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Superposed fold-thrust structures and high-angle faults, Northwestern Calcareous Alps, Austria

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Key words: Northern Calcareous Alps, fold-thrust structures, superposed deformation, deformation partitioning, displacement restoration

ABSTRACT

Structural complexity within the western sector of the Northern Calcareous Alps (NCA) arises from heteroaxial superposition of two sets of fold-thrust structures and transverse high-angle strike-slip faults. Initial WNW- to NW-directed detachment of the carbonate-dominated Inntal, Lechtal and Allgäu sheets in mid- to late Cretaceous time was accompanied by dextral shear along NW-propagated high-angle faults. Partitioned deformations thus caused the highest structural units of the westernmost area to advance at least 60 km relative to a point of reference located some 200 km to the east. Superposed N- to NE-oriented contraction of Paleogene age not only caused deformation of the upper Cretaceous Gosau Group clastics that rest unconformably on early developed structures but profoundly affected deeper and more frontally located parts of the NCA wedge. The superposed deformation was also partitioned, with reverse faults of variable vergence having been linked by NE-striking sinistral transfer faults. The most important of these high-angle faults appears to have been the Embach fault of the lower Inn River valley, along which a Triassic facies change was offset sinistrally by about 20 km. Restoration of displacements on major structures suggests that both Triassic platform-basin transitions and Jurassic extensional fault zones influenced the development of early thrust and transverse fault geometries. During superposed contraction some early propagated NE-striking thrust segments linked up into NE-striking high-angle fault zones, while some early propagated NW-striking high-angle faults served as nucleation zones for superposed reverse faults. In Neogene time NNW-directed motion of the NCA wedge on top of a carpet composed of Cretaceous-Paleogene flysch created ENE-trending fold-thrust structures in the proximal parts of the Molasse basin.

ZUSAMMENFASSUNG

Komplexe Strukturen im westlichen Teil der Nördlichen Kalkalpen sind das Resultat einer Überlagerung zweier Systeme von Falten- und Überschiebungsstrukturen und dazugehöriger steiler Querstörungen. Die initiale WNW- bis NW-gerichtete Abscherung und Stapelung von Inntal-, Lechtal- und Allgäu-Decke in der mittleren bis späten Kreide war von der Entwicklung NW-orientierter dextraler Blattverschiebungen begleitet. Die so aufgeteilte Deformation verursachte eine NW-gerichtete Vorwärtsbewegung der tektonisch höchsten westlichen Deckenbereiche von mindestens 60 km gegenüber einem entsprechenden Beziehungspunkt 200 km östlich davon. Eine den Deckenstapel überprägende N- bis NE-orientierte Einengung während des Paläogens, durch welche hauptsächlich tiefere Anteile des Überschiebungskeils erfasst wurden, verursachte auch eine Deformation der syntektonischen Gosau-Gruppe (Oberkreide), die diskordant auf den bereits früher entstandenen Strukturen abgelagert worden war. Eine überprägende Einengung von wenigstens 10 km wurde durch Transfer an NE-streichenden, gestaffelt angeordneten sinistralen Blattverschiebungen ermöglicht. Die wichtigste dieser Blattverschiebungen ist die Embach-Störung in Unterinntal, für die ein sinistraler Versatz von rund 20 km anzunehmen ist. Eine angenäherte palinspastische Rekonstruktion der grösseren Strukturen zeigt, dass die Geo-

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metrie der initialen Überschiebungs- und Blattverschiebungsflächen wahrscheinlich vor allem durch Heterogenitäten entlang triassischer Plattform-Becken-Übergänge und jurassischer Abschiebungen bestimmt wurde. Bei der Überprägung dienten früh entwickelte Überschiebungen als Teilsegmente für später durchreissende Querstörungen und früh entwickelte Blattverschiebungen als Ausgangsflächen für überlagerte Auf- und Überschiebungen mit variabler Vergenz. Im Neogen bewegte sich der gesamte deformierte Keil der Nördlichen Kalkalpen auf einem Teppich von Flysch auf das südliche Molassebecken, in dem ENE-orientierte Falten- und Überschiebungsstrukturen entstanden.

Introduction

Within the northern Mediterranean fold-thrust belts the direction of horizontal contraction has varied dramatically during Mesozoic-Cenozoic regional deformation (e.g. Burchfiel 1980). Moreover, the fold-thrust belts show a distinct longitudinal segmentation by variably oriented reactivated systems of pre-contraction normal faults (e.g. Ghisetti & Vezzani 1988; Castellarin & Picotti 1990) or by newly propagated high-angle strike-slip faults (Doglioni 1987; Laubscher 1988; Polinski & Eisbacher 1992; Schönborn 1992). Polyphase superposition of contraction structures, longitudinal segmentation and partitioning of deformation are particularly prominent along the northwestern margins of the Adriatic (or Apulian) plate which are preserved in the South Alpine and Austroalpine basement-cover complexes, and are particularly striking in the Northern Calcareous Alps (NCA). Tollmann (1976), Plöchinger (1980) and Linzer et al. (1995) have reviewed the bewildering pattern of Late Mesozoic-Cenozoic contraction structures within the NCA which were originally mapped by Ampferer (e.g. 1915, 1932) and have since been studied by many others. However, the timing and mechanisms of structural superposition within the frontal Austroalpine wedge are still poorly understood.

Our own work, based on detailed mapping, has revealed distinctly heteroaxial fold-thrust patterns that resulted both from initial thrust stacking along a frontal accretionary wedge and from subsequent contraction related to its emplacement onto the Eurasian margin (Eisbacher et al. 1990). Other detailed studies of the westernmost Austroalpine complexes in Switzerland (see Ring et al. 1988; Froitzheim et al. 1994) and in eastern Austria (Decker et al. 1993) suggest similar polyphase deformation patterns, which are also relevant with respect to sensible interpretations of deep reflectors as revealed by commercial seismic reconnaissance surveys within the NCA (Wessely & Zimmer 1993).

Stratigraphic-structural framework of the western NCA

In the NCA the Austroalpine Permo-Mesozoic succession is 3 to 6 km thick and overlies variable pre-Permotriassic basement rocks (Fig. 1b). The Triassic strata were deposited along a SE-facing basin margin, while the Jurassic-Cretaceous units originated along a complex and generally NW-facing extensional margin that ultimately bordered the Piemont-Ligurian ocean (Lemoine & Trümpy 1987; Stampfli & Marthaler 1990). The leading edge of the western NCA is therefore dominated by Jurassic-Cretaceous strata, while Triassic platform carbonates prevail along the trailing eastern edge. Throughout the NCA the Late Cretaceous-Tertiary style of contraction was controlled mainly by three levels of incompetent strata serving as detachments and two intervals of competent Triassic carbonate assemblages (Fig. 1b). Basal detachment occurred within the Permotriassic evaporitic, argillaceous or calcareous-dolomitic beds of the Rotliegend-Buntsandstein-

Reichenhall assemblage that is 100 to 300 m thick. Overlying Middle Triassic strata consist either of the competent Muschelkalk-Wetterstein carbonate assemblage that is 500 to 1800 m thick, or of the incompetent and much thinner Partnach shale unit. Both are capped by the Carnian Raibl formation which is less than 50 m thick above Wetterstein carbonates and more than 500 m thick above Partnach shales and contains evaporitic-argillaceous units that served as a second major detachment level. The competent and well-bedded Norian Hauptdolomit unit above the Raibl formation is about 1200 to 1800 m thick and grades upward into calcareous Plattenkalk facies, bituminous Seefeld facies or Kössen limestone reef-and-shale members up to 200 m thick. The overlying and generally thinly bedded Jurassic-Cretaceous limestone-marl succession, which ranges in thickness from a few tens of metres on platforms to possibly more than 2 km in deep local basins, includes the regionally persistent Oxfordian Ruhpolding radiolarian chert marker unit which is only a few tens of metres thick but serves as an excellent structural marker.

Mid- to Upper Cretaceous southerly-derived synaccretionary clastics of the marine to nonmarine Gosau group contain ophiolitic detritus and are preserved as synclinal erosional remnants within the NCA, while coeval westerly and northerly-derived turbiditic trench deposits are preserved within the fringing or subjacent Rhenodanubian Flysch (Faupl et al. 1987; Gaupp 1982; Gaupp & Batten 1983; Weidich 1984; Winkler 1988; Leiss 1988; Bernoulli & Winkler 1990; Egger 1992; Wagreich 1993 and 1995). In Paleogene time the entire NCA thrust wedge, underplated by ophiolitic melanges and frontally widened by accretion of the Rhenodanubian Flysch, was emplaced onto slope-shelf deposits of the passive Penninic-Helvetic margin of the Eurasian plate (Dietrich 1976; Frisch 1979; Frank 1987; Laubscher 1988; Winkler 1988; Thöni & Jagoutz 1993). Meanwhile nappe formation and metamorphism proceeded at deeper crustal levels (Pfiffner et al. 1990). Oligocene-Miocene emergence of the NCA-wedge above sea level as indicated by cessation of marine deposition on top of the NCA (Wagreich 1995) and by a distinct upward coarsening trend of intramontane clastics (Ortner 1994a), was accompanied by deformation of the Helvetic shelf succession and by progradation of marine to non marine clastics into the Molasse foreland basin on top of the Eurasian platform (Lemcke 1984; Pfiffner 1986; Nachtmann & Wagner 1987; Bachmann et al. 1987).

Structural style of the western NCA

The sole thrust of the Austroalpine thrust wedge drops from an elevation of around 2 km above sea level in westernmost Austria and eastern Switzerland to a depth of about 6 km below sea level in the exploration well Vorderriss I of southern Bavaria, some 100 km to the east (Fig. 1c, Bachmann & Müller 1981; Roeder 1989). A discontinuous carpet of ophiolitic melange, allochthonous slivers of Penninic-Helvetic slope-shelf deposits and Rhenodanubian Flysch, prograded wedges of Molasse clastics, and a buried autochthonous platform cover form a 2–3 km thick package that lies between the NCA sole thrust and the pre-Mesozoic Variscan basement of Eurasia (Wessely & Zimmer 1993).

From north to south the western NCA consist of three thrust sheets, the Allgäu, Lechtal and Inntal sheets (or nappes). Their sole thrusts placed older over younger strata (Tollmann 1976) and thrust contacts are also warm-over-cold discontinuities with regard to pre-thrust vitrinite reflectance and illite cristallinity patterns (Krumm 1984; Krumm et al. 1988; Petschick 1989). Internally, the thrust sheets display major flexural-slip folds and

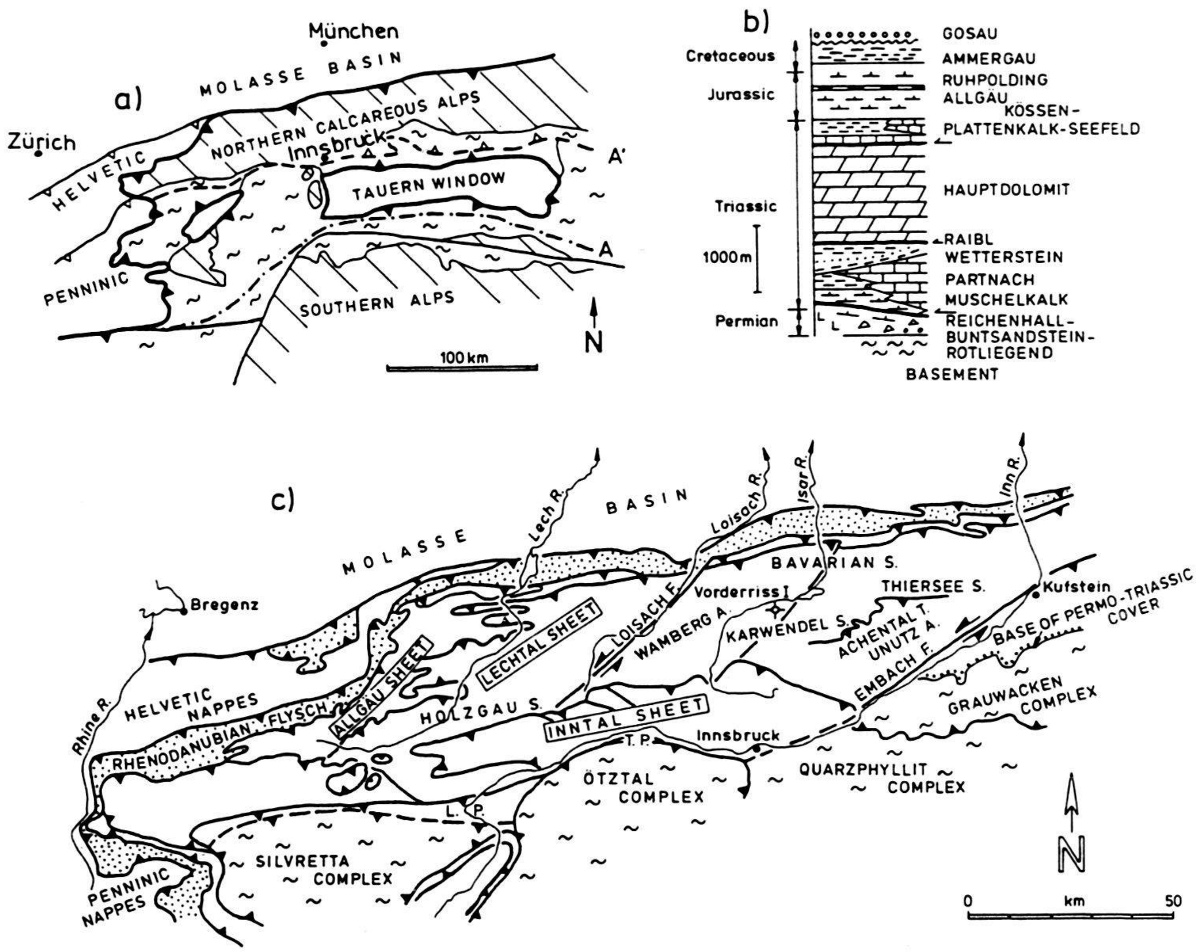

Fig. 1. Sketch map of the tectonic setting and mechanical stratigraphy of the western Austroalpine thrust complex. a) Austroalpine sole thrust (thick line), basement (wavy pattern), Permo-Mesozoic cover (ruling) and a possible trailing edge line (A') for the Northern Calcareous Alps plus basement with a matchup line (A) along which similar cover-basement facies are exposed to the southeast. b) Stratigraphic units and potential detachment levels (arrows) in the sedimentary succession of the western NCA. c) Traces of major thrust sheets, synclines (S), anticlines (A) and high-angle faults (F) of the western NCA and frontal parts of adjacent basement complexes (wavy pattern); L.P. = Landeck phyllonite; T.P. = Telfs phyllite. Also shown is the location of the borehole Vorderriss I which intersected the base of the NCA at a depth of about 6 km.

numerous out-of-syncline thrusts. Out-of-sequence backthrusts and high-angle transverse faults complicate the picture. Cleavage is developed only in anchimetamorphic argillaceous units exposed along the southern border of the NCA. The traces of the sole thrusts outline a geometry of eastplunging anticlinal semi-windows (Tollmann 1976) which permit down-plunge extrapolations of structural style and determination of footwall cutoff lines for key stratigraphic units. Structural down-plunge extrapolations yield a minimum NNW-SSE-contraction value for the western NCA which is in the order of 60%, i.e. a contraction from at least 110 km original line length measured along the Raibl detachment level to a present width of 45 km (Eisbacher et al. 1990).

The **Allgäu** sheet (Fig. 1c) is floored by Raibl strata, internally folded, and, along its leading edge, imbricated with slivers containing northerly derived mid-Cretaceous clastics (Richter 1984). Semiquantitatively balanced sections (Eisbacher et al. 1990), unpublished seismic data (G. Wessely pers. comm. 1994), and evidence from the exploration well Vorderriss I (Bachmann & Müller 1981) all suggest that the trailing edge of the Allgäu sheet is a complex S-dipping imbricate stack of Hauptdolomit-Raibl and possibly Muschelkalk-Wetterstein-Partnach assemblages along an ENE-trending zone located some 25 km south of the NCA leading edge. The **Lechtal sheet** in general is floored by a detachment horizon in basal Triassic or Permian strata and contains both Wetterstein and Partnach facies; it is characterized by inherited Jurassic platform-basin patterns which are now reflected in major anticline-syncline pairs which are cut by NE-striking sinistral high-angle faults. The **Inntal sheet** is preserved in a major syncline of the southern Lechtal sheet; its sole thrust is seen to cut into upper Hauptdolomit footwall strata about 20 km south of its leading edge (Tollmann 1976) and the entire sheet is laced with NW-striking high-angle dextral faults which apparently merge with a major fault system along and on trend with the Inn River valley. The Inntal sheet and Inntal-equivalent erosional klippen exposed to the west are overlain by yet smaller klippen which possibly constitute frontal sedimentary portions of basement-cover complexes presently situated to the south of the NCA.

Of these basement-cover complexes, the **Silvretta complex** in the west consists of a pre-Permian assemblage of high-grade metamorphics. These are fringed to the north by the Landeck phyllonite belt (LP in Fig. 1c) which in turn appears to be overlain unconformably by Permotriassic clastics of the Lechtal sheet (Ampferer 1930; Rockenschaub 1990). The Landeck phyllonite probably originated during a phase of pre-Mesozoic retrogression of higher grade metamorphics (Rockenschaub 1990), but also aquired a very low-grade metamorphic mineral assemblage during early Alpine burial and deformation (Amann 1993; Rockenschaub 1990). The southeastern parts of the high-grade metamorphics and Mesozoic cover of the **Ötztal complex** display an even stronger Alpine metamorphic overprint (Purtscheller & Rammlmair 1982; Frank et al. 1987) and the entire mass was thrust at least 45 km west-northwesterly over the Silvretta-equivalent Campo basement-and-cover complexes in late Cretaceous time (Thöni 1988; Schmid & Haas 1989). The Ötztal complex is also fringed on the north by a low-grade metamorphic sliver, the Telfs phyllite (TP in Pl. 2). If the pre-Mesozoic Landeck phyllonite represents a trailing pre-Mesozoic portion of the western Lechtal sheet then the Telfs phyllonite can be thought of as a trailing portion of the Inntal sheet (Eisbacher et al. 1990). It is not yet established whether the NCA and their phyllonitic basement were originally located to the south (Tollmann 1963), east (Bechstädt 1978) or north (Frank 1987) of the high-grade Ötztal and Silvretta basement wedges and their cover. However, as both the NCA and the Ötztal-Silvretta complexes are now underlain by ophiolitic melange (Waibel & Frisch 1989; Winkler 1988) the present position of these complexes with respect to each other was probably established prior to emplacement of the entire Austroalpine wedge onto the distal passive margin of Eurasia.

Toward the east the **Innsbruck Quarzphyllit** complex, composed of low grade Paleozoic metamorphics, seems to structurally underlie Ötztal metamorphics and therefore probably represents an originally more northerly located part of the Austroalpine basement (Fig. 1c).

The **Grauwacken complex**, which consists of Paleozoic low-grade metamorphics overlies either a carpet of poorly understood high-grade metamorphic slivers or rests directly on Innsbruck Quarzphyllit. It is overlain in a nonconformable sedimentary contact by basal Permotriassic clastics of the NCA. Because of major facies changes and lack of exposures in the lower Inn River valley, the relationship of the Grauwacken complex and its Permotriassic cover to the Permotriassic cover strata of the eastern Lechtal sheet are not entirely clear. However, a minimum restoration by about 20 km along the sinistral Embach fault in the Inn River valley would establish continuity for both a Triassic facies change and Paleogene (?) contraction structures across the valley (see below). In-situ refraction-seismic velocities in the order of 6 km s^{-1}, recorded by Angenheister et al. (1972) below the southernmost NCA, suggest that slivers of pre-Permomesozoic Landeck phyllonite, Telfs phyllite, Grauwacken complex and subjacent Innsbruck Quarzphyllit possibly still occur beneath the basal sedimentary units of the southern Lechtal and Inntal sheets. Recently Linzer et al. (1995) in their Figure 3 have correlated the Landeck phyllonite with the Innsbruck Quarzphyllit which in turn they show to be directly overlain by the NCA sedimentary succession; they consider the Telfs phyllite to be a Penninic unit. Since the authors do not discuss these postulated relationships and omit the role of the Grauwacken complex, the reasoning behind their scheme is difficult to follow.

Since polyphase structures related to both initial thrust sheet detachment and later superposed contraction are preserved best along the southeastern fringe of the NCA the following discussion will proceed from southeast to northwest, beginning with the Unutz-Achental structure, advancing to the Inntal thrust sheet and Stanzer valley fault zone, and ending with a brief description of the structural situation along the frontal NCA. Because the entire NCA-wedge is characterized by pronounced partitioning of deformation into fold-thrust structures and high-angle faults both types of features have to be considered together, in a way demonstrated for much simpler situations by Laubscher (1965) and Bitterli (1990) for the Jura mountains.

Unutz-Achental structure

The southeastern Lechtal sheet is dominated by the NNW-verging and WSW-plunging Unutz anticline, the related Achental thrust and the Karwendel-Thiersee synclines (Pl. 1). The Achental thrust which nucleated in the core of the Unutz anticline below Muschelkalk-Wetterstein carbonates emerges as a complex NE-striking stepover zone between the E-trending Karwendel and Thiersee synclines (Pl. 1). This stepover zone coincides with an Upper Triassic-Jurassic sedimentary depocentre in the footwall (Schütz 1979), parallels an abrupt platform-basin transition in the hangingwall, and possibly developed along an older NE-striking extensional fault zone (Channell et al. 1990, 1992). Cretaceous marls in the footwall of the Achental thrust display subhorizontal shear fibre lineations that indicate NNW-directed thrust motion. Moreover, NW-verging anticline-syncline pairs in Upper Triassic-Jurassic hangingwall strata of the Rofan fold train (Pl. 1) suggest early NW-directed displacements. Total contraction by folding and thrust faulting along the composite Unutz-Achental structure as determined for a cross section near the central Achental thrust is in the order of 8 km. Several NW-striking high-angle dextral faults which cross the Unutz-Achental structure and are here named Kühberg, Issalm, Kramsach and Pertisau faults (Pl. 1), offset is axial surface, steep formation contacts and the NW-verging Eben backlimb thrust. The distributed dextral shear along these faults

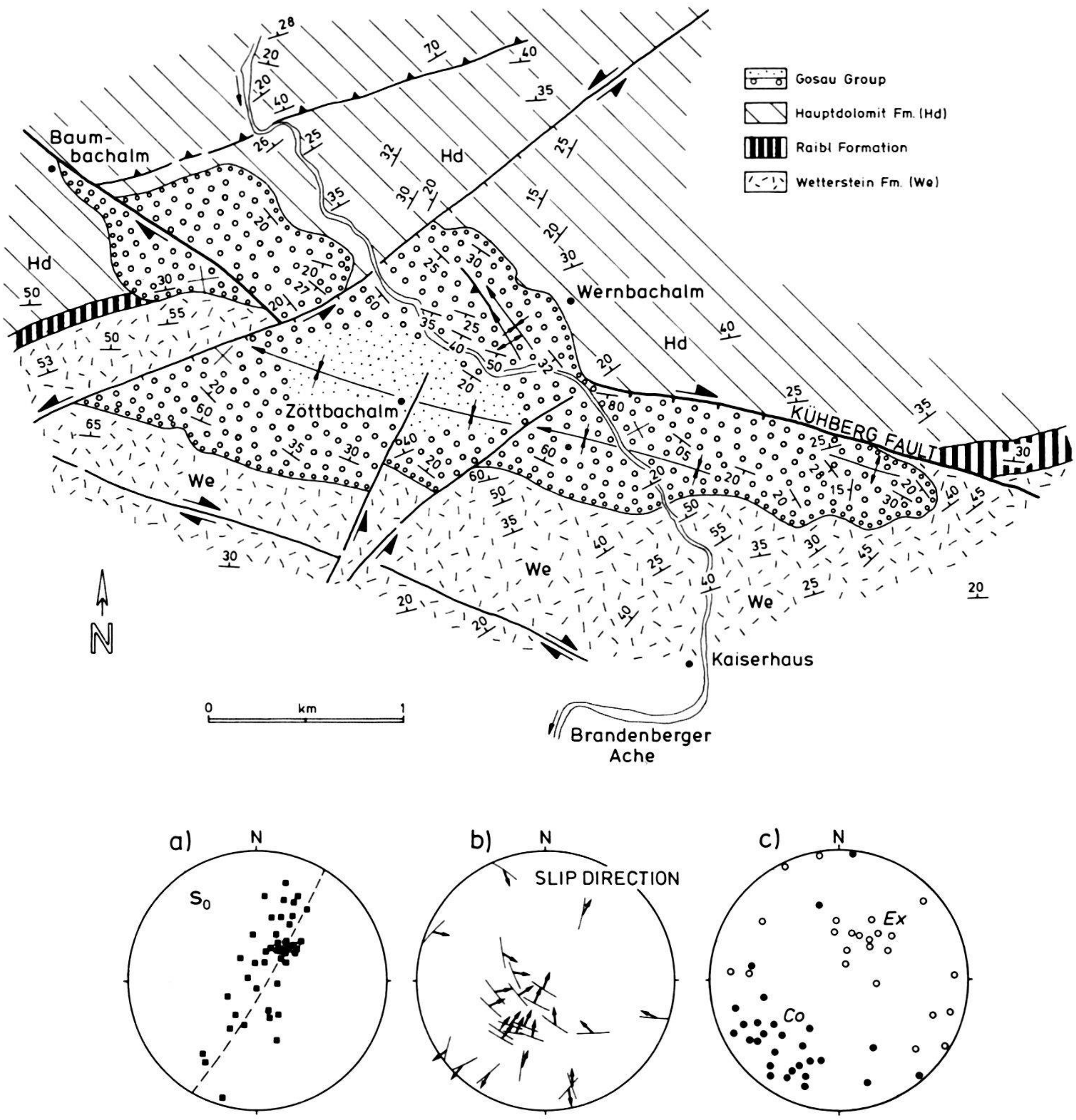

Fig. 2. Sketch map of the erosional Zöttbachalm Gosau remnant (see location in Pl. 1). In spite of the prevailing northeasterly strike of bedding below the sub-Gosau unconformity the Gosau strata themselves were folded into a NW-trending syncline. Stereoplots for the Gosau strata show a) orientation of bedding; b) hangingwall slip directions from fibre lineations on bedding planes or mesoscopic faults, with slip surfaces indicated by great circle segments, and c) compression (Co, filled circles) and extension (Ex, open circles) axes derived from bedding and fault slip assuming a failure angle of 30° to σ_1 for individual slip events (see text).

amounts to a total of roughly 10 km, if the total shear is assumed to be the sum of the offsets along the individual strike-slip faults.

Timing of initial fold-thrust detachment and propagation of high-angle transverse faults is constrained by the sedimentary patterns and structures preserved in remnants of the Upper Cretaceous (Coniacian-Campanian) syntectonic clastics of the Gosau Group.

In the eastern core of the Unutz anticline basal nonmarine Gosau group rests unconformably on strata as old as Wetterstein carbonates while toward the west it overlies strata as young as latest Triassic-early Jurassic. Locally, the angularity of the unconformity exceeds 30°. This indicates that a substantial closure and a WSW-oriented plunge of the structure were well established by about 90 Ma. Because the youngest preserved strata in the Thiersee syncline are mid-Cretaceous (Albian) conglomeratic channel deposits derived from an adjacent lower Cretaceous platform (Weidich 1984), initial uplift, tightening, and erosion of the Unutz-Achental structure must have begun around mid-Cretaceous time (about 100 Ma). The NW-striking transverse faults also appear to have propagated across the anticlinal structure at about this time, because in the Brandenberg Gosau basin of the southern limb, a shallow water mixed clastic-carbonate assemblage of Coniacian-Santonian age (89 to 83 Ma), occupies a northeastern sector, while a deep-water turbiditic clastic assemblage of Coniacian-Campanian age (89 to 71 Ma) is found in a southwestern sector (Herm et al. 1979). Our mapping suggests that the NW-striking Issalm fault marks the border between these two facies domains and that present structural relief of about 500 m displayed by the sub-Gosau unconformity across the fault still reflects the original relief as inferred from the paleoecology of the faunas retrieved (D. Herm pers. comm. 1992). A second major Gosau remnant at Zöttbachalm on the northern limb aligns with and seals the Kühberg fault; this suggests that the NW-striking transverse faults were well established by late Cretaceous time.

Superposed N- to NE-oriented heteroaxial contraction affected both limbs of the Unutz-Thiersee composite structure and the unconformably overlying Gosau group. Thus, the Gosau remnant of Brandenberg on the southern limb is preserved as a SE-plunging syncline while the Zöttbachalm remnant on the northern limb is preserved as a NW-plunging syncline (Pl. 1). Detailed study of the northern remnant also reveals calcite fibre lineations on bedding surfaces and oblique contraction faults that demonstrate slip compatible with NE-SW-oriented regional contraction (Fig. 2). Toward the west, near Achensee, the entire early formed Rofan fold train was tilted by about 20° southwesterly and in the Karwendel-Thiersee stepover zone the NNW-dipping panel of Hauptdolomit and the SSE-dipping Jurassic-Cretaceous strata were deformed into tight arrays of WNW- and ESE-plunging folds respectively. Superposed contraction also affected the geometry of the Achental thrust and its present lobate erosional trace substantiates significant NNE- to NE-oriented contraction that postdated earlier NW- to NNW-directed thrust detachment (Pl. 1).

The timing of superposed deformation can be inferred only indirectly. However, along the Inn River valley all NCA structures are truncated by the major NE-striking Embach fault. This fault caused an apparent sinistral separation of a Partnach-Wetterstein facies transition and of a large synclinal structure by about 20 km (compare PA in Pl. 1 south of the Inn River, with Pa in Pl. 2 north of the Inn River). Subsidence of a small extensional basin filled with mid- to upper Oligocene (about 32 to 25 Ma) marine to nonmarine clastics in the lower Inn River valley (Ortner 1994a) suggests that NE- to NNE-oriented post-Gosau contraction and related convergent strike-slip displacements were outlasted by divergent sinistral strike-slip faulting and local subsidence. Therefore NNE-SSW-oriented contraction is inferred to have occurred sometime between latest Cretaceous (?) and mid-Oligocene time (60 to about 30 Ma).

Inntal thrust sheet

The ENE-trending trace of the Inntal thrust can be followed for about 100 km (Pl. 2). It is offset by numerous NW-striking high-angle oblique and strike-slip faults and the northeastern border of the sheet probably also originated as a NW-striking transverse fault or lateral ramp. The Inntal sheet tapers from a maximum width of 20 km in the east to small erosional klippen in the west, paralleling a middle Traissic facies change from massive Muschelkalk-Wetterstein carbonates in the east to Partnach shales in the west, while the sole thrust climbs from the basal Haselgebirge-Reichenhall detachment level in the east to a hangingwall ramp in Raibl-Hauptdolomit strata in the west. With the rise of the sole thrust into higher stratigraphic levels average wavelengths of folds within the sheet decrease from 5 km in the east to 3 km in the west. For the Inntal sheet an early NNW- to NW-directed thrust displacement of at least 20 km can be inferred a) from the NW- to NNW-verging folds in both Triassic hangingwall strata and Jurassic-Cretaceous footwall strata and b) from the minimum distance between upper Hauptdolomit hangingwall strata exposed along the leading edge of the thrust sheet to a footwall cutoff in upper Hauptdolomit strata below the southern erosional trace of the Inntal sheet near Imst (Pl. 2 and Tollmann 1976). Within the sheet itself folding and out-of-syncline thrusting account for another 10 km of contraction (Eisbacher et al. 1990).

All major ENE-striking fold axial surfaces within the Inntal sheet are systematically offset along NW-striking dextral faults spaced at distances from 2 to 5 km. Cumulative dextral offset on these faults, including the composite Telfs fault zone, amounts to about 15 to 20 km (Pl. 2). Thus, an estimated forward motion of roughly 20 km for the westernmost Inntal sheet relative to its eastern part has to be added to the 20 km of NW-directed thrust displacement.

Timing of initial detachment and deformation partitioning within the Inntal sheet are constrained by several observations: (a) Jurassic-Cretaceous footwall strata in front of the central Inntal sheet were intruded by mafic dikes at about 100 Ma, marking an upper limit to major thrust motion although some footwall deformation may have gone on prior to dike emplacement (Trommsdorff et al. 1990 and pers. comm 1994); (b) locally derived olistostromes and fine grained clastics of Cenomanian age (99 to 93 Ma) were deposited along the southern margin of a Cretaceous basin within the western Lechtal sheet and were overridden by the frontal Inntal sheet (Leiss 1988); (c) nonmarine-marine Gosau clastics of Coniacian to Maastrichtian age (89 to 65 Ma) were deposited unconformably on deeply eroded Hauptdolomit strata in the laterally fault-bounded but generally synclinal Muttekopf succession of the western Inntal sheet (Leiss 1988, Ortner 1994b; Pl. 2); detritus of low-grade metamorphics in this basin suggests that phyllitic rock units (Landeck, Telfs, Grauwacken complex phyllites?) were probably exposed along the trailing edge of the NCA. Thrust emplacement therefore probably occurred in early Late Cretaceous times (about 100 to 85 Ma). Since WNW-directed displacement of the Ötztal complex has been dated at about 90 to 80 Ma (Thöni 1988; Schmid & Haas 1989), stacking of basement slivers thus possibly occurred coevally with thrust emplacement and high-angle fault segmentation of the Inntal sheet. A small klippe (Larsenn klippe) which overrode the southernmost Inntal sheet and parts of the Muttekopf Gosau basin is composed of Triassic carbonates with a facies typical for cover rocks of the Ötztal or Silvretta complexes. However, the direct juxtaposition of high-grade Ötztal-Silvretta metamorphics and sedimentary cover rocks against the southernmost NCA along out-of-sequence thrusts probably occurred later.

Superposed contraction which overprinted both the early developed fold structures and the NW-striking transverse faults was particularly strong along the leading edge of the Inntal sheet. Along the easternmost Inntal thrust trace a system of laterally linked backthrusts affected Triassic footwall strata of the Lechtal sheet; superposed deformation during which early developed WSW-plunging hangingwall folds were carried northeasterly against and over the Eng footwall backthrusts caused the northeasterly overturning of both the backthrusts and the Triassic strata involved in the backthrusts. Muschelkalk-Wetterstein carbonate klippen of the Inntal sheet, preserved on top of overturned Muschelkalk-Wetterstein footwall panels, indicate that the NE-displacement along the Inntal thrust was in the order of 10 km. This NE-SW contraction was transferred westerly along the SW-striking sinistral Isar fault onto the major Zugspitze footwall backthrust, along which a SSW directed advance of a massive Muschelkalk-Wetterstein panel caused a backrotation and high-angle fault segmentation of Muschelkalk-Wetterstein strata of the frontal Inntal hangingwall strata. Further on, southwestward transfer of contraction occurred along the sinistral Loisach fault and led to a tightening of the Burkopf structure, a complex anticline-backthrust system in Hauptdolomit footwall strata that had developed previously in front of the western leading edge of the Inntal sheet. This linked backthrust and strike-slip fault system is considered to have developed simultaneously because the strike-slip faults terminate as lateral cutoff borders to footwall backthrusts and do not seem to cause great offsets within the overlying Inntal sheet. This relationship also suggests that the high-angle faults propagated from the NCA thrust front backwards rather than being caused by Miocene lateral extrusion from the backstop region, as argued by Linzer et al. (1995).

Inside the Inntal sheet overprinting caused a general steepening of the plunges of preexisting ENE-trending folds. It also initiated some backthrusting along the trailing edge, particularly along fault zones that include the Halltal and Tschirgant backthrusts. The Starkenbach backthrust which nucleated below the trailing western Inntal sheet also appears to have propagated from the footwall into the hangingwall strata. In the footwall it caused a displacement of about 4 km, led to an anomalous out-of-sequence cold-over-warm juxtaposition of vitrinite reflectance patterns (Petschick 1989), and probably localized subsequent easterly erosional retreat of the Inntal thrust trace, thus creating the overall lobate geometry of the sheet.

The age of superposed and roughly NNE-oriented contraction was most likely post-Gosau and probably of Paleogene age, because at this stage the NCA toe zone must have impinged against the Eurasian slope causing accelerated foreland subsidence (Malzer et al. 1993) and forcing an end of bathyal deposition along the NCA-toe by mid-Eocene time (Wagreich 1995). Intense fluid motion implied by crystallisation ages of phyllosilicates around 60 Ma (Kralik pers. comm. 1993) in the vicinity of the Starkenbach backthrust support the notion of pervasive Paleogene overprinting in this part of the NCA.

Stanzer valley zone

The Stanzer valley (Fig. 1) which extends west of the Inn River toward the Arlberg pass is fringed on the north by sedimentary strata of the Lechtal sheet, is underlain by the

Landeck phyllonite in the centre and is flanked on the south by high-grade metamorphic rocks of the Silvretta complex (Ampferer 1930; Rockenschaub 1990). Although the steeply N-dipping Permo-Mesozoic succession appears to be in primary depositional contact with Landeck phyllonite the unconformity is intensely sheared and both basement and cover rocks display a phyllitic foliation (Stingl 1984, Rockenschaub 1990; Nowotny et al. 1992).

This foliation dips southerly beneath high-grade Ötztal and Silvretta metamorphics and, in the east, displays a weak ESE-plunging penetrative stretching lineation. Because similar lineations occur locally in basal Permotriassic clastics it is probable that early top-to-WNW motion affected this zone. Thrust stacking above this zone caused low-grade Alpine metamorphism within the Landeck phyllonite with maximum temperatures attaining about 400 °C in the east and less than 300 °C in the west (Amann 1993).

The structures in the Landeck phyllonite were studied in the five areas, which are here referred to as Wenns, Landeck, Flirsch, Arlberg and Wald (Fig. 3). In the central part (Flirsch, Landeck) where the SSW- to S-dipping foliation anisotropy is particularly strong, up-dip propagation of contraction faults produced flexural slip and kink folds with wavelengths on the cm- to m-scale. The hingelines of these folds plunge both east-southeasterly and west-northwesterly and their vergence with respect to te local foliation is north-northeasterly. Since the folds were produced by discrete slip along foliation surfaces the statistical hinge line orientations indicate NNE-SSW-oriented contraction. All areas also display mesoscopic faults with distinct quartz fibre lineations that offset foliation surfaces and locally folds. Along the faults ductile deflection ("drag") of foliation surfaces in the slip direction can be observed. This suggests that discrete slip events across the foliation surfaces were preceded by some ductile flexural deformation of the foliation. Thus, fault planes possibly nucleated and propagated at angles of about 45° to the direction of local compression, an assumption supported by the occasional occurrence of conjugate slip surfaces enclosing angles of about 90°. Based on an assumption of slip at angles of about 45° to the direction of maximum compression, the orientation of a contraction axis S_1, and an extension axis S_3 were derived for each slip surface and fibre lineation pair. The resulting patterns for S_1 and S_3 in all five areas show a distinct preferred orientation, with predominant NNE-oriented contraction axes and ESE-oriented extension axes. Thus NNE-contraction significantly affected the Landeck phyllonite, with a fold-thrust regime (= maximum extension vertical) outlived by a strike-slip regime (=WNW-SSE-horizontal extension). The superposed deformation of the Landeck phyllonite therefore probably occurred at about the brittle-ductile transition for this kind of rock.

North of the Landeck phyllonite belt the sedimentary succession of the southernmost Lechtal sheet ranges in age from Permian to early Late Cretaceous. The steeply N- to NW-dipping or overturned stratal panels are cut by numerous NW-striking faults, some of which are probably inherited early Mesozoic normal faults and were later rotated and variably reactivated. The adjacent broad and locally fault-bounded syncline is cored by steeply dipping lower to mid-Cretaceous calcareous shales and quartzose siltstones which are capped by several klippen of the Triassic carbonate-shale succession (e.g. Krabach klippen) that correspond in structural position to the Inntal sheet (Tollmann 1976). Major SSW-directed backthrusts and reactivated older faults have locally redeformed preexisting NE- to ENE-trending fold structures. This pattern of faults and superposed folds is

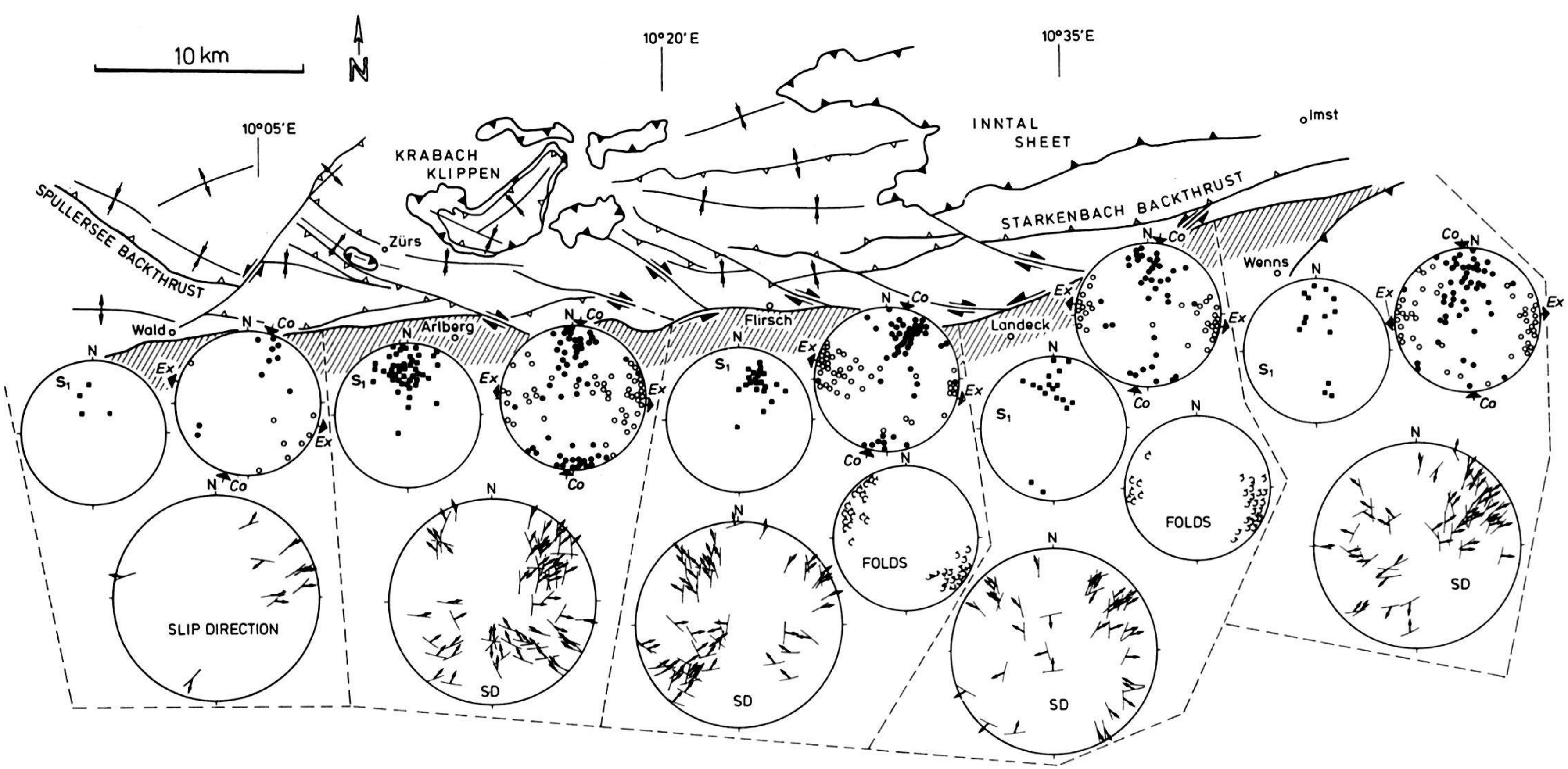

Fig. 3. Sketch map of the Stanzer valley zone along the border between the Landeck phyllonite belt (ruling) and the Permo-Mesozoic succession of the NCA (blank with thrusts and high-angle faults) after Ampferer (1932). Stereoplots for the five areas (Wald, Arlberg, Flirsch, Landeck, Wenns) illustrate mesoscopic fabric data from the Landeck phyllonite. S_1 = poles to phyllonitic foliation; SLIP DIRECTION (SD) = hangingwall slip directions from quartz fibre lineations on mesoscopic faults with great circle segments indicating orientation of slip surfaces; Co, Ex = compression axes (full circles) and extension axes (open circles) derived from mesoscopic fault slip data, assuming failure angles of 45° to σ_1 for individual slip events (see text); FOLDS = hingeline orientation and vergence (as indicated by arrow looking down plunge) of mesoscopic flexural slip and kink folds in highly anisotropic phyllonitic rocks. Note inferred reactivation of early strike-slip faults as reverse faults during N to NNE-oriented superposed contraction of the southernmost NCA.

compatible with a NNE-oriented contraction as registered by mesoscopic folds and mesoscopic fault slip data in Landeck phyllonite. Although timing of the SSW-NNE-oriented contraction within the Stanzer Zone cannot be pinned down it possibly reflects the Paleogene contraction regime that accompanied emplacement of the Austroalpine thrust complex and is well documented in the Austroalpine units of easternmost Switzerland (Ring et al. 1988; Schmid & Froitzheim 1993; Froitzheim et al. 1994).

Restoration of major displacements

The superposition of two heteroaxial sets of contraction and strike-slip structures poses a special problem if one attempts to restore the stratal panels affected by the partitioned displacements in the southern parts of the western NCA. However, mapped structural overlap and strike separations can be used to approximately restore both incipient Paleogene and late Cretaceous 'states-of-deformation' in reference to a point A located near the lower Inn River valley (Fig. 4, top). About 20 km of sinistral displacement along the Embach fault and about 10 km of partitioned NE-SW oriented dip-slip and sinistral strike-slip displacement transfer have been used to derive a restored situation for early Paleogene time, indicated as Paleogene in Fig. 4, centre. In order to retrodeform the Late Cretaceous thrust stacking, both NW-directed contraction and distributed dextral shear are used to account for NW-directed displacement increasing from east to west. Near the western Achental thrust data presented above suggest a total forward motion by thrusting and distributed strike-slip faulting of some 20 km. This amount increases to at least 20 + 20 = 40 km with the forward motion of the eastern Inntal sheet, and to 20 + 20 + 20 = 60 km with distributed strike-slip deformation of the western Inntal sheet (Fig. 4, bottom). All values are minimal relative to a reference point in the lower Inn River valley, some 200 km to the east.

Such an approximate pre-Late Cretaceous restoration shows that the Wetterstein-Partnach facies transition coincides with the positions of some of the incipient thrusts. However, another significant mechanical factor during detachment was probably a pattern of NE-trending extensional faults bounding Jurassic-Lower Cretaceous basins similar in nature to those of the southern Alps (e.g. Winterer & Bosellini 1981; Castellarin & Picotti 1990). The incipient mid-Cretaceous positions of the frontal Lechtal and Allgäu thrusts as shown in Fig. 4 (bottom) are very poorly constrained and based on coutoff lines arrived at by Eisbacher et al. (1990). Additional observations suggest that the frontal part of the NCA underwent an evolution similar to that of the trailing edge.

Structure and deformation history along the frontal NCA

North of the Jurassic-Cretaceous deposits of the Holzgau-Karwendel-Thiersee synclinal outcrop belt (Fig. 1c) of the central Lechtal sheet, the Wamberg anticlinorium and the adjoining Bavarian synclinorium are segmented by major NE-striking sinistral high-angle faults (Fig. 1). Since the leading edge of the Lechtal sheet in general consists of competent Muschelkalk-Wetterstein platform carbonates that vary greatly in thickness and change abruptly into basinal Partnach basinal shale facies, the carbonate-dominated Raibl unit above also varies in facies and thickness (Bachmann & Müller 1981). Fold-thrust structures along the leading edge of the Lechtal sheet are therefore complex and

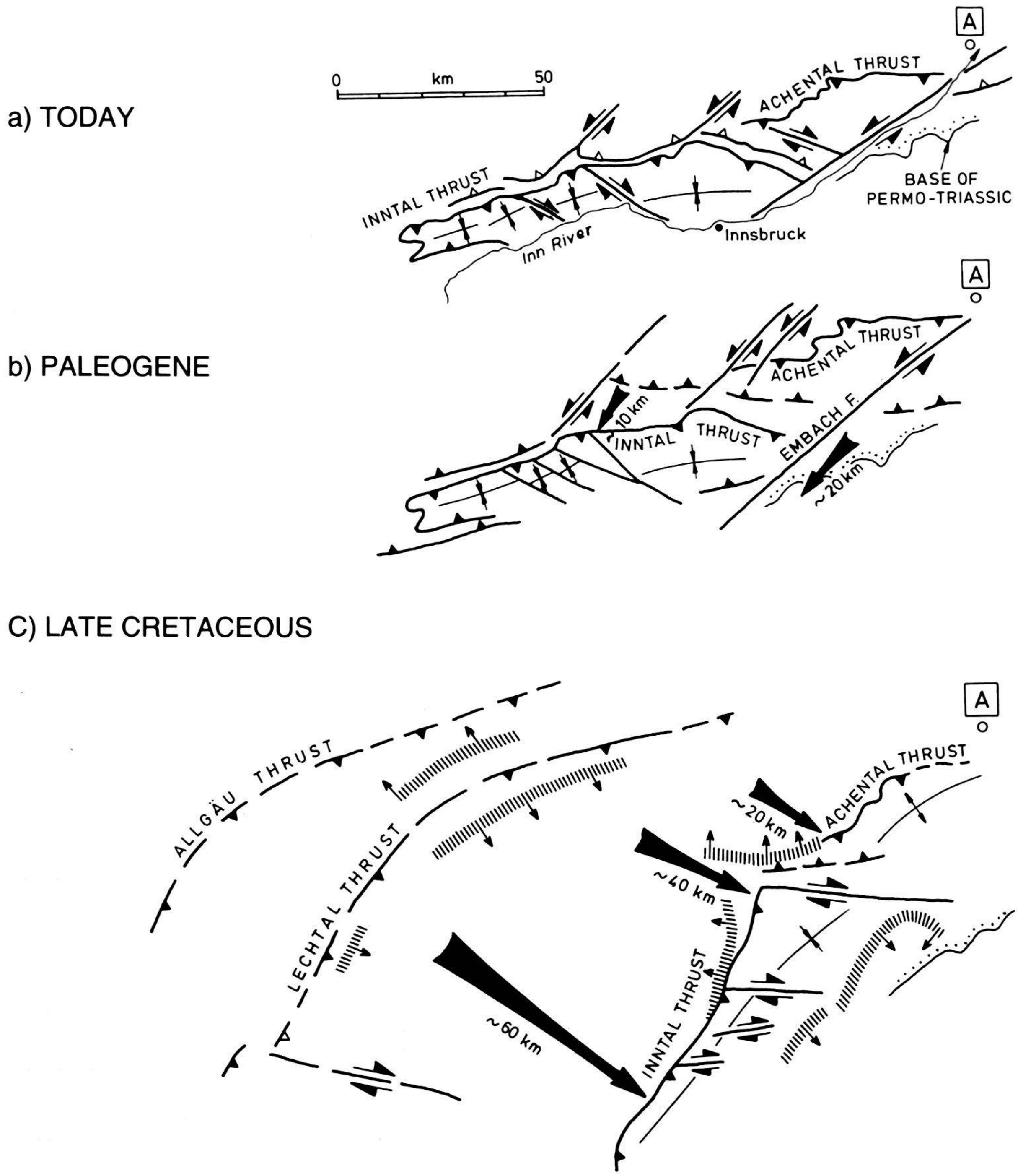

Fig. 4. Semiquantitative minimum restoration of Paleogene and Late Cretaceous displacements on major thrusts and high-angle faults near the trailing NCA wedge, using mapped minimum stratigraphic overlaps and fold axial surface offsets shown in Pl. 1 and 2. Late Cretaceous relative positions of Lechtal and Allgäu leading edges are only schematic, but compatible with regional data, and indicative of the possible influence of Wetterstein platform-Partnach basin transitions (close ruling with arrows) during initial detachment of the thrust sheets.

strongly related to pre-contraction faults, facies and thickness of the Mesozoic succession. In the exploration well Vorderriss I, a distinct cold-over-warm vitrinite reflectance discontinuity within the abnormally thick Raibl unit (Hufnagel et al. 1981) probably indicates the position of one of several early extensional fault systems of the northern Lechtal sheet.

Incipient thrusting of the leading Lechtal sheet onto the trailing Allgäu sheet probably occurred in early late Cretaceous because upper Albian clastics are the youngest perserved deposits on the Allgäu sheet (Gaupp 1982; Winkler 1988). For the Lechtal sheet early late Cretaceous (about 100 to 95 Ma) uplift, subaerial exposure and erosion of anticlinal crests has been inferred by Gaupp (1982) because in early late Cretaceous time (about 95 to 85 Ma) coarse clastics were deposited unconformably in synclinal hangingwall basins of the frontal Lechtal sheet.

In the subjacent Allgäu sheet, exposed mainly below the western Lechtal sheet, several E-plunging anticlinal footwall ridges and synclinal hangingwall lobes (Tollmann 1976; Müller-Wolfskeil & Zacher 1984) clearly reflect a N-S contraction that affected both Lechtal and Allgäu sheets after their initial thrust stacking. In the exploration well Vorderriss I (Hufnagel et al. 1981), the dip of bedding within the Allgäu sheet is also mainly southerly, while higher parts of the Lechtal sheet display southeasterly dips; this suggests a preservation of early developed NW-verging contraction structures only in the higher parts of the wedge. In the basal Austroalpine melange of western Switzerland an older WNW-trending stretching lineation is also overprinted at deeper levels by N- to NNE-trending lineations which indicate a temporal change in the direction of displacement along the Austroalpine sole thrust from WNW to NNE (Ring et al. 1988). Widespread subsidence of the entire NCA-wedge in latest Cretaceous time (85 to 75 Ma) possibly reflects the subduction-related removal ('tectonic erosion') of previously accreted sub-NCA crust (Wagreich 1993) or underplated basement slivers from the lower part of the Austroalpine wedge. It could also reflect a related phase of regional extension (Froitzheim et al. 1994). Mid- to Upper Cretaceous Rhenodanubian turbiditic flysch units derived from emergent Eurasian shelf areas accumulated to a thickness of about 2 km (Egger 1992). They were probably first overridden by the NCA-wedge in latest Cretaceous – earliest Tertiary time (about 75 to 60 Ma) because the southernmost preserved slivers of the flysch succession contain no strata younger than Maastrichtian while in more northerly panels flysch strata as young as Paleocene have been documented. In eastern Switzerland Pfiffner (1986) noted that although deformation was going on in Paleocene time south of the Helvetic shelf, the shelf itself began to subside dramatically only by mid-Eocene time. In the West Carpatians Paleogene to early Miocene (about 50 to 22 Ma) NNE-oriented contraction also overprinted an earlier phase of deformation (Nemcok & Nemcok 1994) and was possibly related to the overall N- to NE-directed advance of the Austroalpine thrust wedge onto the Eurasian shelf and platform.

It therefore seems likely that in Paleogene time progressive frontal accretion and underplating of flysch below the NCA wedge and north-northeasterly motion of the composite Austroalpine wedge over the Eurasian shelf triggered dramatic subsidence and unconformable northeasterly onlap of fine grained Paleogene clastics. This subsidence also accommodated the deposition of latest Eocene – earliest Oligocene (40 to 30 Ma) calcareous-argillaceous petroleum source rocks in the incipient foreland basin (Malzer et al. 1993). Eventual emergence of the NCA above sea level in mid- to late Oligocene time (about 30 to 24 Ma) in turn was accompanied by progradation of coarse NCA-derived clastics in the deepest parts of the eastern Molasse basin (Malzer et al. 1993). Small mid- to late Oligocene marine-nonmarine intramontane basins along NE-striking sinistral fault zones within the NCA acted locally as depocentres for clastic material derived from as far back as the trailing basement complexes of the NCA (Ortner 1994b). Viewed in this broader context it appears possible that at this time emplacement of Periadriatic plutons also was eased by a beginning sinistral transtension within the western Austroalpine thrust complex where traces of E- to ESE-oriented extension are preserved in brittle fabrics (Schmid & Froitzheim 1993; Ring 1994). An even younger dextral transpression in the southern and eastern Alps is possibly of Miocene age (Doglioni 1987; Polinski & Eisbacher 1992).

In the Oligocene-Miocene Molasse strata of the foreland final Neogene NNW-directed regional contraction (Schrader 1988) produced long ENE-trending fold-thrust structures and in small intramontane extensional basins such as that of the lower Inn River valley inversion set in (Ortner 1994b). A few NNE-striking high-angle sinistral faults related to this deformation appear to have propagated from the foreland Molasse basin into the frontal NCA-wedge, providing avenues for fluvial drainage across the NCA mountain front (see Fig. 1).

For the area discussed here Linzer et al. (1995, p. 45) have recently postulated that "NE-striking sinistral faults are Miocene structures and are associated with the lateral extrusion deformation stage of the NCA" without presenting evidence. The uniformly ENE-trending fold-thrust structures in Oligocene-Miocene foreland deposits (Fig. 1) clearly suggest that Neogene contraction was oriented NNW-SSE. As pointed out above major NE-striking faults within the western NCA do not extend to the crystalline basement units which supposedly would have acted as indentors, thus forcing lateral extrusion. Although some Neogene reactivation of fault structures cannot be ruled out, the pervasive superposition of N- to NE-oriented contraction and related sinistral transfer faulting suggests that both originated in Paleogene time during the large-scale motion of the Austroalpine complex against and over the Eurasian distal margin.

Conclusions

Superposed heteroaxial fold-thrust patterns in the western NCA are the result of a distinctly partitioned deformation along fold-thrust structures and transverse strike-slip faults. Development of incipient mid- to late Cretaceous WNW- to NW-vergent fold-thrust structures and distributed dextral shear along NW-striking high-angle faults accompanied initial detachment and stacking of the Inntal, Lechtal and Allgäu sheets. Following the uplift and erosion of early fold-thrust structures and deposition of Upper Cretaceous Gosau Group in small basins, regional subsidence prevailed into Paleogene time (Wagreich 1993, 1995). Superposed Paleogene N- to NE-oriented contraction led to linked thrusting and sinistral displacement along southwestward propagating and NE-striking high-angle strike-slip faults. A crude restoration of inferred displacements derived from overlap and offsets along major structures indicates that Triassic basin-platform transitions and Jurassic normal faults significantly influenced the early development of both high-angle faults and low-angle thrusts. Superposed deformation commonly resulted in the reactivation of early NE-trending thrust segments as high-angle faults or in the reactivation of early NW-trending high-angle faults as reverse faults with variable vergence. Miocene NNW-directed emplacement of the western NCA on top of the Molasse basin occurred on a carpet of frontally accreted flysch and subjacent platform cover strata that served as effective detachments for the passively transported Austroalpine lid.

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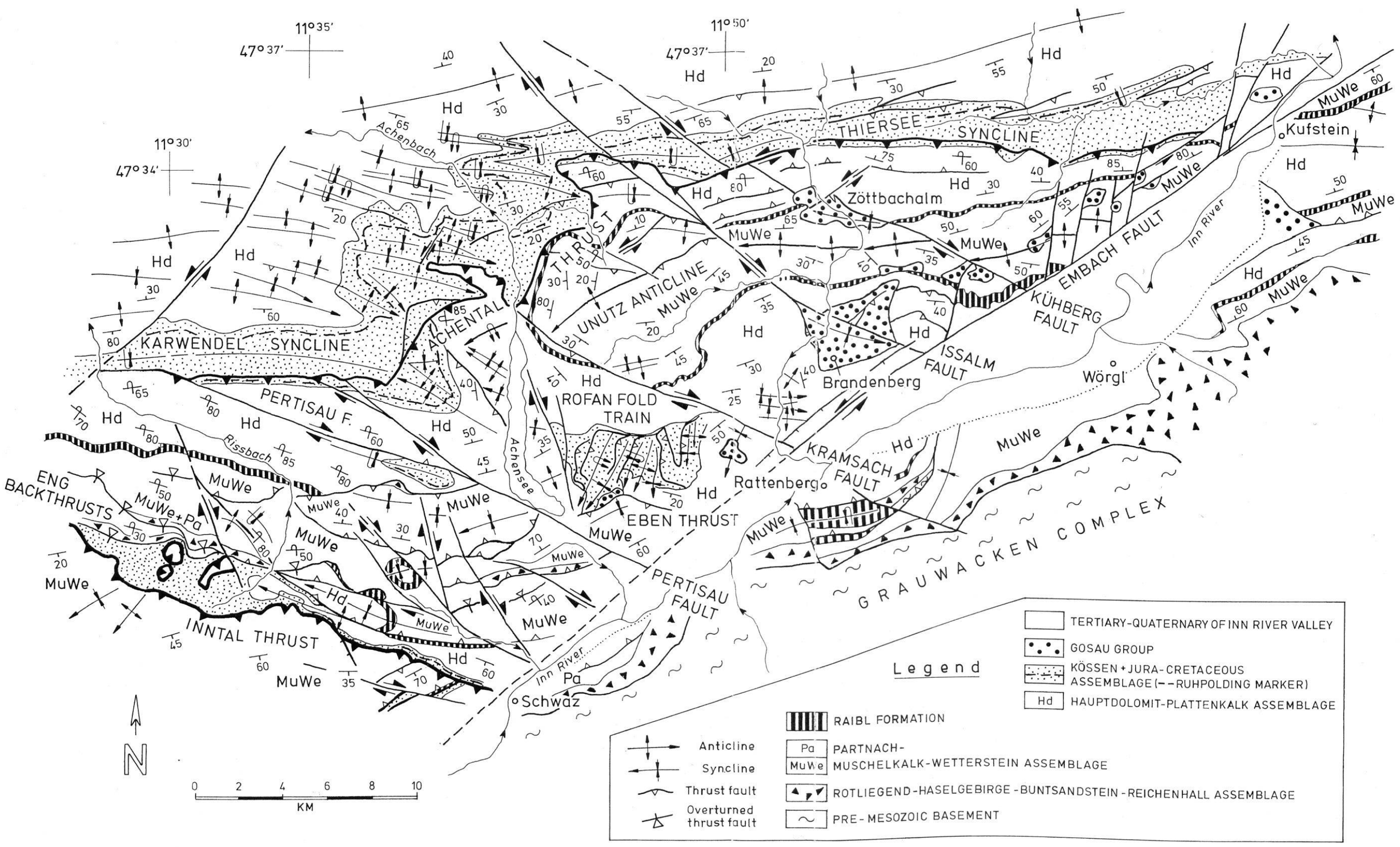
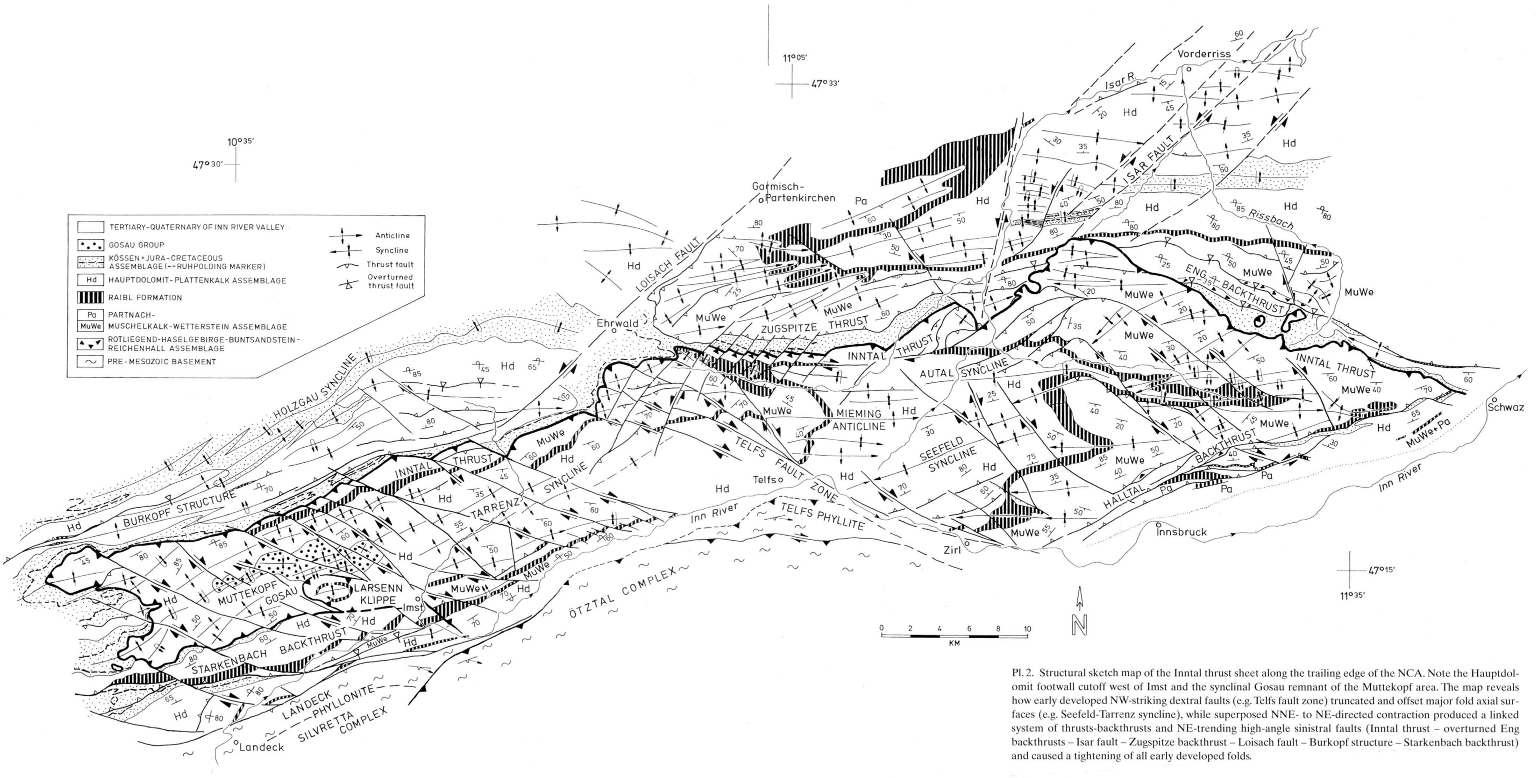


Pl. 1. Structural sketch map of the composite Unutz-Achental structure and the Karwendel-Thiersee synclinal domain, with early NW-striking high-angle faults and the location of Gosau group remnants. Note the high angles between the trends of early-formed NE-trending folds of the Unutz anticline-Rofan fold train and the trend of later-formed WNW-trending folds in the Brandenberg-Zöttbachalm Gosau remnants and on the limbs of the Karwendel and Thiersee synclines; these superposed trends are also expressed in lobate trace of the Achental thrust. The broad axial depression near Achensee probably continues as a synclinal structure east of Kufstein, having been offset sinistrally by about 20 km along the Embach fault that parallels the lower Inn River valley.



Pl. 2. Structural sketch map of the Inntal thrust sheet along the trailing edge of the NCA. Note the Hauptdolomit footwall cutoff west of Imst and the synclinal Gosau remnant of the Muttekopf area. The map reveals how early developed NW-striking dextral faults (e.g. Telfs fault zone) truncated and offset major fold axial surfaces (e.g. Seefeld-Tarrenz syncline), while superposed NNE- to NE-directed contraction produced a linked system of thrusts-backthrusts and NE-trending high-angle sinistral faults (Inntal thrust – overturned Eng backthrusts – Isar fault – Zugspitze backthrust – Loisach fault – Burkopf structure – Starkenbach backthrust) and caused a tightening of all early developed folds.