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Tectonics of the synorogenic "Kreideschiefer basin", northwestern Calcareous Alps, Austria

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Key words: Northern Calcareous Alps, synorogenic clastics, superposed deformation, timing of deformation, emplacement of klippen

ABSTRACT

The deposition of the fine-grained siliciclastic Lech Formation in the "Kreideschiefer basin" which developed on the Lechtal thrust sheet of the northwestern Austroalpine Northern Calcareous Alps (NCA) occurred from Aptian to Cenomanian(?) time. The tectonic framework of the basin reflects the transition between a passively subsiding to extensional setting dominated by carbonate deposition and a setting characterized by regional contraction and clastic deposition. The margins of the marine Kreideschiefer basin were partly reactivated low-angle extensional faults of latest Triassic(?)-Jurassic age and partly incipient thrust faults including the leading edge of the Inntal thrust sheet. The complex pattern of subsidence within the Kreideschiefer basin was related to local extension and loading within an incipient thrust wedge that propagated in a northwesterly direction. The basinal lows received fine-grained siliciclastic detritus derived from distant crystalline source areas and carbonate olistoliths ranging in size from metres to hundreds of metres. The olistoliths were derived from the strongly segmented leading edge of the Inntal thrust sheet prior to its emplacement on top of the Kreideschiefer basin and from basin-bounding fault blocks within the Lechtal sheet. Deformation of the Lechtal thrust sheet and emplacement of the Inntal thrust sheet produced a first tectonic 'compaction' cleavage in the Lech Formation. Allochthonous Triassic-Jurassic strata now preserved as klippen directly on top of the Lech Formation indicate that tectonic compaction and thrust sheet loading occurred before major structures emerged above sea level. Fluvial erosion affected the developing structures first in Turonian-Santonian time when the NCA moved from the southeast to the northwest over the Central Alpine Ötztal-Silvretta complexes. A second phase of north- to north-northeast-directed contraction which occurred during latest Cretaceous(?)-Paleogene time created superimposed fold-thrust structures in the carbonate substratum of the Kreideschiefer basin and a second cleavage within the Lech Formation. This second phase of deformation of the NCA occurred north of the Ötztal-Silvretta complexes when the entire Austroalpine complex moved towards and over the European continental margin.

ZUSAMMENFASSUNG

Die Ablagerung der feinkörnigen Siliziklastika in der Lech Formation des «Kreideschiefer-Beckens» der westlichen Nördlichen Kalkalpen erfolgte im Zeitintervall Apt bis Cenoman(?). Die strukturelle Entwicklung dieses Beckens deutet auf ein Übergangsstadium zwischen der passiven Subsidenz eines komplexen Extensionsbeckens und der aktiven Einengung entlang einer regionalen Deformationsfront im Bereich der späteren Lechtal-Decke. Dabei kam es zur teilweisen Reaktivierung älterer Abschiebungen spättriassischen bis jurassischen Alters und zur Ausbildung neuer Überschiebungsfronten. So sammelten sich im Becken sowohl feinkörnige, quarzreiche Siliziklastika, die aus kristallinen Einzugsbereichen stammen, als auch lokal abgeglittene Karbonat-Olistolithe, deren Durchmesser Meter bis Hektometer betragen. Die Subsidenz des Kreideschiefer-Beckens, die in einem dextral(?)-konvergenten Rahmen erfolgte, wurde durch die nach Nordwesten ausgerichtete Bewegung der stark segmentierten Inntaldecke verstärkt. Infolge der regionalen Überschiebungen entwickelte sich in der Lech-Formation eine erste tektonisch induzierte Kompaktionschieferung. Die Lech-Formation wird direkt von Klippen aus triassisch-jurassischen Karbonaten überlagert, die in ihrer Zusammensetzung der Inntal-Decke entsprechen. Die erste Deformation erfolgte also noch vor dem Einsatz fluviatiler Erosion und wahrscheinlich noch südöstlich der zentralalpinen Silvretta-Ötztal-Komplexe. Die erste Hebung und Erosion der westlichen Kalkalpen im Turon-Santon ist durch Diskordanzen an der Basis oberkretazischer Klastika der Gosaugruppe dokumentiert und erfolgte möglicherweise während der Bewegung der Nördlichen Kalkalpen über die Silvretta-Ötztal-Komplexe. Weitere, raumgreifende nord- bis nordnordost-orientierte Einengungen im Zeitintervall späteste Kreide(?)-Paläogen erzeugten im Kreideschiefer-Becken eine zweite Schieferung und in den bereits gestapelten Decken komplexe Überprägungen der präexistierenden Falten- und Überschiebungsstrukturen. Diese strukturelle Überprägung erfolgte während des Vorrückens des gesamten ostalpinen Deckenkomplexes auf die penninischen und helvetischen Hang-Schelfbereiche am Südrand Europas.

Introduction

The Northern Calcareous Alps (NCA) of western Austria and southern Germany constitute the northernmost and frontal portion of the Austroalpine thrust complex (Fig. 1). Timing, direction and sequence of emplacement of the carbonate-dominated thrust sheets of the western NCA have been the subject of numerous studies since the original mapping of Ampferer (e.g. 1932). The allochthonous nature of the NCA with regard to the European foreland has been demonstrated by regional geological mapping and deep drilling (e.g. Tollmann 1976; Bachmann & Müller 1981; Linzer et al. 1995; Schwerd et al.

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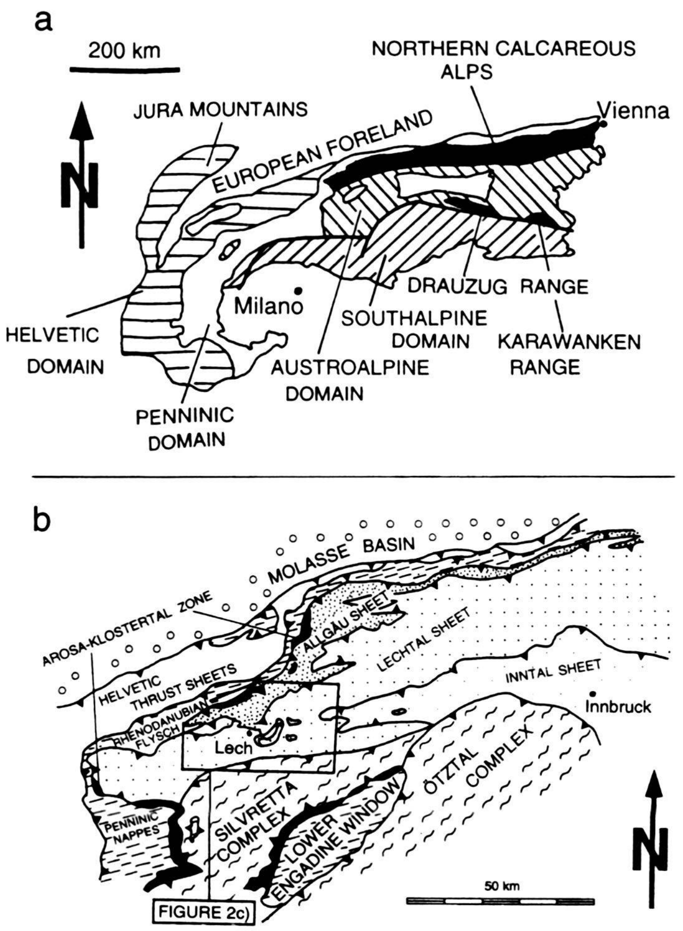

Fig. 1. (a) Tectonic framework of the Austroalpine-South Alpine thrust complexes showing the location of the Northern Calcareous Alps (NCA) in relation to the stratigraphically similar Drauzug range and the northern Karawanken range. (b) Sketch map of the present outcrop pattern of the three major thrust sheets that make up the western NCA and their relationship to Central Alpine Ötztal and Silvretta complexes. Note Index for map in Fig. 2.

1995). Although the amount of internal shortening of the western NCA by folding and thrust faulting has been estimated from a depth-extrapolated cross section (Eisbacher et al. 1990), complexities of Mesozoic sedimentary facies changes and polyphase structural geometries have limited the scope for quantitative kinematic models and palinspastic reconstructions. Recent studies of the ages, the depositional environments and the deformation histories of synorogenic clastics within the NCA have helped considerably in setting up several plausible scenarios for the sequence of deformational events (e.g. Gaupp 1982; Winkler 1988; Wagreich 1995; Eisbacher & Brandner 1996; Eynatten et al. 1996). However, this approach has its limits as well because of the relatively small outcrop areas in which the synorogenic clastics are preserved. In the western NCA the most extensive synorogenic succession of siliciclastics was laid down in the "Kreideschiefer basin". In this paper we shall refer to this clastic succession as Lech Formation (Eynatten & Gaupp 1998; and in press) because its main outcrop area is located in the vicinity of the town of Lech (Fig. 1); we retain the term "Kreideschiefer basin" for the structurally controlled depositional lows in which the Lech Formation occurs today, i.e. mostly in the footwalls of thrust sheets and tectonic klippen (Fig. 2). We attempt to relate these synorogenic deposits, including huge olistoliths, to the early structural development of the western NCA and their regional setting.

Tectonostratigraphic framework of the Kreideschiefer basin

Regionally, the western NCA rest on a carpet of ophiolitic melange and broken formations (Arosa-Klostertal zone), on the allochthonous Rhenodanubian turbiditic flysch and the folded-thrust faulted strata of the Helvetic shelf succession. All of these have in turn been thrust over the Tertiary Molasse foreland basin (Fig. 1). Internally, the western NCA are dominated by the Lechtal thrust sheet which is made up of pre-Mesozoic-to-Cretaceous strata. This thrust sheet has a broadly synclinal structure. It is characterized by numerous folds and NW-directed second order thrust faults. Our mapping has shown that the frontal Lechtal thrust itself developed out of the core of a tight anticline and that this major thrust fault displays an increasing amount of displacement in a northeasterly direction until it clearly separates the Lechtal sheet from the Allgäu sheet; the front of the Allgäu sheet and minor imbricates constitute the front of the NCA (Fig. 1). Towards the southwest the Mohnenfluh-Schafheide thrust system divides the Lechtal sheet into a northern and a southern part (Fig. 2c). The Lechtal thrust and the Mohnenfluh-Schafheide thrust system are linked by a complex system of transfer structures. To the south and southeast the Lechtal sheet is overlain by the Inntal thrust sheet and by a series of prominent klippen. These klippen rest on the mid-Cretaceous synorogenic Kreideschiefer basin. The southernmost part of the western NCA (and the Lechtal sheet) consists of pre-Mesozoic phyllitic (or phyllonitic) basement rocks which in turn appear to be in thrust fault contact below pre-Mesozoic gneiss and amphibolite rocks of the Central Alpine Silvretta complex (Fig. 1b).

The steeply north-dipping to overturned southern limb of the large syncline that dominates the Lechtal sheet includes outcrops of all stratigraphic units and a part of the original NCA-basement. This Palaeozoic(?) phyllitic basement is overlain unconformably by coarse-grained clastics of the Permian Rotliegend unit, by fine- to medium-grained quartzose clastics of the Lower Triassic Buntsandstein Formation and by evaporitic carbonates of the Reichenhall Formation; the Reichenhall Formation is the lowermost potential structural detachment horizon within the sedimentary succession of the western NCA (Fig. 2). The Middle Triassic Muschelkalk-Wetterstein-Arlberg succession is composed of shallow-water platform carbonates that display abrupt lateral facies changes into basinal

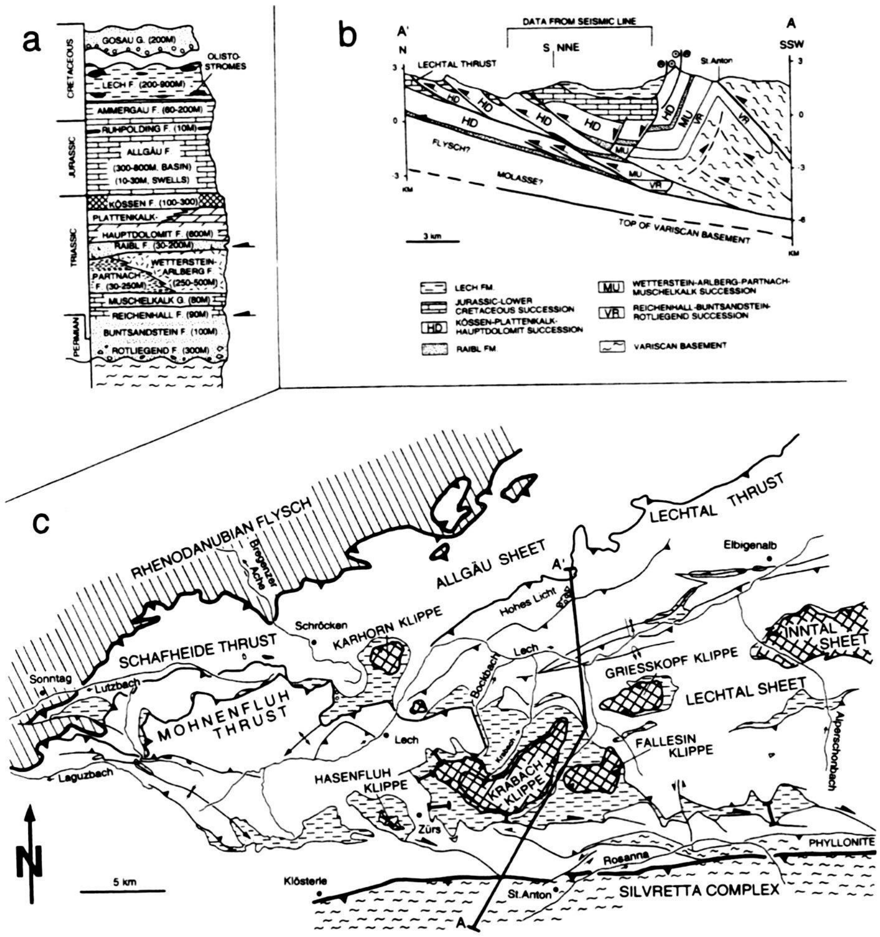

Fig. 2. (a) Sedimentary succession of the western NCA with the approximate thicknesses of formations and potential structural detachment horizons (arrows). (b) Depth extrapolated cross section across a part of the western NCA along line A-A' as indicated in Fig. 2 (c). The central part of the section was constructed using reflectors seen on a seismic line obtained by ÖMV. (c) Sketch map of the western NCA showing major structures and the distribution of the Lech Formation (dashes); Variscan basement of the NCA and the northernmost Silvretta Complex are indicated by wavy pattern. Note the transfer zone between the Lechtal thrust and the Mohnenfluh thrust. Major klippen and sections where the thickness of the Lech Formation was estimated (bars) are also shown.

shale units of the Partnach Formation. The overlying clastic to evaporitic Raibl Formation constitutes a second major detachment horizon in the western NCA. Resting on top of the Raibl Formation the well bedded and competent Upper Triassic Hauptdolomit Formation dominates the structural style of the westernmost NCA (Tollmann 1976; Eisbacher et al. 1990). For the area discussed here the primary thickness of the Hauptdolomit Formation was estimated in a few relatively undisturbed sections. It does not seem to exceed 600 m and grades upwards into the platform limestones of the Plattenkalk Formation and the shale-and-reef-carbonate units of the Kössen Formation. Thin-bedded Jurassic to Lower Cretaceous strata were laid down in strongly subsiding basins on submarine swells, plateaus, rises and seamounts southeast of the Piemont-Ligurian oceanic realm (Bernoulli & Jenkyns 1974; Lemoine & Trümpy 1987; Stampfli & Marthaler 1990, Bertotti et al. 1993). Solution-condensed carbonate-chert successions were preserved on submarine highs and are only tens of metres thick, while a submarine slope facies with hemipelagic marls and locally restricted oligomictic channel-fill conglomerates or slope breccias grade laterally into a basinal facies characterized by monotonous, well bedded calcareous turbidite-hemipelagite successions hundreds of metres thick. In these basinal successions Lower to Middle Jurassic marly turbidities of the Allgäu Formation are overlain by a thin radiolarian chert unit, the Ruhpolding Formation, and by uppermost Jurassic to Lower Cretaceous calcareous turbidites of the Ammergau Formation. In total the Permian to Lower Cretaceous stratal succession of the western NCA is about 3 to 4 km thick and resembles most closely other Austroalpine successions exposed in the Drauzug and in the northern Karawanken ranges of the southeastern Alps (see Brandner & Sperling 1995). We therefore think that prior to their Alpine deformation the western NCA were located to the southeast of the Central Alpine Silvretta and Ötztal complexes.

From our own mapping and from reflectors seen on a commercial seismic line obtained from ÖMV (G. Wessely pers. comm. 1994) we constructed a depth-extrapolated cross section (Fig. 2b) in which the possible base of the Lechtal thrust sheet and thus the trailing edge of the NCA are interpreted to consist of a basement wedge that tapers both to the north and to the south (May 1998). Along this cross section the mid-Cretaceous siliciclastic Lech Formation of the Kreideschiefer basin rests conformably to unconformably on carbonate strata

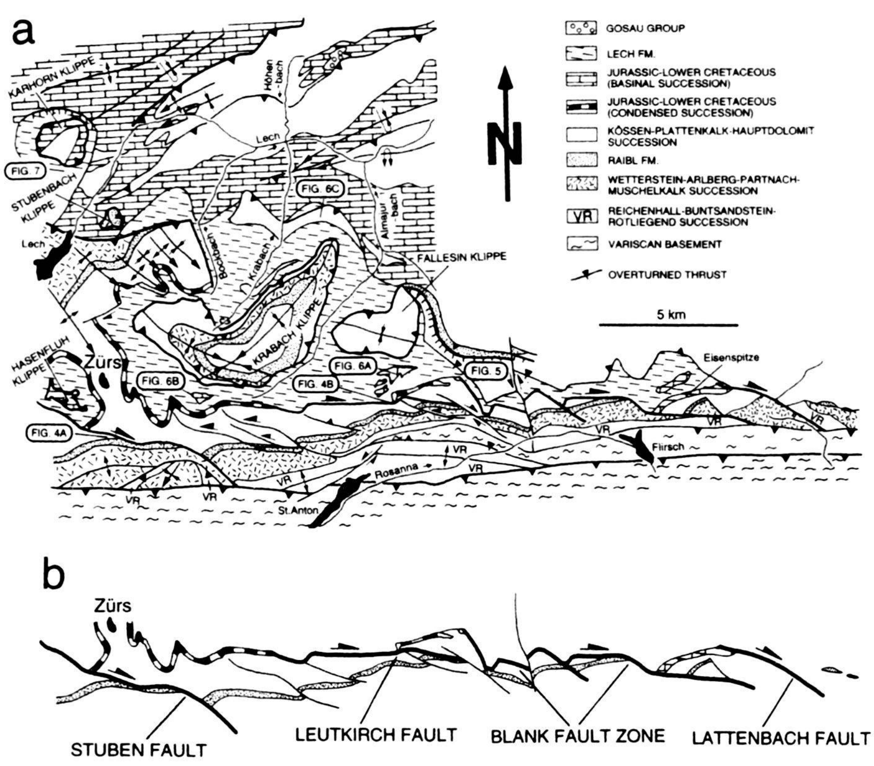

Fig. 3. (a) Geological sketch map of the synclinal western Lechtal thrust sheet showing the location of structures illustrated by detailed maps. (b) Map of the extensional faults as exposed along the steeply N-dipping limb of the syncline that dominates the structure of the southern edge of the Lechtal thrust sheet (same scale as in Fig. 3a).

in the synclinal central part of the Lechtal sheet (Helmcke & Pflaumann 1971; Helmcke 1975; May 1998). The Lech Formation ranges in age from Aptian to Cenomanian(?) (Huckriede 1958; Helmcke 1969; Gaupp 1980; Winkler 1988) and therefore correlates broadly with the fine-grained Tannheim Formation and the coarse-grained Losenstein Formation of the German part of the NCA (Freudenberger & Schwerd 1996). Although the Lech Formation is commonly the youngest stratigraphic unit of the NCA-thrust wedge, in a few places the Triassic-Jurassic carbonate substratum is also overlain in angular unconformity by the coarse-grained clastics of the Upper Cretaceous Gosau Group.

Deposition of the Lech Formation appears to span a transitional tectonic stage in which several earlier developed fault structures of mainly extensional origin controlled the geometry of the basin margins and the bathymetry of the depocentres for the Lech Formation; however, newly-formed thrust faults also influenced deposition and style of deformation. As polyphase fault structures in this part of the NCA have not been described before we discuss the most prominent in the following section.

Early extensional fault zones

The location of the Kreideschiefer basin coincides with an area with abrupt Jurassic facies transitions from thin condensed successions to thick basinal deposits. The area also contains several polyphase faults which are of possible extensional origin, were later reactivated, and are particularly well exposed on the north-dipping to overturned southern limb of the synclinal western Lechtal sheet (Figs. 2 and 3). Although these faults were obviously passively rotated during the formation of the syncline they display mappable extensional separations of the Triassic-Jurassic formations. We describe five of these faults, proceeding from west to east.

Along the ESE-striking **Stuben fault** (Fig. 4a) the Raibl Formation shows an apparent dextral extensional displacement of about 1.6 km. In the footwall the competent Wetterstein and Hauptdolomit formations are cut at relatively high angles whereas the incompetent Raibl Formation is cut at a low angle; below the Raibl Formation the fault probably continues into the phyllitic basement rocks. In the hangingwall of the Stuben fault the strata were rotated about 40° anticlockwise towards the fault and the entire hangingwall panel forms a NNW-trending anticlinal structure reminiscent of a rollover; thinning of Kössen Formation near the fault is probably related to the incipient development of the Stuben fault. Towards the west the siliciclastic Lech Formation rests on and possibly seals parts of the fault trace. Fibre lineations in the hangingwall and asymmetrically sheared blocks of Jurassic rocks indicate that sinistral and top-to-the-south movements also occurred along and near the fault contact during later regional

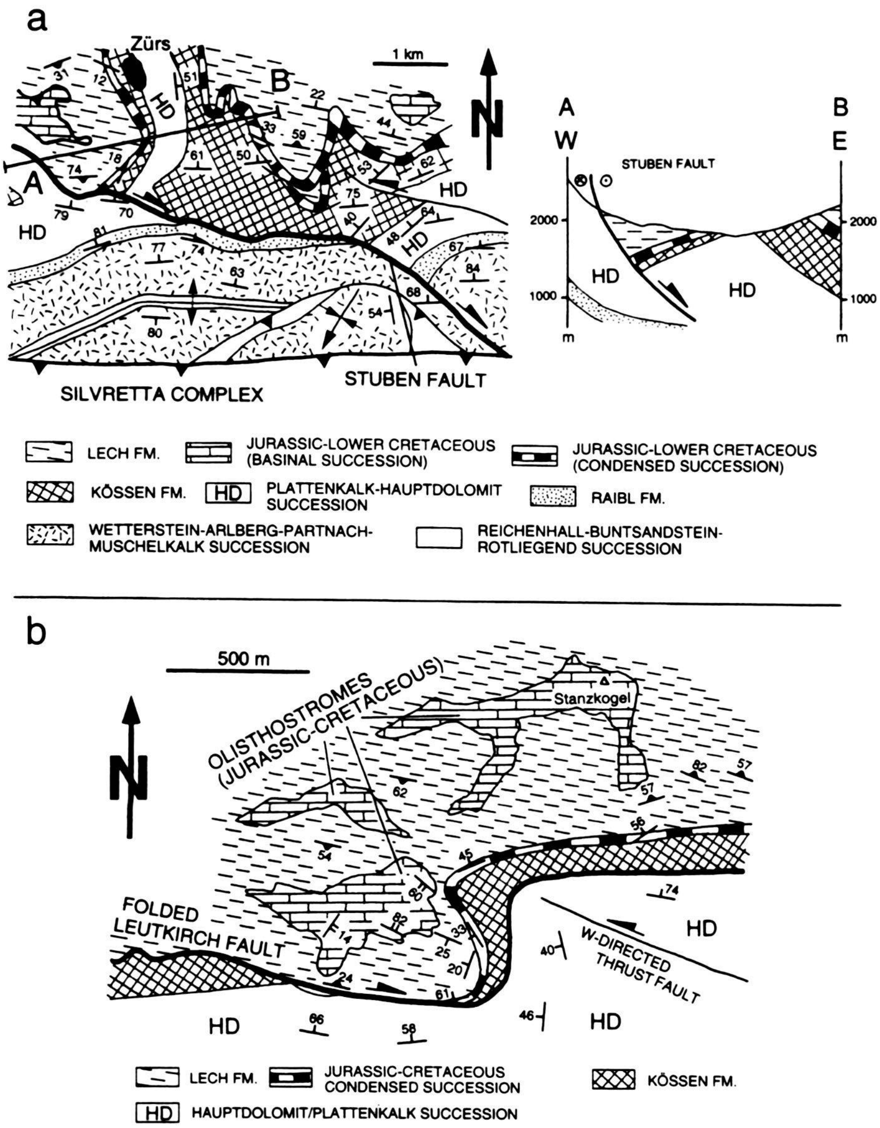

Fig. 4. (a) Sketch map of the eastern part of the Stuben fault and a cross section that illustrates the probable extensional rollover structure in the hangingwall. (b) Sketch map of the Leutkirch fault showing the anticlockwise rotation of the hangingwall strata with respect to the extensional fault and location of olistostromes within the Lech Formation. The W-directed thrust fault in the footwall later overprinted the Leutkirch fault; both faults were then tilted to the north.

contraction. Field relationships thus indicate a stage of pre- to syn-Lech Formation easterly extension along the Stuben fault, the development of a rollover in the hangingwall, and a post-Lech Formation reactivation of the fault as a sinistral-convergent structure.

Along the E-striking **Leutkirch fault** the Kössen Formation shows an apparent extensional displacement of 3.4 km. Upper Triassic to Lower Cretaceous formations in both footwall and hangingwall are cut at low angles to bedding. In the hangingwall Jurassic-Lower Cretaceous strata show anticlockwise rotation of up to 90° into the fault (Fig. 4b). However, shear veins within isolated stratal lenses of the hangingwall indicate later sinistral-convergent displacements along this fault as well. The Leutkirch fault therefore probably originated as a roughly E-dipping low-angle normal fault with a rollover in the hangingwall. It experienced a later top-to-the-west inversion and northerly tilting together with the strata of the southernmost Lechtal sheet.

The E-striking **Blank fault zone** is the largest and most complex extensional structure within the area (Fig. 3). Apparent extensional displacement of the Kössen Formation is about 6.5 km and several branches of the fault zone cut the footwall at both high and low angles to bedding. Towards the east the fault seems to sole out in the evaporitic Reichenhall Formation. The hangingwall, now overturned to the north, was rotated counterclockwise up to 30° into the fault. The Lech Formation overlies and thus seals the fault towards the west. The footwall consists of thin, condensed Jurassic facies and several detached carbonate blocks; a massive Lower Jurassic slope breccia exposed near the Eisenspitze (see Achtnich 1982) is

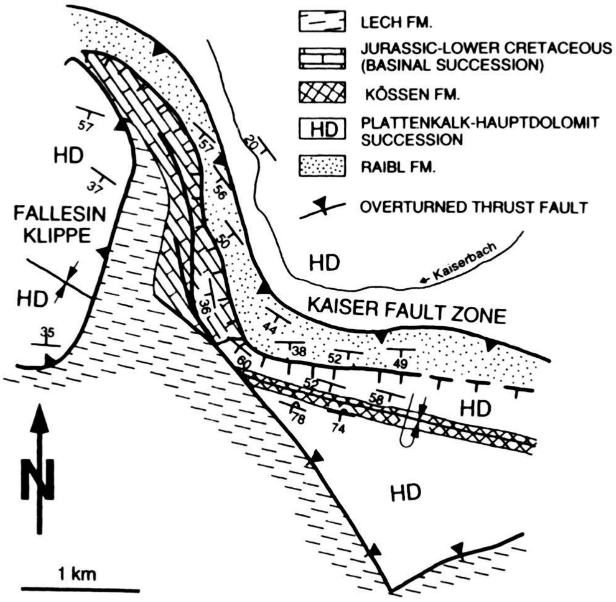

Fig. 5. Sketch map of the extensional Kaiser fault zone, along which the Raibl Formation in the footwall is juxtaposed against Jurassic strata. This fault zone was later overprinted by strong contraction that created a complex local pattern of partly overturned fold-and-thrust structures which, however, did not obliterate the extensional fault zone itself.

part of the hangingwall succession and suggests to us that the fault moved first in Early Jurassic time.

The ESE-striking **Lattenbach fault** cuts NE-striking Triassic units, soles in phyllonitic basement and displays extensional displacement of the steeply N- to NNW-dipping Triassic-Jurassic formations. Another obvious extensional fault in the immediate surroundings of the Kreideschiefer basin is the NW-trending **Kaiser fault zone** (Fig. 5). Along this fault the Raibl Formation in the footwall was juxtaposed against Jurassic strata in the hangingwall suggesting considerable displacement. All of these faults and several other smaller ones experienced intermittent extensional movements during Jurassic-Early Cretaceous time and must have created a complex submarine relief that influenced not only the thickness and facies of Jurassic successions but also the deposition of the Lech Formation and its later deformation.

Deposition of the Lech Formation

The largest remnant of the Lech Formation is situated within a synclinal axial depression of the Lechtal sheet (Fig. 2). It is characterized by monotonous grey mudstones, siltstones, rare sandstone beds and lenticular conglomeratic channel deposits. Interlayered olistostromes and huge single slabs of Triassic-Jurassic carbonates interrupt the monotony of this assemblage. Towards the north smaller outcrops also contain layers of reddish-green siltstones which are regarded typical for the correlative Tannheim Formation in other parts of the western NCA (e.g. Schwerd et al. 1995). Because of later regional contraction and a lack of marker beds the original depositional thickness of the Lech Formation is only poorly constrained. However, at seven localities, shown by bars in Figure 2, minimum thicknesses between the basal contacts of the Lech Formation and the overlying klippen were estimated, taking into account a substantial "tectonic" compaction during later cleavage formation. These thickness estimates vary between 200 and 1000 metres.

Sedimentation of the fine-grained siliciclastics of the Lech Formation occurred from suspension or by dilute turbidity currents in relatively deep water during Aptian-Albian and possibly until early Cenomanian time (Gaupp 1982; Gaupp & Batten 1983; Winkler 1988). In some places there is a gradual vertical transition from Lower Cretaceous marly turbiditic limestones of the Ammergau Formation into the siliciclastic Lech Formation; however, elsewhere the Lech Formation can be seen to rest in apparent basal onlap-unconformity on exposed parts of the low angle faults described above (May 1998). Because of ubiquitous structural overprinting and pervasive cleavage development, the unconformable nature of the contacts is commonly ambiguous. In general the siltstones of the Lech Formation contain an average of 40 to 50% quartz, 10% plagioclase, 30% chloritic and illitic clay minerals and variable amounts of heavy minerals that indicate source areas composed of both metamorphic Palaeozoic basement rocks and of Mesozoic ophiolitic(?) assemblages (Eynatten & Gaupp 1998). The composition of relatively rare coarse-grained channel fill deposits indicate both local sedimentary and distant crystalline rock complexes as source areas (Leiss 1992). We entertain the possibility that syntectonically exhumed pre-Mesozoic Central Alpine crystalline complexes located to the northwest could have been part of the source area for the siliciclastic components of the Lech Formation (see below).

Slabs and blocks of Triassic-Jurassic carbonate strata intercalated with the siliciclastics of the Lech Formation range in size from metres to hectometres and are found mainly near the base and the top of the formation (Fig. 6). Several internally disrupted Hauptdolomit panels even approach the size of the tectonic klippen that rest on top of the Lech Formation. Where olistoliths are part of lenticular olistostromes the individual blocks differ greatly in size, shape and stratigraphic provenance. We interpret both the olistostromes and the large isolated blocks as gravity-induced slide masses. The size of the inferred subaqueous slide blocks such as those exposed near Stanzkogel, Roggspitze or Pimig, (Figs 4 and 6) are comparable in size to those reported from recent subaqueous mass movement deposits (e.g. Reichstein 1991; Moore et al. 1994). The olistoliths were probably detached along fault-controlled slopes bordering the Kreideschiefer basin. One source was most likely the front of the Inntal thrust sheet as it began to override the Lechtal sheet and appoached the depocentre of the Kreideschiefer basin.

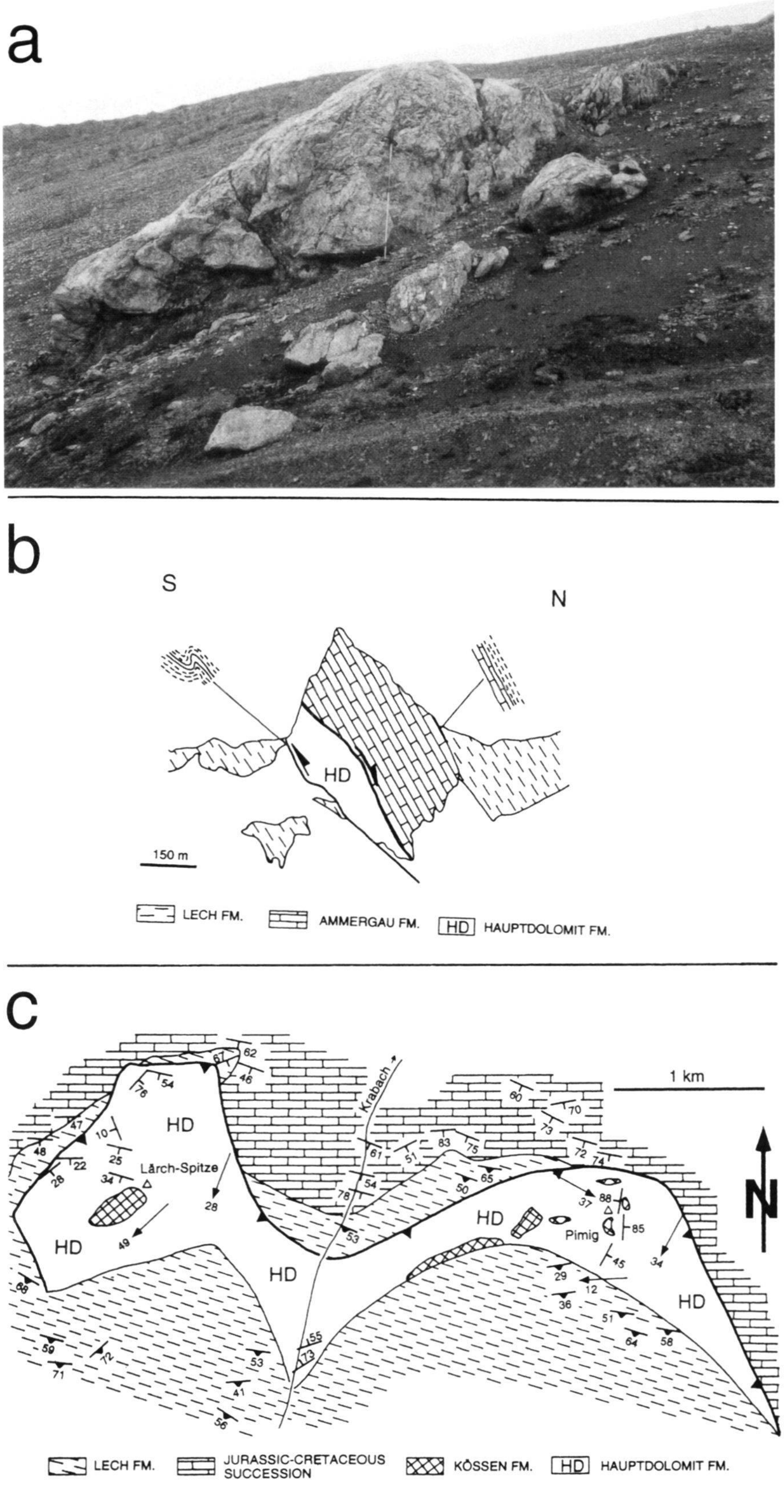

Fig. 6. Olistoliths and olistostromes in the Lech Formation: (a) View of rounded blocks of Ammergau Formation (light-grey) embedded within fine-grained clastics of the Lech Formation (dark-grey) near Stanzkogel (Fig. 4). Staff is approximately 1.5 m long. (b) Field sketch of the Roggspitz olistolith (for location see Fig. 4). Stratal omission between Hauptdolomit Formation and Ammergau Formation is interpreted as a normal fault. Note inferred onlap of the Lech Formation onto the north side and the thrust relationship on the south side of the olistolith. (c) Sketch map of the Pimig olistostrome-olistolith with inferred onlap of Lech Formation on the south side and thrust relationship on the north side of the olistostrome.

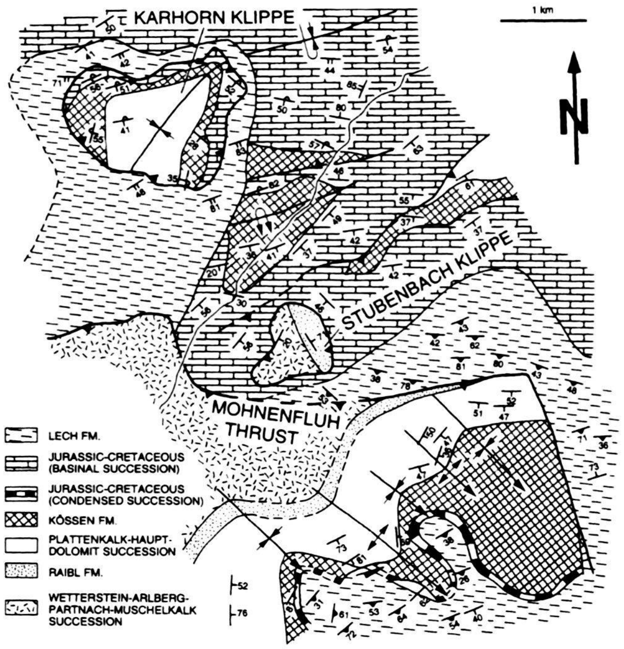

Fig. 7. Sketch map of the easternmost portion of the Mohnenfluh thrust sheet, showing the location of the Stubenbach and Karhorn klippen, both of which were probably derived from the frontal Mohnenfluh thrust sheet; the Karhorn klippe rests upside-down on top of the Lech Formation; after its emplacement on top of the Lech Formation it experienced a northwest-directed contraction.

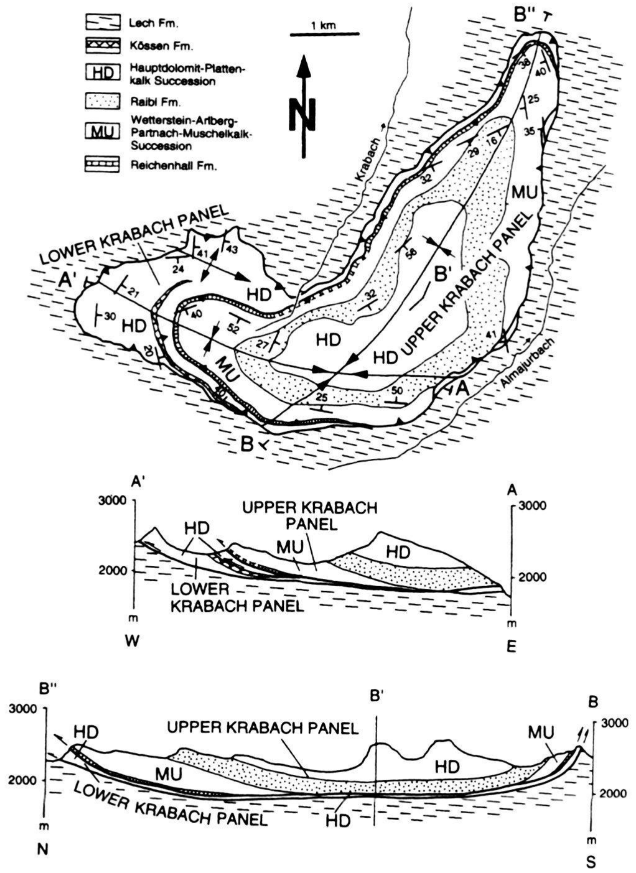

Fig. 8. Sketch map and two cross sections showing internal imbrication and two sets of folds in the upper and lower Krabach thrust panels (see text for discussion).

Emplacement kinematics of the Inntal thrust sheet and related klippen

The Lech Formation is overlain along tectonic contacts by the Inntal thrust sheet to the east, by the Griesskopf, Fallesin and Krabach klippen in the central area and by the Hasenfluh, Stubenbach and Karhorn klippen to the west (Fig. 2). The Griesskopf, Fallesin and Krabach klippen are made up of Triassic strata and are therefore considered to represent erosional remnants of the westernmost Inntal thrust sheet which also consists almost entirely of Triassic formations (Tollmann 1976; Eisbacher & Brandner 1996). A strong transverse segmentation by NW-striking high-angle faults which developed during the emplacement of the Inntal sheet (Eisbacher & Brandner 1996) probably favoured disruption of the northwestern leading edge into semi-isolated stratal panels; this could have led to large-scale submarine slope failures. In contrast, the more westerly located Hasenfluh, Stubenbach, and Karhorn klippen consist of both Triassic and Jurassic strata and were probably derived from nearby fault-controlled structural-topographic highs within the Lechtal sheet. This seems to apply in particular to the large Karhorn klippe which rests upside-down on the Lech Formation in front of the Mohnenfluh thrust where the latter displays considerable vertical displacement (Fig. 7).

The most interesting structural relationships are revealed within the Krabach klippe which consists of two stratal panels (Fig. 8). The lower panel displays NW-vergent imbrications of Hauptdolomit and Kössen formations, whereas the upper panel is composed of an intact succession ranging from Reichenhall to Hauptdolomit formations. The tectonic contact between the two panels is a SE-dipping footwall ramp and both panels form a large NE-trending syncline. Illite crystallinity and coal rank studies by Krumm et al. (1988) indicate that the upper panel experienced much higher diagenetic temperatures than the lower panel. Not only the diagenetic history at higher temperatures but also a distinct sandy facies development in the Middle Triassic Muschelkalk Group suggests that the upper panel of the Krabach klippe was originally located near the trailing southern edge of the Lechtal thrust sheet from where identical high thermal overprints and sandy Muschelkalk facies have been reported (Hirsch 1966; Harsch 1968; Petschick 1989). The structural-stratigraphic relationships therefore suggest that the upper Krabach panel was emplaced along an out-of-sequence thrust along which a part of the trailing Lechtal sheet was sheared off and transported onto a seg-

Fig. 9. Horizontally extended sandstone layers in the Lech Formation below the Hasenfluh klippe. We interpret this extension as a result of loading and 'tectonic' compaction.

ment of the Inntal sheet before both panels were emplaced onto the Lech Formation. After their NNW-directed emplacement onto the Lech Formation both Krabach panels also experienced a NNE-SSW directed contraction that resulted in a superimposed WNW-ESE-trending syncline-anticline pair and a basin-shaped overall klippen geometry (Fig. 8.). The absence of an erosional hiatus and the lack of coarse clastics beneath the klippen suggests that the composite Krabach klippe and all the other klippen were emplaced below sea level, although the intimate association of fine-grained clastics and large olistoliths points to a high submarine relief. Such a scenario could be expected for a faulted continental margin that received terrigenous clastics from an exhumed crystalline source area and slide blocks that had become detached along submarine fault scarps. As the Ligurian-Piemont oceanic domain at that stage still separated Europe from the Austroalpine domain we suggest that the source area for the fine-grained siliciclastics of the Lech Formation might have been the Central or Lower Austroalpine basement complexes then located to the north of the NCA.

To constrain the history of the internal deformation of the Lech Formation and the emplacement kinematics of the overlying klippen several outcrops of basal klippen contacts were studied in detail. In general the shear zones at the base of the klippen are characterized by a silty-argillaceous matrix that envelops isolated and asymmetrically elongated blocks of Triassic-Jurassic carbonate strata. Asymmetry of the shear bodies, vergence of small-scale folds and calcite fibre lineations indicate a dominance of northerly movements of the hangingwall strata; however, in the footwall several northwest- and south-vergent minor folds were observed as well; these folds are closely related to cleavages in the Lech Formation.

Cleavage development in the Lech Formation

Minor and microscale deformational structures occur throughout the Lech Formation. These structures include (a) dewatering-and-compaction fabrics, (b) related boudinage-and-extensional faults in siltstone-sandstone beds, (c) pervasive cleavage and (d) fibre-lineations. Strong indicators of dewatering and compaction are early-formed calcite veins and a fissility subparallel to bedding (Fig. 9). Bedding parallel calcite veins in siltstones are seen to pass into calcite veins oriented at high angles to bedding, and these in turn commonly display buckling or fibre lineations along their walls. The compaction-related extension was not only achieved by homogeneous pure shear but also occurred along discrete slip-surfaces; it led to local bedding-parallel extension of interbedded sandstone layers. Figure 10 shows a stereoplot of fibrous slickenlines measured along vein walls within the Lech Formation of the central outcrop area. They indicate preferred NW-SE-extension.

Cleavage orientation within the central outcrop area shows a statistical maximum that centers at around 100/78 SSW; secondary maxima are oriented at 25/80 WNW and 25/80 ESE (Fig. 11). Locally it can be seen that the 25°-striking cleavage surfaces (S_1) and associated NE-trending small-scale folds were overprinted by a 100°-striking cleavage (S_2) and that the 25°-striking cleavage was rotated around NW-trending hingelines of small-scale folds. Thin section analysis of oriented samples confirmed this overprinting relationship.

X-ray goniometry carried out for the basal crystallographic planes of illite and chlorite also showed that beside a bedding-parallel fissility most samples exhibit two distinct cleavages (Fig. 12a and b). Since the primary stratigraphic overburden of the Kreideschiefer basin could not have been more than 1 km a

b

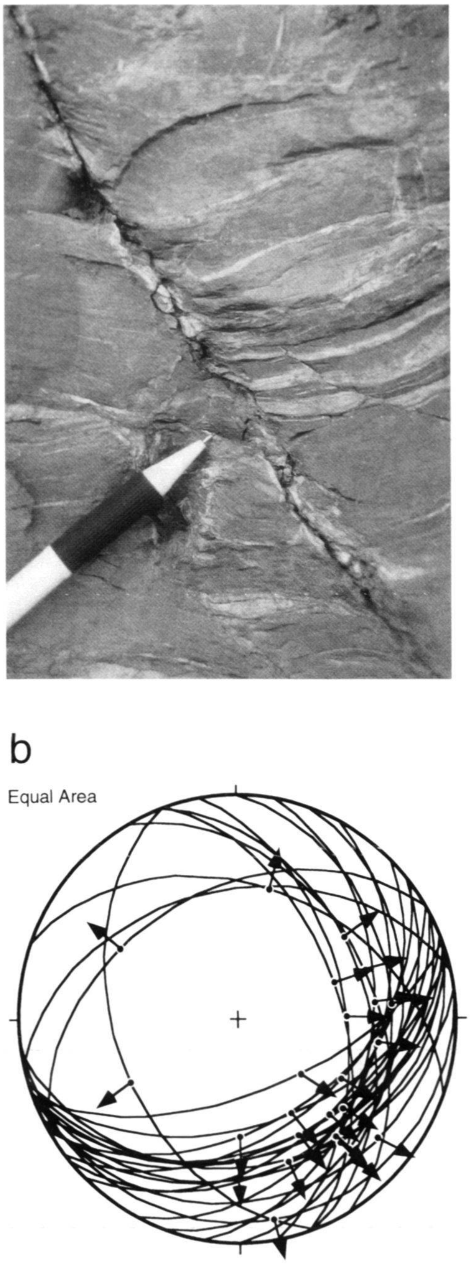

Fig. 10. (a) Compaction, extension and dewatering structures in the fine-grained clastics of the Lech Formation as exposed along the western edge of the Krabach klippe. The subhorizontal, bedding-parallel calcite-veins pass into calcite-veins oriented at a high angle to bedding. Fibre lineations along this high angle calcite-vein indicate that it experienced normal fault displacement. This fault probably originated as one of many extensional faults induced by vertical loading and dewatering. The fault might have acted as a fluid channel during dewatering. View is to the northeast. (b) Stereoplot of the extensional faults measured in the Lech Formation, arrows indicate sense of movement of the hangingwall as determined from the orientation of fibre lineations along the veins.

a b

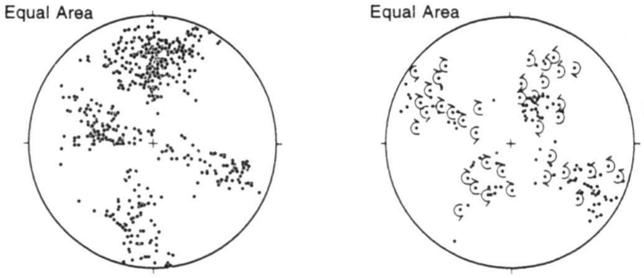

Fig. 11. (a) Poles of cleavage in the Lech Formation. The cleavage displays two maxima: the main maximum is oriented at around 100/78 SSW and a secondary maximum at around 25/80 WNW and 25/80 ESE. Field relationships indicate that the NNE-striking cleavage was modified and rotated during the development of the ESE-striking cleavage. (b) Stereoplot of fold axis of small-scale folds and sense of vergence (shown as rotation axes looking down the plunge) in the Lech Formation. The locally observed refolding of the hinge lines indicated that NE-trending small scale folds were overprinted by NW-trending small scale folds.

we interpret the development of the cleavage as a product of loading by carbonate thrust masses as they moved onto the still porewater-saturated Lech Formation (Fig. 13). Such 'early' cleavage development, although in general more spaced and discontinuous than in the case of the Lech Formation, is well known from frontal portions of accretionary wedges (e.g. Moore et al. 1986). The relatively penetrative nature of cleavage observed in the Lech Formation may be due to the homogeneity of this unit. After initial "tectonic compaction" of the Kreideschiefer basin a N- to NNE-oriented regional contraction created a second set of cleavage surfaces in the Lech Formation.

Timing of deformation

The structural-stratigraphic relationships of the Lech Formation to subjacent rock units and the microscopic deformational fabrics within it suggest that its initial deposition during Aptian-Cenomanian(?) times (approximately 113 to 92 Ma) reflects a change from an extensional carbonate basin environment to a broad belt of dextral(?) transpression. In this setting local subsidence between partly reactivated early-formed faults and in front of thrust sheets created submarine traps for far-travelled siliciclastics derived from locally exposed crystalline terranes. Steep basin margins controlled by both preexisting low-angle extensional faults and newly established NW-verging thrust faults favoured local slope failures. In other parts of the western NCA the ascent of basaltic dikes, dated at around 100 Ma (Trommsdorff et al. 1990), was probably also related to this transitional stage of basin evolution when local extension occurred contemporaneous with incipient regional contraction.

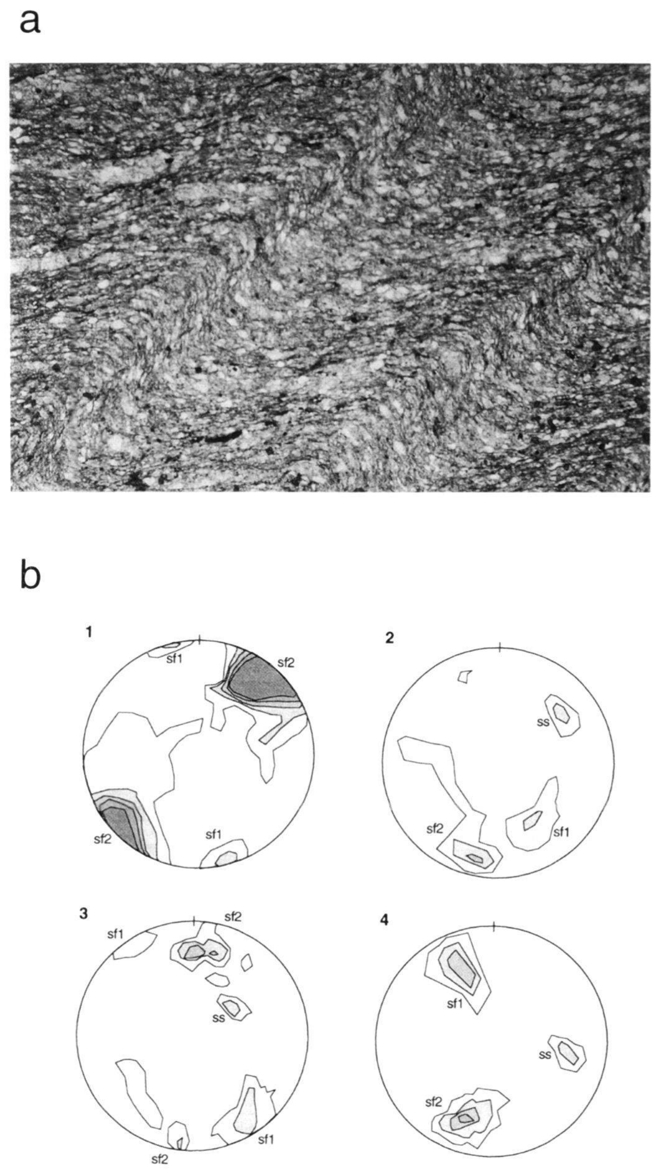

Fig. 12. (a) Thin section of siltstones from the Lech Formation showing refolding of early cleavage by flexural slip crenulation which elsewhere developed into a second cleavage; width of photograph 1 × 1.5 cm. (b) Stereoplots of the X-ray texture-goniometer analysis for four samples of the Lech Formation. The statistical orientation of (001)-planes of illite and chlorite is shown as isolines. The maxima are related to bedding (ss), first cleavage (sf1), and second cleavage (sf2) as observed in hand specimens and in thin sections. (1) Sample shows a main maximum (sf2) and a secondary maximum (sf1); while sf2 is visible both in the hand specimen and in thin section; sf1 can be observed neither in the hand specimen nor in thin section. (2) Sample shows three maxima (ss, sf1, sf2); while ss and sf2 could be observed in the hand specimen and in thin section, sf1 could be observed neither in the hand specimen nor in thin section. (3) Sample shows a major maximum (sf2) and two minor maxima (ss and sf1); while sf2 could be observed in the hand specimen and in thin section, ss and sf1 could be observed neither in the hand specimen nor in thin section. (4) Sample shows two main maxima (sf1 and sf2) and a secondary maximum (ss); while sf1 and sf2 could be observed in the hand specimen and in thin section, ss could be observed neither in the hand specimen nor in thin section.

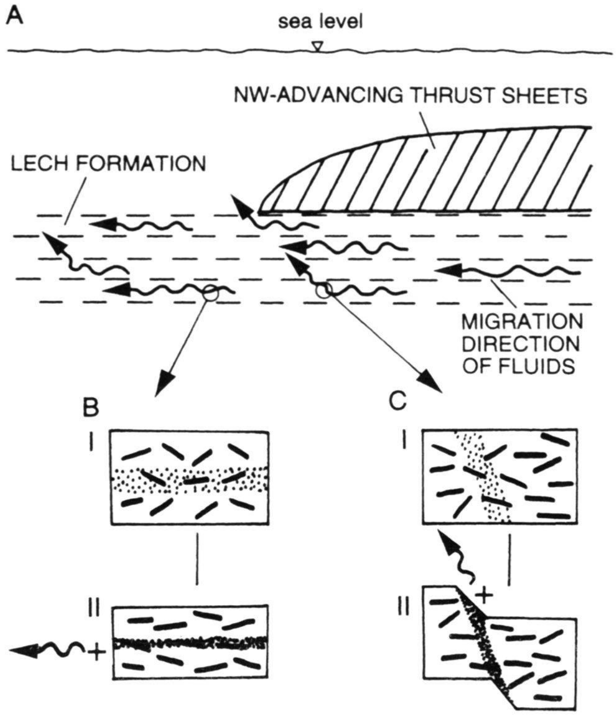

Fig. 13. Schematic model for dewatering and tectonic compaction mechanisms inferred for the Lech Formation. (A) The load of the NW-advancing thrust sheets caused initial compaction and dewatering of the Lech Formation. (B) Loading led to abnormally high pore-pressure in the fine-grained clastics of the Lech Formation and caused local bedding-parallel extension (I); further increase of the pore-pressure led to bedding-parallel fluid expulsion and continued compaction (II); (C) Discrete faults experienced extension because of high pore-pressures and fluid escape along open fractures.

The first major emergence of NCA-fold-thrust-structures above sea-level is documented by angular unconformities seen below the coarse clastics of the basal Upper Cretaceous Gosau Group in the western NCA (Ortner 1994; Wagreich 1995; Eisbacher & Brandner 1996). In the region under discussion a remnant of the Gosau Group that rests unconformably on Lower Jurassic strata is preserved near the peak Hohes Licht, located less than 10 km to the north of the central Kreideschiefer basin (Fig. 2 and Fig. 14). In the western NCA the age of the sub-Gosau unconformity and age of the basal nonmarine clastics are generally considered to be Turonian to Santonian (Wagreich & Faupl 1994). This Late Cretaceous interval of emergence, erosion, and fluvial deposition which lasted from approximately 92 to 85 Ma must have been related to broad regional uplift of the crestal portion of the NCA thrust wedge. After this short period of emergence marine upper Gosau strata of Campanian and younger age indicate renewed regional subsidence of the NCA wedge below sea level (Ortner 1994; Wagreich 1995); at this time the NCA had possibly overridden deeper thrust sheets and had reached the front of the Austroalpine thrust wedge.

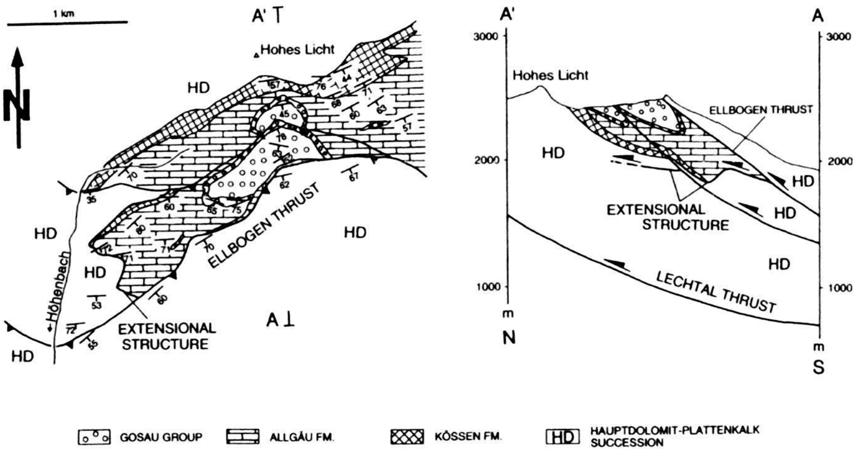

Fig. 14. Sketch map and north-south cross sectio of erosional remnants of basal Gosau Group ex posed within the Lechtal thrust sheet south of th peak "Hohes Licht" (for location see Fig. 2). A complex extensional structure in the footwall o the Ellbogen thrust was subsequently folded an faulted together with the Gosau Group durin north-south oriented contraction.

The outcrop area of the Gosau Group below the peak Hohes Licht is located east of a complex early extensional structure that affected the Mesozoic substratum (Fig. 14). The Gosau Group itself forms two ESE-trending and NNE-verging synclines separated by an E-striking and N-directed thrust fault. South of the two synclines the Ellbogen thrust carries Hauptdolomit Formation over Jurassic marls; these marls display superimposed sets of shear veins with slickenlines which suggest early top-to-the-northwest displacements overprinted by top-to-the-north movements along the thrust fault. The younger of the two deformations appears to have produced the two large folds and a weak E-striking cleavage in the Gosau Group. Most probably the second deformation phase was related to the overall northerly emplacement of the entire Austroalpine thrust complex onto the distal margin of Europe from latest Cretaceous to earliest Miocene time (e.g. Froitzheim et al. 1994; Eisbacher & Brandner 1996); in the western NCA details and timing of this regionally important deformation phase are still poorly constrained.

A regional kinematic model for the development of the Kreideschiefer basin

The sedimentation of the siliciclastic Lech Formation in the Kreideschiefer basin during Aptian-Cenomanian(?) time probably heralded the beginning of broadly convergent movements within the western NCA which then were still located south of partly emergent crystalline basement complexes (Ötztal, Silvretta?). Deposition of the Lech Formation occurred in a relative deep basin bordered by both inherited extensional faults and by the NW-verging fold-thrust structures of the frontal Inntal sheet (Fig. 15a). Locally divergent step-over structures possibly created the most pronounced bathymetric lows (Fig. 15b) and an accentuated relief along basin-bounding faults favoured the detachment of huge slide blocks. The advance of the fault-segmented Inntal thrust sheet loaded and thermally upgraded the southernmost Lechtal sheet; it also le to the development of a first compaction cleavage in the fine grained clastics of the Lech Formation (Fig. 15c). Near th westernmost termination of the Inntal thrust sheet footwal strata were emplaced along an out-of-sequence thrust on to of the Inntal sheet before the fault-segmented Inntal shee moved onto the Lech Formation. This double thrust panel i now preserved in the Krabach klippe. In Turonian(?)-Conia cian time fold-thrust structures of the NCA emerged above se level as they moved over the Central Alpine complexes an were eroded, with detritus being preserved in the Gosau basin (Fig. 15d). Renewed regional subsidence of the NCA belov sea level was followed by the contraction of the entire wester NCA during their advance over the European continenta margin (Fig. 15e). While the pre-Gosau phase of contractio within the western NCA probably still occurred southeast o the Central Alpine Ötztal-Silvretta complexes, the later phase of the superimposed N- to NNE-oriented contraction foun the western NCA already located to the north of the Centra Alpine complexes.

Conclusions

In the western parts of the Northern Calcareous Alps (NCA several major faults that cut uppermost Triassic(?)-Jurassi strata were probably part of an early Mesozoic extensiona fault system. This fault system can be documented in th steeply N-dipping stratal succession within the trailing portio of the Lechtal thrust sheet. The extensional faults coincid roughly with a zone where thin-condensed Jurassic succession change into thick basinal facies, suggesting that the faults ar mainly of Jurassic age. The fine-grained siliciclastics of th mid-Cretaceous synorogenic Lech Formation were therefor deposited on a highly structured carbonate substratum and th geometry of the "Kreideschiefer basin" was controlled both b reactivated low-angle faults and by approaching thrust sheets

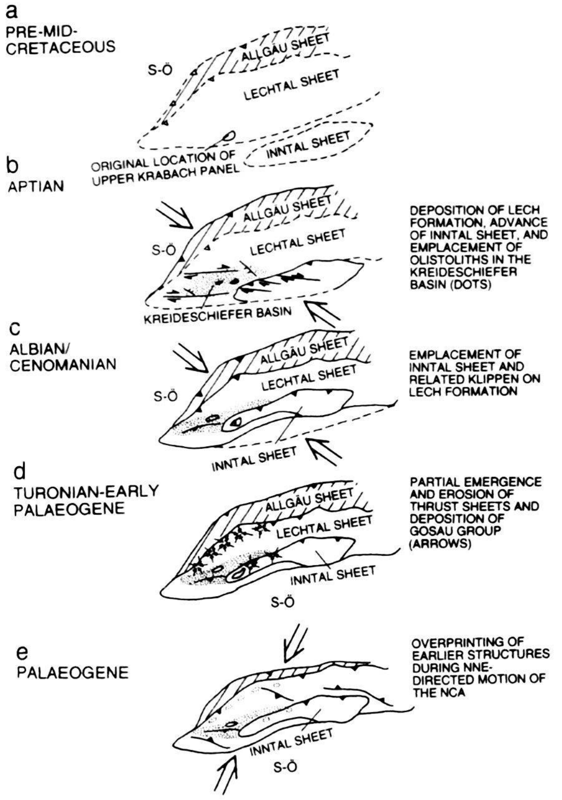

Fig. 15. Palinspastic and kinematic model for the development and deformation of the western NCA (see text for discussion). S-Ö indicates the possible location of the Silvretta-Ötztal complexes with respect to the NCA.

Along the submarine slopes forming the margins of the Kreideschiefer basin large slide masses became detached and were incorporated within the Lech Formation. Eventually even larger carbonate thrust masses, now preserved as klippen on top of the Lech Formation, overrode the Kreideschiefer basin. Stratigraphic similarities and provenance of siliciclastics in the Lech Formation from a distant emerging crystalline complex suggest that this deformation probably occurred at a time when the NCA were still located to the south or southeast of the Central Austroalpine Silvretta and Ötztal complexes. The NW-directed emplacement of the carbonate thrust sheets induced a first tectonic compaction cleavage in the Lech Formation. A second cleavage was imprinted onto the Lech Formation during superposed north-south oriented contraction. This deformation occurred after the NCA had experienced a short lived emergence above sea level and fluvial erosion that resulted in the deposition of the nonmarine basal Gosau Group in Late Cretaceous time. The second regional deformation was related to the N- to NNE-directed movement of the NCA, now located in front of the Central Austroalpine basement complexes while they approached the southern margin of Europe.

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