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ROLE OF HIGH-ANGLE FAULTS DURING HETEROAXIAL CONTRACTION, INNTAL THRUST SHEET, NORTHERN CALCAREOUS ALPS, WESTERN AUSTRIA

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With 7 figures

Abstract:
During Late Cretaceous/two-stage contraction of sedimentary strata within the Austroalpine accretionary wedge initial fold-thrust detachment and subsequent heteroaxial shortening were controlled by low-strength stratigraphic heterogeneities and by the propagation of transverse high-angle faults. For the Inntal thrust sheet of the Northern Calcareous Alps (NCA) about 20 km of NW-directed thrust movement was accompanied by internal shortening and by distributed dextral displacement along NW-striking transfer faults by about 15 to 20 km. Thrust sheet segmentation along high-angle transfer faults led to significant relief between stratal panels of variable vergence and accounts for local deposition in and patchy preservation of Upper Cretaceous syndeformational clastic basins. One of the authors (R.B.) interprets orogen-parallel striking normal faults with Upper Cretaceous scarp breccias as an indication of today's NW–SE extension of the early alpine nappe edifice.
Superimposed NNE–SSW-oriented heteroaxial contraction in latest Cretaceous-Paleogene time by about 10 km reactivated initial transfer faults as high-angle reverse faults, with a new set of NE-striking high-angle sinistral faults propagating from the footwall into the frontal Inntal hangingwall. This increased the plunge of pre-existing folds and produced a new set of plunging folds within fault-bounded panels. High-angle faults thus accommodated polyphase shortening of the NCA-wedge and superimposed basins that formed along transverse zones with major structural relief.

Zusammenfassung:
Während der oberkretazischen, zweiphasigen Einengung des sedimentären Schichtenstapels innerhalb des ostalpinen Akkretionskeiles werden die initialen Abscherhorizonte der Faltenüberschiebungen und die nachfolgenden heteroaxialen Krustenverkürzungen durch stratigraphisch vorgegebene Horizonte geringerer Scherfestigkeit und durch propagierende steilstehende Querstörungen kontrolliert. Die NW-gerichtete Überschiebung der Inntaldecke im Ausmaß von mindestens 20 km wurde sowohl von interner Verkürzung als auch von etwa 15–20 km weiten dextralen Seitenverschiebungen entlang NW-streichenden Transferstörungen begleitet. Die Segmentierung des Deckenkörpers durch die steilstehenden Transferstörungen führte zu einem signifikanten Relief der mit variabler Vergenz gelagerten Schichtstapel, das die synorogene klastische Sedimentation innerhalb der oberkretazischen Gosaubecken nach sich zog. Einer der Autoren (R.B.) sieht zudem in orogenparallel verlaufenden Abschiebungsstrukturen, die von Scarp-Breccien begleitet werden, einen Hinweis auf eine distensive Gosaubeckenbildung.
Die ursprünglichen Transferstörungen werden in der obersten Kreide und im Paläogen durch eine NNE–SSW-orientierte Krustenverkürzung von ca. 10 km als steile Aufschiebungen reaktiviert. Ein neues Set von sinistralen, NE-streichenden Blattverschiebungen setzt sich von der Liegendscholle in den frontalen Bereich der Inntal-Hangendscholle fort. Das Abtauchen der präexisitierenden Faltenstrukturen wird dadurch verstärkt, und es entstehen neue Sets von Falten mit abtauchenden Faltenachsen innerhalb der mit Störungen begrenzten Schichtstapel.
Steilstehende Querstörungen spielten daher sowohl bei der polyphasen Krustenverkürzung der Nördlichen Kalkalpen, als auch bei den Krustendehnungen eine wesentliche Rolle.

Introduction

Fold-thrust belts and accretionary wedges are thought to grow by forward and downward propagation of deformation, which, within more or less constant fields of regional contraction, results in wedge-shaped cross sections (ORIEL & ARMSTRONG, 1965; BALLY et al., 1966; PRICE, 1981; BOYER & ELLIOTT, 1982; DAHLEN et al., 1984). Geometric details of individual structures within fold-thrust wedges are controlled mainly by variations in stratal competence, thickness, facies, and basement configuration prior to the onset of contraction (LAUBSCHER, 1965, 1981; DAHLSTROM, 1969, 1970; THOMAS, 1990; GHISETTI & VEZZANI, 1988; HARRISON & BALLY, 1988; MCCLAY et al., 1989; CASTELLARIN & PICOTTI, 1990; DARDEAU & GRACIANSKY, 1990; HUMAYON et al., 1991; SCHÖNBORN, 1992). Recently, the interaction of major high-angle faults with growing foldthrust structures in arcuate thrust belts or accretionary wedges has been recognized as significant by BENVENUTO & PRICE (1979), SCHMIDT et al. (1988), NAMSON & DAVIS (1988), MCDOUGALL & KHAN (1990), PEIZHEN et al. (1990), and BITTERLI (1990) among others. In such settings the propagating networks of high-angle faults that truncate or interfer with fold-thrust structures range in scale from local extension fractures and tear faults to major strike-slip or convergent transfer faults that relay contraction from one segment of a fold-thrust belt to another.

In western Austria the accretionary wedge of the Northern Calcareous Alps (NCA) displays a bewildering pattern of high- and low-angle faults which developed during latest Mesozoic-Paleogene detachment, stacking and final motion of the Austroalpine crustal thrust plates towards the southern continental margin of Europe (TOLLMANN, 1976). Accessibility and outcrop permit a reasonable appraisal of the significance of high-angle structures during the protracted but polyphase-heteroaxial deformation of sedimentary strata at relatively shallow crustal levels. To document and understand some of the baffling structural relationships we have selected the highest NCA-structure, the Inntal thrust sheet, exposed north of the Inn valley, Tirol (fig. 1).

Tectonic setting and mechanical stratigraphy of the Northern Calcareous Alps (NCA)

The arcuate Austroalpine accretionary wedge (fig. 1) originated during W- to NNW-directed detachment of both pre-Mesozoic crystalline basement and Mesozoic platformal and basinal strata, 3 to 4 km thick, along the northwestern sector of the convergent Adriatic plate margin (DIETRICH, 1976; FRANK, 1987; LAUBSCHER, 1988). Syndeformational Upper Cretaceous clastics deposited on deformed carbonate strata within the NCA are generally referred to as Gosau Group (FAUPL et al., 1987; LEISS, 1988). They correlate roughly with turbiditic successions of adjacent slope and deep sea environments (GAUPP, 1982; GAUPP & BATTEN, 1983; WEIDICH, 1984; WINKLER, 1988; BERNOULLI & WINKLER, 1990). In Paleogene time the Austroalpine thrust sheets with a basal carpet of ophiolitic melange and slivers of basement were emplaced over distal European crust, parts of which developed into the Penninic and Helvetic basement-cover nappes below the relatively stiff Austroalpine lid (FRISCH, 1979; WAIBEL & FRISCH, 1989; LAUBSCHER, 1988; STAMPFLI & MARTHALER, 1990). Subsequent crustal stacking below this lid induced major Neogene uplift in eastern Switzerland (HURFORD et al., 1989; PFIFFNER et al., 1990), and caused eastward tilting and erosional retreat of the westernmost Austroalpine thrust complexes including the sedimentary NCA. Along their western up-plunge termination the NCA are about 50 km wide and consist of the sedimentary Allgäu, Lechtal, and Inntal sheets which are exposed in E-plunging synclinal semi-klippen and anticlinal semi-windows (AMPFERER, 1932; TOLLMANN, 1976). To the east the NCA sole thrust dips below sea level and has been intersected at a depth of about 6 km in the petroleum exploration well Vorderriss I (fig. 1b, BACHMANN & MÜLLER, 1981). Overall shortening within the western NCA wedge is roughly 60% (EISBACHER et al., 1990). Coal rank and illite crystallinity studies within the NCA suggest that the three main thrusts are warm-over-cold discontinuities and that there is a general north-to-south increase of paleotemperatures (KRUMM, 1984; KRUMM et al., 1988; PETSCHICK, 1989). In-

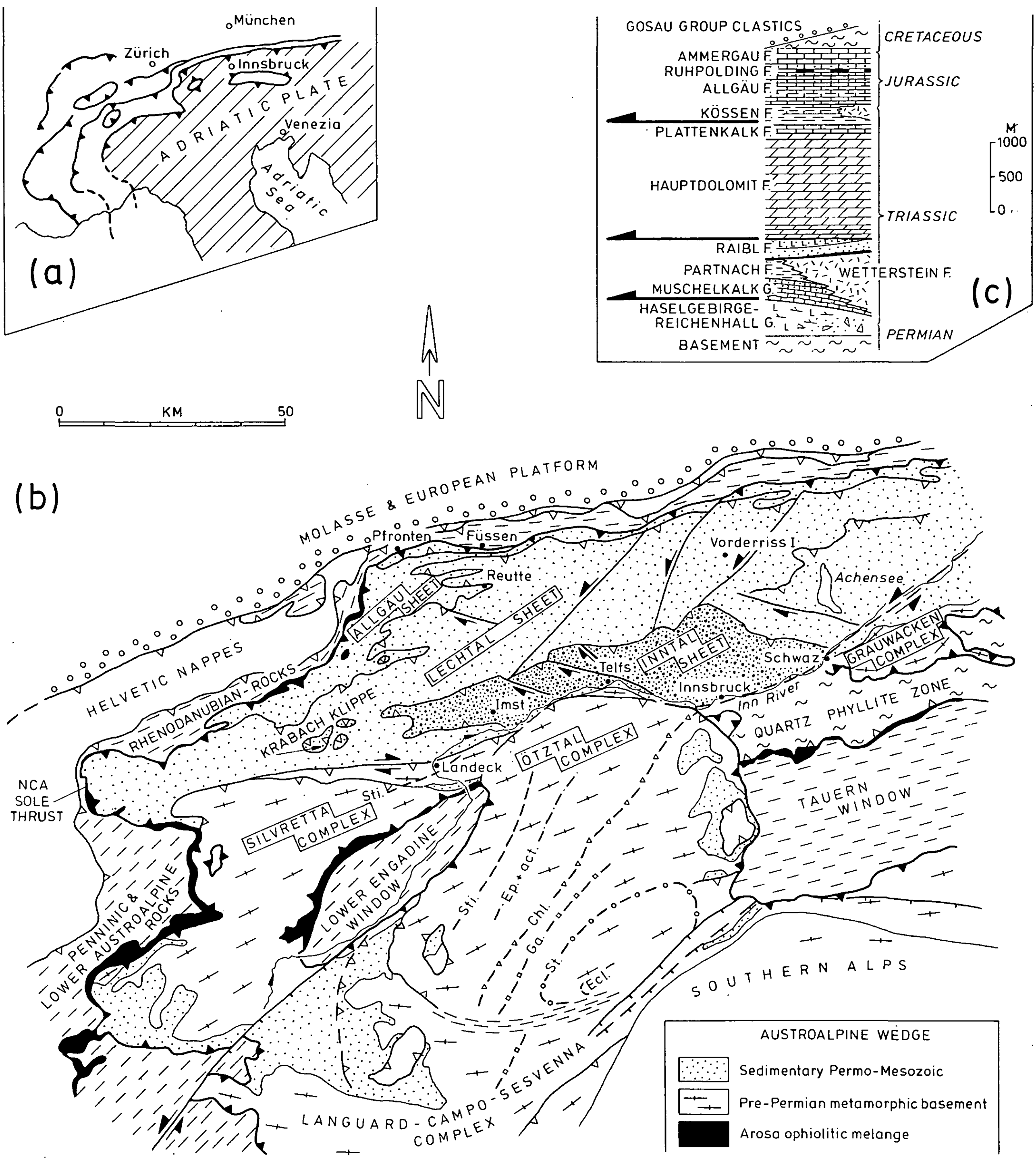


Fig. 1:

(a) Tectonic framework of the northwestern Adriatic plate margin as exposed within the Alps.

(b) Present outcrop pattern of the allochthonous Austroalpine cover and basement units of the frontal Adriatic plate which is soled by ophiolitic melange. The transported Late Cretaceous metamorphic isograds for stilpnomelane, epidote, chlorite, garnet, staurolite and the occurrence of eclogite within the Ötztal sheet are after FRANK et al. (1987). The main thrust sheets of the Northern Calcareous Alps (NCA) are outlined roughly as is their relationship to the trailing basement units.

(c) Sedimentary formations and principal detachment horizons within the NCA wedge.

crease of Late Cretaceous regional metamorphism continues southeasterly into basement-cover complexes located south of the NCA (PURTSCHELLER & RAMMLMAIR, 1982; HOINKES et al., 1982).

The structural relationships between the sedimentary NCA and the basement-cover complexes exposed on the south side of the Inn River valley (fig. 1 b) are still poorly understood. Field evidence so far suggests that the large and internally complex Lechtal sheet of the NCA is in primary but sheared contact with frontal slivers of the Silvretta complex in the west and with phyllitic rocks of the Paleozoic Grauwacken complex in the east (FRANK, 1987; LAUBSCHER, 1989; EISBACHER et al., 1990; ROCKENSCHAUB, 1990). The Allgäu sheet therefore is considered to be a lower Lechtal imbricate, while the Inntal sheet is probably a trailing upper imbricate of the Lechtal sheet (Fig. 1 b). Because the Ötztal complex lies structurally on top of the southeastern Silvretta complex (THÖNI, 1981; SCHMID & HAAS, 1989) we presume that movement of the Ötztal basement was kinematically related to motion of and deformation within the Inntal sheet. Alternatively, a correlation of the Ötztal complex and the Lechtal sheet would be possible too. The sedimentary contact of the Inntal sheet with the Grauwackenzone, a variscan deformed, low-grade metamorphic basement complex, along the lower Inn valley area supports this interpretation by one of the authors (R.B.). The increasing grade of metamorphism in the Ötztal cover-basement complex implies that a thick thrust mass must have existed on top of the Ötztal complex towards the southeast. The Quartz Phyllite zone along the Inn valley (Fig. 1 b) is a sub-Grauwacken low-grade metamorphic sliver of unknown provenance, but possibly was originally situated in front of the NCA platform (TOLLMANN, 1976).

Within the NCA the development of flexural-slip folds, blind or emergent thrusts, folded sole thrusts, and high-angle transfer structures was controlled by the behaviour of two mechanically dominant carbonate units of Triassic age: the Muschelkalk-Wetterstein interval and the Hauptdolomit Formation (Fig. 1 c). Basal detachment of the NCA occurred along the 100 to 300 m thick Permo-Triassic shale-evaporite units of the Haselgebirge-Reichenhall interval which commonly is pervasively brecciated along major thrust ramps. The Muschelkalk-Wetterstein interval above the basal detachment consists of massive to thick-bedded reef or platform carbonates about 500 to 2000 m thick which interfinger locally with thinly bedded nodular Muschelkalk limestone and regionally with calcareous mudrock of the much thinner Partnach Formation. The overlying incompetent Raibl Formation therefore varies from about 100 m above massive Wetterstein Formation to 750 m above the Partnach Formation. It consists of clastic and/or carbonate cycles including an upper evaporitic interval which constitutes the detachment horizon for the overlying Hauptdolomit Formation. The Hauptdolomit Formation is a competent but well bedded dolostone unit, about 1500 m thick, which, towards the top, changes into calcareous Plattenkalk facies, bituminous Seefeld facies or calcareous mudrock of the Kössen Formation. All these serve as upper detachments for the thin-bedded Jurassic-Cretaceous succession above. For the sake of convenience the uppermost Triassic Kössen shale-limestone couplet has been grouped with the Jurassic-Cretaceous succession in the sketch maps. Jurassic-Cretaceous strata are as thin as 100 m in platformal settings and as thick as 1000 m in basinal settings. A thin radiolarian chert unit, the Ruhpolding Formation, serves as convenient structural marker. Within the NCA, cleavage developed only in anchimetamorphic argillaceous units of the southernmost outcrop belt.

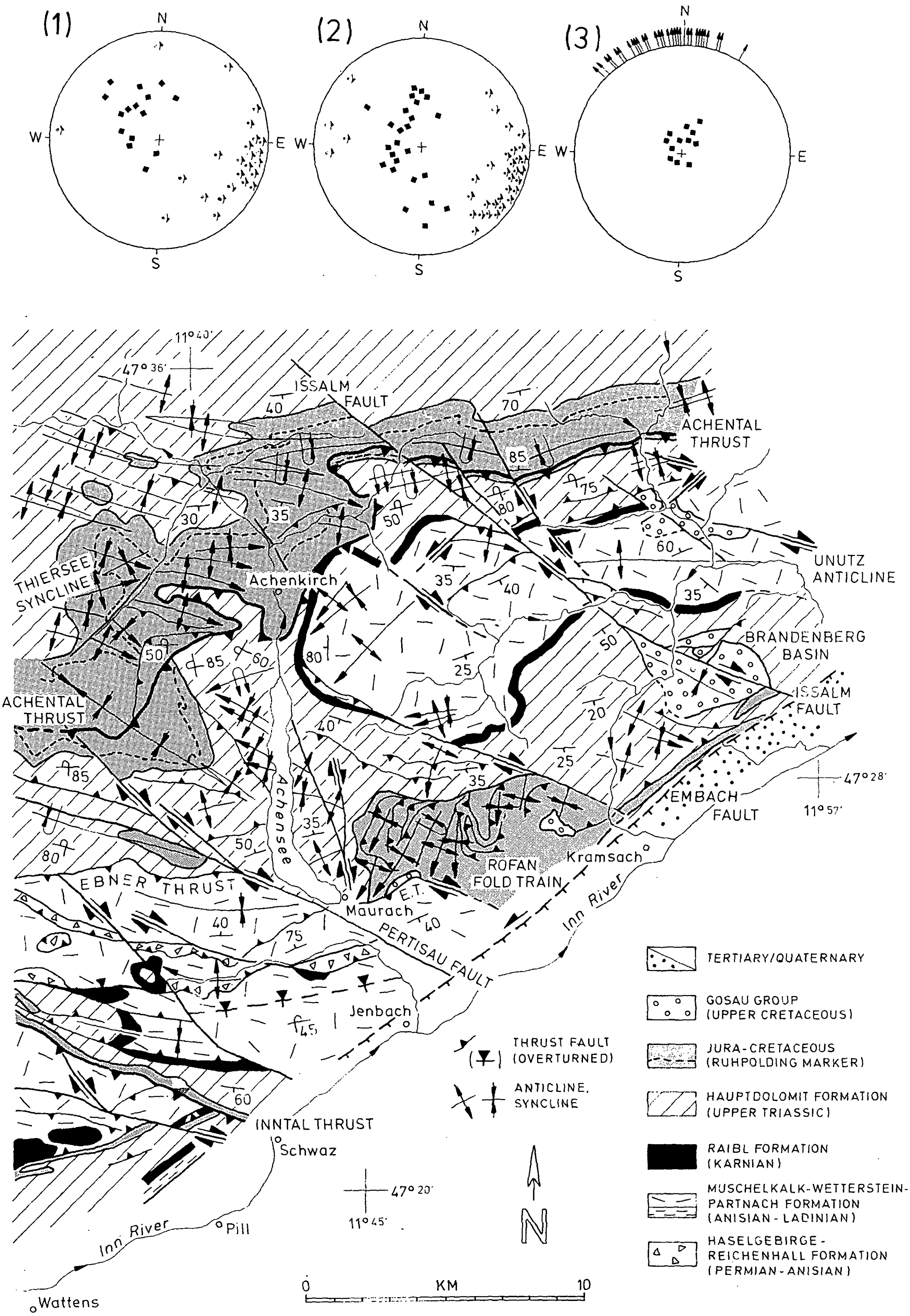
Geometry of the Inntal sheet

The ENE-trending frontal thrust trace of the lobate Inntal sheet can be mapped for about 100 km along strike (fig. 1). To the east it is deflected sharply to the southeast and disappears in the Inn valley, while to the west erosion has created a large E-plunging semi-window near the Inn valley defining the main body of the sheet. The sheet is about 20 km wide in the east and 10 km wide in the west and towards the area beyond it is represented by several erosional klippen (e.g. Krabach klippe in Fig. 1). Within the broadly synclinal Inntal sheet a westward decrease in the proportion of Muschelkalk-Wetterstein carbonates and a westward rise in the position of the sole thrust from within the basal Haselgebirge-Reichenhall interval to the Raibl and upper Hauptdolomit levels is expressed in a change of wavelengths of subsidiary fold-thrust structures from about 5 km in the east to around 3 km in the west. High-angle transfer faults within the Inntal sheet are also spaced progressively closer towards the west. Near the Inn valley proximity of pre-Mesozoic basement and pronounced facies changes coincide with backthrusts within both the Inntal and Lechtal sheets (see below). The Ötztal, Silvretta, and Grauwacken basement complexes thus represent northward tapering backstops for both Inntal and Lechtal sheets (EISBACHER et al., 1990). Since the Inntal sheet appears to have been detached along the trailing portion of the Lechtal sheet, progressive detachment, high-angle faulting, internal deformation, and heteroaxial overprinting are discussed by proceeding from the Achensee area on the east to the westernmost exposures of the sheet.

Achensee area

The Achensee area encompasses the trailing edge of the Lechtal sheet east of the Inntal thrust trace (fig. 1). The area is dominated by the NW-verging composite Unutz anticline – Achental thrust structure that is segmented by NWstriking high-angle transfer faults, the most prominent of which are the Issalm, Kramsach and Pertisau faults (fig. 2). The Unutz-Achental-structure represents an arrested stage of fold-thrust detachment along the trailing portion of the Lechtal sheet, a situation quite similar to that which probably preceded detachment of the Inntal sheet to the west. The SW-plunging Unutz anticline is cored by competent Wetterstein and Hauptdolomit carbonates with overlying Jurassic-Cretaceous strata changing from relatively thin platformslope facies in the Rofan fold train of the hangingwall to considerably thicker basinal facies in the adjacent Thiersee syncline (NAGEL, 1975; CHANNELL et al., 1992). The Achental thrust structure probably nucleated along a roughly NE-striking synsedimentary normal fault zone of Jurassic age (CHANNELL et al., 1990) and propagated from below the overturned forelimb of the Unutz hangingwall anticline into tightly folded Jurassic-Cretaceous strata of the Thiersee syncline. There the m- to 100 m-scale folds developed by stratal detachment above the Hauptdolomit Formation. The Achental thrust, exposed east of Achenkirch, is associated with semipenetrative shear veins in Lower Cretaceous argillaceous footwall. Calcite fibre lineations indicate a mean N- to NNW-directed motion perpendicular to the general ENE-striking thrust trace (fig. 2, diagram 3). The thrust disappears and/or at least loses displacement both to the east and west within a strike distance of about 15 km. A strike projection of steeply dipping to overturned Jurassic-Cretaceous strata (e.g. Ruhpolding chert marker) into the area beneath the central thrust segment indicates minimum forward thrust displacement of about 7 km. This motion was accompanied by propagation of and dextral displacement along NW-striking high-angle transfer faults. Some rotation around local vertical axis is also suggested by paleomagnetic data from Lower Jurassic redbeds (CHANNELL et al., 1990). To the west the Unutz – Achental structure is truncated by the dextral Pertisau transfer fault which also offsets the Ebner backlimb thrust by about 6 km. Along the transfer faults displacement is accommodated between the Unutz – Achental structure on the east and the Inntal thrust on the west. The northwesterly strike of the easternmost segment of the Inntal thrust trace suggests that it also originated as a dextral transfer fault.

Throughout the Achensee area there are numerous superimposed folds with axial surfaces oriented at relatively high angles to the trend of the Unutz – Achental structure (fig. 2). They are particularly prominent in the upright limb of the Thiersee syncline. Their geometry also determined the lobate erosional geometry of the Achental thrust trace. Superimposed contraction appears to have been substantial in Achental hangingwall strata as well and is indicated by strongly


(1)
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N
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ISSALM FAULT
ACHENTAL THRUST
THIERSEE SYNCLINE
Achenkirch
UNUTZ ANTICLINE
BRANDENBERG BASIN
ISSALM FAULT
EMBACH FAULT
47° 28'
11° 57'
Achensee
ROFAN FOLD TRAIN
Kramsach
Maurach
E.T.
EBNER THRUST
PERTISAU FAULT
Inn River
Jenbach
INNTAL THRUST
Schwaz
Inn River
Pill
Wattens
47° 20'
11° 45'
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THRUST FAULT (OVERTURNED)
ANTICLINE, SYNCLINE
TERTIARY/QUATERNARY
GOSAU GROUP (UPPER CRETACEOUS)
JURA-CRETACEOUS (RUHPOLDING MARKER)
HAUPTDOLOMIT FORMATION (UPPER TRIASSIC)
RAIBL FORMATION (KARNIAN)
MUSCHELKALK-WETTERSTEIN-PARTNACH FORMATION (ANISIAN - LADINIAN)
HASELGEBIRGE-REICHENHALL FORMATION (PERMIAN-ANISIAN)

NW-plunging folds in Hauptdolomit Formation along the Achensee shore (fig. 2). Pre-existing NW-striking high-angle transfer faults were locally reactivated as reverse structures. In suitably oriented stratal panels bordered by faults the heteroaxial contraction thus produced folds whose plunges were clearly determined by pre-existing stratal dip (fig. 2, diagrams 1 and 2).

Timing of initial detachment and heteroaxial superposition of fold-thrust structures in the Achensee area are constrained by remnants of syntectonic clastics. Thus, the youngest deformed strata in the Thiersee syncline are Albian calcareous mudrocks which locally are interbedded with conglomeratic channel deposits composed of limestone clasts derived from a nearby Lower Cretaceous shallow water platform (WEIDICH, 1984). Therefore, closure of the syncline and emergence above sea level of anticlinal structures probably commenced by late Albian time. Upper Cretaceous (Coniacian-Santonian) nonmarine-marine Gosau Group strata of the Brandenberg Basin rest unconformably on Triassic strata down to the level of the Wetterstein Formation and straddle the high-angle Issalm transfer fault. Detailed biostratigraphic work of HERM et al. (1979) shows that the trace of the Issalm fault separates a shallow-water carbonate-clastic facies domain of Coniacian age on the northeast from a turbiditic deeper water clastic facies of Coniacian-Santonian age on the southwest. Depositional relief of about 500 m, inferred from the paleoecology of the two domains (HERM, 1992), is still reflected by the structural relief of the basal unconformity. Post-Gosau deformation of the Brandenberg strata produced a NW-trending anticline-syncline pair (fig. 2). Similar trending folds were observed in other remnants of the Gosau Group a few kilometres to the north. We therefore propose that the early NW-SE-oriented contraction and associated propagation of NW-striking dextral transfer faults from the trailing edge of the Lechtal sheet commenced in mid-Cretaceous time at about 100 Ma. Pronounced subsidence along high-angle transfer faults occurred during the Late Cretaceous, between 90 and 80 Ma. A superimposed NE–SW-oriented contraction probably caused stratal shortening and uplift of the deposits after 80 Ma. Finally, the NE-striking Embach fault along the Inn River valley truncated all structures of the NCA and borders a lower Oligocene clastic basin (STINGL, 1990). The superimposed contraction therefore is crudely constrained between about 80 and 30 Ma. The approximate timing of the two deformation events and the role of high-angle transfer faults within the trailing Lechtal sheet is relevant with respect to the timing of initial detachment, emplacement, and deformation of the Inntal sheet to the west.

Inntal sheet

a) Eastern Inntal sheet

In the easternmost Inntal sheet open W- to SW-plunging folds are truncated by NW-striking high-angle faults and by the NW-striking lateral border of the Inntal thrust sheet (fig. 3). The main ENE-striking frontal thrust is overlain by multiple NW-directed imbricates of competent Muschelkalk-Wetterstein strata. Internally, the geometry of the sheet is governed by the major Mieming anticline-Autal syncline pair which is also offset by several WNW- to NW-trending dextral transfer faults and by the Seefeld axial depression (fig. 3). Most of the dextral high-angle transfer faults do not extend

Fig. 2: Geologic sketch map for the trailing Lechtal sheet in the Achensee area, east of the Inntal thrust trace (see fig. 1). Note the major NE- to ENE-trending Unutz-Achental-Thiersee structures and related NW-striking highangle transfer faults, one of which controlled the location of the syndeformational Upper Cretaceous Brandenberg basin. Superimposed WNW-trending folds whose plunge and geometry determined the eventual erosional outcrop pattern are also prevalent on the mesoscopic scale as shown by stereonet diagrams for dominant stratal dips (squares) and asymmetric folds (vergence by circle around the fold axis dot) in the areas west (a) and east (b) of Achenkirch. Diagram (c) illustrates stratal dips (squares) and trend of shear vein lineations (arrows) in argillaceous footwall rocks below the Achental thrust east of Achenkirch.

into the Lechtal sheet beyond the Inntal thrust front. The trailing edge of the sheet is characterized by the major S-directed Halltal backthrust and related imbricates which, in the past, have been interpreted as parts of the footwall below a 'freely floating' Inntal sheet (TOLLMANN, 1976). However, the Halltal backthrust clearly cuts upsection from west to east and progressively deeper footwall imbricates contain a higher proportion of basinal Partnach mudrock facies in place of Wetterstein platform carbonates (fig. 3). Also, a southward rising basement surface below the basal evaporitic Haselgebirge-Reichenhall detachment, indicated by refraction seismic interfaces with velocities of up to 6 km s^{-1} near the Inn valley (ANGENHEISTER et al., 1972), suggests a basement controlled backthrust zone within the southernmost Inntal sheet. Partnach mudrock facies also dominates imbricated panels of Triassic strata above the Grauwacken zone basement exposed south of the Inn River.

Because the eastern end of the Inntal thrust strikes into the Inn valley a potential footwall cutoff structure for the Inntal front is difficult to define. However, the complex structure in steeply N-dipping to overturned Wetterstein strata in the Lechtal sheet east of Schwaz indicate that detachment of Wetterstein-Muschelkalk strata probably occurred along trend to the west, somewhere in the vicinity of the present Inn valley. This would imply a NNW- to NW-directed thrust motion of at least 20 km. In the footwall east of the main Inntal thrust trace massive Wetterstein facies also changes northerly into Partnach mudrock (DONOFRIO et al., 1980) and we therefore infer that most of the Triassic footwall below the Inntal sheet consists of Wetterstein-Hauptdolomit carbonate facies. During progressive contraction the Eng- and Zugspitze backthrust zones in the footwall carried the Wetterstein-Partnach facies transition southward over Jura-Cretaceous strata which constitute the immediate footwall of the Inntal thrust sheet (sections AB and CD in fig. 3).

Post-thrust emplacement deformation of the Inntal sheet probably continued within a changed field of contraction and resulted in the presently exposed hangingwall-footwall pattern. Towards the east NNE-directed motion of the Inntal sheet by at least about 4 to 8 km is suggested by Muschelkalk-Wetterstein klippen and by the northnortheasterly overturned footwall panel including the earlier formed Eng backthrusts. Along the original thrust front near Mittenwald the NE-striking sinistral Isar transfer fault of the footwall accommodated the advancing Inntal thrust, the Jura-Cretaceous footwall outcrop was closed and backthrusts were tilted into a vertical orientation. West of the Isar fault zone, the Zugspitze backthrust, continued to move in a south-southwesterly direction and backtilted the frontal Inntal thrust. Thus, NNE-directed motion of the Inntal sheet in the east, sinistral displacement transfer in the centre, and south-southeasterly motion of the Zugspitze backthrust in the west all accommodated NNE–SSW-oriented contraction amounting to about 5 to 10 km. This pattern of contraction was superimposed onto NW-directed structures which had developed in the Inntal sheet during earlier thrust motion. Superimposed deformation also accentuated the Seefeld axial depression and accounts for the bulbous plunging geometry of the Mieming anticline.

b) Western Inntal sheet

Towards its western up-plunge termination both hangingwall folds and related branch thrusts in the Inntal sheet are cut and offset by NW-striking high-angle transfer faults (fig. 4). Dextral offsets on individual high-angle faults are generally small, tend to decrease from southeast to northwest, and most of them do not seem to extend beyond the frontal Inntal thrust. Between the major Telfs transfer zone and the syntectonic Muttekopf Gosau basin distributed dextral separation of the Tarrenz synclinal axial surface and the SSE-dipping Raibl Formation is in the order of 10 to 20 km. Towards the trailing edge of the Inntal sheet high-angle transfer faults separate stratal panels with variable structural vergence (fig. 5). Near the locality of Imst, shortening is accommodated within the strongly NW-vergent Tarrenz syncline, by the SSE-vergent Tschirgant backfold-thrust structure (NIEDERBACHER, 1982), and by

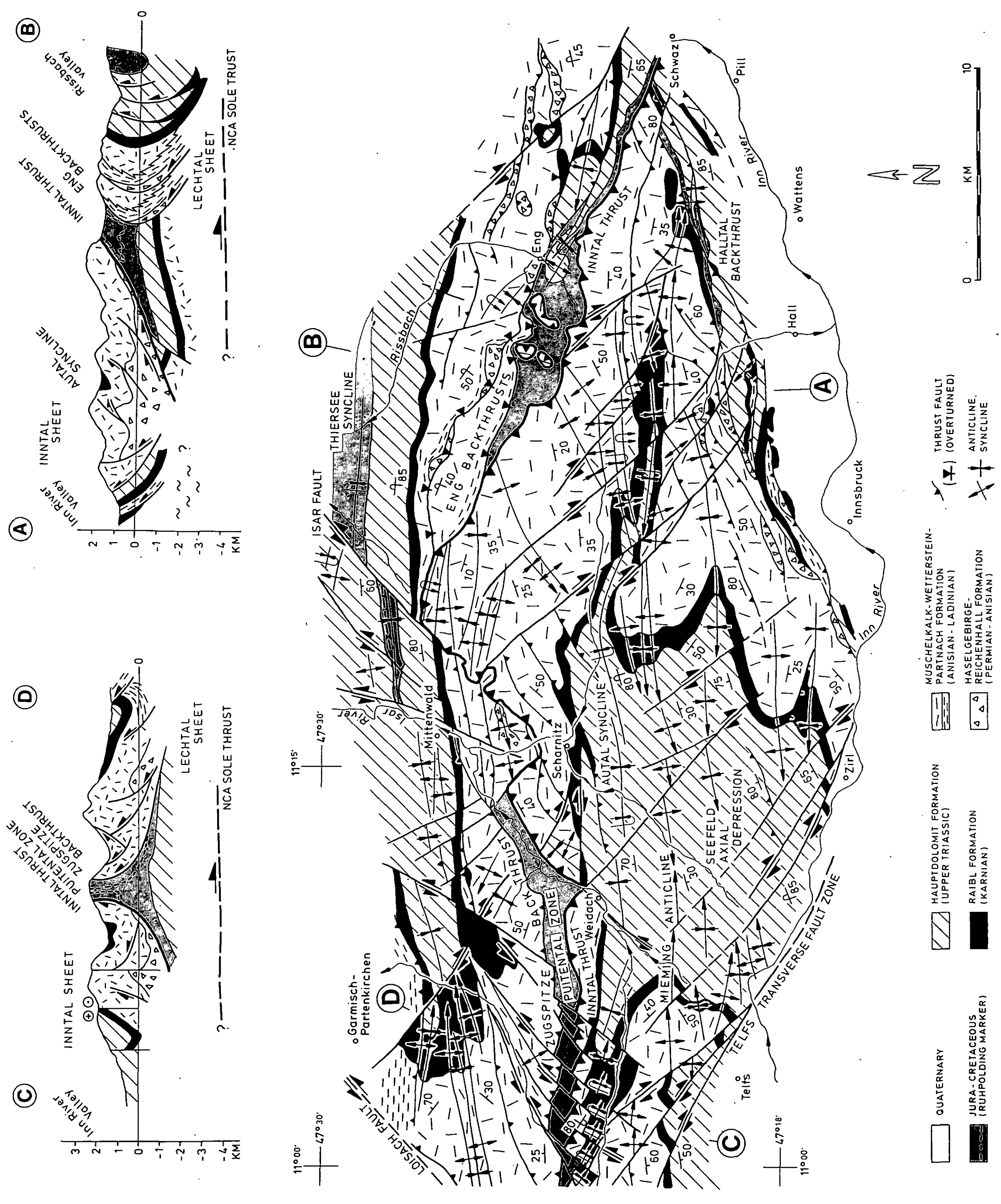

Fig. 3: Geologic sketch map of the eastern Inntal sheet. Note the ENE-trending fold thrust structures within the Inntal sheet which are truncated by the NW-striking eastern segment of the Inntal sole thrust and by other high-angle dextral transfer faults. Superimposed heteroaxial contraction with SSW-directed motion of the Zugspitze backthrust and NNW-directed motion with overturning of the Eng footwall backthrusts is illustrated by the two cross sections. These motions were accommodated by sinistral-convergent displacement transfer amounting to about 5 to 10 km and including the SW-propagated Isar fault and others which cut the earlier NW-striking faults.

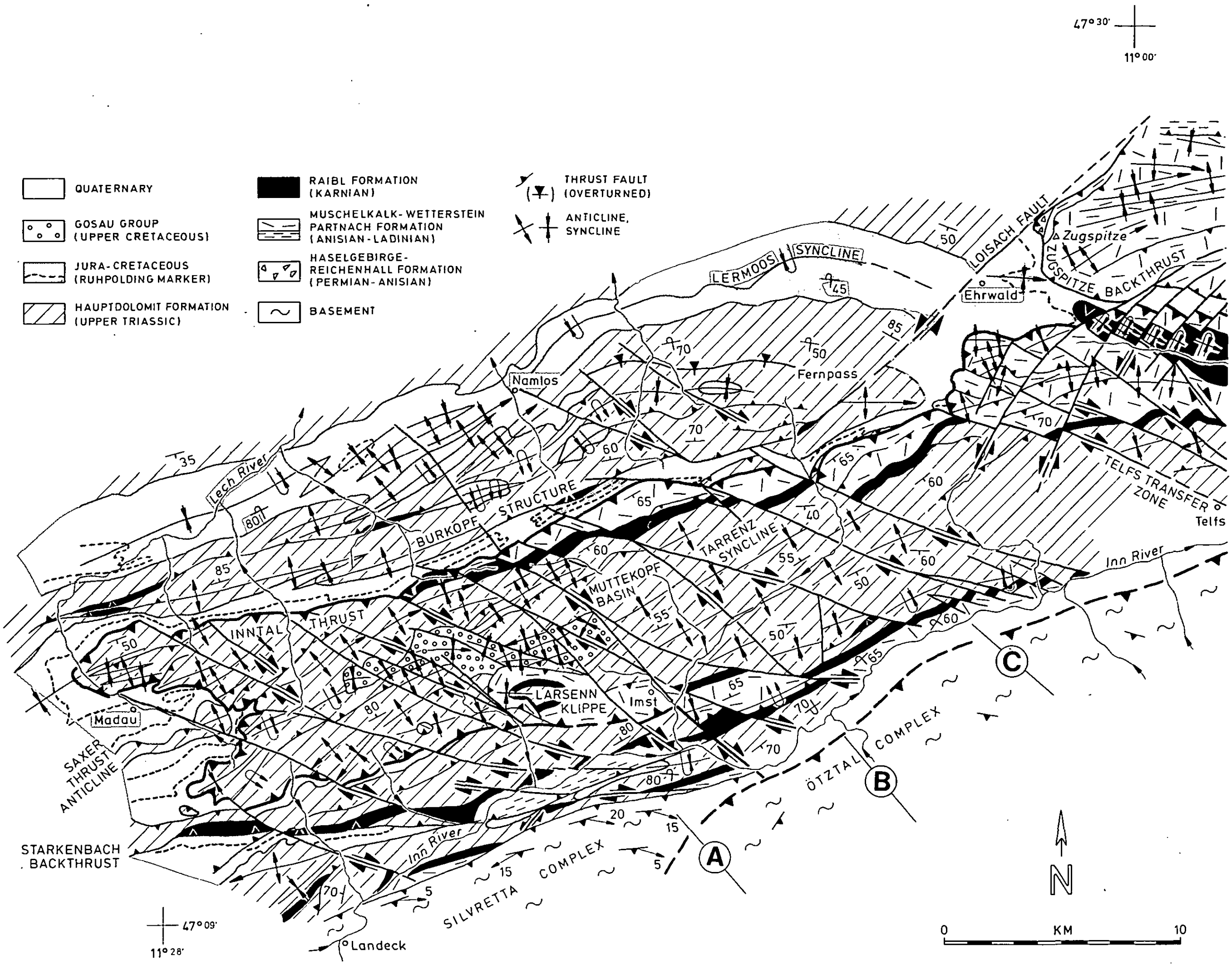

Fig. 4: Geologic sketch map of the western Inntal sheet. Note that ENE-trending folds and the frontal thrust are displaced by numerous NW-striking transfer faults which appear to have propagated in a northwesterly direction. A diving footwall fold is outlined by the Ruhpolding chert marker east of Madau. Erosional remnants of the Upper Cretaceous clastic Muttekopf basin are located along a major dextral transfer fault and in front of the Larsenn klippe, whose emplacement could have occurred as part of the forward motion of the Ötztal sheet and thus may have enhanced local tectonic subsidence. Erosion along the Starkenbach footwall backthrust has exposed a potential footwall cutoff for Hauptdolomit Formation in the frontal Inntal sheet and the Silvretta basement units which are characterized by retrograde semi-penetrative stretching lineations (shown as arrows) and indicate dextral shear.

emplacement of the Larsenn klippe. Loading by the Larsenn thrust may have aided local subsidence of the Muttekopf basin along a major high-angle transfer fault (fig. 4). To the west transfer faults are seen to cut footwall strata below the Inntal sheet. They also merge with W-trending semi-penetrative dextral shear zones within the steeply dipping transition zone between the Lechtal sheet and Silvretta basement rocks. The prevailing NNW- to NW-vergence of subsidiary folds both in hangingwall Hauptdolomit strata and in the intermediate Jurassic-Cretaceous footwall suggest a broadly NNW- to NW-directed thrust detachment and emplacement of the Inntal sheet), as inferred by TOLLMANN (1976). There is strong evidence that contraction of footwall strata below the Inntal sheet began while forward motion of the sheet was still going on. Near the locality of Madau (fig. 4) the footwall geometry of the Jurassic Ruhpolding marker, first mapped by AMPFERER (1932), demonstrates that during development of the Saxer thrust-anticline in the footwall the Jurassic-

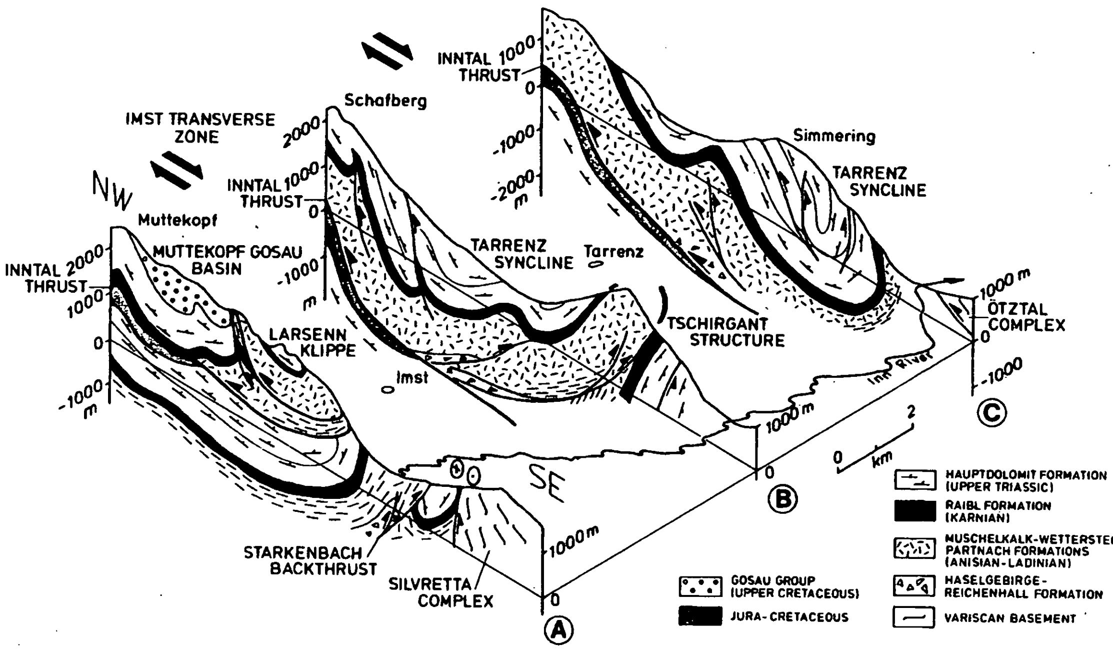

Fig. 5: Three partial sections which display the variable vergence and structural style of individual stratal panels separated by high-angle transfer faults within the trailing portion of the western Inntal sheet (for location see fig. 4).

Cretaceous strata along the anticlinal crest were extended below the moving Inntal sheet and rolled forward into a NNW-diving anticline filling the core of an adjacent syncline before motion of the hangingwall was impeded by footwall backthrusting along the Burkopf and Starkenbach backthrusts. The latter facilitated erosion of an E-plunging semi-window revealing the probable footwall cutoff of Hauptdolomit strata at a distance of about 20 km to the southeast of the frontal Inntal thrust trace. Thus, NW-directed thrust displacement of at least about 20 km, similar in magnitude to the eastern Inntal sheet, can be inferred for the western part of the sheet. However, displacement by thrusting was accompanied by the equally significant longitudinal segmentation of the thrust sheet along dextral transfer faults. These seemingly propagated into the direction of thrust sheet motion which was accompanied by some footwall contraction below the sheet. Backthrusting along the Burkopf structure probably occurred within a slightly changed field of contraction and was transferred from the broadly SSW-directed Zugspitze thrust via the SW-propagating sinistral Loisach fault and caused significant tightening of all footwall structures (EISBACHER et al., 1990). Other NE-striking sinistral faults which propagated from the Lechtal sheet southwesterly cut both the Inntal thrust front and the earlier developed NW-striking dextral transfer faults. Near the Starkenbach backthrust which is a cold-over-warm paleogeothermal discontinuity (KRUMM et al., 1988) cleavage in argillaceous units was refolded into E–W-trending 'retrograde' kink bands.

c) Timing of contraction and displacement transfer within the Inntal sheet

Timing of detachment and internal deformation of the Inntal sheet are relatively well constrained. Jurassic-Cretaceous footwall strata in the Puitental zone near the Zugspitze backthrust contain mafic dikes which intruded at about 100 Ma and suggest a broadly extensional framework (TROMMSDORFF et al., 1990). Locally derived olistostromes of probable Cenomanian age are overridden by the western Inntal sheet near Madau, while on top of the sheet syndeformational Gosau Group of Coniacian to Maastrichtian age (about 90 to 70 Ma) was

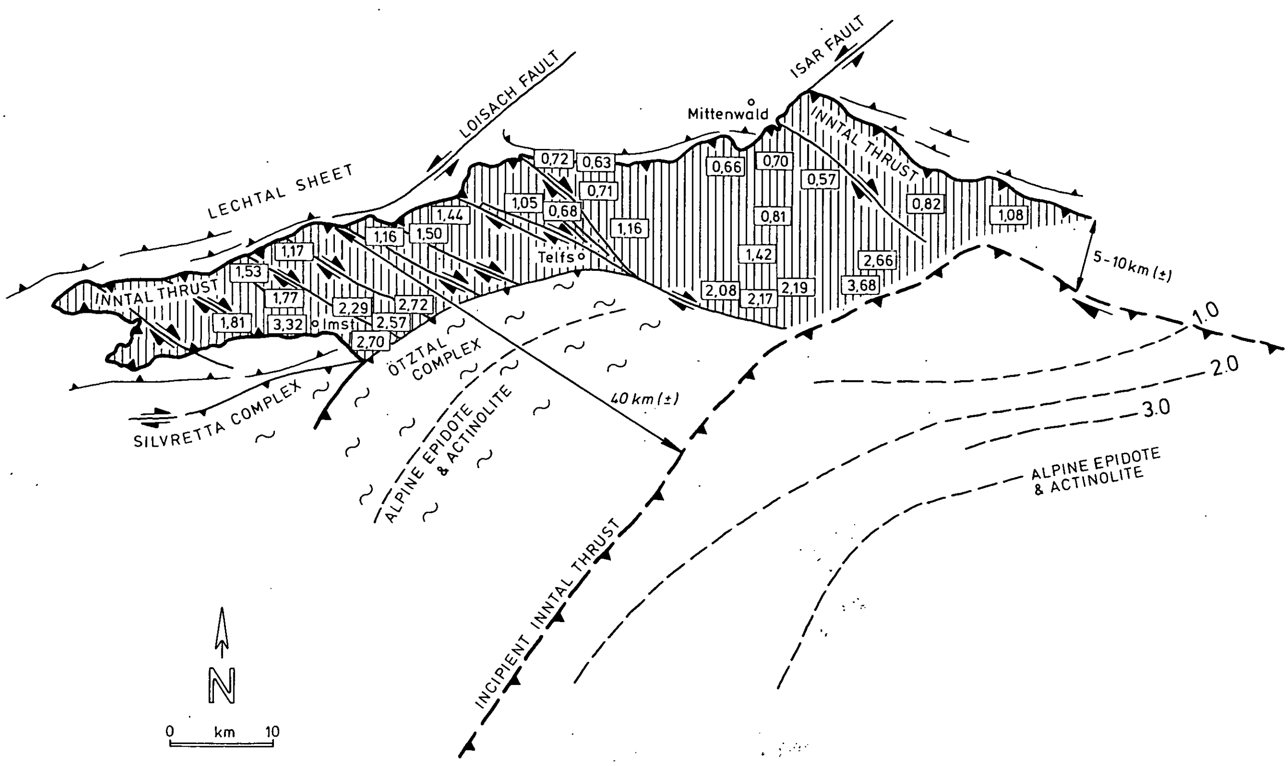

Fig. 6: Approximate restoration of the incipient Inntal thrust and trailing Ötztal complex relative to the LechtalSilvretta complexes. Vitrinite reflectance values Rmax in the Raibl Formation (after PETSCHICK, 1989) and transported metamorphic isograd are also restored and demonstrate that NW-directed thrust and distributed dextral transfer displacements in the Inntal sheet during the Late Cretaceous amounted to about 40 km and that they increased towards the west. About 10 of NE-directed motion is implied for the superimposed contraction event.

deposited unconformably on Hauptdolomit Formation in the synclinal Muttekopf basin (LEISS, 1988; ORTNER, 1992, 1994)).

This basin contains coarse mass flow deposits with huge limestone slabs of Kössen reef facies and fining-upwards cycles of turbiditic sandstones and conglomerates containing detritus derived from pre-Triassic basement (WOPFNER, 1954) and ultramafic source areas (DIETRICH & FRANZ, 1976). Since WNW-directed thrusting of the Ötztal basement complex has been dated also at about 90 to 70 Ma (THÖNI, 1988; SCHMID & HAAS, 1989), it is probable that emplacement and deformation of the Inntal sheet was driven by thrust motion of the Ötztal complex onto the Silvretta complex. The small Larsenn klippe (fig. 5) could have been part of the frontal cover of the Ötztal complex. Numerous semi-penetrative and/or chlorite-coated brittle shear zones in both Silvretta and Ötztal basement rocks display striations and semipenetrative stretching lineations that indicate oblique dextral motion. The WNW- to NW-striking high-angle faults which propagated from the Inn valley into the Inntal thrust sheet probably created the relief for sedimentary source areas and transfer fault basins, before continued contraction and backthrusting elevated the entire Inntal edifice above sea level during latest Cretaceous-Paleogene time.

A palinspastic model for the Inntal sheet in which about 20 km of NW-directed thrusting, 10 to 20 km of distributed dextral shear along high-angle NW-striking faults, and about 5 to 10 km of NNE-directed superimposed thrusting are restored shows an original NE-trending thrust front with the realigned coal rank values of PETSCHICK (1989) for the Raibl Formation (fig. 6). A NW- to WNW-directed motion of at least about 40 km for the sheet amounts roughly to the thrust overlap of Ötztal over the Silvretta complex, as inferred by SCHMID & HAAS (1989).

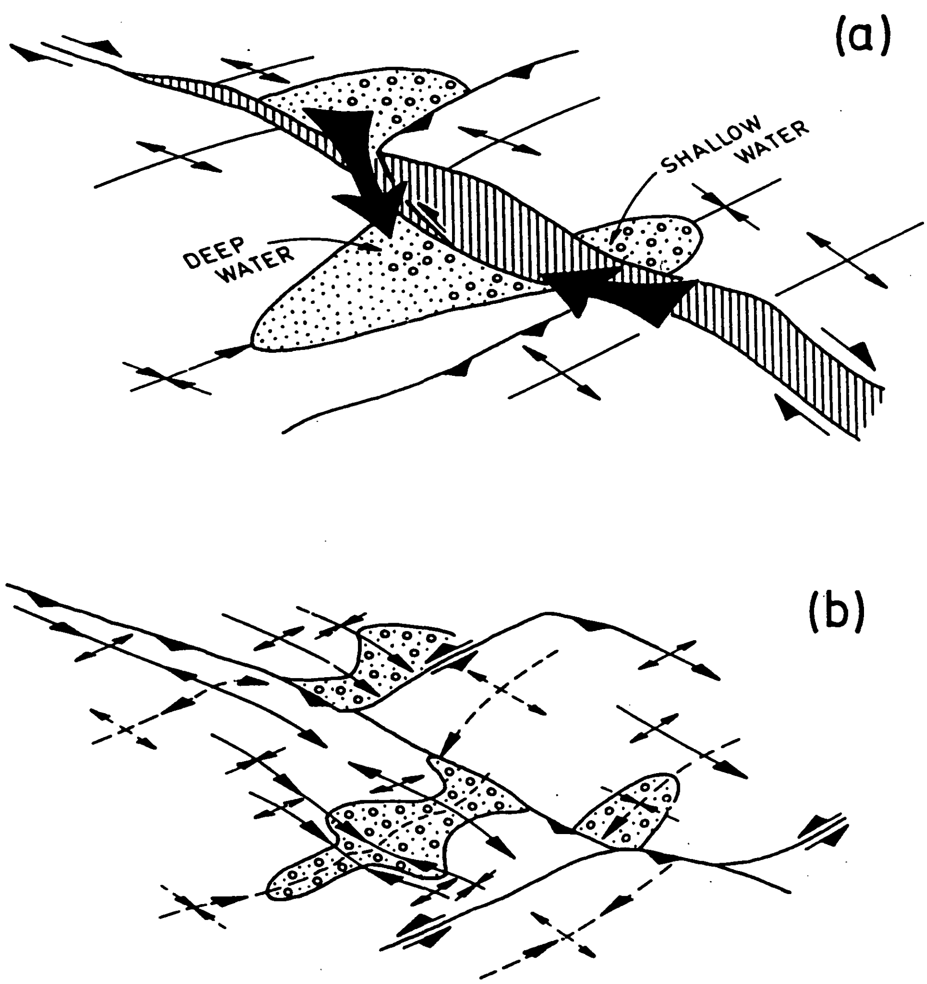

Fig. 7:
(a) Model for the development of erosional source areas and small syndeformational clastic basins adjacent to high-angle transfer faults within growing foldthrust belt or accretionary wedges, as displayed by the Brandenberg and Muttekopf basins of the western NCA. The strong overprint by intragosauian normal faulting is not shown in this model.
(b) The effect of heteroaxial contraction on pre-existing folds, thrust faults, and high-angle transfer faults as displayed by structures within and adjacent to the Inntal sheet of the NCA wedge.

Transfer fault basins in accretionary settings

Although uplift and erosion down to the level of Triassic formations seem to have accompanied initial fold-thrust detachment along the trailing edge of the Lechtal sheet and within the Inntal sheet foundering of short-lived syntectonic basins occurred soon thereafter. Although the Upper Cretaceous Brandenberg and Muttekopf Gosau basins developed in synclines which are located behind major thrusts they are also located adjacent to high-angle transfer faults. Since the high-angle faults appear to have propagated roughly in the direction of regional contraction and since fold-thrust structures along several high-angle faults show variable vergence it can be inferred that the shear stresses along the faults were low. Relative vertical displacements along the transfer faults thus could have led to the juxtaposition of high standing anticlinal sedimentary source areas and low lying synclinal depositional sinks. High-gradient sedimentary transport could occur across and low-gradient transport along high-angle faults. The developing basins therefore contained elements of both piggyback basins (ORI & FRIEND, 1984) and strike-slip pull-aparts (CROW-

ELL, 1974) depending on the local angle between the strike of the transfer fault and the general direction of contraction. The bewildering sedimentary assemblages ranging from fluvial conglomerates and small bioherms to deep water turbidites, the highly variable sedimentary provenance, and the short subsidence history which was followed by irregular uplift are possibly all characteristic for transfer fault basins in other accretionary settings as well. Subsidence is probably strongest near releasing bends of transfer faults and need not have been accompanied by large strike-slip displacements (see also WORRALL, 1991). The resulting structural pattern in the sedimentary fill of transfer basins reflects both synand post-depositional conditions. Fig. 7 is a model for the initial development and subsequent deformation of a transfer basin within a changing field of contraction as visualized for the example of the Brandenberg basin within the trailing Lechtal sheet of the NCA.

The southern margin of the Brandenberg basin is formed by a strong intragosauian normal fault with an offset of about 1 km, along which megabreccias accumulated (BRANDNER & ORTNER, 1995). It is assumed by one of the authors (R.B.) that strong subsidence in a NW–SE oriented field of distension overprinted older basin structures. The normal fault is lacking in the earlier version of the basin model in fig. 7.

High-angle faults and progressive heteroaxial fold-thrust development

Progressive contraction of the mechanically heterogeneous Permo-Mesozoic sedimentary succession within the frontal Austroalpine accretionary wedge was achieved by partitioning of regional deformation onto fold-thrust and high-angle transfer structures. This partitioning first accommodated NW–SE-oriented contraction along an arcuate belt of sedimentary strata with associated stacking of crystalline thrust sheets between about 95 and 80 Ma (see also FRANK, 1987; SCHMID & HAAS, 1989; RATSCHBACHER et al., 1989; THÖNI, 1988). As displayed by the structure of the Inntal sheet, continuing shortening appears to have occurred within a changed NNE–SSW-oriented field of contraction, resulting in complex hangingwall-footwall interference and in the southwesterly propagation of new NE-striking high-angle sinistral faults. This second structural event was possibly also responsible for the downward change in the orientation of stretching lineations from WNW–ESE to N–S within the Arosa melange near the western NCA-sole thrust (RING et al., 1988) and could have been related to early Paleogene (?) impingement of the NCA-wedge against the European continental margin.

The presence of both high-angle and low-angle faults substantially eased heteroaxial overprinting. Thus, inclined stratal panels, confined laterally by high-angle faults, responded to the changed pattern of contraction individually and thereby the 'corrugated iron' effect of pre-existing fold trains was reduced. In other area pre-existing stratal dips were translated directly into plunge of newly developing folds. Also, pre-existing high-angle strike-slip faults accommodated reverse displacement. New transfer faults nucleated preferably along favourably oriented axial surfaces of pre-existing flexural-slip folds and propagated southwestward thus transferring displacement onto major backthrusts which impeded further thrust motion, but accommodated shortening at deeper levels of the NCA wedge.

Conclusions

Within the NCA accretionary wedge low-angle fold-thrust detachment and high-angle transfer faulting interacted to accommodate both initial motion and post-emplacement deformation of the Inntal thrust sheet of the Northern Calcareous Alps. Thus, early NW-directed thrust motion amounted to about 20 km and was accompanied by distributed high-angle dextral shear that amounted to about 10 to 20 km and affected both advancing hangingwall and overridden footwall strata. Since high-angle transfer faults formed the border between thrust panels with different structural vergence the resulting structural relief within the detached Inntal sheet and along the trailing Lechtal sheet led to subsidence of syntectonic Upper Cretaceous transfer fault basins. Orogen-parallel extensional faulting overprinted the earlier nappe pile and the supposed structural relief and accommodated Gosau basin sedimentation (in the view of one of the authors – R.B.). During superimposed NNE–SSW-oriented heteroaxial contraction pre-existing high-angle faults eased development of new plunging folds in tilted but laterally fault-bounded stratal panels and induced SW-directed propagation of sinistral transfer faults and backthrusting within footwall strata by about 5 to 10 km. Heteroaxial structural overprinting was probably related to latest Cretaceous(?)-Paleogene impingement of the NCA-wedge against the outer European platform and terminated deposition within the transfer fault basins. Transfer fault basins such as those hosting the Upper Cretaceous Gosau Group within the western NCA are typically heterogeneous in composition, variable in sediment provenance and short-lived. In other accretionary settings their presence may reveal the presence of otherwise enigmatic transverse discontinuities.

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