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The Steinplatte complex (Late Triassic, Northern Calcareous Alps, Austria) – subsidence-controlled development of a carbonate-platform-to-intrashelf-basin-transition

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ABSTRACT:

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In Rhaetian (Late Triassic) times, the Hauptdolomit/Dachstein carbonate shelf situated at the passive continental margin of the northwestern Tethys was characterized by an extensional tectonic regime. Rifting and spreading movements fragmented this shelf into a loosely fitted mosaic of fault-bounded blocks characterized by a differential subsidence pattern. This is expressed in significant thickness variations of platform carbonates and in the formation of the intrashelf Kössen Basin. In this study, it can be demonstrated that tectonic subsidence triggered the development of a carbonate platform margin and that the influence of eustatic sea-level changes was negligible.

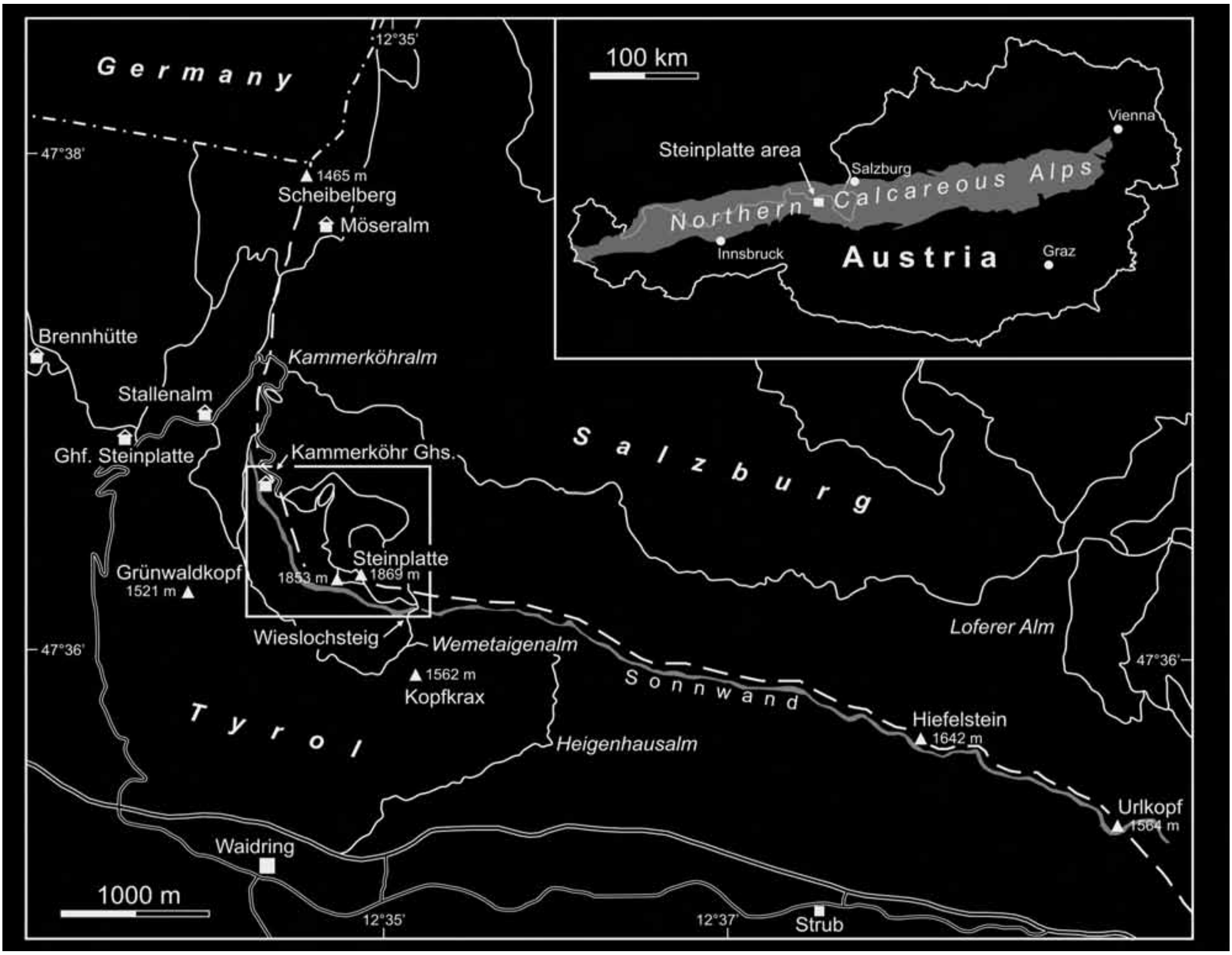
The Steinplatte complex developed at the transition of the Kössen Basin to the Dachstein Carbonate Platform. Small-scale isolated carbonate mounds situated on a smoothly inclined homoclinal ramp characterized the initial phase and acted as nuclei of further carbonate buildup growth. However, only the ideal palaeogeographic position far enough away from the carbonate-suppressive terrigenous influence of the Kössen Beds, combined with vigorous carbonate production stimulated by rapid subsidence-caused sea-level rise, favoured continuous mound growth. Once established, the carbonate buildup was characterized by rapid aggradational growth, developing a palaeogeographic high with a steep slope and a depression with decreased sedimentation behind, several kilometres distant from the Dachstein Carbonate Platform. Contemporaneously, isostatic adjustment caused an accommodation minimum on the nearby margin of the Dachstein Carbonate Platform leading to its westward progradation. Fading out of subsidence caused filling of the former depression in the back of the buildup by prograding shallow-water Dachstein Limestones. Thus, a new platform margin was established in the Steinplatte area, elevated almost 200 m above the adjacent Kössen Basin.

At the Triassic-Jurassic boundary, the Steinplatte complex was subjected to subaerial exposure by a sudden tectonic uplift followed by a rapid isostatic drop. Emergence is indicated by levels of karstified limestones directly underlying supposed exposure surfaces. Final drowning of the Steinplatte complex as well as of the whole Dachstein Carbonate Platform is indicated by the cover of Early Jurassic (Sinemurian) deeper water, ammonite-bearing limestones (Adnet Formation).

Key words: Northern Calcareous Alps; Steinplatte; Subsidence; Rhaetian; Reef; Carbonate Platform.

INTRODUCTION AND PREVIOUS WORK

The upper Triassic Steinplatte complex (Northern Calcareous Alps, Austria) is one of the most intensively studied fossil carbonate bodies of Earth's history. In this respect, it is comparable with the Permian Capitan Reef complex of the Guadalupe Mountains of New Mexico/Texas, USA (Newell *et al.* 1953; Saller *et al.* 1999). The Steinplatte complex represents a reefal structure at a carbonate platform margin. Its unique outcrop quality, namely tectonically undisturbed outcrops, preservation of original slope topography and perpendicular cliff walls, has made it a favoured subject of investigation for geologists and palaeontologists for almost 150 years. Comprehensive overviews of the history of investigations are given in Piller (1981) and Stanton and Flügel (1989). Research began in 1871, when Mojsisovics first recognized the reefal nature of the Steinplatte complex. Studies up to Sieber (1937) concentrated on the acquisition of the geological and palaeontological inventory of the Steinplatte. The dissertation of Ohlen (1959) presented for the first time a facies model based on both the available research results of modern carbonate sedimentation and the well-developed model of ancient reefs which Newell *et al.* (1953) had documented for the Capitan Reef. Ohlen's facies model was partly corrected and rendered more precise by Piller (1981), who elaborated a clear facies zonation based on fossil communities in the youngest part of the carbonate complex. In addition, Piller (1981) and Piller and Lobitzer (1979) emphasized the palaeogeographical position of the Steinplatte complex at the northwestern margin of the upper Triassic Dachstein Carbonate Platform. The studies of Stanton and Flügel (1989, 1995) greatly extended the microfacies studies begun by Piller (1981). In particular, the perpendicular walls of the prominent western cliff side of the Steinplatte were sampled in order to trace biofacies over the whole outcrop and in the transition to the interfingering Kössen Beds. The result was an incredibly detailed microfacies study and a reinterpretation of the



Text-fig. 1. Locality map of the Steinplatte area. Narrow shaded band marks the cliff on the west and the south side of the Steinplatte complex. Boxed area indicates field of geological map (Text-fig. 4)

Steinplatte complex as a *distally-steepened ramp* instead of representing a *reef-rimmed margin* as suggested by Ohlen (1959) and Piller (1981). Golebiowski (1991) investigated the lithostratigraphy and biofacies of the Kössen Beds and also the interfingering of the Kössen Beds with the Dachstein Carbonate Platform in the Steinplatte area. His detailed lithostratigraphic subdivision of the Upper Kössen Beds (Eiberg Member) allows a systematic correlation with the carbonate succession of the Steinplatte complex.

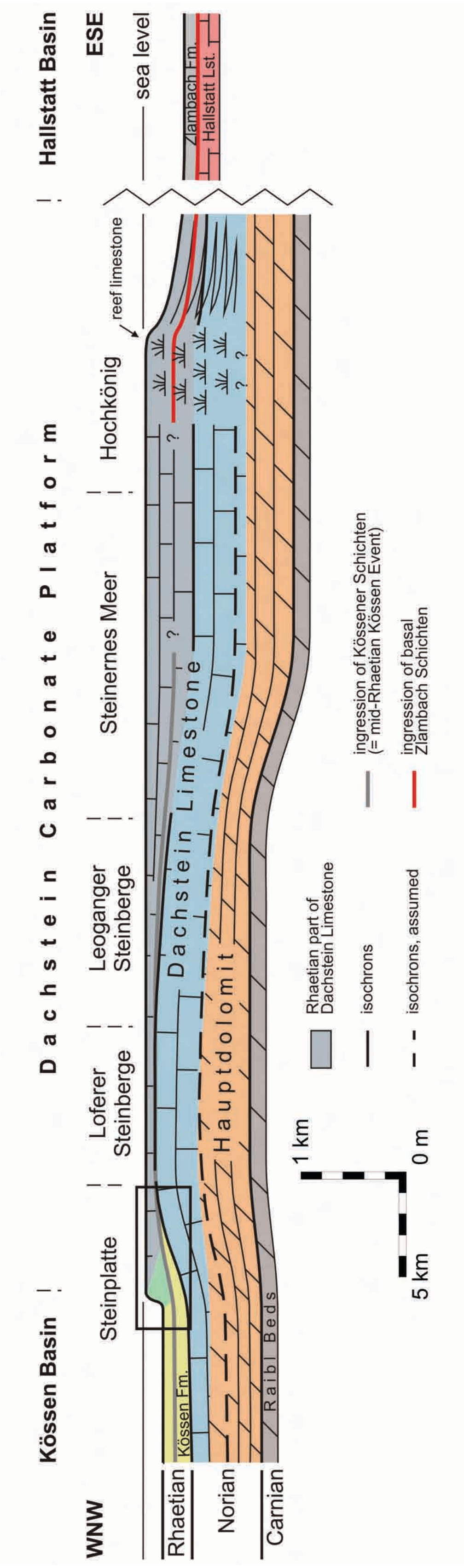
All the above-mentioned studies provide a comprehensive database concerning the geology, palaeontology, microfacies, facies models and stratigraphy of the Steinplatte complex. However, the spatial and temporal evolution of this carbonate buildup as well as the controlling factors for its development have not yet been worked out in detail. The aim of the present study is to close this gap in knowledge. Furthermore, a detailed geological map of the Steinplatte complex has been missing to date and is presented here. Meanwhile, new, straightened, high-resolution aerial photographs and a digital topographical map are available which allow detailed mapping, geometric constructions and accurate correlations that were not previously possible. The results are a refinement of the facies model of the Steinplatte complex and a detailed elaboration of its position at an intrashelf-basin-to-carbonate-platform-transition.

LOCATION AND GEOGRAPHY

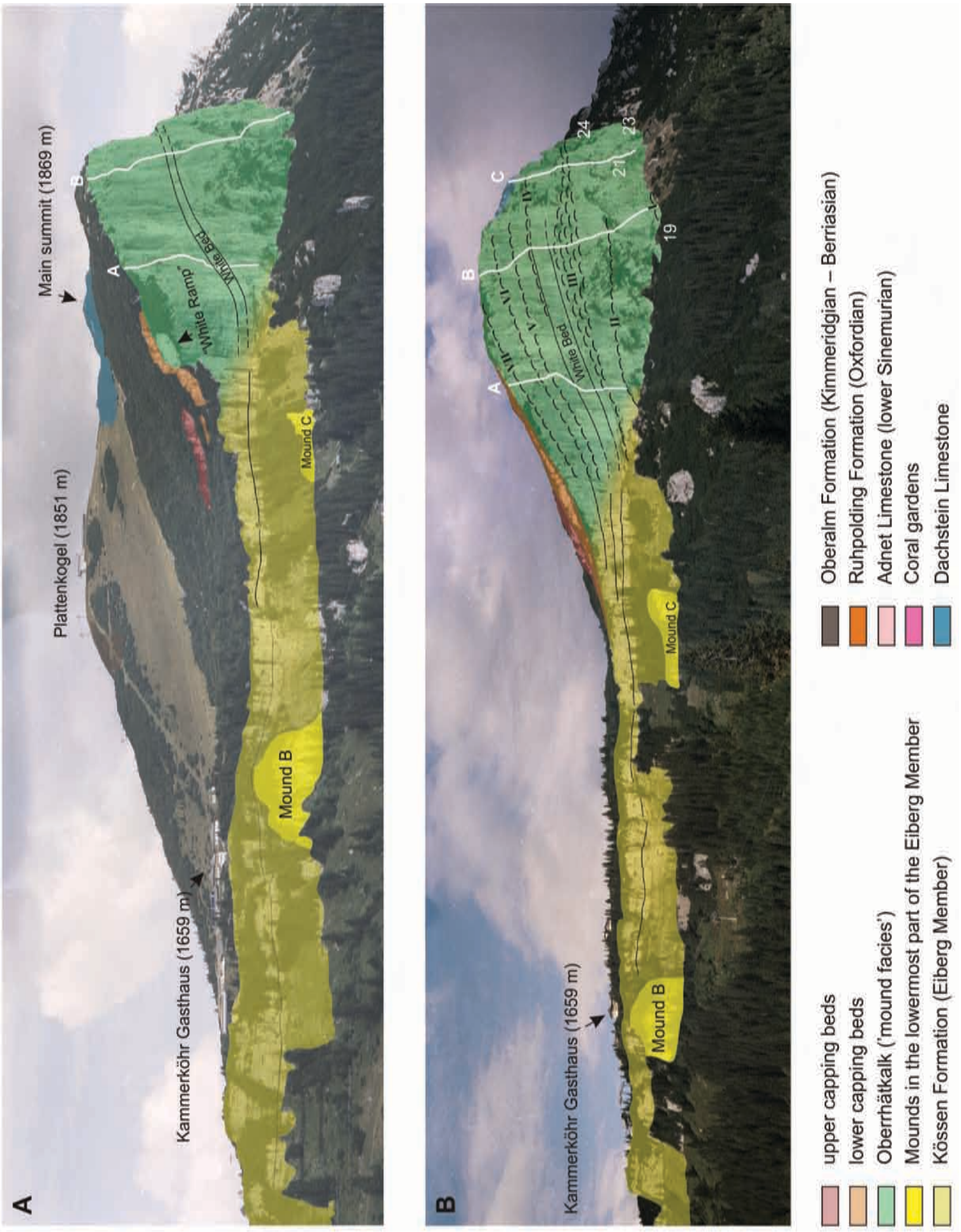
The Steinplatte complex is located at the boundary between the provinces of Tyrol and Salzburg, a few kilometres south of the Austrian-German border (Text-fig. 1). The small town of Waidring is situated in the valley to the south. The Steinplatte forms a prominent mountain (1869 m) bordered by impressive cliff walls on its western and southern (Sonnwand) sides.

PALAEOGEOGRAPHIC SETTING

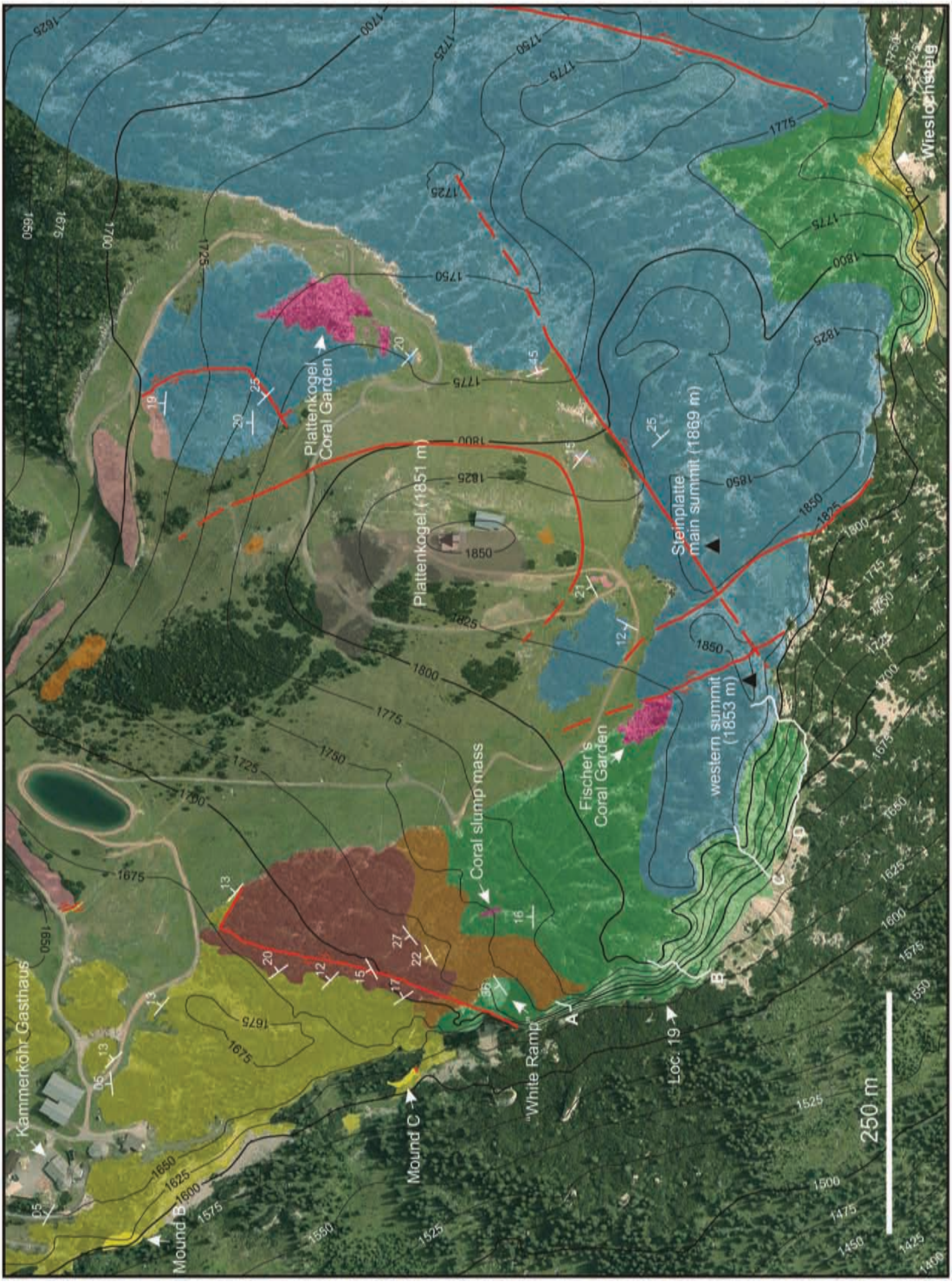
During Late Triassic times, the Northern Calcareous Alps were part of an about 500 km long and 300



Text-fig. 2. End-Rhaetian stratigraphic cross-section of the Dachstein Carbonate Platform between the intrashelf Kössen Basin and the Tethys-facing Hallstatt Basin. Note low thickness of Rhaetian Dachstein Limestone in the Loferer Steinberge, probably due to subsidence minima. Note the five times vertical exaggeration. Based on information concerning thicknesses of stratigraphic units in Hahn (1910, 1913), Ohlen (1959), Golebiowski (1991) and Satterley (1996). Rectangle on the left side indicates area of Text-fig. 9



Text-fig. 3. The Steinplatte complex from two different perspectives. A) Looking ESE from near Brennhütte. B) Looking ENE from Grünwaldkopf. Flat-lying Kössen Beds (yellow) grade laterally into up to 36° ("White Ramp") inclined Oberrhätkalk (green). Width of outcrop is ca. 1000 m. Note overlying Dachstein Limestone (blue) in the summit area. Cliff sections (A–C), marker horizon (White Bed), shell beds (I–VII) and localities (19, 21, 23, 24) inserted from Stanton and Flügel (1989). Legend also applies to Text-fig. 4



Text-fig. 4. Locality and geological map of the Steinplatte area. Based on orthophotos 4028-43, 44, 51 and 52, scale 1 : 2000, Bundesamt für Eich- und Vermessungswesen (BEV). A–D = Cliff sections of Stanton and Flügel (1989, 1995). Red lines = major faults. For legend see Text-fig. 3

km wide shelf at the passive continental margin of the northwestern Neotethys, situated about 30° north of the equator (Marcoux *et al.* 1993). Tropical conditions favoured the establishment of giant, more than 2000 m thick, carbonate platforms (Loferer and Leoganger Steinberge, Steinernes Meer, Hochkönig, Tennengebirge, Dachstein Mountains, Totes Gebirge, Hochschwab, Hohe Wand) composed essentially of Hauptdolomit and Dachstein Limestone (Text-fig. 2). Rhythmic successions in the Dachstein Limestone from subaerial to shallow subtidal deposits are well known as “Lofer Cyclothems” (Fischer 1964). The southern and southwestern, ocean-facing, margins of the carbonate platforms were rimmed by thick reefal carbonates formed by massive Dachstein Limestone (e.g. Braun 1998; Satterley 1994; Wurm 1982; Zankl 1969) (Text-fig. 2). Platform margins were characterized by gentle slopes passing into the pelagic realm of the Hallstatt facies.

The Hauptdolomit/Dachstein carbonate shelf was, however, not as tectonically stable as it seems at first view. In Norian and Rhaetian times, the extensional tectonic regime at the northwestern margin of the Tethys ocean caused a differential subsidence pattern expressed in significant thickness variations of platform successions. Moreover, increased subsidence in the northern part (Hauptdolomit) of the carbonate shelf caused the formation of the Kössen Basin with the onset of the Rhaetian. Carbonate buildups like the Steinplatte complex (Piller 1981; Stanton and Flügel 1989; this study) and the patch reefs of Adnet (Bernecker *et al.* 1999) and the Rötelwand (Schäfer 1979) near Hallein (Salzburg) developed at the transition between this intrashelf basin and the Dachstein Carbonate Platform.

GEOLOGICAL AND STRATIGRAPHICAL SETTING

Structurally, the Steinplatte complex is situated on the southwestern, NE-dipping limb of the Osterhorn-Unken syncline, which is part of the Tirolikum tectonic unit (Tollmann 1985). The basement is formed by the lower Norian Hauptdolomit, which has a thickness of about 500 m (Hahn 1910). The first calcareous intercalations indicate the transition to, or rather the interfingering with, the overlying upper Norian Dachstein Limestone (Plattenkalk) which has a total thickness of ca. 250 m (Hahn 1910). This gradual facies transition is diachronous and becomes older to the east (below Sonnwand) and southeast (Loferer Steinberge, Leoganger Steinberge, Steinernes Meer) (Text-fig. 2). The thickness of the Dachstein Limestone thus increases at the expense of the Hauptdolomit, indicating a transgressive north- and northwestward (= landward) propagation of the Dachstein Carbonate Platform. The first marly intercalations in the succession mark the base of the Kössen Beds (nearly coeval with the onset of the Rhaetian, see Krystyn *et al.* 2007, p. 197), which have an overall thickness up to the Triassic-Jurassic boundary of ca. 240 m (Golebiowski 1991). The Kössen Beds are subdivided into the lower, 160 m thick Hochalm Member and the upper Eiberg Member, 80 m in thickness. The Hochalm Member wedges out below the Sonnwand, with the exception of its uppermost part (Units 3 and 4), which extends far onto the Dachstein Carbonate Platform (= Kössen event of Satterley 1996), reflecting the widest extension of the Kössen Basin in the mid-Rhaetian. This event can still be recognized far to the east and southeast at the Steinernes Meer (Satterley 1996) as well as at the Hochkalter (Barth 1968) and the Totes Gebirge (Piller 1976). The upper Kössen Eiberg Member passes into the massive carbonate complex of the Steinplatte (Text-fig. 3), traditionally known as the Oberrhätkalk (‘mound facies’ in Stanton and Flügel 1989) which itself grades eastward into the upper Rhaetian part of the thick-bedded Dachstein Limestone. In the summit area of the Steinplatte as well as at the locality of Wieslochsteig and northeast of Plattenkogel, the uppermost Rhaetian part of the Dachstein Limestone (‘capping beds’ in Stanton and Flügel 1989) overlies the massive Oberrhätkalk (Text-fig. 4).

DETAILED STRATIGRAPHIC CORRELATION AND MAPPING OF THE KÖSSEN-BASIN-STEINPLATTE-COMPLEX-TRANSITION

Previous studies by Golebiowski (1991, and unpublished data) and Stanton and Flügel (1989) are the basis for a detailed correlation of the Kössen Beds with the Steinplatte complex and the Dachstein Carbonate Platform. These authors presented different schemes of lithostratigraphic subdivision of the upper Kössen Beds (Eiberg Member), the rationalization of which was one of the challenges for detailed correlation (Text-fig. 5). Another problem was the lateral tracing of strata of the sections (A–D) logged by Stanton and Flügel (1989) in the perpendicular cliff wall along the slope into the basinal strata (Text-figs 3, 5), and in the opposite direction towards the Dachstein Carbonate Platform (Text-figs 5, 9). For this purpose, a new topographic base map was constructed based on high-resolution, straightened aerial photographs combined with a contour-line map. Supported by GPS navigation and a detailed photograph of the western cliff (Text-fig. 3), a precise positioning of the cliff wall sections in the new topographic map was possible (Text-fig. 4). The result allows for the first time a precise determination of the palaeotopography of the Steinplatte complex (Text-fig. 6). Moreover, the detailed stratigraphic correlation enables the development of an accurate multistage facies model (Text-fig. 9).

The new topographic map also served as the base for a detailed geological map of the Steinplatte complex (Text-fig. 4). As a result of accurate correlation and mapping, the weaknesses and inaccuracies of earlier maps and facies models (Ohlen 1959; Piller 1981) became evident. Due to the lack of a detailed stratigraphic framework, these earlier constructions simplistically treated the easily accessible and traceable surface of the Steinplatte complex between the Kammerköhr Gasthaus, Steinplatte summit and Wieslochsteig as being coeval. The geological map (Text-fig. 4), as well as the correlation of sections (Text-fig. 5), clearly demonstrate that this is not the case. Erosion has truncated the upper part of the northern slope and thus exposed different stratigraphic levels.

CHRONOSTRATIGRAPHY AND RHAETIAN TIME SCALE

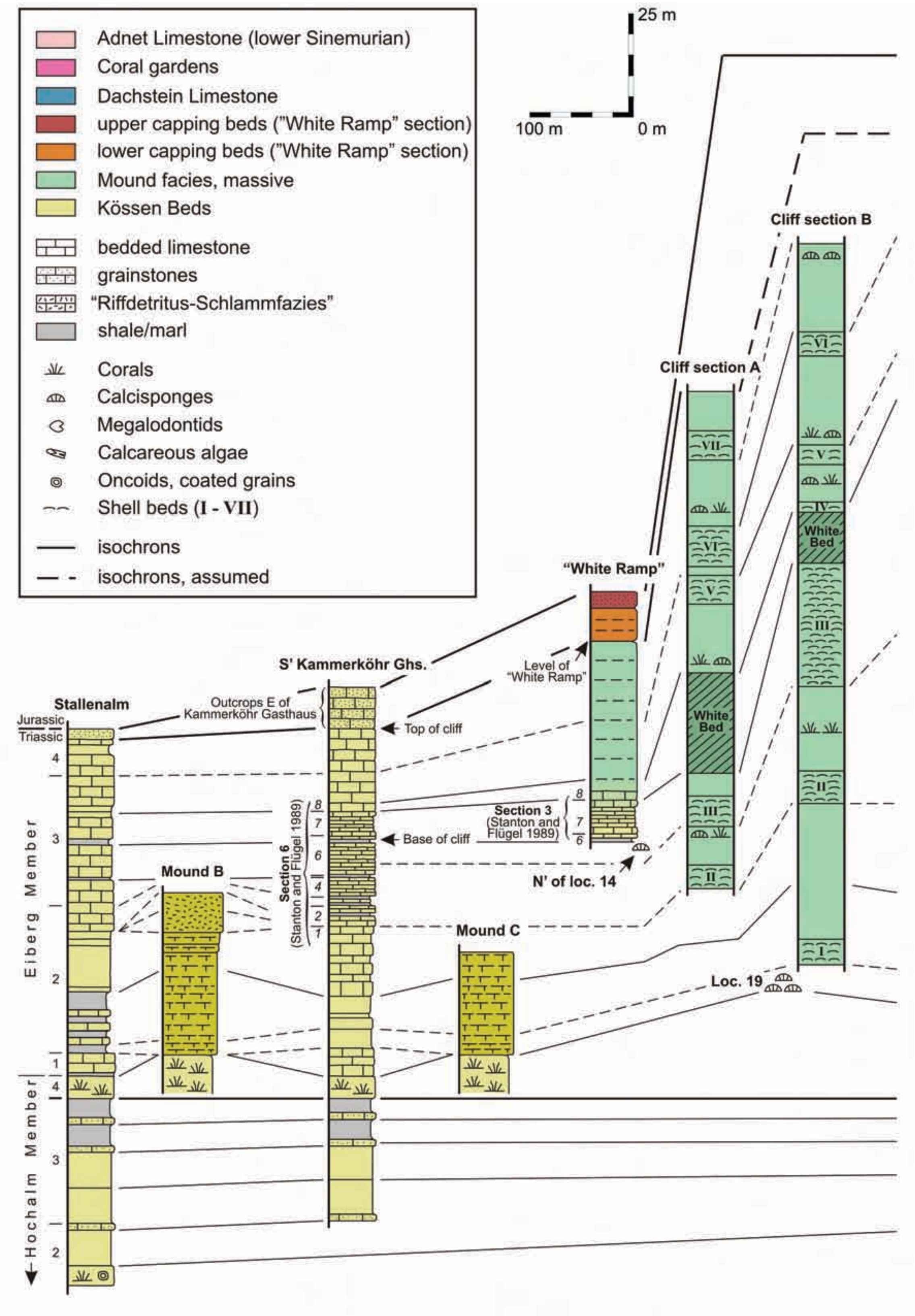
For the chronostratigraphic presentation of the Rhaetian succession of the Steinplatte area (Text-fig. 7) as well as for the presentation of time-linear subsidence curves (Text-fig. 8), the construction of a Rhaetian time scale was required. The sedimentary record of the Kössen Beds, as completely represented in the Hochalm section (Golebiowski 1991), was evaluated as not being time-linear because of continuously diminishing rock accumulation rates due to increasing water depth and decreasing carbonate productivity. Rock accumulation rates were highest in the lower Hochalm Member, where carbonate productivity was stimulated to keep up with rising sea level due to stepwise, tectonic subsidence producing shallowing-upward cycles and repeated re-establishment of shallow-water conditions (Dachstein Limestone facies). At the end of deposition of the Hochalm Member (Unit 3) in the mid-Rhaetian, carbonate production finally failed to keep up with rising sea level, and deeper subtidal conditions characterized by much lower sedimentation rates were established. All this led to a non-uniform record of time.

The Oyuklu section in Turkey (Gallet *et al.* 2007) represents a basinal succession characterized by a homogeneous lithology, this being the most important precondition for a linear record of time. Furthermore, Rhaetian conodont stratigraphy is well documented in this section and can easily be correlated with the alpine conodont and ammonoid stratigraphy and with the lithology of the Kössen Formation (Krystyn 1988). The resulting proportional Rhaetian time-scale is presented in Text-fig. 7. But what about the absolute length of the Rhaetian? Isotopic ages are completely missing in the long Late Triassic interval between the Ladinian-Carnian boundary and the Triassic-Jurassic boundary. According to Brack *et al.* (2005), this interval is 35 Ma long, representing the greatest gap of isotopic dating in the Phanerozoic! Therefore, until reliable isotopic ages have been acquired, the numeric Rhaetian time scale must be estimated indirectly. Due to the lack of constraining isotopic ages, recent estimates for the duration of the Rhaetian vary between 3.3 Ma and 6 Ma (Brack *et al.* 2005; Gallet *et al.* 2003, 2007; Ogg 2004). Some of these estimates are based on a correlation with the 'astronomically-tuned' continental section of the Newark Basin (Kent and Olsen 1999). However, the latest studies suggest that at least part of the Rhaetian is missing in the Newark section (Gallet *et al.* 2007). If this is true, this section cannot be used for estimates of the duration of the Rhaetian.

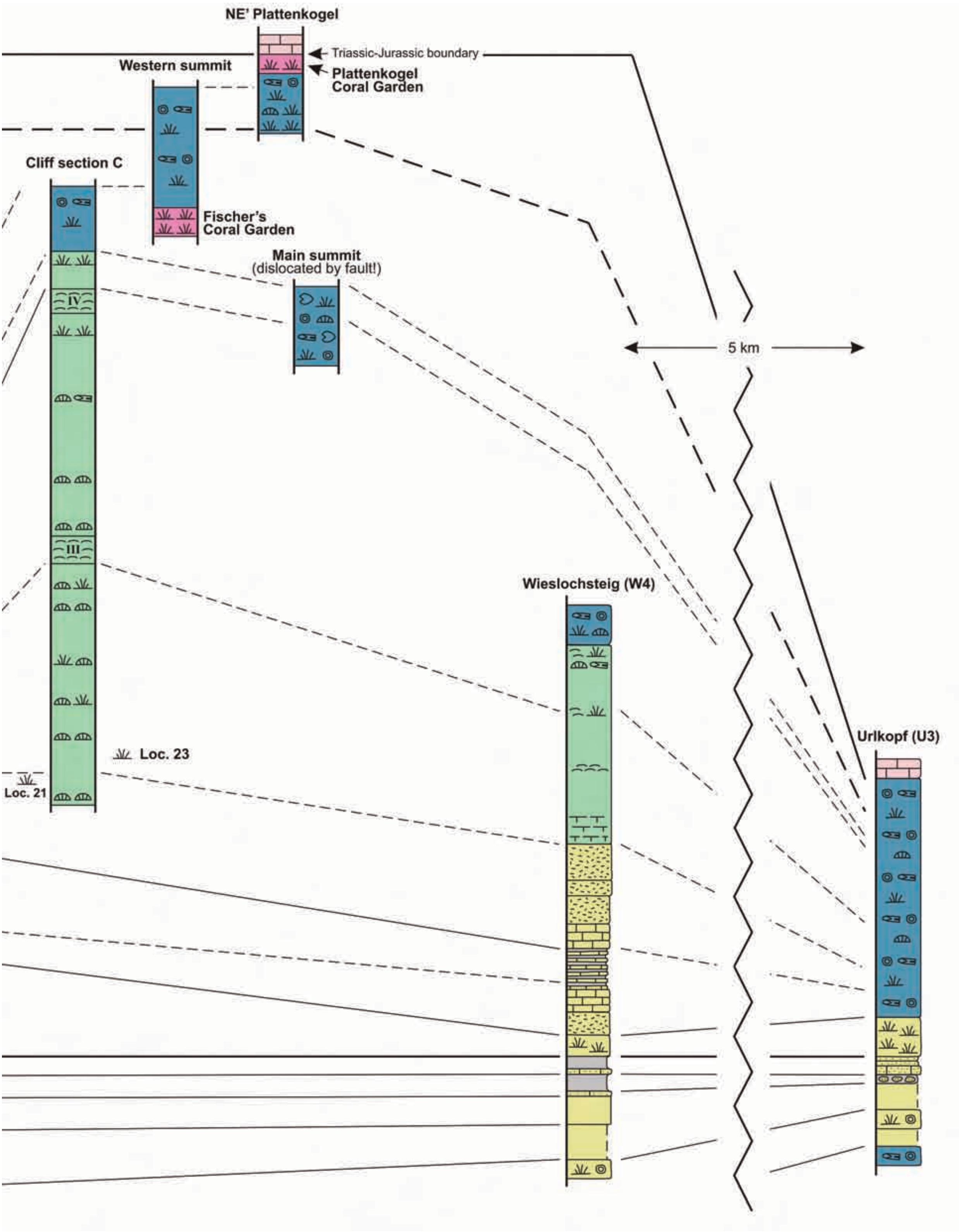
In this study, a much shorter duration of the Rhaetian of about 2 Ma is considered, based on the following arguments: According to Schlager (2000, fig. 3), the 'mound facies' (Oberrhätkalk), which makes up the bulk of the sedimentary thickness of the Steinplatte, can be assigned to the 'tropical factory' which is characterized by rock accumulation rates of 15 to 27 cm/1000a if measured over an interval of 1–3 Ma. This would imply that the 'mound facies', with its maximum thickness of 180 m (Text-figs 5, 6), would have accumulated in 0.7–1.2 Ma. In the Steinplatte area, the 'mound facies' makes up a bit more than 50 % of the Rhaetian (Text-fig. 6) which would then come to a total of ca. 2 Ma. It must, however, be emphasized here that this estimation is very speculative, involving many uncertainties and not constrained by 'real' data. The author suggests it merely as a comment on the duration of the Rhaetian Stage.

SUBSIDENCE-CONTROLLED EVOLUTION OF THE KÖSSEN BASIN

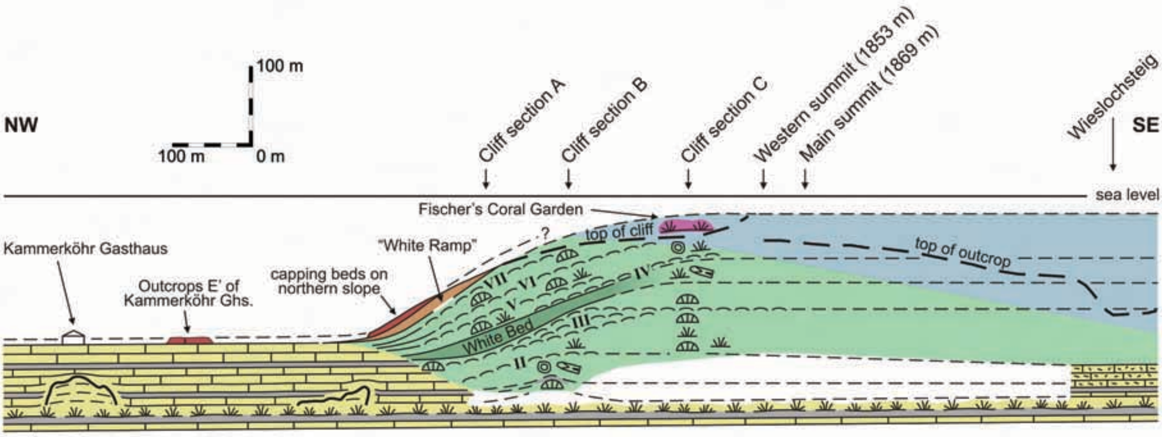
The Kössen Basin was initiated at the beginning of the Rhaetian by increased subsidence in the northern part (Hauptdolomit) of the Dachstein carbonate shelf. Enhanced humidity in the Keuper hinterland to the north resulted in terrigenous input supporting the



Text-fig. 5. Correlation of upper Rhaetian sections of the Steinplatte complex. Based on Stanton



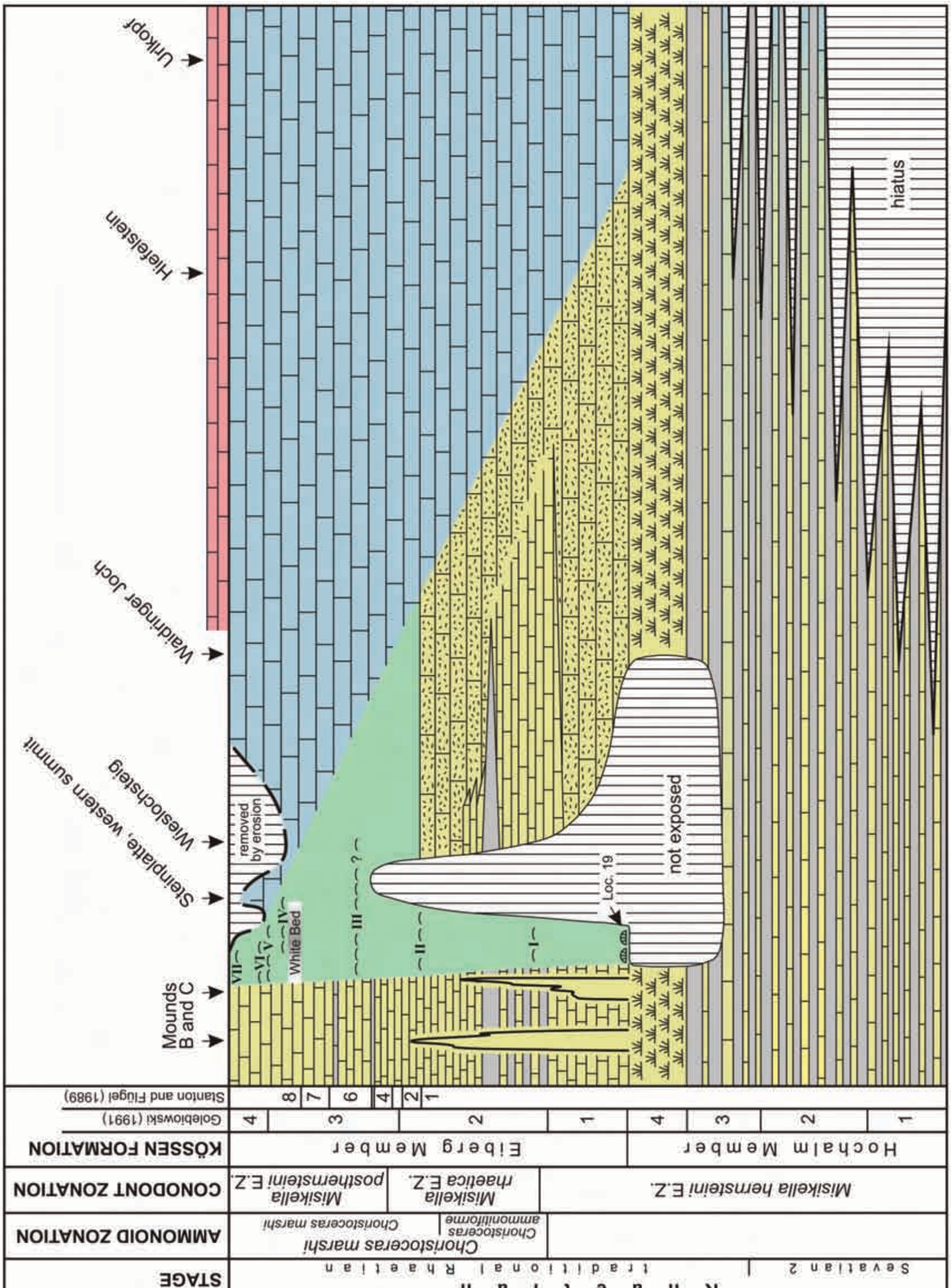
and Flügel (1989), Golebiowski (1991, and unpublished data) and author's own observations



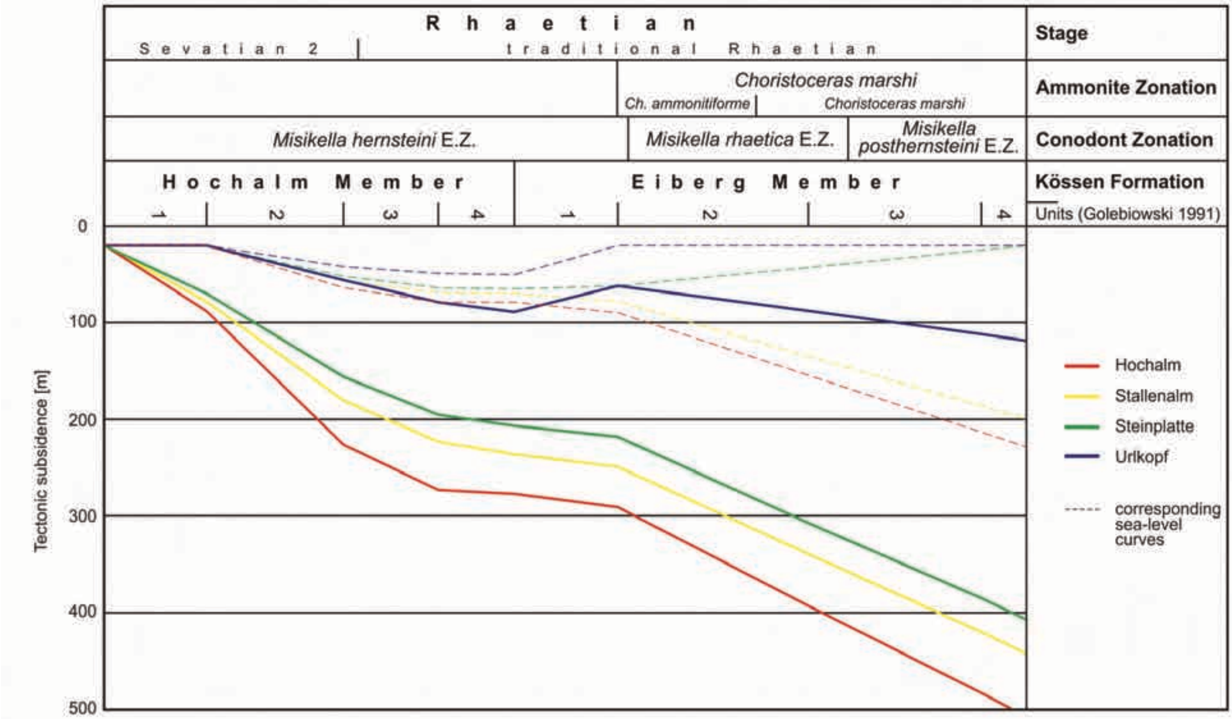
Text-fig. 6. End-Rhaetian facies model of the Steinplatte complex. Fischer's Coral Garden is projected into the assumed stratigraphic position of section C. For legend see Text-fig. 5

evolution of a depocentre by suppression of carbonate production. Coevally, a deepening trend is also observed on the adjacent Dachstein Carbonate Platform, where a gradual transition from well-developed intertidal Lofer cycles to subtidal, thick-bedded coral limestones took place. A trend to increased subsidence was already present in Norian times and led to a maximum thickness of the Hauptdolomit of 2000 m where the Kössen Basin was subsequently established. However, high accumulation rates in the Kössen Basin contrasted with a strongly reduced accommodation potential at the margin of the Dachstein Carbonate Platform (e.g. Urlkopf, Hochkalter, Loferer Steinberge) (Text-fig. 2). The latter is characterized by low sedimentary thicknesses resulting from subsidence minima due to isostatic adjustment in that area. Farther to the east (Leoganger Steinberge, Steinernes Meer, Hochkönig) subsidence increased again, expressed by increasing thicknesses of Rhaetian strata (Text-fig. 2). In areas of rapid aggradational reef growth (e.g. Steinplatte, Hochkönig), tectonic subsidence was enhanced by sedimentary load. In the depositional interval of the Hochalm Member, the thickness was much greater in the Kössen Basin (> 160 m) than on the nearby carbonate platform, where it was only 25 m (Text-fig. 9A). The sedimentary budget of the Kössen Basin in this interval consisted of about 25% shallow-water carbonates, a percentage progressively reduced at the expense of shaly and marly sediments as the basin filled. This means that shallow-water carbonate productivity was even higher in the basinal area than on the platform. Increased subsidence created accommodation space in the basin by rising sea level, stimulating carbonate production to keep up, whereas coevally reduced subsidence on the platform caused accommodation minima and thus sediment starvation. In addition, there was a significant export of sediment from the platform to the basin (tempestites) at that time. On the other hand, the Kössen Basin became a sedimentary trap for the terrigenous input from the north which was then no longer able to reach the carbonate platform.. The sedimentary burden thus amplified the tectonic subsidence. The terrigenous input was, however, merely a supporting factor for the formation of the Kössen Basin and not the cause, as suggested by Hüssner *et al.* (1996) and Gawlick (2000).

Shallowing-upward cycles are developed in the Hochalm Member (Golebiowski 1991). They are interpreted as being caused by fault-related and thus stepped tectonic subsidence rather than by eustatic sea-level fluctuations (Satterley 1996). Carbonate productivity should have been able to keep up with any low-amplitude glacio-eustatic sea-level rises in the ice-free Late Triassic. The repeated abrupt change from shallow-water coated grainstones to shale indicates either a sudden stop in carbonate production, a surge in the supply of fine-grained terrigenous sediment, or a sudden deepening event accompanied by sediment starvation (inactive shallow-water carbonate factory, hardgrounds!). Satterley (1996) suggested a stepped (because fault-controlled) rather than constant subsidence which led to a sequence of tectonic deepening events with each involving only a few metres increase in water depth. This is enough to interrupt shallow subtidal carbonate production but not enough for drowning. In the following interval of tectonic quiescence, carbonate production recovered and kept up with sea level again. Significantly different cycle thicknesses also argue for such a non-periodic influence. At the end of deposition of the Hochalm Member (Unit 3; Text-fig. 7) in the mid-Rhaetian, carbonate production finally failed to keep up with rising sea-



Text-fig. 7. Chronostratigraphic cross-section of Rhaetian intrashelf-basin-to-platform-margin transition in the Steinplatte–Urlkopf area. Based on Golebiowski (1991 and unpublished data), Stanton and Flügel (1989) and author's own observations. For legend see Text-fig. 5. E.Z. = extinction zone. For the construction of the Rhaetian time scale see chapter 'Chronostratigraphy And Rhaetian Time Scale'. Age of the Triassic-Jurassic boundary was taken from Pálfy (2008)



Text-fig. 8. Rhaetian subsidence curves of sections in the Kössen Basin and Steinplatte area

level and a maximum transgressive incursion of the Kössen Beds onto the Dachstein Carbonate Platform took place (Kössen event). At the same time, on the Tethys-facing side of the platform at Hochkönig, thin red sediment layers were intercalated in the slope of the reef limestone, indicating a slight spill-over of basal Zlambach Beds from the Hallstatt Basin onto the platform (Krystyn 1980; Satterley 1996). It was thus a transgression of great regional extent. At this time, the Dachstein Carbonate Platform was reduced to about half of its former size, barely escaping the drowning.

SPATIAL AND TEMPORAL EVOLUTION OF THE DACHSTEIN-CARBONATE-PLATFORM-TO-KÖSSEN-BASIN-TRANSITION IN THE STEINPLATTE AREA

Palaeogeographically, the Steinplatte complex is situated at the southern margin of the Kössen Basin and is intrinsically tied to the evolution of the basin. However, the sedimentary succession of the Steinplatte shows an inverse development, i.e. the rapid evolution of a thick carbonate complex which develops into a steep-sloping margin of the Dachstein Carbonate Platform. The transition from this platform into the Kössen Basin is perfectly exposed in the western cliff of the Steinplatte, and along the southern cliffs of the Sonnwand to the Urlkopf (Text-fig. 1), over a distance of 9 km. In the following explanations, the spatial and temporal development of this platform-to-basin-transition is simplistically subdivided into six stages (Text-fig. 9A, B):

Stage 1 (Hochalm Member, Unit 4)

Following the mid-Rhaetian Kössen event, the transition of the Dachstein Carbonate Platform to the Kössen Basin at the time of deposition of the "Hauptlithodendronkalk" was characterized by a smoothly inclined (< 0.5°), NW-dipping *homoclinal ramp*.

Stage 2 (Eiberg Member, uppermost part of unit 2)

An initial mound complex (loc. 19 in Stanton and Flügel 1989 and Text-fig. 3), built of calcisponge boundstones, developed coevally with some isolated mounds (B and C) in the Steinplatte area, several kilometres distant from the margin of the Dachstein Carbonate Platform. Initiation and rapid aggradational growth of this 'mound facies' (Stanton and Flügel 1989) was obviously determined by a perfect interaction of the following factors: 1) Growth at a site where the terrigenous input of the Kössen Beds was lowered so far that it no longer hindered carbonate production.

2) Carbonate production was able to keep up with rapid subsidence-caused sea-level rise. 3) Once established, the exposed position of the initial 'mound facies' offered a preferred site for filter-feeding organisms such as echinoderms, bivalves, sponges and corals because of better oxygenation and food supply, an effect that further enhanced vigorous mound growth. Rapid aggradational growth led to the formation of an asymmetrical buildup with a steep northwestern (25°) and flat southeastern slope. In the slight depression between the newly established buildup and the carbonate platform margin, a so-called "Riffdetritus-Schlammfazies" (Golebiowski 1991) was deposited. These deposits are characterized by a mixture of deeper subtidal sediments (peloidal, bioclastic packstones corresponding to the coeval Kössen Beds), interspersed with mound-derived detritus. Coevally, shallow-water platform carbonates of Dachstein Limestone facies (coated bioclastic grainstones with calcareous algae and coral patch reefs) were re-established in the Urlkopf area, corresponding to those present prior to the Kössen event incursion. The Dachstein Carbonate Platform thus showed a strongly prograding tendency in contrast to the detached initial mound phase, which was characterized by aggradation and slight retrogradation.

Stage 3 (Eiberg Member, upper part of unit 3)

Rapid aggradational and retrogradational growth of the 'mound facies' continued and the slight depression behind the former topographic high became filled by retrograding 'mound facies' from the west and prograding Dachstein Limestone from the east. Hence, a new platform margin was established at the Steinplatte. In cliff-section C (Text-figs 3–5), numerous calcareous algae (solenoporans) appeared for the first time (Stanton and Flügel 1989), indicating that the 'mound facies' has reached the euphotic zone and changed growth strategy from keep-up to catch-up. Relative sea-level fall at this time was probably due to decreasing subsidence. At the same time, the situation in the Kössen Basin had gradually changed to deep subtidal conditions (water depths of about 130 m) with low sedimentation rates.

Stage 4 (Eiberg Member, upper part of unit 4)

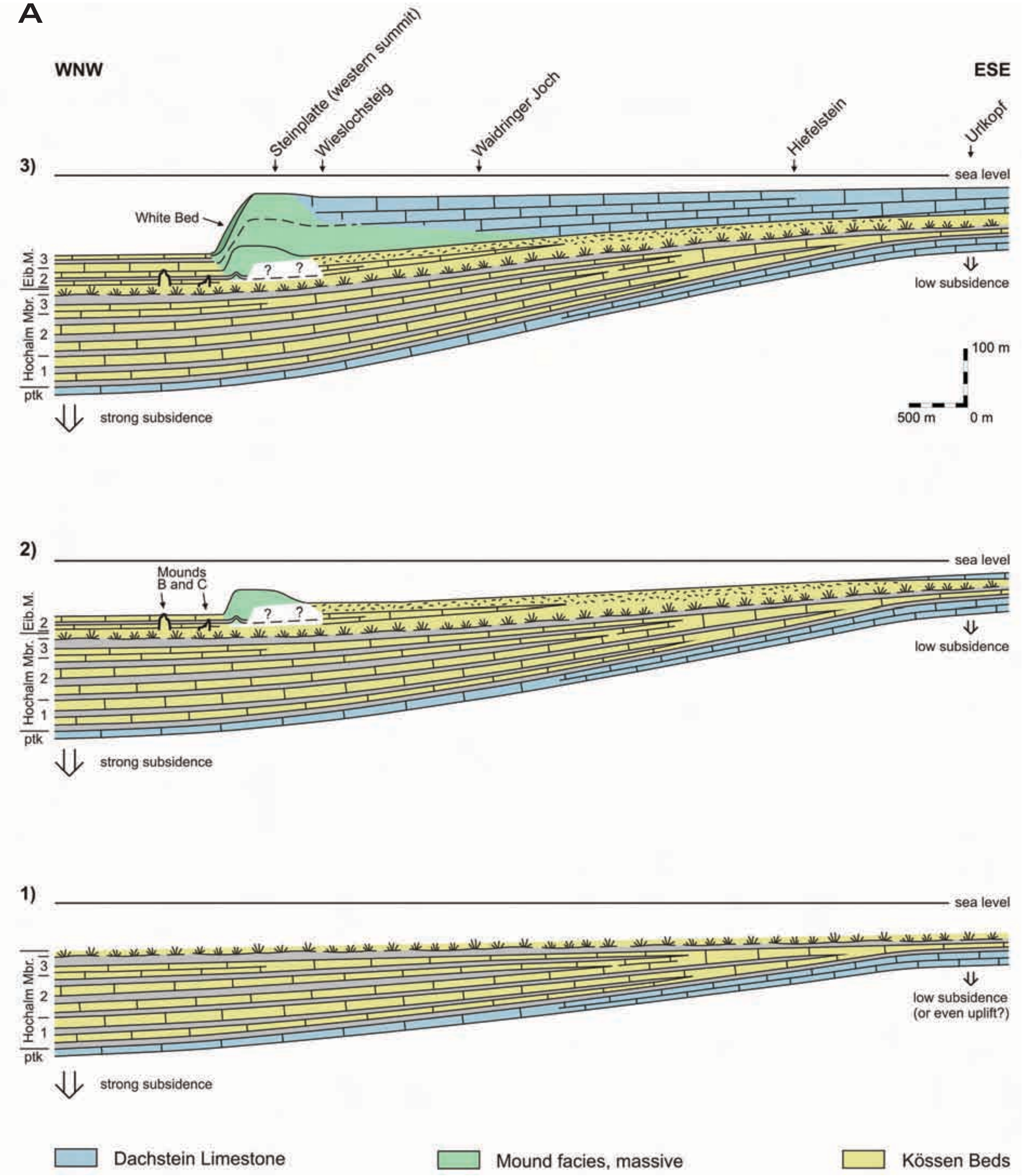
Continued rapid aggradational growth of the 'mound facies' resulted in the steepest (35°) development of the slope ("White Ramp") at the new platform margin. The prograding Dachstein Limestone had meanwhile reached the Steinplatte area where it now overlay the 'mound facies'. Coral limestones (Fischer's Coral Garden) were deposited but their limited extent (about 1500 m^2, see Text-fig. 4) as well as their supposed allochthonous nature (Stanton and Flügel 1989), do not support a *rimmed-reef margin* of the Dachstein Carbonate Platform at this time. This cannot, however, be proven with reasonable certainty because the front of the Dachstein Carbonate Platform at the Steinplatte complex has been eroded (Text-fig. 9B).

Stage 5 (Eiberg Member, uppermost part of unit 4)

Deposition took place of the capping beds in the lower part of the northern slope and of Dachstein Limestone in the summit area and in the outcrop northeast of Plattenkogel (Text-fig. 4). The Steinplatte complex reached its highest elevation (ca 180 m) above the adjacent basin. Interestingly, throughout the entire Rhaetian, the adjacent Kössen Basin had received no significant shedding from the steep slope of the Steinplatte complex. At Plattenkogel Coral Garden (Text-figs 4, 5), the topmost part of the Dachstein Limestone ('capping beds' in Stanton and Flügel 1989) is directly overlain by lower Jurassic strata (Rakús 1993; Krystyn *et al.* 2005). There are three beds, immediately below this boundary, each 1–2 m thick and characterized by stacked exposure, truncation surfaces and karstification (Stanton and Flügel 1989). The two bedding surfaces separating beds 1 and 2 and beds 2 and 3 probably correlate with two unconformities in the Adnet reef in the Tropfbruch quarry (near Salzburg) immediately below the Triassic-Jurassic boundary. These unconformities are interpreted as karstification surfaces resulting from subaerial exposure caused by slight sea-level drops, each followed by renewed flooding and reef growth (Bernecker *et al.* 1999). It is not yet clear whether eustatic sea-level changes or regional tectonics (slight tectonic uplifts followed by isostatic drops) were responsible for these small-scale sea-level changes in the latest Rhaetian.

Stage 6 (Eiberg Member, Top of unit 4)

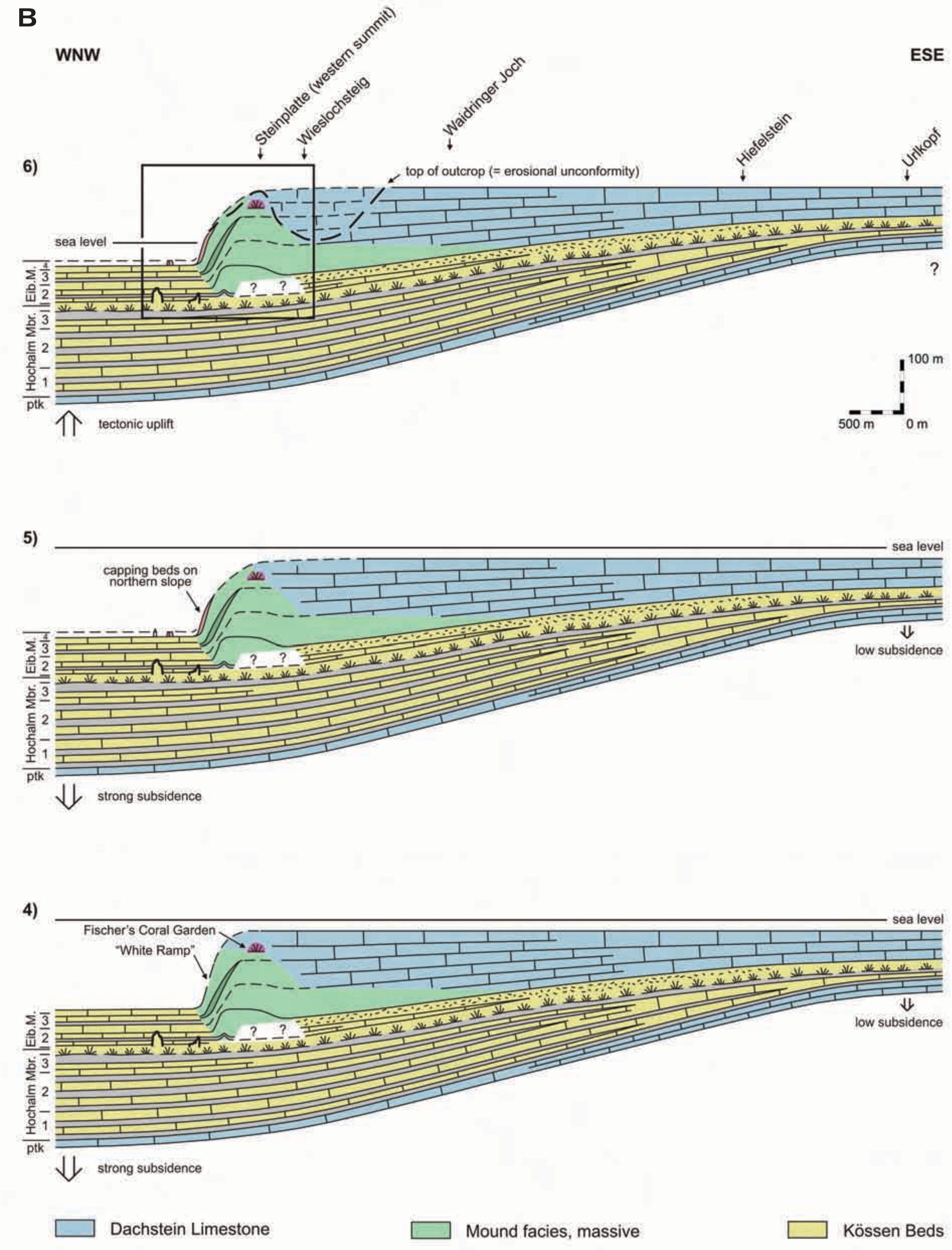
Immediately prior to the Triassic-Jurassic boundary, a tectonically-driven sea-level fall exposed the Steinplatte complex. This is indicated by a karst surface separating the Dachstein Limestone from overlying red lower Jurassic sediments (Adnet Formation). Karstification features like fissures, dissolution cavities and internal sediments are most common to a depth of about 40 m below the top of the Steinplatte complex, but can, however, be found to depths of 100 m. During subaerial exposure the flux of freshwater through the carbonate sediment displaced marine water and was able to penetrate many times deeper than the freshwater head. Therefore an emergence of maximum 40 m is assumed here. Subaerial exposure and a prominent karst surface at the Triassic-Jurassic boundary are a well-known phenomenon in the Northern Calcareous Alps (e.g. Mazzullo *et al.* 1990; Satterley *et al.* 1994; Bernecker *et al.* 1999). Although coeval with an eustatic sea-level lowstand (Hallam 1988), an abrupt sea-level



Text-fig. 9A, B. Six-stage development model of sedimentary geometry of Rhaetian carbonate-platform-to-basin-transect in the Steinplatte–Urlkopf area. Model is based on thickness of sedimentary sections in Text-fig. 5. Note the five times vertical exaggeration. For further legend see Text-fig. 5. Rectangle in stage 7 indicates area of Text-fig. 6

fall of up to 40 m (as in this study) during a greenhouse period can be better explained by a relatively sudden tectonic uplift.

Renewed flooding and subsequent drowning of the Steinplatte complex by tectonic subsidence occurred in the Early Jurassic (Hettangian and Sinemurian) when



deeper marine ammonite-bearing limestones (e.g. Adnet Formation) were deposited (Garrison and Fischer 1969). This drowning affected the whole Austroalpine carbonate shelf.

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