (crevasse splays) in an overbank environment (Fig. 20). Subsequent soft sediment deformation (dewatering) and indistinct pedogenic processes overprinted these layers to a certain degree. Similarly, layers 4–5 are assumed to represent post-sedimentary altered (including tectonic activity) deposits of a succeeding flooding event (crevasse splay).

Above, a sand layer (6) forms the base of a calcic horizon (7). The calcrete horizon contains ferruginous nodules (some might be rhizoconcretions) as well as cemented meniscate burrows (up to dm long, some cm wide). Carbonate nodules are discrete or amalgamated to each other. Upon a diffuse, irregular boundary, a pelitic layer (8) follows, which includes many ferruginous nodules and some meniscate burrows. Layers 6–8 are interpreted as deposits of another flooding event (crevasse splay) within an overbank environment. The moderately developed calcrete (7) directs to an extended period (10^3–10^4 yrs?) of pedogenesis as well as to an overall arid/semi-arid climate with seasonally variable precipitation (for further palaeoclimate estimations see GROSS et al., 2011; BÖHME & VASILYAN, 2014).

The sandy layer (9) indistinctly fines upwards and merges into silty fine sand (10) with abundant ferruginous nodules as well as burrows of variable shape and size (Fig. 21b, c). Large meniscate burrows of both layers equal possible freshwater crayfish burrows from the Bavarian Upper Freshwater Molasse (SCHMID, 2002). We interpret both strata as crevasse splay deposits, which subsequently experienced weak pedogenesis and intensive bioturbation.

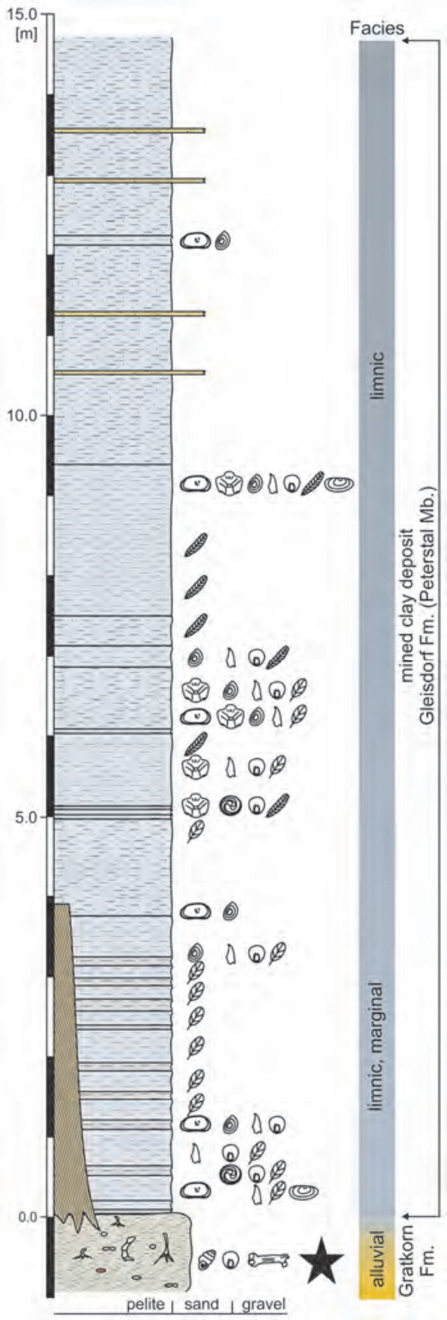

Fig. 19. Section of the Gratkorn clay deposit (after GROSS et al., 2014; for legend see Fig. 20).

Layer 10 grades upwards into a ~0.4 m thick, angular blocky structured, silty fine sand to fine sandy silt horizon (layer 11a; Fig. 21d). Frequently ferruginous nodules, numerous oxidised root traces, some septaria-like glaebules, clustered pits of hackberry (*Celtis*), few terrestrial snails as well as extremely rare phosphatic coprolites occur. Layer 11a pass gradually into a slightly laminated, intensively mottled fine sandy silt (11b; Fig. 21e), which enclose a lot of oxidised root traces, *Celtis* endocarps, snails and locally accumulated owl pellets as well as sand filled burrows of variable dimensions. The vertebrate fauna of Gratkorn (except rare fish remains from the hanging wall pelites) originate from layers 11a and b. Vertebrate remains are largely rubiginously stained, adhere ferruginous rhizoconcretions and coatings as well as fibrous, drab-haloed root traces. However, several remains (in particular from layer 11b) are almost whitish, while others are nearly black coloured.

These strata are interpreted as pedogenically altered overbank deposits, influenced only occasionally from the braiding river system during flooding. The rather uniform appearance of this floodplain palaeosol (no distinct soil horizons), semi-articulated vertebrate remains (without signs of fluvial relocation), preserved pellets of nocturnal raptors and rare coprolite findings argue for a fairly short period of soil formation (probably in the order of a few decades only; GROSS et al., 2011; HAVLIK et al., 2014; PRIETO et al., 2014).

The co-occurrence of calcic- (some are septaria) and ferric nodules, of aragonitic *Celtis* endocarps and snail shells as well as vertebrate bones and teeth indicate transient water logging during soil development and thus to alternating wet and dry periods (RETALLACK, 2001). This match to a semi-arid to sub-humid climate with less than 500 mm mean annual precipitation during soil formation (GROSS et al., 2011; BÖHME & VASILYAN, 2014). Relict bedding, intense mottling and drab colouring hints to a more pronounced hydromorphic setting for the upper part of the vertebrate bearing layer (11b) and a shorter inference of pedogenic processes in comparison to the lower part (11a). Especially, the preserved owl pellets signify a very fast (<1 yr?) burial of layer 11b (PRIETO et al., 2010, 2014; GROSS et al., 2011).

Ferric staining and incrustation of vertebrate remains as well as ferruginous rhizoconcretions refer to varying redox-conditions within the soil. Selective bleaching of bones due to thin, drab-haloed root traces points to seasonal variations in water logging of the rhizosphere (RETALLACK, 2001). Anyway, the variable colouring of vertebrate remains (especially in layer 11b) hints to changing moisture of the palaeosol. Possibly, even within one season, water logging varied significantly laterally due to the local topography of the overbank area.

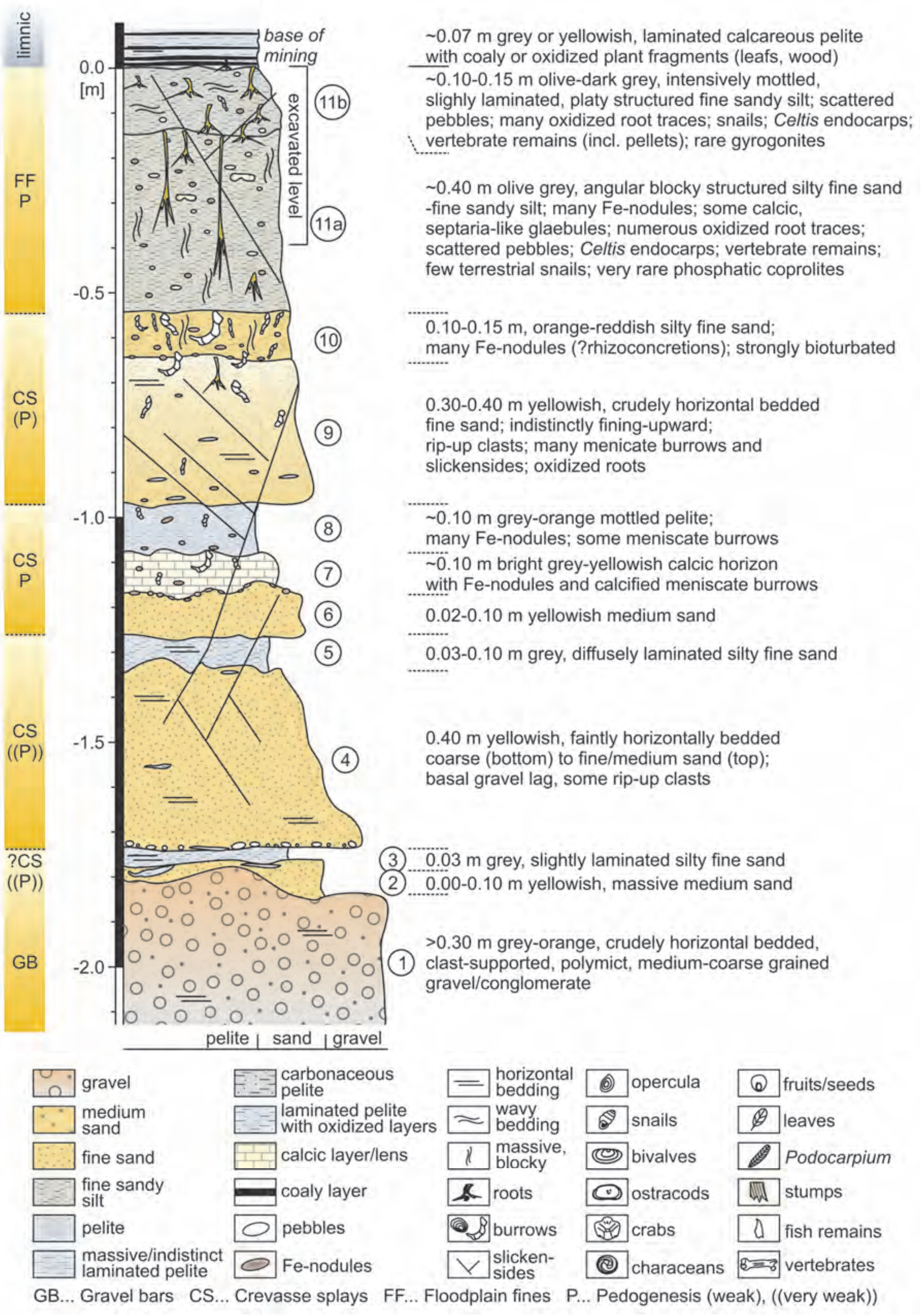

Fig. 20. Section below the mining floor of the Gratkorn clay pit (after GROSS et al., 2011, 2014).

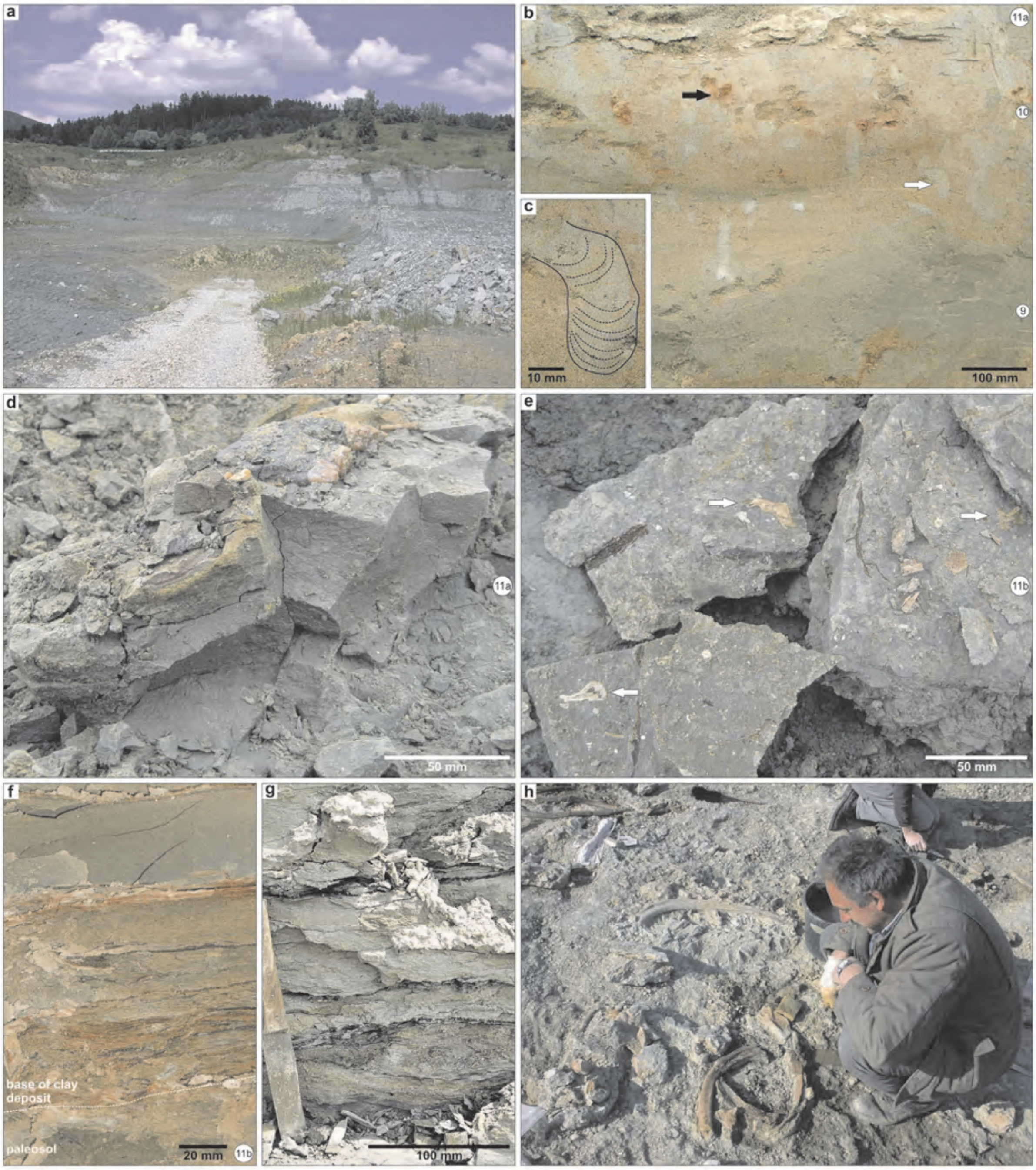

Fig. 21. a) Gratkorn clay pit: below the grey clay deposit, the brownish palaeosols is partly exposed (May 2005); b) Intensively bioturbated sand (especially layer 10; white arrow = burrow redrawn in c; black arrow = ferruginous nodules, possibly rhizoconcretions); c) Example of a large (dm deep), meniscate burrow; d) Angular blocky structured, silty to fine sandy lower part (layer 11a) of the Gratkorn palaeosol enclosing a suid jaw; e) Platy structured, silty upper part of the Gratkorn palaeosol (layer 11b) enclosing a cricetid skeleton (white arrows), numerous, oxidised rhizoconcretions as well as whitish coloured gastropod and *Celtis* remains; f) Transition from the uppermost part of the palaeosol (layer 11b) to plant rich, laminated pelites (in this case, both are in an oxidised stage); g) Laminated, non-oxidised, grey pelite with cm-thick lignitic interlayers (lower part of clay deposit); h) Excavation of a disarticulated *Deinotherium*-skeleton (April 2006).

Similarly, gastropod, small and large mammal assemblages as well as isotope analyses refer to a well-structured, riparian landscape (HARZHAUSER et al., 2008; AIGLSTORFER et al., 2014a; PRIETO et al., 2014).

Ubiquitous root traces testify that the soils surface was planted in some way. However, only the primarily mineralised and thus favourably preservable *Celtis* endocarps provide concrete palaeobotanical evidence that medium-sized hackberry trees have been growing on the fossiliferous substrate (layer 11a–b) at its time of formation (HAVLIK et al., 2014). Vital infaunal life on the floodplain soil is indicated by the abundant occurrence of subterranean snails (HARZHAUSER et al., 2008) and tentative insect ichnofossils (HAVLIK et al., 2014).

The vertebrate bearing layer (11) is covered by laminated, calcareous pelites with a large amount of carbonaceous or diagenetically oxidised leaf litter (largely monocotyledons, *Salix*, *Potamogeton*; Fig. 21f, g). Except rare root traces in the lowermost centimetres of the clay deposit, pedogenic features are absent. Sporadically, slightly silicified, autochthonous lignitic tree trunks (*Taxodioxylon*; HAVLIK et al., 2014), possibly several metres in height, were excavated during mining.

In particular, the lower four metres of the >15 m thick clay deposit yield frequently cm-thick lignitic intercalations. Up-section, the pelites include only subordinately plant-rich and fine sandy layers. Diversity of the fossil leaf flora is quite low but dozen of seed and fruit taxa, beside several freshwater ostracod species are documented from the clay deposit (MELLER & GROSS, 2006; GROSS, 2008). Some layers enclose claws and exuvia of freshwater crabs (KLAUS & GROSS, 2010), freshwater gastropods (e.g., *Bithynia* opercula), characean gyrogonites and fish fragments (bones and cyprinid pharyngeal teeth; BÖHME & VASILYAN, 2014). Sphaeriid bivalves were occasionally found in the lowermost parts of the section, while unionids are rarely present in the upper part. Sporadically, insect (beetle, bug) and isopod (wood lice) remains as well as avian eggshells were discovered in the lowermost part (GROSS et al., 2011; HAVLIK et al., 2014).

Based on the ostracod record as well as on potamid crab and fish findings, a shallow, partly richly vegetated freshwater lake environment within a warm, perhaps subtropical climate is assumed as depositional setting for the clay deposit (GROSS, 2008; KLAUS & GROSS, 2010; BÖHME & VASILYAN, 2014).

3.8.3. Taphonomy of larger vertebrates

At the beginning of the excavations, postcranial elements (ribs, limb bones, vertebras) and isolated teeth of a *Deinotherium*-skeleton were found scattered within an area of ~140 m^2 (Fig. 21h). The bones are weakly permineralised and experienced some post-depositional damage due to compaction. Some bones are clearly affected by slickensides, others were heavily decomposed, indicating a longer surface exposure and weathering of the carcass. However, several specimens might have suffered damage because of trampling (GROSS et al., 2011; AIGLSTORFER et al., 2014b; HAVLIK et al., 2014).

Although all skeletons of larger vertebrates were found disarticulated, many skeletal parts belonging to the same individual are embedded in short distances from each other. The material displays no obvious signs of abrasion (e.g., rolling) or re-working due to, e.g., fluvial transportation and lacks any preferred orientation.

The bones of medium sized animals (e.g., turtles, tragulids) show a high degree of primary fragmentation and are often heavily splintered. These cracked bones infer the activity of predators and/or scavengers, which might be partially responsible for local accumulation and/or dislocation, and, maybe, for some taphonomical biases. The record of carnivores is still poor; however, very rare coprolites, a few teeth and one mustelid skull indicate their presence. Due to the findings of *Varanus* sp., this large-sized monitor lizard might have been represented a significant predator/scavenger within this terrestrial food web additionally.

Frequently, the bone splinters itself bear minute biting traces. Equally, many tortoise plates and mammalian bones exhibit similar, several mm-long and ~mm-wide, more or less parallel series of grooves, affecting regularly the complete margins of these bones. These marks resemble well the ichnogenus *Machinus*. They are assumed to be traces of gnawing produced by rodents and/or insectivores (e.g., squirrels, hamsters or shrews) to obtain nutrients (collagen and vitamins) from the bones. Alternatively, such animals simply could have used it to sharpen their teeth. Additionally, randomly arranged, several mm-long and -wide scratches sometimes occur on compact bones. These marks are very similar to structures related to traces of osteophagous termite activity (GROSS et al., 2011; HAVLIK et al., 2014; PRIETO et al., 2014).

3.8.4. Taphonomy of small vertebrates

In the first excavation campaign, small vertebrates were only scarcely found. Afterwards in an area of about two square metres a few dozen of gymnures, hamsters and ectothermic vertebrate skeletons and associated elements (skulls, jaws, extremities) were discovered in the upper part of the palaeosol (layer 11b; Fig. 21e). Bones and teeth are generally very well preserved, most often only insignificantly corroded and mainly beige coloured (PRIETO et al., 2010). PRIETO et al. (2010, 2014) explain such extreme local concentration of small vertebrate remains as the result of pellet accumulations at feeding/resting places of birds of prey, in more detail of owls. In contrast to, e.g., diurnal raptors or mammalian carnivores, owls cause only minor effects of digestion. Thus, the low grade of corrosion, the extreme concentration and the roughly equal co-occurrence of cranial and postcranial elements point to accumulated owl pellets. Those pellets reflect more or less the local small vertebrate fauna around the locality. Taxonomical biases may have occurred due to alimentary preferences of the owl as well as the abundance of prey (PRIETO et al., 2010, 2014).

Moreover, the presence of pellets excludes a considerable postdepositional dislocation or a long surface exposure and therefore underlines a rapid deposition (<1 yr?) of the upper part of this palaeosol (layer 11b). Perhaps, some single microvertebrate skeleton associations might be persevered *in situ*, maybe in their burrows (e.g., spadefoot toads, glass lizard, hamsters or talpids). Unfortunately, such burrows are not recorded up to now, making this suggestion tentatively.

Altogether, the vertebrate taphocoenose of Gratkorn experienced a variety of predepositional modification, and after burial, compaction (in early phases probably also trampling) and subterranean life as well as abiotic soil forming processes acted on it. However, the weak stage of soil development and the observed taphonomic features point to a rather low extent of time-averaging of the fossil community (maybe only or even less than tens or hundreds of years). The presence of pellet remains even indicate a much more rapid burial for the upper part of the palaeosol (layer 11b). In a strict sense, this is definitely not an example for an “event horizon” – like a sudden mass mortality event – and the structure of the taphocoenose is certainly obscured to some degree. Nonetheless, we are facing to an *in situ* evolved *Fossillagerstätte*, which developed quite rapidly.

3.8.5. Biochronological significance of the Gratkorn vertebrate fauna

Fossil vertebrates from Gratkorn are exceptional by their preservation as well as their diversity. Do date, 65 vertebrate species (except carnivore mammals) are described, belonging to fishes (2 taxa), amphibians (8 species), reptiles (17 species), birds (4 species), and mammals (34 species), thus comprising all major vertebrate groups. To our knowledge, this is the highest recorded vertebrate diversity for stratified deposits in the late middle Miocene of Europe.

This high diversity, which is also documented by 17 terrestrial gastropod species (HARZHAUSER et al., 2008), may be explained by ecosystem diversity, rapid sediment accumulation and long-term systematic excavations, minimizing taphonomic biases. Furthermore, integrated stratigraphic investigations firmly correlate the Gratkorn Fm. chronostratigraphically with the beginning of the late Sarmatian *s.str.*

Thus, exceptional preservation, high biodiversity, extremely low time-averaging, and a substantiated chronostratigraphy are outstanding features, which render Gratkorn to a key locality for the Central Paratethys and beyond. Especially mammalian biochronology suffers from problems related to low diversity, missing documentation of excavations, high time-averaging, unresolved geologic and chronostratigraphic background, preventing so far mammalian biostratigraphic schemes on continental scale for the Miocene.

Biochronologic investigations concordantly place Gratkorn to MN 7+8 at the end of the middle Miocene (DAXNER-HÖCK, 2010; PRIETO et al., 2010, 2014; GROSS et al., 2011). However, a more detailed stratigraphic correlation is complicated by still insufficiently resolved evolutionary lineages, stratigraphically mixed comparative faunas, and, maybe most importantly, by lack or uncertainty of chronostratigraphic ages for many of the Central European mammalian faunas (e.g., AIGLSTORFER et al., 2014b, c; PRIETO et al., 2014). To overcome these problems future work is needed in which Gratkorn is a benchmark towards a mammalian biostratigraphic subdivision of the Central Paratethyan area.

References: AIGLSTORFER et al. (2014a–c), BÖHME & VASILYAN (2014), GROSS (2008, 2015), GROSS et al. (2007b, 2011, 2014), HARZHAUSER et al. (2008), PRIETO et al. (2014).

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