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The Drowning Sequence of Mount Bürgl in the Salzkammergut Area (Northern Calcareous Alps, Austria): Evidence for a Diachronous Late Jurassic to Early Cretaceous Drowning of the Plassen Carbonate Platform

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Abstract

The Kimmeridgian to Tithonian Wolfgangsee Carbonate Platform as the northernmost platform of the Plassen Carbonate Platform *sensu lato* (s.l.) in the Northern Calcareous Alps was drowned in the Late Tithonian. The pre-drowning phase (Early Kimmeridgian to early Late Tithonian), the drowning phase and the post-drowning phase (both Late Tithonian) are preserved at Mount Bürgl. The A) drowning event of the northern Wolfgangsee Carbonate Platform, the B) formation of a north-directed newly formed reef rim of the Plassen Carbonate Platform *sensu stricto* (s.s.) as well as the C) onset of resedimentation of enormous amounts of shallow-water debris from the central Plassen Carbonate Platform (s.s.) to the north, the D) enhanced subsidence with a prominent facies change at the Plassen Carbonate Platform (s.s.), and E) Tithonian normal faulting in the central Northern Calcareous Alps are more or less time-equivalent events. With respect to A)-E) we explain the Late Tithonian drowning of the Wolfgangsee Carbonate Platform as a result of the change in the overall tectonic regime: the compressional regime lasted until Late Oxfordian followed by a period of decreasing tectonic activity and relative tectonic quiescence in Kimmeridgian to Early Tithonian, and a subsequent extensional tectonic regime, that started around the Early/Late Tithonian boundary being responsible for the changes A) to E). The generally accepted model of a Kimmeridgian to early Early Cretaceous phase of tectonic quiescence during the evolution of the Plassen Carbonate Platform (s.l.), which formed a post-tectonic cover, must be replaced by a model of both diachronous platform onset and diachronous drowning in an active tectonic regime.

Die Wolfgangsee Karbonatplattform repräsentiert die nördlichste eigenständige Karbonatplattformentwicklung des Plassen Karbonatplattformzyklus *sensu lato* (s.l.) in den Nördlichen Kalkalpen. Ihre Entwicklung umfasst den Zeitraum Kimmeridgium bis Tithonium, wobei sie im spätem Tithonium ertrinkt. Der Bürgl weist als einziges Vorkommen eine komplette Entwicklung der Schichtfolge dieser Plattform auf: die Seichtwasser-Karbonatentwicklung im Zeitraum frühes Kimmeridgium bis frühes Ober-Tithonium (pre-drowning Phase), die Phase des Ertrinkens im späten Ober-Tithonium (drowning Phase) und die Entwicklung der Sedimentation nach dem Ertrinken (post-drowning Phase). Es lassen sich somit sehr verschiedenartige Ereignisse bzw. Entwicklungen während der oberjurassischen Plassen Karbonatplattform-Entwicklung zeitlich hinreichend gut korrelierend parallelisieren: A) das Ertrinken der Wolfgangsee Karbonatplattform, B) das Herausbilden eines neuen nordgerichteten Riffgürtels im Bereich der Plassen Karbonatplattform sensu stricto (s.s.), C) das Einsetzen der Umlagerung enormer Mengen von Flachwasserdetritus der Plassen Karbonatplattform (s.s.) nach Norden, D) der markante Fazieswechsel in der Abfolge der Plassen Karbonatplattform (s.s.) verursacht durch stark ansteigende Subsidenz und E) das Entstehen von extensionalen Abschiebungen in den zentralen Nördlichen Kalkalpen. Die Summe dieser Veränderungen, einschließlich des Ertrinkens der Wolfgangsee Karbonatplattform, als Ausdruck des Wechsels im Kräftespiel des übergeordneten geodynamischen Kontextes ermöglicht folgende generelle Interpretation: das stark von Kompressionstektonik-dominierte Regime bis zum späten Oxfordium wird durch eine Entwicklung im Zeitraum Kimmeridgium bis frühes Tithonium abgelöst, in der auf Grund der abnehmenden Kompressionstektonik eine Phase der tektonischen Umstellung und damit relativer tektonischer Ruhe das Sedimentationsgeschehen prägt. Zum späten Tithonium hin wird das tektonische Regime zunehmend von extensionaler Tektonik dominiert, die für die markanten Veränderungen A) bis E) verantwortlich zeichnet. Auf Grund der Ergebnisse muß das heute generell verbreitete Modell, welches die Entwicklung der Plassen Karbonatplattform als post-tektonisch auflagernden „Deckel" unter absolut ruhigen tektonischen Verhältnissen gebildet sieht, durch folgende Vorstellung ersetzt werden: die Plassen Karbonatplattform besteht aus mehreren unabhängigen Karbonatplattformen, bei denen sowohl Einsetzen und als auch Absterben jeweils unabhängig und nicht zeitgleich erfolgt, gesteuert durch tektonische Prozesse in einem sich vom kompressionalen zum extensionalen umstellenden geodynamischen Regime.

1. Introduction

The Late Jurassic period, especially the timespan Oxfordian-Tithonian, was a period of widespread reef evolution in the Tethyan realm (Kiessling, 2002; Leinfelder et al., 2002). The Late Jurassic to Early Cretaceous shallow-water Plassen Carbonate Platform (s.l.) is not only a key to understand the early tectonic history (Late Jurassic to Early Cretaceous) of the Northern Calcareous Alps, but is also important for the reconstruction of the Jurassic orogenic phases in the western Neotethys realm. In general, its evolution was interpreted as have happened during a time of tectonic quiescence ("Jurassic neoautochthony": Mandl, 1982; Tollmann 1985, 1987) after the formation of radiolarite basins and rises (nappe fronts) during Middle and early Late Jurassic times (Gawlick et al., 1999). Middle Jurassic ongoing convergence in the Neotethys realm led to ophiolite obduction (Gawlick et al., 2008; Schmid et al., 2008) and imbrication of the outer Neotethys continental margin since the ?Bajocian, progressively affecting the inner parts of this continental margin until Oxfordian. Thrusting propagated from the outer (Hallstatt Zone) towards the inner shelf area (Dachstein and Hauptdolomit facies zones, Tirolic units). The sedimentation pattern in the Tirolic units (Fig. 1) dramatically changed in the Middle Jurassic (Gawlick and Frisch, 2003), and not in the Oxfordian as formerly assumed (Tollmann, 1985). Significant sedimentation resumed with the deposition of cherty deep-water sediments of the Ruhpolding Radiolarite Group, which documented the change from condensed carbonates to almost purely siliceous sediments (Fig. 2). In the Middle Jurassic the sedimentary evolution in the southern part of the Tirolic realm (Upper Tirolic nappe stack with Bajocian to Oxfordian Hallstatt Mélange) clearly differed from that in the northern part (Lower Tirolic nappe with Oxfordian Tauglboden Mélange) (Fig. 3). The main difference of Hallstatt and Tauglboden Mélanges was the time of the onset and the different composition of huge mass flows in the trench-like basins (for definition see Gawlick and Frisch, 2003; Gawlick et al., 2007b 2009). These mélanges are interpreted as carbonate-clastic radiolaritic trench-like basin fills formed in sequence in front of propagating nappes on the imbricated continental margin.

In the Northern Calcareous Alps of Austria/Germany (Fig. 1) shallow-water carbonates were reported from the Plassen Car-bonate Platform (s.l.) (e.g., Fenninger and Holzer, 1972; Steiger and Wurm, 1980), with a duration of Late Oxfordian/Kimmeridgian to Berriasian (Gawlick and Schlagintweit, 2006; Auer et al., 2009) (Fig. 2). Most occurrences of the Plassen Carbonate Platform are preserved in the central Northern Calcareous Alps (Fig. 3A).

The Plassen Carbonate Platform (Late Oxfordian to Early Berriasian) developed on top of the advancing and rising nappes and prograded towards the older trench-like basin fills in a shallowing-upward cycle in a continuously convergent regime with decreasing tectonic activity (Gawlick and Schlagintweit, 2006) (Fig. 3B). The biostratigraphic dating of these platform carbonates (e.g., with dasycladales, benthic foraminifera, microproblematica and others) and their sedimentary base, their installation, evolution and disappearing are key elements to unravel an enigmatic period of the western Neotethys evolution and to get a better general understanding of the elimination of a shallow-water carbonate platform (drowning/demise, subsequent erosion and redeposition in contemporaneously formed basins) in an active tectonic regime. The tectonic regime of the Northern Calcareous Alps during growth of the Plassen Carbonate Platform (s.l.) was characterized by ophio-

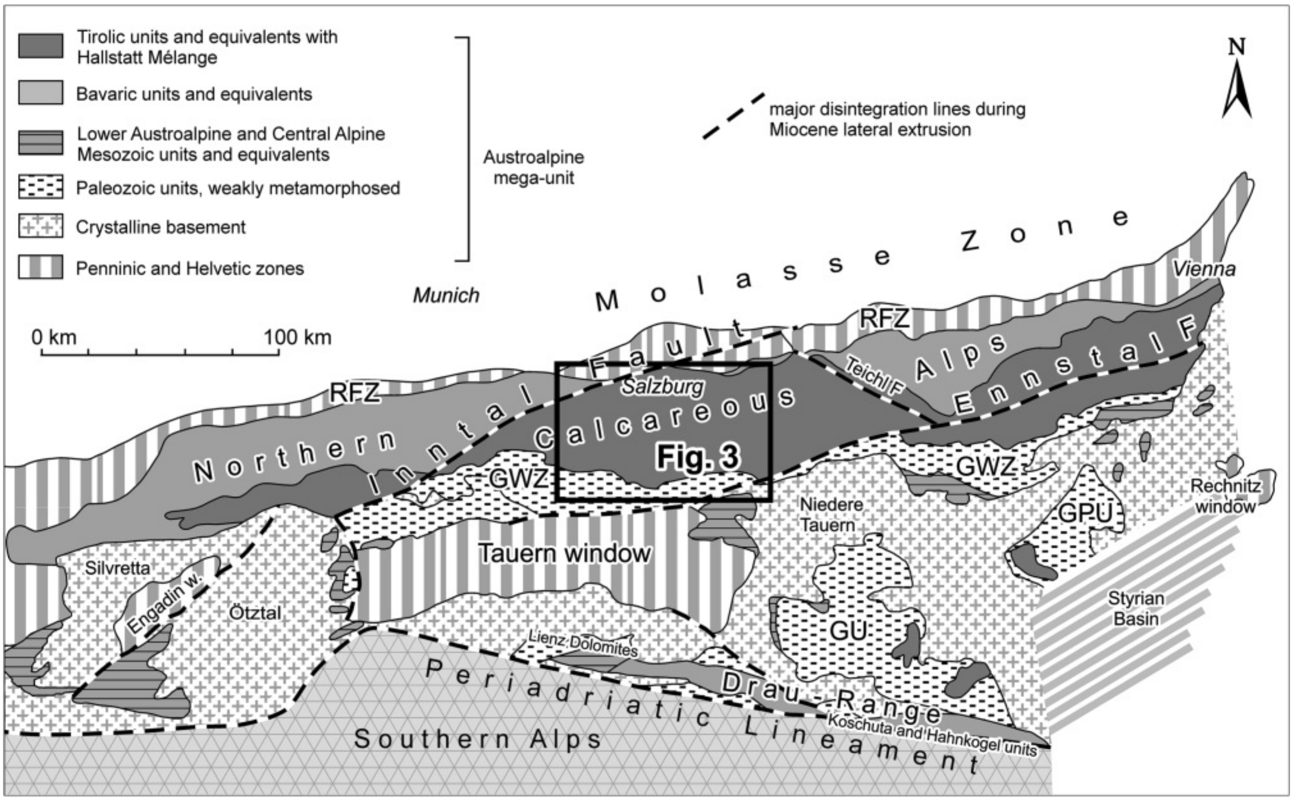

Figure 1: Tectonic map of the Eastern Alps and study area (after Tollmann, 1977 and Frisch and Gawlick, 2003). *GPU* Graz Paleozoic unit. *GU* Gurktal unit. *GWZ* Greywacke Zone. *RFZ* Rhenodanubian Flysch Zone.

litic emplacements, crustal stacking, and extensional tectonics and/or strike-slip movements (Missoni and Gawlick, 2010). Until now, the stratigraphic range of these shallow-water carbonates in the Northern Calcareous Alps was poorly known and is still a matter of ongoing discussion.

The individual evolution of each of these platforms depends on the tectonic events due to the partial closure of the Neotethys Ocean. After decreasing of thrust propagation towards the inner shelf area (from Hallstatt facies belts to Dachstein/Hauptdolomit facies belt – Fig. 3) from the Middle to early Late Jurassic (Gawlick et al., 1999; Gawlick and Frisch, 2003) a time of relative tectonic quiescence followed due to the decrease of compression in Kimmeridgian to Early Tithonian times. During this period the first cycle of shallow-water carbonates was formed under still ongoing but relatively moderate tectonic movements. According to Gawlick and Schlaginweit (2006), three independent, newly established shallow-water carbonates platforms evolved on top of the rising nappe fronts at that time, forming together the Plassen Carbonate Platform (Fig. 3B):

1. The northernmost platform, the Wolfgangsee Carbonate Platform at the northern edge of the Tauglboden Basin was formed since the Oxfordian/Kimmeridgian boundary with its onset on top of the Brunnwinkl Rise (Gawlick et al., 2007a).
2. The central platform, the Plassen Carbonate Platform (s.s.) with the type locality of the Plassen Formation - Mount Plassen - was formed on top of the Trattberg Rise facing the Sillenkopf Basin to the south since the Late Oxfordian (Auer et al., 2009).
3. In the south of the Sillenkopf Basin on top of the Hallstatt imbricates the Lärchberg Carbonate Platform (type locality Mount Loferer Kalvarienberg) started to evolve around the Oxfordian/Kimmeridgian boundary (Ferneck 1962; Darga and Schlagintweit, 1991; Dya, 1992; Schlagintweit and Ebli, 2000; Missoni et al., 2001; Gawlick et al., 2009).

These three platforms prograded over the adjacent remaining deep-water radiolarite basins and started to fill them up (Fig. 3B). Starting in late Early Tithonian, a new pulse of tectonic movements led to the extensional tectonic collapse of the Trattberg Rise (Schlagintweit and Gawlick, 2007; Gawlick and Schlagintweit, 2009; compare Ortner et al., 2008). Due to this event, new accomodation space formed north of the Plassen Carbonate Platform (s.s.) related to the activity of normal faults dipping towards the Tauglboden Basin. During Late Tithonian, a new reefal platform rim was formed on the northern edge of the Plassen Carbonate Platform (s.s.) (Gawlick and Schlagintweit, 2009), which shed an enormous amount of carbonate debris to this basin (Gawlick et al., 2005) (= southward enlarged Oxfordian to Early Tithonian Tauglboden Basin). Backstepping of this newly formed platform (Gawlick and Schlagintweit, 2009) due to increasing subsidence in Late Tithonian to Early Berriasian and increasing siliciclastic input from the south led to Late Berriasian drowning of the Plassen Carbonate Platform (s.s.) (Gawlick and Schlagintweit, 2006). The complete evolution of the Wolfgangsee Carbonate Platform to the north was unknown so far due to the lack of adequate biostratigraphic data. Therefore, previous investigators

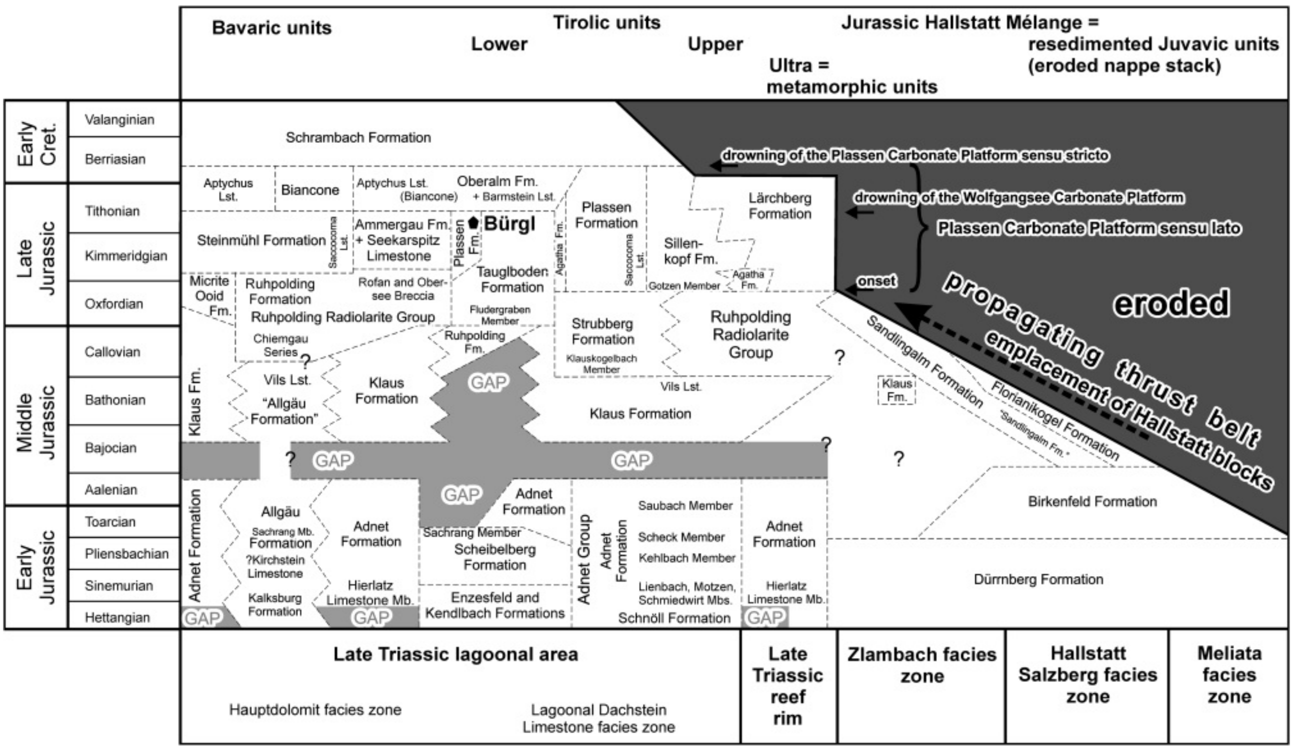

FIGURE 2: Stratigraphic table and main tectonic events of the Jurassic to Early Cretaceous in the central Northern Calcareous Alps with its lateral variations depending on the palaeogeographic position (modified after Gawlick and Schlagintweit, 2006; Suzuki and Gawlick, 2009) with focus on the Plassen Carbonate Platform. The life span of the Plassen Carbonate Platform is Late Oxfordian to Early Berriasian (Gawlick and Schlagintweit, 2006; Auer et al., 2009).

(Fenninger and Holzer, 1972; Plöchinger, 1973) suspected that also in this area platform evolution stopped contemporaneous with the Plassen Carbonate Platform (s.s.).

We describe the evolution from the onset of the Wolfgangsee Carbonate Platform in Early Kimmeridgian to its final drowning in Late Tithonian (compare Gawlick et al., 2007a, 2009). The whole sedimentary cycle was found at Mount Bürgl (=Bürglstein) southeast of the lake Wolfgangsee (Fig. 3A, Fig. 4). The knowledge about the exact stratigraphic ranges of the shallow-water carbonates is of special importance, since the early orogenetic evolution of the Late Jurassic system is discussed vividly and controversially (e.g., Schweigl and Neubauer, 1997a, b; Gawlick et al. 1999; Frisch and Gawlick, 2003; Frank and Schlager, 2006; Ortner et al., 2008). This drowning sequence sheds new light on the evolution of the Wolfgangsee Carbonate Platform and delivers further data to evaluate recently evolved geodynamic models of the evolution of radiolarite basins.

2. General evolution of the Plassen Carbonate Platform

In the Northern Calcareous Alps, the Plassen Carbonate Platform (s.l.) (Late Oxfordian to Berriasian) represents the first establishment of carbonate platform deposition since the Late Triassic (e.g., Tollmann, 1976). From a geological point of view, the Plassen Carbonate Platform (s.l.) is exclusively situated in the Lower and Upper Tirolic units (Fig. 2, Fig. 3). In the Bavaric units concomitant sediments (e.g., Steinmühl Formation, Saccocoma Limestone, Ammergau Formation without Seekarspitz Limestone, Aptychus Limestone – Fig. 2) were deposited under hemipelagic conditions (Gawlick et al., 2009). Due to tectonic and erosional processes, the Plassen Carbonate Platform (s.l.) is recorded in form of isolated occurrences concentrated in the middle part of the Northern Calcareous Alps and reaches to the east as far as Vienna. Their original palaeogeographic configuration has been strongly modified during the post-depositional Cretaceous and Cenozoic tectonic cycles (Tollmann, 1985; Schweigl and Neubauer, 1997a; Linzer et al., 1995; Frisch and Gawlick, 2003). Despite a lot of new knowledge about its geometry and evolution (Gawlick et al., 2005, 2007a, b; Schlagintweit and Gawlick, 2007b; Auer et al., 2009) especially the drowning process of the Plassen Carbonate Platform (s.s.) and its interplay with terrigeneous-siliciclastic input (in the southern parts of the Northern Calcareous Alps) or strong tectonic subsidence (in the northern parts of the Northern Calcareous Alps) is still far from being completely

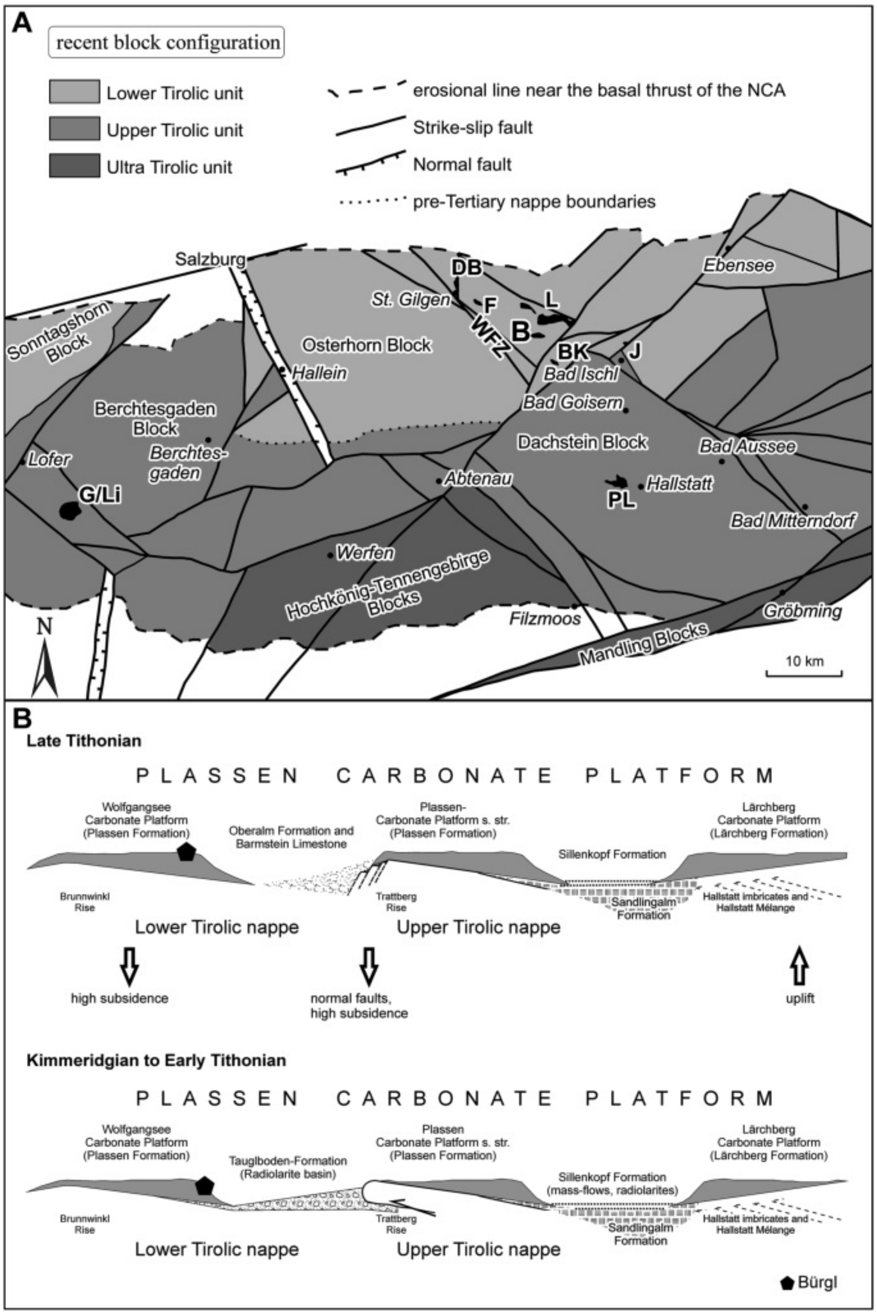

Figure 3: A) In-situ occurrences of the Wolfgangsee Carbonate Platform in the area of the Upper Tirolic Nappe sensu Frisch and Gawlick (2003): *DB* Drei Büder. *F* Falkensten. *L* Lugberg. *J* Jainzen. *B* Bürgl. *BK* Brustwandkopf. *WFZ* Wolfgangsee fault zone. Also indicated is the type locality of the Plassen Carbonate Platform (s.s.) Mount Plassen (PL) and the most complete succession of the Lächberg carbonate platform Mount Gerhardstein/Litzlkogel (G/Li) in the Upper Tirolic Nappe. Lateral extrusion in sense of Ratschbacher et al. (1991). B) Nomenclature of the Plassen Carbonate Platform (s.l.) in the Kimmeridgian to Tithonian.

understood (Gawlick and Schlagintweit, 2006 for discussion). A time and facies equivalent platform was recently detected on top of the Mirdita ophiolite nappes in Albania (Gawlick et al., 2008; Schlagintweit et al., 2008) showing clearly the overall tectonic and sedimentological features in the whole Neotethys realm.

A relatively long period of non-deposition before and after the Plassen Carbonate Platform (s.l.) evolution was the generally accepted view in literature (e.g., Tollmann, 1985; Schweigl and Neubauer, 1997a: p. 306, ”two great hiatuses“, text-fig. 2). Dating of cherty sediments underlying the platform carbonates with radiolarians contrasts this view and indicates continuous sedimentation with a shallowing-upward trend (e.g., Missoni, 2003; Wegerer et al., 2003; Schlagintweit et al., 2003; Gawlick et al., 2004; Auer et al., 2009; Suzuki and Gawlick, 2009). There are no hints or a major gap in the depositional record that, for example, would be expected in case of a transgression onto emerged land areas (e.g., model of Schweigl and Neubauer, 1997a). At all re-investigated Plassen Carbonate Platform (s.l.) occurrences the upper Middle to Upper Jurassic cherty limestones and radiolarites are overlain by condensed intervals of hemipelagic ”Protoglobigerina“ or Saccocoma limestones passing over to the shallow-water platform successions.

With respect to alternative geodynamic concepts for the Middle to Late Jurassic the shallow-water carbonate occurrences (including the most important Plassen Carbonate Platform (s.l.) localities) became the focus of detailed re-investigations. This led to new reconstructions of platform geometries and contemporaneous tectonic movements (Gawlick et al., 2005, 2007a; Schlagintweit and Gawlick, 2007 Gawlick and Schlagintweit, 2009). It became evident that the Plassen Carbonate Platform (s.l.) may show specific depositional environments and stratigraphic ranges at different localities. For example, Tithonian or younger shallow-water rocks are missing at Mount Krahstein (Gawlick et al., 2004) and at Mount Rettenstein (southern Salzkammergut) (Auer et al., 2006) or at Mount Falkenstein (lake Wolfgangsee) (Kügler et al., 2003).

According to previous assumptions (e.g., Tollmann, 1976, 1985), the Plassen Carbonate Platform (s.l.) sediments were deposited on Bahama-type platforms with steep slopes (Flügel and Fenninger, 1966; Rasser and Sanders, 2003). This generalized model is to be modified to include also ramp settings with abundant microbial crusts and diverse micro-encrusters in the initial phase of platform evolution and progradation of its flanks (Schlagintweit et al., 2003; Schlagintweit and Gawlick, 2008). Especially the Plassen Carbonate Platform (s.s.), which is best investigated, can be characterized as an isolated platform surrounded by remaining deep-water basins with carbonate clastic radiolaritic basin fills (e. g., Tauglboden Basin to the north: Schlager and Schlager, 1973; Gawlick and Frisch, 2003; Sillenkopf Basin to the south: Missoni et al., 2001; Fig. 3B).

From our studies it has become clear that all platforms of the Plassen Carbonate Platform (s.l.) were formed on the uplifting fronts of advancing nappes (e.g., Trattberg Rise – Gawlick et al., 1999; Gawlick et al., 2005 or Brunnwinkl Rise – Gawlick et al., 2007a; Fig. 3B) and were characterized by a shallowing upward trend. Deposition of shallow-water carbonates started on these morphological highs in the Late Oxfordian to Kimmeridgian and was followed by rapid platform progradation over adjacent basins.

The basal evolution of the Plassen Carbonate Platform (s.l.) is fairly well understood, a lot of uncertainties remain concerning the top of the Plassen Carbonate Platform (s.l.) and the following basin formation stage. Only one drowning sequence of Late

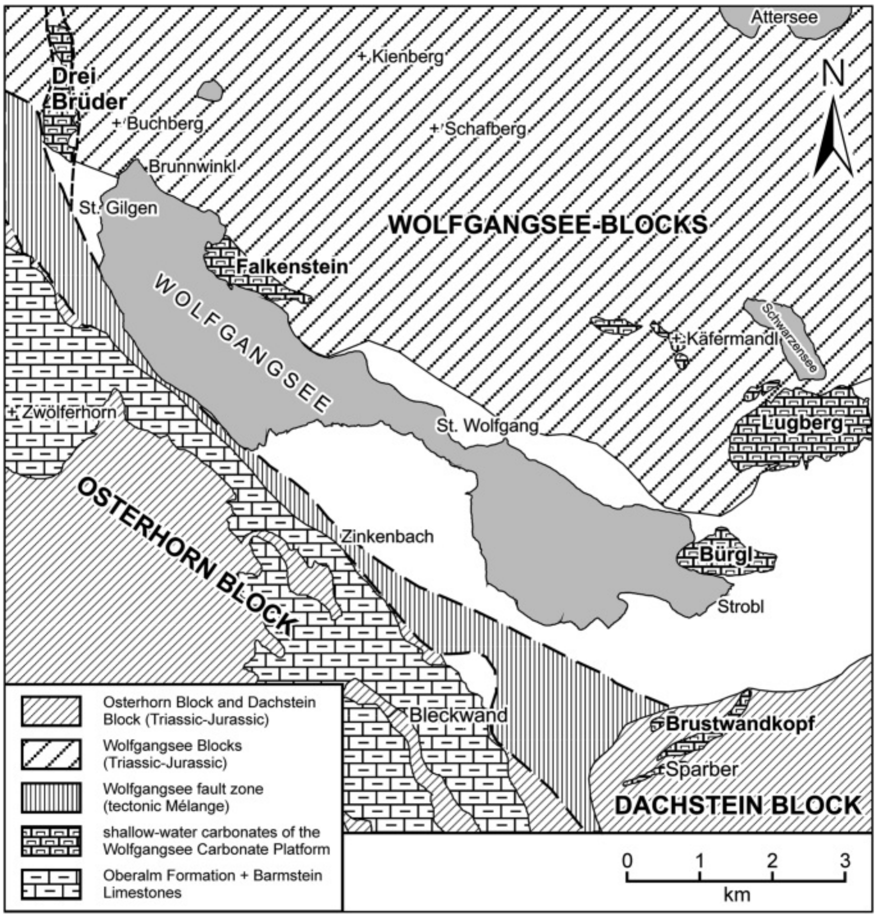

Figure 4: Simplified geologic-tectonic map of the Wolfgangsee area based on Plöchinger (1973), and location of the occurrences of the Late Jurassic Wolfgangsee Carbonate Platform north of the Wolfgangsee fault zone: Bürgl, Drei Brüder, Falkenstein, Lugberg. Tectonical block configuration based on Frisch and Gawlick (2003).

Berriasian age was found on top of the Plassen Carbonate Platform (s.s.) (Gawlick and Schlagintweit, 2006).

3. Geological Setting

Mount Bürgl (or Bürglstein) is located at the south-eastern end of lake Wolfgangsee in the Austrian Salzkammergut (Figs. 3, 4). Mount Bürgl represents an elongated, east-west extending isolated forested mountain with a rounded summit (altitude: 745 m) surrounded by flat landscape (Fig. 5). The east-west extension is about 1.4 km, the maximum north-south extension 0.55 km, and it therefore covers an area of approximately 0.45 km^2. Mount Bürgl is composed of Upper Jurassic shallow-water carbonates belonging to the so-called Wolfgangsee Carbonate Platform (Gawlick et al., 2007a). Within the Late Jurassic rise-and-basin system, the Wolfgangsee Carbonate Platform is the northernmost part of the Plassen Carbonate Platform (s.l.) evolution (Fig. 3B). The remnants of this platform are today recorded by Mounts Drei Brüder, Mount Falkenstein, Mount Lugberg and the southernmost occurrence Mount Bürgl, which are all located within an approximately 15 km long and NW-SE extending zone along the northern side of lake Wolfgangsee (Leischner, 1961; Plöchinger, 1964, 1973; Fenninger and Holzer, 1972). Further to the east, Mount Brustwandkopf and Mount Jainzen are further remnants of the Wolfgangsee Carbonate Platform (Gawlick et al., 2007a) (Fig. 3A).

Mount Bürgl provides the only complete section from the Early Kimmeridgian onset of the platform evolution to the drowning

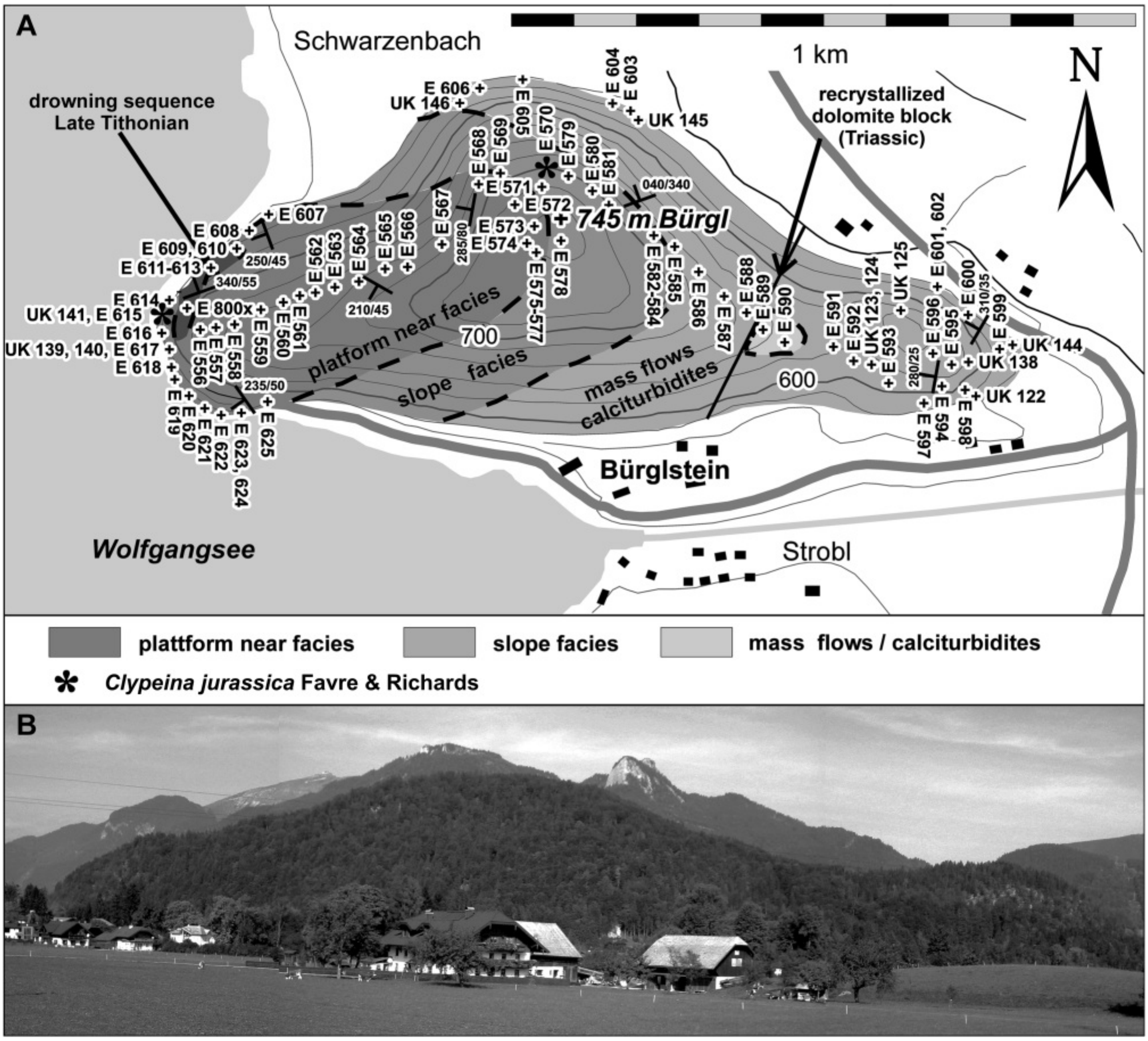

Figure 5: A) Facies map of Mount Bürgl, part of the Wolfgangsee Carbonate Platform (Gawlick et al. 2008, for details) samples and general dipping. Facies reconstruction is based on thin-section analysis of the samples indicated. Back rotating of younger tectonic movements shows a palaeoslope in southwestern directions as well as the drowning sequence in the western part of Mount Bürgl of about 15 degrees on the slope. The whole sedimentary succession is characterized by a shallowing-upward cycle during Kimmeridgian/Early Tithonian with platform near facies. In Late Tithonian a complete drowning sequence is preserved on top of the reef near facies as well as on the slope. See text for explanation. B) Mount Bürgl, view from the south-east; houses in the foreground belong to the village of Strobl.

in the Late Tithonian and is therefore best suited to study the evolution of this platform. All other occurrences provide only data for the basal part of the platform evolution, the younger parts are eroded (Kügler et al., 2003; Gawlick et al., 2007a).

4. Facies and stratigraphy of the Wolfgangsee carbonate platform

Biostratigraphic data are not available throughout whole sections of the Late Jurassic shallow-water carbonates of the Wolfgangsee Carbonate Platform. Few data are available from the mostly covered underlying radiolarites (Kügler et al., 2003), which are of Callovian to Oxfordian age at Mount Falkenstein.

The Late Jurassic shallow-water evolution of the Wolfgangsee Carbonate Platform starts with basal ooid-bearing resediments (Mounts Drei Brüder, Lugberg, Bürgl) followed by slope sediments often with intercalated breccias; platform margin deposits with corals and stromatoporoids form the topmost parts (Kügler et al., 2003; Gawlick et al., 2007a). At Mount Drei Brüder and Mount Lugberg, the benthic foraminifers *Labyrinthina mirabilis* Weynschenk, 1951 and "*Kilianina*" rahonensis Foury and Vincent, 1967 were detected in the basal resediments. These taxa are referred mainly to the Kimmeridgian (e.g., Bassoullet, 1997). Taking into consideration the results from other localities in the Wolfgangsee area (Mounts Falkenstein, Lugberg, Drei Brüder), a Kimmeridgian platform onset is assumed (Gawlick et al., 2007a), whereas a Late Oxfordian age for parts of the basal resediments can not completely be excluded. The thickness of the whole Late Jurassic shallow-water succession is approximately 200-300 m.

Most occurrences of the Wolfgangsee Carbonate Platform provide only resedimented material, only Mount Jainzen to the west shows true reefal intervals (Rasser and Sanders, 2003; Schlagintweit et al., 2005). Here the transition from the cherty basinal sediments to the shallow-water carbonates is not exposed. The succession comprises mainly micritic limestones of slope and platform margin facies; high-energetic microfacies-types are rare. One main characteristic is the nearly overall presence of corals and stromatoporoids. The stromatoporoids of the platform margin (e.g., *Actinostromaria*, *Astrostylopsis*, *Sestrostomella*, *Ellipsactinia*) are associated with the microproblematica *Crescentiella* and *Radiomura*, other sponges (pharetronids, *Calcistella*, *Thalamopora*, *Neuropora*) occur mainly in the fore-reef and upper slope area (Fig. 6). The micritic *Ellipsactinia* limestones belong to the lowermost portion of the succession exposed. Amongst the corals, the most frequent are microsolenids with predominantly flat morphologies, characteristic for a low sedimentation rate and greater water depths (e.g. Gill et al. 2004 for details), indicated also by the absence of dasycladalean green algae. The repeated occurrence of low diversity microsolenid limestones on the one side and other non-microsolenid corals on the other side indicate a cyclic sedimentation pattern (transgressive-regressive cycles) in an upper slope/fore-reef to reefal position. Also reef-flat/backreef facies composed of *Bacinella-Lithocodium-Thaumatoporella* bindstones may occur within these cycles.

4.1 Mount Bürgl

At Mount Bürgl only the resediments of this reef-rim are preserved. Especially the best exposed upper part of the succession consists of thick-bedded reefal resediments, of assumed Early Tithonian age, because the overlying calpionellid-bearing limestones are of Late Tithonian age (see below). In conclusion the stratigraphic evolution of the Wolfgangsee Carbonate Platform can be manifested within the Kimmeridgian-Lower Tithonian time interval; an uppermost Oxfordian age for parts of the basal resediments, however, cannot be excluded.

From east to west, Mount Bürgl (Fig. 5) is composed of resediments and slope lithologies (Fig. 7) followed by platform margin deposits as youngest sediments, indicating a continuous shallowing-upward; underlying strata are poorly exposed and consist of cherty sediments, partly with resediments of older strata. The general dipping of the Upper Jurassic strata is towards the west in direction of lake Wolfgangsee. At the eastern side of Mount Bürgl, the deeper and older part of the section is preserved and at the western part, close to lake Wolfgangsee, calpionellid wackestones of the Late Tithonian *Crassicollaria* Zone were detected (Table 1). These sediments directly overly the fore-reef shallow-water carbonates of Mount Bürgl as part of a drowning sequence.

Starting from the east, about 2/3 of Mount Bürgl is composed of resediments (mass-flows, breccias, calciturbidites) and slope sediments. The calciturbidites contain ooids, *Crescentiella morronensis* (Crescenti, 1969), benthic foraminifers with for example *Protopeneroplis striata* Weynschenk, 1950 (Fig. 8/1), debris of thaumatoporellaceans, echinoderms, rare representatives of *Halimeda misiki* Schlagintweit et al., 2008 (Fig. 8/5), *Salpingoporella pygmaea* (Gümbel, 1891), and one section of the udoteacean alga *Juraella bifurcata* Bernier, 1984. The more coarse-grained fore-reefal mass-flows are composed of Upper Jurassic shallow-water carbonate clasts with common ooids, bioclasts of stromatoporoids, e.g., common *Actinostromina grossa* (Germovsek, 1954) or stromatoporoid *Milleporidium* sp. together with rare *Calciagglutispongia yabei* (Flügel and Hötzl, 1966) (Fig. 8/7) and also Upper Triassic (Dachstein Limestone) or Lower to Middle Jurassic (?Adnet or ?Klaus Limestone) extraclasts (Fig. 7/1-2). The nuclei of the resedimented ooids often consist of benthic foraminifers *Protopeneroplis striata* Weynschenk, 1950 or *Mohlerina basiliensis* (Mohler, 1938). Slope lithologies comprise mostly fine-grained packstones with small benthic foraminifers, microencruster *Crescentiella morronensis* (Crescenti, 1969) and other microbiota (Fig. 7/3, 8/2). Platform margin deposits are bioclastic packstones with corals (Fig. 7/5), stromatoporoid sponges (e.g., *Sestrostomella*, Fig. 8/9), sclerosponges (e.g., *Neuropora*), solenoporacean algae (Fig. 8/8), rare dasycladalean algae such as *Salpingoporella pygmaea* (Gümbel, 1891) (Fig. 7/4) or boundstones with microencrusters, e.g., *Radiomura cautica* Senowbari-Daryan and Schäfer, 1979 and microbolitic crusts (Fig. 7/6-7). These platform margin deposits make up the summit and the western slope of Mount Bürgl adjacent lake Wolfgangsee. Lagoonal limestones reported

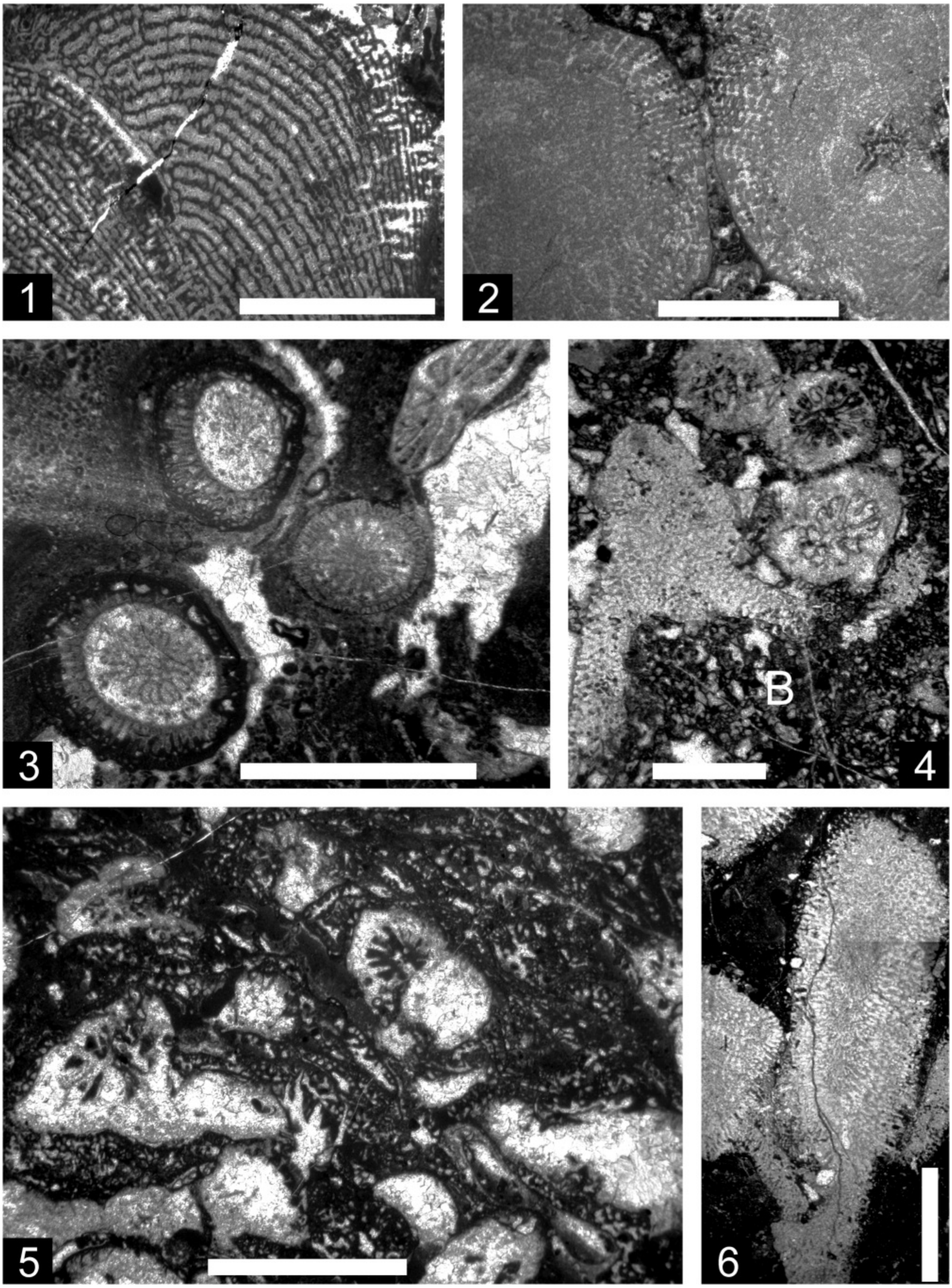

Figure 6: Upper Jurassic reefoid lithologies from Mount Jainzen. 1) Wackestone with *Ellipsactinia caprense* Canavari, 1893. Sample D-522, scale bar = 5 mm. 2) Microsolenid floatstone. Sample D-572, scale bar = 5 mm. 3) Coral rudstone with cement filled voids. Sample D-580, scale bar = 5 mm. 4) Dark-grey micro-encrusters *Lithocodium-Bacinella*(B)-*Thaumatoporella* binding coral and stromatoporoid (here: *Milleporidium*) debris (Bindstone). Sample D-558, scale bar = 2 mm. 5) Coral debris bound by dark-grey micro-encrusters *Lithocodium-Bacinella-Thaumatoporella* and benthic foraminifer *Coscinophragma* aff. *cribrosa* (Reuss, 1846). Sample A-3394-2, scale bar = 5 mm. 6) *Milleporidium* bafflestone. Sample D-573, scale bar = 5 mm.

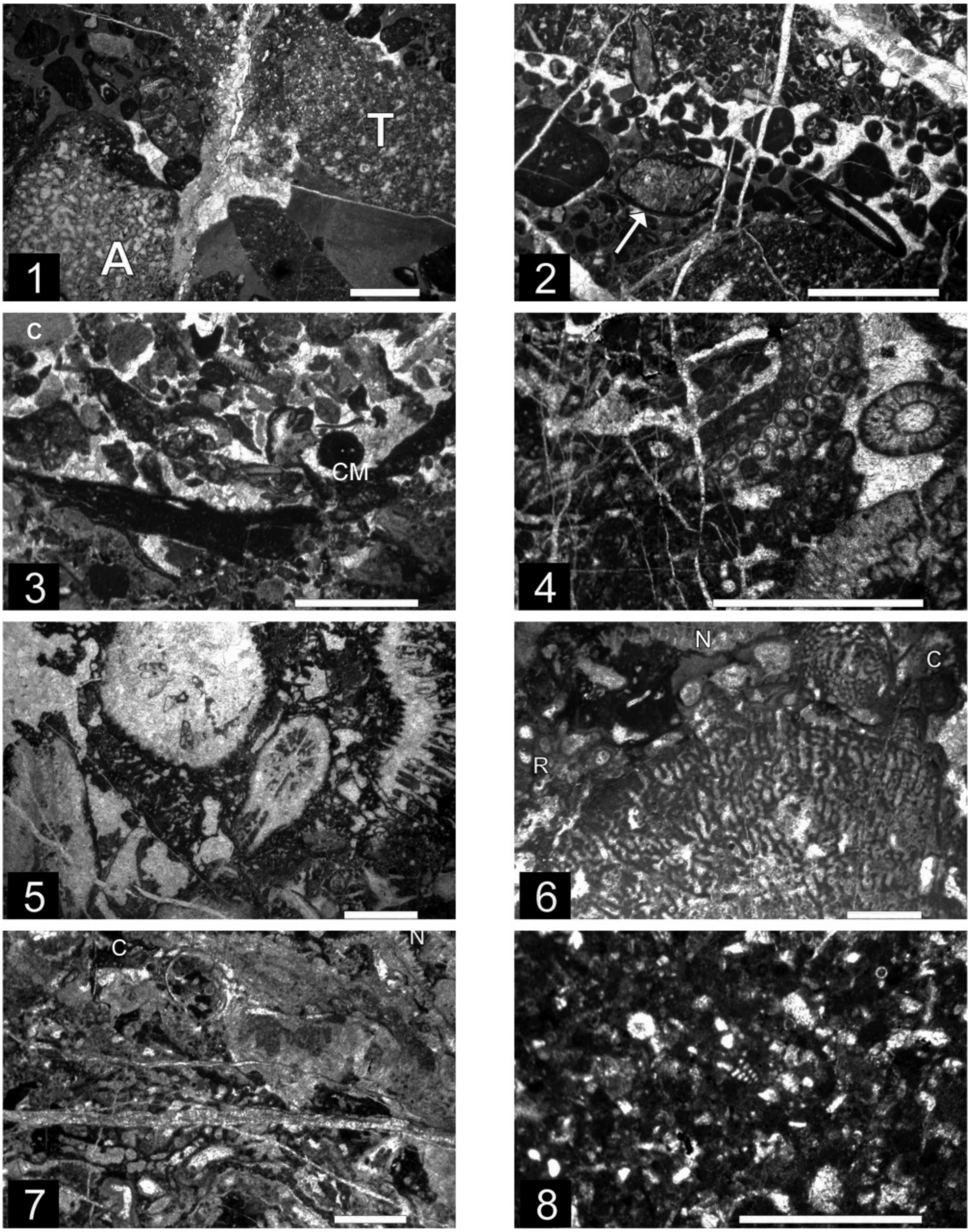

Figure 7: Facies evolution of the Wolfgangsee Carbonate Platform of Mount Bürgl.
1) Mass-flow with Late Triassic extraclasts (T) and Late Jurassic shallow-water clasts and stromatoporoid *Actinostromina grossa* (Germovsek, 1954) (A). Sample E 577, scale bar 2 mm. 2) Mass flows with extraclasts (? Liassic Klaus Limestone, arrow) and Late Jurassic shallow-water limestones. Sample E 578. 3) Well washed-out packstone with remains of crinoids (C) and microencruster *Crescentiella morronensis* (Crescenti, 1969) (CM). Sample E 581. 4) Packstone with dasycladalean algae *Salpingoporella pygmaea* (Gümbel, 1891) (right) and a larger unknown taxon (left). Sample E 596. 5) Bioclastic packstone with debris of corals. Sample E 608. 6) Boundstone with “stromatoporoid” sponges, sclerosponges (*Neuropora*, N), microencruster *Crescentiella morronensis* (Crescenti, 1969) (C) and *Radiomura cautica* Senowbari-Daryan and Schäfer, 1979 (R); sample UK 141. 7) Boundstone with microencruster (e.g. *Crescentiella*, C) and sclerosponges (e.g. *Neuropora*, N); sample E 619. 8) Packstone with radiolarians, calpionellids, sponge spicules, textulariid foraminifera; sample E 828. Scale bars 2 mm for 1-7), 1 mm for 8)

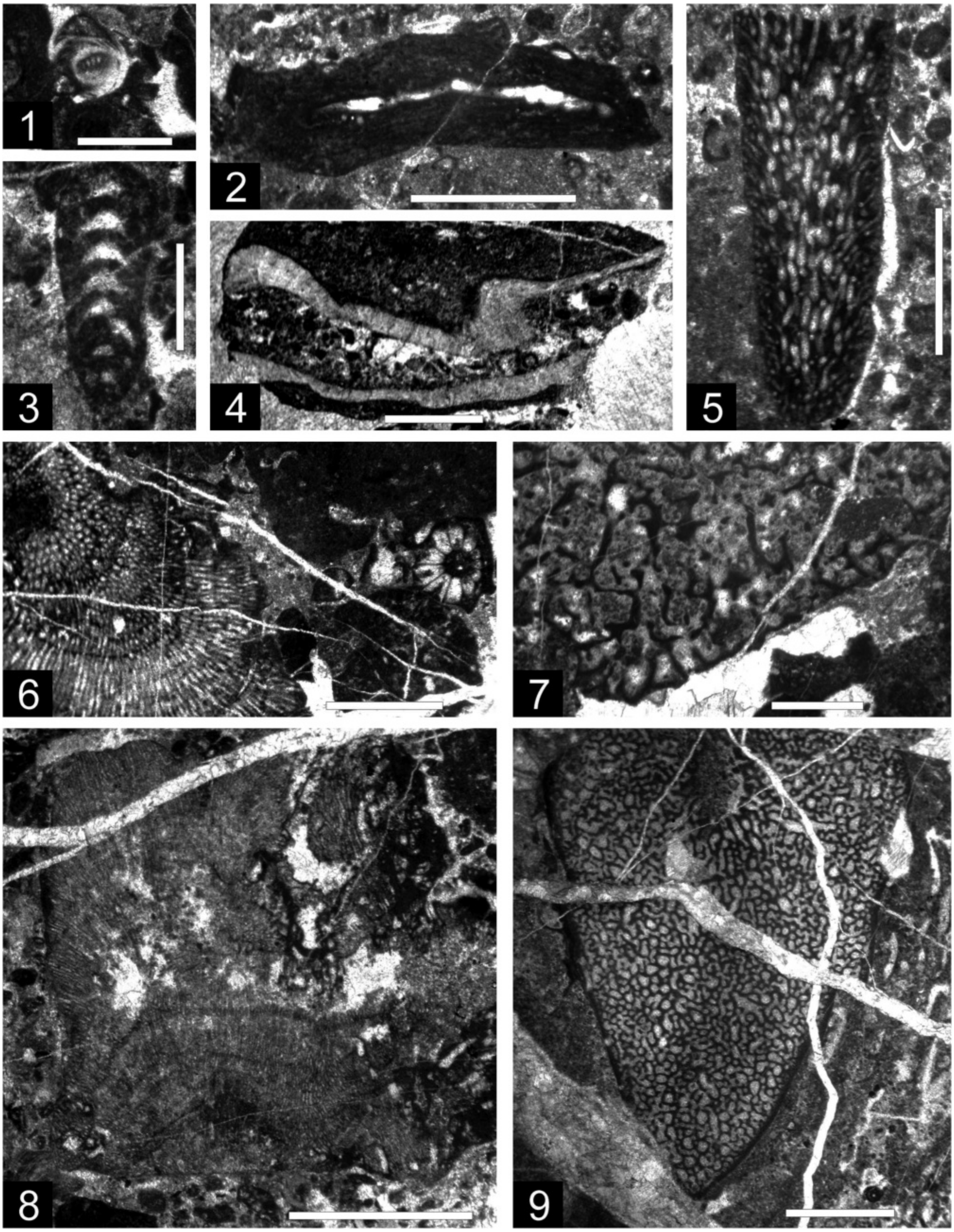

Figure 8: Micropalaeontology of the Plassen Carbonate Platform of Mount Bürgl.
1) Benthic foraminifer *Protopeneroplis striata* Weynschenk, 1950; note the distinct irregular coiling. Sample E 602. 2) Microencruster *Crescentiella morronensis* (Crescenti, 1969). Sample E 581. 3) Benthic foraminifer *Lituola*? *baculiformis* Schlagintweit and Gawlick, 2009, sample E 579. 4) Possible crustacean remain *Carpathocancer*? *plassenensis* (Schlagintweit and Gawlick, 2002). Sample E 617. 5) Green alga *Halimeda misiki* Schlagintweit, Dragastan and Gawlick, 2008. Sample E 580. 6) Rivulariacean alga (left) and dasycladale *Clypeina jurassica* Favre & Richards (right). Sample E 615. 7) Oblique section of calcisponge *Calciagglutispongia yabei* (Flügel and Hötzl, 1966). Sample E 588. 8) Solenoporacean alga *Solenopora* sp., a generally very rare component of the platform margin facies of the Plassen Carbonate Platform (s.l.). Sample E 617. 9) Sponge *Sestrostomella* sp. Sample E 620. Scale bars 0.5 mm for 1-2, 5), 1 mm for 3-4, 6-7) and 2 mm for 8).

from other localities of the Plassen Carbonate Platform (s.l.) and following the platform margin and back-reef deposits (Schlagintweit et al., 2003) are missing at Mount Bürgl. Two fragments of the dasycladale Clypeina jurassica Favre & Richards together with rivulariacean algae, however, show lagoonal influences (Fig. 8/6). Lagoonal limestones, however, are not reported from today's erosional remnants of Wolfgangsee Carbonate Platform. A schematic reconstruction from the reefal area to the basinal area is shown in Fig. 9. At the western slope towards lake Wolfgangsee, the drowning sequence, described in the following, is exposed (Fig. 7, Fig. 10).

4.2 The drowning sequence

The drowning sequence abruptly follows platform margin (reefal, fore-reefal) deposits (Fig. 10), which show no evidence for emergence/subaerial exposure. The rapid lithological change from shallow-marine carbonates to hemipelagic deeper slope sediments is termed a drowning unconformity in the sense of Schlager (1989).

The drowning phase near the platform top resp. the upper slope is partly characterized by the change in microfacies from reefal rudstones of a platform-near facies belt to echinoderm dominated grainstones together with recrystallized bioclasts of shallow-marine biota. The investigated drowning sequence on top of the shallow-water carbonates (Fig. 10) starts with a 20 metre thick series of coarse-grained mass flows, in the upper part with intercalated fine-grained calarenites, both made up of reefal material. The sequence after the drowning unconformity (Fig. 10) was dated by means of calpionellids (Fig. 11), using the calpionellid biozonation of Remane (1985) and the revised zonal and subzonal subdevision of Grün and Blau (1997). The section on top of the drowning unconformity starts with thin bedded biomicritic, partly cherty limestones with some intercalated fine-grained allodapic limestones. Occasionally also some greenish marly intercalations occur. Slump deposits occur especially in the middle part of the section (Fig. 10). The first analysed sample following the drowning disconformity (E 829, see Fig. 10) shows the co-occurrence *Calpionella alpina* Lorenz, 1902 and *Crassicollaria* div. sp. (Fig. 11) that, according to the biochronological framework of calpionellids corresponds to the Late Tithonian intermedia Subzone, the A2 of Remane (1985). The first *Calpionella alpina* appears approximately at the base of the intermedia Subzone (Grün and Blau, 1997, Fig. 2). The *intermedia* calpionellid subzone of the Late Tithonian (~ 145 Ma) corresponds with the lower part of the *durangites* ammonite zone (e.g., Grün and Blau, 1997; Geyssant, 1997).

The uppermost part of the exposed section (Fig. 10) consists of thin bedded, very fine-grained cherty limestones, with marly intercalations. Allodapic layers are very fine-grained and thin. The first sample on the base of this part of the section (E 825) shows also the co-occurrence of *Crassicollaria intermedia* (Durand-Delga, 1957) and *Calpionella alpina* Lorenz, 1902 together with several other species (Tab. 1).

5. Discussion and conclusions

The Plassen Carbonate Platform (s.l.) consists of three independent platforms (Wolfgangsee, Plassen s.s., Lärchberg Carbonate Platforms), which developed on top of the Jurassic advancing and rising nappe fronts. From there the platforms prograded in Kimmeridgian to Early Tithonian times towards the older carbonate clastic radiolaritic basins (Bajocian to Ox-

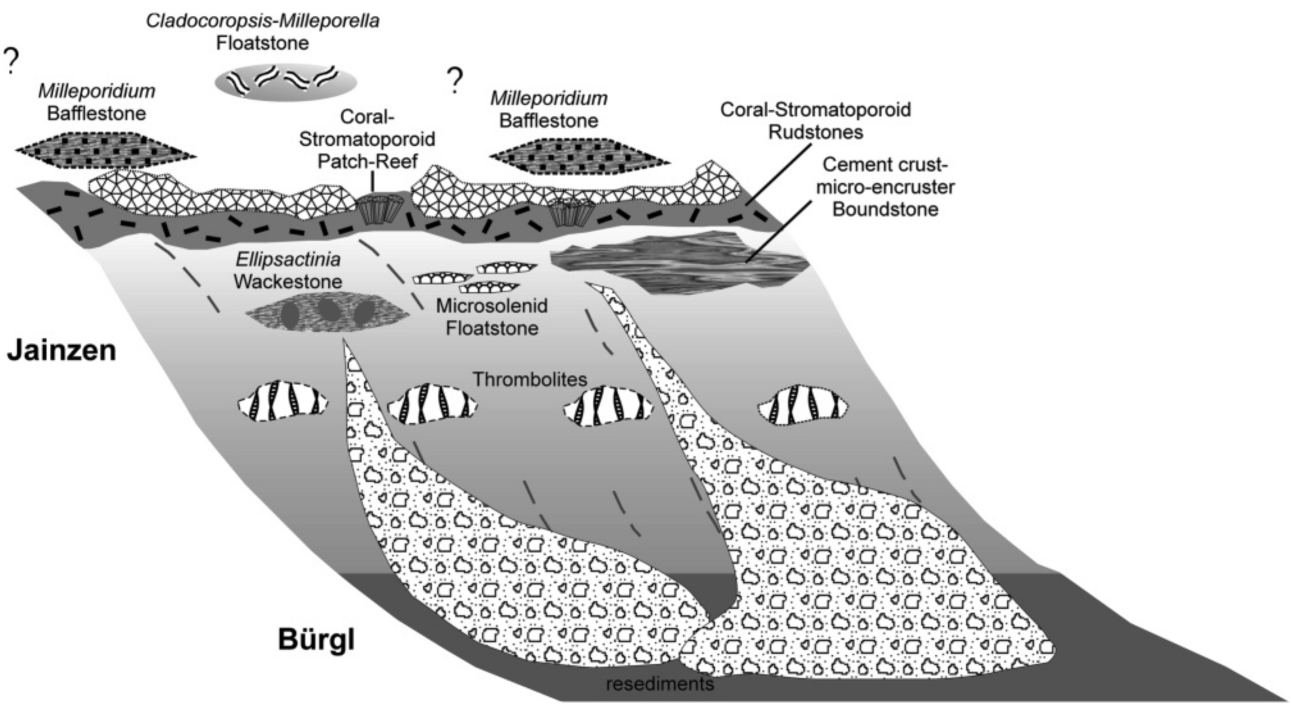

Figure 9: Facies reconstruction of the reef to basin transition of the Wolfgangsee Carbonate Platform, based on Schlagintweit et al. (2005) and this paper.

fordian) within a period of relative tectonic quiescence. In this time span the Plassen Carbonate Platform (s.l.) followed the tectono-morphologic features formed in the framework of Middle to early Late Jurassic orogenic processes. Sometime between the Early and Late Tithonian to the Jurassic/Cretaceous boundary this constellation changed rather abruptly due

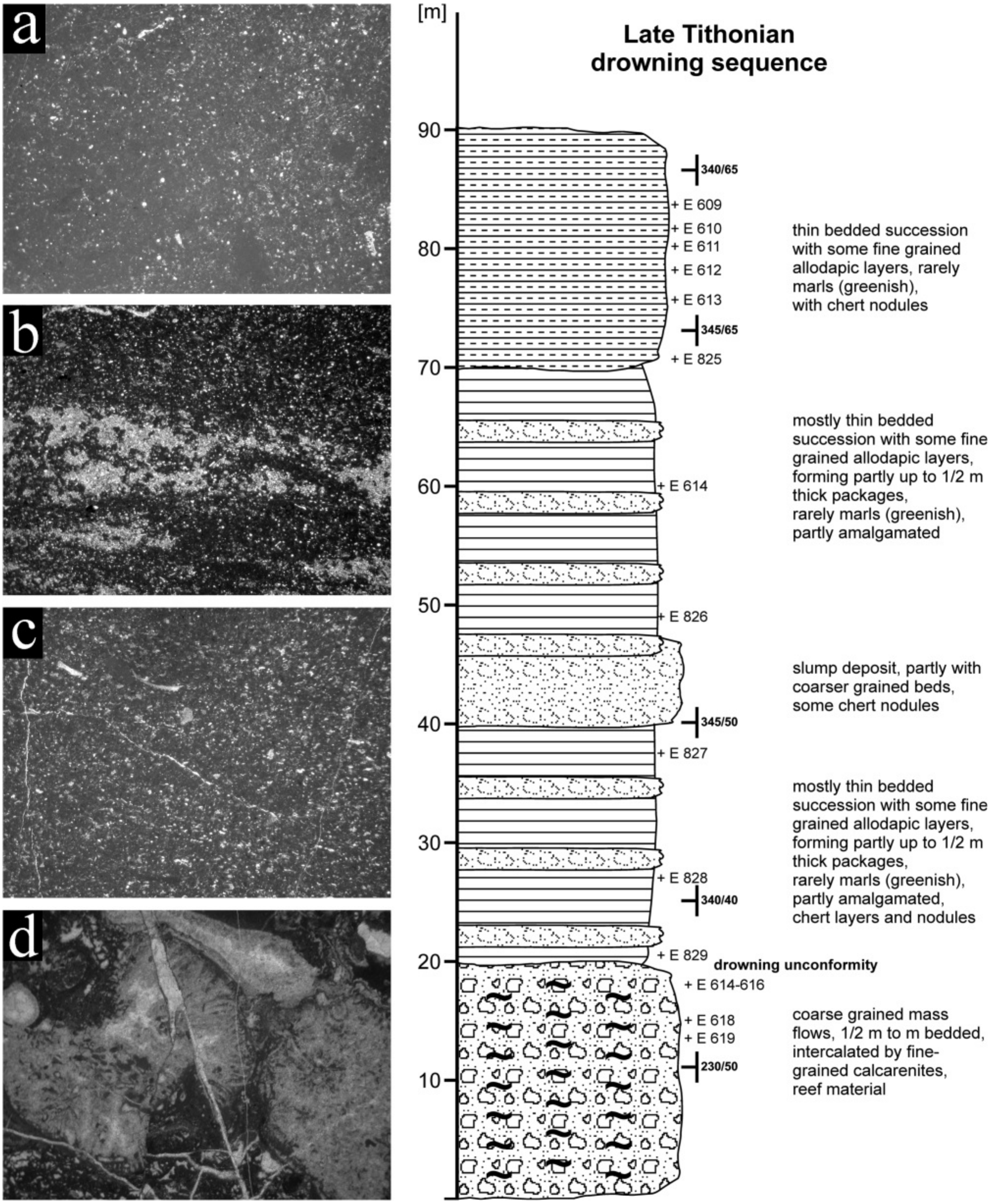

Figure 10: Late Tithonian drowning sequence of Mount Bürgl of the Wolfgangsee Carbonate Platform. The succession is preserved at the north-western side of Mount Bürgl. For sample localities see Fig. 4. a) The youngest part of the succession is completely free of shallow-water material. b) Very fine-grained hemipelagic packstone with remnants of shallow-water debris, peloids and some foraminifera. Radiolarians form the source for the cherty layers. c) Fine-grained distal turbidite of Late Tithonian age with few foraminifera and some relicts of shallow-water debris. d) Coarse grained reef debris occur below the drowning unconformity.

to a newly detected and poorly understood intense extensional tectonic activity. The Middle/Late Jurassic basin and rise configuration became rearranged, and some south-dipping emergent thrusts, e.g. the Trattberg Rise between the Upper and Lower Tirolic nappe, became now overprinted by north-dipping normal faults (Gawlick and Schlagintweit, 2009). At the same time the former central Plassen Carbonate Platform (s.s.) collapsed and enormous volumes of the latter were mobilised and resedimented in the adjacent basins, especially in the Tauglboden Basin to the north. Parts of the former platform, the northern Wolfgangsee Carbonate Platform drowned in Late Tithonian (*intermedia* calpionellid subzone) due to rapid subsidence whereas the Plassen Carbonate Platform (s.s.) counterbalanced the increasing subsidence by carbonate production for long times and drowned later in the Late Berriasian (*oblonga* calpionellid subzone). At this time also in the northern parts of the Northern Calcareous Alps the sedimentation changed from radiolaritic-calcareous to siliciclastic influenced.

The drowning event of the Wolfgangsee Carbonate Platform in the north, the onset of the Barmstein Limestone-type resedimentation from the central Plassen Carbonate Platform (s.s.) in northern directions to the enlarged Tauglboden Basin, the creation of a new reef-rim facing the Tauglboden Basin to the north, and the enhanced subsidence with a prominent facies change in the sedimentary succession of the Plassen Carbonate Platform (s.s.) are more or less time-equivalent events (Gawlick and Schlagintweit, 2009). This coincidence is due to a general new sedimentological cycle caused by tectonics, which started around the Early/Late Tithonian boundary or in the Late Tithonian.

The reasons of drowning events are generally discussed as result of four main reasons

A) mass-extinctions, possibly caused by environmental deterioration (Flügel, 2004),
B) large (relative) sea-level changes, caused by tectonic plus eustatic events (e.g., Schlager, 1981; Purdy and Bertram, 1993)
C) repeated emergence and submergence due to small-scaled sea-level changes (Schlager, 1998; Wilson et al., 1998) or
D) changes in sedimentation, especially the increase of the siliciclastic input (Schlager, 1989).

The causes occur in response to global changes, geodynamic changes or regional tectonics. However, drowning of carbonate platforms is reflected by a drastic change in microfacies, sediment composition and dominant grain types (see Flügel, 2004: pp 756-757). These changes commonly produce a drowning unconformity (Schlager, 1989). This unconformity

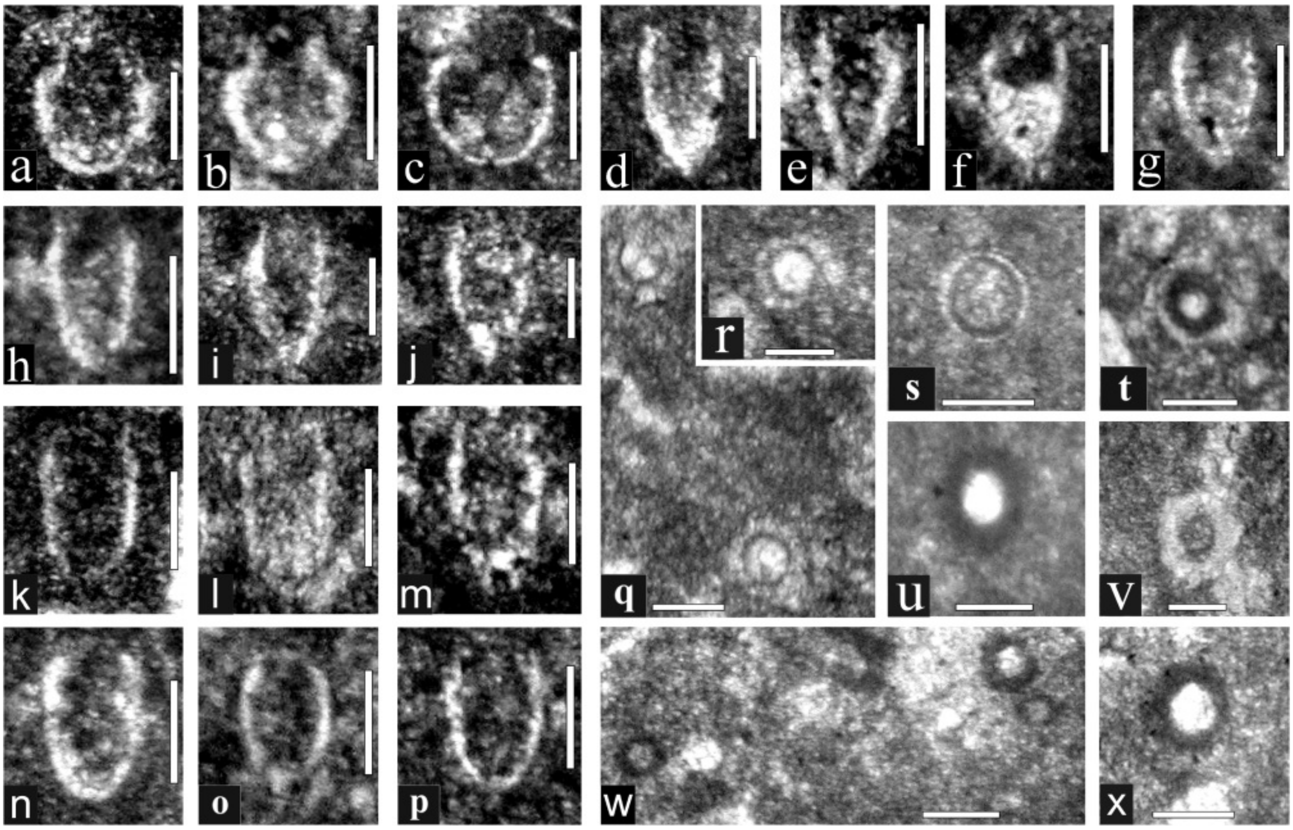

Figure 11: Calpionelids (a-p) and calcisphaerulids (q-w) from the Late Tithonian drowning sequence of Mount Bürgl. Scale bars = 0.05 mm. a-c) *Calpionella alpina* Lorenz, 1902 (medium-sized variety), samples E 826, E 829, E 614. d-g) *Crassicollaria intermedia* (Durand Delga, 1957), samples E 825, E 826, E 828, E 614. h, l-m) *Crassicollaria massutiniana* (Colom, 1948), samples E 614, E 825, E 825, E 828. i-j) *Crassicollaria* cf. *brevis* Remane, 1964, sample E 825. n-p) *Remaniella ferasini* (Catalano, 1965), samples E 825, E 828, E 825. q-r) *Colomisphaera lapidosa* (Vogler, 1941). Sample E 829. s) *Stomiosphaerina proxima* Rehanek, 1987. Sample E 825. t) *Cadosina semiradiata semiradiata* Wanner, 1940. Sample E 829. u, x) *Cadosina fusca fusca* Wanner, 1940. Sample E 825. v) calcisphaerulid indet. Sample E 829. w) *Cadosina minuta* Borza, 1980. Sample E 825.

Sample Number	Calpionellids	Age
E 609	*Calpionella alpina* Lorenz, 1902 (elongated forms) *Crassicollaria intermedia* (Durand-Delga, 1957) *Remaniella* cf. *ferasini* (Catalano, 1965)	*Crassicollaria* subzone Late Tithonian
E 610	*Calpionella alpina* Lorenz, 1902 *Crassicollaria* cf. *brevis* Remane, 1964	*Crassicollaria* subzone Late Tithonian
E 611	*Calpionella alpina* Lorenz, 1902	*Crassicollaria* subzone Late Tithonian
E 613	*Calpionella alpina* Lorenz, 1902 *Crassicollaria* cf. *brevis* Remane, 1964	*Crassicollaria* subzone Late Tithonian
E 825	*Calpionella alpina* Lorenz, 1902 *Crassicollaria* cf. *brevis* Remane, 1964 *Crassicollaria intermedia* (Durand-Delga, 1957) *Crassicollaria massutiniana* (Colom, 1948) *Remaniella* cf. *ferasini* (Catalano, 1965)	*Crassicollaria* subzone Late Tithonian
E 614	*Calpionella alpina* Lorenz, 1902 *Crassicollaria intermedia* (Durand-Delga, 1957)	*Crassicollaria* subzone Late Tithonian
E 826	*Calpionella alpina* Lorenz, 1902 *Crassicollaria intermedia* (Durand-Delga, 1957) *Crassicollaria parvula* Remane, 1964	*Crassicollaria* subzone Late Tithonian
E 827	*Calpionella alpina* Lorenz, 1902 *Crassicollaria intermedia* (Durand-Delga, 1957) *Crassicollaria* cf. *brevis* Remane, 1964	*Crassicollaria* subzone Late Tithonian
E 828	*Calpionella alpina* Lorenz, 1902 *Crassicollaria* cf. *brevis* Remane, 1964 *Crassicollaria massutiniana* (Colom, 1948)	*Crassicollaria* subzone Late Tithonian
E 829	*Calpionella alpina* Lorenz, 1902 *Crassicollaria* cf. *brevis* Remane, 1964 *Crassicollaria parvula* Remane, 1964	*Crassicollaria* subzone Late Tithonian

Table 1: Calpionellids in the samples of the Late Tithonian drowning sequence of Mount Bürgl. For location of the samples see Fig. 7.

is formed by a relative seal-level rise or highstand, because drowning can occur only if the platform top is flooded (Schlager, 2005). Detailed studies of the drowning of carbonate platforms formed under strong (and changing) tectonic movements are relatively rare. Especially drowning events of carbonate platforms formed on top of nappe stacks of active continental margins are very rarely preserved and therefore the knowledge about the processes of the demise of such platforms is low (compare Flügel, 2004).

The conditions in the life cycle of the Plassen Carbonate Platform (s.l.) changed decreasing tectonic shortening in the timespan Late Oxfordian to Kimmeridgian to extension, which resulted in the creation of normal faults associated with increasing subsidence around the Early/Late Tithonian boundary (Gawlick et al., 2005; Schlagintweit and Gawlick, 2007; Gawlick and Schlagintweit, 2009). The reason of this change in the overall tectonic regime is still unclear, but it might be due to the uplift of an orogen in the southern part of the Northern Calcareous Alps (Hallstatt imbricates = internal parts of the Middle-Late Jurassic orogenic wedge) after ophiolite obduction (Missoni and Gawlick, 2010, in press).

This evolution mirrors exactly the scenario known from the Dinarides, where the obducted ophiolites (Gawlick et al., 2008; Schmid et al., 2008) were sealed by a Kimmeridgian-(Early) Tithonian carbonate platform (Kurbnesh Carbonate Platform – Schlagintweit et al., 2008), similar to those of the Northern Calcareous Alps. These platforms on top of the obducted ophiolites were uplifted and eroded in Late Tithonian times (Schlagintweit et al., 2008). In the Albanides, Kimmeridgian-Tithonian reef slope sediments (intermixed with older Triassic clasts from the accreted Hallstatt facies belt and with ophiolite material) occur directly in front of the ophiolite nappes (Schlagintweit et al., 2008). Similar, but more fine-grained and therefore more distal mass flows were found in the Northern Calcareous Alps in the Kimmeridgian-Tithonian Sillenkopf Basin (Missoni et al., 2001; Missoni, 2003).

Although the reasons for this extensional tectonics are not fully understood, the result of these movements led to asymmetric and partly extremely rapid subsidence in different areas where the platforms were formed. Rapid subsidence in the central part (= Plassen Carbonate Platform (s.s.); Schlagintweit et al., 2003; Gawlick and Schlagintweit, 2006) was counterbalanced by carbonate production in the Tithonian to Berriasian, but increasing subsidence led to drowning of the northern platform (= Wolfgangsee Carbonate Platform, Gawlick et al., 2007a) in the Late Tithonian. This level marks the starting of the second order transgressive cycle T 10 of the Tethyan Stratigraphic Cycles (Jacquin et al., 1998: Fig. 2) and the base of the *durangites* ammonite zone (145 MA) and corresponds to the base of the *intermedia* calpionellid subzone (see Fig. 6 in Grün and Blau, 1997). These long-term cycles are "surprisingly synchronous over wide areas, even though extensional tectonics was particularly active at that time" (Jacquin et al., 1998: p. 445).

It is therefore still unclear, whether regional tectonic events in the north-western Tethyan realm or long-term sea-level changes were the main factors controlling the evolution of the Plassen Carbonate Platform (s.l.), and especially the drowning of the Wolfgangsee Carbonate Platform needs further detailed investigations in the sequences of shallow- and deep-water successions in the whole realm.

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