Field Trip PRE-1
Upper Cretaceous and Paleogene at the northwestern Tethyan margin (Austria, S Germany): Boundaries, Events, Cycles and Sequences

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17 August 2017 Upper Cretaceous-Paleogene Gosau Group at Gams/Styria

Route: Vienna–Gams/Styria

Stop 1. Cretaceous/Paleogene boundary at Knappengraben
Stop 2. Cretaceous/Paleogene boundary at Krautgraben/Gamsbach
Stop 3. Mid-Maastrichtian ammonite site E of Haid
Stop 4. Upper Turonian sandstones and rudists at Pitzengraben and along Noth road
Stop 5. Gams Geozentrum Museum

Overnight at Abtenau, Lammertaler Hof, Abtenau, www.lammertalerhof.at

18 August 2017 Upper Cretaceous Gosau Group at Gosau Valley and Rußbach

Stop 6. Lake Gosau (Gosausee) in the Gosau valley
Stop 7. Upper Santonian rudist-limestones above a Santonian transgression
Stop 8. Sandkalkbank/Schattau-Rußbach (Upper Santonian)
Stop 9. Pass Gschütt/Streiteck Formation (lunch stop)
Stop 10. Parking area Rußbach
Stop 11. Section through the Lower Gosau Subgroup, Randograben

Overnight at Abtenau, Lammertaler Hof, Abtenau, www.lammertalerhof.at

19 August 2017 Cretaceous transect from the Alps to the Foreland (Germany)

Stop 12. Postalm road, Abtenau, Gosau Group
Stop 13 Cenomanian–Turonian at Rehkogelgraben/Hagenmühle (Upper Austria)
Stop 14. Schutzfelsen near Pentling
Stop 15. Dantschermühle section near Bad Abbach (Germany)

Overnight at Prösslbräu, Adlersberg, www.adlersberg.com & Hotel Krieger, Mariaort, www.gasthof-krieger.de

20 August 2017 Danubian Cretaceous Group, Bodenwöhrer Senke, Regensburg, Germany

Stop 16. Sandpit near Trischlberg
Stop 17. Parish church in Neubäu am See (optional)
Stop 18. Haimerl quarry near Grub
Stop 19. Obertrübenbach quarry

Obertrübenbach–Vienna, end of field trip

Introduction to the Geology of the Eastern Alps

The Eastern Alps and the Alpine foreland provide a classical area for geology and geologists, being investigated in detail since the 18th century and having been visited and described by eminent geologists like SEDGWICK & MURCHISON (1832). Classical geological concepts have been developed from the study of the Alps and in particular its eastern margin such as the process of "eustasy" by EDUARD SUESS (1888).

Geological Overview

The Eastern Alps represent a highly compressed segment of the Alpine mountain chain, located between the Rhine valley to the west and the Neogene Vienna Basin at the border to Slovakia toward the east. The Eastern Alps comprise a thrust orogen, which originated within the western Tethys paleogeographic domain due to repeated convergence between the European and the African plate and microplates such as the Adriatic/Apulian plate in-between.

The orogenic evolution can be divided into several stages of deformation: a Jurassic to Cretaceous, "Eoalpine" stage, followed by Meso- and Neoalpine deformational events from the Late Eocene and Miocene onwards. The geodynamic evolution is strongly discussed because of polyphase deformation overprinting Mesozoic structures, the incompleteness of the sedimentary record and the less constrained paleogeographic and paleotectonic positions of individual tectonic domains. These led to a variety of proposed models for the evolution of the Eastern Alps during the Mesozoic, differing especially in the inferred positions and timing of subduction zones, collisions and suturing (e.g. FAUPL & WAGREICH, 2000; STÜWE & SCHUSTER, 2010; HANDY et al., 2015).

Five major tectonic units representing different paleogeographic realms can be distinguished from the European foreland to the Eastern Alps (Text-Fig. 1):

(1) The **foreland** represented by the Molasse basin and its underlying **Mesozoic autochthonous strata** representing the northern part of the broad European shelf including the Danubian Cretaceous Group ("Regensburg gulf") above Variscan deformed basement.
(2) The **Helvetic zone**, including Helvetic and Ultrahelvetic units of the European shelf and continental slope, and the Gresten Klippen Zone in the eastern part of the Eastern Alps;
(3) The **Penninic zone**, including the Rhenodanubian Flysch Zone and metamorphosed rocks exposed in tectonic windows in the central parts of the Eastern Alps;
(4) The **Austroalpine zone** including the Northern Calcareous Alps, and
(5) The **Southalpine zone** at the southern border of Austria, both units of the Austroalpine microplate. The Austroalpine zone is subdivided into Lower and Upper thrust complexes and includes both basement and cover units. Within the Upper Austroalpine zone the **Northern Calcareous Alps** (NCA) represent a polyphase structured pile of cover nappes composed of thick Triassic-Jurassic carbonate successions.

Alpine orogeny commenced with the closure of a Triassic Neo-Tethys oceanic branch ("Hallstatt-Meliata Ocean") within the Austroalpine domain during the Middle to Late Jurassic. Contemporaneously, the Penninic Ocean, a continuation of the Ligurian Ocean (and thus the Atlantic Ocean), opened by oblique rifting and spreading between the European plate and the Austroalpine microplate, connected to the opening of the Atlantic Ocean. Jurassic subduction processes in the Hallstatt-Meliata Ocean resulted in an elevated suture zone towards the present south of the NCA. The Penninic Ocean´s tectonic regime changed to transpression and subduction during the Cretaceous, and an accretionary wedge developed to the north of the NCA. During the Early Cretaceous, the sedimentary cover of the NCA was sheared off from its basement and stacked into a complex nappe pile (Text-Fig. 2). Later on, a second main phase of compression and thrusting during the Eocene–Oligocene structured the Alpine orogen, followed by mountain building and foreland subsidence. Oligocene to Miocene lateral extrusion lead to strike-slip faulting, dismembering and the formation of intramontane basins like the Vienna Basin, on top of Alpine thrust structures.

Stratigraphic Overview

European Foreland and Helvetic zones

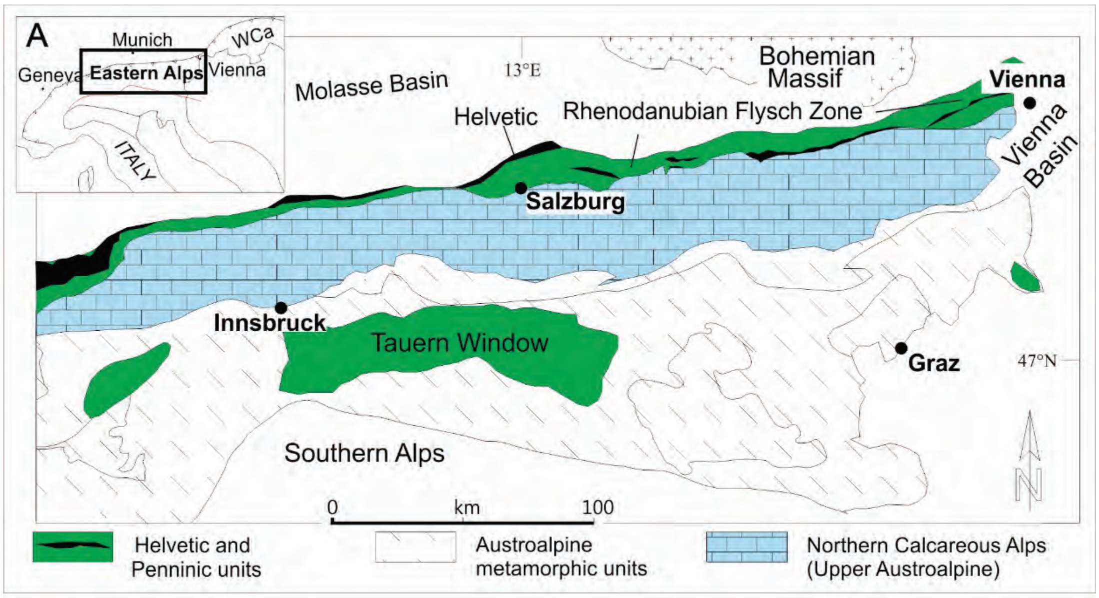
The Helvetic domain and the European Foreland comprise sedimentary strata deposited on the shelf and upper slope of the European plate in a passive margin setting during the Jurassic to Cretaceous. Upper Jurassic reef limestones crop out north of Vienna due to Alpine thrusting. Marginal marine to shelf sediments from Albian to Cenomanian transgression and strongly influenced by sea-level changes comprise strata of the Regensburg gulf, a broad embayment to the west of the island of the Variscan Bohemian Massif. Lower Cretaceous shallow-water to pelagic deposits of the Helvetic realm are exposed mainly in thrust complexes in the western part of the Eastern Alps, overlain by Upper Cretaceous shallow-water marls and limestones.

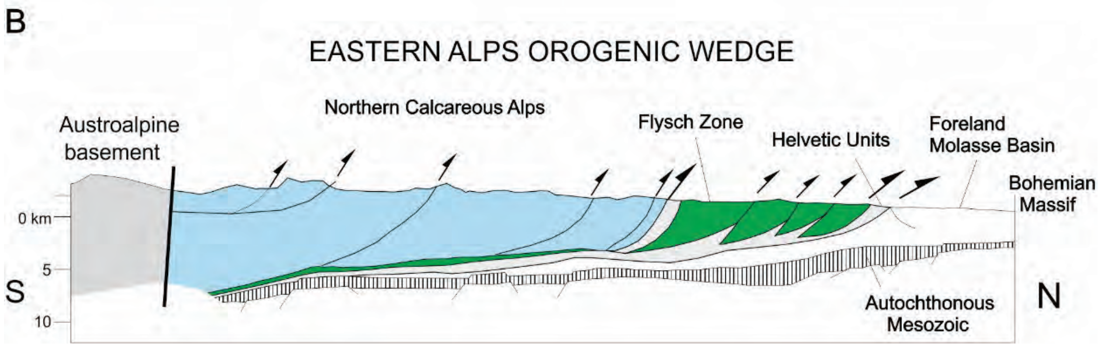
Penninic zones

The Penninic zone developed due to extension and spreading between the European foreland/Helvetic zones and the Austroalpine microplate during the Jurassic (South Penninic units) and Cretaceous (North Penninic units) times (Text-Fig. 2).
During Early Cretaceous predominantly turbiditic deep-water sedimentation began within the North Penninic Rhenodanubian Flysch Zone. The succession started with carbonate-dominated flysch deposits, but passed into turbidites rich in siliciclastic material in the uppermost Early Cretaceous. In the main flysch nappe, the Upper Cretaceous turbidite successions are subdivided by several thin-bedded variegated red pelitic intervals. Sedimentation ranges up to the Early Eocene. Metamorphic South Penninic successions are known from the Tauern Window, including ophiolitic complexes and metamorphosed shales, suggested a fully oceanic basin during the Jurassic.

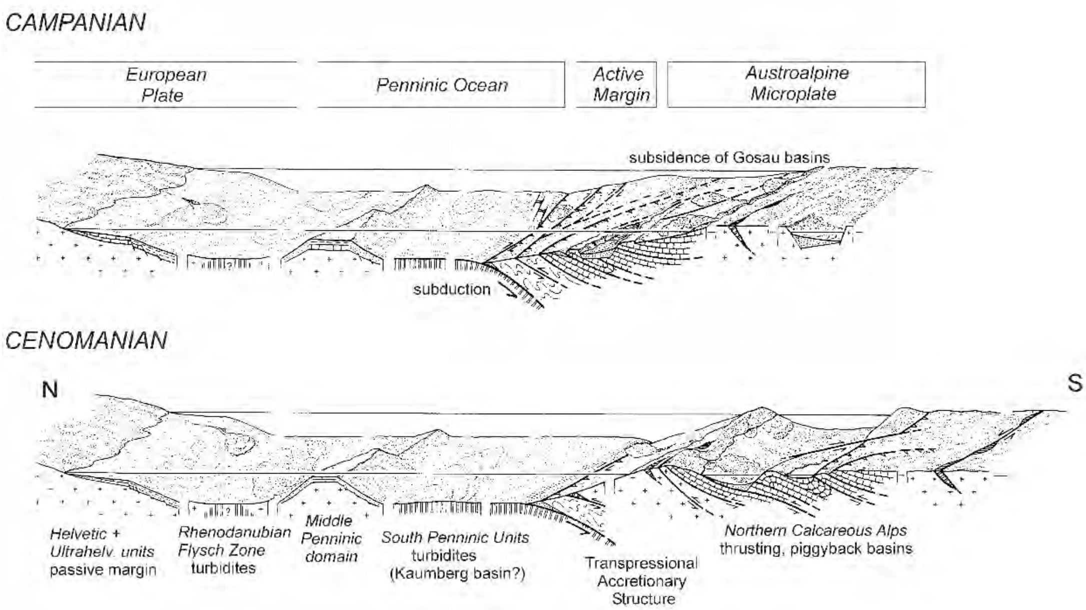
Austroalpine zones

The Austroalpine domain is considered as a partly individual microplate at the northern margin of the Apulian plate (e.g. FAUPL & WAGREICH, 2000). The best documented sedimentary successions of the Austroalpine domain are preserved within the Northern Calcareous Alps (NCA, Text-Fig. 1). Based upon restoration of Neogene fault tectonics, the Eastern Alps had about half the length of the present-day mountain chain during the Late Cretaceous. Metamorphic units of the Austroalpine, including former basement units of the NCA, are situated to the south of the NCA and its Paleozoic base.
Within the Northern Calcareous Alps (Text-Figs. 2, 3) a wide carbonate shelf/platform succession of Triassic age is preserved. Huge Middle Triassic and Upper Triassic platform carbonates (e.g. Wetterstein Limestone, Hauptdolomite and Dachstein Limestone) characterize the NCA (LINZER & TARI, 2012). Jurassic deepening led to establishment of Ammonitico Rosso (Adnet Formation), radiolarites and siliceous deep-water limestones that grade into deep-water carbonate facies of the Lower Cretaceous (Schrambach Formation). Lower and Upper Cretaceous to Paleogene terrigenous clastics such as the Gosau Group (e.g. FAUPL & WAGREICH, 1996) exemplify the growing influence of (eoalpine) orogeny.





Text-Fig. 1 (A): Tectonic sketch-map of the Eastern Alps.
Text-Fig. 2 (B): Simplified cross-section of the eastern part of the Eastern Alps.



Text-Fig. 3: Palinspastic reconstruction of the Eastern Alps during Late Cretaceous times (FAUPL & WAGREICH, 2000).

The Gosau Group of Gams

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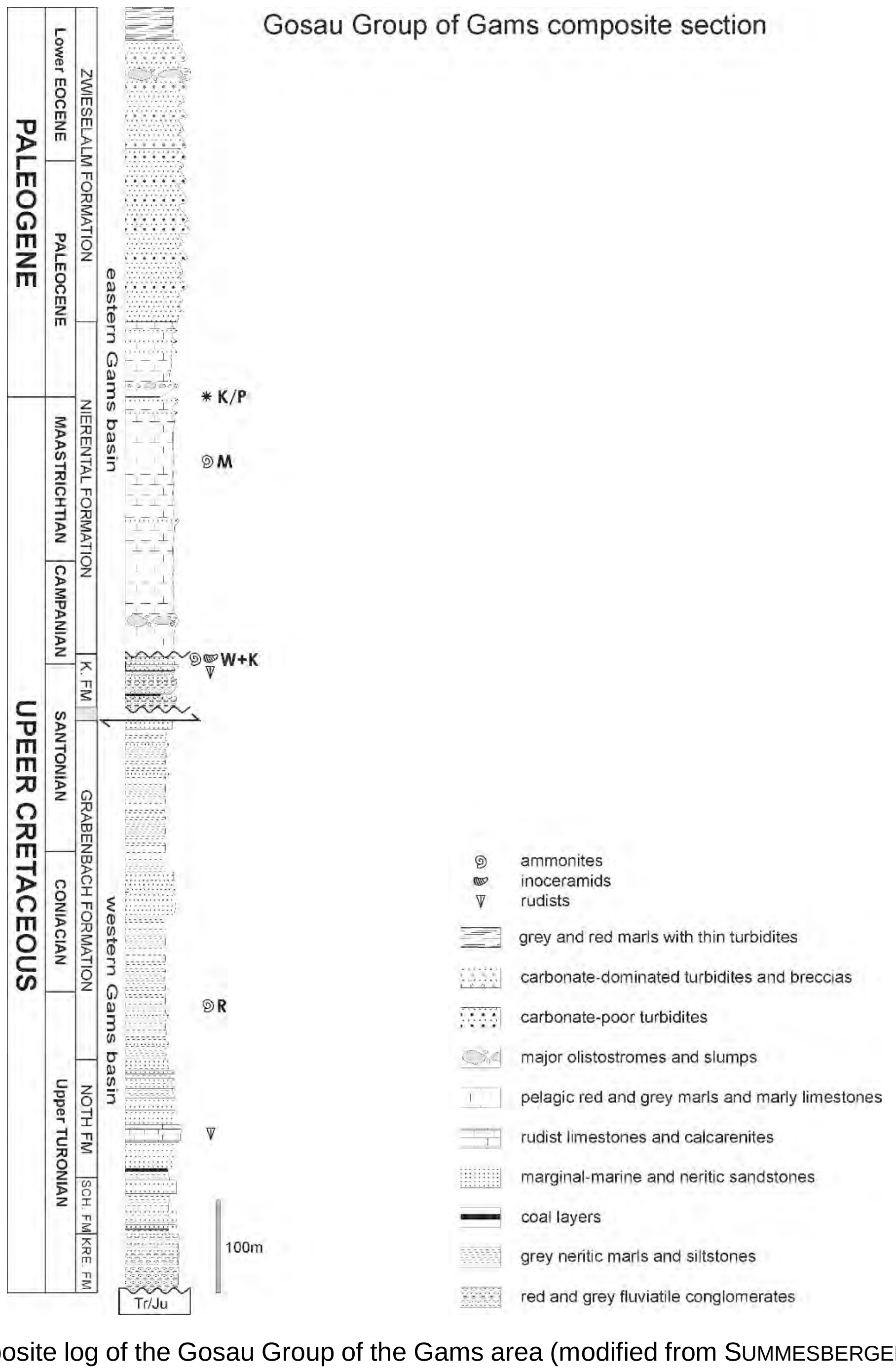
The Gosau Group of Gams consists of a terrestrial to shallow-marine part of Late Turonian to Early Campanian age (Lower Gosau Subgroup) and deep-marine Campanian to Lower Eocene deposits (KOLLMANN, 1964; Upper Gosau Subgroup). Outcrops of the Lower Gosau Subgroup are more or less restricted to the western part of the E–W-elongated outcrop belt ("western basin" of KOLLMANN, 1964; KOLLMANN & SUMMESBERGER, 1982). The following lithostratigraphic units could be distinguished based on KOLLMANN (1964; comp. Text-Fig. 4):



Text-Fig. 4: Composite log of the Gosau Group of the Gams area (modified from SUMMESBERGER et al., 2009). Abbreviations: K. FM = Krimpenbach Formation, SCH. FM = Schönleiten Formation, KRE. FM = Kreuzgraben Formation; Fossil site abbreviations: R = Radstadt, W = Wentneralm, M = Maastrichtian, K/P = Cretaceous/Paleogene boundary).

(1) A basal unit of red alluvial conglomerates up to 70 m thick (Kreuzgraben Formation).
(2) A succession of shales and clays with rarely intercalated sandstones and coaly clays, containing marine fossils, coal and jet (Schönleiten Formation).
(3) A succession up to 400 m thick of grey shales containing coal seams, sandstone with serpentinite sands, *Trochacteon* and rudist (*Hippurites*) limestones ("Noth Formation"; Upper Turonian; see SANDERS & PONS, 1999).
(4) Several hundred meters of grey silty shales with rare sandstone tempestites (Grabenbach Formation; Upper Turonian–Santonian), containing ammonites and inoceramids.
(5) A transgressive succession of conglomerates, sandstones and grey shales (Krimpenbach Formation, Late Santonian–Late Campanian age, SUMMESBERGER et al., 1999; WAGREICH, 2004).
(6) Deep-water shales and turbidites of the Nierental Formation, including turbidites and olisthostromes (Upper Campanian–Lower Paleocene).
(7) Turbiditic successions of the Zwieselalm Formation (Middle Paleocene–Lower Eocene).

Stop 1. Cretaceous/Paleogene boundary at Knappengraben

Coordinates: E 14°51'50", N 47°39'51".
Location: Outcrop along a forest road.
Topic: K/Pg – Cretaceous/Paleogene boundary section.
Lithostratigraphic unit: Nierental Formation (Upper Gosau Subgroup).
Age: Late Maastrichtian (CC26)–Early Paleocene (NP1).
Tectonic unit: Untersberg Nappe/Göller Nappe (Tirolicum), NCA.
Specialities: K/Pg boundary section behind fence; discussion on impact and volcanism.
References: STRADNER & RÖGL (1988), LAHODYNSKY (1988a, b), GRACHEV et al. (2005).

The outcrop is located 700 m south of the farm house at the crossing between the forest road and the Knappengraben torrent. It is protected by a fenced shelter. Detailed studies on the K/Pg boundary of Gams have first been performed at the Knappengraben outcrop. The lithological section has been described by LAHODYNSKY (1988a, b). Nanno- and micropalaeontological work has been performed by STRADNER & RÖGL (1988), EGGER et al. (2004), GRACHEV et al. (2005) and GRACHEV (2009). Up to 9 ppb Ir have been found in the boundary clay.
In the outcrop a section of the Nierental Formation across the K/Pg boundary is exposed. Beds are dipping at 40° towards SSE. The base is formed by pale grey, Upper Maastrichtian shaly limestones with a well-defined ichnofauna (*Chondrites, Zoophycos, Thalassinoides*). The transitional layer consists of dark grey clay containing small mica particles. It is overlain by grey clays and thin, yellowish to brown fine-grained sandstone layers.
The stratigraphically lower part consists of light grey shaly limestones with dark spots of approximately 1 mm in diameter (*Chondrites*). The burrows are filled with dark boundary clay. Foraminifera indicate the *Abathomphalus mayaroensis*- or *Pseudoguembelina hariaensis* zones. The K/Pg boundary clay has a thickness of about 2 cm. It is vertically heterogeneous and its texture varies according to its clastic content and the clay matrix distribution. The lower part of the transitional clay contains an assemblage of small heterohelicids and hedbergellids including *H. holmdelensis* (GRACHEV et al., 2005: holmdelensis Zone) followed by a barren 0.2 cm interval of dark green to black clay and the FO of *Globoconusa daubjergensis* and *Subbotina fringa* (*Globoconusa daubjergensis* and *Subbotina fringa* zones in GRACHEV et al., 2005).

Stop 2. Cretaceous/Paleogene boundary at Krautgraben/Gamsbach

Coordinates: E 14°51'50", N 47°39'51".
Location: Outcrops along a bend of Krautgraben (= upper Gamsbach) main creek.
Topic: Cretaceous/Paleogene boundary section. Stratigraphy, sedimentology, geochemistry and mineralogy data.
Lithostratigraphic unit: Nierental Formation (Upper Gosau Subgroup).
Age: Late Maastrichtian (CC26)–Early Paleocene (NP1).
Tectonic unit: Untersberg Nappe/Göller Nappe (Tirolicum), NCA.
Specialities: New K/Pg boundary section investigated by GRACHEV (2009) and EGGER et al. (2009).
References: GRACHEV (2009), EGGER et al. (2009), PUNEKAR et al. (2016).

The second K/Pg boundary site in the Gams area is found in the Krautgraben, the valley of the Gamsbach about 1.25 km west of the Knappengraben site (Text-Fig. 5). The base of the 6.5 m long section lies 2.5 m below the K/Pg boundary. EGGER et al. (2009) reported results from a combined palaeontological and geochemical analysis of that section; later PUNEKAR et al. (2016) gave a more detailed survey.

The section is part of the Nierental Formation of the Gosau Group. The log of the section is given in Text-Figure 3. The most conspicuous feature is the ca. 2 cm thick boundary clay. The base of this clay has been taken as 0-meter level in the columnar log.

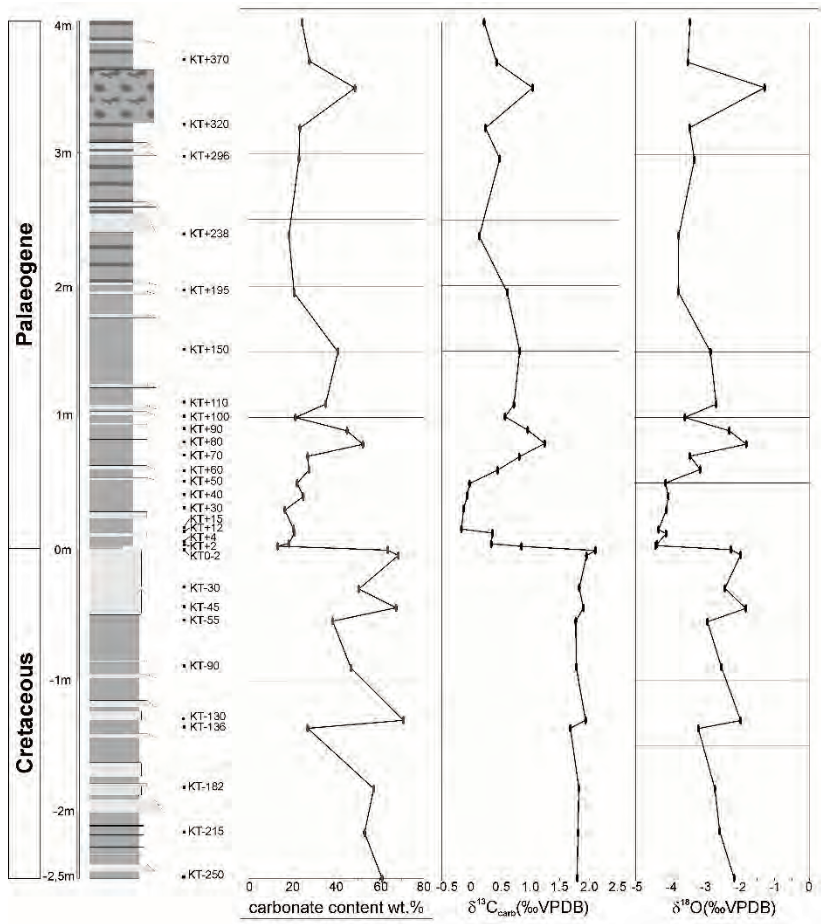
The Gamsbach section consists mainly of fine-grained pelitic rocks. Below the K/Pg boundary light to medium grey marlstones and marly limestones occur (mean carbonate content of 11 samples is 54.9 wt.%), which are interbedded with thin (< 15 cm) sandstone turbidites. Dark grey mottles due bioturbation are present especially in more indurated marly limestone beds. Chondrites- and well indurated, bioturbated marly limestone with an irregular, wavy upper surface. Above this surface, 0.2 to 0.4 cm of yellowish clay marks the base of the Paleocene. The yellowish clay is overlain by grey clay with a maximum carbonate content of about 13 wt.% in the upper part of the layer. The overlying 200 cm thick middle to dark grey marl to marlstone contains ca. 20–50 wt.% carbonate. Twelve thin (0.5 to 5 cm) sandy to silty turbidite layers are intercalated in the first 9 cm of this marlstone. The colour of the marls and marlstones changes upsection from light to medium grey, and they are interbedded with brown to reddish layers. Turbiditic beds become thicker there (up to 14 cm). A variegated marl/marlstone bed (40 cm thick) occurs at 323 cm. It contains clasts of red and brown marly limestone up to 15 cm in diameter and some slump folds. Above this mass-flow bed, the greyish-red marl-marlstone succession extends to the top of the section, 400 cm above the K/Pg boundary.

The section comprises the upper part of the Cretaceous *Nephrolithus frequens* Zone (CC26) and the lower part of the Paleocene *Markalius inversus* Zone (NP1). The boundary is characterized by

(1) enrichment of the contents of the siderophile elements Ir, Co, Ni, and Cr compared to the background and continental crustal values,

(2) sudden decrease of carbonate content and carbon and oxygen isotope values,

(3) an acme of the calcareous dinoflagellate cyst *Operculodinella operculata*, which is succeeded by an acme of the small coccolith species *Neobiscutum parvulum*. The *Neobiscutum* acme is associated with a positive excursion of $\delta^{18}O$ indicating a transient cooling of ocean surface waters due to short-lived changes in the configuration of ocean circulation after the impact.



Text-Fig. 5: Stratigraphic log of the Gamsbach section, with carbonate content and variation in the stable isotope abundances (EGGER et al., 2009).

Stop 3. Mid-Maastrichtian ammonite site E of Haid
Coordinates: E 14°51'35", N 47°40'00".
Location: Outcrops along a forest road and creek northeast of Haid.
Lithostratigraphic unit: Nierental Formation (Upper Gosau Subgroup).
Age: Middle Maastrichtian, upper part of *Gansserina gansseri* Zone, CC25b/ UC20a[TP].
Tectonic unit: Untersberg Nappe/Göller Nappe (Tirolicum), NCA.
Specialities: Youngest ammonites of the Gosau Group.
References: SUMMESBERGER et al. (2009).

The investigated outcrop within the Nierental Formation exposes about 5 meters of thin and evenly bedded sandy/silty grey shales and marls with a few intercalations of coarse sandstones below 10 cm thickness. The beds are a few centimetres thick; the bedding planes are more or less even. Some bedding planes are coated by a rusty cover. Bioturbation is common, especially in the lower part of the outcrop. *Chondrites* is a typical trace fossil present at topmost parts of graded sandstone/siltstone turbidite beds. Some bedding planes also show grazing traces by echinoids. Pelitic beds can be subdivided into soft sandy turbiditic shales and more indurated marls, which are interpreted as hemipelagic. The stratigraphic position of the cephalopod-bearing grey marl bed is below a 16 cm thick graded sandstone layer and thus is also interpreted as a hemipelagic, non-turbiditic layer.

Cephalopods and chronostratigraphic correlation
Pachydiscus (*Pachydiscus*) *gollevillensis* (D'ORBIGNY 1850)
Glyptoxoceras cf. *rugatum* (FORBES 1846)
Neancyloceras bipunctatum (SCHLÜTER 1872)

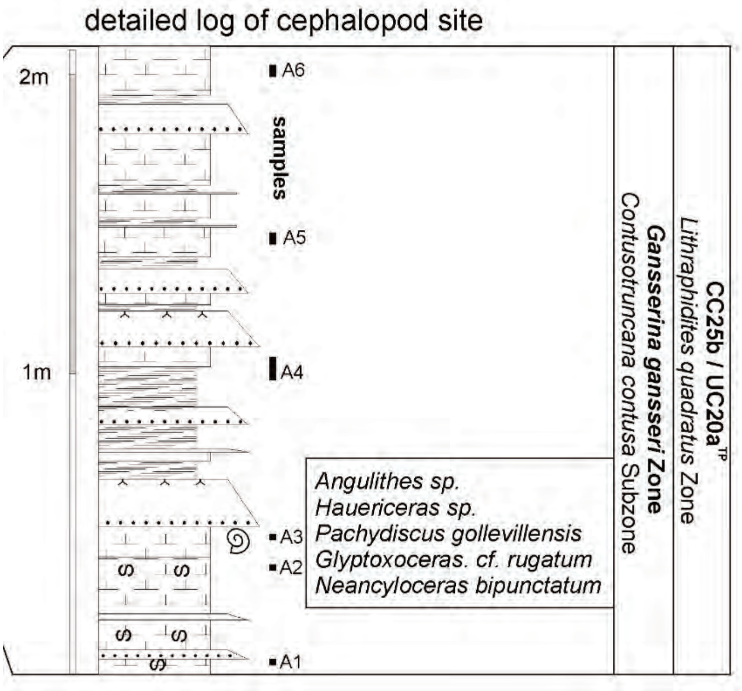
Hauericeras sp. indet. juv.
Angulithes (*Angulithes*) sp. indet.

The most indicative ammonite taxon present is *Pachydiscus* (*P.*) *gollevillensis* (D'ORBIGNY, 1850), which ranges at Zumaya (Spain) from the upper part of the *gansseri* Zone to the middle *mayaroensis* Zone (WARD & KENNEDY, 1993). In terms of ammonite zones this corresponds to the *Anapachydiscus fresvillensis* Zone, which is upper Lower Maastrichtian to lower Upper Maastrichtian. The LO level of *P.* (*P.*) *gollevillensis* at Zumaya is within the Upper Maastrichtian zones of *Anapachydiscus fresvillensis* and *Abathophalus mayaroensis* (WARD & KENNEDY, 1993), and above the FO of *Lithraphidites quadratus*, within nannofossil zone UC20 (BURNETT, 1998). At Sopelana I (Spain) *P. gollevillensis* occurs about 50 m below the K/Pg boundary near the base of the *mayaroensis* Zone (WARD & KENNEDY, 1993). Its extinction level is about 10 m below K/P. Thus, *P. gollevillensis* is mainly a Late Maastrichtian species, appearing at the top of the upper Lower Maastrichtian *gansseri* Zone.

Nannoplankton
The most important marker species recognized is *Lithraphidites quadratus.* This species is rare to very rare (1 specimen in around 100 fields of view). The presence of *L. quadratus* in all the samples and the absence of *Micula murus* and *Nephrolithus frequens* allow the recognition of standard nannofossil zones CC25b (according to SISSINGH, 1977; PERCH-NIELSEN, 1985) and UC20a^{TP} (BURNETT, 1998). The presence of *Corollithion completum* further corroborates this assignment according to BURNETT (1998). An early Late Maastrichtian age is interpreted in correlation to belemnite zonations (*tegulatus /junior* Subzone or younger; BURNETT, 1998). Very rarely, Campanian to early Maastrichtian taxa such as *Broinsonia* and *Uniplanarius* are found, which are interpreted as reworked from older strata.

Planktonic Foraminifera
Samples contain a foraminifera assemblage characterized by high amounts (> 90 %) of planktonic foraminifera. The most characteristic and stratigraphically important taxa present are *Globotruncanita stuarti, Rosita contusa, Abathomphalus intermedius,* and *Racemiguembelina intermedia. Globotruncanita stuarti* and *Rosita contusa* are typical Maastrichtian species. *Abathomphalus intermedius* and *Racemiguembelina intermedia* both have a first occurrence higher up in the Maastrichtian, within the *Gansserina gansseri* Zone. *Racemiguembelina fructicosa* occurs below the *Abathomphalus mayaroensis* Zone.
Thus, the samples can be attributed to the upper part of the *Gansserina gansseri* Zone (Text-Fig. 6), the *Contusotruncana contusa* (Sub-)Zone, within the upper part of the of the *Gansserina gansseri* Zone, just below the first occurrence of *Abathomphalus mayaroensis*. Combining nannofossil (CC25b/UC20a^{TP}) and planktic foraminiferal data (upper part of *Gansserina gansseri* Zone, *Contusotruncana contusa* (Sub-)Zone, CF5; below the first occurrence of *Abathomphalus mayaroensis*) gives a more precise stratigraphic frame for the cephalopod fauna and allows correlation to other zonations, e.g. the boreal belemnite zonation of northern Europe. The first occurrence of *Lithraphidites quadratus* was recognized within the *Belemnitella junior* Zone of NW Germany, i.e. within the *tegulatus/junior* Subzone, the lowermost subzone of the Upper Maastrichtian. According to the absence of the nannofossil *Micula murus* in our samples, the age cannot be younger than the top of the *Belemnitella junior* Zone. Integrating foraminiferal data, especially the lack of *Abathomphalus mayaroensis*, leads to a correlation of the investigated cephalopod horizon with the interval from the base of the *Spyridoceramus tegulatus /Belemnitella junior*

Subzone to the lower part of the *Tenuipteria argentea/Belemnitella junior* Subzone (BURNETT, 1998).



Text-Fig. 6: Section east of Haid (SUMMESBERGER et al., 2009).

Stop 4. Upper Turonian sandstones and rudists at Pitzengraben and along Noth road

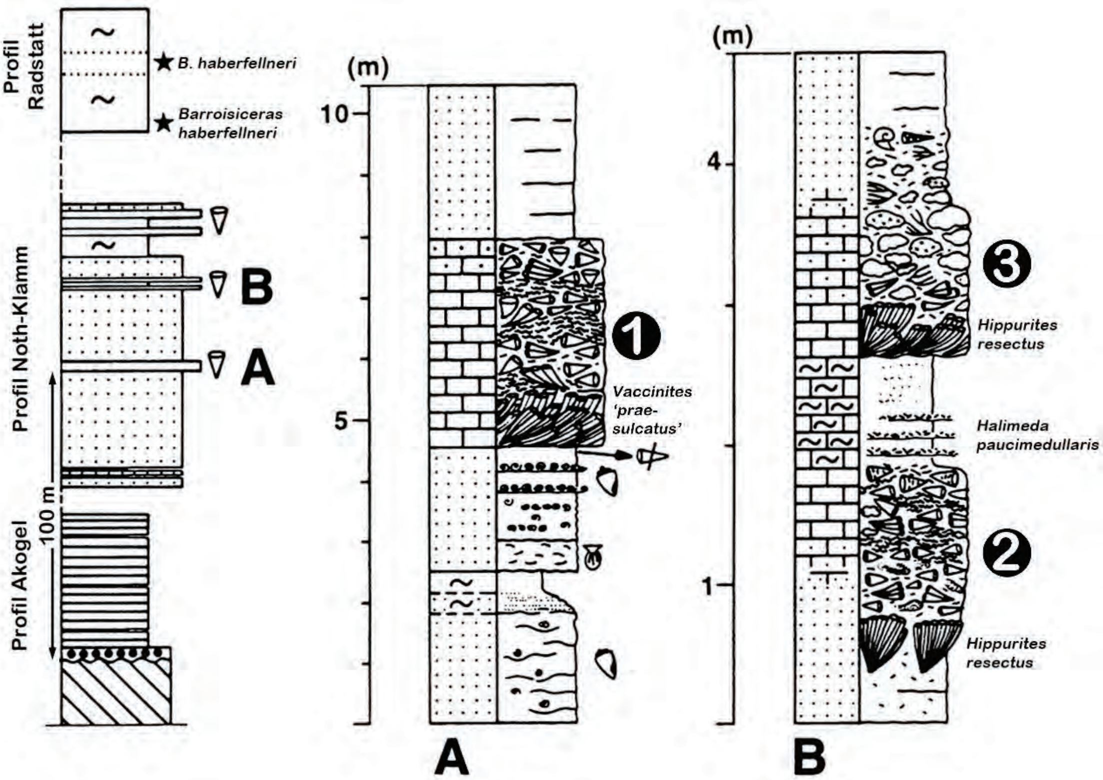
Coordinates: E 14°51'50", N 47°39'51".
Location: Roadside and riverbed outcrops W of the Noth gorge E of Gams (Styria); protected site!
Topic: Rudist reef, *Trochacteon lamarcki*, sandstones.
Lithostratigraphic unit: Noth Formation (Lower Gosau Subgroup).
Age: Late Turonian.
Tectonic unit: Untersberg Nappe/Göller Nappe (Tirolicum), NCA.
Specialities: Natural monument and Geopark.
References: SUMMESBERGER & KENNEDY (1996), SANDERS & PONS (1999), WAGREICH et al. (2009a, b).

The Pitzengraben outcrop shows the development of rudist formations on a wave-dominated, mixed siliciclastic-carbonate shelf. The basal part of the section comprises arenites with layers of paralic coal. One of these layers is exposed at the mouth of an abandoned coal mine.

The section A (Text-Fig. 7) which begins above the coal. Hybrid arenites with small benthic foraminifers and accumulations of *Trochacateon lamarcki* (SOWERBY) are sharply overlain by biostrome 1. In its lower part it is composed of densely packed hippuritids (*Vaccinites* cf. *sulcatus*). The upper part consists of an open to packed parautochthonous fabric of radiolitids and subordinate hippuritids. Lenses of floatstone composed of fragments from the radial funnel plates of radiolitids recognizable by their zig-zag pattern are intercalated. In the topmost part of the biostrome, the wackestone- to floatstone-matrix contains a few percent of siliciclastic sand and is mottled with burrows that are filled with sandstone. The biostrome is overlain by sandstone.

The higher part of the section (B) shows a monospecific thicket (biostrome 2) of *Hippurites resectus* in hybrid arenites with abundant *Quinqueloculina* and *Cuneolina* (Text-Fig. 7). The thicket is overlain by burrow-mottled sandy limestone with toppled *H. resectus* and *Radiolites*. Above follows a bioturbated, open parautochthonous biostrome of radiolitids. At the top, the biostrome grades into an interval of organic-rich, marly wackestones with

miliolids, *Cuneolina*, ostracods and coalified plant fragments. To save this outcrop it is protected by Austrian nature conservation law. Any kind of alteration is prohibited.
Serpentinitic sandstones are a conspicuous feature of this outcrop. Modal analysis indicates that serpentinitic grains make up more than 50 percent of particles. Chrome spinel is the predominating heavy mineral. Although no present-day local source for the serpentinitic grains is known, serpentinized ophiolitic bodies, which were interpreted as remnants of a Tethys (Hallstatt-Meliata) suture, must have been present within the NCA during the Cretaceous.



Text-Fig. 7: Rudist formations in mixed siliciclastic-carbonate environments, Pitzengraben, Gams (modified from SANDERS & PONS, 1999).

The overlying Radstadt section is nowadays fully covered by road construction material. It yielded a macrofauna characteristic of the Turonian/Coniacian boundary interval (KOLLMANN & SUMMESBERGER, 1982; SUMMESBERGER, 1985; SUMMESBERGER & KENNEDY, 1996). The bivalve *Didymotis costata* was found together with the ammonites *Barroisiceras haberfellneri and Reesidites minimus*. The occurrence of *Didymotis costata* is regarded as a marker for the base of the Coniacian. The lower part of the section is characterized by the presence of *Marginotruncana* taxa of the *coronota-pseudolinneiana*-group, the *sigali-renzi*-group, rare *Marginotruncana schneegansi* and the absence of both *Helvetoglobotruncana helvetica* and *Dicarinella primitiva*. This indicates the Late Turonian *Marginotruncana sigali* zone. The Turonian/Coniacian boundary with *Didymotis* at the Radstadt section is within nannofossil zone CC13 (*Marthasterites furcatus* zone). Up to this level *M. furcatus* is accompanied by common *Quadrum gartneri*. *Micula decussata* occurs further upwards in the Middle Coniacian.

Optional Stop 5 may include a visit to the Geozentrum, a museum that is connected to the Gams Geopark.

The type locality of the Gosau Group near Gosau

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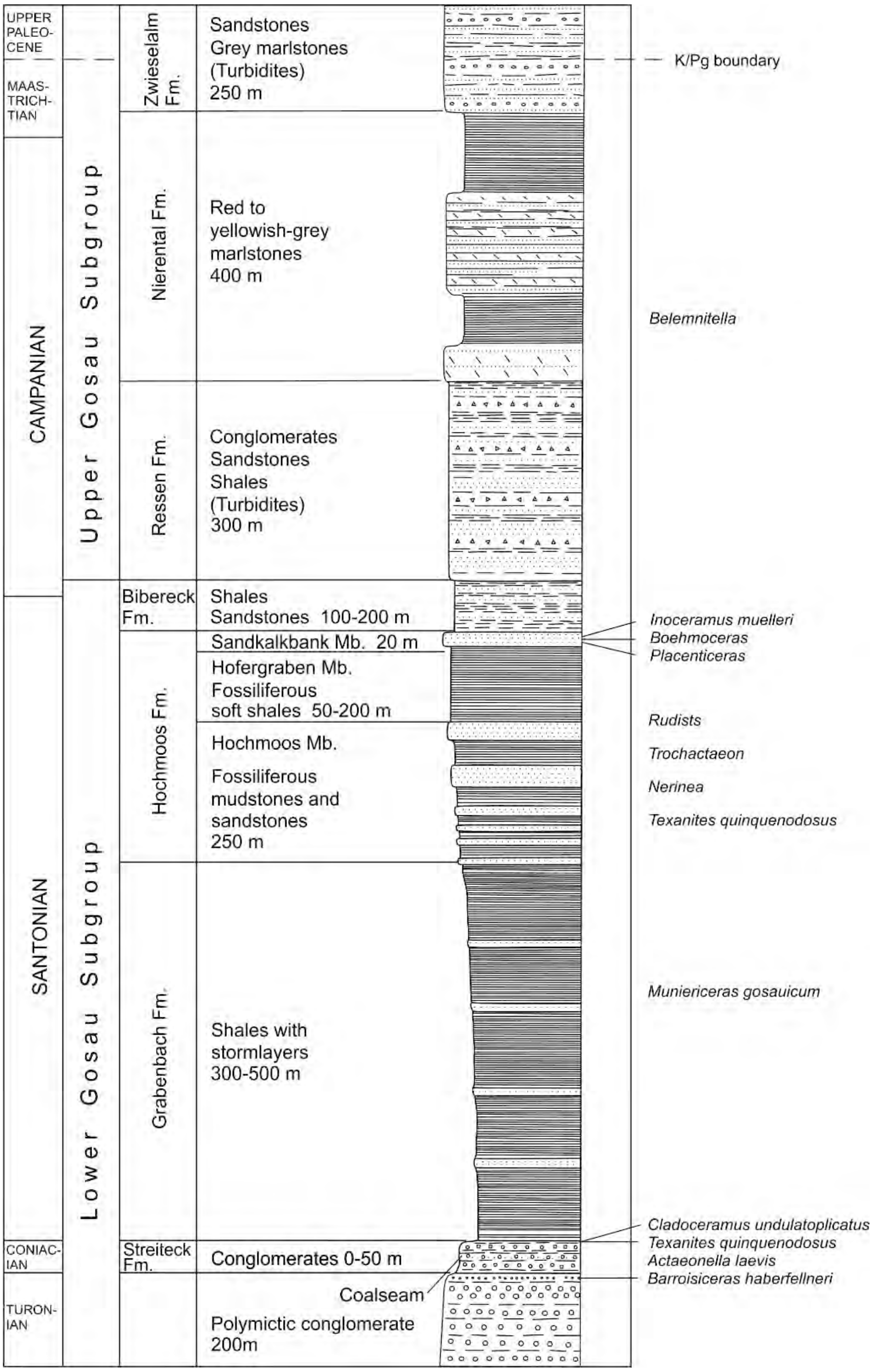
Upper Cretaceous deposits of the area of the villages Gosau (Upper Austria), Rußbach and Abtenau (Salzburg) comprise the type locality of the Gosau Group (Text-Fig. 8). Classical descriptions include SEDGWICK & MURCHISON (1832) and REUSS (1854).

The basin fill comprises about 1,000 m of Upper Turonian to Lower Campanian terrestrial and shallow-water sediments of the Lower Gosau Subgroup, which are unconformable overlain by more than 1,200 m thick deep-water deposits of the Upper Gosau Subgroup. The Upper Gosau Subgroup clearly seals Upper Turonian–Santonian basin bounding structures, as deep-water deposits of the UGS onlap the Triassic substrata. A reconstruction of the basin geometry of the Lower Gosau Subgroup results in an original basin about 8 to 10 km wide and 10 km long. Deposits in the area of Abtenau indicate that the composite Upper Cretaceous basin extended at least over 25 km.

The biostratigraphy, lithostratigraphy and sedimentology of the basin fill have been discussed in detail by HÖFLING (1985), TRÖGER & SUMMESBERGER (1994), SUMMESBERGER & KENNEDY (1996), WAGREICH (1992) based on WEIGEL (1937) and KOLLMANN (1982). At the base an up to 350 m thick interval of red alluvial conglomerates (**Kreuzgraben Formation**) of probably Late Turonian age is overlain by a transgressive succession of shallow-marine shales and backstepping coarsening-upward paracycles of the Upper Turonian to Coniacian **Streiteck Formation.** Conglomerates of the Kreuzgraben Formation were interpreted to record progradation and retrogradation of alluvial fans whereas parasequences of the Streiteck Formation are the result of fan-delta progradation. Foraminiferal assemblages suggest water depths of about 150 to 300 m at maximum flooding in early Santonian time, at the base of **Grabenbach Formation**. Storm-influenced shelf and near-shore sediments of up to 500 m, including rudist bioherms (HÖFLING, 1985), fill the basin in Santonian to early Campanian times, but are interrupted by a short erosional phase in early Campanian time (Grabenbach, **Hochmoos** and **Bibereck Formations**). The overlying Upper Gosau Subgroup starts with a sandstone-rich turbidite fan interval (**Ressen Formation**, Lower Campanian), followed by (hemi)pelagic shales and marly limestones (**Nierental Formation**, Upper Campanian–Maastrichtian) and a turbiditic interval (**Zwieselalm Formation**, Upper Maastrichtian–Paleocene/Eocene).



Text-Fig. 8: Composite lithostratigraphic section of the Gosau Group of Gosau and Rußbach including a selection of macrofossils; modified from SUMMESBERGER et al. (2017a, b, c).

Stop 6. Lake Gosau (Gosausee) in the Gosau valley

Coordinates: E 13°29'51", N 47°31'58".

Location: Parking area of Gosausee cable car near Gosausee (Upper Austria).

Topic: Dachstein Mountain scenery; Triassic of the NCA; Nierental Formation of the Rote Wand section.

Lithostratigraphic unit: Nierental Formation.

Age: Campanian–Maastrichtian.

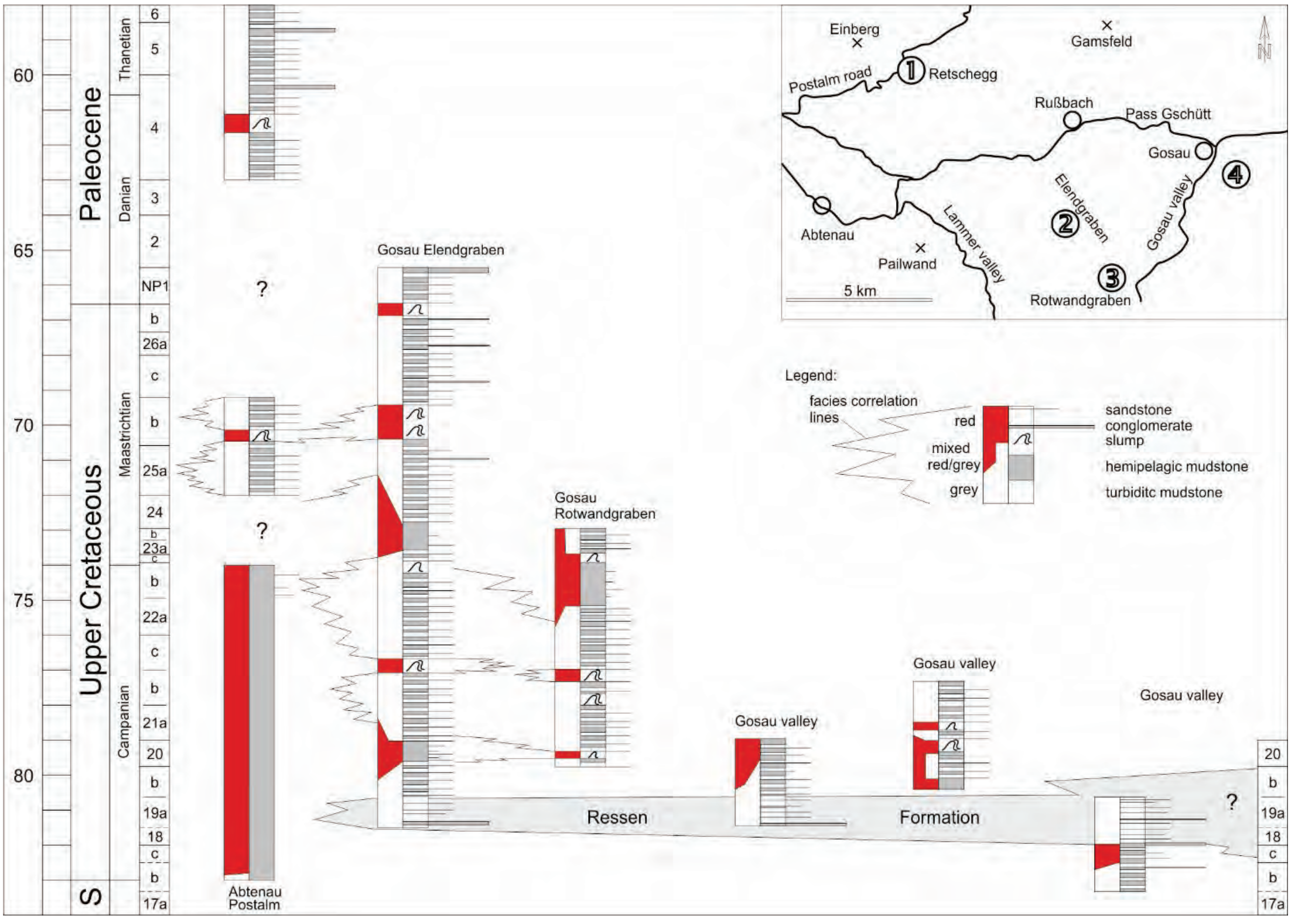
Tectonic unit: Dachstein Nappe, NCA.

Specialities: View and photo stop.

References: PREISINGER et al. (1986), PERYT et al. (1997), WAGREICH & KRENMAYR (1993, 2005).

The scenery of the Lake Gosau and the Hohe Dachstein Mountain (3,004/2,996 m) is one of the most spectacular views of the Salzkammergut. The Triassic carbonates surrounding the lake comprise reef limestones of the Dachsteinkalk at the Gosaukamm, bedded cyclic Dachstein limestone of the Dachstein itself and deeper-water limestones (Pötschenkalk).

The not so famous view from the Gosausee to the north shows the "Rote Wand": interbedded hemipelagic and turbiditic red and grey shaly limestones of the Nierental Formation (Upper Campanian–Maastrichtian–Danian), including a complete K/Pg-boundary section (PREISINGER et al., 1986; Text-Fig. 9). Nannofossil biostratigraphy (WAGREICH & KRENMAYR, 1993, 2005) prove significant diachroneity of red, (hemi)pelagite rich intervals even in nearby sections, thus indicating the predominance of local factors (tectonics, sediment supply) in the control of pelagic CORB (Cretaceous Oceanic Red Beds) intervals rather than global processes like eustatic sea-level changes.



Text-Fig. 9: CORBs and nannofossil biostratigraphy of the Nierental Formation including the Rote Wand section (Rotwandgraben, modified from WAGREICH & KRENMAYR, 2005).

Stop 7. Upper Santonian rudist-limestones above a Santonian transgression

Coordinates: E 13°30'54", N 47°32'60".
Location: Outcrops along the Gosau valley main road at inn Gosauschmied.
Topic: Upper Santonian rudist-limestones above a Santonian transgression.
Lithostratigraphic unit: Hochmoos Formation (Lower Gosau Subgroup).
Age: Late Santonian CC17/ UC12-13.
Tectonic unit: Dachstein Nappe, NCA.
Specialities: Transgressive dolomite sands, rudists, large but rare radiolitids.
References: EGGER et al. (2000).

The rudist limestones at Gosauschmied (Gosau Hintertal) record a Santonian transgression starting with conglomerates, dolomitic sandstones and brackish marls, overlain by limestones rich in miliolids and rudists.

Stop 8. Sandkalkbank/Schattau-Rußbach (Upper Santonian)

Coordinates: E 13°30’48”, N 47°34’50”.
Location: Forest road to the Finstergraben N of village Gosau (Upper Austria).
Topic: Sandy to silty shales with macrofauna.
Lithostratigraphic unit: Hochmoos Formation.
Age: Late Santonian.
Tectonic unit: Dachstein Nappe, NCA.
Specialities: Fossils.
References: EGGER et al. (2000), WAGREICH et al. (2009a, b).

Outcrops along the Zwieselalm forest road expose fossiliferous silty to sandy shales of the Hochmoos Formation (Hofergraben Member, SUMMESBERGER et al., 2017a), interpreted as shallow marine pelitic deposits of the transition zone between nearshore and offshore sea. Sandstones of the Hochmoos Formation include nearshore/shoreface sediments, burrowed by *Ophiomorpha*-type burrows. Immediately above the silty shales the sandstones of the 20 m thick Sandkalkbank Member is visible. It yielded an abundant mollusk fauna with 23 gastropod taxa (KOLLMANN, 1980), 50 bivalve taxa (DHONDT, 1984) and 22 ammonite taxa (SUMMESBERGER, 1985). *Pinna* in life position and the articulated infauna of bivalves indicates a soft substratum and a low water energy level together with a fast sedimentation rate. The stratigraphic position in the upper part of the Late Santonian is based upon correlation of the heteromorph ammonite *Boehmoceras* with the Münster basin (Germany). Palaeobiogeographical connections to the Münster basin, North America (Gulf coast, Western Interior), Japan and Madagascar indicate a worldwide system of open waterways in Late Santonian times. Subtropical to tropical climate can be concluded from the occurrence of hermatypic corals and rudists in the Hochmoos Formation. The gastropod *Pleurotomaria* indicates the presence of cooler water temperatures at slightly greater depths; scaphitids and belemnites are absent.
Biostratigraphically the Sandkalkbank Member of the Hochmoos Formation belongs to the Upper Santonian *Boehmoceras arculus* Zone. The occurrence of *Boehmoceras arculus* allows precise correlation to the Münster basin (Germany) and to the Tombigbee Sand of Mississippi and Alabama. The correlative Schattau section was described by WAGREICH et al. (2009a) and more recently in detail by SUMMESBERGER et al. (2017c). There, the Upper Santonian Sandkalkbank Member is overlain by silty marls of the Bibereck Formation, yielding abundant echinoids including remnants of *Marsupites laevigatus* indicating still the *Dicarinella asymetrica* Zone below the base of the Campanian.

Ammonites

Gaudryceras mite (HAUER)
Saghalinites nuperus (VAN HOEPEN)
Damesites sugata (FORBES)
? *Parapuzosia* cf. *seppenradensis* (LANDOIS)
Kitchinites stenomphalus SUMMESBERGER
Hauericeras welschi GROSSOUVRE
Eupachydiscus isculensis (REDTENBACHER)
*Nowakites draschei (*REDTENBACHER)
Diaziceras austriacum (SUMMESBERGER)

Placenticeras polyopsis (DUJARDIN)
Placenticeras maherndli SUMMESBERGER
Placenticeras paraplanum (WIEDMANN)
Reginaites gappi WIEDMANN
Amapondella amapondensis (VAN HOEPEN)
Nostoceratide gen. et sp. indet. (? *Jouaniceras*)
Glyptoxoceras crispatum (MOBERG)
Baculites fuchsi REDTENBACHER
Baculites tanakai MATSUMOTO & OBATA
Baculites sp.
Boehmoceras arculus (MORTON)
Boehmoceras krekeleri (WEGNER)

Gastropods
Pleurotomaria sp.
Bathrotomaria subgigantea (D'ORBIGNY)
Keilostoma tabulata (ZEKELI)
Climacopoma quadrata (SOWERBY)
Torquesia rigida (SOWERBY)
Exechocirsus reticosus (SOWERBY)
Quadrinervus subtilis (ZEKELI)
Cyphosolenus sp.
Helicaulax gibbosus (ZEKELI)
Xenophora plicata (ZEKELI)
Pseudamaura sp.
Lunatia semiglobosa (ZEKELI)
Mesorhytis cancellata (SOWERBY)
?Palaeopsephaea sp.
Fusinus reussi (ZEKELI)
Fusinus subabbreviatus (ZEKELI)
Woodsella turbinata (ZEKELI)
Fuside indet.
Tudicla indet.
Volutide indet.
Gosavia squamosa (ZEKELI)
Licoarenus sp.
Acteonella elongata KOLLMANN

Bivalves
Nucula concinna SOWERBY
Nucula redempta ZITTEL
Nucula cf. *N. stachei* ZITTEL
Arca aquisgranensis J. MUELLER
Barbatia? inaequidentata (ZITTEL)
Cucullaea cf. *matheroniana* (D'ORBIGNY)
Limopsis calva SOWERBY
Glycymeris marrotianus (D'ORBIGNY)
Glycymeris noricus (ZITTEL)
Inoperna flagellifera (FORBES)
Modiolus typicus (FORBES)
Modiolus capitatus (ZITTEL)

Modiolus cf. *siliquus* (MATHÉRON)
Pinna cf. *cretacea* (SCHLOTHEIM)
Gervillia solenoides DEFRANCE
Gervbillaria neptuni (GOLDFUSS)
Pseudoptera raricosta (REUSS)
Aguileria ? falcata (ZITTEL)
Cordiceramus muelleri (PETRASCHECK)
Sphenoceramus angustus (BEYENBURG)
Platyceramus cycloides ahsenensis (SEITZ)
Camptonectes virgatus (NILSSON)
Merklinia septemplicata (NILSSON)
Neithea coquandi (PÉRON)
Spondylus coquandianus D'ORBIGNY
Spondylus requienianus MATHÉRON
Plagiostoma cretaceoum (WOODS)
Pycnodonte vesiculare (LAMARCK)
Ceratostreon pliciferum (DUJARDIN)
Mutiella ? coarctata (ZITTEL)
Astarte similis (MUENSTER in GOLDFUSS)
Crassatella macrodonta (J. SOWERBY)
Granocardium productum (J. SOWERBY)
Linearia costulata (GOLDFUSS)
Icanotia impar (ZITTEL)
Proveniella testacea (ZITTEL)
Ambocardia planidorsata (ZITTEL)
Pitar s.l. *matheroni ?* (ZITTEL)
Cytherea cf. *polymorpha* (ZITTEL)
Cyprimeria ? discus (MATHÉRON)
Legumen martinianus (MATHÉRON)
Cyclorisma ? dubiosa (ZITTEL)
Corbula ? angustata J. SOWERBY
Pholadomya nodulifera ? MUENSTER in GOLDFUSS
Cercomya ? producta (ZITTEL)
Poromya frequens (ZITTEL)

Stop 9. Pass Gschütt/Streiteck Formation (lunch stop)
Coordinates: E 13°29'13", N 47°35'33".
Location: Parking area at Streiteck, E Russbach (Salzburg), W Pass Gschütt.
Topic: Fan-delta cycles and shallow-marine sands.
Lithostratigraphic unit: Streiteck Formation.
Age: Coniacian.
Tectonic unit: Dachstein Nappe, NCA.
Specialities: Late Cretaceous basin formation, lunch stop.
References: WAGREICH & DECKER (2001).

Cyclic fan-delta conglomerates and sandstones and shallow-marine bioturbated sands including Skolithos are exposed along the Pass Gschütt road. A view to northwest reveals a large normal fault that formed the Gosau basin margin in Late Turonian to Santonian times.

Stop 10. Parking area Rußbach

Coordinates: E 13°27'42", N 47°35'19".
Location: Parking area of cable car to Horneck, SW Rußbach (Salzburg).
Topic: Tempestites and shales of the Grabenbach Formation; transgression onto Triassic limestones.
Lithostratigraphic unit: Grabenbach Formation.
Age: Early Santonian.
Tectonic unit: Dachstein Nappe (Juvavicum).
Specialities: Not much to see any more.
References: EGGER et al. (2000).

At the parking area of the cable car Rußbach/Horneck a reduced succession of the Lower Gosau Subgroup was exposed (Text-Fig. 10). A thin interval of conglomerates and coals is followed by shales and fine grained sandstones of the Grabenbach Formation. Ammonites and inoceramids prove an early Santonian age. Planktonic foraminifera give evidence for the *Dicarinella concavata* Zone, nannofossils indicate standard zone UC11/CC14-15 (e.g. *Marthasterites furcatus*, *Micula decussata*). Sandstones of the Grabenbach Formation show features of tempestites (e.g. small-scaled hummocky cross stratification, wave ripples, flute casts). The outcrop yielded *Cladoceramus undulatoplicatus* (ROEMER), *Platyceramus cycloides cycloides* (WEGNER) and Texanites quinquenodosus (REDTENBACHER) besides other species.

Text-Fig. 10: Rußbach, parking area at the cable car station (Hornspitzbahn). Basal Grabenbach Formation with ammonites and inoceramids, resting upon layers of shales with pebbles, coalseam, corals, gastropods (Streiteck Formation). Transgression upon Triassic rocks (right side).

Stop 11. Section through the Lower Gosau Subgroup, Randograben

Coordinates: First part at E 13°28'42", N 47°36'02".

Location: Section along the forest road to Randobach, NW Rußbach (Salzburg), to Stöcklwaldgraben and Schneckenwand.

Topic: Section within the Lower Gosau Subgroup; red terrestrial conglomerates of alluvial fans, fan-delta sediments, shelf shales and tempestites, rudist bioherm.

Lithostratigraphic units: Kreuzgraben Formation, Streiteck Formation, Grabenbach Formation, Hochmoos Formation (Lower Gosau Subgroup).

Age: Late Turonian–Santonian.

Tectonic unit: Dachstein Nappe, NCA.

Specialities: Hiking tour through stratigraphy with future natural monument (Schneckenwand).

References: KOLLMANN & SUMMESBERGER (1982), EGGER et al. (2000).

Outcrops within the Randograben provide a nearly complete section within the lower part of the Lower Gosau Subgroup. Outcrops include fan-delta conglomerate cycles, shelf shales and marls with a few siliciclastic tempestites of the Grabenbach Formation and fossiliferous marls and limestones of the Hochmoos Formation. Walk upstream (at first stratigraphically downwards) along forest road to junction to the Stöcklwaldgraben and (from now stratigraphically upwards) up to the Schneckenwand.

Stop 11/1. Hochmoos Formation with coarse and fine-grained tempestites.
An 80 m coarsening/thickening upward succession within the Hochmoos Formation grades from silty shales to sandstones and ends with fine conglomerates. The sandstones are strongly bioturbated, including *Ophiomorpha*- and *Thalassinoides*-burrows and show shell-layers at their bases and hummocky cross-stratification. The microfauna is predominated by miliolids and ostracods. Nannofossil data indicate CC16 to CC17 by the presence of *Lucianorhabdus cayeuxii* and rare *Calculites obscurus*. Bivalves (*Pinna*, Pholadidae) in life position.

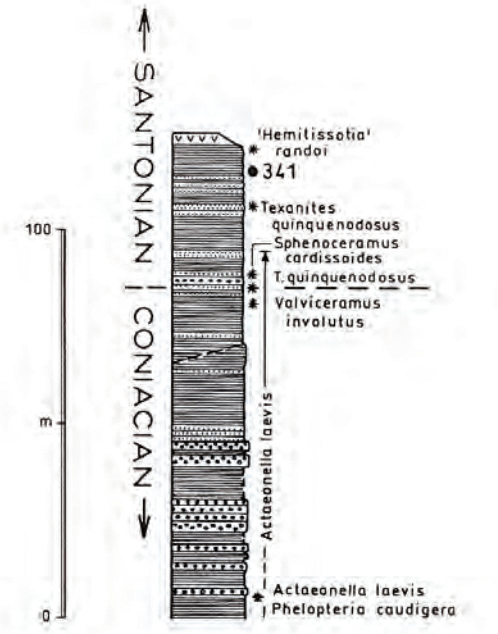
Stop 11/2. Exposures in the streambed, visit depending on water conditions: relatively fossiliferous Grabenbach Formation.
70 m upstream from the first bridge over the Randobach creek. Hard sandstone on the left side of the riverbed containing:
Muniericeras gosauicum (HAUER)
Texanites quinquenodosus (REDTENBACHER)
Baculites sp.
Fossils are typical of Santonian, possibly Middle Santonian age.

Stop 11/3. Coniacian/Santonian boundary in the transition from marly fossiliferous Streiteck Formation to shaly Grabenbach Formation in streambed. Marls include (after TRÖGER & SUMMESBERGER, 1994):
Cladoceramus undulatoplicatus (ROEMER)
Platyceramus cycloides cycloides (WEGNER)
Sphenoceramus cardissoides (GOLDFUSS)
Parapuzosia daubreéi (GROSSOUVRE)
Eulophoceras natalensei
Texanites quinquenodosus (REDTENBACHER)
All fossils are indicative of early Santonian age. The FO of *Dicarinella asymetrica*, *Sigalia carpatica* and nannofossils of the *Amphizygus* group characterize the boundary interval. The content of planktonic foraminifera is gradually increasing into the Santonian.

Stop 11/4. Roadside exposure in Streiteck Formation possibly of top Coniacian age with abundant *Acteonella laevis.*

Stop 11/5. Overgrown exposure in lower part of the Streiteck Formation with fine conglomerates and clayey intercalations with coal seams (Coniacian), and red conglomerates of the Kreuzgraben Formation (Upper Turonian).

Stop 11/6. Streiteck Formation in the Stöcklwaldgraben (Text-Fig. 11) including Top-Coniacian.
The content of planktonic foraminifera is gradually increasing up to 40 % from the Coniacian into the Santonian, where the planktonic foraminiferal fauna consists mostly of large sized marginotruncanids, biserial planktonics, dicarinellids and archeoglobigerinids. The assumed waterdepth ranges from approximately 20 meters to a maximum of 150 meters and is based on foraminiferal paleoecology.



Text-Fig. 11: The Coniacian/Santonian boundary in the Stöcklwaldgraben, a subsidiary of the Randograben. Top-Coniacian is proved by the occurrence of *Volviceramus involutus*, basal Santonian by the co-occurrence of *Texanites quinquenodosus*, *Sphenoceramus cardissoides* and *Cladoceramus undulatoplicatus*; *Eulophoceras natalense* ("*Hemitissotia randoi*" of older literature) is a useful local marker of the Lower Santonian (TRÖGER & SUMMESBERGER, 1994); according to WAGREICH (1992) *Dicarinella asymetrica* starts in the topmost part of the section.

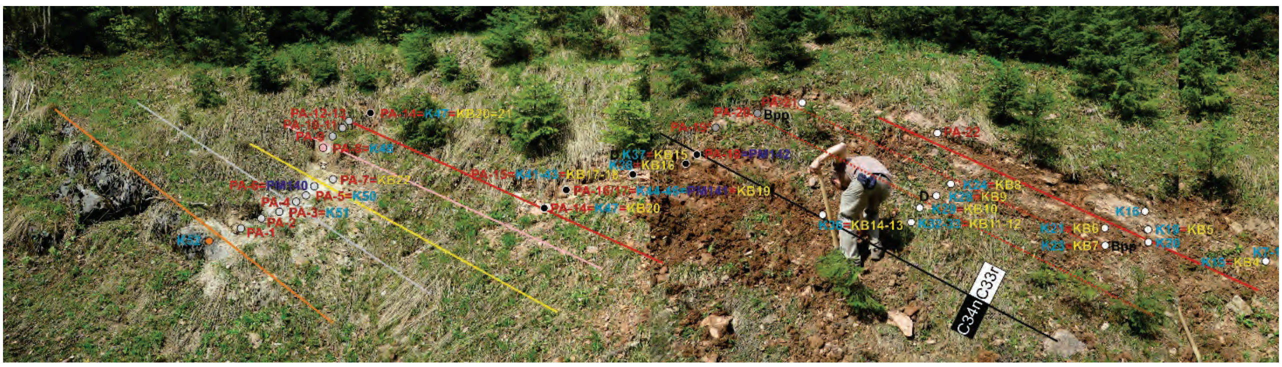
Stop 11/7. Schneckenwand outcrop of Hochmoos Formation (Upper Santonian) with abundant *Trochactaeon giganteus*. A lagoonal setting is interpreted for these gastropod mass occurrences (Natural Monument, no hammering allowed).

Stop 12. Postalm road, Abtenau, Gosau Group

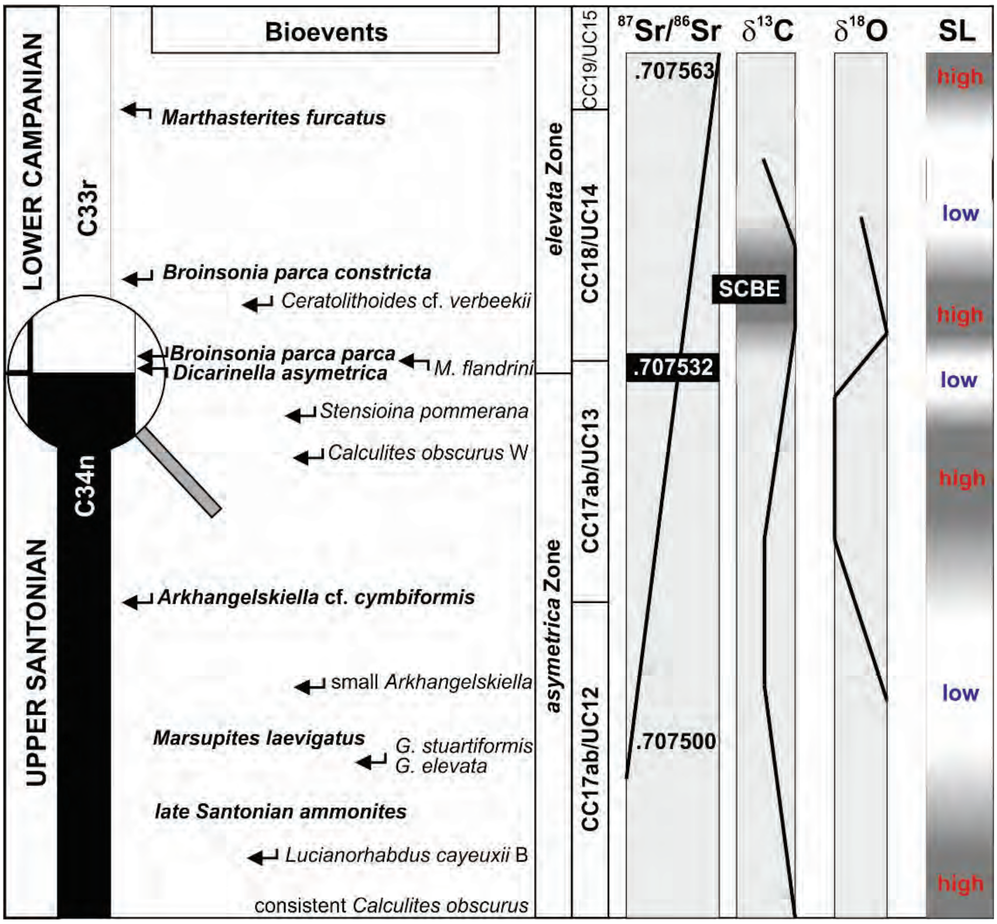
Coordinates: E 13°23'11", N 47°36'44".
Location: Postalm roadcut (Salzburg) near Rigaus, 7 km NNW of Abtenau (Salzburg).
Topic: Section through the upper part of the Gosau Group; sequence boundary on top of Hochmoos Formation; red marly cyclic limestones of Nierental Formation; Zwieselalm Formation.
Lithostratigraphic units: Gosau Group, Hochmoos-, Bibereck- and Nierental Formation.
Age: Late Santonian–Campanian.
Tectonic unit: Lammer Unit, NCA.
Specialities: Mountain road to one of the largest alpine meadow areas of the Postalm.
References: KRENMAYR (1996), WAGREICH et al. (2012), WOLFGRING et al. (2015), WOLFGRING & WAGREICH (2016), NEUHUBER et al. (2016).

Stop 12/1. Santonian/Campanian boundary

The boundary between the Lower Gosau Subgroup and the Upper Gosau Subgroup is characterized by short-time uplift and erosion at this basin-marginal setting, followed by fast subsidence into bathyal depths. A robust magnetostratigraphy was established. Including nearby complementary sections, palaeomagnetic data can be integrated with stable isotope data, planktonic foraminifera and calcareous nannoplankton biostratigraphy, strontium isotope stratigraphy, and ammonite, crinoid and inoceramid data. The Postalm section (Text-Fig. 12) shows a deepening trend from Upper Santonian conglomerates (Hochmoos Formation) and grey shelf marls (Bibereck Formation) to pelagic bathyal red marly limestones (Nierental Formation) of Campanian age. Palaeomagnetic data allow identifying the top of Chron C34n and the following reversal in the lower part of the red marly limestones. A 1 m-thick interval of high magnetic susceptibility is present at the end of C34n. Two of the main suggested biomarkers to pinpoint the Santonian/Campanian boundary, i.e. the last occurrence of the planktonic foraminifer *Dicarinella asymetrica* and the first occurrence of the nannofossil *Broinsonia parca parca*, occur in close proximity to the reversal, which is suggested herein as the primary marker event for the base of the Campanian. Strontium isotope stratigraphy indicates a value of 0.707534. Both carbon and oxygen isotope values show a negative excursion just below the boundary. The positive Santonian/Campanian boundary carbon isotope event (SCBE) starts probably just at the boundary level. This interval is considered to correspond to a short sea-level high in the Late Santonian followed by a lowstand at the Santonian/Campanian boundary (Text-Fig. 13). Macrofossil data from the nearby Schattau section (Wagreich et al., 2009a; Summesberger et al., 2017b, c) indicate the Late Santonian *Paraplanum* ammonite Subzone, the presence of the crinoid *Marsupites laevigatus* and inoceramids, e.g. *Cordiceramus muelleri muelleri,* below the boundary as defined by magnetostratigraphy.



Text-Fig. 12: Postalm-road near Abtenau-Rigaus, Top of Hochmoos Formation to the left, followed by grey marls of Bibereck Formation and red marly limestones of the Nierental Formation, including the base of the Campanian as defined by the base of magnetochron C33r.

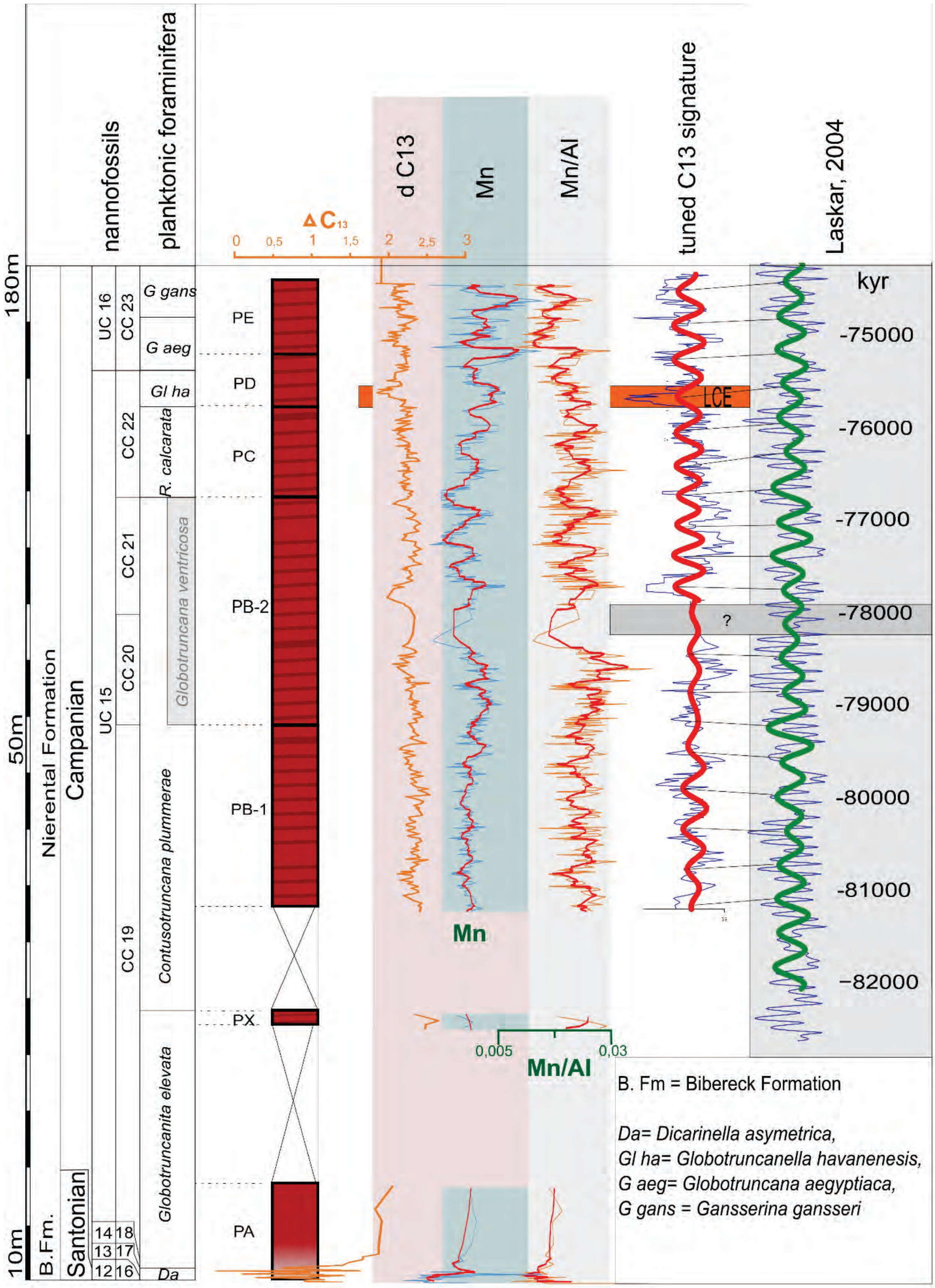


Text-Fig. 13: Composite stratigraphy and events around the Santonian/Campanian boundary interval at the Postalm PA and nearby Gosau Group sections.

Stop 12/2. Campanian Nierental Formation

The Nierental Formation (Upper Gosau Subgroup) is characterized by marlstones and red marly limestones (Text-Fig. 14). The red marly limestones (carbonate contents 67–80 %) are interpreted as pelagites (KRENMAYR, 1996). Percentages of planktonic foraminifera of the total sediment are more than 10 %. No grain size trends within the siliciclastic fraction was detectable. Sedimentation rates are about 20 mm/1,000 a. Fragments of inoceramids concentrated by bottom currents increase upsection. In the uppermost part of the section, mm-thick grey, fine sandstone to siltstone turbidite layers are intercalated. They represent distal turbidites of a small, but sandstone-rich deep-water fan of the Ressen Formation of the Gosau area.

Biostratigraphic data are based on moderately preserved nannofossil assemblages, which indicate a complete Campanian section from UC14/CC18 (FO of *Broinsonia parca*) to UC16/CC23. Planktonic foraminifera include the *D. asymetrica* to *G. gansseri* Zones. A complete cyclic record of the Upper Campanian is preserved.



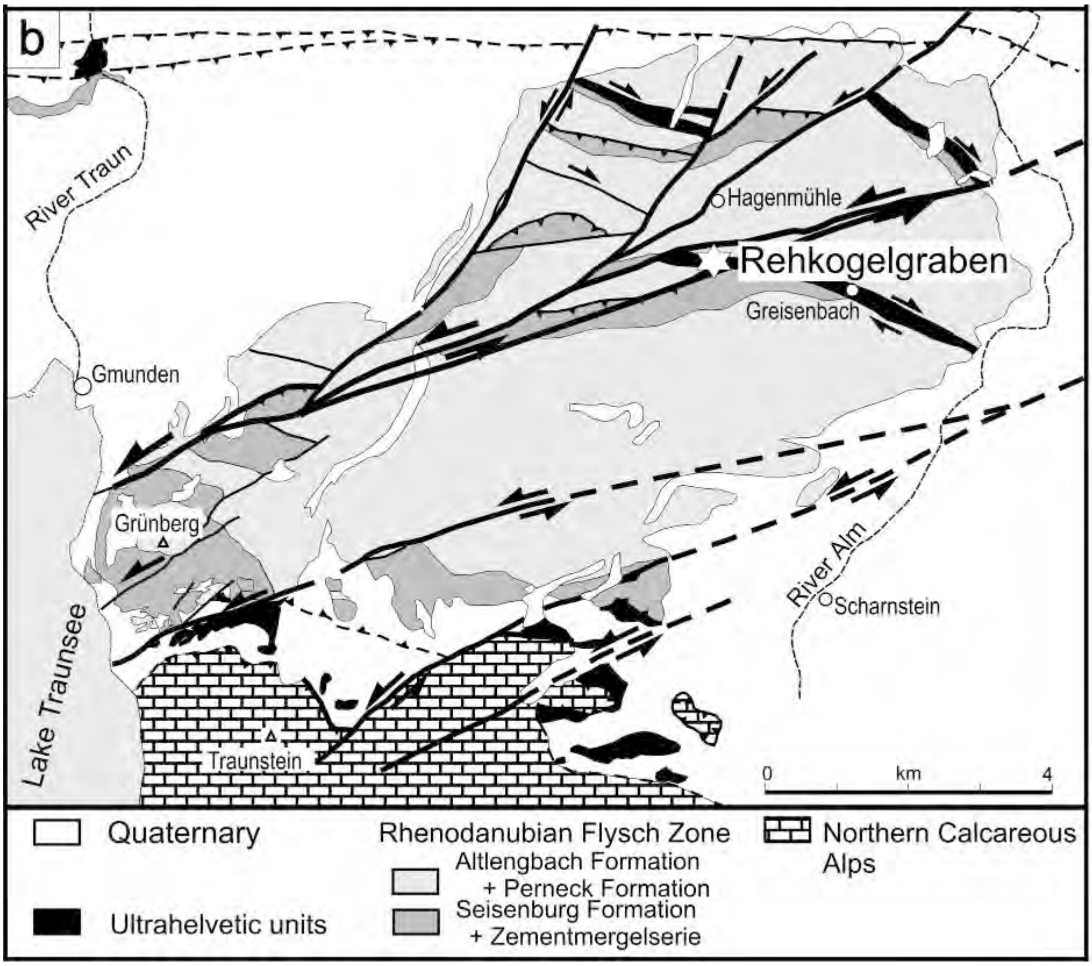
Text-Fig. 14: Postalm section along the road cut. Although the lower part of the Campanian is partly covered, the upper part is continuously exposed and shows a highly cyclic record including the *calcarata* Zone.

Stop 13. Cenomanian–Turonian at Rehkogelgraben/Hagenmühle (Upper Austria)

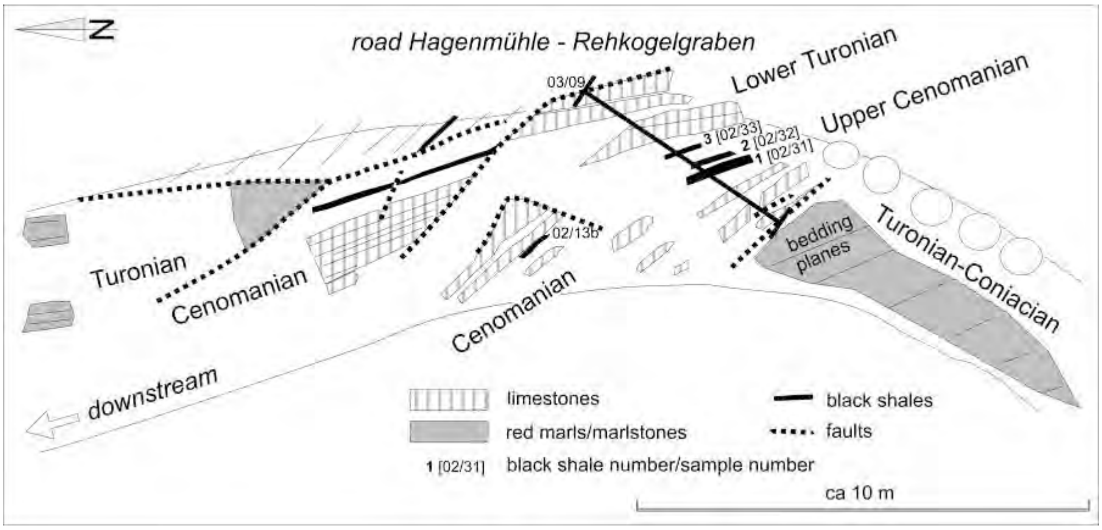
Coordinates: E 13°55’30”, N 47°56’08”.
Location: Outcrops in Rehkogelgraben creek.
Topic: Hemipelagic sediments, black shales and the Cenomanian-Turonian transition, CORBs.
Lithostratigraphic unit: “Buntmergelserie” (Upper Gosau Subgroup).
Age: Upper part of *Gansserina gansseri* Zone, CC25b/ UC20a^{TP}.
Tectonic unit: Ultrahelvetic Unit.
Specialities: Black shales below water table and cyclicity including CORBs.
References: RÖGL in KOLLMANN & SUMMESBERGER (1982), WAGREICH et al. (2008), GEBHARDT et al. (2010), PAVLISHINA & WAGREICH (2012).

The Ultrahelvetic units of Austria preserve remnants of the European continental slope sediments, positioned originally between the foreland and Helvetic shelf to the north and the abyssal Rhenodanubian/Penninic Flysch basins, a part of the Alpine Tethys. The Rehkogelgraben section (KOLLMANN & SUMMESBERGER, 1982) belongs to an Ultrahelvetic tectonic slice within the Rhenodanubian Flysch Zone between Hagenmühle and Greisenbach, to the east of Gmunden (Upper Austria, Text-Fig. 15). Strata within these tectonic windows have been traditionally attributed to the “Buntmergelserie”, an informal lithostratigraphic unit comprising Aptian/Albian to Eocene pelagic and hemipelagic shales, marlstones, and marly limestones with rhythmic limestone and marl alterations. Upper to middle bathyal water depths have been inferred for the Ultrahelvetic units. The Cenomanian/Turonian boundary section includes distinctive black shale horizons and a transition from black shales into marly limestones and red marls, which are typical for Ultrahelvetic sections in Upper Austria (Text-Fig. 16). Above this succession, a distinct red pelagic interval follows from the Lower/Middle Turonian onwards, a typical CORB (Cretaceous Oceanic Red Beds) facies, including Santonian cyclic CORBs with red marlstones and white marly limestones (NEUHUBER & WAGREICH, 2009, 2010).

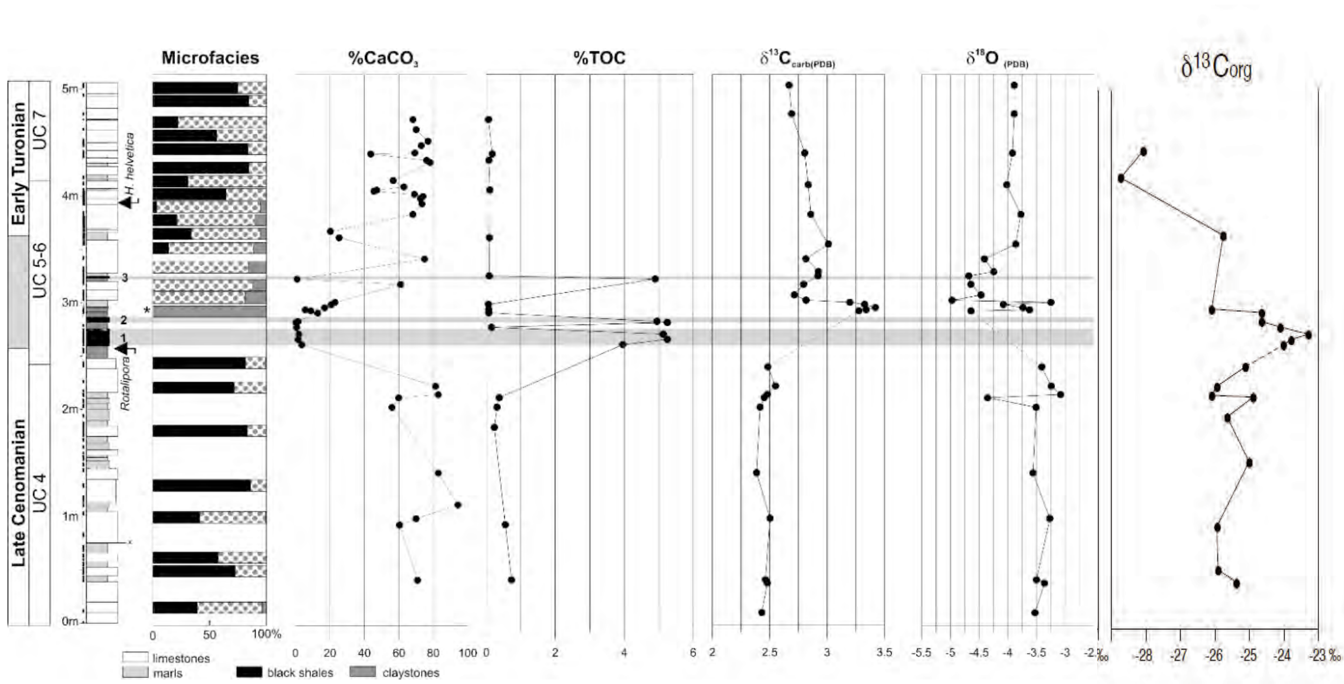
The Cenomanian/Turonian boundary section comprises a 5 m thick succession of Upper Cenomanian marl-limestone cycles overlain by a black shale interval composed of three black shale layers and carbonate-free claystones, followed by Lower Turonian white to light grey marly limestones with thin marl layers (Text-Fig. 17). The main biostratigraphic events in the section are the last occurrence of *Rotalipora* and the first occurrences of the planktonic foraminifer *Helvetoglobotruncana helvetica* and the nannofossil *Quadrum gartneri*. The thickest black shale horizon has a TOC content of about 5 %, with predominantly marine organic matter of kerogen type II. Vitrinite reflectance and Rock-Eval parameter T_{max} (< 424° C) indicate low maturity. HI values range from 261 to 362 mg HC/g TOC. $\delta^{13}C$ values of bulk rock carbonates and organic matter display the well-documented positive shift around the black shale interval, allowing correlation of the Rehkogelgraben section with other sections such as the GSSP succession at Pueblo, USA. In the lower part of the section, $\delta^{13}C_{carb}$ values lie uniformly around 2.5 ‰ and show a slight decrease before the first minor peak of 2.6 ‰, which is associated with the LO of the nannofossil *Lithraphidites acutus.* The FO of the nannofossil *Eprolithus octopetalus*, above black shale 2, is associated with a second carbon isotope peak of up to 3.4 ‰, followed by a small peak below 3 ‰ immediately after last the increase in TOC, succeed by a final peak of 3 ‰. Towards the top of the section, values progressively decrease down to 2.7. Sedimentation rates at Rehkogelgraben (average 2.5 mm/ka) are significantly low.



Text-Fig. 15: Geological sketch map of the area east of Gmunden, including outcrop Rehkogelgraben.



Text-Fig. 16: Map view sketch of the Cenomanian-Turonian outcrop in the creek Rehkogelgraben.



Text-Fig. 17: Sedimentological log of the Rehkogelgraben Cenomanian–Turonian section, including microfacies data based on counts of planktonic foraminifera (black), calcispheres (stippled) and radiolaria (grey) in selected thin sections, carbonate and TOC contents, carbon and oxygen isotope values (WAGREICH et al., 2008; GEBHARDT et al., 2010).

The Danubian Cretaceous Group of Bavaria

(Markus Wilmsen[1], Birgit Niebuhr[1] & Thomas Pürner[2])
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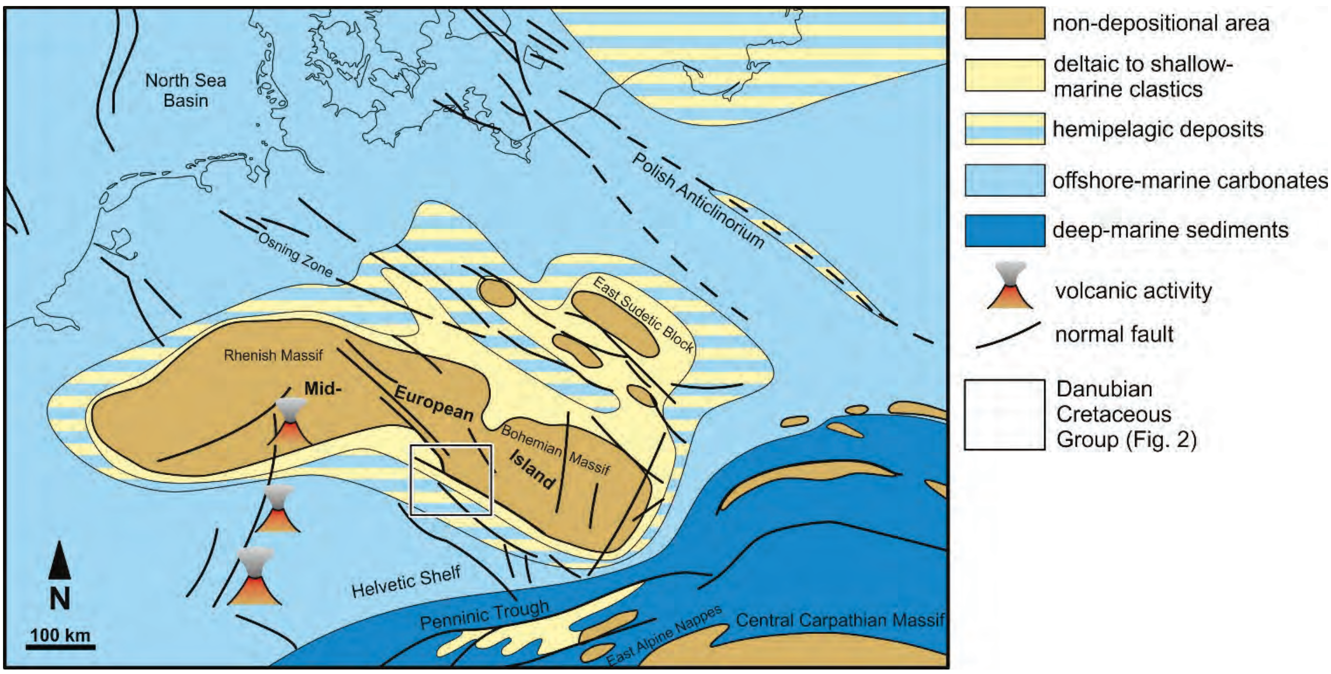
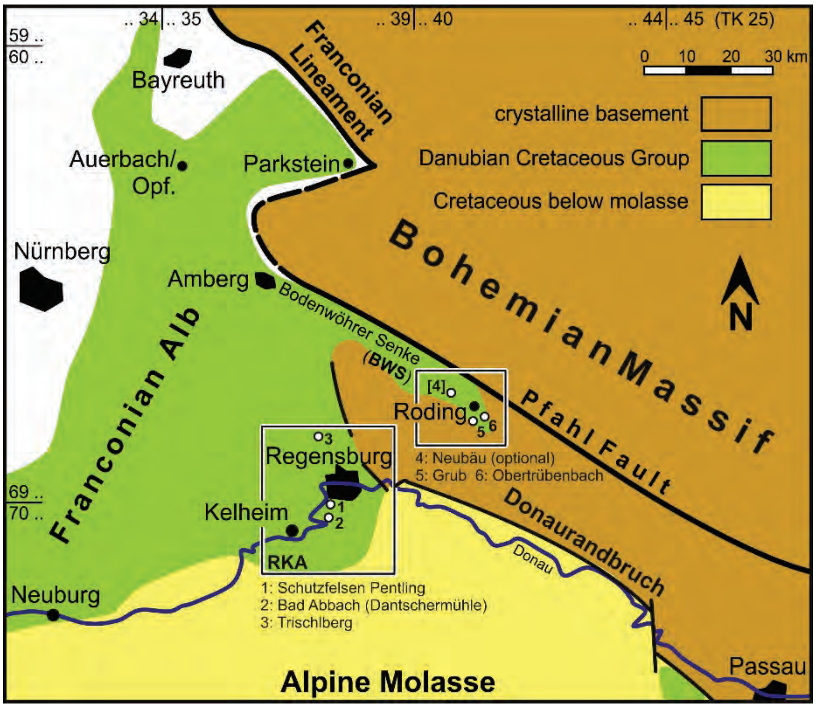
Geological setting and lithostratigraphic framework

At the southern margin of the Mid European Island (MEI), a large, E–W trending positive structure in Central Europe (ZIEGLER, 1990; VEJBAEK et al., 2010), Cretaceous strata of the Danubian Cretaceous Group (NIEBUHR et al., 2009) reflect dynamic depositional conditions in a peri-continental setting at the northern margin of the Alpine Tethys (Text-Fig. 18). Related to the rather proximal position close to elevated topography of the Bohemian Massif, sediments of highly variable facies and thickness accumulated, representing various depositional environments including continental, marginal marine and neritic settings (e.g. NIEBUHR et al., 2009, 2011, 2012, 2014; WILMSEN et al., 2010a; RICHARDT et al., 2013). 3rd-order sea-level changes superimposed onto the general 2nd-order rise during the early Late Cretaceous are well represented by conspicuous sedimentary unconformities (e.g., WILMSEN et al., 2014) defining in total ten Cenomanian and Turonian depositional sequences that almost exclusively consist of transgressive and highstand systems tracts only (NIEBUHR et al., 2014). Their correlative nature across different basins in the periphery of the Mid-European Island suggest eustatic sea-level changes as one of the main drivers of stratigraphic architectures and onlap patterns during the early Late Cretaceous (NIEBUHR et al., 2014; JANETSCHKE et al., 2015). Further control on basin development and sedimentation was related to the onset of tectonic inversion along the marginal faults of the Bohemian Massif in the Middle Turonian (NIEBUHR et al., 2011). The onset of this widespread Late Cretaceous inversion phase (e.g., ZIEGLER et al., 1995) was related to a change in relative motion between the European and African plates (NE-directed convergence) at ca. 90 Ma, i.e. within the Turonian (KLEY & VOIGT, 2008).



Text-Fig. 18: Late Cretaceous palaeogeography in Central Europe (modified after VEJBAEK et al., 2010). The area of Text-Figure 19 is framed.

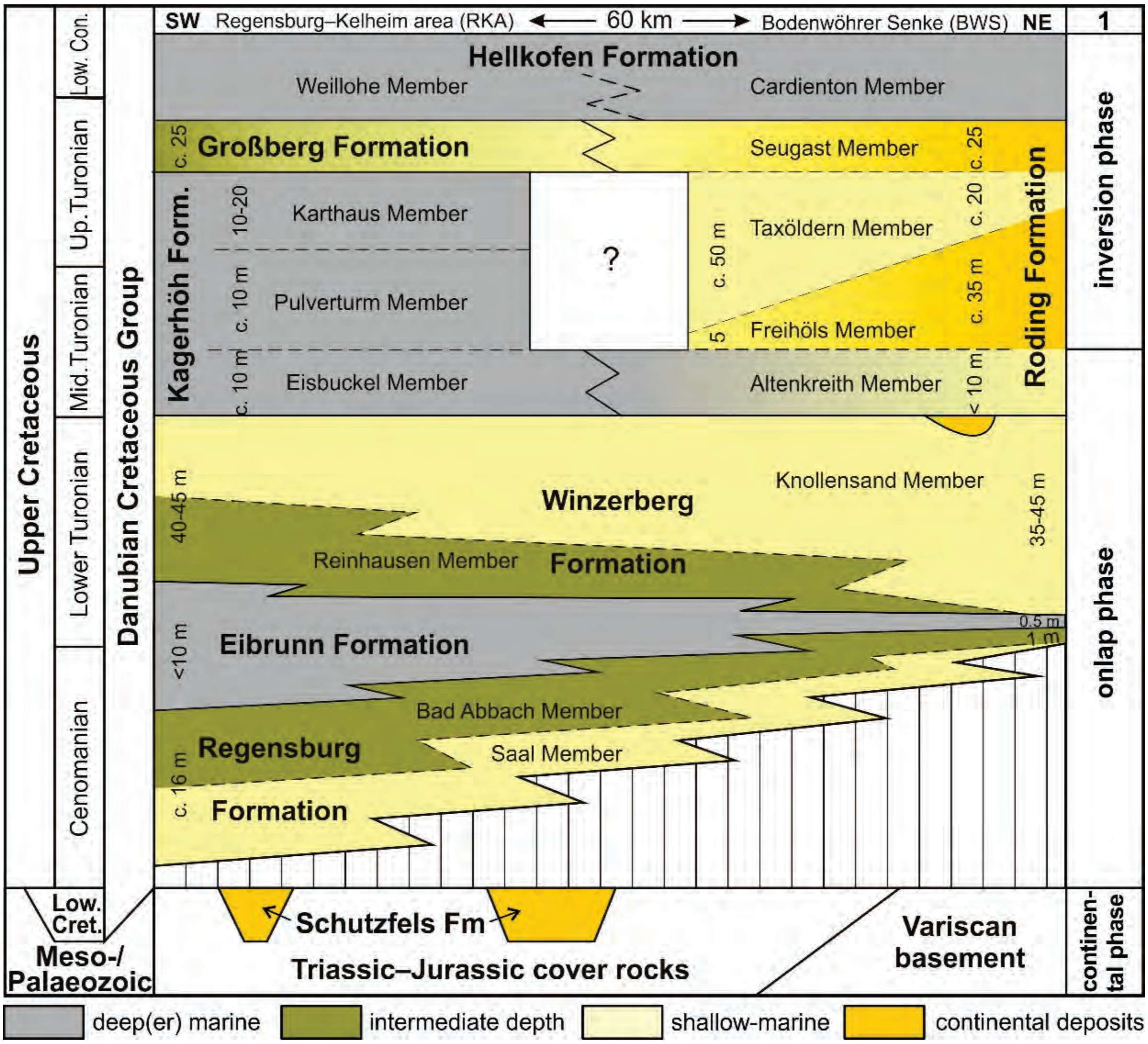
The extra-Alpine Cretaceous sedimentary strata of northern and north-eastern Bavaria (i.e., the Danubian Cretaceous Group) attain thicknesses of up to 500 m and comprise clays, marls, opokas, limestones, calcarenites, sandstones and conglomerates (e.g., NIEBUHR et al., 2009, 2011, 2012; WILMSEN et al., 2010a, b; RICHARDT et al., 2013). Initial marine transgression from the Tethyan Ocean in the south into southern part of the Danubian Cretaceous Basin (Regensburg–Kelheim area, Text-Fig. 19) occurred in Early Cenomanian times across a peneplained landscape mainly composed of Upper Jurassic carbonates (WILMSEN & NIEBUHR, 2010; WILMSEN et al., 2010a). The onlapping deposits are represented by the glauconitic sandstones (Saal Member) and silty to spiculitic marlstones (Bad Abbach Member) of the time-transgressive Regensburg Formation (WILMSEN et al., 2010a; Text-Fig. 20). The preceding continental episode during the Early Cretaceous is documented by a major paleokarst on top of the widespread Upper Jurassic carbonates (Weißjura Group of NIEBUHR & PÜRNER, 2014) and the patchily distributed pre-Cenomanian Schutzfels Formation, the oldest continental deposits of the Danubian Cretaceous Group, which is mainly preserved in sinkholes (Text-Fig. 20). With a north-eastward-directed trend, the early Late Cretaceous sea arrived in the proximal regions of the Danubian Cretaceous Basin, i.e., the Bodenwöhrer Senke (Text-Fig. 19) not before the mid-Late Cenomanian to earliest Turonian (WILMSEN et al., 2010a, b; RICHARDT et al., 2013), resulting in the onlap of the Regensburg Formation onto older Mesozoic strata (Triassic, Jurassic) and Variscan basement rocks of the Bohemian Massif (eastern part of the Mid-European Island). Following a maximum flooding episode in the earliest Turonian (marly offshore deposits of the Eibrunn Formation), the spiculitic calcareous siltstones (Reinhausen Member) and sandstones (Knollensand Member) of the Lower Turonian Winzerberg Formation filled the accommodation generated by the latest Cenomanian–earliest Turonian sea-level rise with more or less equal thicknesses in the entire depositional area (Text-Fig. 20). The onlap phase of the Danubian Cretaceous Group continued into the early Middle Turonian with the lower Middle Turonian Eisbuckel Member of the lower Kagerhöh Formation and the Altenkreith Member of the lower Roding Formation, respectively (NIEBUHR et al., 2014; Text-Fig. 20).



Text-Fig. 19: Distribution of the principal geological units in northeastern Bavaria (modified after NIEBUHR et al. 2014).
The Regensburg–Kelheim area (RKA) and the Bodenwöhrer Senke (BWS) as well as the six visited outcrops are indicated.

From the mid-Middle Turonian onwards, strong facies differentiation between proximal and distal areas started to develop, caused by the onset of initial inversion tectonics at the southwestern margin of the Bohemian Massif (NIEBUHR et al., 2011) related to SW/NE-directed compression (KLEY & VOIGT, 2008) and beginning the inversion phase in the deposition of the Danubian Cretaceous Group (NIEBUHR et al., 2014). Until Coniacian times, predominantly marine influenced deposition continued, interrupted in the Bodenwöhrer Senke by some non-marine to estuarine episodes during the Middle–Late Turonian (Freihöls and Seugast members of the Roding Formation; NIEBUHR et al., 2011; Text-Fig. 20). In the Regensburg–Kelheim area, the calcareous upper Middle to Upper Turonian Pulverturm and Karthaus members of the Kagerhöh Formation as well as the Upper Turonian Großberg Formation correspond to the coeval Freihöls, Taxöldern and Seugast members of the Roding Formation in the proximal Bodenwöhrer Senke. The uppermost Turonian to Lower Coniacian Hellkofen Formation is again distributed across both principal depositional domains (Text-Fig. 20).

The outcrops visited during this field trip are located in the Regensburg–Kelheim area (stops 1–3) and within the Bodenwöhrer Senke (stops 4–6). Their study allows a reconstruction of the Early Cretaceous continental phase and the Cenomanian to early Middle Turonian onlap phase of the Danubian Cretaceous Group (cf. NIEBUHR et al., 2014; Text-Fig. 20). Due to the limitation of time, the inversion phase will not be treated in the framework of this field trip (see NIEBUHR et al., 2011 for details).



Text-Fig. 20: Lithostratigraphy of the Danubian Cretaceous Group (modified after NIEBUHR et al., 2014). Note the distal–proximal trends from the Regensburg–Kelheim area (RKA) to the Bodenwöhrer Senke (BWS). 1: tectono-sedimentary stratigraphic phases of NIEBUHR et al. (2014). See text for further explanation.

Stop 14. Schutzfelsen near Pentling

Coordinates: E 12°02'48", N 48°59'31".

Location: Outcrops along the outer bank of the River Danube northwest of Pentling, southwest of Regensburg.

Topic: Depositional setting and stratigraphy of Lower Cretaceous terrestrial deposits.

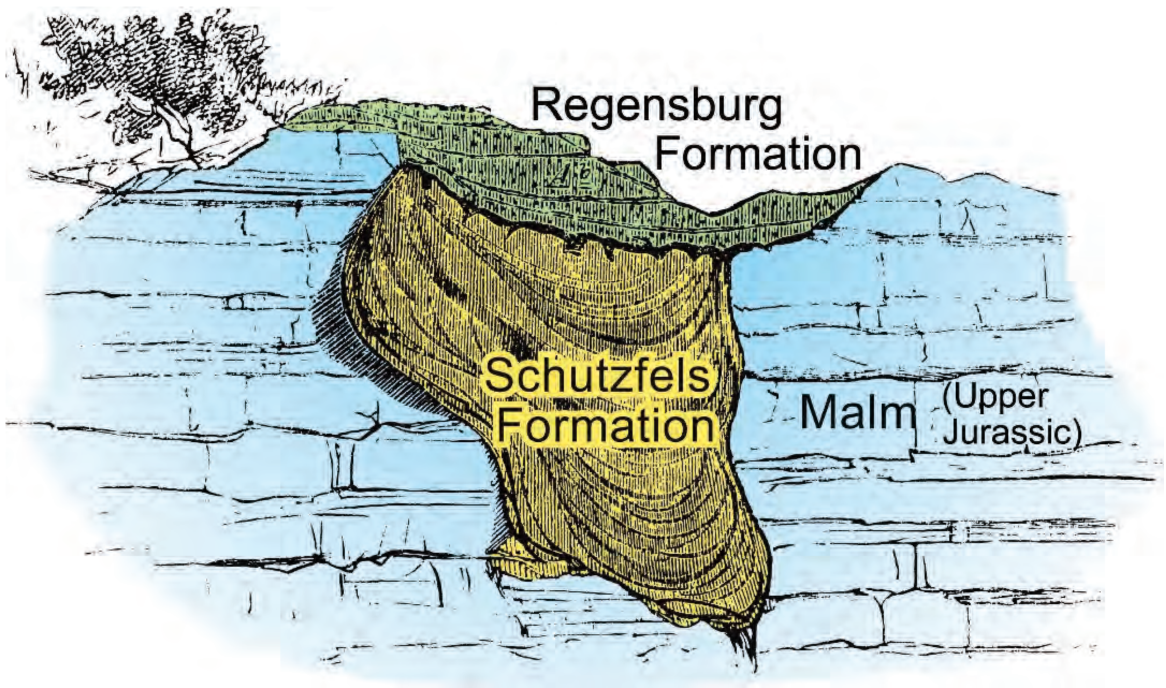
Lithostratigraphic units: Schutzfels- and Regensburg Formation.

Age: Early Cretaceous (post-Early Tithonian to pre-Cenomanian) and Early Cenomanian.

Specialities: Deposition and preservation of Lower Cretaceous terrestrial deposits in pre-Cenomanian sinkholes covered by shallow-marine Cenomanian greensands of the Regensburg Formation.

References: GÜMBEL (1854, 1868), TRUSHEIM (1935), NIEBUHR et al. (2009), BAYERISCHES LANDESAMT FÜR UMWELT (2011).

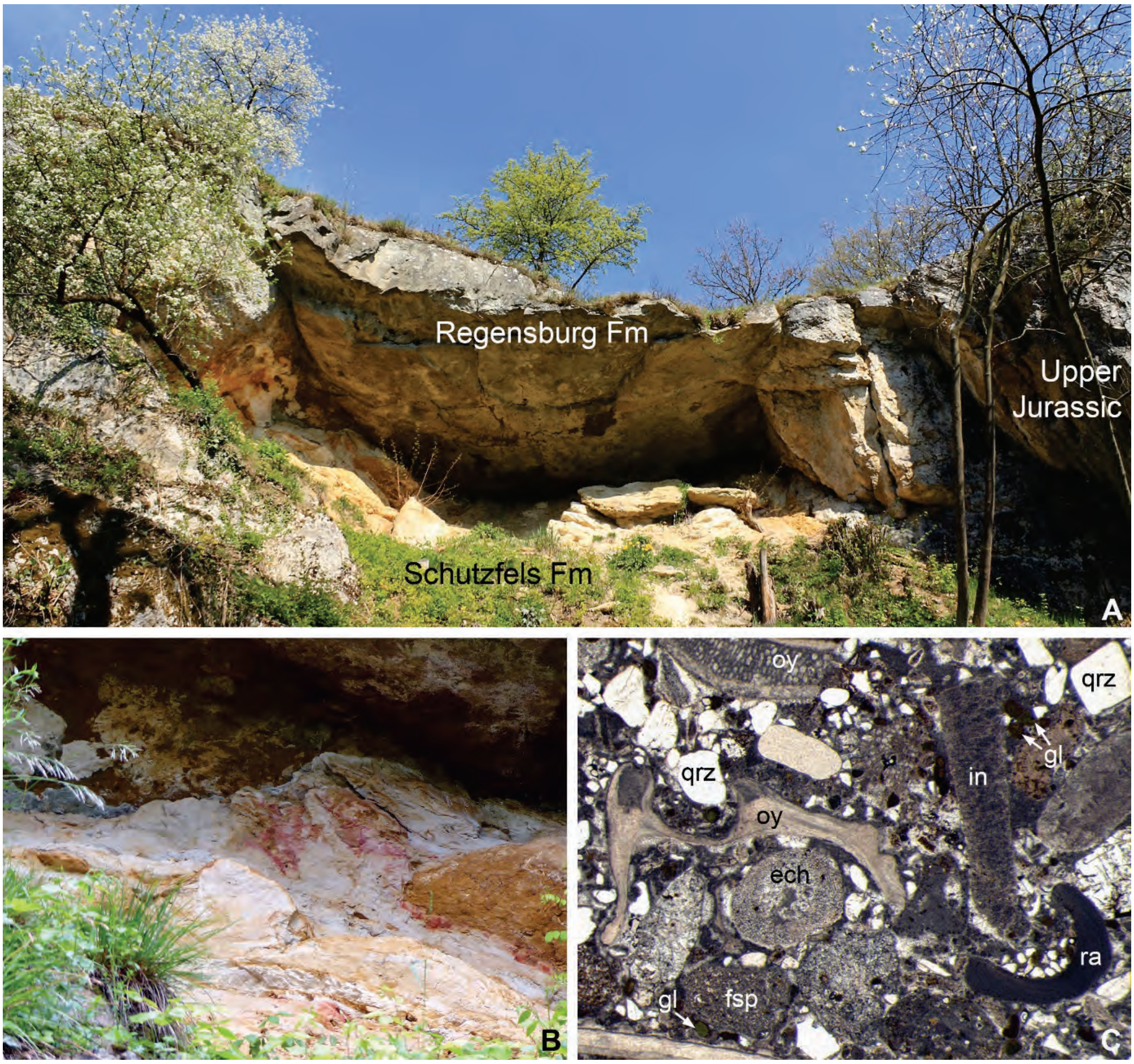
The Schutzfelsen exposes a poorly lithified succession of varicoloured continental siliciclastics that rest within an Early Cretaceous sinkhole that formed in massive Upper Jurassic dolomites of the Frankenalb Formation of NIEBUHR & PÜRNER (2014). Both units are covered by Lower Cenomanian strata of the shallow marine Regensburg Formation. It was the well-known Bavarian geologist Carl Wilhelm Gümbel (1823–1898) who coined in 1854 the name "Schutzfelsschichten" (Schutzfels beds) for these continental strata (Text-Fig. 21), and the Schutzfelsen is thus the type locality of the Lower Cretaceous Schutzfels Formation (NIEBUHR et al., 2009). The name "Schutzfelsen" (rock shelter) is related to the botanist David Heinrich Hoppe (1760–1846) who used the cave-like outcrop as shelter when he was overtaken by a heavy thunderstorm during a botanical hike in the area. While waiting for the waning of the storm, Hoppe got the idea for the inception of a botanical society in Regensburg, and somewhat later on the 14th of May 1790, he and three other naturalists founded the oldest still-existing botanical society of the world at the Schutzfelsen – the "Regensburgische Botanische Gesellschaft" (http://www.regensburgische-botanische-gesellschaft.de/). The Schutzfelsen is classified as Geotop no. 56 of the 100 most important geological heritage sites of Bavaria (BAYERISCHES LANDESAMT FÜR UMWELT, 2011). So please do not use your hammers.



Text-Fig. 21: The geological situation at the Schutzfelsen near Pentling (modified after GÜMBEL, 1854).

Generally, the Schutzfels Formation consists of siliciclastic sediments, commonly clays, silts, sands and gravels (and mixtures of it) that are only partially or locally lithified (kaolinitic and siliceous cements may occur). Quartz predominates with 90–95 %, but feldspar, clay minerals and organic remains also occur. In some areas, e.g. near Auerbach and Sulzbach-Rosenberg (Oberpfalz), sedimentary iron ores have been deposited in elongated troughs, forming the Amberg Member of the Schutzfels Formation and providing the basis for regionally important iron mining and smelting for more than a thousand years (the last mines have been shut-down towards the end of the last century). The strata of the Schutzfels Formation are often very variegated with colours ranging from white, yellow to brown, red, violet, green and black. The source of the clastics were the basement rocks of the Bohemian Massif (Moldanubian Zone) in the northeast as shown by SCHNITZER (1953) on the basis of heavy mineral associations. The material was transported by rivers across a karst landscape towards the south and southwest and deposited in fluvial to limnic environments. Originally, the Schutzfels Formation was much more widespread in distribution (e.g. between Neuburg an der Donau und Solnhofen). In many areas, however, it has been eroded prior to or by the transgression of the marine strata of the Danubian Cretaceous Group. As a consequence, the Schutzfels Formation is today very patchily distributed and mainly preserved in sinkholes that formed during the Early Cretaceous in Upper Jurassic carbonates. Unfortunately, it is nearly barren of fossils, only plant debris and a few poorly diagnostic leaf imprints have been reported (TRUSHEIM, 1935). Thus, the age of the Schutzfels Formation can only be inferred from its stratigraphic position, post-dating the deposition of the Upper Jurassic carbonates (see NIEBUHR & PÜRNER, 2014, for a regional synopsis of the Upper Jurassic Weißjura Group) and pre-dating Early Cenomanian transgressive deposits of the marine Regensburg and Wellheim Formations (WILMSEN & NIEBUHR, 2010; WILMSEN et al., 2010a; SCHNEIDER et al., 2013).

At the type locality, the Schutzfels Formation occurs as an infill into a ca. 10-m-wide and > 5-m-deep sinkhole within massive Upper Jurassic dolomites (Text-Fig. 22A). It consists of a chaotic mixture of poorly lithified silty/argillaceous to sandy deposits with scattered quartz pebbles up to a few centimetres in diameter. Colours vary from yellow-brown to red-violet (Text-Fig. 22B). Spectacular are the sharp, near-vertical primary contacts between the massive Upper Jurassic dolomites and the Schutzfels Formation at the walls of the sinkhole. Downward-convex infill structures, however, as indicated in the original drawing of GÜMBEL (1854) are hardly discernable today (Text-Fig. 21). The overlying Regensburg Formation consists of pebble- and granule-bearing bioclastic rudstones and bioclastic sandstones (Text-Fig. 22C). The green colour is related to glaucony that forms a considerable portion of the rock (10–20 %). Oyster, inoceramid, echinoderm, bryozoan and red algae debris (Text-Fig. 22C) confirm the fully marine high-energy environment of the lower Regensburg Formation. The increasing thickness of the Regensburg Formation across the Schutzfelsen and its thinning onto the hard Upper Jurassic dolomites (Text-Figs. 21, 22A) indicate a preferential erosion of the soft Schutzfels Formation during initial transgression. Downward-oriented veins of greensands into the upper Schutzfels Formation are difficult to explain but may be related to the injection of overlying soft, still water-saturated Regensburg Formation caused by renewed synsedimentary collapse of the underlying sinkhole.



Text-Fig. 22: Field and microfacies aspects of the Schutzfelsen near Pentling. A: outcrop situation in 2011: The Schutzfels Formation is embraced between Upper Jurassic carbonates and the Regensburg Formation forms the roof of the rock shelter (view to the east). B: close-up of the Schutzfels Formation showing varicoloured siliciclastic sediments infilling a karst sinkhole within the Upper Jurassic carbonates (field of view ca. 4 m). C: microfacies image showing the bioclastic rudstone fabric of the lower Regensburg Formation at the Schutzfelsen (width of photomicrograph is 8 mm). Abbreviations: ech = echinoderms, fsp = feldspar, gl = glauconite, in = inoceramids, oy = oysters, qrz = quartz, ra = red algae.

Stop 15. Dantschermühle section near Bad Abbach (Germany)

Coordinates: E 12°00’56”, N 48°55’29”.

Location: Abandoned quarry near Dantschermühle, south of Bad Abbach.

Topic: Depositional setting and stratigraphy of Cenomanian to lowermost Turonian transgressive deposits.

Lithostratigraphic units: Regensburg, Eibrunn and lowermost Winzerberg Formations.

Age: Early Cenomanian to Early Turonian.

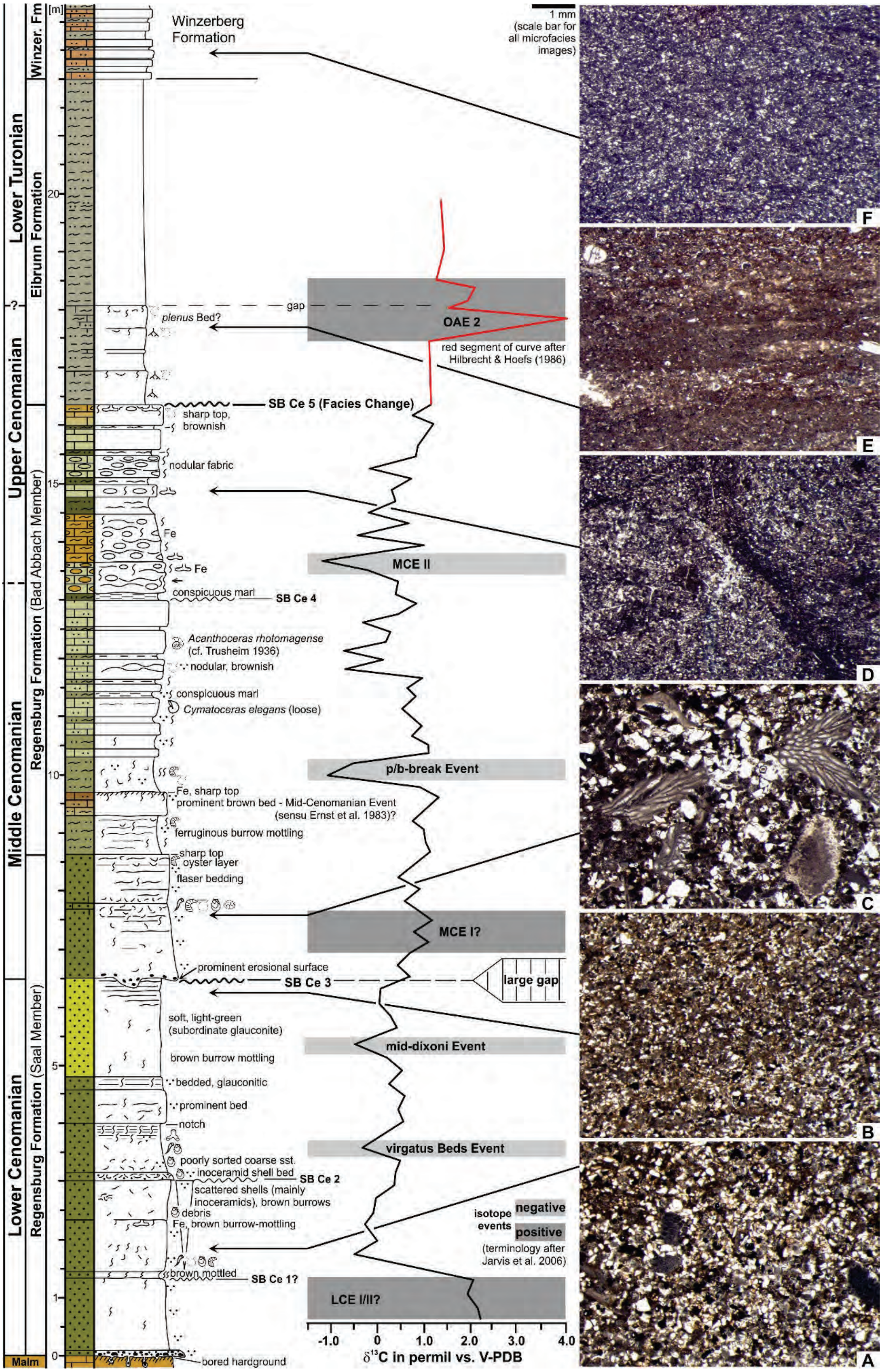
Specialities: Early Cenomanian abrasion platform overlain by retrogradational stacked shelf sediments.

References: GÜMBEL (1854), TRUSHEIM (1935), DACQUÉ (1939), NIEBUHR et al. (2009, 2014), WILMSEN & NIEBUHR (2010), WILMSEN et al. (2010a).

The section is located on the southern flank of the Mühlberg near the Dantschermühle, south of Bad Abbach, ca. 10 km south-southwest of Regensburg (Text-Fig. 19). In the abandoned quarry, a ca. 25 m thick succession of the lower Danubian Cretaceous Group is exposed, including the Regensburg, Eibrunn and lower Winzerberg Formations (Text-Fig. 20). The succession at Dantschermühle includes the type section of the Regensburg Formation and likewise that of the upper Bad Abbach Member of the formation (NIEBUHR et al., 2009). Until the early nineteenth century, the thick-bedded glauconitic sandstones of the lower Saal Member of the Regensburg Formation have been quarried here as freestones. This so-called "Regensburger Grünsandstein" was in great demand since Roman times and quarried in many places south of Regensburg. Many world-famous historical buildings in Bavaria are constructed from this freestone, e.g., the Dom (cathedral) and the Steinerne Brücke in Regensburg as well as the Pinakothek in Munich.

In the Dantschermühle section (Text-Fig. 23), the Regensburg Formation starts with a thin microconglomerate (currently poorly exposed) on a flat and bored surface on top of thick-bedded to massive Upper Jurassic carbonates (Kelheim Member of the Frankenalb Formation of NIEBUHR & PÜRNER, 2014). The borings can be related to lithophagous bivalves and have been termed "Pholadenlöcher" in the old literature (TRUSHEIM, 1935). In modern ichnotaxonomy, this trace fossil is termed *Gastrochaenolites torpedo.* The lower 8.50 m-thick Saal Member consists of bioturbated, fine- to medium-grained, calcareous glauconitic sandstones (Text-Fig. 23A). Noteworthy are a strongly bioturbated horizon 1.40 m above the base, a sharp-based inoceramid layer 3 m above the base and a conspicuous erosion surface at the 6.50 m-level. The latter surface cuts into fine-grained, poorly glauconitic calcareous sandstones (Text-Fig. 23B) and is overlain by medium- to coarse-grained, strongly glauconitic bioclastic sandstones yielding fragments of serpulids, oysters, inoceramids, pectinids, brachiopods, and bryozoans (Text-Fig. 23C). The top of the Saal Member is sharp and marked by an oyster layer. Ammonites (*Mantelliceras mantelli*) and inoceramid bivalves (*Inoceramus virgatus*) from strata of nearby sections equivalent to the Saal Member below the erosion surface at the 6.50 m-level at Dantschermühle indicate an Early Cenomanian age (TRÖGER et al., 2009; WILMSEN et al., 2009; WILMSEN & NIEBUHR, 2010).

The following 7.60 m-thick Bad Abbach Member consists of an intercalation of silty to fine-sandy bioturbated marls and silty, spiculitic marly limestones (Text-Fig. 23D), the fabric of which becomes more nodular upsection. Macrofossils are comparatively scarce, comprising oysters and thin-shelled pectinids as well as very rare nautilids and ammonoids (TRUSHEIM, 1935; DACQUÉ, 1939) typically for Middle and lower Upper Cenomanian strata elsewhere. A limestone bed topped by a strongly bioturbated, ferruginous omission surface occurs at 9.70 m and a conspicuous marl bed at 13 m caps a thickening-upward trend commencing above a thick marl bed overlying the omission surface. The Bad Abbach Member of the Regensburg Formation is terminated at another ferruginous and bioturbated omission surface at 16.30 m.



Text-Fig. 23: Stratigraphic log, carbon stable isotopes and microfacies (A–F) of the succession at Dantschermühle near Bad Abbach (modified after WILMSEN et al., 2010a). The scale bar at the top applies to all microfacies images. For key to symbols, see Text-Figure 24.

The succession continues with silty-argillaceous marls of the Eibrunn Formation (ca. 6.50 m thick) that may show faint laminations (Text-Fig. 23E). In its lower part, bioturbation by *Chondrites* is common and ca. 1.60 m above the base, a slightly more calcareous, one to two dm-thick nodular horizon ("Kalkmergelbank" of FÖRSTER et al., 1983) has been recorded, yielding the belemnite *Praeactinocamax plenus* and, slightly below, a mid-Upper Cenomanian (*Metoicoceras geslinianum* zonal) ammonite fauna (FÖRSTER et al., 1983; RÖPER & ROTHGAENGER 1995). Above, lowermost Turonian planktic foraminifera and inoceramids have been recorded from the upper Eibrunn Formation (FÖRSTER et al., 1983; HILBRECHT, 1986; TRÖGER et al., 2009). The intercalation of fine-grained siliceous marly limestone beds at 22.50 m mark the base of the Lower Turonian Winzerberg Formation, the lower few metres of which are exposed at the top of the section (Text-Fig. 23F).

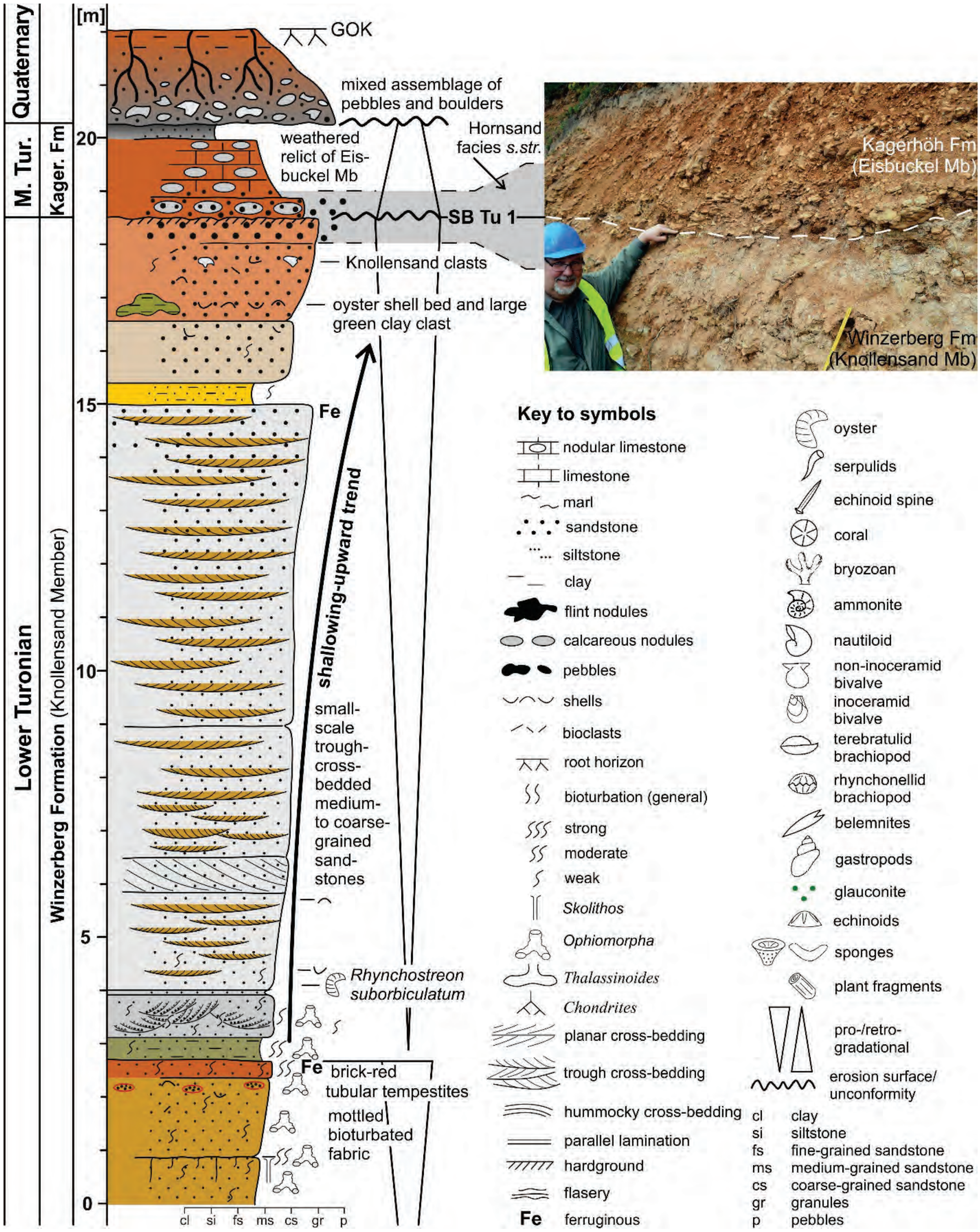
The carbon stable isotope curve of the Regensburg Formation at Dantschermühle is characterized by a relatively flat signature with low values between -1.0 and +1.0 ‰ $\delta^{13}C$ vs. V-PDB (Text-Fig. 23), typical for basin margin sections (e.g. VOIGT & HILBRECHT, 1997). Merely in the lowermost part, values of +2.0 to +2.2 ‰ $\delta^{13}C$ are recorded. Above the erosional surface at 6.50 m there is a slight shift towards heavier values of +0.5 to +1.0 ‰ $\delta^{13}C$ above that level up to c. 11.50 m with a major negative peak in the marl above the brown omission surface at 10 m. The succession from 12 m to the top of the formation is characterized by relatively strong fluctuations and an increase to values between +1.5 to +2.0 ‰ $\delta^{13}C$. For the lower Eibrunn Formation, the curve of HILBRECHT & HOEFS (1986) was used. It is characterized by a major positive excursion up to +4.0 ‰ $\delta^{13}C$ between 1.10 m to 2.20 m above the formational boundary. Based on the bio- and event stratigraphical tie-points, the carbon stable isotope curve of the Regensburg Formation at Dantschermühle can be correlated to condensed successions elsewhere and a number of the Cenomanian isotope events of JARVIS et al. (2006) have been identified (Text-Fig. 23).

The Dantschermühle section documents the early Late Cretaceous transgression of the lower Danubian Cretaceous Group in the Regensburg–Kelheim area (WILMSEN et al., 2010a). The initial stages of transgression are recorded by means of an Early Cenomanian abrasion platform with borings of lithophagous bivalves. Relatively fine-grained sediments started to accumulate not before the fair-weather wave base rose above the sea floor (bioturbated glauconitic sandstones of the Saal Member). Continuous sea-level rise resulted in further deepening of the depositional setting and the accumulation of increasingly distal facies during the Cenomanian (Bad Abbach Member and Eibrunn Formation) with a (second order) maximum flooding interval in the earliest Turonian part of the Eibrunn Formation. Short-lived periods of sea-level fall and lowstand are recorded by intercalated sedimentary unconformities, the most prominent of which are the erosional surface at 6.50 m (sequence boundary SB Ce 3 in the Early/Middle Cenomanian boundary interval) and the top surface of the Regensburg Formation (SB Ce 5 in the mid-Late Cenomanian, Text-Fig. 23; see NIEBUHR et al., 2014 and JANETSCHKE et al., 2015, for recent sequence stratigraphic synopses).

Stop 16. Sandpit near Trischlberg

Coordinates: E 12°01'22", N 49°08'23".
Location: Active sandpit of the Erutec GmbH near Trischlberg.
Topic: Depositional setting and stratigraphy of the Winzerberg Formation.
Lithostratigraphic units: Knollensand Member of the Winzerberg Formation and lowermost part of the Eisbuckel Member of the Kagerhöh Formation.

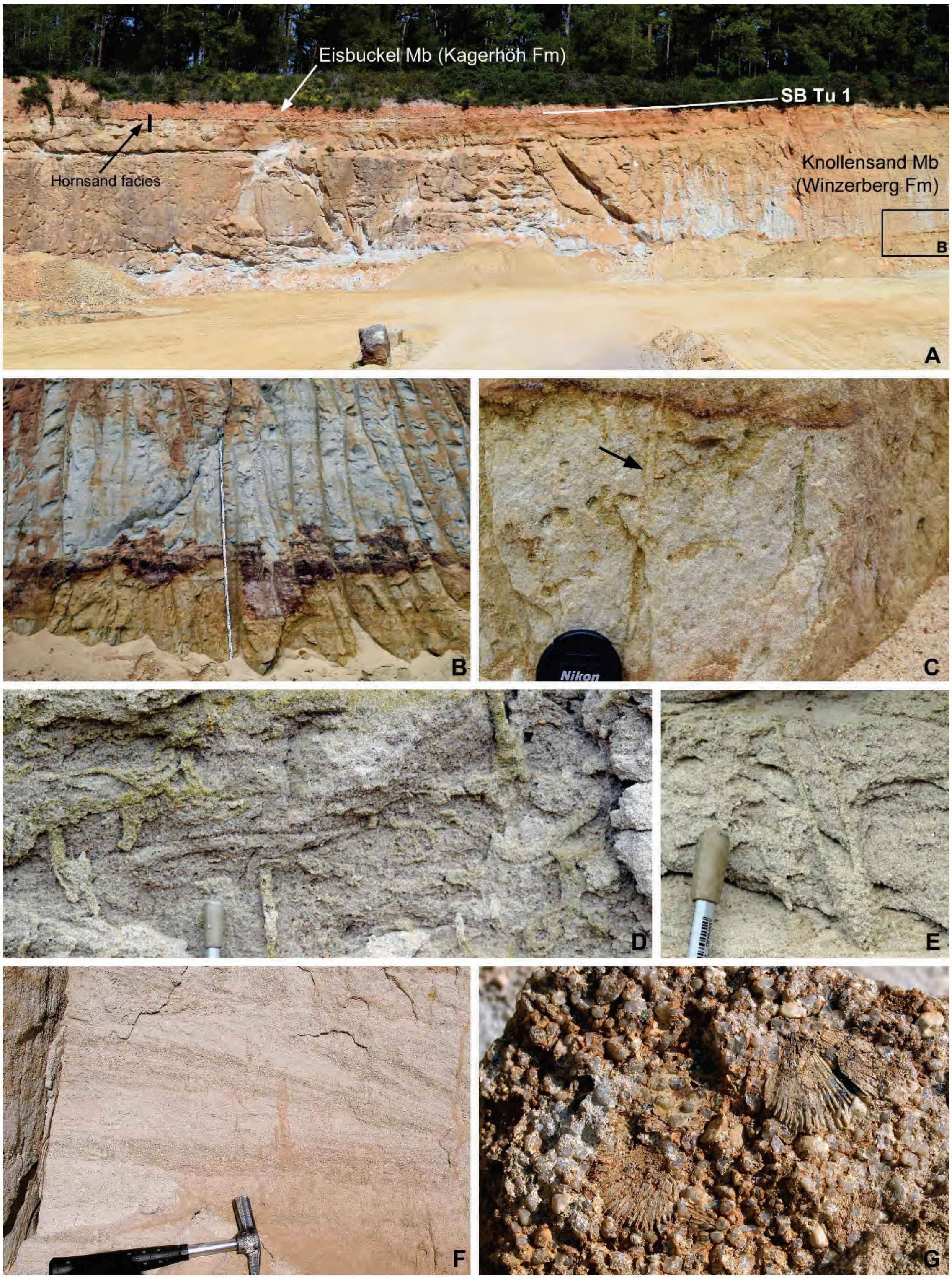
Age: Early to earliest Middle Turonian.
Specialities: Dynamic deposition on a graded siliciclastic shelf system, sea-level development during the Early to Middle Turonian.
References: NIEBUHR et al. (2009, 2014), RICHARDT et al. (2013), WILMSEN et al. (2014).



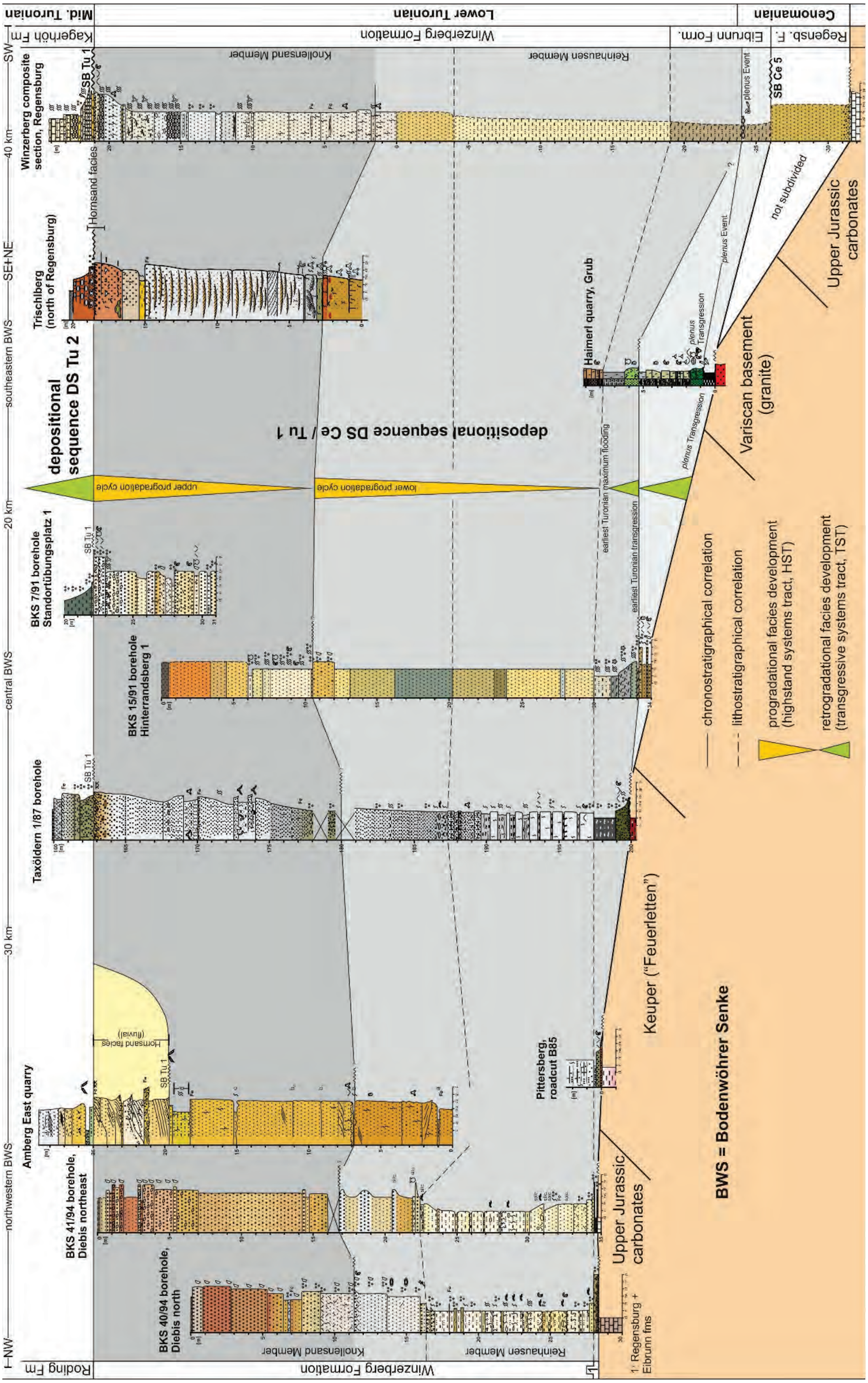
Text-Fig. 24: Stratigraphic log of the Trischlberg sandpit. The unconformable contact of the Winzerberg and Kagerhöh formations (SB Tu 1) is shown by Tom Pürner in the inset photograph. The key to symbols applies for all other figures, too.

The Lower Turonian Winzerberg Formation represents an Early Turonian graded shelf system that developed in the Danubian Cretaceous Basin after the earliest Turonian maximum flooding of depositional sequence DS Ce/Tu 1 (WILMSEN, 2010a, b; RICHARDT et al., 2013; NIEBUHR et al., 2014). During the earliest Turonian maximum flooding interval that corresponds to a global eustatic peak (e.g., correlating to the K140 maximum flooding surface of SHARLAND et al., 2001 on the Arabian Plate), the offshore marls of the Eibrunn Formation even spread into the proximal Bodenwöhrer Senke, forming the distal facies of the shelf system. The mid- and inner shelf facies are represented by the Reinhausen Member (silty spiculites and calcareous siltstones) and the Knollensand Member (fine- to coarse-grained sandstones) of the Lower Turonian Winzerberg Formation forming the highstand systems tract of DS Ce/Tu 1. The formation is overall progradational, filling the accommodation generated by the sea-level rise of of DS Ce/Tu 1, and consists of two stacked progradational cycles (high-frequency sequences) corresponding to the 400-kyr long-eccentricity cycle of the Milankovitch Band (RICHARDT et al., 2013). The depositional sequence is capped by a conspicuous subaerial unconformity in the Lower–Middle Turonian boundary interval (SB Tu 1; RICHARDT et al., 2013; NIEBUHR et al., 2014; WILMSEN et al., 2014). It is associated with the coarse-grained Hornsand facies (“Hornsand unconformity”) and comprises a stratigraphic gap within the earliest Middle Turonian (see WILMSEN et al., 2014 for details). From the Amberg area, fluvial incision and the backfilling of the incised valleys during the Middle Turonian base-level rise have been reported as well (RICHARDT et al., 2013). The Hornsand (facies) is a regional marker bed that has been mainly used for mapping purposes. Lithologically, it is microconglomerate predominantly consisting of well-rounded granules of quartz with subordinate rock fragments such as lydite. It forms a kind of lag deposit within the latest highstand deposits below and the early transgressive deposits above SB Tu 1 (NIEBUHR et al., 2009).

The Trischlberg sandpit exposes a ca. 20 m-thick succession of the upper Winzerberg Formation (Knollensand Member, upper Lower Turonian) and the lower Eisbuckel Member (lower Middle Turonian) of the Kagerhöh Formation (Text-Figs. 24, 25A). In the lower part of the section, intensively bioturbated, yellow-brownish, medium-grained sandstones are exposed; *Ophiomorpha* and *Skolithos* traces can be recognized (Text-Fig. 25B, C). Above a brick-red ferruginous horizon, cross-bedded, grey to greenish-grey medium- to coarse-grained sandstones with well-developed *Ophiomorpha saxonica* burrows follow (Text-Figs. 25B, D, E). Upsection, the grain size gradually increases, bioturbation disappears and small- to medium-scale trough cross-bedding predominates (Text-Fig. 25F). Occasionally interstratified silicified shell remains (mainly oyster fragments) testify the marine origin of the Knollensand Member. The development culminates in a very coarse-grained, microconglomeratic sandstone bed with scattered oyster shells of *Rhynchostreon suborbiculatum* that develops into the Hornsand facies towards the top (Text-Fig. 25G). The bed also contains a large clast of greenish clays. At a sharp surface representing sequence boundary SB Tu 1, the Winzerberg Formation is overlain by upsection fining (calcareous) sandstones of the Eisbuckel Member of the Kagerhöh Formation. In its lowermost part, granules and coarse sand grains of the underlying Hornsand facies are disseminated. The Eisbuckel Member is a strongly decomposed erosional relict of Tertiary weathering processes (evident by the reddish colour) and overlain by medium- to dark-brown loamy Quaternary deposits containing a mixed assemblage of pebbles and boulders, capped by a soil horizon (Text-Fig. 24).



Text-Fig. 25: Field aspects of the Lower to lower Middle Turonian succession in the Trischlberg section. A: overview of the exposure situation in May 2017 at the northern wall of the sandpit. Important units and surfaces as well as the close-up seen in B are marked. B: contact of the lower part of the Knollensand Member (bioturbated brownish sandstones) and the upper part consisting of grey, trough cross-bedded sandstone (scale is three meters long). C: lower part of the Knollensand Member showing intensely bioturbated medium-grained sandstones; a *Skolithos*-like vertical burrow is marked by an arrow (lens cap for scale). D: in the upper part of the Knollensand Member, bioturbation becomes increasingly rare upsection; in the lowermost part, *Ophiomorpha* burrows are still common (pencil for scale). E: sub-vertical shaft of *Ophiomorpha saxonica* (pencil for scale). F: cross-bedded coarse-grained sandstones predominate the upper part of the Knollensand Member (hammer for scale). G: typical textural feature of the Hornsand facies that is developed at the contact of the Winzerberg and Kagerhöh Formations including two small pectinid bivalves (field of view ca. 10 cm).



Text-Fig. 26: Regional correlation diagram of the Winzerberg Formation (modified and supplemented after RICHARDT et al., 2013). Note the onlap into the Bodenwöhrer Senke (BWS) during the transgressive systems tract of DS Ce/Tu 1 and the infilling of the accommodation during the highstand systems tract (for key to symbols, see Text-Figure 24).

The Trischlberg section can be nicely integrated into the regional facies model and correlation panel of the Winzerberg Formation (cf. RICHARDT et al., 2013; Text-Fig. 26). It exposes the (late) highstand interval of depositional sequence DS Ce/Tu 1. This is indicated by the overall progradational facies development from bioturbated to cross-bedded sandstone, the upwards increasing grain size and the decrease in trace fossils. *Ophiomorpha* burrows are typical for instable sandy substrates of the proximal mid- to inner shelf. The ferruginous bed in the lower part of the section probably corresponds to the top of the lower progradational cycle within the Winzerberg Formation (Text-Fig. 26). The upper cycle is fully exposed in the Trischlberg sandpit and capped by SB Tu 1, most likely representing a subaerial unconformity (WILMSEN et al., 2014). The overlying, upwards-fining Eisbuckel Member of the Kagerhöh Formation demonstrates the renewed marine onlap during the early Middle Turonian transgression.

Stop 17. Parish church in Neubäu am See (optional)

Coordinates: E 12°24’59”, N 49°14’10”.

Location: Catholic parish church (Pfarrkirche) “Mariä Namen” in Neubäu am See near Roding.

Topic: Marginal facies of the Danubian Cretaceous Basin during the Middle to Late Turonian inversion phase.

Lithostratigraphic unit: Freihöls Member of the Roding Formation.

Age: Middle to Late Turonian.

Specialities: Coarse-grained siliciclastic deposits of the proximal Bodenwöhrer Senke used as a local freestone.

References: NIEBUHR et al. (2009, 2011).

The parish church “Mariä Namen” (Marian name) in Neubäu (sometimes also termed “Maria-Hilf-Kirche”) was built in 1901 in new Romanesque (Neuromanik) style by the famous architect Johann Baptist Schott (1853–1913) from Munich. The church was consecrated on 20th of July, 1907. Schott also built the Basilica of St. Anna in Altötting, St. Josef in Weiden, or the parish churches in Teisnach and Zwiesel, and is one of the outstanding church architects in Bavaria during the Historicism. The parish church in Neubäu is justifiably one of the most beautiful new Romanesque buildings in East Bavaria (Text-Fig. 27A). At the turn of the nineteenth and twentieth centuries, many people wanted the old art styles back. In the emerging industrial age, which demanded inhumane working conditions and in which child labor was customary, people deliberately fled into the emotional and romantic – time was not yet ripe for a breakthrough to modernity. The church building of Neubäu should therefore be like a heavenly fortress and anticipate the splendor of heaven. Strong round arches rest on consoles and give a view of the church ship and the altar. Schott has truly left a great impression in Neubäu by creating a really harmonious space.

The Middle to Upper Turonian Roding Formation in the Bodenwöhrer Senke was deposited close to the southwestern margin of the Bohemian Massif. It has a thickness ranging from 75 m in the northwest to 120 m in the central and southeastern parts of the Bodenwöhrer Senke (NIEBUHR et al., 2011). The Roding Formation nearly exclusively comprises siliciclastic strata (clays, silt- and sandstones, reddish to brown lithic-arkosic pebble sandstones and gravelstones) and is subdivided into the Altenkreith, Freihöls, Taxöldern and Seugast members (from base to top; Text-Fig. 20). The Altenkreith and Taxöldern members are marine in origin (inner to mid-shelf sediments) while the Freihöls and Seugast members are (predominantly) non-marine units (alluvial fan and river deposits, occasional estuarine influence). The Roding Formation rests with a major unconformity (sequence boundary SB Tu 1) on the Lower Turonian Winzerberg Formation and is sharply overlain by the upper uppermost Turonian–Lower Coniacian deeper marine clays and marls of the Hellkofen Formation (Text-Fig. 20). Also the boundaries of the Freihöls and Seugast members are significant erosional unconformities resulting from rapid and substantial relative sea-level falls. Based on erosional and/or non-depositional unconformities (sequence boundaries, SB Tu 1–5), four depositional sequences (DS Tu 2–5) have been identified in the Middle–Upper Turonian succession of the Bodenwöhrer Senke with a 2nd-order maximum flooding in DS Tu 3 in the late Middle Turonian (NIEBUHR et al. 2011). Correlative surfaces have also been recognized in the Regensburg–Kelheim area in the contemporaneous Kagerhöh and Großberg formations, and sequence stratigraphy thus offers an important tool for correlation (NIEBUHR et al. 2014). However, based on conspicuous changes in basin configuration, subsidence patterns and sediment supply, the base of the mid-Middle Turonian Freihöls Member indicates the onset of Late Cretaceous inversion at the southeastern margin of the Bohemian Massif. Consequently, the mainly eustatically-controlled onlap phase and the tectonically-influenced inversion phase of the Danubian Cretaceous Group have been delimited at this level (NIEBUHR et al., 2014; see Text-Fig. 20).

Text-Fig. 27: Freihöls Member of the Roding Formation (Middle to Upper Turonian) used as freestone at the parish church “Mariä Namen” in Neubäu am See. A: the church as seen from the south. B: door frame showing the immature, coarse-grained fabric (field of view ca. 1 m). C: better sorted facies consisting of dm-scale units grading from quartz (micro-)conglomerate to coarse-grained sandstone; note the good rounding of the quartz granules and pebbles in the upper bed (lens cap for scale). D: close-up view of the poorly sorted pebbly coarse-grained sandstone facies of the Freihöls Member (lens cap for scale).

Due to its commonly poor lithification, the strata of the Roding Formation have mostly been excavated in shallow sandpits as local construction sands. The unit is thus poorly exposed and almost all of the more continuous sections studied by NIEBUHR et al. (2011) are cores. The inhomogenous poorly sorted fabric, the coarse grain size and the variable component spectrum furthermore complicate the potential use of the Roding Formation for construction purposes. Consequently, it is rare to find it as a freestone. The church in Neubäu is thus an exception, most likely owing to the fact that it would have been much more expensive to use better material from other sources that are quite distant (e.g. Triassic sandstones from Franconia) and/or very costly (e.g. greensands of the Regensburg Formation). The parish church in Neubäu thus offers a good opportunity to study the lithofacies of the Roding Formation. A quick inspection of the door frames and outer walls readily shows the poorly sorted, coarse-grained pebbly sandstone to conglomerate fabric of the rocks (Text-Figs. 27B, D). Poorly rounded (milky) quartz is the main component, with subordinate rock fragments and rare feldspar grains. Sharp-based graded beds with better sorting and rounding of the quartz grains can also be observed (Text-Fig. 27C). The lithofacies shows the proximity of the source area (the boundary fault to the Bohemian Massif, the Pfahl Fault, is only a few kilometers to the northeast). Based on the observations and the comparison to the core sections Roding 1/06 and Pösing 9/02 (the composite type section of the Roding Formation) and another nearby borehole section (BKS 7/91; see NIEBUHR et al., 2011 for details), the rocks used as freestones for the church at Neubäu can be assigned to the non-marine Freihöls Member of the Roding Formation (Text-Fig. 20). At the beginning of the 20th century, when the church was built, there was only one larger quarry in the vicinity, i.e. at Lindtach, ca. 4 km east-northeast of Neubäu. In this now abandoned quarry, ca. 10 m of a beige-brown to reddish medium- to coarse-grained, in part pebbly sandstone with occasional layers of quartz pebbles are exposed, assigned to the Freihöls Member.

Stop 18. Haimerl quarry near Grub

Coordinates: E 12°30’45”, N 49°09’10”.

Location: Active quarry of the Haimerl gravel works, south of Roding.

Topic: Late Cenomanian to Early Turonian sea-level history in the Bodenwöhrer Senke.

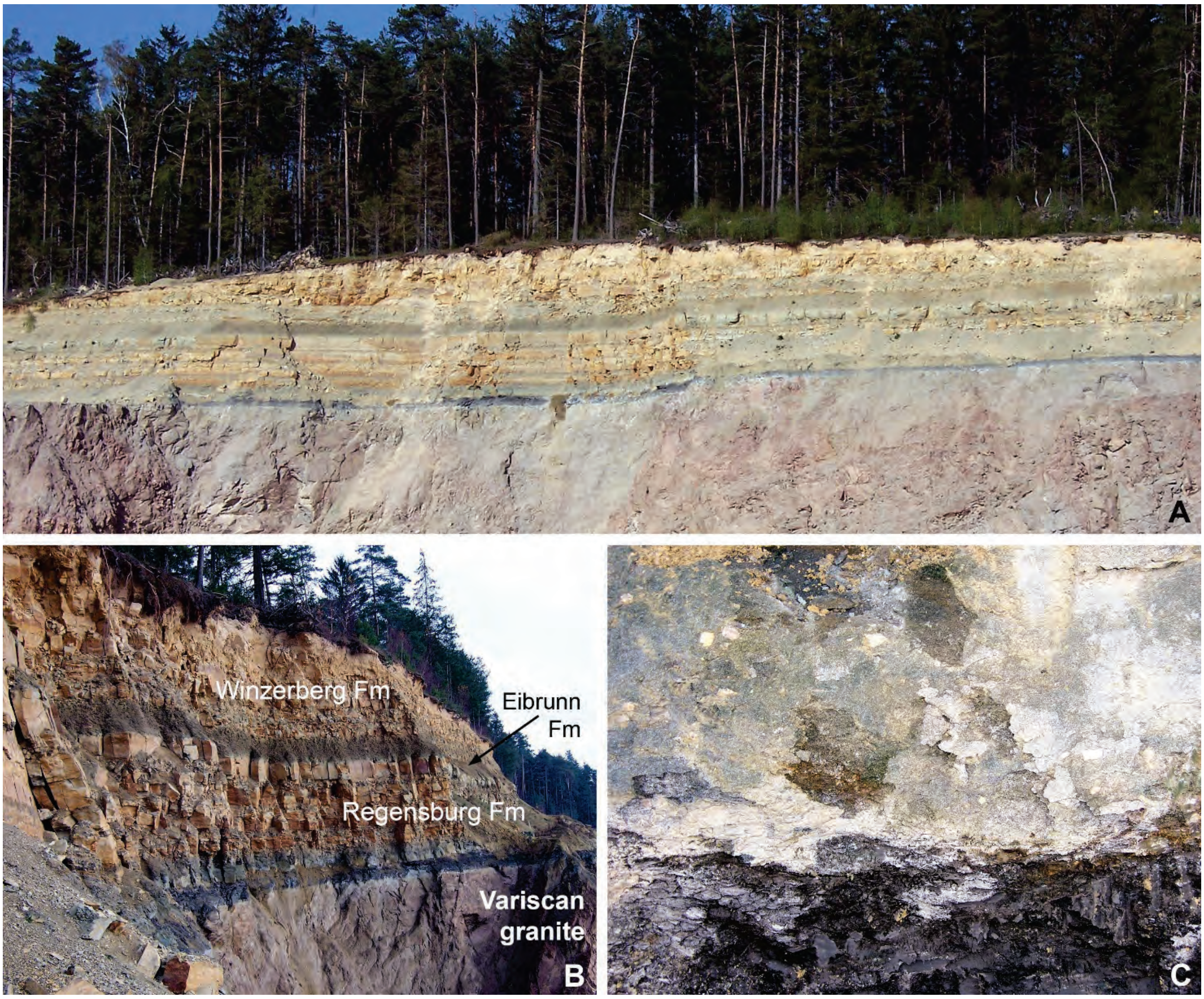
Lithostratigraphic units: Regensburg, Eibrunn and lowermost Winzerberg Formations (Reinhausen Member).

Age: Late Cenomanian (*Metoicoceras geslinianum* Zone) to Early Turonian.

Specialities: Onlap pattern of the Regensburg Formation onto a peneplain of Variscan basement rocks; earliest Turonian maximum flooding interval; carbon stable isotopes and bioevents.

References: NIEBUHR et al. (2009, 2014), WILMSEN & NIEBUHR (2010), WILMSEN et al. (2010a, b), RICHARDT et al. (2013).

The Grub section is located in the active quarry of the Haimerl gravel works, ca. 5 km south of Roding (Bodenwöhrer Senke). It exposes a ca. 10 m thick succession of the Regensburg, Eibrunn and lower Winzerberg Formations, which rests on a flat-topped Variscan granite (Text-Figs. 28A, 29). In contrast to the situation in the Regensburg–Kelheim area, the onlap of Upper Cretaceous marine deposits onto Triassic–Jurassic strata or Palaeozoic basements rocks is much younger in the Bodenwöhrer Senke (WILMSEN et al., 2010a, b; RICHARDT et al., 2013; NIEBUHR et al., 2014). In the Roding area, the Regensburg Formation transgresses onto a medium- to coarse-crystalline, partly porphyric granite (Wald Pluton) of the Moldanubian Zone that intruded in the Carboniferous (ca. 325 Ma) during the late stages of the Variscan orogeny in considerable crustal depth. By early Late Cretaceous times, the granites have been exhumed and formed the substrate for the Late Cenomanian and earliest Turonian transgressions. The integrated stratigraphy and facies analysis of the two exposures in Grub and Obertrübenbach allows an understanding of the sea-level dynamics during this crucial interval of Earth history including a shallow-water record of the oceanic anoxic event (OAE) 2.

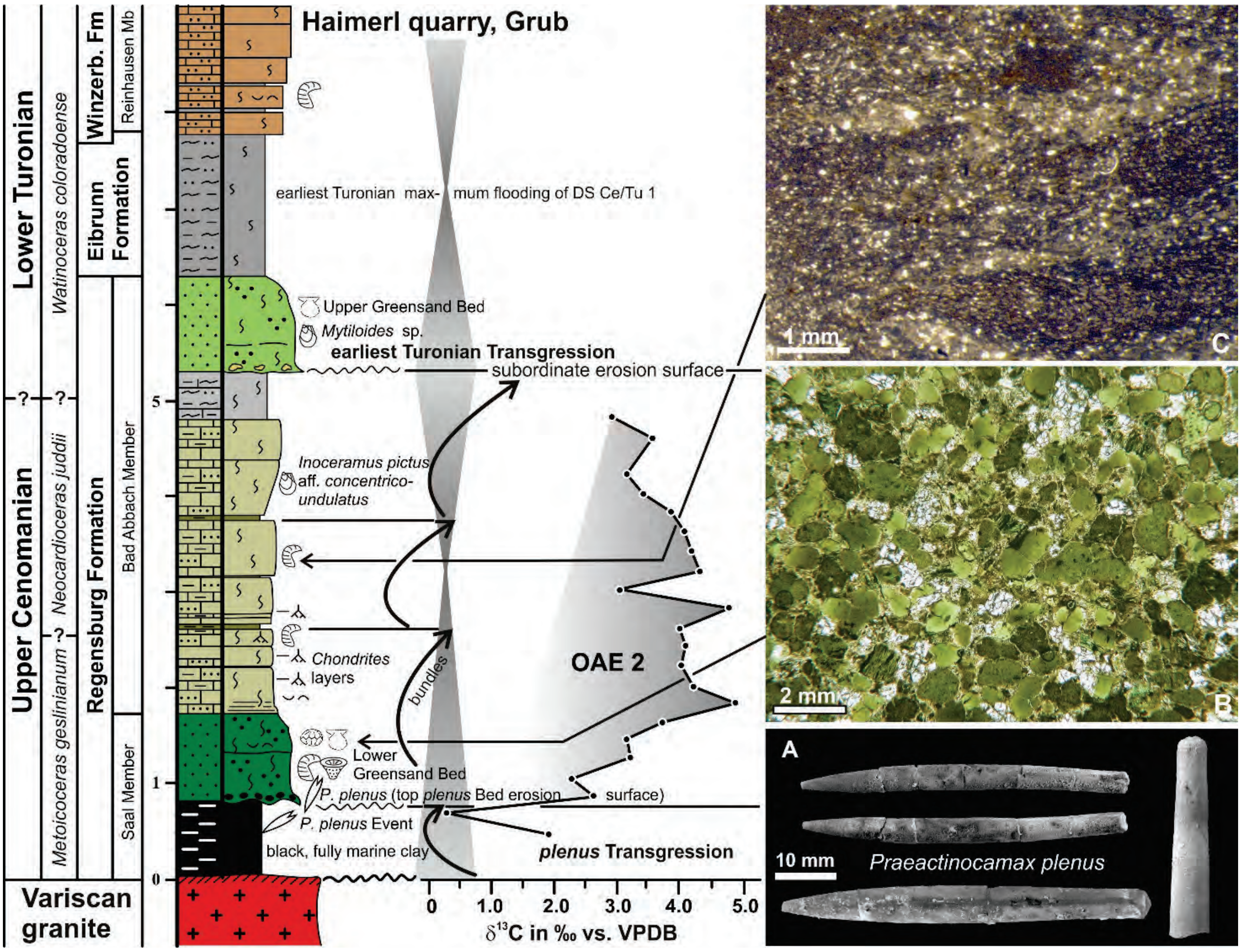


Text-Fig. 28: Upper Cenomanian to Lower Turonian succession in the Haimerl quarry near Grub. A: view of the northeastern quarry wall showing the Upper Cretaceous strata resting on a flat surface atop a red-brown Variscan granite ("Kristallgranit"); see image B for details. B: close-up view of the stratigraphic succession at Grub: The Regensburg Formation (here upper Upper Cenomanian) is resting with a basal black clay horizon on the Variscan granite and is overlain by a ca. 1.5 m-thick tongue of the Eibrunn Formation (lowermost Turonian) that, in turn, grades into the lower Reinhausen Member of the Lower Turonian Winzerberg Formation. C: contact of the basal black clay horizon and the Lower Greensand Bed of the Regensburg Formation; the interval contains the *Praeactinocamax plenus* Event (field of view ca 0.5 m wide).

The succession in the Haimerl quarry (Text-Fig. 29) starts upon a peneplain at the top of the granite with a 0.80 m thick black calcareous clay (Text-Fig. 28A), at the base of which patchily distributed granules and pebbles of reworked Liassic iron ores may occur. The clay contains sponge spicules, benthic foraminifera and, in its upper part, the belemnite *Praeactinocamax plenus* (Wilmsen et al., 2010b; Text-Fig. 29A). Furthermore, it yielded some glauconite, well-preserved calcareous nannoplankton and a varied association of palynomorphs, including a fully marine, diverse assemblage of Cenomanian dinoflagellates (det. P. Hochuli, Zürich). Pollen and spores are relatively rare compared to marine palynomorphs. Other marine palynomorphs than dinoflagellates include acritarchs (common), *Tasmanites* spp. and organic chamber linings of foraminifers.

The black clay is unconformably overlain along an irregular erosion surface by a 0.80 to 0.90 m thick, medium- to coarse-grained glauconitic-bioclastic sandstone bed with a basal lag of dark phosphatitic clasts and poorly rounded orange alkali feldspar granules as well as fragments of belemnite guards (Lower Greensand Bed, Text-Figs. 28C, 29). In its upper part it is a glauconitite, consisting of more than 50 % glaucony grains (Text-Fig. 29B). In addition, the bed is heavily bioturbated and contains oysters, pectinids, siliceous sponges, brachiopods and plant remains. It fines upwards, grading into the overlying silty, siliceous, bioturbated marls and marly limestones (Text-Fig. 29C) of the 4.60 m-thick Bad Abbach Member which contains relatively abundant fish remains but is otherwise relatively poor in fossils. In the lower part of the member, *Chondrites* layers are common and some small oysters [*Pycnodonte* (*Phygraea*) *versicularis vesiculosa*] occur; in the upper part, the inoceramid bivalve *Inoceramus pictus* aff. *concentricoundulatus* was found (TRÖGER et al., 2009). Five to ten cm-thick silty marl seams subdivide the Bad Abbach Member into bedding bundles. The member is terminated by a ca. 0.90 m thick, fine- to medium-grained glauconitic sandstone bed (Upper Greensand Bed). Its base is clearly erosional and rip-up-clasts of up to 50 mm from the underlying strata occur in its lower part. Fossils are very scarce, only rare pectinids and an inoceramid bivalve (*Mytiloides* sp.) have been found. The bed grades into the overlying dark-grey, silty to fine-sandy marls of the only 1.50 m-thick Eibrunn Formation. The section is terminated by a few metres of fine-grained siliceous, marly siltstones of the lower Winzerberg Formation (Reinhausen Member).

The bulk-rock carbon stable isotope record of the Regensburg Formation at Grub is characterized by a major positive excursion reaching values of up to +5.0 ‰ $\delta^{13}C_{carb}$. The $\delta^{13}C$ values start to increase within the Lower Greensand Bed from relatively low values at the top of the underlying black clay and reach an initial maximum at the transition into the Bad Abbach Member (Text-Fig. 29). A second maximum occurs 2.75 m above the base of the section. The $\delta^{13}C$ values stay high (above +3 ‰ $\delta^{13}C$) up to the 5 m-level, below the Upper Greensand Bed. Upsection, samples had too low carbonate contents and did not provide meaningful $\delta^{13}C$ results.
The succession at Grub documents the Late Cenomanian and Early Turonian flooding of the Bodenwöhrer Senke. Initial onlap of the Regensburg Formation occurred during the plenus Transgression (*Metoicoceras geslinianum* Zone) as evident from the *plenus* Event that has been recorded in Grub in the uppermost part of the black basal clay horizon (Text-Fig. 29). In Regensburg, this event has been recorded from the lower Eibrunn Formation (HILBRECHT, 1986; WILMSEN et al., 2010b), highlighting the diachronous character of lithostratigraphic units, especially during transgressions. The direct superposition of a granite peneplain by offshore marine clay demonstrates the extraordinary high rate of the plenus Transgression (WILMSEN et al., 2010a; RICHARDT et al., 2013). The base of the Lower Greensand Bed indicates an intermittent shallowing with erosion, corresponding to the erosion surface at the top of bed 3 in the classical southern English plenus Marls succession (JEFFRIES, 1963). Above, a considerable deepening is recorded by the fine-grained deposits of the Bad Abbach Member that ranges (according to the isotope stratigraphy) into the latest Cenomanian *Neocardioceras juddii* Zone (Text-Fig. 29).



Text-Fig. 29: Stratigraphic log, integrated stratigraphy (litho-, bio- and event stratigraphy as well as carbon stable isotopes) and microfacies of the Grub section. A: adolescent specimens of *Praeactinocamax plenus* from the plenus Event of Grub. B: thin-section photomicrograph from the upper part of the Lower Greensand Bed showing the glauconitite fabric (Saal Member of the lower Regensburg Formation). C: thin-section photomicrograph from the Bad Abbach Member of the upper Regensburg Formation showing the fine-grained, silty wackestone fabric. For key to symbols, see Text-Figure 24.

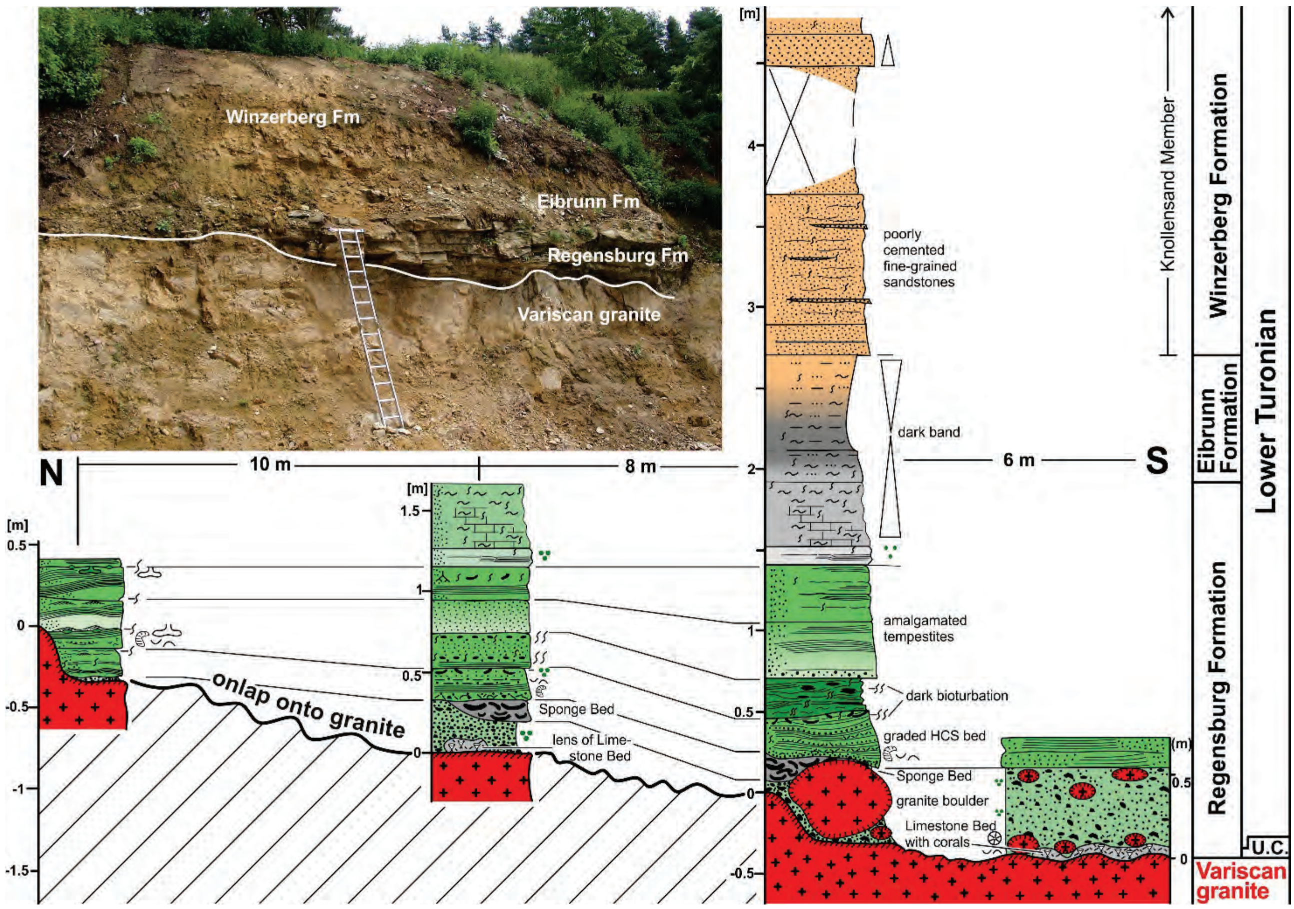
The unconformable base of the Upper Greensand Bed indicates another short-lived period of shallowing in the Cenomanian–Turonian boundary interval. The transgressive facies development into the overlying Eibrunn Formation is of earliest Turonian age, supported by the record of *Mytiloides* sp. from the Upper Greensand Bed. The earliest Turonian maximum flooding recorded by the tongue of the Eibrunn Formation corresponds to a global eustatic peak (i.e. the K140 maximum flooding surface of Sharland et al., 2001, on the Arabian Plate). The major positive $\delta^{13}C$ excursion in the Regensburg Formation at Grub corresponds to the oceanic anoxic event (OAE) 2 (Schlanger et al., 1987) and can be used to calibrate the stratigraphic succession, e.g. to the classical *plenus* Marls succession of southern England (Paul et al., 1999; Gale et al., 2005; Jarvis et al., 2006) or northern Germany (Voigt et al., 2007, 2008).

Stop 19. Obertrübenbach quarry

Coordinates: E 12°32'53", N 49°10'03".
Location: Abandoned quarry near Obertrübenbach, south of Roding.
Topic: Latest Cenomanian to Early Turonian sea-level history in the Bodenwöhrer Senke.
Lithostratigraphic units: Regensburg-, Eibrunn- and lowermost Winzerberg Formation.

Age: Early Turonian (latest Cenomanian erosional remnants currently not exposed).
Specialities: Small-scale onlap patterns of the Regensburg Formation onto basement rocks, earliest Turonian cliff drowning and maximum flooding interval; carbon stable isotopes.
References: TRUSHEIM (1935), NIEBUHR (2008), NIEBUHR et al. (2009, 2014), WILMSEN & NIEBUHR (2010), WILMSEN et al. (2010a, b), BAYERISCHES LANDESAMT FÜR UMWELT (2011).

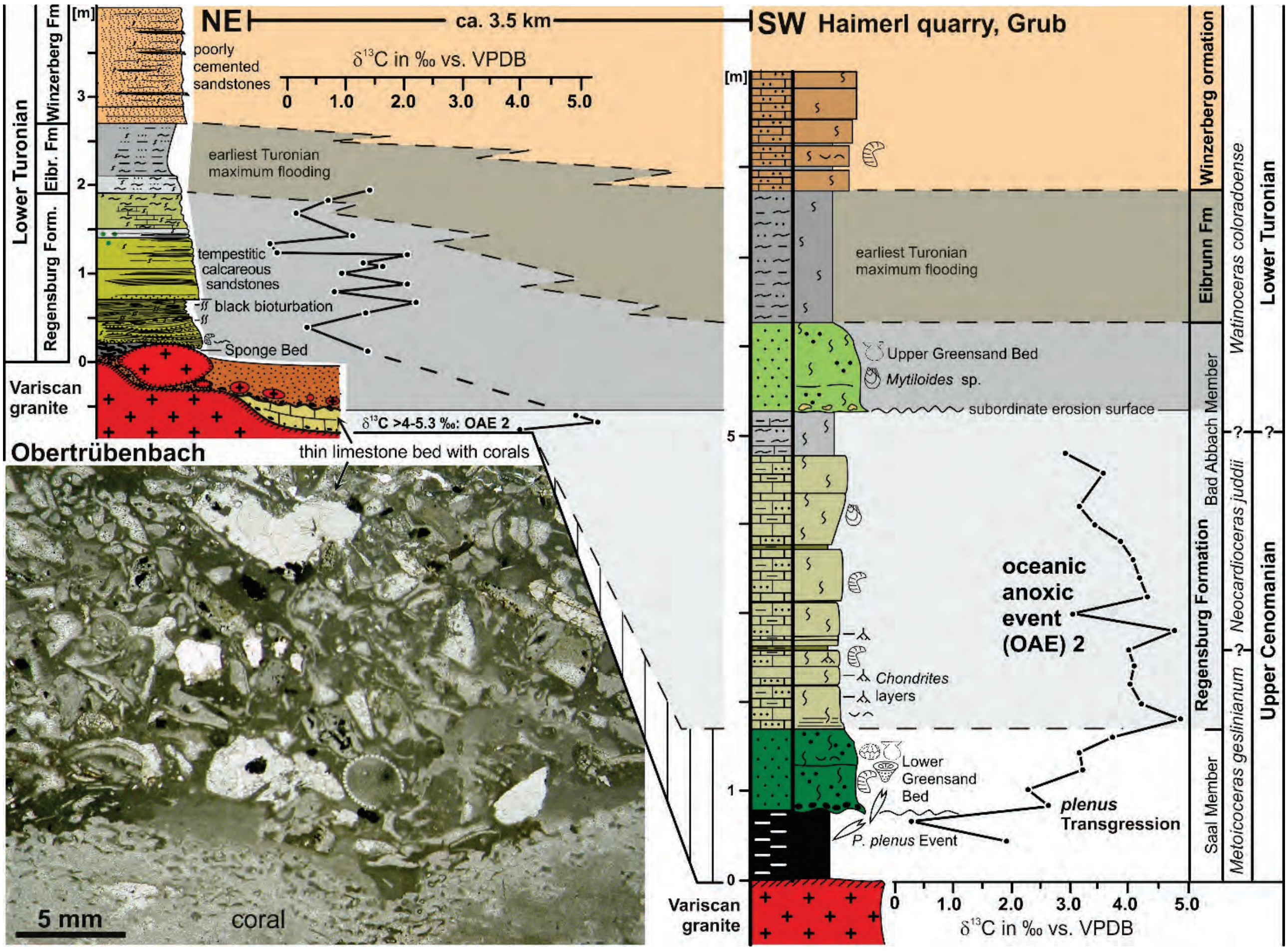
The abandoned Obertrübenbach quarry is located 3.5 km south-southeast of Roding near a small local road connecting Unter- and Obertrübenbach. It exposes a thin succession of the Regensburg, Eibrunn and lowermost Winzerberg Formations resting on a Variscan granite. The exposure is classified as Geotop no. 75 of the 100 most important geological heritage sites of Bavaria (BAYERISCHES LANDESAMT FÜR UMWELT, 2011) – so please do not use your hammers. Lithostratigraphically, the succession at Obertrübenbach is equivalent to the section at Grub. However, as will be shown below, the onlap at Obertrübenbach occurred even later than in Grub, i.e. mainly during the earliest Turonian.



Text-Fig. 30: Stratigraphic logs and onlap patterns in the Obertrübenbach quarry (outcrop situation as of 2008, view to the east; modified after NIEBUHR, 2008). For key to symbols, see Text-Figure 24.

The top surface of the granite at Obertrübenbach shows, in contrast to the situation at Grub, a strong relief (Text-Fig. 30). In the southern part of the small quarry, the succession starts with a thin (ca. 0.15 m) Limestone Bed of bioclastic float- and packstone yielding solitary and colonial (i.e. microsolenid) corals, siliceous sponges, oysters, spines of regular echinoids, serpulids, terebratulid brachiopods, bryozoans and shark teeth. The Limestone Bed is erosionally overlain by a several dm-thick unit of immature, pebbly sandstones/conglomerate which thins towards the northern part of the outcrop where it directly onlaps the granite as a basal conglomerate (Text-Fig. 30). The unit also contains scattered rounded granite cobbles and boulders up to 0.80 m in diameter. The succession continues with a siliceous sponge biostrome (Sponge Bed; Text-Fig. 30), likewise pinching out towards the north, followed by a graded, hummocky cross-stratified, fine- to medium-grained, lithoclastic glauconitic sandstone bed with black, colour-contrasting bioturbation at the top. Upsection, a unit of dm-thick, parallel-laminated and/or hummocky cross-bedded, fine-grained calcareous sandstones with glauconite and oyster debris follows, terminating the Regensburg Formation. The strata of the Regensburg Formation show conspicuous onlap patterns from South to North within the quarry with a minimum relief of 2 m in a distance of ca. 25 m (Text-Fig. 30). The transition into the only 0.80 m thin silty Eibrunn Formation is gradual, and the lower Winzerberg Formation, consisting of medium- to coarse-grained sandstones (Knollensand Member), concludes the Obertrübenbach section.

The carbon stable isotope curve of the Regensburg Formation at Obertrübenbach (cf. NIEBUHR, 2008; WILMSEN et al., 2010a) is characterized by very high values of +3.8 to +5.4 ‰ $\delta^{13}C_{carb}$ only in the thin erosional remnant of the Limestone Bed resting directly on the granite in the southern part of the quarry (Text-Fig. 31). The parallel-laminated/hummocky cross-stratified calcareous sandstones above the erosion surface yielded relatively low values ranging between -1.0 and +2.3 ‰ $\delta^{13}C$. Samples from the Eibrunn Formation provided no data due to their low carbonate contents.



Text-Fig. 31: Correlation of the Grub and Obertrübenbach sections (modified and supplemented after Wilmsen et al., 2010a). The thin uppermost Cenomanian coral-bearing limestone bed at the southern margin of the Obertrübenbach quarry is shown as thin-section photomicrograph; note microsolenid coral in the lower part and the bioclastic packstone fabric. For key to symbols see Fig. 24.

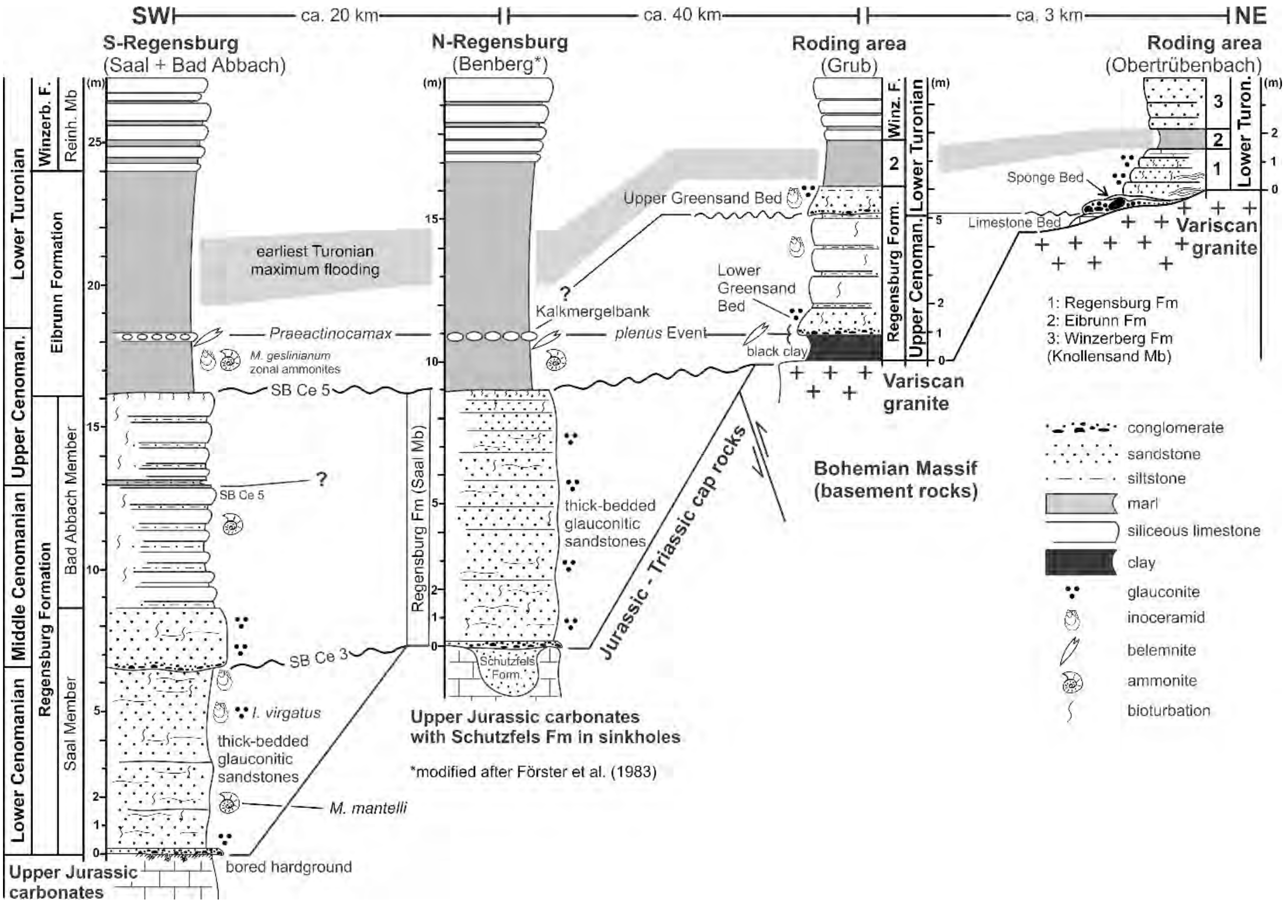
The succession at Obertrübenbach further details the Late Cenomanian–Early Turonian transgression history of the Bodenwöhrer Senke, especially when compared to the section of Grub, ca. 3 km to the southwest (Text-Fig. 31). The thin coral-bearing limestone bed occurring at the southern margin of the Obertrübenbach quarry yielded high $\delta^{13}C$ values typical of the OAE 2 and is thus a proximal (lagoonal?) shallow-water equivalent of the Saal Member of the Regensburg Formation at Grub (Text-Fig. 31). The erosion surface at the top of this bed corresponds to subordinate unconformity at the base of the Upper Greensand Bed at Grub (Cenomanian–Turonian boundary interval). The main onlap at Obertrübenbach thus corresponds to the earliest Turonian Transgression, supported by the low, i.e. post-OAE 2 $\delta^{13}C$ values (Text-Fig. 31). The Regensburg Formation at Obertrübenbach is equivalent to the Upper Greensand Bed and possibly parts of the Eibrunn Formation at Grub. The maximum flooding in the earliest Turonian is reflected by the deposition of a very thin and proximal tongue of the Eibrunn Formation. This event, corresponding to the maximum flooding of depositional sequence DS Ce/Tu 1, can be correlated across the north-western part of the Bodenwöhrer Senke where it is associated with the first onlap of marine strata (Richardt et al., 2013; see Text-Fig. 26). The relative proximity of the source area at Obertrübenbach during the Early Turonian is reflected by the fact that the Winzerberg Formation directly starts with the sandy Knollensand Member (Text-Figs. 20, 30). An identical sequence of sea-level changes can be recognized of the other side of the Bohemian Massif in the Saxonian Cretaceous Basin (Wilmsen et al., 2011).

The Danubian Cretaceous Group – some conclusions

The strata of the Danubian Cretaceous Group reflect dynamic depositional conditions in a peri-continental setting at the northern margin of the Alpine Tethys, representing various depositional environments including continental, marginal marine and neritic settings. According to the tectono-sedimentary background, three major phase can be differentiated (Niebuhr et al., 2014): An Early Cretaceous continental phase, a Cenomanian–early Middle Turonian onlap phase mainly governed by eustatic sea-level fluctuations, and an inversion phase starting in the late Middle Turonian (Text-Fig. 20).

The Early Cretaceous continental phase is documented by the Schutzfels-Formation which consists of siliciclastic sediments, commonly varicoloured clays, silts, sands and gravels. The sources of the sediments were the basement rocks of the Bohemian Massif (Moldanubian Zone) in the northeast. The material was transported across a karst landscape towards the south and southwest and deposited in fluvial to limnic environments. Originally, the Schutzfels Formation was much more widespread in distribution but has been eroded prior to or by the transgression of the marine strata of the Danubian Cretaceous Group. Consequently, the Schutzfels Formation is today very patchily distributed and mainly preserved in sinkholes that formed during the Early Cretaceous continental phase in widespread Upper Jurassic carbonates (Weißjura Group of Niebuhr & Pürner, 2014).

The Cenomanian–early Middle Turonian onlap phase is related to the major global early Late Cretaceous sea-level rise (e.g. Hancock & Kauffman, 1979; Hancock, 1989). The distribution of sedimentation areas and facies as well as stratigraphic architectures was thus mainly governed by eustatic sea-level changes and the pre-transgression topography. Onlap of marine strata of the Regensburg Formation started in the Regensburg–Kelheim area in the early Early Cenomanian (*M. mantelli* Zone) and nearshore glauconitic-bioclastic sandstones predominated (Saal Member), followed by Middle to lower Upper Cenomanian mid-shelf siliceous carbonates intercalated with fine-sandy to silty marls (Bad Abbach Member, Text-Fig. 32). Starting the mid-Late Cenomanian *M. geslinianum* Zone, a considerable deepening pulse during the mid-Late Cenomanian (plenus Transgression) led to the deposition of the deeper shelf silty marls of the Eibrunn Formation which range into the Early Turonian. During the *plenus* Transgression, also the proximal Bodenwöhrer Senke was flooded, indicated by the onlap of the Regensburg Formation onto Variscan granites of the Bohemian Massif, overlain by a thin tongue of lowermost Turonian Eibrunn Formation (Text-Fig. 32). The early Late Cretaceous sea-level rise culminated in an earliest Turonian maximum flooding interval (Text-Fig. 32). The accommodation generated by the Late Cenomanian–Early Turonian sea-level rise was subsequently filled by the Lower Turonian Winzerberg Formation that is capped by the inter-regional sequence boundary SB Tu 1 (Text-Fig. 26).



Text-Fig. 32: Schematic correlation of Cenomanian–Lower Turonian sections from the Regensburg–Kelheim area to the Bodenwöhrer Senke (modified and supplemented after WILMSEN et al., 2010b). Note the regional onlap patterns.

The Regensburg and Eibrunn formations are highly diachronous lithostratigraphic units. Their regional distribution and northeast-directed onlap pattern onto the southwestern margin of the Bohemian Massif can be related to roughly coast-parallel (i.e. NW/SE-trending) facies belts shifting landward on an inclined surface in time (Text-Fig. 32; WILMSEN et al., 2010a). It lasted ca. 6 Ma that the coastline transgressed from southwest of the Regensburg–Kelheim area to the cliff-forming basement rocks southeast of Roding (= 60 km distance), resulting in a mean rate of coastal shift of 10 km/Ma. Additional support for this model of coast-parallel facies belts comes from the considerable subsurface extension of the Regensburg and Eibrunn formations along the strike of the Bohemian Massif to the southeast into the North Alpine Foreland Basin of Austria where the Regensburg Formation forms the reservoir rock and the Eibrunn Formation the seal of a petroleum system (GROSS et al., 2015).

During the inversion phase starting in the Middle Turonian, SW/NE-directed compressional tectonics became of increasing importance for the deposition of the Danubian Cretaceous Group. However, this phase in the evolution of the Danubian Cretaceous Basin has not been detailed here (see NIEBUHR et al., 2011, 2014, for additional information).

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