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Cretaceous thrusting in the western part of the Northern Calcareous Alps (Austria) – evidences from synorogenic sedimentation and structural data

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Abstract

The application of a simple ramp-flat model to Cretaceous nappe stacking in the Northern Calcareous Alps and its relation to synorogenic sedimentation allows to assess the large scale geometry of the nappe stack. Different synorogenic formations are related to specific positions within the ramp-flat model: Gosau and Branderfleck Fms. are found on the hangingwall anticlines of the Inntal and Lechtal nappes, respectively, Losenstein and Tannheim Fms. on the upper footwall flat of the Lechtal thrust and the Lech Fm. on the upper footwall flat of the Inntal thrust. The youngest sediments deposited on the upper footwall flat give an approximate age of thrusting, and therefore a sequence of thrusting can be deduced from the ages of synorogenic sediments. Generally, thrusting propagates from the S(E) to the N(W): the oldest thrust at the end of the Barremian is the Juvavic thrust, followed by the Lechtal thrust in the Aptian/Albian. The Inntal thrust in the Albian/Cenomanian is out-of-sequence, followed by thrusting of the Allgäu and Lechtal nappes onto the Cenoman-Randschuppe and Arosazone after the Turonian. Contemporaneous N-directed thrusting in the Northern Calcareous Alps and west-directed thrusting in the southern part (Achental thrust) and in the basement of the Northern Calcareous Alps call for a model of strain partitioning along deep reaching E-W-striking faults near the southern margin of the Northern Calcareous Alps.

1. Introduction

The Northern Calcareous Alps are a thin-skinned fold-and-thrust belt along the northern margin of the Austroalpine nappe pile (Fig. 1). The thrust architecture of the Eastern Alps is a result of polyphase thrusting (and normal faulting) in different directions (e. g. FROITZHEIM et al. 1994; EISBACHER and BRANDNER, 1996; NEUBAUER et al., 2000). Thrusting was accompanied by synorogenic sedimentation. In the Northern Calcareous Alps, a complete sedimentary succession from the Jurassic to the end of the Oligocene is present, covering the whole time of deformation. This paper reevaluates the timing of nappe stacking in the western Northern Calcareous Alps in the light of sedimentation ages and geometries of synorogenic deposits.

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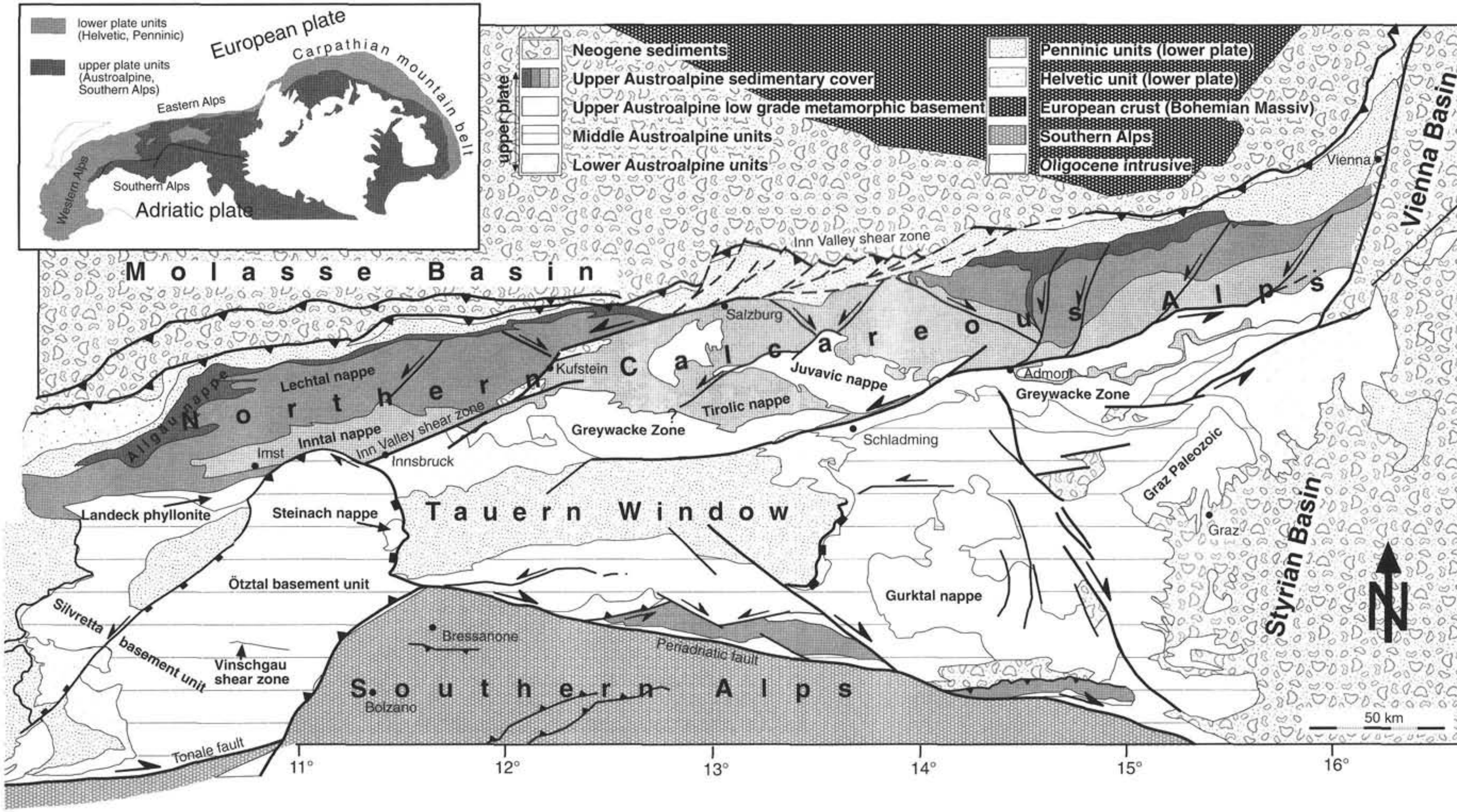

Fig. 1
Simplified geological overview of the Eastern Alps. Thick black lines delineate young (Oligocene and Miocene) faults.

The existence of far-travelled nappes in the Northern Calcareous Alps was subject of a long-lasting controversy (for a review, see TOLLMANN, 1986). Generally the nappe theory in the Northern Calcareous Alps was accepted since the late 1960s, however observations from some areas (Zugspitze, Wetterstein mountains; MILLER, 1963) are not fully consistent with a model of large distance NNW-directed thrusting (TOLLMANN, 1976). West of the Inn Valley, the model proposed for the Northern Calcareous Alps suggests a main nappe body ("Stammdecke" = Lechtal nappe; TOLLMANN, 1976). The Allgäu Nappe and the Cenoman-Randschuppe in the north form frontal imbricates, the Inntal nappe at the southern margin of the western Northern Calcareous Alps is thought to represent a trailing imbricate of the Lechtal nappe. East of the Inn Valley, the main nappe body is the Tirolic nappe, equivalent to the Inntal nappe. At its southern margin, the Tirolic nappe is still in contact with its basement, the Greywacke Zone. The Lower and Upper Juvavic units are two tectonically higher nappe units. The age of nappe stacking in the Northern Calcareous Alps was generally assumed to be the boundary between Early and Late Cretaceous (e. g. FLÜGEL et al., 1987; TOLLMANN, 1987; OBERHAUSER, 1995). In the last few years, another Upper Jurassic event of nappe stacking was described, related to the closure of the Hallstatt-Meliata ocean (GAWLICK et al., 1999).

Prior to deformation the Northern Calcareous Alps formed part of the southeastern passive continental margin of the Penninic Ocean. Sedimentation was characterized by deep marine calcareous and siliceous deposits. Synorogenic sedimentation developed continuously from Jurassic-Early Cretaceous passive margin deposits and is characterized by an increase in siliciclastic detritus and occurrence of ophiolithic detritus (Lech Fm., Losenstein Fm., Schrambach Fm., Roßfeld Fm., Lackbach Fm.). These deposits are often overlain by the thrust units. Upper Cretaceous to Paleogene synorogenic deposits (Branderfleck Fm., Gosau Group) overly the locally deeply eroded Triassic to Early Cretaceous rocks with an angular unconformity. The Gosau Group and Branderfleck Fm. are mixed carbonatic-siliciclastic successions starting with terrestrial and shallow marine deposits, respectively.

1.1 Relationship between synorogenic sediments and thrusting

A simple ramp-flat model illustrates what to expect during concurrent sedimentation and thrusting in a marine basinal

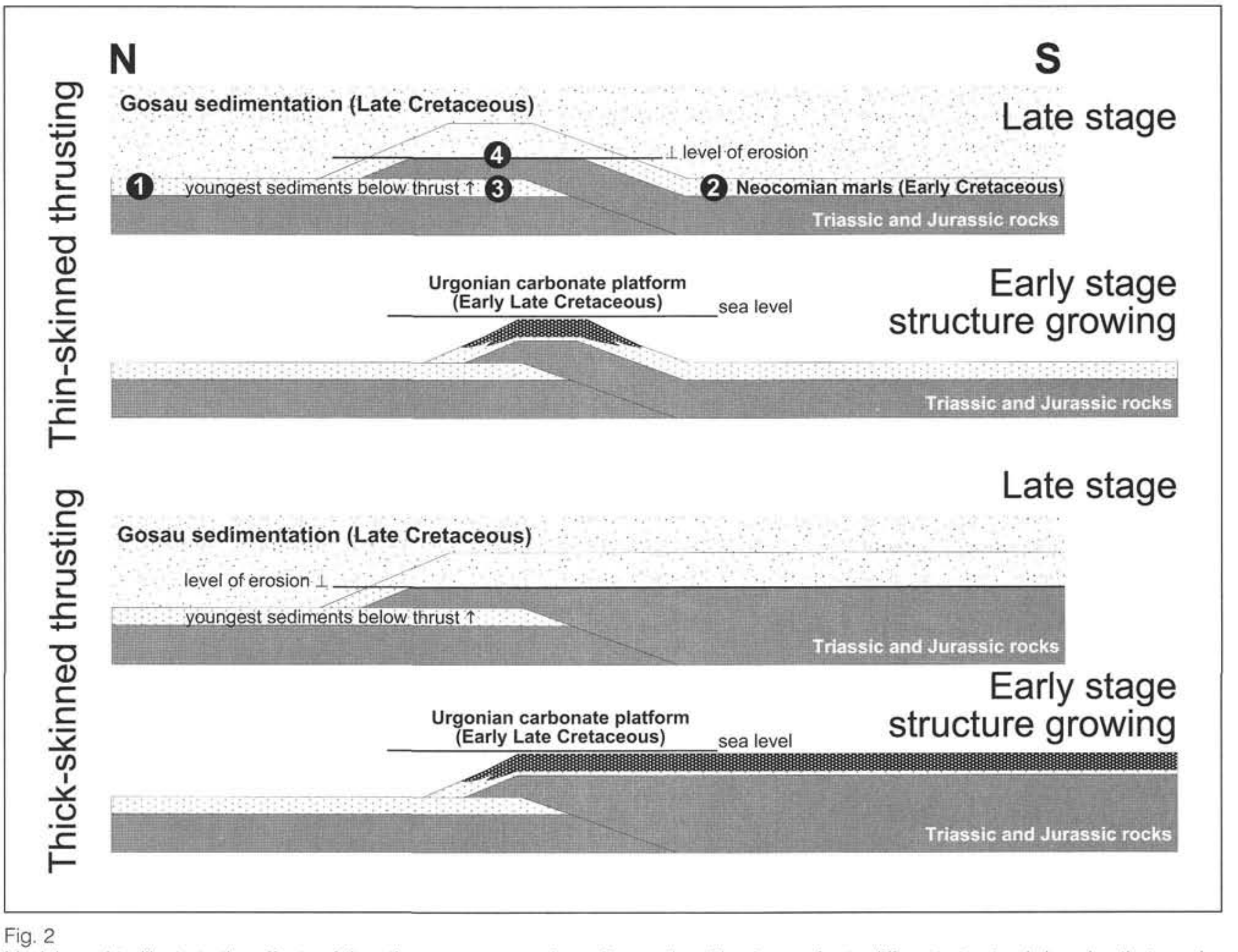

Fig. 2
Model used to illustrate the effects of thrusting on synorogenic sedimentation. Numbers refer to different structural domains that can be identified in the field (for explanation, see text). The early stage of thrust evolution shows a situation not preserved due to subsequent erosion. However, pebbles from lower Cretaceous carbonate platforms are frequently found in lower Cretaceous basinal deposits and Upper Cretaceous conglomerates (e. g. SCHLAGINTWEIT, 1991).

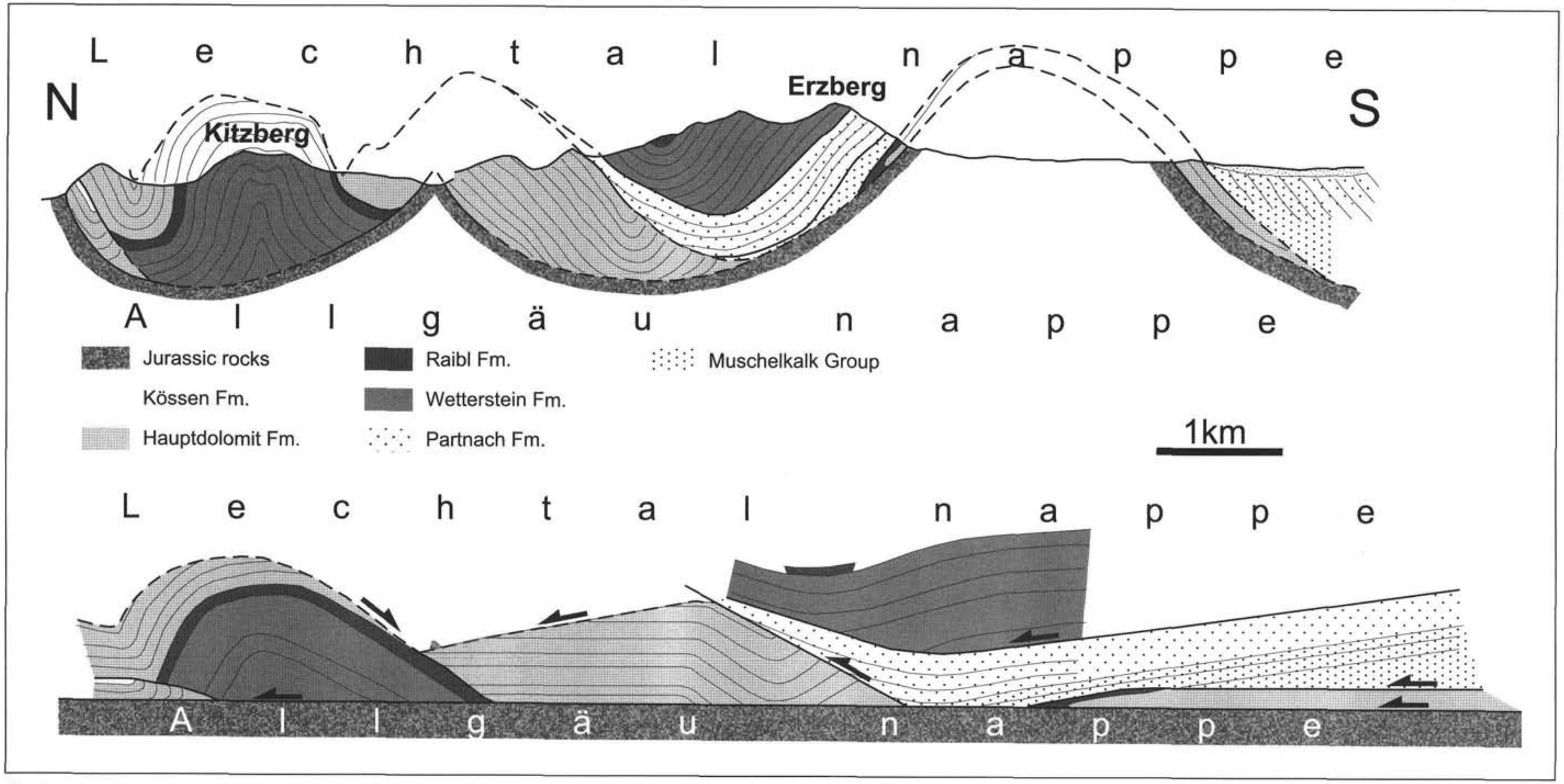

Fig. 3
N-S cross section from the frontal part of the Lechtal nappe, redrawn from MÜLLER-WOLFSKEIL and ZACHER (1984), illustrating the truncation of N-vergent folds by the Lechtal thrust (top). Unfolding of the thrust does not eliminate the folds (bottom). For location of cross section see Fig. 4

setting (Fig. 2). The frontal part of the thrust unit starts to climb up the ramp and travel across the flat. Therefore, the age of the youngest deposits below the thrust records the age of onset of thrusting. Growth of the hangingwall anticline leads to a relative sea level fall on top of the fold. As a consequence, shallow marine conditions lead to carbonate platform growth or at least to development of small biogenic buildups above the structure. Continued growth of the structure will lead to uplift above sea level and erosion of the carbonate platform or biogenic buildups and part of the ramp anticline.

Depending on the style of thrusting different types of platforms develop: Thin-skinned thrusting leads to the growth of small isolated platforms on top of the hangingwall anticlines, whereas thick-skinned thrusting leads to the development of large platforms. Growth of the platforms also depends on the rates of vertical growth of the structures, because rapid vertical growth leads to the development of very short-lived larger platforms, which soon are followed by growth of small attached buildups on the flanks of the growing structure going along with erosion in the central part of the structure. These buildups will shed small amounts of detritus into the adjacent basin.

Four different domains related to the growth structure can be distinguished:

1. Continuous sedimentation outlasting thrust activity is to be expected in the area not reached by the overthrust unit.
2. Due to minor deformation above the flat behind the ramp anticline, the succession of synorogenic deposits may show an internal (angular) unconformity.
3. Synorogenic deposits overlain by the thrust unit are to be expected below the hangingwall ramp and flat.
4. Significantly younger synorogenic deposits unconformably overlying (deeply) eroded preorogenic strata will be found on top of the ramp anticline.

2. Nappe geometries and age of synorogenic sediments in the western Northern Calcareous Alps

Kilometric to hectometric folds of the Northern Calcareous Alps are all oriented WSW-ENE, indicating a general translation of the nappe stack towards the NNW. This evidence is supported by the geometry of the nappe stack, with narrow nappe units extending over the whole length of the orogen. In detail, the situation is somewhat complex, because the shape of the nappes of the Northern Calcareous Alps is to a large extent controlled by facies boundaries of the Middle Triassic carbonate platforms and basins (e. g. EISBACHER and BRANDNER, 1996).

2.1 The Lechtal and Allgäu nappes

Lower Triassic evaporites form the basal detachment of the northern Lechtal nappe. In the south, a sedimentary contact to a metamorphic basement, the Landeck phyllonite is preserved (STINGL, 1984), which represents the northernmost part of the Silvretta basement complex (ROCKENSCHAUB, 1990). In the westernmost part of the Northern Calcareous Alps, the Lechtal thrust (= thrust of the Lechtal nappe over the Allgäu nappe) disappears in a tight anticline (MAY and EISBACHER, 1999) and Upper Triassic rocks form the base of the Lechtal Nappe. The oldest rocks of the Allgäu nappe are Upper Triassic in age. Tight to isoclinal ENE-WSW trending folds in the Lechtal nappe are truncated by the Lechtal thrust (TOLLMANN 1976, MÜLLER-WOLFSKEIL and ZACHER 1984; Fig. 3), and all folds are coaxial. In the footwall of the Lechtal thrust, small scale folds in incompetent Jurassic rocks are consistently N-verging and the axes are WSW-ENE-trending (KIRSCHNER, 1996). Therefore, compression throughout nappe stacking was oriented approximately NNW-SSE.

The Lechtal Nappe overlies Aptian/Albian deposits of the Allgäu nappe, which form the upper end of continuous Jurassic-Cretaceous sedimentation (Tannheim Fm.; Tannheim: ZACHER, 1966; GAUPP, 1982; 11 in Fig. 4; Krähenwand: GAUPP et al., 1997; 12 in Fig. 4). The northern part of the Lechtal Nappe itself is unconformably overlain by Upper Cretaceous deposits of Cenomanian to Santonian age (Branderfleck Fm.; Branderfleck: GAUPP, 1982; WINKLER, 1988; GAUPP et al., 1997; 13 in Fig. 4; Wetzstein-Laine and Kaltwasser-Laine: WINKLER, 1988; 14 in Fig. 4; Roßstein-Almen: WEIDICH, 1984; 16 in Fig. 4; Regau: WEIDICH, 1986; 17 in Fig. 4; N Vorderriß: SCHMIDT-THOMÉ, 1950; 15 in Fig. 4). Structures sealed by Cenomanian deposits on the Lechtal nappe are gentle folds with both approximately N-S and E-W-trending axes (e. g. CUSTODIS and SCHMIDT-THOMÉ, 1939) and roughly E-W-trending faults (RICHTER, 1926). Cenomanian rocks overlie Upper Triassic to Jurassic rocks with an angular unconformity. The contact of Cenomanian to older rocks is characterized by red infiltration of joints below the unconformity (?karstification). The surfaces of the older rock and of larger pebbles above the contact are bored by organisms, and occasionally overgrown by oysters (GAUPP, 1982). Obviously, a rocky shore was established after a period of erosion. Upsection, the succession rapidly passes into deep marine marls intercalated with turbidites and coarse matrix supported breccias ("Blockbrekzien"; l. c.). In more southerly areas (Fig. 4), continuous sedimentation on the Lechtal nappe reaches to the Albian/Cenomanian (Lech Fm. or Lechtaler Kreideschiefer; section Appenzell: WINKLER, 1988, VON EYNATTEN, 1996; section Holzgau: WINKLER, 1988; section Grießbachalm: LEISS, 1992).

GAUPP (1982) argued that the frontal Lechtal nappe (Falkensteinzug) had its present day position on top of the Allgäu nappe at the beginning of the Cenomanian, because characteristic siliceous carbonates of Liassic age of the northern part of the nappe are redeposited into the Cenomanian synorogenic sediments of the "Cenomanrandschuppe", the frontal part of the Allgäu nappe.

In the model outlined above (Fig. 2), the northern part of the Lechtal nappe would correspond to a hangingwall anticline with erosion and deformation followed by terrestrial, shallow to deep marine sedimentation (domain 4). Domain 1 with continuous concordant sedimentation is preserved in the Cenomanrandschuppe, where the sedimentary successions reach up into the Turonian (GAUPP, 1982). Domain 3 is represented by the Aptian/Albian deposits of the Allgäu nappe overlain by the Lechtal nappe. Domain 2 is found on the southern part of the Lechtal nappe, where continuous sedimentation reaches into the Albian/Cenomanian. Sedimentation can be interpreted to be concurrent with upramp-

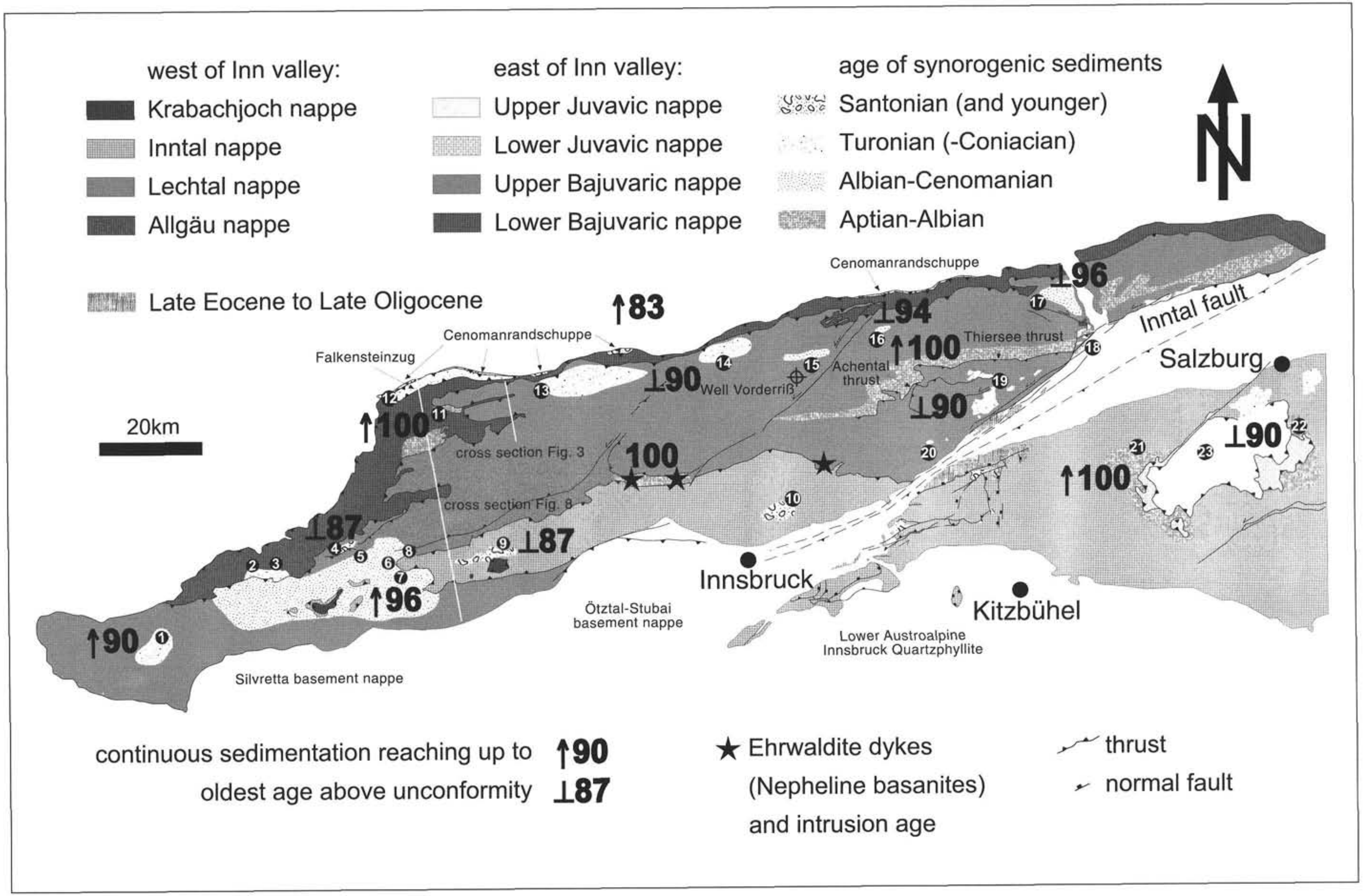

Fig. 4
Synorogenic deposits in the western part of the Northern Calcareous Alps. Numbers refer to locations used in text. The Oligocene Inntal fault is restored assuming major thrusting and sinistral offset in the range of 40 km (ORTNER and STINGL, 2001).

ing of the Lechtal nappe onto the Allgäu nappe at the end of the Albian. The southern end of the Allgäu nappe below the Lechtal nappe after Albian thrustung should have been somewhere below the northern end of the continuous sedimentation up to the Albian/Cenomanian and the southern end of the Upper Cretaceous transgression onto older rocks, along a line connecting the Hohe Licht Gosau (4 in Fig. 4) and the northern margin of the Inntal nappe.

The Lechtal nappe has been substantially transported over the Allgäu nappe to the NNW, as seen in the well Vorderriss, where the Allgäu nappe was penetrated about 12 km south of the northern margin of the Lechtal nappe (BACHMANN and MÜLLER, 1981). Using a balanced cross section, EISBACHER et al. (1990) estimated 28 km of northward thrusting over the Allgäu nappe. This is in accordance with the results from the analysis of synorogenic deposits.

2.2 The Inntal Nappe

The Inntal Nappe in the western part of the Northern Calcareous Alps has a sedimentary succession starting in the Permoscythian and reaching up to the Upper Triassic. Permian to Lower Triassic rocks are only present in the eastern and central parts of the Inntal Unit (Fig. 5). Towards the west, Middle Triassic rocks form the base of the Inntal nappe, and in the westernmost part, Upper Triassic rocks are the lowermost unit. This large scale wedge geometry of the Inntal Nappe in E-W direction follows the primary geometry of the Middle Triassic Wetterstein limestone carbonate platform, which interfingers with marly basinal deposits towards the west, going along with a reduction in thickness of the carbonate platform (NIEDERBACHER, 1982; Fig. 5). The Inntal thrust (= the thrust sparating the Inntal and Lechtal nappes) follows the base of the lowermost km-thick competent rock unit and climbs up to the base of the Hauptdolomit Fm. where the Wetterstein limestone carbonate platform disappears (EISBACHER and BRANDNER, 1996). Therefore, the westernmost part of the Inntal nappe is built exclusively by Upper Triassic dolomites (Hauptdolomit Fm.). An interpretation of this geometry in terms of west-directed thrusting is not likely because of the extremely flat ramp required at the base of the Middle Triassic carbonate platform (~2.5°) and the resulting extremely thin nappe body in relation to its great length in E-W direction.

In the westernmost part of the Inntal nappe, Upper Triassic dolomites overlie synorogenic deposits of Late Albian/Cenomanian age (Lech Fm. or Lechtaler Kreideschiefer; section Appenzell: WINKLER 1988, VON EYNATTEN 1996, 7 in Fig. 4; section Holzgau: WINKLER 1988, 5 in Fig. 4; section Grießbachalm: LEISS 1992, 8 in Fig. 4; Bischenalm: LEISS 1992; 6 in Fig. 4) on top of the Lechtal Nappe. The Inntal Nappe has no Jurassic sedi-

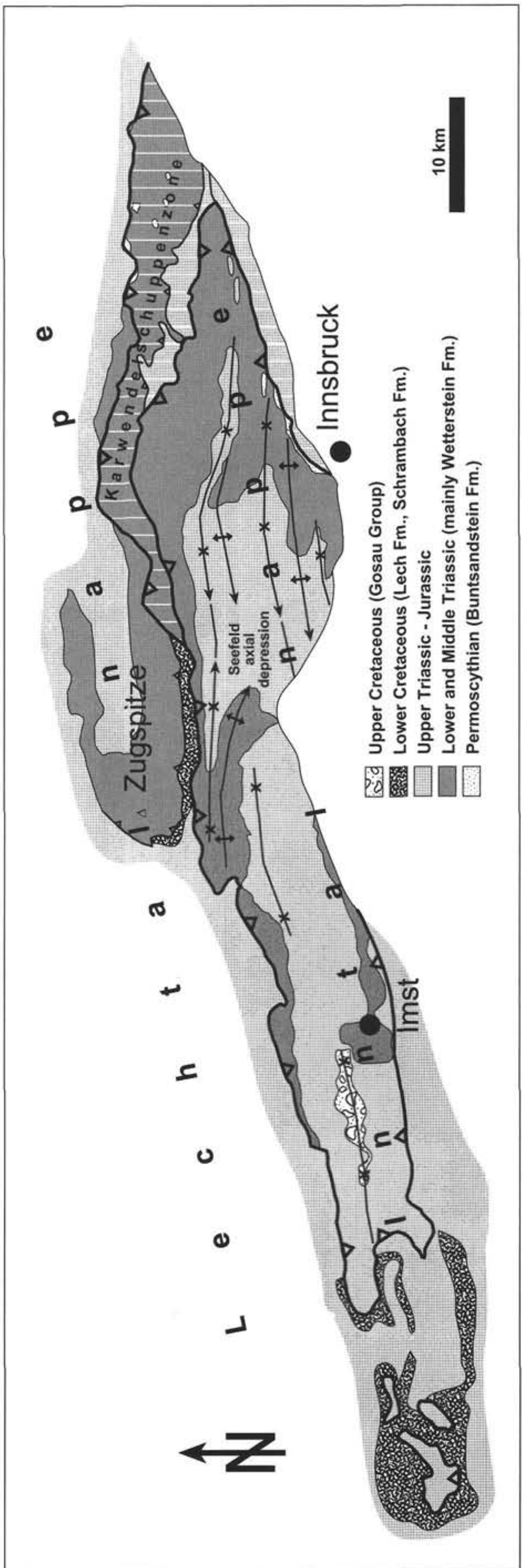

Fig. 5
Geological sketch showing the major outcrops of the Middle Triassic carbonate platform (Wetterstein Fm.) in the eastern part of the Inntal nappe and adjacent parts of the Lechtal nappe (Zugspitze). Towards the west, the carbonate platform thins and interfingers with basinal marls. The Inntal thrust follows this facies boundary. Vertical hatch indicates the Karwendelschuppenzone, belonging to the Inntal nappe.

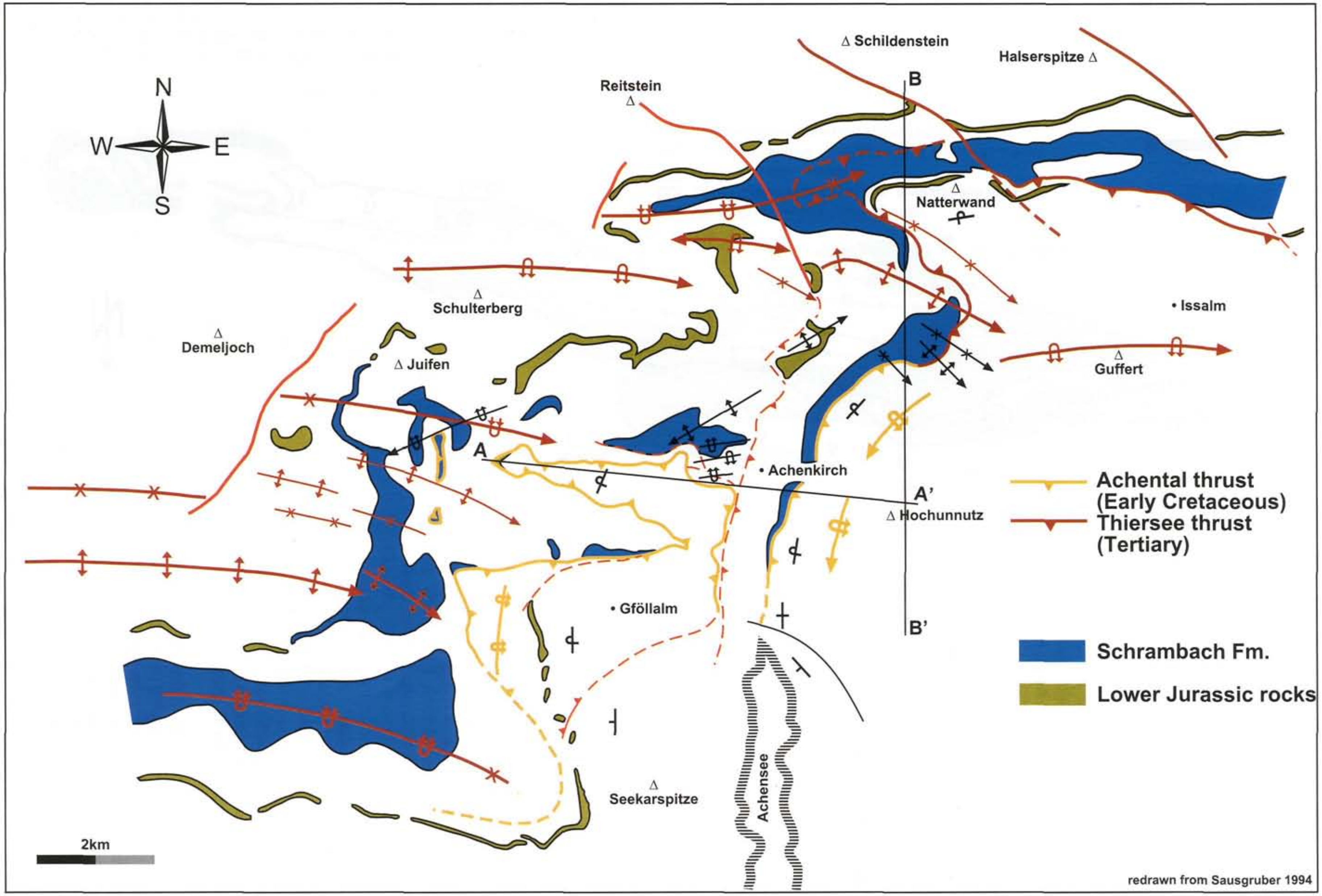

Fig. 6
Geological sketch of the Achensee area (redrawn and modified from SAUSGRUBER, 1994). A-A', B-B' … traces of cross sections in Fig. 7.

mentary succession, but was affected by erosion down to the Upper Triassic prior to transgression of Upper Cretaceous synorogenic deposits, the Gosau Group. Gosau deposits are preserved in the western part of the Inntal Nappe (Muttekopf: e. g. ORTNER 1994, 2001 and references therein; 9 in Fig. 4), and a very small outcrop in the eastern part (Großer Lafatscher: KROIS and STINGL 1994, 10 in Fig. 4). In relation to NNW-directed thrusting, the westernmost part of the Inntal nappe area can be interpreted to overlie the upper footwall flat (domain 3 in model), because klippen of the Inntal Nappe overlie the Late Albian/Cenomanian deposits (Fig. 4). Domain 4 of the model is represented by the area where Gosau deposits overlie deeply eroded Upper Triassic rocks on the Inntal nappe.

West of the westernmost Inntal nappe klippen, continuous sedimentation on the Lechtal (Brandnertal [Rätikon], Lorüns [Lechtaler Alpen]: OBERHAUSER 1963; 1 in Fig. 4) and Allgäu nappes (Hochberg syncline: LEISS 1992; Mohnenfluh: GAUPP et al. 1997; 2 and 3 in Fig.4, respectively) reaches up to the Turonian. This region was not reached by Cenomanian thrusting of the Inntal Nappe.

Below the present day Inntal nappe margin, the top of the Albian/Cenomanian sedimentary sequence is locally formed by debris flows bringing shallow water debris into deep water deposits of Albian/Cenomanian age (Griesbachalm; LEISS 1992, 8 in Fig. 4). A possible source of the shallow water debris is the Inntal Nappe itself. During thrusting, littoral carbonates formed on the uplifting nappe and were redeposited into the neighbouring basinal areas. Subsequently, erosion completely removed these carbonates because of ongoing uplift due to thrusting.

2.2.1 Post Nappe-stacking movements

A detailed analysis of fold geometry in the area of the Muttekopf Gosau outcrop showed, that Gosau deposits seal dekametric gentle folds with N-S trending axes and dekametric and kilometric gentle to open folds with NE-SW trending axes (ORTNER 1994, 2001). Coeval with sedimentation between Coniacian and Maastrichtian, the direction of contraction changed from NW-SE to N-S (ORTNER 2001). The Muttekopf Gosau outcrop is preserved in the leading syncline of a syncline-anticline pair above a blind thrust, which breaks through to the surface towards the east (ORTNER 2001). Therefore, folding records minor west- and northwestward prior to Gosau sedimentation and major northwest- to northward contraction in the Inntal nappe contemporanous to Gosau sedimentation. The amount of northward thrusting is limited, because in the central part of the Inntal Nappe (in the Wetterstein and Mieming Mountains), the primary geometries of the Triassic Wetterstein limestone carbonate platform are still preserved and can be correlated across the nappe boundaries between Inntal and Lechtal nappes and the Karwendelschuppenzone (RÜFFER and BECHSTÄDT, 1995). MILLER (1963) estimated not more than a few km of northward thrusting of the Inntal nappe over the Lechtal nappe.

2.3 The Thiersee thrust

Regionally, a major E-W striking thrust fault (Thiersee thrust) cuts the western Northern Calcareous Alps between the Inn Valley and the Achensee area and superimposes steep to inverted Triassic to Jurassic rocks on Aptian/Albian rocks (Schrambach Fm.: HAGN, 1982; HARLOFF, 1989; Fig. 4, 6, 7). At the eastern end of the thrust near the Inn Valley, Turonian synorogenic deposits overlie both the hangingwall (Hechtsee Gosau: RISCH, 1985; 18 in Fig. 4) and the footwall (Gosau of Breitenau: RISCH, 1985; 18 in Fig. 4) of the thrust (Fig. 4). Further westwards, no Upper Cretaceous synorogenic deposits are preserved below the Thiersee thrust. The hangingwall of the thrust carries a synorogenic succession of Turonian and younger age (Gosau of Brandenberg: SANDERS 1997, SANDERS et al. 1997, Gosau of Maurach: SANDERS 1996; 19 and 20 in Fig. 4). If interpreted in the context of the model described in the introduction, the hangingwall of the Thiersee thrust belongs to domain 4. However, there are no klippen north of the Thiersee thrust, and the interpretation of the footwall of the thrust as domain 3 (upper flat of a ramp-flat system) is not possible (Fig. 7, B-B'), because the geometry rather resembles a ramp situation. The evidence from the northern Lechtal nappe (see above), the Hechtsee and Breitenau Gosau deposits suggests that the Lechtal nappe north and northeast of the Inntal nappe including hangingwall and footwall of the Thiersee thrust belongs to domain 4, as in all areas Upper Cretaceous synorogenic deposits unconformably overlie older rocks, recording the upramping of the Lechtal nappe onto the Allgäu nappe after the end of continuous sedimentation on the Lechtal nappe in the Aptian/Albian. The presence of Upper Cretaceous rocks in the footwall suggests a post-Gosau (Tertiary) age of the Thiersee thrust.

2.4 The Achental thrust

Detailed structural investigations were performed in the Achensee area (QUENSTEDT, 1933, 1951; FUCHS, 1944; SPENGLER, 1953, 1956; SPIELER and BRANDNER, 1989; CHANNELL et al. 1990, 1992; EISBACHER and BRANDNER, 1995, 1996; SAUSGRUBER, 1994; AUER, 2001). At the western end of the Thiersee thrust, the thrust turns south and runs into the Karwendel syncline west of the Achensee, where it disappears. The N-S striking part of the thrust is termed Achental thrust. A recumbent fold with middle Triassic limestones (Wetterstein Fm.) in the core covered by thinned Upper Triassic rocks (Raibl and Hauptdolomit Fms.; Unnutz fold) forms the hangingwall of the Achental thrust (Fig. 7, A-A'). West of the Achensee, klippen of overturned Upper Triassic and Jurassic rocks in the hangingwall of the Achental thrust ("Achentaler Schubmasse" sensu QUENSTEDT, 1933) prove that the Unnutz fold becomes nearly isoclinal in Upper Triassic and younger rocks. In E-W cross section the geometry of the structure can be interpreted as a progressive rollover fault propagation fold (Fig. 7, inset C; STORTI and SALVINI, 1996; on outcrop scale, these geometries are also known as hinge collapse structures in chevron folds). The growth of the structure involves development as a classic fold propagation fold (SUPPÉ and MEDWEDEFF, 1990), combined with strong layer-parallel shear leading to development of an isoclinal fold in the cover of the fold propagation fold. Horizontal shortening compensated in fault propagation folding and subsequent synclinal breakthrough thrusting (Fig. 7, inset C; SUPPÉ and MEDWEDEFF, 1990) is in the range of 5 km. Additional shortening leading to layer-parallel shear and isoclinal folding of the Upper Triassic cover of the fold amounts to 4 km.

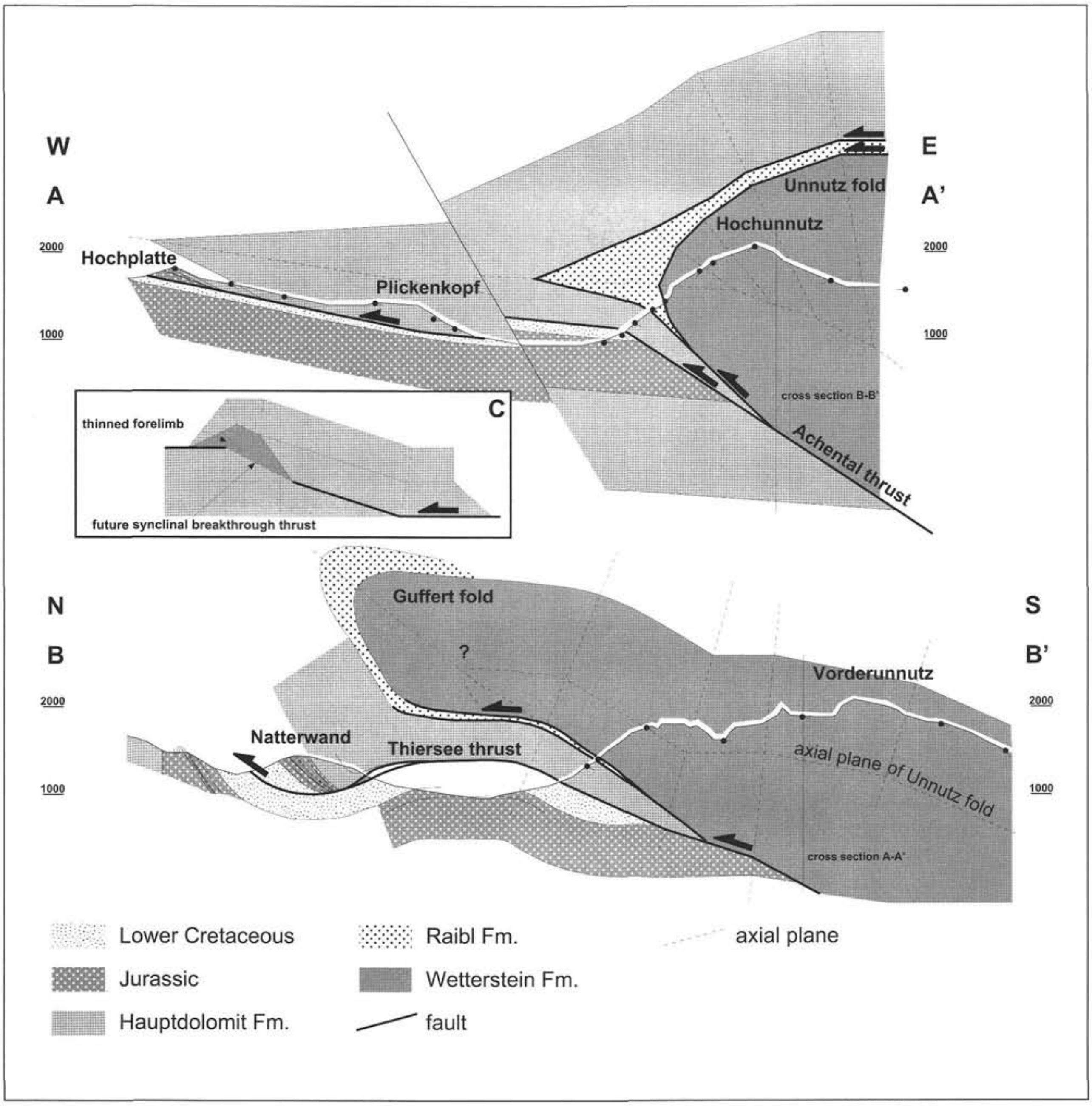

Fig. 7
Cross sections through the Achensee area. For traces of cross sections, see Fig. 6. On a large scale, the axial plane of the Unnutz fold is bent around younger fold axes.

A N-S cross section through the structure shows that the breakthrough thrust of the Unnutz fold is identical with the Thiersee thrust (Fig. 7, B-B'). From the construction of orthogonal intersecting cross sections it is inferred that the Thiersee thrust dips with approximately 23° to the south. Generally, the thrust plane is steeper than bedding in the footwall. This indicates a ramp situation. In its frontmost part, where the thrust plane is parallel to bedding in the footwall, the shear plane is folded around an anticline with SE-plunging axis, and, less evident but clearly to see in the N-S cross section, the axial plane of the Unnutz fold is also folded (Fig. 7, B-B'). To the south, the complete isoclinally folded Middle Triassic carbonate complex disappears below Upper Triassic rocks. The overturned thinned Upper Triassic cover of the Unnutz fold was further stretched during northdirected transport. The northernmost part of the hangingwall of the Thiersee thrust also formed a recumbent fold with Wetterstein limestone in its core (Guffert fold).

Four classes of interpretations have been put forward to explain the complex geometry of the area described above:

1. rotational movements. These interpretations proposed that the Unnutz fold originally was laterally continuous with the Guffert fold and was rotated into its N-S-trending position later by kinking of the anticline (AMPFERER, 1921, 1941) or rotation of fault-delimited blocks (SPENGLER, 1953, 1956; AUER, 2001).
2. torsional movements. NAGEL (1975) proposed that the hangingwall of the Thiersee thrust travelled farther to the

north than the hanginwall of a thrust in the Karwendel syncline during northdirected thrusting, leading to torsion in the hanginwall unit.

3. forced folding. According to EISBACHER and BRANDNER (1995, 1996), the Unnutz fold developed as a forced fold above an oblique ramp formed at a margin of the Wetterstein limestone carbonate platform and/or an inverted Jurassic normal fault during NW to NNW-directed contraction. However, if the thrust direction was NNW (350°), as documented by slickensides in the footwall (l. c.; SAUSGRUBER, 1994), a northward translation of 51 km is required for 9 km shortening in E-W direction, which is by far out of range of the observed offset of the Thiersee thrust (ca. 7 km; see Fig. 6).
4. polyphase thrusting. FUCHS (1944), SPIELER and BRANDNER (1989), CHANNELL et al. (1990, 1992) suggested that the complex geometry was the result of repeated heteroaxial thrusting.

In the following, a sequence of deformations leading to the observed situation is proposed, partly following the interpretation 4:

Initially, a fault propagation fold cored by Wetterstein limestone formed above a basal detachment horizon well below the Middle Triassic Wetterstein limestone platform during west-directed thrusting (Achental thrust; see Fig 7, A- A'). The fold was delimited to the north by a E-W striking transfer fault, now buried in the Thiersee syncline. The southern end of the structure is not known, because the fold disappears to the south below younger rocks. Folding was accompanied by bedding parallel west directed shear in the incompetent Raibl Fm., leading to the formation of a isoclinal recumbent fold west of the Unnutz (Fig. 7, A-A'). Reactivation of the Achental thrust coeval with activity of the Thiersee thrust cuts the already existing Unnutz fault propagation fold (synclinal breakthrough thrust; see above) and transports the recumbent anticline to the NNW. This phase of deformation is documented in the widespread brittle fault planes with calcite fibers in the Lower Cretaceous marls below the thrust plane (SAUSGRUBER, 1994; EISBACHER and BRANDNER, 1995) and is coeval with the formation of the Guffert fold. Fault planes at the Achental and Thiersee thrusts show a progressive change in thrust direction from NW to NE, also documented by metric to hectometric folds partly refolding the thrust and the axial plane of the Unnutz fold (Fig. 7).

The application of the model outlined in the introduction of the paper is not straightforward. The thrust plane below the frontal part of the Unnutz structure ist parallel to bedding in the footwall and is interpreted to represent the upper flat of the thrust (domain 3). The youngest deposits below the thrust have a Barremian age (NAGEL et al., 1976), and this is the maximum age for west-directed thrusting. East of the Achental thrust, younger synorogenic deposits unconformably overly deeply eroded Triassic rocks (Gosau Group of Maurach, Pletzachalm, Brandenberg and Hechtsee; domain 4 in Fig. 2). In the eastern part of the Thiersee syncline, synorogenic deposits of the Schrambach Fm. are unconformably overlain by the synorogenic Gosau Group (domain 2). The youngest part of the Schrambach Fm. preserved in the core of the Thiersee syncline are the "Thiersee Schichten", which are defined by the intercalations of carbonate mass flows in the marly succession of the Schrambach Fm. (HAGN, 1982; HARLOFF, 1989). These mass flows transport the debris of an Albian carbonate platform into the basin, indicating that south of the Thiersee syncline uplift led to platform development (WEIDICH, 1986; SCHLAGINTWEIT, 1991). In the local context, uplift is interpreted to be caused by west directed thrusting at the Achental thrust. To the north, the westward moving unit must have been delimited by a transform fault, which is now buried below the Thiersee thrust, but can be reconstructed using the contrasting facies developments of Jurassic rocks in the hanging- and footwall of the Thiersee thrust (e. g. NAGEL et al., 1976). Continued uplift during the Middle Cretaceous led to erosion of the Middle Cretaceous carbonate platform and the Jurassic succession in most parts of the hangingwall of the Achental thrust.

2.5 The Berchtesgaden nappe complex

The Lower and Upper Juvavic units of the Berchtesgaden nappe complex overlie Middle Cretaceous synorogenic deposits of Upper Barremian/Aptian (Unken: DARGA and WEIDICH, 1986; 21 in Fig. 4) or Hauterivian age (Roßfeld: DECKER et al. 1987; 22 in Fig. 4) of the Tirolic unit. The back of the Berchtesgaden nappe complex is eroded down to the Dachstein Fm. and unconformably overlain by synorogenic clastics of the Gosau Group of Turonian age (RISCH, 1988; 23 in Fig. 4). This means that the northwesternmost part of the Juvavic nappe complex reached its present day position at the end of the Barremian.

3. Discussion

In the western Northern Calcareous Alps, thrusting started in the Aptian/Albian by imbrication of the Lechtal nappe onto the Allgäu nappe. However, thrusting of the Lechtal nappe over the Allgäu nappe postdated initial folding of the sedimentary succession, because the basal thrust of the Lechtal nappe truncates some of the folds (TOLLMANN 1976, MÜLLER-WOLFSKEIL and ZACHER 1984; Fig. 3). Therefore another thrust plane, possibly at the base of the Allgäu nappe, was active prior to activity of the Lechtal thrust. Thrusting of the Inntal nappe postdates thrusting of the Lechtal nappe. Hence the thrusts in the western Northern Calcareous Alps propagated from the front to more internal areas of the thrust belt and from bottom to top (breakback thrust sequence). Only thrusting of the Juvavic nappe complex in the central part of the Northern Calcareous Alps (Fig. 1) is slightly older. Accretion of South Penninic units (Arosa and Walsertal zones), which directly underlie the western Northern Calcareous Alps, took place after the Turonian, as sedimentation in the Arosa zone (OBERHAUSER, 1983) and Walsertal zone (WINKLER and BERNOULLI, 1986) lasted until that time. Therefore imbrication of the nappes of the Northern Calcareous Alps preceded accretion (and subduction) of Penninic units and presumably took place when the Northern Calcareous were still in contact with their basement. Independent evidence for this comes from volcanic dykes in the Western Northern Calcareous Alps of Aptian/Albian age (Ehrwaldite; TROMMSDORFF, 1990; Fig. 4) derived from melting in a subcrustal mantle, which show an subcontinental geochemical signature and therefore preclude a begin of subduction of the Penninic ocean before Aptian/Albian. Pre-Turonian NW-directed thrusting must have taken place in a

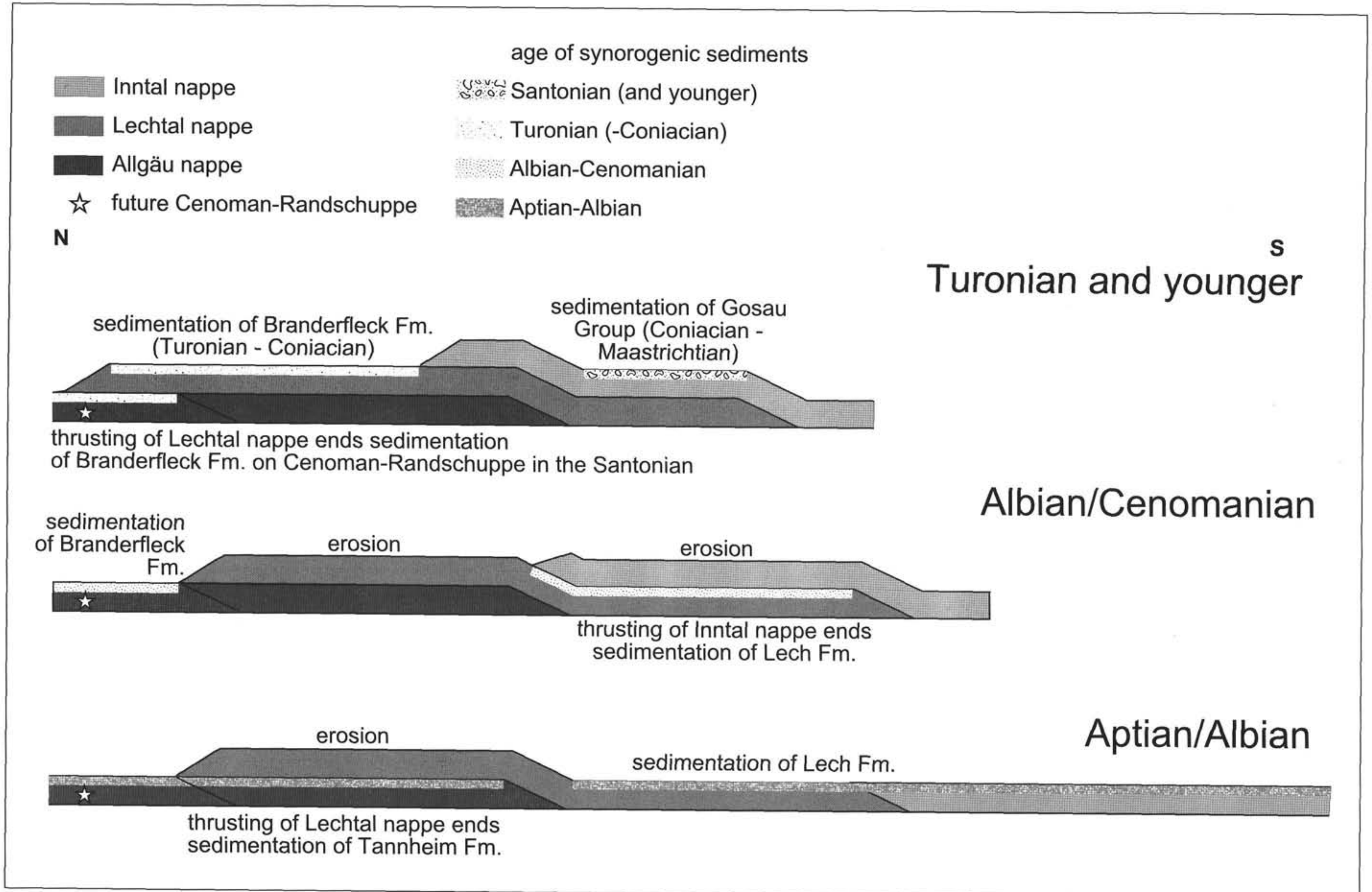

Fig. 8
Simplified model of thrusting in the western Northern Calcareous Alps, showing the sequence of nappe stacking and its relation to synorogenic sedimentation. Approximate position of cross section shown in Fig. 4.

foreland situation to another orogeny in the southeast, possibly related to the closure of the Meliata ocean (KOZUR and MOSTLER, 1992).

The sedimentary contacts of the Tirolic nappe, equivalent to the Inntal nappe, to the Greywacke zone, and of the Lechtal nappe sediments to the Silvretta crystalline (Fig. 1; STINGL, 1984; SPIESS, 1985; FRANK, 1987) indicate that the thin-skinned nappes in the Northern Calcareous Alps are the tips of thick skinned thrusts imbricating basement units. In the Early Cretaceous, the Northern Calcareous Alps were still in contact with their basement, also in their present day frontal parts. In the Greywacke Zone (RATSCHBACHER, 1986) and the Silvretta unit (SCHMID and HAAS, 1989; FROITZHEIM et al., 1997), Upper Cretaceous WNW-directed thrusting is well documented (e. g. Vinschgau shear zone; age data reviewed by FROITZHEIM et al., 1997). According to these data, WNW-directed thrusting in the Silvretta, Scarl and Lower Austroalpine basement units (west of the Ötztal unit) lasted from ca. 100 to 80 Ma (Late Albian to Early Campanian). This age of thrusting overlaps with the age of NW- to NNW-directed thrusting and shortening in the Northern Calcareous Alps, as demonstrated above. A possible explanation for this discrepancy is the assumption of transpressional deformation from the Middle Cretaceous onwards (e. g. RATSCHBACHER, 1986). The presence of deep reaching, presently approximately E-W-striking transform faults could be the reason for the partitioning of NW-directed shear into west-directed thrusting to the south and NNW-directed thrusting in the north. In this context, the westvergent Unnutz fold can possibly be interpreted to be a structure located south of a transform fault, which is now buried below the Thiersee thrust. The position of these hypothetical transform faults has not been described up to now. A result of strain partitioning would be that, irrespective of the actual orientation of contraction, apparent shortening will always be oriented parallel to the transform fault north of the fault, and orthogonal to the transform fault south of the fault. This is true for the western Northern Calcareous Alps, where the axes of large scale folds are constantly oriented WSW-ENE from the Aptian/Albian to the Oligocene (e. g. TOLLMANN, 1976; ORTNER and STINGL, 2001).

In N-S cross section, W-directed shortening in the basement units to the south leads to addition of material in the southern end of the plane of section, depending on the locus of thrust fronts. In this case, the critical taper model (DAVIS et al., 1983; PLATT, 1986) predicts forward propagation of thrusting in case of strong thickening and does not offer an explanation for the observed out-of-sequence thrusting of the Inntal nappe. An explanation could be the assumption that the incorporation of the broad Lechtal sheet into the orogenic wedge led to a drop in taper and consequently to thickening of the wedge behind the Lechtal thrust front to keep taper constant. Another controlling factor is the actual orientation of shortening, as a more westerly oriented far field maximum compressive stress will lead to an increase in west-directed shortening and decrease of northdirected shortening, and a more northerly directed far field maximum compressive stress will lead to an increase of north-directed shortening, leading to an increase of friction at the base of the wedge and, as a consequence, to internal shortening (= out-of-sequence thrusting) of the wedge.

4. Conclusions

Using a simple ramp flat model (Fig. 2), synorogenic formations of the western Northern Calcareous Alps can be divided into two groups. On the upper footwall flat of the Lechtal thrust, the end of continuous sedimentation, concordantly developing from Jurassic-Cretaceous passive margin deposits, marks the advent of the Lechtal thrust sheet in the Aptian/Albian (Fig. 8). The hangingwall anticline of the Lechtal sheet carries the Branderfleck and Gosau Fms., whose deposition was preceded by erosion. The upper footwall flat of the Inntal thrust is characterized by the Lech Fm. („Lechtaler Kreideschiefer"), the hangingwall anticline is again overlain by Gosau Fm. The upper footwall flat of the Juvavic nappes carries the Lackbach and Roßfeld Fms., Gosau Fm. overlies the back of the nappe. The youngest sedimentation age below the thrust gives the maximum age of thrusting, if it is clear from the large scale structure of the area that the position of the sample is in the footwall flat, and not in a ramp position.

Evidence from synorogenic sedimentation also allows to define the sequence of thrusting for the nappes of the western Northern Calcareous Alps. The thrust sequence is not simply forward propagating, but jumps from the back of the orogen (emplacement of Juvavic nappe complex at the end of the Baremmian) to the front (emplacement of Lechtal on Allgäu nappe in Aptian/Albian), and then to more internal areas (emplacement of Inntal on Lechtal nappe in Albian/Cenomanian). The reason for this unsystematic behavior of the nappes of the Northern Calcareous Alps may be the mode of thrusting in a regime of strain partitioning. Coeval W-directed thrusting in the basement units (southern part of the Northern Calcareous Alps, Greywacke zone, Silvretta and Ötztal basement units) and N-directed thrusting in the nappes of the Northern Calcareous Alps must be separated by a zone of dextral strike slip faulting, where strain partitioning can take place. Orientation of shortening in this model is mainly controlled by the faults, and not by the orientation of far field stress.

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