



Deformation around a detached half-graben shoulder during nappe stacking (Northern Calcareous Alps, Austria)

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Abstract

This study describes the inversion of a rift-related graben shoulder during emplacement and transport of a major thrust sheet in the external part of the western Northern Calcareous Alps (NCA). Structural fieldwork was carried out along the Lechtal thrust, separating the tectonically deeper Allgäu thrust sheet from the Lechtal thrust sheet. An irregularly shaped Early Jurassic normal fault and an adjacent basin are present in the immediate footwall of the Lechtal thrust. The Early Jurassic age of the basin formation is indirectly established by thickness differences in the syntectonic deposits. Scaly fabric and small-scale drag folds document top S to top SW kinematics at the normal fault. During Alpine orogeny the Lechtal thrust is forced to recess around the graben shoulder in the footwall. A transpressive, dextral tear-fault develops in the hanging wall to compensate for lateral differences of shortening. The normal fault is too steep for inversion, and a shortcut thrust across the half-graben shoulder developed at a shallower angle. It transports the detached half-graben shoulder into the neighbouring basin. Albian to Paleogene transport of the Lechtal thrust sheet caused deformation below the Lechtal thrust, creating a shear zone with isoclinal folds, break thrusts, boudinaged beds and development of S–C fabric. Kinematic analyses of S–C fabrics and small-scale fold axes along the Lechtal thrust show consistent top NW to top N shortening directions in accordance with Cretaceous to Paleogene thrust directions in the NCA.

Keywords Jurassic normal faulting · Basin inversion · Thrust tectonics · Northern Calcareous Alps

1 Introduction

In many cases complex structural style in fold-and-thrust belts is related to obscured pre-existing normal faults and inverted basins (e.g. Channell et al. 1990; May and Eisbacher 1999; Pace et al. 2014; Martinez et al. 2015). Compressive overprint or lack of outcrop information may prevent exact localisation of these normal faults. Basin inversion has been studied for more than twenty years in numerous fold-and-thrust belts employing fieldwork and analogue modelling, partly because of economic implications and seismic hazard assessment (e.g. Bonini et al. 2012

and references therein). Pre-existent basins may cause sudden facies and thickness changes, control fault orientation during inversion, or lateral differences in the amount of shortening.

This study describes the inversion of a half-graben shoulder in the footwall of a major thrust (Fig. 1), and discusses timing and kinematics of deformation around this former basin margin. Inversion of a local basin occurs in a strongly deformed zone of the western NCA, characterised by isoclinal folding and multiple stacking of slices. Data were obtained by structural mapping at the 1:10.000 scale. Structural and kinematic data on rift-related normal faulting in the lower thrust sheet and on the emplacement of the overlying thrust sheet during inversion are provided to illustrate the effects of basin geometry with a steep half-graben shoulder on the structures formed during subsequent shortening.

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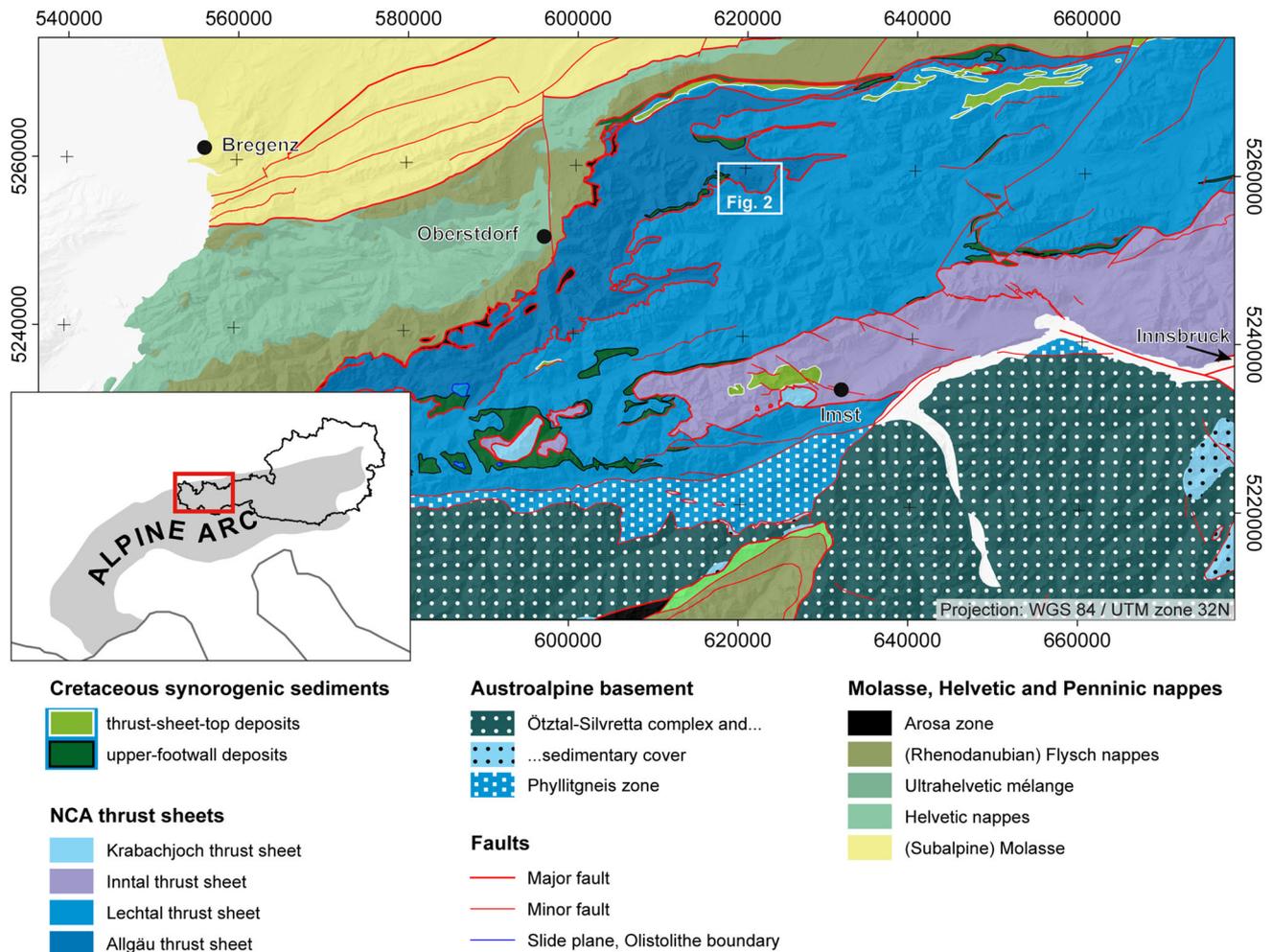


Fig. 1 Tectonic boundaries of the western NCA and surrounding tectonic units according to Tollmann (1976b), and Cretaceous syntectonic sediments (Ortner 2003a; Ortner and Gaupp 2007). White

rectangle outlines the study area shown in Fig. 2. Inset indicates the location of Fig. 1 within Austria

2 Geological setting

Within the Eastern Alps, the fold- and thrust belt of the NCA represents the sedimentary cover of the northern- and uppermost tectonic unit of the Adria-derived Upper Austroalpine (Schmid et al. 2004). During Early Jurassic times, this Austroalpine realm was affected by rifting of the Alpine Tethys (Frisch 1979; Eberli 1988; Froitzheim and Manatschal 1996; Handy et al. 2010). Early Jurassic rifting also affected the paleo-geographically most external parts of the NCA (Channell et al. 1990; May and Eisbacher 1999), represented by the Allgäu- and the Lechtal thrust sheets. There, synsedimentary normal faulting is common, as shown by mostly small scale or obscured normal faults (Channell et al. 1990; Eisbacher and Brandner 1996), scarp (mega-)breccia formation and by Jurassic terrigenous siliciclastic sediment input (Achnich 1982; Eberli 1988; Bischof et al. 2010).

During Cretaceous orogeny, the western NCA thrust sheets were sheared off their basement in the external part, transported over tens of kilometres (Eisbacher et al. 1990) and stacked in four thrust sheets. These are, from the tectonically deepest to highest: Allgäu thrust sheet, Lechtal thrust sheet, Inntal thrust sheet and Krabachjoch thrust sheet (Fig. 1). Deformation was accompanied by sedimentation, which provides a means of dating thrust sheet emplacement and fold activity within the thrust belt. These Cretaceous synorogenic clastic sediments are subdivided into upper-footwall deposits and thrust-sheet-top deposits (Ortner 2003a; Ortner and Gaupp 2007). Upper-footwall deposits are the youngest sediments below a thrust sheet and provide the maximum age of thrusting, while the re-transgression of thrust-sheet-top deposits on top of the nappe takes place during and after transport. The ages of these syntectonic deposits bracket thrust-sheet transport. Applying this concept shows that the western NCA thrust

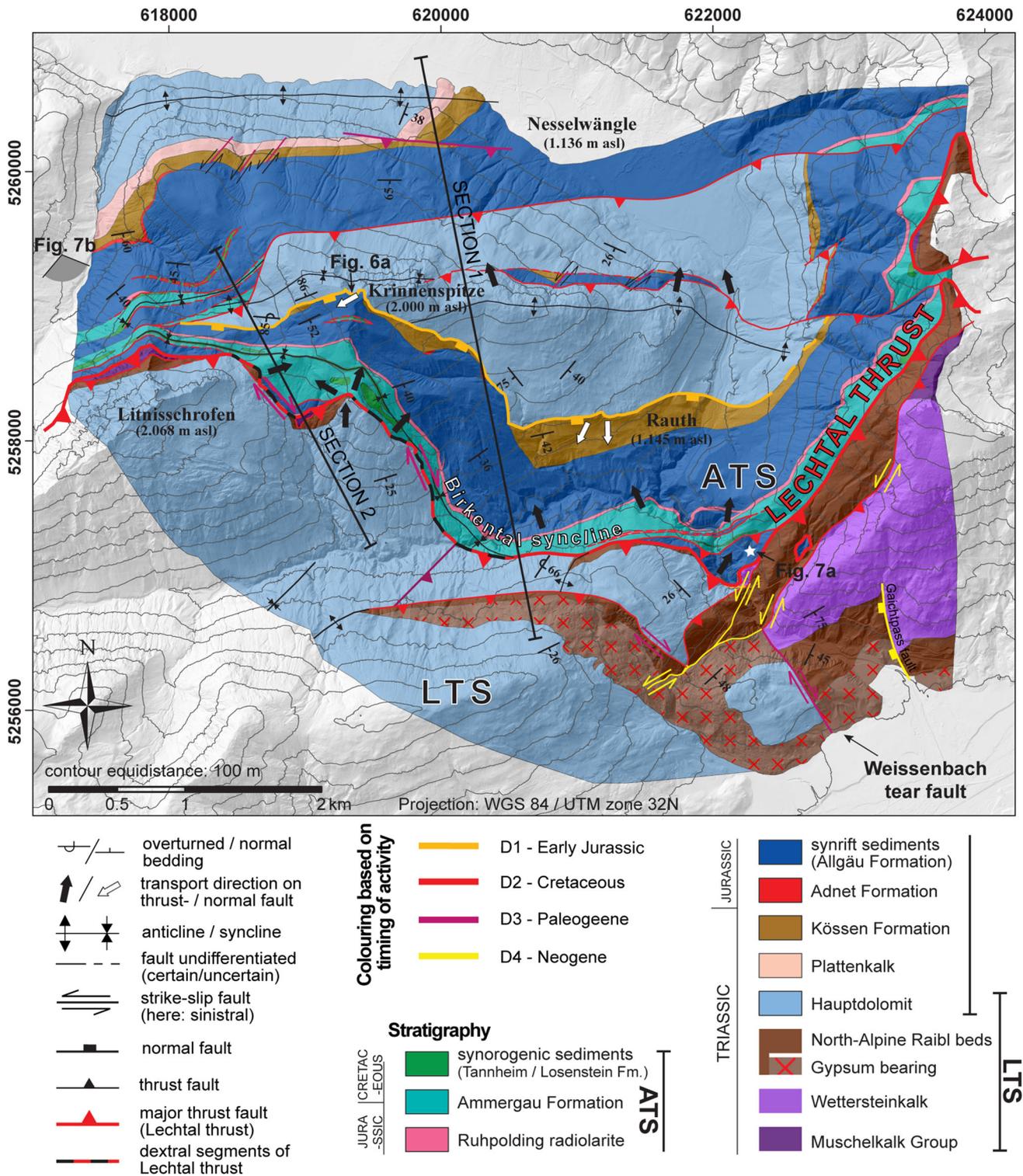


Fig. 2 Geological map of the study area. Fault colour indicates timing of activity (see chapter 5). Indicated traces refer to cross sections shown in Fig. 3. ATS: Allgäu thrust sheet; LTS: Lechtal thrust sheet

sheets were emplaced from the late Early Cretaceous onwards (Ortner 2003a). The Allgäu thrust sheet was emplaced onto a marginal slice, the Cenoman-

Randschuppe in the Coniacian, the Lechtal thrust sheet onto the Allgäu thrust sheet in the Albian. However, the Inntal thrust sheet was stacked onto the Lechtal thrust sheet

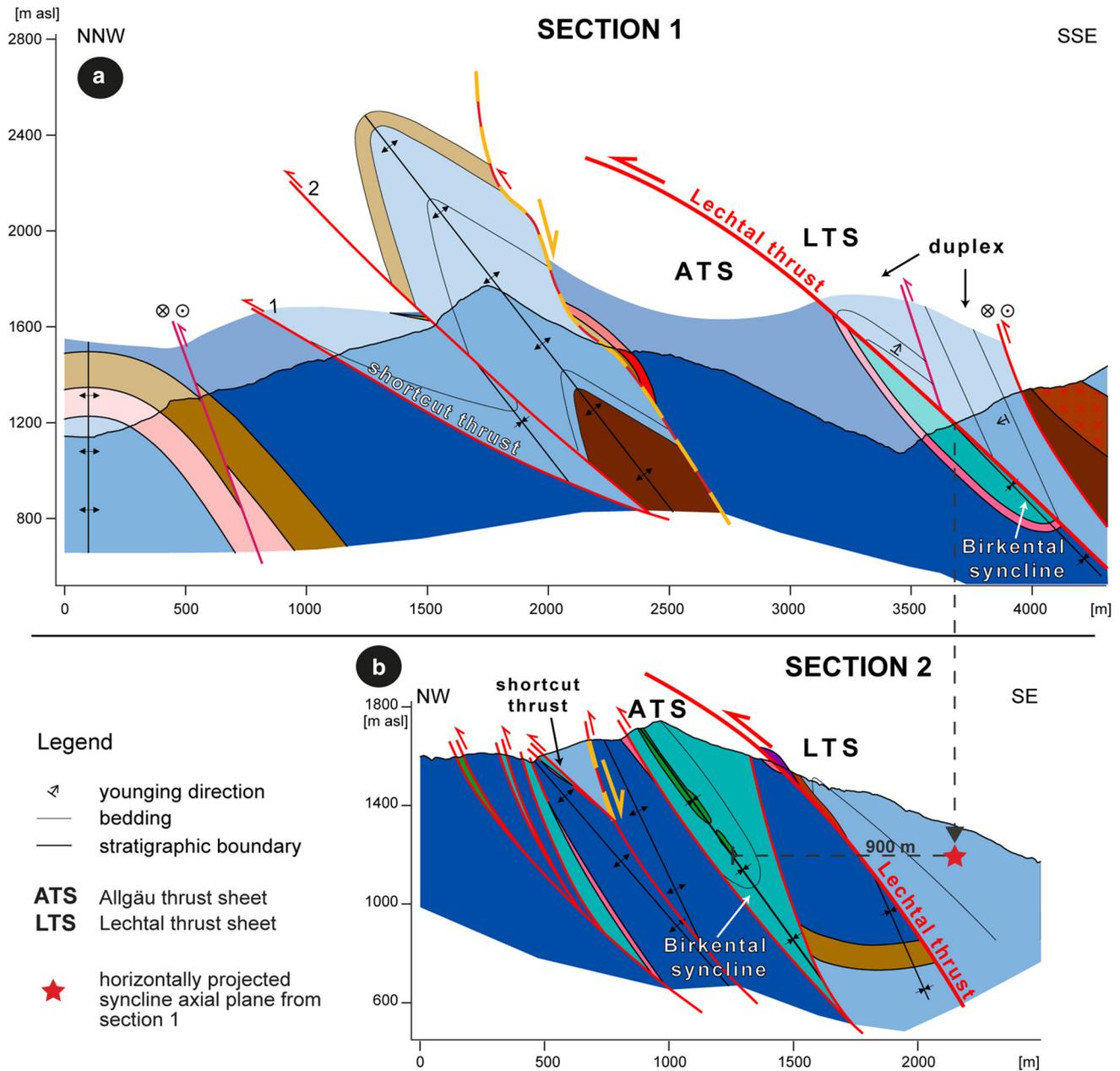


Fig. 3 Cross sections in the study area (see Fig. 2 for location and colour legend). **a** Eastern cross section 1: note fault-bounded block of Hauptdolomit left of the centre of the section, delimited by a normal fault, the thick Allgäu Fm. to the S, and, the shortcut thrusts labelled 1 and 2 to the north. **b** Western cross section 2 where the same fault block is cut near its western termination. Tight folding and thrusting

affect a 1 km thick zone below the Lechtal thrust. A horizontal projection of the axial plane of the Birkental syncline parallel to the general strike of the Lechtal thrust demonstrates 900 m dextral offset between the two sections across the NW–SE striking segment of the Lechtal thrust. Abbreviations: ATS: Allgäu thrust sheet; LTS: Lechtal thrust sheet

out-of-sequence in the Cenomanian. Generally, thrust activity propagated from S to N and reached the South Penninic units in the Turonian or Coniacian (Winkler 1988). Thrust sheet emplacement and thrust sheet internal folding took place during NW-directed transport (Linzer et al. 1995; Eisbacher and Brandner 1996; Ortner 2001, 2003a). NW-ward thrusting and folding was accompanied by NW-striking, dextral transpressive tear

faults (Ortner et al. 2016). Thrust-sheet-top deposits accumulated during thrusting and coeval folding in Late Cretaceous to Paleogene times and document growth of individual structures (Ortner 2001; Ortner et al. 2016). Thus, shortening did not cease after thrust sheet emplacement. While the NCA were transported over Penninic and tectonically deeper units, major thrusts of the NCA were folded at kilometre-scale, and growth strata in thrust-sheet-

top deposits document significant N–S contraction well into the Cenozoic.

In the northwestern NCA the lowermost and paleogeographically most external Allgäu thrust sheet is exposed in a large area (Fig. 1). Due to a shallow eastern plunge of the NCA thrust belt, the Lechtal thrust sheet appears in klippen and half-klippen above the tectonically deeper Allgäu thrust sheet. Hence, glacially formed valley flanks often expose the Lechtal thrust in quasi-3D, which facilitates structural and kinematic analysis. Deformation style and fold architecture is mainly controlled by thick rigid Triassic platform carbonates (Wettersteinkalk and Hauptdolomit, see below), whereas low-strength stratigraphic units (the gypsum bearing North-Alpine Raibl beds and the marl-rich Jurassic sedimentary succession, see below) floor and core folds and represent the preferred décollement horizons.

3 Sedimentary succession

The sedimentary succession of the NCA documents sea-level changes, tectonic events and paleogeographic evolution from Permian to Paleogene times (Brandner 1984). During the Permian and Triassic, long lasting subsidence permitted the accumulation of up to 5 km of sediments on the SE passive margin of Eurasia (Schlager and Schöllnberger 1974; Brandner 1984; Lein 1987). Rifting of the Alpine Tethys separated the Adriatic plate from Eurasia, and controlled facies of Lower to Middle Jurassic sediments. Upper Jurassic deposits are post-rift and settled on the new NW passive margin of the Adriatic plate towards the Alpine Tethys (Frisch 1979; Eberli 1988; Froitzheim and Manatschal 1996). Syn-orogenic deposition started diachronously during the Early Cretaceous in response to Eoalpine orogeny that inverted the older, SE passive margin.

In the Lechtal thrust sheet, Anisian/Ladinian cherty pelagic limestones of the Muschelkalk Group are the oldest stratigraphic unit (Bechstädt and Mostler 1974; Nittel 2006). Only the upper, lagoonal part of the Ladinian Wettersteinkalk platform is present (Ott 1972), the reef and foreereef is missing in the study area. The transition to the overlying, mixed carbonatic-siliciclastic sediments, namely the Carnian North-Alpine Raibl beds, is characterised by an erosional unconformity. Bedded carbonates and an extraordinarily thick (up to 250 m) succession of cellular dolomites and gypsum also belong to the North-Alpine Raibl beds (Jerz 1964). During the Norian up to 2000 m of Hauptdolomit were deposited in a large lagoon (Fruth and Scherreiks 1984). The Hauptdolomit is the only stratigraphic unit present in the Lechtal- and the Allgäu thrust sheet. The Late Norian to Rhaetian Plattenkalk (Tollmann

1976a) marks the return to limestone-dominated shallow marine sedimentation. The overlying Rhaetian Kössen Fm. is characterised by intercalation of marls and basinal limestones (Golebiowski 1991).

The red nodular limestones of the Adnet Fm. represent a Jurassic condensed deep swell facies (Huckriede 1958; Jacobshagen 1965), and is thin or missing in most sections. In contrast, the up to 550 m thick basinal facies, the Allgäu Fm. is widespread in the study area (Fig. 2). The pelagic, bioturbated marly limestones of the Lower Allgäu Fm. are intercalated with sandstones, calcareous arenites and micro-breccias and have a Hettangian to Pliensbachian age (Jacobshagen 1965). In some regions of the western NCA the components of these clastic horizons can reach enormous sizes (Achnich 1982; Bischof et al. 2010). Manganese-rich black marls and mudstones of the Middle Allgäu Fm. of Toarcian age (Jacobshagen 1965) correlate with the worldwide oceanic anoxic event (Jenkyns 1985; Neumeister et al. 2016). The deposition of cherty limestones of the Upper Allgäu Fm. continued into the Middle Jurassic (Jacobshagen 1965). Red to green cherts and marls of the Ruhpolding radiolarite accumulated during the early Late Jurassic. A recovery of carbonate production in the Kimmeridgian (Bernoulli 1971; Bartolini et al. 1996) leads to sedimentation of pelagic limestones of the Ammergau Fm., which lasts until the Middle Aptian without a clear hiatus or significant increase in marl content (Zacher 1966).

A change from carbonatic to mixed carbonatic-siliciclastic sedimentation characterises the start of synorogenic sedimentation with the Tannheim Fm. in the Late Aptian, which grades into the conglomeratic Losenstein Fm. in the Albian (Zacher 1966). Siliciclastic sedimentation was confined to an orogen-parallel basin (Gaupp 1982). A coarsening upward sequence and an increase of exotic siliciclastic as well as mafic crystalline pebbles towards the top in the component spectrum (Zacher 1966) indicates the approach of the orogenic front before the depositional area was finally closed by the Lechtal thrust in the Albian (Ortner 2003a).

4 Field data

4.1 Structural overview

In the study area (Fig. 2) the foot- and hanging wall of the Lechtal thrust are exposed. The Lechtal thrust is one of the major thrusts within the NCA and has at least 28 kilometres displacement (Eisbacher et al. 1990) separating the tectonically deeper Allgäu thrust sheet from the Lechtal thrust sheet.

The Lechtal thrust sheet of the study area has a Middle- to Late Triassic sedimentary succession from the

Muschelkalk Group to the Hauptdolomit. Several faults of different orientation, kinematics and age of activity cross-cut this thrust sheet (Fig. 2). A high-angle, NW striking and dextral strike-slip fault (Weissenbach tear fault) divides the Lechtal thrust sheet into two tectonic domains and brought the Hauptdolomit and the Wettersteinkalk to the same structural level (Fig. 2). A scissor fault in the eastern domain (Gaichtpass fault of Fig. 2) is parallel to the Weissenbach tear fault and has probably comparable kinematics, whereas two slices, originating from the upright and overturned limb of a tight fold, are stacked in a duplex in the western domain (Figs. 2, 3a). The thrust of the southern slice runs into an anticline to the W (Fig. 2) previously described by Müller-Wolfskeil and Zacher (1984). Both domains are overprinted by a NE striking, sinistral transtensive fault system (coloured yellow in Fig. 2), which also displaces the Weissenbach tear fault.

The Allgäu thrust sheet of the study area consists of Late Triassic to Early Cretaceous strata from the Hauptdolomit to the Losenstein Fm. Kilometre-scale folds are slightly E-plunging and mainly controlled by the rigid Hauptdolomit. Whereas the northernmost anticline is upright and symmetrical, both the syncline and anticline at Krinnenspitze (2000 m asl) are tight and N-verging, and their amplitudes increase towards the E (Figs. 2, 3a). Two out-

of-sequence thrusts dissect these tight folds (1 and 2 of Fig. 3a), truncating them at the top or base, ultimately isolating single fold limbs.

4.2 Normal faulting in the Allgäu thrust sheet

The internally folded and thrustured Hauptdolomit of the Krinnenspitze in the Allgäu thrust sheet is surrounded by Late-Triassic and Jurassic basinal sediments (Fig. 2). In the southern part, an E–W to SE–NW striking normal fault is developed, against which the Hauptdolomit pinches out towards the W. Along this non-planar fault the Hauptdolomit in the footwall is juxtaposed obliquely with pelagic marly limestones of the Lower Allgäu Fm. (Figs. 2, 4). Towards the N, the Hauptdolomit is delimited by a shallow S dipping reverse fault with top NW kinematics (Figs. 2, 3a, b).

Along the normal fault, several slices of Kössen Fm. and, in one case, Adnet Fm. occur immediately on top of the fault (Figs. 2, 3a). Bedding planes within these slices are often subparallel to the normal fault, whereas an angular unconformity to the overlying Allgäu Fm. is observed. Bedding orientation of the Allgäu Fm. does not change adjacent to the normal fault and follows the main trend. Decametric to metric kink folds affect the Kössen

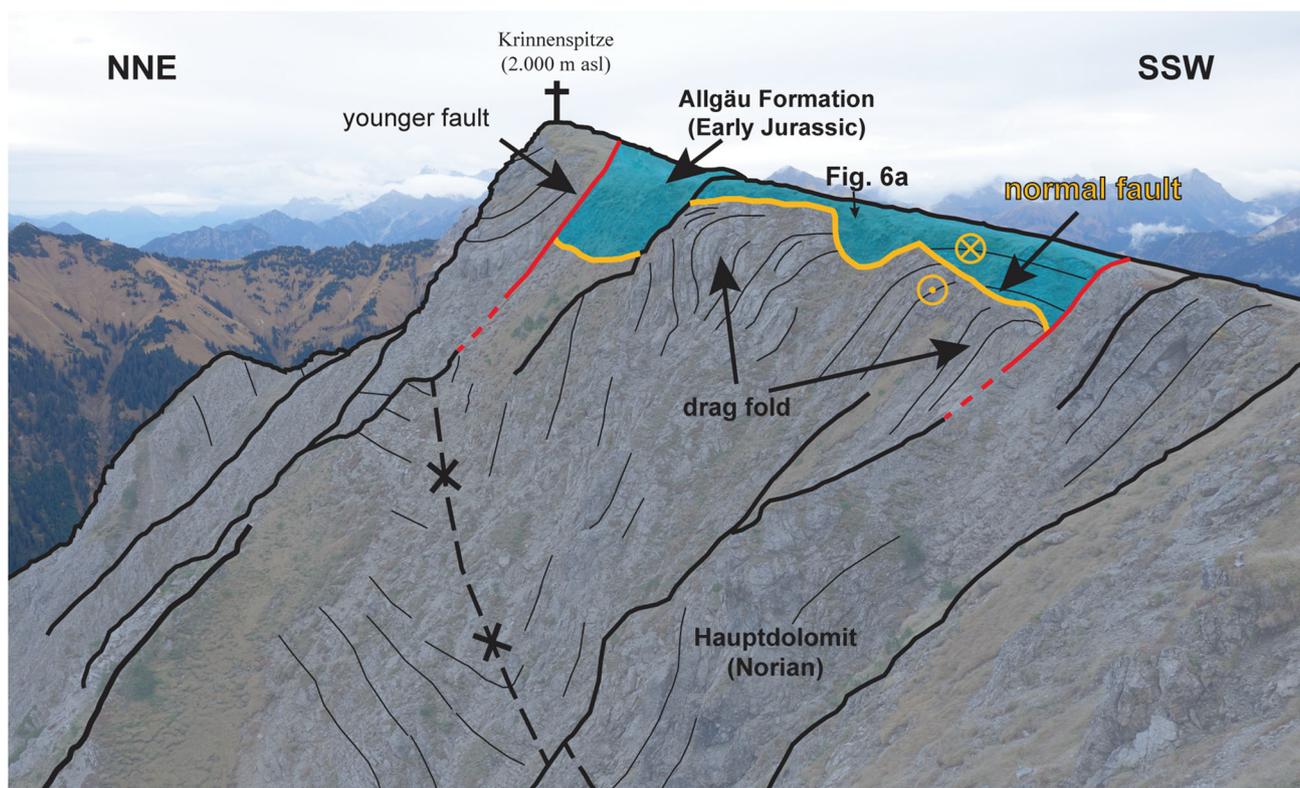
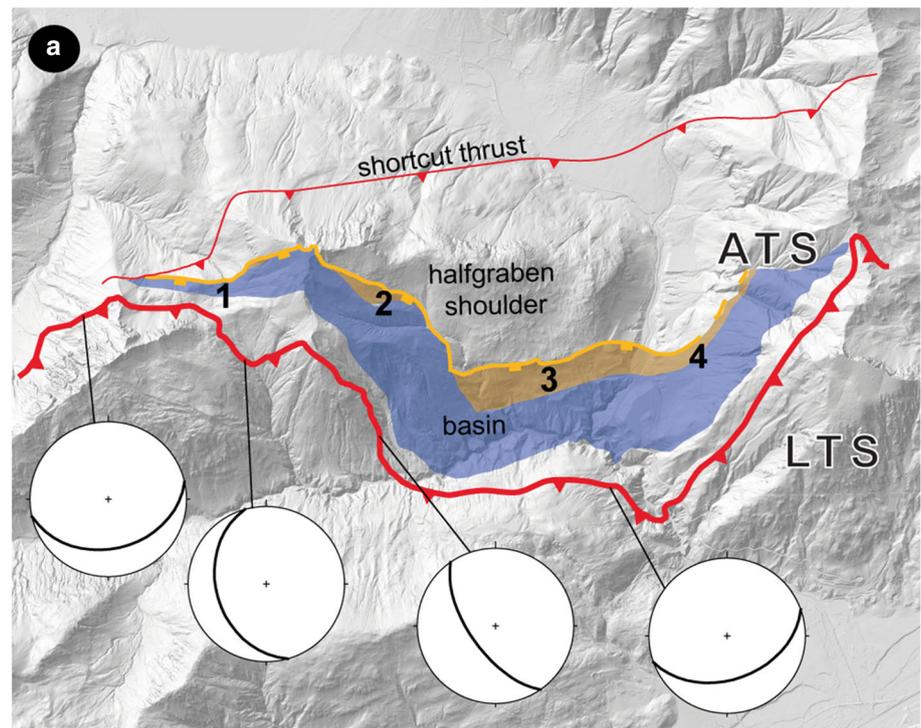
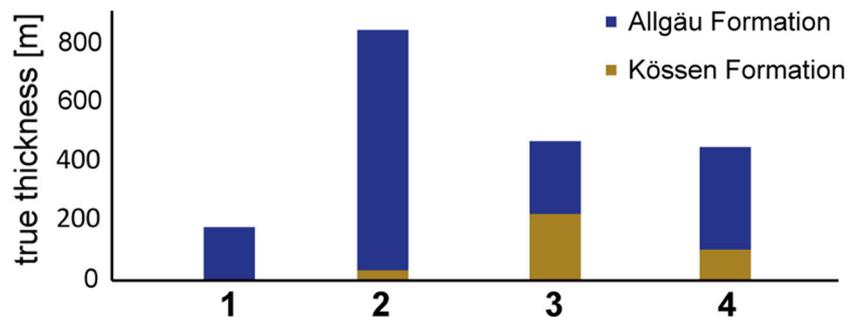


Fig. 4 Interpreted photograph of the N-face of Krinnenspitze, showing the normal fault (see Fig. 2 for location). The Lower Allgäu Fm. sediments are juxtaposed obliquely with the Hauptdolomit. Bedding of Hauptdolomit is dragged SW-ward below the normal fault

Fig. 5 a Simplified version of the tectonic map of Fig. 2 highlighting geometries and the relationship between the normal fault and associated basinal sediments to the Lechtal thrust. The attached stereographic plots depict calculated orientations of the Lechtal thrust at selected locations along strike. ATS: Allgäu thrust sheet; LTS: Lechtal thrust sheet. **b** Sediment thickness of basinal sediments in the hanging wall of the normal fault calculated without considering folding and faulting



b Thickness in Rhaetian-Lower Jurassic basinal sediments



Fm. in the hanging wall, indicating buttressing against the high angle normal fault (compare Pace et al. 2014). This causes the almost doubled sediment thickness in the Kössen Fm. at the location Rauth (Figs. 2 and column 3 in Fig. 5b).

Adjacent to the normal fault intensive shearing affects the pelagic marls and marl-rich limestones of the Allgäu and Kössen Fms. as manifested by the formation of asymmetric folds with thickened fold hinges and stretched limbs, destruction of stratification and development of scaly fabrics (Maltman 1998; Pini 1999; Vannucchi et al. 2003). The latter pervasively forms in a narrow zone in the immediate contact to the fault and consists of S-(foliation) planes and C-(shear) planes. The S-planes develop by alignment of thin elongated and slightly bent flakes surrounded by marl, whereas the C-planes dissect the S-planes in an angle of 5–15 degrees and develop very fine and thin

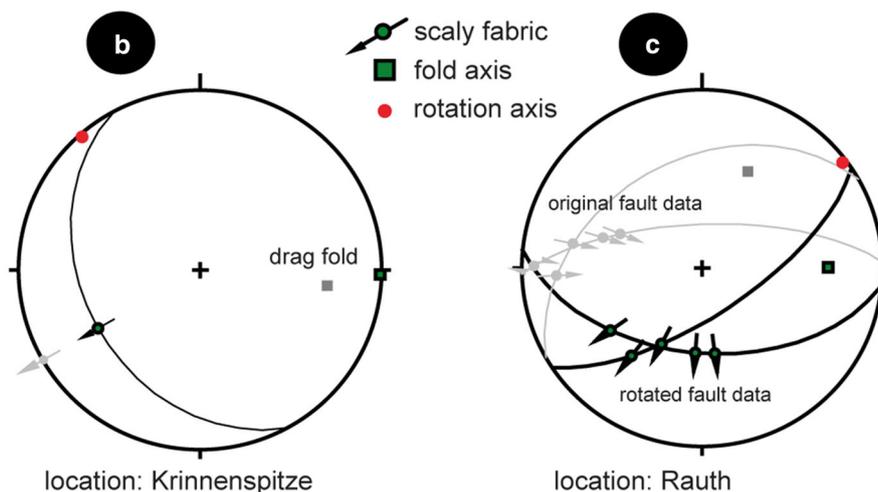
slickensides (white arrow in Fig. 6a). Using the C-planes and slickensides of these scaly fabrics as shear indicators, top S to top SW faulting is deduced (Fig. 6b, c). Fault data and fold axes of Fig. 6b, c are shown after rotation with local Hauptdolomit bedding to horizontal about bedding strike in order to retro-deform the fold-related tilt to obtain the paleo-directions of normal faulting. Small-scale asymmetric folds, accompanying scaly fabrics in the hanging wall (Fig. 6c) in combination with decametre-scale drag folds in the subvertical footwall strata (Fig. 6b), support this top S to top SW shear direction along the normal fault (Fig. 4).

Sediment thickness of the basinal sediments in the hanging wall of the normal fault (Kössen Fm. and Allgäu Fm.) changes laterally (Fig. 5), and correlates with changes in the geometry of the normal fault. Adjacent to the western half of the normal fault the sediment thickness of

Fig. 6 a Scaly fabric in marls and marl-rich limestones developed during synsedimentary extension. The marl flakes represent the foliation planes (S) and are dissected by shear planes (C). Slickensides on C-plane are indicated by a white arrow. **b** Shear indicators derived from scaly fabrics and asymmetric drag folds from locations Krinnenspitze (left) and Rauth (right) indicating top SW to top SE normal faulting



Normal faulting related shear indicators



the Allgäu Fm. is more than doubled (column 2 in Fig. 5b), while the Kössen Fm. occurs in a tectonically reduced slice. In contrast, the tectonically doubled thickness of the Kössen Fm. in the central part of the normal fault (column 3 in Fig. 5b) reflects the changing geometry of the normal fault towards a steep, almost vertical buttress. In the easternmost part, the sediment thickness (column 4 of Fig. 5b) is constant and can be used as a reference for undeformed thickness. Correlation of the westernmost calculated thickness (column 1 of Fig. 5b) to the normal fault geometry is ambiguous and probably affected by the proximity of the Lechtal thrust.

In cross section, the triangular-shaped Hauptdolomit block below the Lechtal thrust (Fig. 3b) can be interpreted as an inverted half-graben shoulder detached by a shortcut thrust, as documented in several fold-and-thrust belts (e.g.

McClay and Buchanan 1992). The local basin acted as a sediment trap for the Allgäu Fm. in Early Jurassic times as indicated by the large sediment thickness (Fig. 5b). Thrusting along the shortcut thrust detaches the Hauptdolomit half-graben shoulder and transports it onto Jurassic basinal sediments of an adjacent basin in the N (Figs. 2a, 3b).

4.3 Lechtal thrust

The Lechtal thrust at the base of the Lechtal thrust sheet was active in late Albian times according to the age of upper-footwall deposits of the Allgäu thrust sheet (Tannheim Fm., Losenstein Fm.; Ortner 2003a). Eoalpine shortening in the NCA was NW-directed (Eisbacher et al. 1990; Linzer et al. 1995; May and Eisbacher 1999; Ortner

2003a) and results in a general NE–SW strike of the Lechtal thrust in map view (Fig. 1). Although the Lechtal thrust of the study area is exclusively S-dipping (Fig. 2), it is regionally folded after thrusting, as documented by Müller-Wolfskeil and Zacher (1984).

Below the Lechtal thrust, the low-strength Jurassic to Cretaceous sediments are isoclinally folded and internally deformed within a shear zone (Fig. 7b). Fold axes in this highly deformed zone trend between NE–SW to E–W with variable plunges (orange dots in Fig. 7c) and a top NW to top N shortening direction can be inferred. Pervasive

shearing of these marly and ductile deforming Jurassic carbonates (e.g. Ammergau Fm., Allgäu Fm.) is manifested by shear-related structures defining S–C fabrics (Fig. 7a). These structures include macroscopic foliation- and shear planes and pervasive macro- and microscopic pressure solution seams. In order to avoid ambiguity in comparison to the development of scaly fabrics associated with normal faulting, the association of shear- and foliation planes in marl-rich limestones, developed during emplacement of the Lechtal thrust sheet, is referred to as S–C fabric, following the terminology of Bullock et al. (2014). The S (foliation)

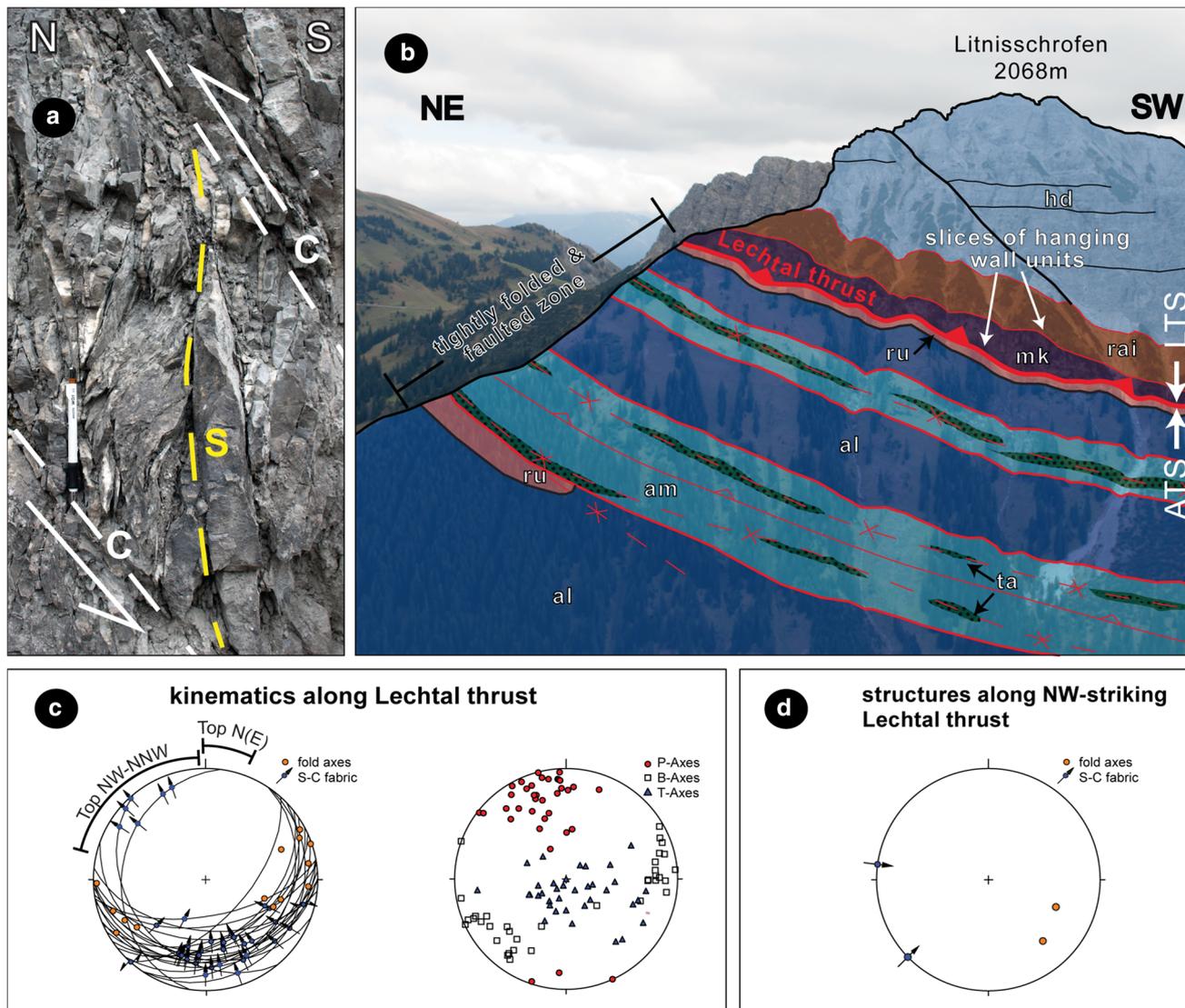


Fig. 7 a S–C fabric of a shear zone related to thrusting below the Lechtal thrust (for exact location see white star in Fig. 2). S–C fabrics are formed by S-(foliation) planes and C-(shear) planes. b Interpreted photograph showing deformation in the shear zone of the Lechtal thrust at Litnisschrofen (western study area, see Fig. 2). The slices immediately above the Lechtal thrust have incomplete stratigraphy because of cut-outs at tectonic contacts. Tight folding and cut-out of strata characterise this shear zone. ATS: Allgäu thrust sheet; LTS:

Lechtal thrust sheet; mk: Muschelkalk Group; hd: Hauptdolomit; rai: North-Alpine Raibl beds; al: Allgäu Fm.; ru: Ruhpolding radiolarite.; am: Ammergau Fm.; ta: Tannheim Fm. c Stereographic plots of kinematic data including fold axes of parasitic folds (orange dots) and shear planes of S–C fabrics (blue arrows) at the Lechtal thrust (left) and PT-axes plot of S–C fabrics (right). d Stereographic plot showing S–C fabrics and fold axes along the NW-striking part of the Lechtal thrust

plane is modified by pressure solution, although still recognizable as the primary sedimentary bedding plane. The S-planes are bent due to dragging at C-planes. The C-planes have a planar shape and cut S-planes at an angle between 20° and 35°. Although the nature of the deformation mechanism is brittle and associated with pressure solution, the strain is ductile at a larger scale because of the development of pressure solution seams and progressive fragmentation of bedding into sigmoidal pieces. Similar to the S–C fabrics developed in metamorphic rocks (e.g. Passchier and Trouw 2005), such composite fabrics also form in tectonic shear zones affecting marl-rich limestones.

Using the intersection of S- and C-planes, which is perpendicular to the shear direction in stereographic projection, S–C fabrics can be used as shear indicators. Shear directions below the Lechtal thrust, as well as the shortening direction from P-axes scatters between top NW to top N (blue arrows in Fig. 7c left and red dots in Fig. 7c right). This is coherent with the measured and calculated fold axes (orange dots in Fig. 7c). The distribution of the measured S–C fabrics is displayed in the tectonic map of Fig. 2.

A second set of shear planes cuts down section from the shear zone orientation at 5°–15° in the shear direction. Inferred shear sense and orientation with respect to the major thrust are comparable to synthetic Riedel shears using brittle terminology. Given the fact that the S–C fabrics are of ductile nature, these shear planes are named *C'*, forming shear bands (S–*C'* structures or ECC structures sensu Passchier and Trouw 2005) together with the C-planes. These shear planes pervasively occur in an advanced stage of shearing. After tight to isoclinal folding below the Lechtal thrust, shear bands on the decametre scale cause thinning and boudinage of competent stratigraphic units (Ammergau Fm., Losenstein Fm.) or even omission of units in case of the Ruhpolding radiolarite at the contacts between the Allgäu- and Ammergau Fms. (Fig. 7b).

Deformation in the shear zone below the Lechtal thrust is not laterally uniform. Locally an isoclinal syncline without any internal thrusts is observed (the Birkental syncline; Fig. 3a), which represents the stratigraphically coherent state prior to shear zone development. In contrast, a more than 1 km thick shear zone of tightly folded and sheared sediments is observed where the Hauptdolomit of the Allgäu thrust sheet pinches out to the W (Figs. 3b, 5b). Immediately above the Lechtal thrust, a Muschelkalk- and a Raibl slice occur. The slices are in correct stratigraphic order, but the basal parts of the Muschelkalk Group and the Wettersteinkalk are missing in the succession at tectonic boundaries (Figs. 2, 3b, 7b).

The local trend of the Lechtal thrust is strongly curved and arcuate in the study area (Fig. 2), in spite of its regional

NE–SW orientation (Fig. 1). The calculation of the orientation of the Lechtal thrust from its surface trace along strike allows the distinction of two strike domains (stereographic plots in Fig. 5a). The first domain is in accordance with the general ENE–WSW strike of the thrust. Additionally, two separate NW–SE segments are also present (dashed parts of the Lechtal thrust shown in the western part of Fig. 2). The transition into these NW–SE striking domains is gradual. Dextral shear accompanies the NW-striking segments. This is indicated by several independent observations: (1) S–C fabrics and fold axes along the NW-striking segments (Fig. 7d) have a different orientation compared to structures along the general NE–SW oriented Lechtal thrust (Fig. 7c); (2) a slice of North-Alpine Raibl beds is dextrally offset along the western NW-striking segment (Fig. 2); (3) when comparing the two sections of Fig. 3, the trace of the Birkental syncline below the Lechtal thrust is offset dextrally by 900 m across the eastern NW-striking segment.

5 Discussion and structural evolution

The structural complexity of strongly sheared and thrust units overlying low-strength sediments buttressed against a rigid tectonic high in the footwall of a major thrust demands rheological contrasts in the footwall prior to thrusting. Folding of footwall units and subsequent out-of-sequence thrusting would generate a similar structural situation, but one that could be expected to extend more regionally. The rigid Hauptdolomit at Krinnenspitze, delimited by an irregularly shaped normal fault in the S and a thrust in the N, in combination with large sediment thickness in the Allgäu Fm. and glide blocks in the hanging wall of the normal fault, calls for the interpretation of a Jurassic normal fault that became inverted during Alpine orogeny.

Deformation in basinal sediments along the Jurassic normal fault in the Allgäu thrust sheet, such as asymmetric folds and scaly fabrics bound to a single or several beds, and destructed sedimentary bedding, all indicate deformation in non- to partly lithified conditions in fine grained sediments (Ortner 2007; Odonne et al. 2011). A close relationship between soft sediment deformation in the Lower Allgäu Fm. and normal fault activity seems likely. In combination with the locally larger thickness of basinal sediments and the occurrence of Rhaetian slices along the normal fault, basin formation is indirectly dated as Early Jurassic. Apart from that, there is no clear evidence for earlier normal faulting already starting in the Latest Triassic, as documented by Ortner (2014), or continuing into the Middle Jurassic. The increase in sediment thickness by about 400 meters in the western basin could potentially

provide an estimate for the minimum offset along the normal fault. However, this estimate is rather speculative due to the missing cut-off point in the hanging wall and because of the unknown amount of compressive structural overprint along the normal fault. Variable basinal sediment thicknesses in the hanging wall of the normal fault suggest increasing offset from E to W. The position of the Kössen slices along the normal fault can be interpreted as the result of combined paleo-mass-movement and tectonic processes. The slices were probably dragged along the fault, which also resulted in scaly fabric formation. An interpretation in terms of extensional duplexes (Gibbs 1984) as origin of the slices can be excluded, as formation of duplexes demands a large amount of stretching along a low-angle detachment. The cut-off angle of the normal fault cannot be observed and is most likely not preserved, as the low-strength basinal sediments were dragged during synsedimentary normal faulting and were additionally folded while being buttressed against the half-graben shoulder during inversion.

During Alpine orogeny, the pre-existing basin and its steeply dipping normal fault of the half-graben shoulder act as a rigid buttress in front of the Lechtal thrust sheet approaching from the SE. Progressive differential footwall deformation around the half-graben shoulder causes the Lechtal thrust to recess around this pre-existing rheological irregularity. More shortening in the footwall in the W, where the half-graben shoulder ends (compare sections 1 and 2 of Fig. 3), causes the Lechtal thrust sheet to develop a lateral ramp with a dextral component of shear (Fig. 8a). Bending of the Lechtal thrust seems to be a result of locally stronger shortening in the W as a consequence of the thicker Jurassic basin being filled by incompetent rocks.

The Weissenbach tear fault lies in the SE prolongation of the NW striking segment of the Jurassic normal fault after retro-deforming WNW–ESE sinistral strike-slip faulting (yellow faults in LTS in Fig. 2). Thus, the generation of the Weissenbach fault during Lechtal thrust emplacement can be directly linked to the irregular shape of the half-graben in the footwall. The steeply dipping Early Jurassic normal fault is at an inappropriate angle for reactivation during Alpine shortening. Thus, development of a shortcut thrust cutting across the half-graben shoulder is necessary. Basinal sediments in the hanging wall of the shortcut thrust are buttressed against the steep half-graben shoulder, but most of the deformation takes place along the shortcut thrust. The oblique orientation of the half-graben shoulder compared to the shortcut thrust during inversion causes pinch-out of the Hauptdolomit (Fig. 9). After detachment, the half-graben shoulder is transported into the next basin (Fig. 3b). In comparison to other inverted basins in fold-and-thrust belts (e.g. Bond and McClay 1995; Mencos et al. 2015; Granado et al. 2017) transport along the shortcut thrust documented in this study is more

pronounced and represents a later deformation stage when compared to the foreland basins described by these authors.

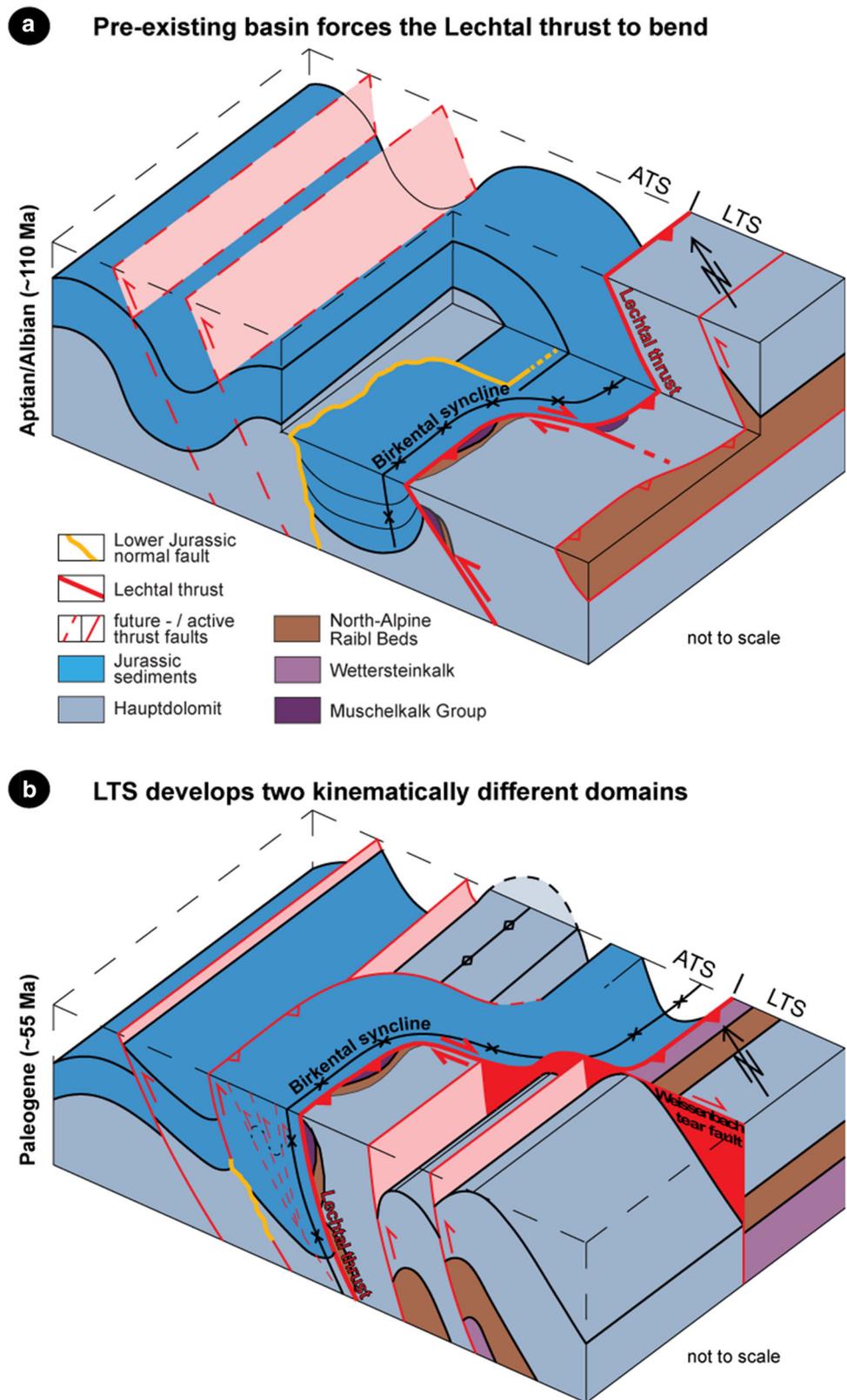
A change in shortening direction from top NW to top N inferred from shear indicators in Fig. 7c can be associated with the Late Cretaceous to Paleogene deformation (e.g. Eisbacher and Brandner 1996; Froitzheim et al. 1994). The Lechtal thrust sheet is buttressed against the steeply dipping normal fault of the Jurassic basin, resulting in the formation of the duplex accompanied by dextral shear along the Weissenbach tear fault in the Lechtal thrust sheet (Fig. 8b). Development of NW-striking tear faults in the Late Cretaceous is common in the NCA (Eisbacher and Brandner 1996; Ortner et al. 2016), and tear faulting in the Lechtal thrust sheet is required for compensating the lateral differences of shortening. The formation of NE-directed S–C fabrics in the incompetent sediments below the NW-striking segments of the Lechtal thrust (Fig. 7d) is possibly a consequence of strain partitioning occurring in the part of the Lechtal thrust sheet, that is buttressed against the half-graben shoulder. Thus, strain along the NW-striking part of the Lechtal thrust may be partitioned into a top NE to top E component plus a dextral strike slip component.

Extensional features such as the thinning and cut-out of Jurassic strata in the shear zone below the Lechtal thrust (Fig. 7b) can be explained by the development of shear bands cutting down section. The marl-rich and low-strength Jurassic to Cretaceous strata below the Lechtal thrust deform in a ductile manner during thrust sheet transport and develop macroscopic structures comparable to mylonitic shear zones (O'Brien et al. 1987; Dennis and Secor 1990). Hence, the formation of S–C' structures has the potential to thin strata during simple shear, especially when cutting across competent layers, e.g., the Ruhpolding radiolarite, where local offset increases as deformation becomes less penetrative.

A deformation sequence consisting of five distinguishable deformation stages can be elaborated for the study area, based on the age of synorogenic sediments, thrust directions derived from S–C fabrics and crosscutting relationships (for the spatial distribution of fault activity see Fig. 2):

- D1 (Early Jurassic): Extension due to rifting related to the opening of the Alpine Tethys and syntectonic deposition of basinal sediments.
- D2 (Early Cretaceous): NW directed shortening causing folding and thrusting within both, the Allgäu- and Lechtal thrust sheets, and emplacement of the Lechtal thrust sheet.
- D3 (Late Cretaceous? to Paleogene): N–S to NE–SW shortening causing the disruption of folds, nappe-internal stacking and regional folding of the Lechtal thrust.

Fig. 8 Schematic block models of the study area for the Late Cretaceous to Paleogene deformation events. **a** Late Cretaceous block model illustrating the emplacement of the Lechtal thrust sheet (LTS) onto the Allgäu thrust sheet (ATS). The Lechtal thrust is accompanied by dextral strike slip faults where it recesses around the rheological irregularity of the Early Jurassic half-graben shoulder and its basin in the footwall. Folding and out-of-sequence thrusting (dashed lines) take place in the Allgäu thrust sheet and nappe internal thrusting occurs in the Lechtal thrust sheet. Dextral bending of the Lechtal thrust generates a discrete high angle tear fault in the Lechtal thrust sheet. The Birkental syncline in the Allgäu thrust sheet immediately below the Lechtal thrust mimics the bend of the Lechtal thrust. **b** Block model illustrating the Paleogene deformation. Within the Lechtal thrust sheet the NW-striking dextral Weissenbach tear fault laterally compensates differential shortening, which is expressed by duplex stacking in the W and normal strain in the E. In the Allgäu thrust sheet out-of-sequence thrusts dissect the regional fold architecture, and a tightly folded and thrust tectonic shear zone develops below the Lechtal thrust (indicated by red dashed lines)



- D4 (Neogene): E-W directed extension in the Lechtal thrust sheet leading to transensional strike-slip faults

overprinting pre-existing compressional structures (Decker et al. 1993; Ortner 2003b).

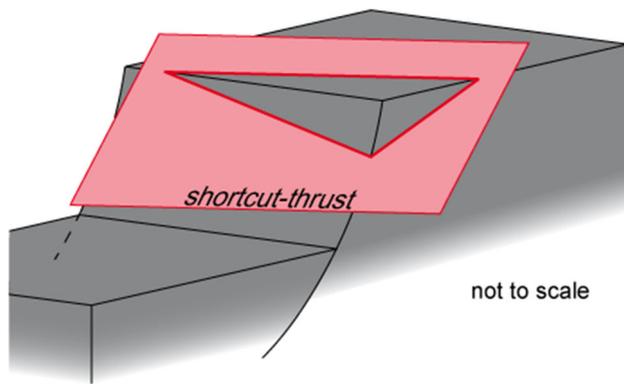


Fig. 9 Oblique thrusting along shortcut-thrust compared to half-graben shoulder leading to pinching-out of the half-graben shoulder remnant

6 Conclusions

The presence of a rift-related half-graben shoulder delimited by a steep normal fault controls tectonic style during subsequent basin inversion during Cretaceous to Paleogene shortening. Early Jurassic basin formation and normal faulting in the Allgäu thrust sheet (Fig. 10) is indirectly datable by tectonically triggered soft sediment deformation of basinal sediments and is expressed by a larger thickness of basinal sediments within the Jurassic basin (Lower Allgäu Fm.) adjacent to the half-graben shoulder and several stratigraphically incoherent Late Triassic tectonic slices (Kössen Fm.) along the normal fault.

During Cretaceous to Paleogene shortening the steeply dipping half-graben shoulder of the Early Jurassic basin acts as a rheologic irregularity during transport of the Lechtal thrust sheet. It directly causes the formation of the following deformation structures:

- evolution of shortcut thrusts cutting across the footwall of the normal fault due to its unfavourable angle for inversion (Fig. 10)
- forcing of the Lechtal thrust to recess around the Hauptdolomit buttress by bending accompanied by dextral shear
- bending of fold axis and S–C fabrics immediately below the major Lechtal thrust due to buttressing of the Lechtal thrust sheet against the steep half-graben shoulder
- development of a duplex accompanied by the dextral Weissenbach tear fault in the Lechtal thrust sheet. Tear fault formation is necessary to compensate lateral differences of shortening within the Lechtal thrust sheet.

The direction of thrusting along the Lechtal thrust is top NW to top N as documented by kinematic analyses of S–C

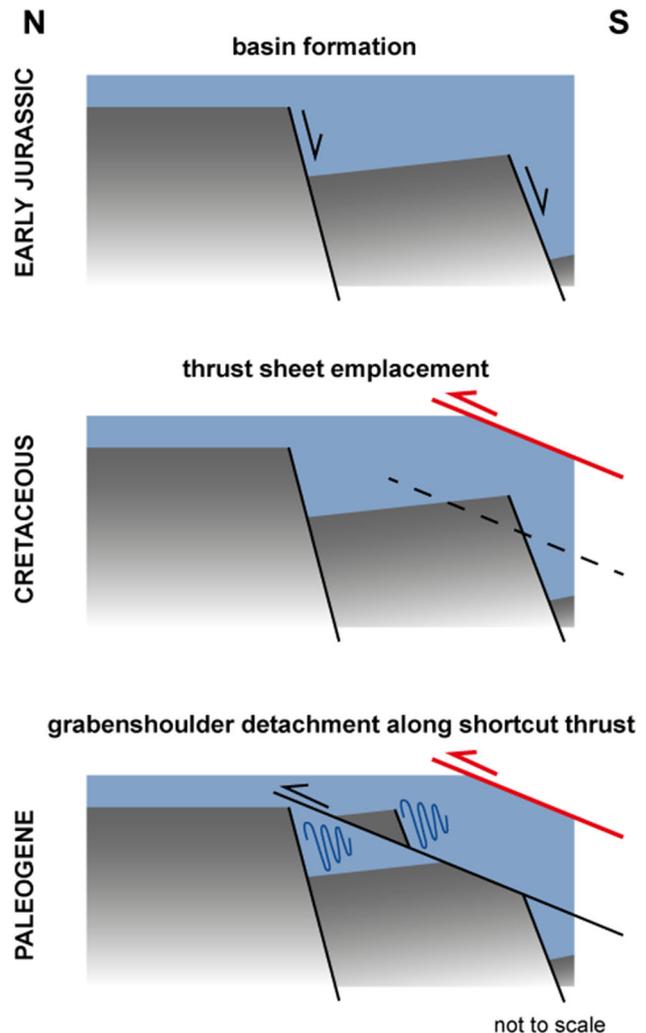


Fig. 10 Schematic evolutionary model of local basin formation in the Allgäu thrust sheet during Early Jurassic extension and detachment of the half-graben shoulder by a shortcut thrust formed during Alpine orogeny. Jurassic to Cretaceous strata (blue) are buttressed against the high-angle normal faults, where they are intensively folded and sheared

fabrics and small-scale fold axes. As a consequence of the transport of the Lechtal thrust sheet, a shear zone is formed in the low-strength Jurassic to Cretaceous sediments of the Allgäu thrust sheet, exhibiting penetrative S–C fabrics, isoclinal folds, break thrusts and local boudinage of more competent units by shear bands.

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