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A depth-extrapolated structural transect across the Northern Calcareous Alps of western Tirol

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ABSTRACT

In a first-order depth extrapolation for a NW-SE oriented transect across the Northern Calcareous Alps (NCA) in western Tirol we have used vaguely known sole-thrust and footwall-cutoff positions for the Allgäu, Lechtal and Inntal nappes. Line-balancing is based on structural style determined by detailed regional mapping and down-plunge projections. Shortening of the NCA by about 60% produced a thrust wedge with an inferred thickness increase from 3 km on the NW to 8 km on the SE. Shortening was achieved by thrust detachment on three décollement horizons, by synthetic nappe-internal branch thrusting, folding, out-of-syncline backthrusting and wedging. Stacking and deformation of the nappes which occurred essentially between 97 and 70 Ma was probably contemporaneous with dextrally-oblique emplacement of trailing basement wedges (Silvretta and Ötztal complexes) over the NCA and with the nappe-internal segmentation by cross faults.

ZUSAMMENFASSUNG

Zur Konstruktion eines extrapolierten NW-SE Tiefenprofils durch die Nördlichen Kalkalpen im westlichen Tirol wurden die angenähert bekannte Tiefenlage der Sohlüberschiebung sowie die Liegendabrisse der Allgäu-, Lechtal- und Inntaldecke als Rahmen benützt. Schichtlängenausgleich im Profil basiert auf dem durch Kartierung ermittelten Strukturstil und auf seiner Extrapolation in Richtung des Abtauchens. Einengung in den Kalkalpen um rund 60% erzeugte einen sedimentären Keil, dessen Mächtigkeit von 3 km im Nordwesten auf 8 km im Südosten zunimmt. Dabei kam es zur Abscherung an drei Décollement-Horizonten, zur Entwicklung interner Zweigüberschiebungen, zur Bildung von Falten bzw. Rücküberschiebungen aus dem Kern von Synklinalen und schliesslich zur Verkeilung. Die Stapelung und Deformation der Decken erfolgte im wesentlichen zwischen 97 Ma und 70 Ma und damit praktisch gleichzeitig mit der Hebung und der schräg-dextralen Platznahme der kristallinen Silvretta- und Ötztalkomplexe am Südrand der Kalkalpen sowie mit einer deckeninternen tektonischen Segmentierung entlang von Querverschiebungen.

Regional setting

The Northern Calcareous Alps (NCA) are the frontal sedimentary portion of the upper Austroalpine thrust wedge. In western Austria, southern Bavaria and easternmost Switzerland this wedge is seen to rest allochthonously either on a carpet of mélange which consists of lithologies derived from pre-orogenic Penninic to lower Austroalpine basement and sedimentary cover (Arosa Zone) or on Penninic syn-

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orogenic flysch (Rhenodanubian Flysch). The intensely deformed Penninic to lower Austroalpine substratum which originally was located north of the NCA rests in turn allochthonously on the folded European shelf strata preserved in the lower Penninic and Helvetic nappes and on the gently south-dipping European platform with its superimposed late orogenic clastic Molasse basin (Tollmann 1976, Frisch 1979, Trümpy 1980, Frank 1987, Laubscher 1988). The sole thrust of the NCA is well exposed along the western up-plunge termination of the NCA where late-orogenic uplift in the Penninic and Helvetic domains of eastern Switzerland initiated an easterly erosional retreat of the thrust trace. Above the sole thrust major fold structures in the NCA plunge to the NE and E; the sole thrust itself dips gently to the east. Some 100 km to the east of this region and 15 km south of the NCA frontal thrust (Fig. 1), the sole thrust has been intersected at a depth of about 6 km below sea level in the deep exploration well Vorderriss 1 (Bachmann & Müller 1981). It may drop deeper in a southerly direction towards the Inn valley; however, major changes in structural style and possible basement involvement preclude reliable geometric extrapolations into this area (for one possibility see Brandner 1980; for another Roeder 1989). South of the Inn valley the sole thrust emerges at the base of crystalline thrust sheets along the circumference of major tectonic windows (Lower Engadine and Tauern windows) eroded through Austroalpine crystalline basement.

The sedimentary strata of the NCA represent facies of the Tethyan platform and extended margin. They range in age from Permian to Early Cretaceous (Fig. 2) and are 3 to 4 km thick. They also contain two structurally dominant carbonate units (Fig. 2): (1) the middle Triassic Muschelkalk-Wetterstein interval, a calcareous to dolomitic platform-reef assemblage 600 to 1,500 m thick that is characterized by abrupt facies and thickness changes into a basinal shale unit, the Partnach Formation; (2) the upper Triassic Hauptdolomit Formation, an evenly bedded cyclic dolostone unit 1,000 to 1,500 m thick. There are also three potential decollement horizons: (1) below the Muschelkalk-Wetterstein-Partnach assemblage the basal Permotriassic evaporitic Haselgebirge, Buntsandstein and Reichenhall formations, (2) in the middle the shale-evaporite members of the Carnian Raibl Formation between the dominant Wetterstein and Hauptdolomit formations, and (3) several upper decollement levels within shales or thinly bedded calcareous strata of the varied platformal to basinal Jura-Cretaceous succession above the Hauptdolomit Formation.

In Tirol and Bavaria the NCA are made up of three thrust sheets or nappes which from bottom to top, i.e. from N to S, are the Allgäu, Lechtal, and Inntal nappes. Considerable thrust displacement can be inferred from stratigraphic juxtapositions, illite crystallinity jumps, and coal rank discontinuities along the thrust traces (Ampferer 1932, Tollmann 1976, Krumm 1984, Petschik 1989). In the western part of the NCA erosional retreat of the thrust fronts has produced a pattern of klippen and westward rising synclinal semi-klippen (Fig. 1), an outcrop pattern that is accentuated by a relief of about 1,500 m but which also attests to significant footwall-hangingwall interaction during progressive internal shortening of the nappe pile. All three nappes show NE- to E-trending folds cut by synthetic or antithetic branch thrusts and by arrays of high-angle cross faults (tear or transverse faults) with significant strike-slip displacement. The presence of multiple levels of potential decollements, abrupt facies changes and as yet poorly understood synsedimentary faults within the platform succession

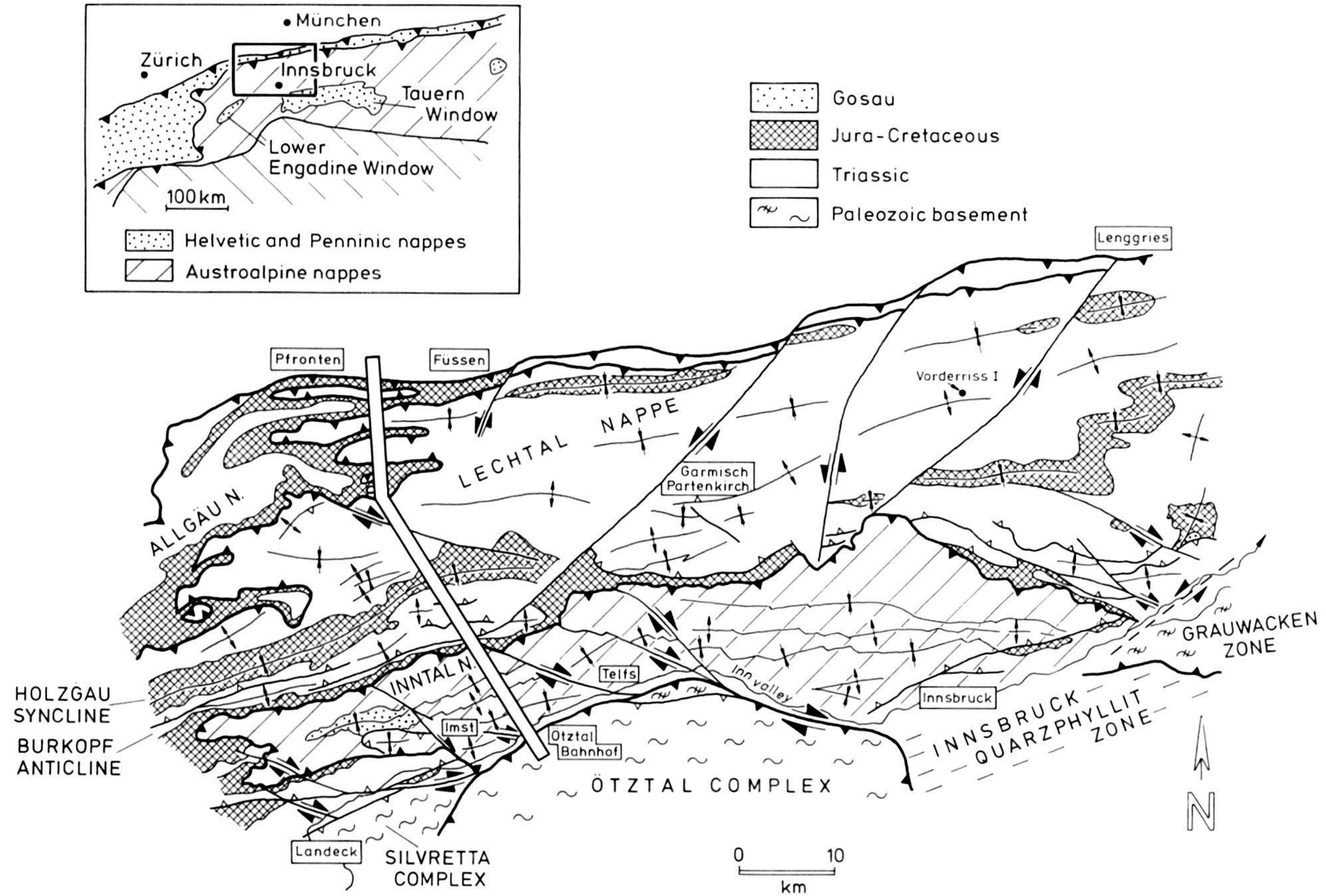

Fig. 1. Regional index map of the Allgäu, Lechtal, and Inntal nappe (oblique ruling) and the adjacent basement units of the Austroalpine edifice of Tirol. Location of the transect shown in Plate 1 is indicated by an open bar. Note the lobate pattern of semi-klippen in the westerly up-plunge direction of the nappes and the position of the Vorderriss I exploration well in which the Allgäu nappe was still encountered.

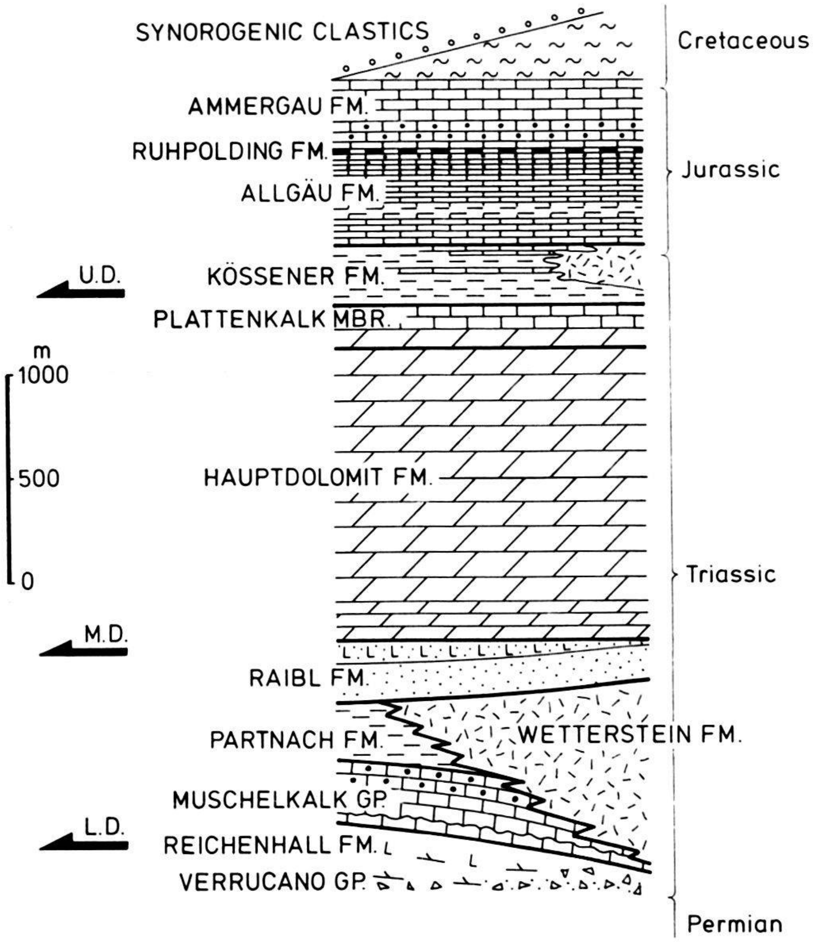

Fig. 2. Generalized stratigraphic column for the Northern Calcareous Alps of Tirol with the three decollement levels discussed in the text. "Verrucano" includes evaporitic-shaly Haselgebirge and sandy Buntsandstein.

have resulted in a complex superposition of in-sequence and out-of-sequence faults during progressive shortening.

Based on previous mapping by Ampferer (1914), Zacher (1966), Müller-Wolfskeil & Zacher (1984), Niederbacher (1982) and a very useful compilation by Tollmann (1976), we carried out field studies in all three nappes in order to derive a depth extrapolation from near-surface regional structures along a transect across the NCA between their frontal portion (Pfronten-Füssen) and the Inn valley (Ötztal-Bahnhof). The transect is oriented perpendicular to both the trend of major folds and to the strike of subsidiary thrust faults (Plate 1). In order to gain an understanding of the internal kinematics of the thrust wedge and to assure reasonable palinspastic patterns for the implied facies and thickness changes our work along the section was complimented by mapping up- and down-plunge from the section. In the absence of seismic or drill hole information we placed the NCA sole thrust at a depth somewhat less than, but compatible with, the 6 km intersection in the Vorderriss 1 well. One of our aims in this study was to appraise the significance of cross faults during the 3D-development of the NCA. The significance of transverse faults in the development of fold-thrust belts with low-strength decollement horizons has been emphasized by LAUBSCHER (1965, 1981) for the Jura Mountains and more recently (LAUBSCHER 1989) for the westernmost NCA. We will hint briefly at some of our conclusions concerning this aspect of NCA geology; its documentation is still in progress.

Northern Calcareous Alps and Austroalpine basement complexes

The NCA are bordered in the south by pre-Permotriassic basement units which from west to east are the Silvretta, Ötztal, Innsbruck Quarzphyllit, and Grauwacken Zone complexes (Fig. 1). The palinspastics of these complexes have been subject to major controversy (see FRANK 1987 and TOLLMANN 1987). We will take a possibly simplistic, but pragmatic view.

The *Silvretta complex* appears to be part of a trailing basement portion of the Lechtal nappe; however, considerable relative displacement can be assumed to have taken place between the Variscan metamorphics in the south and the sedimentary cover strata in the north (FRANK 1987, LAUBSCHER 1989). Detailed mapping along this zone between Imst and Landeck by POLINSKI (1989) has convinced us that although the strongly retrograded and sheared metamorphic basement is tectonically interleaved with very low-grade metamorphic redbeds of the basal Permotriassic cover, the redbeds themselves are overlain in stratigraphic continuity by anchimetamorphic lower Triassic shale-carbonate units which seem to be part of the Lechtal nappe. However, a facies change from relatively thick middle Triassic carbonate units in the north to thinner dolomitic and shaly units in the south indicates that structural complications in the southernmost Lechtal nappe along the Inn valley are probably partly inherited from synsedimentary fault structures that had developed during the subsidence stage of the NCA platform. Retrograde foliations in phyllonitic basement slivers and cleavage in the Permotriassic redbeds dip to the SSE; a subhorizontal to gently ESE-plunging stretching lineation and microkinematic indicators in both rock types suggest that tectonothermal retrogression of the basement and a presumably contemporaneous prograde deformation of the redbeds occurred during Alpine oblique dextral shear. East-trending kink folds which further deformed both phyllonitic foliations and cleavages indicate that later N-S shortening of the area occurred at a higher crustal level.

In the region south of Imst the *Ötztal complex* rests in thrust contact on top of retrograde rocks of the easternmost Silvretta complex; along its entire northern fringe the Ötztal complex is also characterized by zones of phyllite and phyllonitic gneisses juxtaposed against each other along brittle shear zones. Chlorite-coated striations in the shear zones indicate convergent dextral shear (LINZER 1989). Towards the S and SE the metamorphic Variscan rocks of the Ötztal complex display an Alpine prograde metamorphic overprint which not only affects the high-grade Variscan basement but also the post-Variscan mafic dikes and a relatively thin Mesozoic cover (PURTSCHELLER 1978, PURTSCHELLER & RAMMELMAIR 1982, HOINKES et al. 1982). Systematic southwestward increase of metamorphic grade and the presence of crystalline klippen on top of Mesozoic cover rocks suggest the former existence of another major basement thrust sheet above the Ötztal complex. Cooling of the Alpine metamorphic mineral assemblages within the Ötztal complex has been dated at around 90 to 70 Ma (THÖNI

1981, 1988) and seems to have been related to WNW-directed thrust emplacement of the Ötztal complex onto the Austroalpine Languard-Campo-Sesvenna complex on the south (Schmid & Haas 1989, Thöni 1989) and onto the Silvretta complex north of the Lower Engadine window. Relationships between the sedimentary Inntal nappe and the crystalline frontal Ötztal complex are obscured by thick Pleistocene drift along the Inn valley.

The *Innsbruck Quarzphyllit complex* consists of predominantly low-grade Paleozoic metamorphics that are generally considered to be part of a lower Austroalpine basement sliver situated between the NCA sole thrust and the Penninic units of the Tauern window (Tollmann 1976). In a section drawn recently by Roeder (1989, Fig. 7) the Innsbruck Quarzphyllit has been implied to represent the metamorphic basement of the Inntal nappe. Resting on the Innsbruck Quarzphyllit there are small klippen of gneissic rocks which are probably erosional remnants of the Ötztal complex.

The generally low-grade Paleozoic *Grauwacken Zone complex* is situated east of and above the Innsbruck Quarzphyllit; Permotriassic-Mesozoic strata of the eastern continuation of the Lechtal nappe rest in unconformable stratigraphic contact on the Grauwacken Zone.

Considering the regional relationships outlined briefly above we favour as a working hypothesis a regional model in which the Silvretta complex in the west and the Grauwacken Zone in the east are the trailing basement equivalents of the Lechtal nappe. By analogy the Ötztal complex in between is considered to be the trailing basement equivalent of the Inntal nappe. Basement emerged by displacement along major out-of-sequence faults located along and on trend with the Inn valley (e.g. Ötztal thrust). In our cross section we therefore assume that parts of the Silvretta and/or Grauwacken complexes with their sedimentary cover extend laterally beneath the out-of-sequence Ötztal thrust. We do not pretend, however, to have properly balanced or geometrically resolved this highly speculative portion of our section. In the following we discuss the major structures along the transect from south to north (Plate 1).

Inntal nappe

In terms of internal structural style the Inntal nappe consists of an eastern and a western part. In the eastern part massive to thick bedded Muschelkalk-Wetterstein assemblages dominate the structural pattern, whereas in the west bedded Hauptdolomit strata resting on Partnach shales dominate the internal structure of the thrust sheet. On the Inntal nappe strata younger than Hauptdolomit Formation were either not deposited or were eroded prior to the onset of major shortening. However, upper Cretaceous (Coniacian-Maastrichtian) synorogenic clastics of the Muttekopf-Gosau group rest unconformably on Hauptdolomit Formation in a major synclinal structure west of Imst.

The trace of the Inntal thrust begins in the Inn valley about 20 km east of Innsbruck (Fig. 2), swings northwesterly into the NCA, then cuts upsection from the Haselgebirge-Reichenhall lower decollement horizon into the Raibl middle decollement towards the west; the up-plunge termination of the Inntal nappe shows Hauptdolomit strata resting on Jura-Cretaceous units. Erosion of Inntal nappe above a late south-directed footwall thrust in the Lechtal nappe created a major east-trending thrust trace north of the Inn valley between Imst and Landeck (Fig. 1). Detailed mapping within the Inntal nappe has revealed numerous WNW- to NW-striking cross faults spaced at a distance between about 2 to 4 km. These cross faults offset dextrally the axial surfaces of ENE-trending folds by a few hundred to several thousand metres, but displacements in general tend to decrease towards the frontal thrust trace. This suggests that cross faults nucleated mainly along or below the trailing portion of the Inntal nappe. Only a few WNW-oriented cross faults extend directly from the Inntal nappe into the footwall area beyond the Inntal nappe. We infer that dextral movements along these cross faults occurred during emplacement and subsequent internal shortening of the Inntal nappe.

Along our line of section the Inntal nappe consists of a major south-verging anticline-thrust, possibly related to a subsurface wedge of crystalline basement, and a broad syncline to the north of it (Plate 1). On strike to the northeast and southwest of the section the thickness of the dominating Wetterstein Formation decreases dramatically and massive carbonates are replaced partly by Partnach shales; vergence of folds and/or structural style also change abruptly along the NW-striking cross faults of this area and it is possible that the facies changes themselves localized the development of cross faults. Field relationships suggest that cross faults developed after initial stages of folding and thrust propagation and that they propagated mainly within the Inntal nappe where they transferred thrust displacement; the latter seems to increase from east to west. Continued internal shortening was achieved by two converging footwall-wedges, one in the south and the other in the north; however, preexisting cross faults probably interferred with the lateral propagation of both hangingwall and footwall structures.

A depth extrapolation of the internal structural pattern in the Inntal nappe by layer-length balancing results in a measured original layer length at the base of the Raibl Formation of about 22 km (Plate 1); this length was contracted by about 8 km to the present distance of 14 km. Since the Inntal thrust is seen to cut down-section into the Lechtal nappe just west of Imst, the footwall cutoff for the Raibl Formation in the Lechtal nappe has been placed roughly along regional strike east of Imst. The present subhorizontal distance between the hangingwall and footwall cutoffs of Raibl Formation amounts to about 12 km. Contraction by combined internal shortening and thrusting parallel to the plane of section thus amounts to about 20 km.

Lechtal nappe

The structural pattern within the Lechtal nappe is dominated by Hauptdolomit Formation and overlying basinal Jura-Cretaceous successions of variable thickness. Large parts of the platformal Muschelkalk-Wetterstein facies seem to have been replaced by basinal Partnach shales. Along the northern front of the Lechtal nappe mid- to upper Cretaceous synorogenic clastics rest unconformably on upper Triassic-lower Cretaceous rocks in areas with broadly synclinal structures (Gaupp 1983).

Immediately below and north of the Inntal thrust the Jura-Cretaceous succession is relatively thin (50 to 150 m); however, it displays isoclinal NNW-verging folds and subsidiary thrusts that developed partly during emplacement of the Inntal nappe. North of the Jura-Cretaceous outcrop the anticlinal Burkopf structure exposes a core of Hauptdolomit Formation and slivers of Raibl evaporites along south-directed backthrusts; these complex backthrusts are partly reactivated synsedimentary faults, because thickness of Jura-Cretaceous strata in the Holzgau syncline on the northwest is in excess of 400 to 800 m and the thickness increases along the Burkopf structure. The south-directed back-thrusts were rotated and overturned northward during continued shortening of Hauptdolomit in the Burkopf structure (MEIER 1987). This structural pattern and the amount of shortening along the Burkopf anticline suggests that it is underlain by a complex triangle zone composed of tectonically thickened Raibl and Partnach strata. Beyond the Holzgau syncline the rising frontal hangingwall of the Lechtal nappe is characterized by interfingering Partnach and Wetterstein facies assemblages. Together with off-scraped slivers of the lower and middle decollement (Reichenhall, Raibl units) blocks of all other lithologies form a heterogeneous carpet that defines the base of the Lechtal nappe (TOLLMANN 1976, MÜLLER-WOLFSKEIL & ZACHER 1984). Major footwall anticlines probably separate the semi-klippen of the thrust sheet and the frontal Falkenstein klippe from the main body of the Lechtal nappe.

The Lechtal nappe is also cut by several NW-striking dextral cross faults. However, outside our transect NE-striking sinistral cross faults are regionally more important; the NE-striking faults can be traced from the frontal thrust trace of the NCA towards the zone of backthrusting along the Burkopf structure (Fig. 1). East of our section NE-striking cross faults also seem to have propagated into and below the Inntal nappe where locally they are seen to offset the earlier generation of WNW-striking cross faults (LINZER 1989). Apparently, backthrusting in the Lechtal nappe and related movement on cross faults in the Lechtal nappe also steepened the frontal Inntal thrust (Plate 1). The former areal extent of the Inntal nappe beyond its present trace is not known but it is assumed to have been only in the order of a few kilometres.

Along the plane of the layer-length balanced section original layer length measured at the base of the Raibl Formation is about 56 km; this length was contracted by about 11 km to 45 km. Assuming a position for the footwall cutoff at least as far south as in the Vorderriss 1 well and roughly on strike with the regionally inferred up-plunge termination of the Allgäu nappe a horizontal distance measured between the hangingwall cutoff for the Raibl Formation in the Lechtal nappe and its footwall cutoff in the Allgäu nappe is about 28 km. This amounts to a combined internal shortening and thrust displacement of about 39 km.

Allgäu nappe

The structural style of the Allgäu nappe is dominated by polyharmonic folds and folded thrust splays within a relatively thick Jura-Cretaceous succession overlying the Hauptdolomit Formation. In general the Hauptdolomit pierces the crests of en-echelon anticlines. Down-plunge extrapolation of these structures is problematic. We therefore have drawn a conservative section with typical fold wavelengths for the Hauptdolomit unit at the base of the Allgäu nappe (Plate 1). This construction results in a minimum amount of internal shortening and assumes decollement along and below the Raibl Formation. A minimum layer length of about 30 km thus would have been shortened by at least 3 km to about 27 km.

Minimum shortening of the NCA wedge

An estimate for the minimum amount of shortening (l_0–l) for the NCA in the plane of our section has been obtained by summing up inferred original layer length l_0 (total) = 22 + 56 + 30 = 108 km. Subtracting from this value the present distance between the southernmost and the northernmost Raibl occurrences of l = 46 km gives a value of shortening (l_0–l) of about 62 km. Shortening expressed as (l_0–l)/l_0 therefore is about 57%. This is probably a minimum value. Our section assumes a present wedge geometry with a thickness of 3 km at the front and 8 km near the Inn valley.

Timing and kinematics of nappe emplacement

Age, depositional environment, and provenance of synorogenic clastics in the western NCA have been discussed by GAUPP (1982), GAUPP & BATTEN (1983), WINKLER (1988) and LEISS (1988). On the Allgäu nappe sedimentation of northerly derived Losenstein clastics of late Albian age (about 100 to 97 Ma) was at least locally terminated by the approach of the Lechtal nappe. On top of the frontal Lechtal nappe NCA-derived coarse detritus is abundant in the lower Branderfleck beds of Cenomanian-Turonian age (97 to 88 Ma) which are preserved in synclinal structures and rest unconformably on older rocks of the Lechtal nappe. In other parts of the Lechtal nappe (Holzgau synclinorium) middle Albian basinal limestones seem to be the youngest strata preserved (WINKLER 1988). It is therefore reasonable to assume that hangingwall advance, anticlinal uplift along ramps, erosion, and subsequent deposition of erosional detritus in hangingwall synclines of the Lechtal nappe began in Cenomanian time (at about 97 Ma).

Along the trailing edge of the Lechtal nappe sedimentation of synorogenic coarse clastics of Cenomanian age was terminated by the advance and emplacement of the Inntal nappe (LEISS 1988). Syndeformational sedimentation on the Inntal nappe itself began with coarse Muttekopf-Gosau clastics of Coniacian age and continued into earliest Paleocene time (88 to 65 Ma). These Gosau clastics were deposited on top of an erosional unconformity and are preserved in a synclinal piggyback basin behind the Inntal thrust front. It therefore seems that internal deformation and thrust emergence of the Inntal nappe began at about in Turonian to Coniacian time (91 to 88 Ma).

WNW-directed thrusting of the Ötztal complex contemporaneous with emplacement of the Inntal nappe is suggested by ages between 90 and 70 Ma for cooling of Alpine metamorphic minerals and by isochrons obtained on mylonites (THÖNI 1989). A close temporal-spacial relationship between the uplift of the Ötztal complex and thrusting of the Inntal nappe is also suggested by the presence of metamorphic detritus in the synorogenic Muttekopf-Gosau clastics of the Inntal nappe (WOPFNER 1954). Emergence of the Ötztal complex thus was possibly linked to movement on the Inntal thrust and the development of WNW-striking dextral cross faults.

Continued internal shortening by backthrusting and SW-directed propagation of NE-striking sinistral cross faults contributed to uplift of the NCA above depositional baselevels after 65 Ma; these events were probably related to the Paleogene closure of Penninic basins along the southeastern continental margin of Europe (FRISCH 1979).

Discussion and conclusions

Synorogenic clastics (Gaupp 1983, Leiss 1988) indicate that incipient emplacement of nappes in the NCA could have followed a front-to-back pattern, but that within 5 or 10 Ma the entire width of the wedge was being deformed by thrusting and folding. Detachment probably proceeded along several levels. Early NW- to WNW-directed thrust displacements were accompanied by nucleation of and movement along similarly oriented dextral cross faults that seem to have propagated from the thick trailing portion of the NCA wedge towards the NW. In a broader regional context it is interesting to note that the late Cretaceous shortening of the NCA coincided with the beginning of intraplate compression within the European foreland crust, a process which reached as far as 1,200 km N and NW of the Alps (Ziegler 1989). Later, roughly S-directed backthrusts and NE-oriented sinistral cross faults overprinted the existing structural pattern of the NCA. Total shortening of the NCA in excess of about 60% led to considerable tectonic thickening by wedging, particularly in the southernmost parts of the NCA which are about 8 km thick.

Ring et al. (1988) have recently studied stretching directions in the Arosa melange below the NCA wedge and found that early WNW-oriented stretching fabrics were overprinted by later N- to NNE-oriented stretching fabrics. It is possible that the two patterns of stretching in the Arosa melange correspond to the two sequences of shortening and cross fault development within the NCA wedge. This would imply that late Cretaceous nappe emplacement and Paleogene internal shortening of the NCA were contemporaneous with displacement of the entire wedge along the NCA sole thrust.

The inferred front-to-back thrust sequence during the initial fold-and-thrust development could have been influenced by paleotopography and facies patterns which in Jura-Cretaceous time possibly were controlled by strong crustal subsidence in the South Penninic–lower Austroalpine domains on the north of the NCA (Lemoine & Trümpy 1987). It is conceivable that the crustal substratum of the NCA failed first along this extended and deeply subsided frontal zone before the remaining platform experienced detachment and internal shortening. Numerous unresolved pre-shortening stratigraphic anomalies near the front and within the Allgäu, Lechtal, and Inntal nappes indicate that synsedimentary fault zones locally influenced development of subsequent thrusts and cross faults. Since major thrusts, backthrusts and cross faults in the NCA disrupt coal rank and illite crystallinity patterns and since both generally indicate southward-increasing paleotemperatures (Krumm 1984, Petschik 1989) a major thermal event probably affected the crustal substratum of the southern NCA just prior to thrusting. This thermal event could have mechanically weakened the trailing basement of the NCA to such an extent that its wholesale detachment became possible.

Acknowledgments

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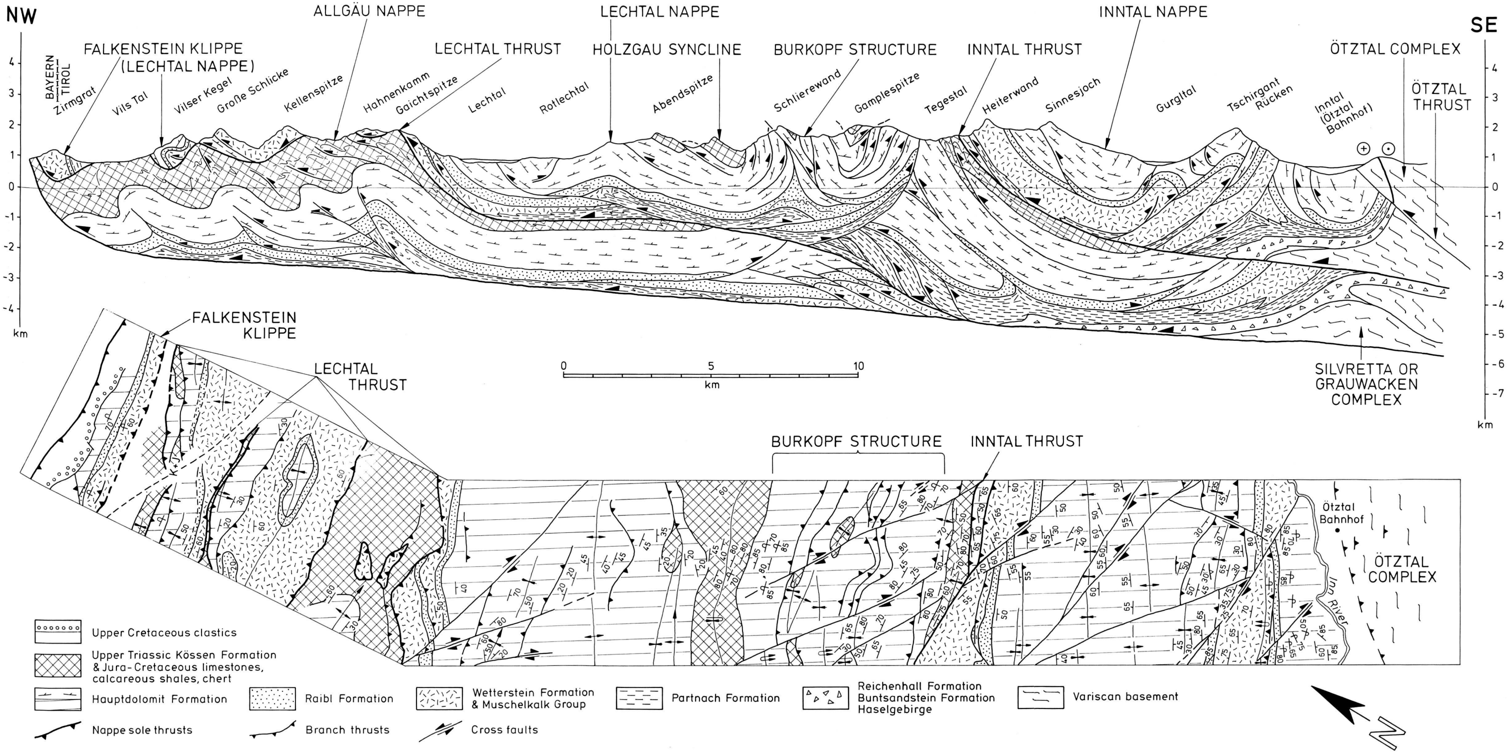
Plate 1

Predictive structural depth extrapolation for a transect across the NCA along a strip indicated in Figure 1. The legend in the strip map and in the section differentiates mechanically distinct intervals rather than chronostratigraphic subdivisions.


NW
SE
FALKENSTEIN KLIPPE
(LECHTAL NAPPE)
ALLGÄU NAPPE
LECHTAL THRUST
LECHTAL NAPPE
HOLZGAU SYNCLINE
BURKOPF STRUCTURE
INNTAL THRUST
INNTAL NAPPE
ÖTZTAL COMPLEX
ÖTZTAL THRUST
BAYERN
TIROL
Zirmgrat
Vils Tal
Vilser Kegel
Große Schlicke
Kellenspitze
Hahnenkamm
Gaichtspitze
Lechtal
Rotlechtal
Abendspitze
Schlierewand
Gamplespitze
Tegestal
Heiterwand
Sinnesjoch
Gurgltal
Tschirgant Rücken
Inntal (Ötztal Bahnhof)
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
km
SILVRETTA OR GRAUWACKEN COMPLEX
0
5
10
km
FALKENSTEIN KLIPPE
LECHTAL THRUST
BURKOPF STRUCTURE
INNTAL THRUST
Ötztal Bahnhof
ÖTZTAL COMPLEX
Inn River
Upper Cretaceous clastics
Upper Triassic Kössen Formation & Jura-Cretaceous limestones, calcareous shales, chert
Hauptdolomit Formation
Raibl Formation
Wetterstein Formation & Muschelkalk Group
Partnach Formation
Reichenhall Formation
Buntsandstein Formation
Haselgebirge
Variscan basement
Nappe sole thrusts
Branch thrusts
Cross faults
N