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Late Jurassic tectonics and sedimentation: breccias in the Unken syncline, central Northern Calcareous Alps

HUGO ORTNER[1,*], MICHAELA USTASZEWSKI[1,2] & MARTIN RITTNER[1,3]

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ABSTRACT

This study analyses and discusses well preserved examples of Late Jurassic structures in the Northern Calcareous Alps, located at the Loferer Alm, about 35 km southwest of Salzburg. A detailed sedimentary and structural study of the area was carried out for a better understanding of the local Late Jurassic evolution. The Grubhörndl and Schwarzenbergklamm breccias are chaotic, coarse-grained and locally sourced breccias with mountain-sized and hotel-sized clasts, respectively. Both breccias belong to one single body of breccias, the Grubhörndl breccia representing its more proximal and the Schwarzenbergklamm breccia its more distal part, respectively. Breccia deposition occurred during the time of deposition of the Ruhpolding Radiolarite since the Schwarzenbergklamm breccia is underlain and overlain by these radiolarites. Formation of the breccias was related to a major, presumably north-south trending normal fault scarp. It was accompanied and post-dated by west-directed gravitational sliding of the Upper Triassic limestone ("Oberrhätkalk"), which was extended by about 6% on top of a glide plane in underlying marls. The breccia and slide-related structures are sealed and blanketed by Upper Jurassic and Lower Cretaceous sediments. The normal fault scarp, along which the breccia formed, was probably part of a pull-apart basin associated with strike slip movements. On a regional scale, however, we consider this Late Jurassic strike-slip activity in the western part of the Northern Calcareous Alps to be synchronous with gravitational emplacement of "exotic" slides and breccias (Hallstatt mélange), triggered by Late Jurassic shortening in the eastern part of the Northern Calcareous Alps. Hence, two competing processes affected one and the same continental margin.

Introduction

The Late Jurassic evolution of the Northern Calcareous Alps (NCA) is a subject of controversy among Alpine geologists. Thereby the position and timing of the closure of the (north) westernmost Tethys embayment (Meliata Ocean) relative to the paleoposition of the NCA is the most contentious issue. Throughout the Triassic, before the opening of the Alpine Tethys, the NCA formed the southeastern continental margin of the European plate against the Meliata Ocean, which was part of the Neotethys (e.g. Stampfli et al. 1998; Schmid et al. 2004). During the Middle and Late Triassic, thick carbonate series accumulated on the inner passive margin, whereas the outer margin was characterized by deep swell deposits (e.g. Mandl 2000) and/or distal periplatform carbonates (Gawlick & Böhm 2000). During Jurassic rifting, the NCA were separated from the European continent by the evolving Piemont-Ligurian Ocean of the Alpine Tethys, and subsequently formed the northwestern margin of the Apulian plate (e.g. Frisch 1979; Faupl & Wagreich 2000). Deposits of the well-studied continental margin and continent-ocean transition crop out in the Austroalpine nappes of eastern Switzerland and westernmost Austria (Eberli 1988; Froitzheim & Eberli 1990; Froitzheim & Manatschal 1996) and in the western part of the Southern Alps (Bertotti et al. 1993). In these areas, half-graben rift basins and low-angle normal faults developed in the Late Triassic to Early Jurassic and the resulting submarine topography persisted to the end of the Middle Jurassic. In response to rifting, the former inner passive margin in the NCA disintegrated and subsided, causing the drowning of carbonate platforms, with the depositional environment changing to a deep water setting. Southeast of the NCA, obduction in the Meliata ocean started in the Middle Jurassic (e.g. see Dimo-Lahitte et al. 2001 for geochronology of the metamorphic sole related to obduction in Albania), followed by obduction onto the eastern margin of the Apulian plate and collision in the Early Cretaceous (Schmid et al. 2008). In the eastern NCA and western Carpathians the obducted unit is not preserved, but documented by ophiolitic detritus in Up-

[1]University of Innsbruck, Institute of Geology and Palaeontology, Innrain 52, A-6020 Innsbruck, Austria.
[2]now at: Department of Geosciences, National Taiwan University, No.1, Sec.4, Roosevelt Road, Taipei 10617, Taiwan.
[3]now at: Department of Geology, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK.
*Corresponding author: Hugo Ortner. E-mail: hugo.ortner@uibk.ac.at

per Jurassic mélange formations (Kozur & Mostler 1992; Mandl & Ondrejickova 1993). Moreover, pebble analysis (Gruber et al. 1992; Schuster et al. 2007) and chemical analysis of detrital chromium spinel grains (Pober & Faupl 1988) from synorogenic sediments suggest a proximity of the obducted ophiolites to the NCA in the Late Early to Late Cretaceous, when inversion of the passive margin of the NCA and the Eoalpine stacking of thrust sheets began (e.g. Tollmann 1976; May & Eisbacher 1999; Ortner 2003).

Breccias related to the degradation of submarine topography are a common feature within Jurassic deposits of the Eastern Alps (e.g. Bernoulli & Jenkyns 1970; Achtnich 1982; Eberli 1988; Wächter 1987; Froitzheim & Eberli 1990). The tectonic interpretation of breccia deposits is therefore often concerned with the question of how submarine topography did form. In the central part of the Northern Calcareous Alps, Jurassic deep-water carbonates are associated with large slide blocks and blocky breccias, composed of older passive margin sediments (Gawlick et al. 1999a; Mandl 2000). Previous geodynamic interpretations of the breccias have been dependent on the age of the sediments involved. For the Early Jurassic, Channell et al. (1992), Böhm et al. (1995) and Ebli (1997) concluded that sliding and breccia sedimentation were related to block tilting associated with rifting. However, Middle and Late Jurassic (mega-) breccias have also been interpreted as related to compressive tectonics. For example, Tollmann (1987) and Mandl (2000) favour a model of gravitational mobilisation and gliding due to tectonic movements in the hinterland of the

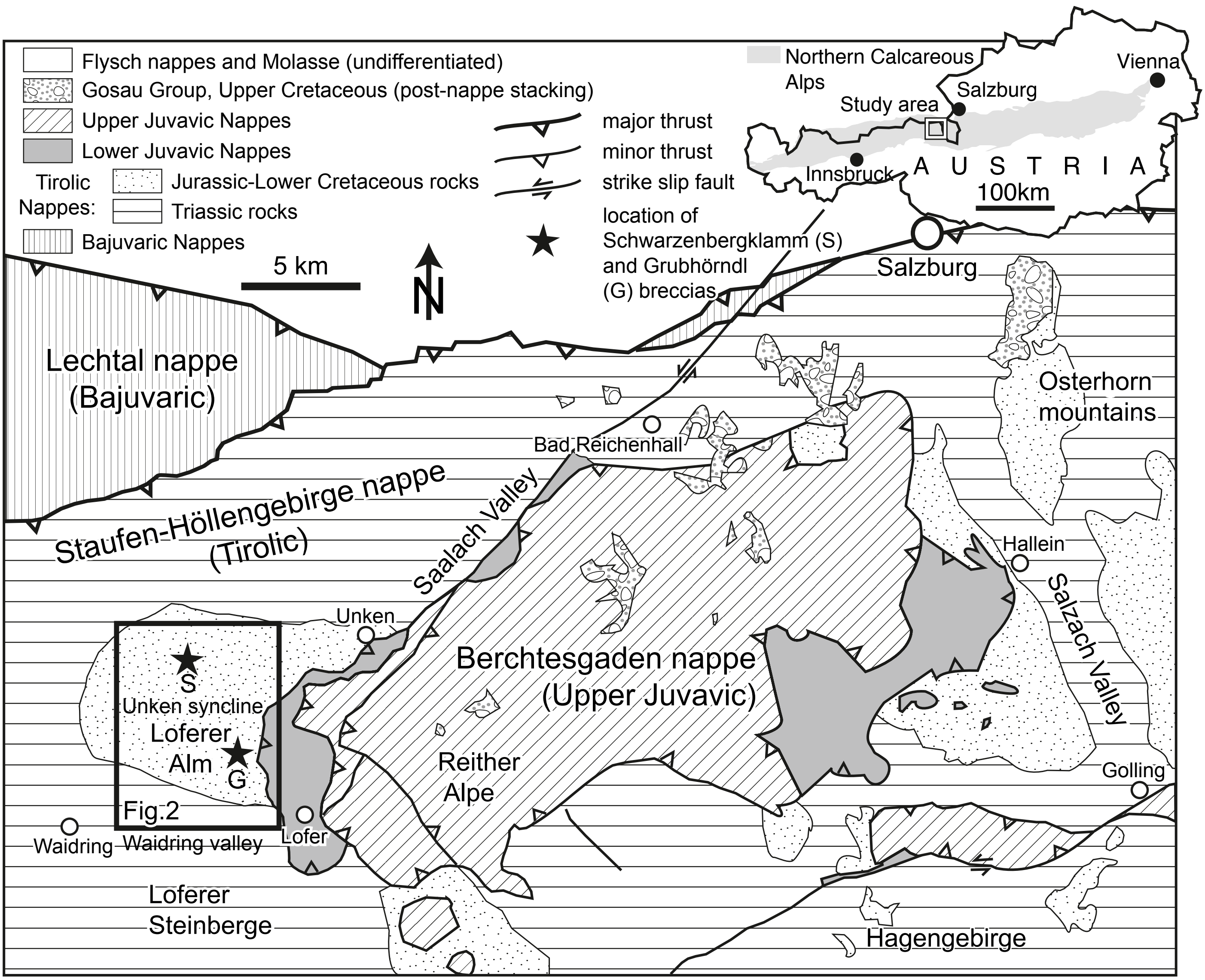


Fig. 1. Tectonic overview of the investigated area based on Schweigl & Neubauer (1997); tectonic subdivision of the thrust sheets of the NCA based on Tollmann (1976).

mega breccias. Frank & Schlager (2006) suggested an interpretation in terms of a depositional domain dissected by major strike-slip faults. Gawlick et al. (1999a) and Frisch & Gawlick (2003) interpret the depositional realm in terms of a foreland basin related to Middle to Upper Jurassic orogeny, which also involved Late Jurassic subduction and high-pressure/low-temperature metamorphism at the southern margin of the Central NCA; however, these authors did not present or discuss associated deformation structures visible in the field.

Previous studies

The Grubhörndl and Schwarzenbergklamm breccias of the Unken syncline (Figs. 1, 2) have been studied for almost a century. Hahn (1910) identified these two occurrences of breccias as Rhaetian and Mid-Liassic sedimentary deposits, respectively. Vortisch (1931) interpreted the Schwarzenbergklamm breccia to be a tectonic breccia attached to a bedding-parallel shear plane. This interpretation was rejected by Fischer (1965), who described the Schwarzenbergklamm breccia as a Jurassic scarp-breccia generated along the western continuation of the "Torrener-Lammer" fault zone. Garrison & Fischer (1969) and Diersche (1980) followed the argument of Fischer (1965) and interpreted the Schwarzenbergklamm breccia as a submarine mass flow deposit generated by a local east-west striking fault scarp, oriented parallel to the Waidring valley. Wächter (1987) gave a detailed sedimentological description of the Schwarzenbergklamm breccia. Channell et al. (1992) presented a paleogeographic reconstruction of the Unken syncline with minor roughly north-south striking Liassic normal faults related to a major E–W striking south-directed normal fault, which separated the future Staufen-Höllengebirge nappe from the Lechtal nappe and was reactivated as a thrust fault during Eoalpine orogeny. Gawlick et al. (1999a, 2002) interpreted the Schwarzenbergklamm breccia as a piece of evidence for the Kimmeridgian orogeny and compared this breccia with deposits in the Tauglboden basin in the Osterhorn Mountains located further to the east (ca. 10 km south/southeast of Salzburg).

Sedimentary succession of the Unken syncline

The Mesozoic of the Unken syncline is characterized by the following succession (Fig. 3). During a tectonically quiet period in the Triassic, shallow water carbonate platform sediments (e.g., Wetterstein Formation, Hauptdolomit Formation, Dachstein limestone) accumulated on the NCA part of the rapidly subsiding Tethyan shelf. In the Rhaetian, reefal limestone ("Oberrhätkalk") interfingered with contemporaneous Kössen marls in an adjacent basin (e.g. Stanton & Flügel 1995). In Early Jurassic times breccias related to tectonic activity were deposited along horst-and-graben structures. These are exposed immediately south of the investigated area (Krainer et al. 1994). However, in the Unken syncline, pre-Jurassic morphology of the Late Rhaetian reef controlled the distribution of facies after a major Earliest Jurassic relative sea-level rise due to subsidence. Lower to Middle Jurassic condensed nodular limestones (i.e. Upper Hettangian Adnet Formation to Bajocian Klaus Formation; Garrison & Fisher 1969) covered the top of the Late Rhaetian reef, while the Kössen basin was filled by Lower Jurassic allodapic limestones and marl-dominated sediments (Kendlbach Formation, Scheibelberg Formation, Allgäu Formation), before Middle Jurassic red nodular limestones of the Klaus Formation covered the former basin (Fischer 1969; Krainer & Mostler 1997). Because the Adnet and Klaus Formations can only be distinguished when biostratigraphic data are available, and because the total thickness of both units is only about 15 meters, we could not distinguish the two formations and mapped "red limestones". A pronounced change in sedimentation occurred at the end of the Middle Jurassic ("Ruhpoldinger Wende"; Schlager & Schöllnberger 1974), as is expressed by widespread deposition of Ruhpolding Radiolarite. This was also the time of deposition of the Grubhörndl and Schwarzenbergklamm breccias, deposited near a rejuvenated submarine topographic gradient, which controlled the distribution of facies in subsequent sedimentary units. On top of the Grubhörndl breccia and southwest of the Grubhörndl, hardgrounds with poorly preserved imprints of ammonites indicate a break in sedimentation, probably even some erosion or dissolution. Contemporaneously, essentially Kimmeridgian-age allodapic radiolarian limestones and siliceous marls of the Tauglboden Formation (sensu Gawlick et al.,1999b) were deposited in the basins. The Tauglboden Formation differs from the Ruhpolding Radiolarite by its content of bio- and coarse lithoclastic material (Schlager & Schlager 1973). Because the radiolarian limestones and siliceous marls overlie both the Ruhpolding Radiolarite and the breccias, and since the latter are contained within the Ruhpolding Radiolarite (see below), we refrain from considering the breccias as part of the Tauglboden Formation in analogy to the stratigraphic succession of the Osterhorn mountains (l.c.; Vecsei et al. 1989). Beyond the area of breccia deposition, pre-Jurassic topography continued to control facies distribution. Upper Jurassic deep water limestones, partly intercalated with bio-/lithoclastic turbidites of the Upper Tithonian to Berriasian Oberalm Formation (Garrison 1967), onlapped onto the breccia and exhumed red limestones and Late Rhaetian limestone, thus levelling out the Early Jurassic relief. Allodapic turbiditic Barmstein beds, which represent a bioclastic shallow water input from a near platform, are intercalated with the Oberalm Formation. The concomitant shallow-water Lärchkogel limestone was accumulated on Late Jurassic topographic highs on top of a mélange of Hallstatt limestones of the Lower Juvavic tectonic unit (e.g. Sanders et al. 2007). Early Cretaceous siliciclastic deposition of the Rossfeld Formation and Lackbach beds preceded overthrusting of the synorogenic sediments (e.g. Darga & Weidich 1986).

Local tectonic setting

The Unken syncline is an open fold structure in the Staufen-Höllengebirge-nappe of the Tirolic nappes of the NCA, located

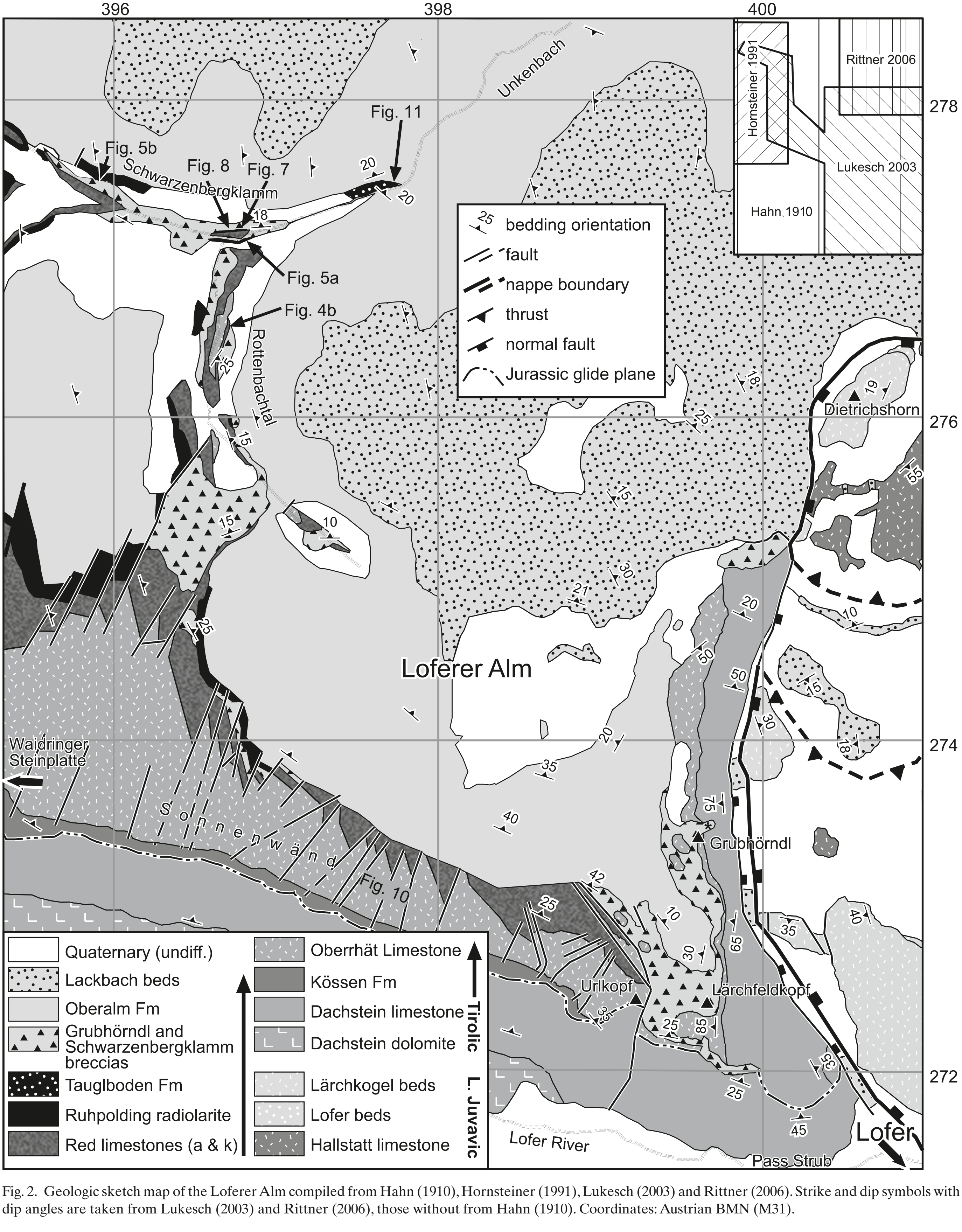


Fig. 2. Geologic sketch map of the Loferer Alm compiled from Hahn (1910), Hornsteiner (1991), Lukesch (2003) and Rittner (2006). Strike and dip symbols with dip angles are taken from Lukesch (2003) and Rittner (2006), those without from Hahn (1910). Coordinates: Austrian BMN (M31).

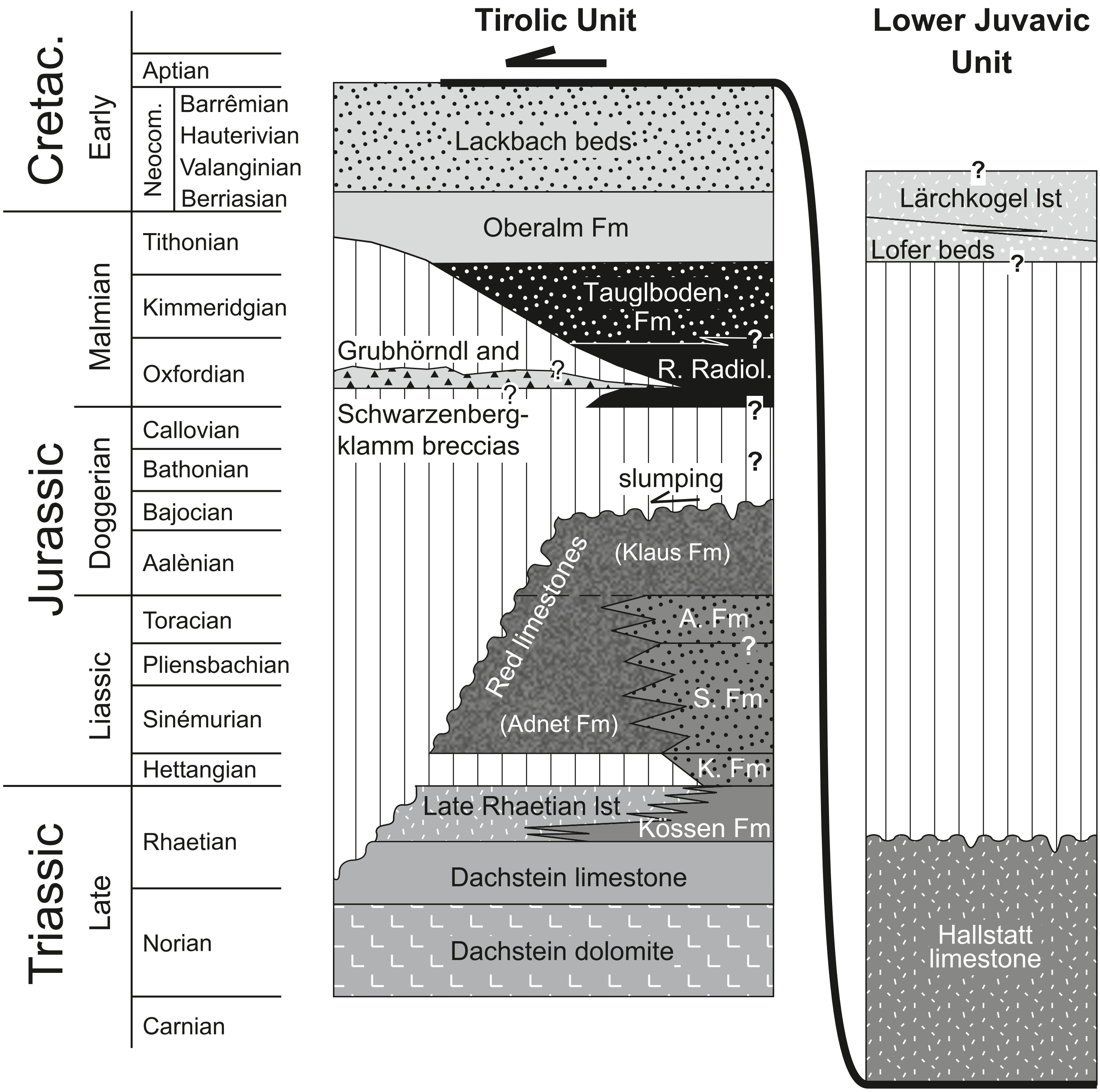


Fig. 3. Chronostratigraphy of sedimentary units in the Unken syncline. Compiled from Hahn (1910), Garrison (1967), Garrison & Fischer (1969), Fischer (1969), Diersche (1980), Tollmann (1985), Krainer & Mostler (1997), Gawlick et al. (1999b), Sanders et al, (2007) and own observations. K. Fm = Kendlbach Formation, S. Fm = Scheibelberg Formation, A. Fm = Allgäu Formation, R. Radiol. = Ruhpolding Radiolarite, lst = limestone. Formal and informal subdivisions used in accordance with the Stratigrapic Chart of Austria (Piller et al., 2004), except "Oberrhätkalk", which is Late Rhaetian limestone.

near the Loferer Alm and in the Unkenbach valley, about 35 kilometres southwest of Salzburg (Fig. 1). To the north, the Staufen-Höllengebirge nappe is thrust onto the Lechtal thrust sheet of the Bajuvaric nappe system. Southeast of the investigated area, the Lower Juvavic nappe rests on the Staufen-Höllengebirge nappe, as well as on synorogenic deposits of the Lackbach beds. The latter deposits provide a lower age limit for thrusting that cannot have started before Barremian times (Ortner 2003). The Lower Juvavic nappe carried the shallow water deposits of the Lärchberg beds (Lofer beds and Lärchkogel limestone; Ferneck 1962; Dya 1992) into the Early Cretaceous basin, where these carbonate strata are also found as pebbles

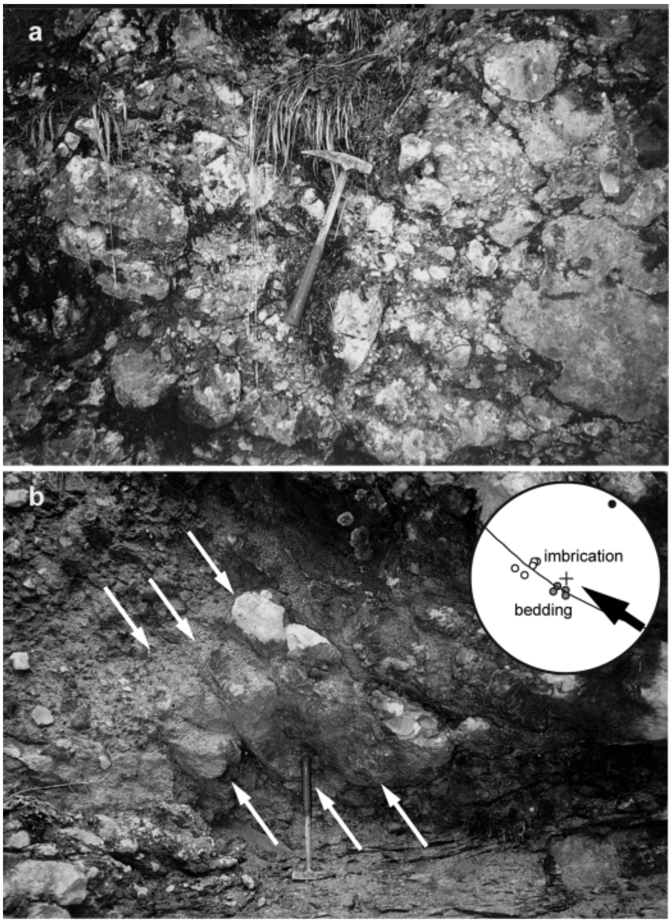


Fig. 4. a) Typical field appearance of the Schwarzenbergklamm and Grubörndl breccias (see Fig. 2 for location). Clast supported breccia composed of unsorted sub-angular carbonate clasts and a marl matrix. b) Imbricate clasts in the Schwarzenbergklamm breccia just above the basal contact to red marly limestones of the Adnet and Klaus Formations. Black arrow in inset indicates sediment transport direction derived from orientation of platy imbricate clasts (white circles: poles to clast surfaces) and bedding (grey circles: poles to bedding). Hammer for scale is 30 cm long.

in the Lackbach beds (Darga & Weidich 1986). The main aim of this contribution is to document structures associated with an Upper Jurassic megabreccia in the Unken syncline. We discuss the sedimentology and three-dimensional distribution of the Grubhörndl and Schwarzenbergklamm breccias and their relation to under- and overlying deposits and adjacent structures. We then compare our data with published results on the Late Jurassic evolution of the NCA.

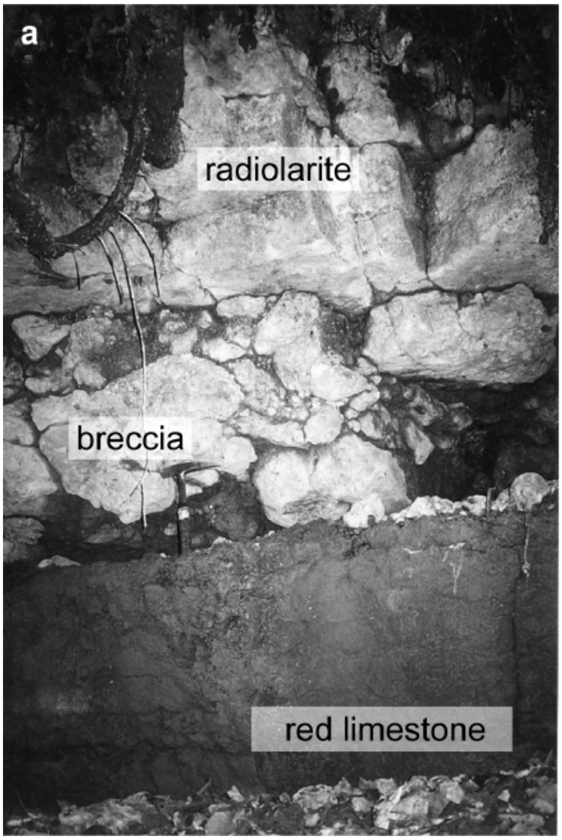
The Grubhörndl and Schwarzenbergklamm breccias

Description of the breccias

The Grubhörndl breccia and the Schwarzenbergklamm breccia are chaotic, clast- to matrix-supported and lack any kind of sorting (Fig. 4a). The matrix consists of red calcareous micrite. The clasts are angular to sub-angular and consist mainly of "Late Rhaetian" limestone, subordinately of Dachstein limestone, marls of the Kössen Formation, red limestones of the Adnet and Klaus Formations and the Ruhpolding Radiolarite. The clast sizes range from a few millimetres to several meters in diameter. Single blocks measure up to 40 meters in the Schwarzenbergklamm breccia and several hundreds of meters in the Grubhörndl breccia. In the Schwarzenbergklamm breccia, different flow units can be differentiated whereby the base of younger flows cuts into older breccia deposits. Occasionally, imbricated clasts can be found (Fig. 4b). The contact of the breccia with the underlying sediment represents a disconformity or unconformity. In the first case, the breccia was deposited without erosion and gravitationally sank into unconsolidated radiolarite (Fig. 5b). In the second case, an erosive contact of the breccia with the underlying strata could be inferred, whereby the breccia seems to cut stepwise into the underlying sediments at first sight (Fig. 7). However, the presence of a centimetre-thick discontinuous bed of Ruhpolding Radiolarite at the base of the breccia precludes erosion by the breccia and suggests pre-radiolarite slumping during deposition of the youngest parts of the Klaus Formation. Locally, deformation of the underlying red limestones, caused by the overriding breccia, is observed (Unkenbach valley, Fig. 8).

Figure 6a shows the mapped distribution of the Schwarzenbergklamm and Grubhörndl breccias. The Schwarzenbergklamm breccia crops out in the Rottenbach valley, in the Schwarzenbachklamm and in the western Unkenbach valley (Hornsteiner 1991). The Grubhörndl breccia is restricted to an area east of the Loferer Alm. South of Strub Pass, small outcrops of a comparable breccia are found at the Anderlalm. These could represent a southern continuation of the Grubhörndl breccia. A striking feature of the Grubhörndl breccia and the Anderlalm outcrops is their 3 to 5 km north-south extent and their rather narrow east-west extent of less than 500 meters. The Schwarzenbergklamm breccia extends 2 kilometres in a north-south direction, and 2.5 kilometres in an east-west direction. The approximate thickness of the breccias is shown in Figures 6a and 6b. The extraordinary thickness at Grubhörndl and Lärchfeldkopf is a result of the presence of one very large block. The thickness diminishes rapidly towards west and north, but increases slightly in the Schwarzenbergklamm because of a 40 m high block of Late Rhaetian limestone embedded in the breccia.

Sediment transport directions of the Schwarzenbergklamm breccia derived from the long axes of channels and fold axes of slumps were equivocal (Garrison 1964; Wächter 1987). However, these authors inferred north-directed paleoflow for paleogeographical reasons. We measured the imbrication of platy clasts within the breccia (Figs. 4, 6b) and shear structures in red nodular limestones at the base of the breccia near the large block within the Schwarzenbergklamm breccia (Fig. 8). These data indicate sediment transport toward the (W)NW during deposition of the breccia.



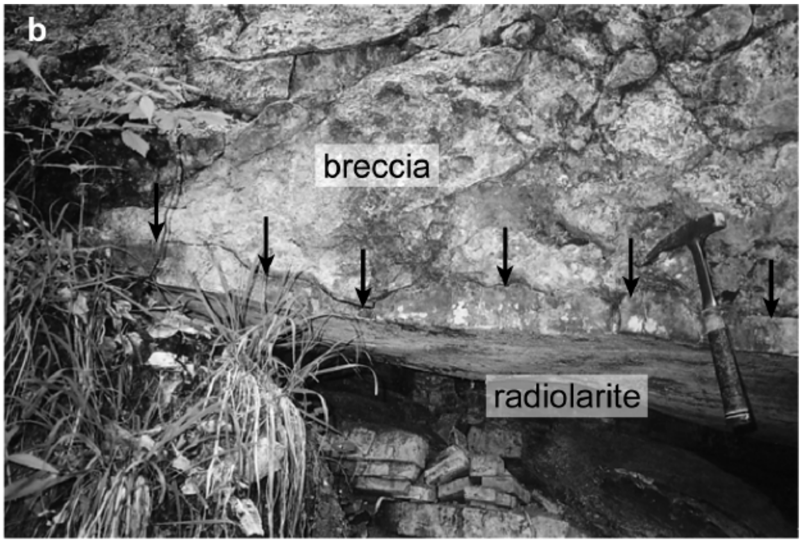


Fig. 5. Relationship of the Schwarzenbergklamm breccia to the Ruhpolding Radiolarite (see Fig. 2 for locations). a) Thin layer of breccia underlain by red limestones of the Adnet or Klaus Formation and overlain by Ruhpolding Radiolarite, 10 m from the outcrop depicted in Fig. 6, where the breccia is at least several meters thick, indicating a pronounced positive topography on top of the breccia body. b) Basal contact of the Schwarzenbergklamm breccia with Ruhpolding Radiolarite. The breccia is gravitationally sunken into the chert after deposition. Together, these outcrops show that the breccia was emplaced during deposition of radiolarian cherts. Hammer for scale is 20 cm high.

Sedimentological interpretation of the breccias

According to Pickering et al. (1986), scarp breccias are characterized by angular components with extreme size variation (micro- to megabreccias), a high percentage of structurally older components, and a matrix devoid of dynamic sedimentary structures. As these characteristics are found in the Grubhörndl breccia, we propose that the Grubhörndl breccia formed as a scarp breccia. The Schwarzenbergklamm breccia is in close geographic vicinity (Fig. 6) and similar in terms of composition and texture, but it shows some evidence for sediment transport, i.e. erosion at the channel basis and imbrications of clasts. We therefore interpret the Schwarzenbergklamm breccia as a portion of the Grubhörndl breccia that was mobilized and transported by debris flows. The large block in the core of the Schwarzenbergklamm breccia can be interpreted as an outrunner block, which became detached from the main breccia mass and which slid further into the basin. This could have occurred by hydroplaning in the frontal part of the debris flow (Prior et al. 1984; Ilstad et al. 2004; De Blasio et al. 2006). The irregular patchy distribution of the Schwarzenbergklamm breccia and its rapid lateral thickness changes (Fig. 6a) are very similar to what is observed between the main body and the outrunner blocks of modern submarine debris flows (Ilstad et al. 2004). The shear structures found at the base of the breccia near the block probably document grounding of the block after water-lubricated transport. The large diameter of the clasts and the rapid decrease of thickness indicate proximity to the scarp, which is assumed to be located east of the line Dietrichshorn-Grubhörndl-Lärchfeldkopf-Anderlkogel (Figs. 2, 6c). It is not possible to reconstruct the exact geometry of the fault, because it was overthrust in the Early Cretaceous, then reactivated in the Miocene with an opposite direction of movement, with at least 500 meters of downfaulting of the eastern block. East of the inferred fault, the former source area of the breccias is covered by the Juvavic nappes.

The mega-block of the Grubhörndl breccia at the Lärchfeldkopf

A block, several hundred meters long and about 350 m high and surrounded by breccia on three sides, is located at the Lärchfeldkopf south of the Grubhörndl (Fig. 9). The block rests on breccia, is covered by it on the western side and overlain by it. The western part of the block consists of Late Rhaetian limestone and the eastern part of Dachstein limestone The sedimentary layering of the block is oriented at 90° to the underlying sedimentary strata (Fig. 9). Below the eastern part of the block, the Late Rhaetian limestone is missing and is replaced by breccia. In the two-dimensional view of Figure 9 the eastern end of the Late Rhaetian limestone is a subvertical step. Within the

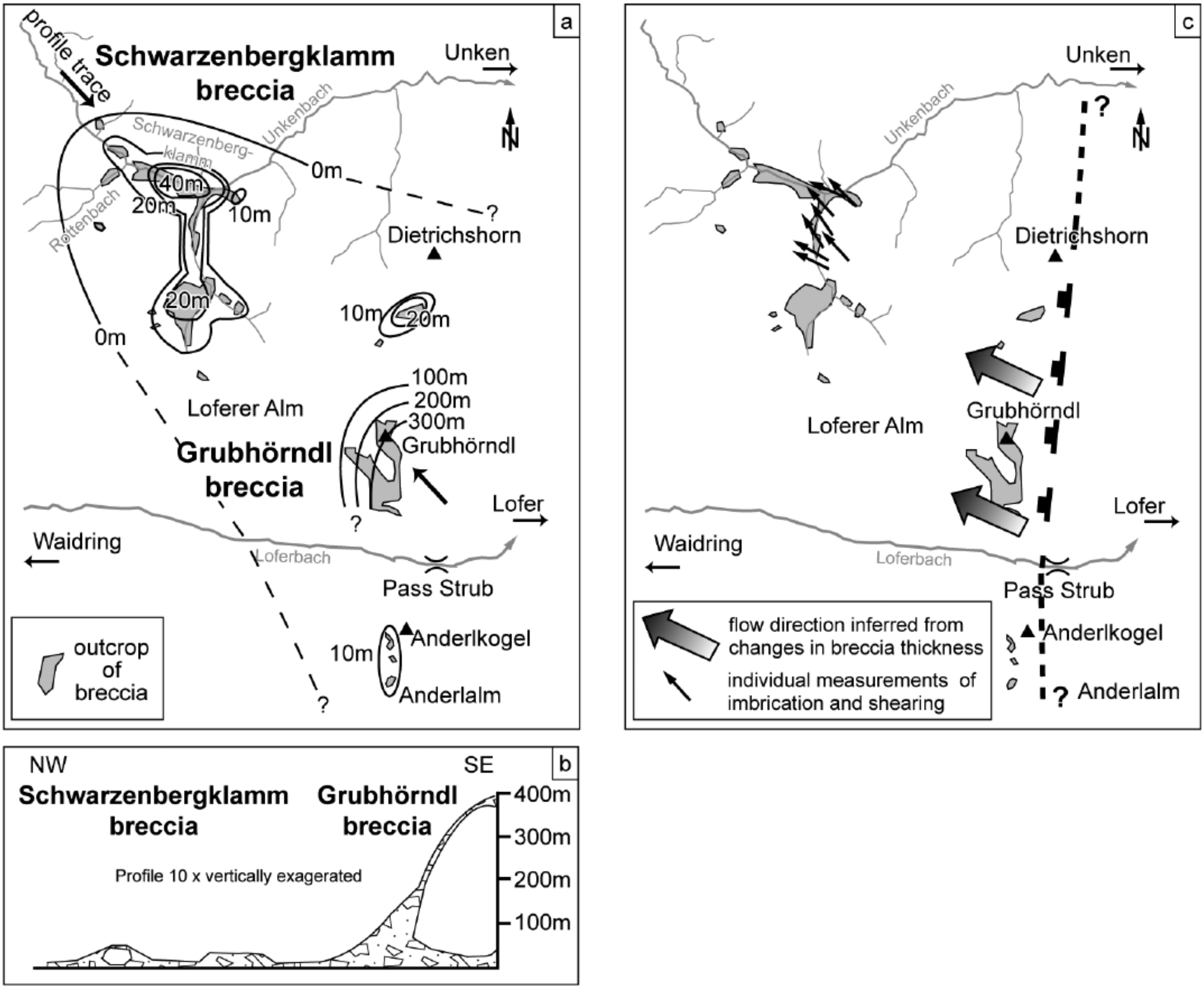


Fig. 6. a) Distribution of thickness of the breccia deposits in the Unken syncline in map view, and, b) in cross section. c) Small arrows: Sediment transport direction deduced from clast imbrication and shear structures at the base of the breccia. Large arrows: Sediment transport inferred from thickness distribution of the breccia deposits.

underlying Dachstein limestone, throughgoing bedding shows that it is not cut by a vertical fault. Therefore, the Late Rhaetian limestone must have moved westward on a bedding-plane-parallel glide surface within the Kössen Formation beneath the Late Rhaetian limestone (Fig. 9).

It is not easy to imagine the scenario in which this block arrived at its present position. One possible scenario would be toppling in the footwall of a major normal fault. In this case the following sequence of events would be necessary: (1) Creation of a major fault scarp, at least as high as the thickness of the block, i.e. several hundred meters, combined with westward tilting. (2) Gliding of the Late Rhaetian limestone in the hanging wall of the detachment, thus creating accommodation space progressively filled by breccia. (3) Gliding of a large block in the footwall on a bedding plane within the Dachstein limestone across the normal fault into the breccias, such that about half or a third of the block still overlies the footwall. (4) Progressive offset across the normal fault, which leads to progressive tilting of the block into the adjacent basin on the footwall. The latter model is supported by the presence of an array of west-directed normal faults in the Late Rhaetian limestone and red limestones of the Adnet and Klaus Formations of the Sonnwänd (Fig. 2, left side of Fig. 9, Fig. 10), and by half grabens in the Tauglboden Formation in the Unkenbach valley (see below). Examples of large gliding rock masses and allochthonous blocks, as well as different explanations for the development of submarine mega-breccias, have been reported in the literature from different parts of the world, although none of them

Fig. 7. Basal contact of the Schwarzenbergklamm breccia to the red limestones of the Adnet or Klaus Formation (see Fig. 2 for location). A thin discontinuous chert bed of the Ruhpolding Radiolarite underlies the breccia (arrows). The step in the contact must therefore be older than deposition of radiolarian chert and probably represents a slump scar within the red limestones.

includes a block tilted by 90 degrees (compare e.g.: Carrasco 1985; Conaghan et al. 1976; Freeman-Lynde & Ryan 1985; Greb & Weisenfluh 1996; Hesthammer & Fossen 1999; Mullins et al. 1991; Schlager et al. 1984; Surlyk & Ineson 1992; van Weering et al. 1998; Woodcock 1979). The breccia bodies are onlapped by younger sediments. While the thinner part of the Schwarzenbergklamm breccia is overlain and onlapped by the Ruhpolding Radiolarite, the surfaces of the thick parts of the Schwarzenbergklamm breccia and the Grubhörndl breccia were above base level of sedimentation and were only later onlapped by the Oberalm and Ammergau Formations. Southwest of the Grubhörndl (star in Fig. 9), the Grubhörndl breccia body is overlain by a condensation surface, which in turn is overlain by turbidites with coarse-grained shallow water bioclastic debris belonging into the Oberalm Formation (Barmstein beds). Thus, field evidence shows that the submarine topography created by the breccia bodies persisted for several million years and before the base level of sedimentation rose high enough for an onlap of younger formations. The occurrence of large pieces of shallow water organisms indicates the proximity of a carbonate platform, possibly on top of the footwall fault scarp.

Age of the breccias

The age of the breccias was determined by lithostratigraphic correlation because no indicative fossils that would provide a biostratigraphic age were found in the matrix. In the area of the Loferer Alm, the Grubhörndl breccia was deposited on Dachstein and Late Rhaetian limestones (Fig. 9). The breccia consists of reworked Dachstein limestone, Late Rhaetian limestone, marls of the Kössen Formation, red limestones of the Adnet and Klaus Formations and Ruhpolding Radiolarite. Oberalm Formation onlaps the top of the breccia, thus indicating the end of breccia deposition. The Grubhörndl breccia therefore postdates the onset of deposition of the Ruhpolding Radiolarite and predates deposition of the Oberalm Formation. The Schwarzenbergklamm breccia occurs partly above and partly below the Ruhpolding Radiolarite (Figs. 2, 6, 8). Thus the age of the breccia body can be restricted to the time interval corresponding to the deposition of the Ruhpolding Radiolarite. As both the Grubhörndl and the Schwarzenbergklamm breccia are thought to belong to the same breccia body, this is true for the deposition of both breccias.

The onset of deposition of the Ruhpolding Radiolarite was previously thought to be uniformly Oxfordian (Schlager & Schöllnberger 1974). However, biostratigraphic data from more eastern and southern parts of the central NCA indicate an earlier onset of radiolarite deposition (e.g. Suzuki et al. 2001; review in Gawlick & Frisch 2003). In the westernmost part of the Unken syncline, the youngest rocks below the Ruhpolding Radiolarite are red nodular limestones of the Klaus Formation, which were dated to the Aalenian in two sections at Unkenbach and Scheibelberg (Fischer 1969), and to the Bajocian in the Kammerkehr area (Hahn 1910). The stratigraphic contact to the Ruhpolding Radiolarite is not conformable, however, and is characterized by slump-related scars (Fig. 7) or breccias (Fischer 1969). Direct dating of radiolarian faunas from the Ruhpolding Radiolarite gave an Oxfordian to Mid-Kimmeridgian age (Diersche 1980). The end of deposition of the Ruhpolding Radiolarite is unconstrained because no biostratigraphic data from the Tauglboden Formation of the Unken syncline are available. In the type area in the Osterhorn Mountains further east the Tauglboden Formation ranges from the Late Oxfordian to the Early Tithonian (Gawlick et al., 1999b), overlying Callovian to Oxfordian Ruhpolding Radiolarite (Gawlick et al. 2003). Deposition of the Oberalm Formation in the Unken syncline starts in the Early Tithonian (Garrison 1967), similar to the Osterhorn Mountains (Steiger 1981). The Ruhpolding Radiolarite underlying the Schwarzenbergklamm breccia has a thickness between a few centimetres and one meter. Taking into account the total thickness of about 20 m, the breccia must have been emplaced shortly after the beginning of radiolarite deposition, hence in the Oxfordian. If, however, the onset of deposition of the Ruhpolding Radiolarite is earlier, e.g. Callovian, as in the Osterhorn Mountains (Gawlick et al. 2003), the age of the breccia would also shift to the late Middle Jurassic.

Extensional structures observed in the study area

At the Sonnwänd south of the Loferer Alm (Fig. 1) between Waidringer Steinplatte and Urlkopf (Fig. 10), west-dipping normal faults rooting in the marls of the Kössen Formation cut through Late Rhaetian limestone and Lower to Middle Jurassic red limestones. Upper Jurassic Oberalm Formation seals the faults (Fig. 2, 9). Bedding in the underlying Dachstein limestone is not offset by these faults (Fig. 9, 10). In order to demonstrate the significance of these normal faults, we esti-

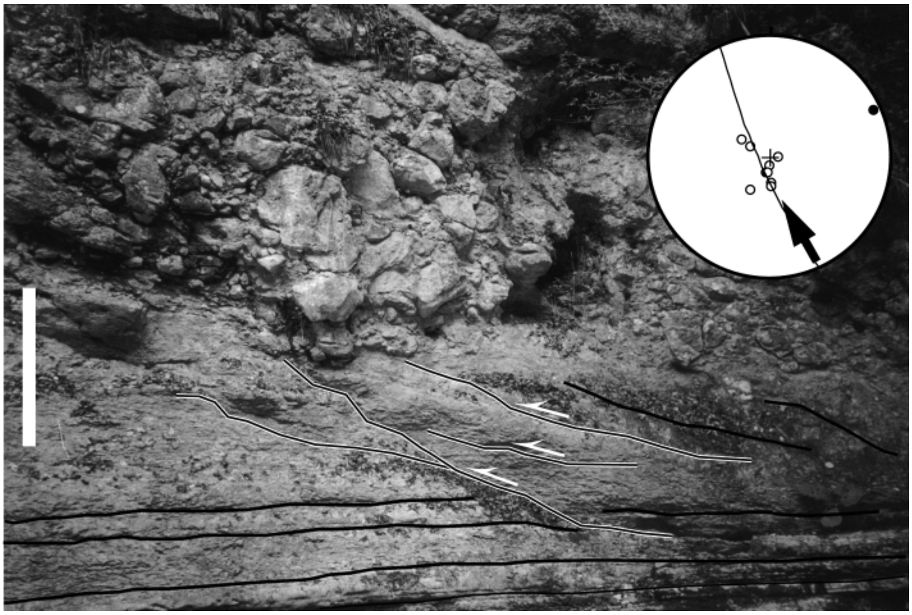


Fig. 8. Shear structures at the base of the Schwarzenbergklamm breccia (see Fig. 2 for location). These structures are found below the base of a large block (ø 40 m) within the breccia and are probably related to grounding of the block after transport on top of a water cushion by hydroplaning. Inset shows bedding orientations (white circles: poles to bedding) and transport direction deduced (black arrow).

mated the stretching factor within the Late Rhaetian limestone of the Sonnwänd area (Fig. 10). Due to the low overburden of Lower to Upper Jurassic sediments (total thickness of a few meters) on top of the Rhaetian platform, negligible or no confining pressure acted at the onset of Upper Jurassic extension. The observed normal faults probably were initiated as tensile fractures, orthogonal to the extension direction, i.e. sub-vertical to vertical. Further extension led to domino-style rotation of the fault blocks. As a consequence, bedding in the limestone is perpendicular to the normal faults. As there is no continuous marker bed in the massive Late Rhaetian limestone, arbitrary reference beds have been chosen where fault dips and fault block widths are homogeneous (Fig. 10). Stretching factors calculated from the observed block and fault geometries range from $\beta = 1.06$ to $\beta = 1.12$.

In the Unkenbach valley, fine grained breccias and radiolaria-bearing marly limestone of the Kimmeridgian Tauglboden Formation form a monocline several metres wide (Fig. 11), with a near-horizontal western, and an approximately 20° E-dipping eastern limb. Angular unconformities in the eastern limb document erosion after tilting, followed by deposition parallel to the erosion surface resulting in progressively shallower dips up section. A pronounced angular unconformity marks the boundary between the marly limestones and the marls of the Tithonian Oberalm Formation, which are not tilted and therefore seal the structure.

Although it is tempting to interpret the unconformities as a result of block tilting observed in the underlying Late Rhaetian limestone, the geometry of the structure precludes a direct connection. Progressive domino-style faulting in the subsurface would create basins in which planar bedding would become progressively shallower between angular unconformities, and individual sub basins should be separated by steep faults with diminishing offset up section. The observed monoclinal folding is therefore interpreted as a rollover anticline formed in the hangingwall block of a listric normal fault. The relatively sharp bend in the core of the rollover calls for a shallow detachment, probably within the Tauglboden Formation. Multiple angular unconformities in the Tauglboden Formation indicate progressive tilting of the hanging wall block. The axis of the rollover anticline is oriented north-south and indicates westward normal movement (Fig. 11), which is in concert with the earlier extension phase. The Tithonian Oberalm Formation seals these structures, thus indicating the cessation of extension.

Discussion and conclusion

The detailed documentation of Jurassic sedimentary rocks and related structures in the Unken syncline allows for a reconstruction of the conditions of megabreccia deposition during the Late Jurassic (Fig. 12). Two different controls on facies distribution can be distinguished. During the Early and Middle Jurassic, facies distribution is mainly controlled by the pre-Jurassic topography of the Late Triassic Steinplatte reef with its pronounced slope to the north. In the early Late Jurassic, deposition of megabreccias was linked to tectonic activity, which created a new submarine topography with a west-directed slope along a major N–S-striking fault. The combination of inherited and newly formed slope controlled the observed transport direction of the Schwarzenbergklamm breccia toward the NW. Based on the similarity of clast composition, the two breccia bodies, which previously were described separately, are interpreted as one large breccia body. The Grubhörndl breccia represents the more proximal unit, probably attached to a fault scarp, whereas the Schwarzenbergklamm breccia was transported by debris flows further into the basin. The key observa-

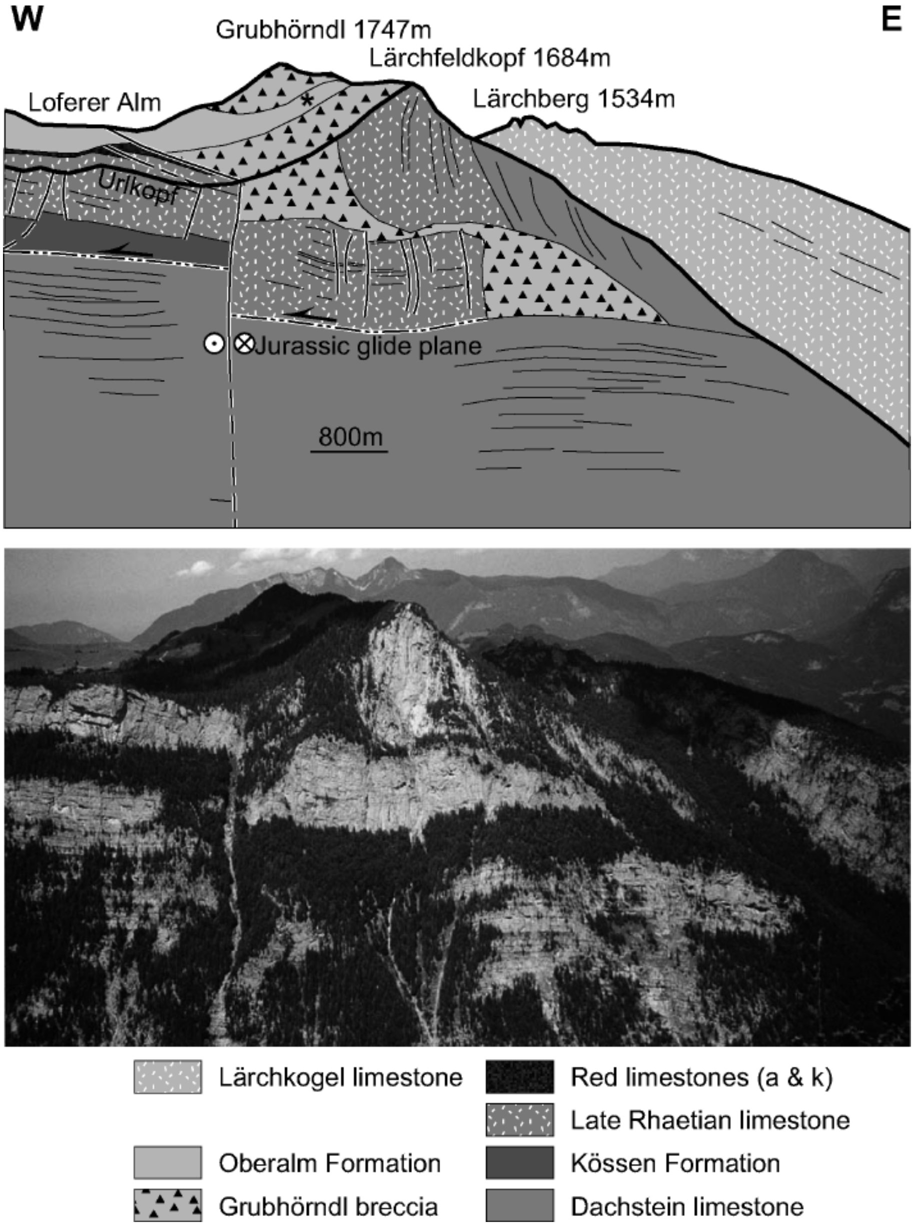


Fig. 9. Aerial view of the southern face of the Lärchfeldkopf and Grubhörndl, showing most of the features described in this paper. The Dachstein limestone is overlain by the Kössen Formation, which interfingers with the Late Rhaetian limestone to the north. Due to a young sinistral fault, a more internal portion of the Late Rhaetian reef, which directly grew on the Dachstein limestone and originally was located further south, is now found east of the fault. The Kössen Formation west of the fault and a bedding plane east of the fault were used as a detachment during gravity-driven westward gliding of the Late Rhaetian limestone. The space created by gliding was filled by Grubhörndl breccia and an embedded mega block. Normal faults crosscutting the Late Rhaetian limestone and rooting in the detachment crosscut red limestones of the Adnet and Klaus Formations, but are sealed by the Ammergau Formation. The Grubhörndl breccia is onlapped by Oberalm and Ammergau Formations. The star in the Oberalm Formation denotes the location of large shallow water fossils in the Oberalm Formation.

tions are (1) the N–S elongation of the several hundred meters thick Grubhörndl breccia, (2) its rapid thinning to the NW, and, (3) the onlap of the younger sedimentary units, demonstrating that the submarine topography was slowly blanketed.

Smaller structures, such as the domino-style faults crosscutting the Late Rhaetian limestone and the roll-over structure in the Tauglboden Formation are attributed to gravity-driven westward gliding of the Late Rhaetian limestone and portions of the Tauglboden Formation in response to westward tilting. Tilting could be a consequence of an E-dipping normal fault to the west and outside the investigated area. As discussed previously, tilting is a necessary precondition for the deposition of the mega block within the Grubhörndl breccia. Therefore, a N–S-oriented scarp of a major west-dipping normal fault is the most probable setting for the deposition of the Grubhörndl breccia. Fischer (1965) previously proposed N-directed sediment transport of the Schwarzenbergklamm breccia from an E–W-oriented fault scarp along the Waidring valley. However, no major vertical offset is observed in a N–S section across the valley (Lukesch 2003; profile West of Pestal & Hejl 2005).

In the eastern and central NCA Middle to Late Jurassic tectonic processes have been the subject of controversy. The following alternative scenarios have been proposed (1) The NCA are influenced by rifting of the Apulian continental margin adjacent to the Piemont-Ligurian ocean; and this scenario involves extension (Vecsei et al. 1989; Lackschewitz et al. 1991;

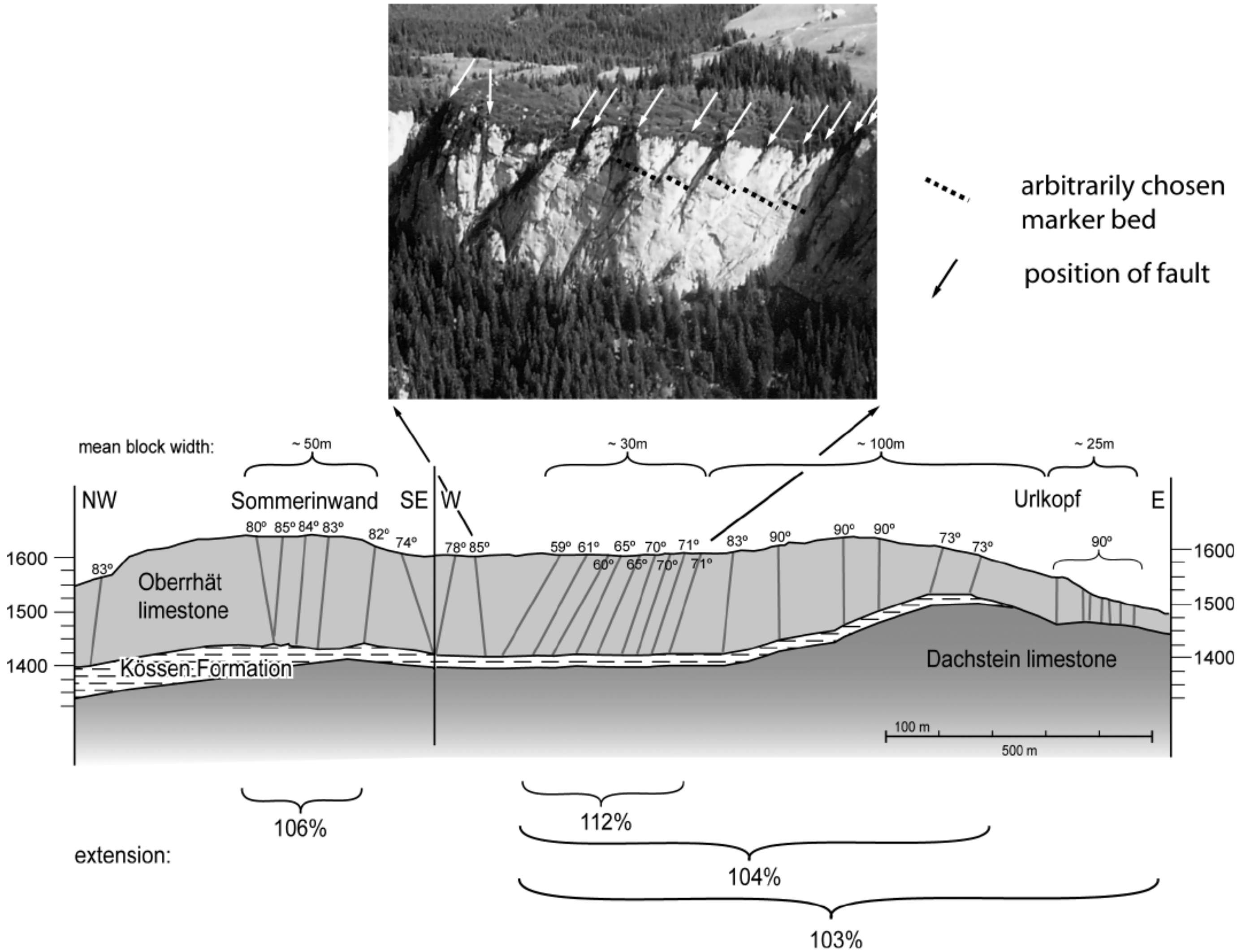


Fig. 10. Normal faults crosscutting the Late Rhaetian limestone (top) and determination of the stretching factor (see Fig. 2 for location). In spite of the clear fault geometry, extension is small.

Hebbeln et al. 1996; May & Eisbacher 1999; Auer & Eisbacher 2003). (2) Nappe stacking and related compression in response to closure of the Meliata Ocean is the main controlling factor (Braun 1998; Gawlick et al. 1999a; Frisch & Gawlick 2003). (3) Jurassic strike-slip faulting in the NCA explains the distribution of Upper Triassic facies, as was proposed by Fischer (1965). Similar concepts were used by e.g. Wächter (1987), Channell et al. (1990), and by Frank & Schlager (2006). The latter also evaluated all the three hypotheses.

We will not repeat this discussion here, except for stating that the observations reported here and for our area of investigation, are in accordance with hypotheses (1) and (3), but not with the thrusting scenario (2). The orientations of early Late Jurassic faults, across which facies changes were reported, vary. Lackschewitz et al. (1991) and Auer & Eisbacher (2003) reported E–W-striking faults, whereas Eberli (1988) and Froitzheim & Eberli (1990) reconstructed N–S-striking faults. Some authors interpreted a complex more or less orthogonal pattern of N–S and E–W-striking faults (Channell et al. 1990; 1992; May & Eisbacher 1999). The structures described in this study are N–S-striking. However, the Grubhörndl breccia and the associated normal fault abruptly end to the north, where the offset must be taken up by some other structure. Such a structure might be a precursor of the so-called Saalachtal fault ("Saalachtal Westbruch"; Hahn 1910), which was later reactivated during the Miocene (Rittner 2006). Large vertical offsets along normal faults, which do not decrease toward the end of the fault, are found within strike-slip systems associated with pull-apart basins (e.g. Aydin & Nur 1982).

On a larger scale, we propose that the above-mentioned three scenarios should perhaps not be treated as mutually exclusive. Each of them describes some other aspect of the complex

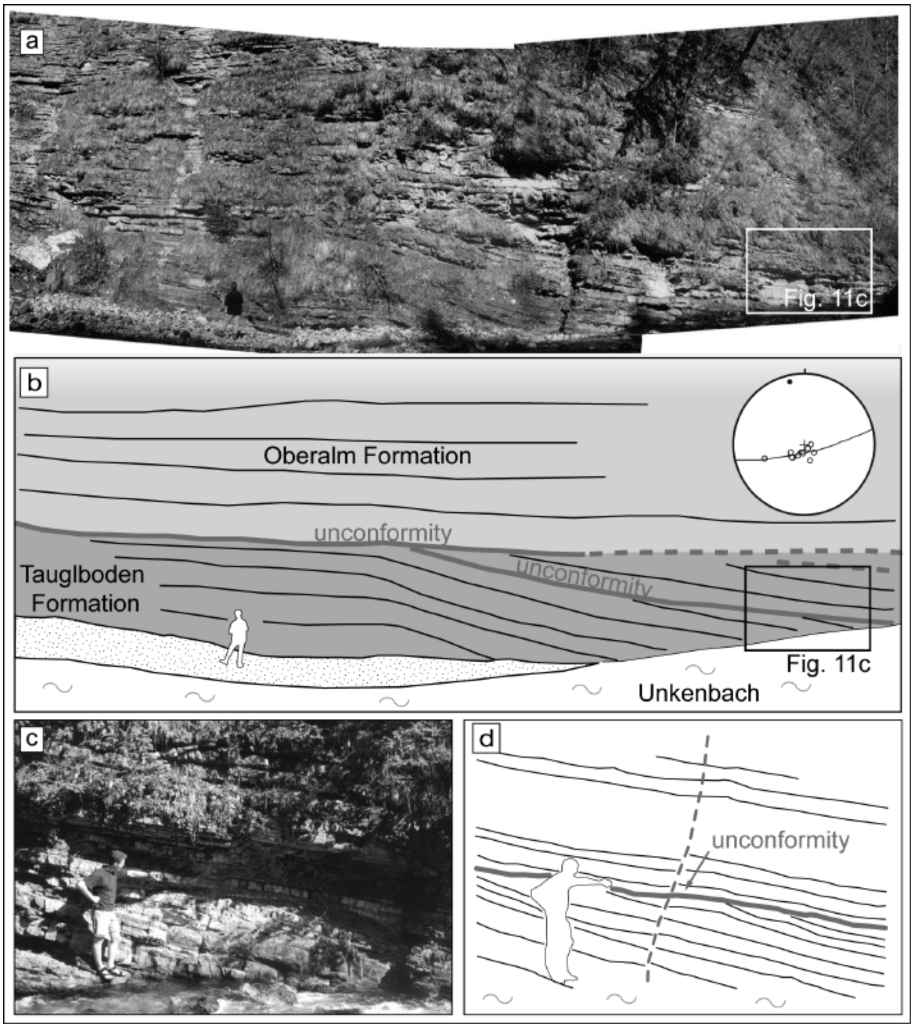


Fig. 11. a) Field photograph and b) sketch of angular unconformities in the Tauglboden Formation, sealed by the Oberalm Formation c) Field photograph and d) sketch of angular unconformity within the Tauglboden Formation All unconformities are erosional, and therefore document deformation, erosion and then sedimentation. See Fig. 2 for location.

evolution of the NCA within the Alps-Carpathian-Dinarides system. During the Jurassic the NCA were located between the opening Piemont-Liguria Ocean to the northwest and the closing Meliata Ocean to the southeast. To the northwest the Jurassic sedimentary succession of the Austroalpine units is controlled by the opening of the Piemont-Liguria ocean: in distal, ocean-near parts of the continental margin (Lower Austroalpine nappes), coarse grained syn-rift sediments of the Lower and early Middle Jurassic Allgäu Formation were deposited in half-graben basins (Eberli 1988). There, these basins and exhumed mantle rocks, formed at the ocean-continent transition, are overlain by post-rift radiolarian cherts and Aptychus/Calpionella pelagic limestones (Dietrich 1970; Weissert & Bernoulli 1985; Froitzheim & Manatschal 1996), which are also abundant in and at the margins of the entire Alpine Tethys (Bernoulli & Jenkyns 1974; Bill et al. 2001).

However, the widespread occurrence of mega-slides and breccias, not only in the syn-rift sediments, but also in Middle to Upper Jurassic post-rift sediments in the central and eastern NCA, was documented in many previous studies (i.e. Tollmann 1987; Mandl 2000; Gawlick et al. 1999a, 2002; Gawlick & Frisch 2003) and points to the activity of another process affecting this same continental margin: Gravitative emplacement of the Hallstatt melange requires tectonic transport of Hallstatt facies sediments, belonging to the outer continental margin facing the Meliata ocean, onto the inner continental margin (Gawlick et al. 1999a, Mandl 2000), represented by the southernmost part of the Tirolic nappe. However, in our opinion, this Jurassic nappe stack is not preserved in the Eastern Alps. As shown by Mandl (2000) and Frisch & Gawlick (2003), late Early Cretaceous thrusting, following the obduction of the Meliata realm (Schmid et al. 2008), superimposed southern parts of the Tirolic nappes out-of-sequence with respect to emplacement of the Hallstatt melange onto northern parts. During this event, the Lower Juvavic nappe, which contains the Hallstatt melange, and the Upper Juvavic nappe, which originally represents a more southern part of the Tirolic unit, both did form. Cretaceous stacking also transported an ophiolithic unit, tec-

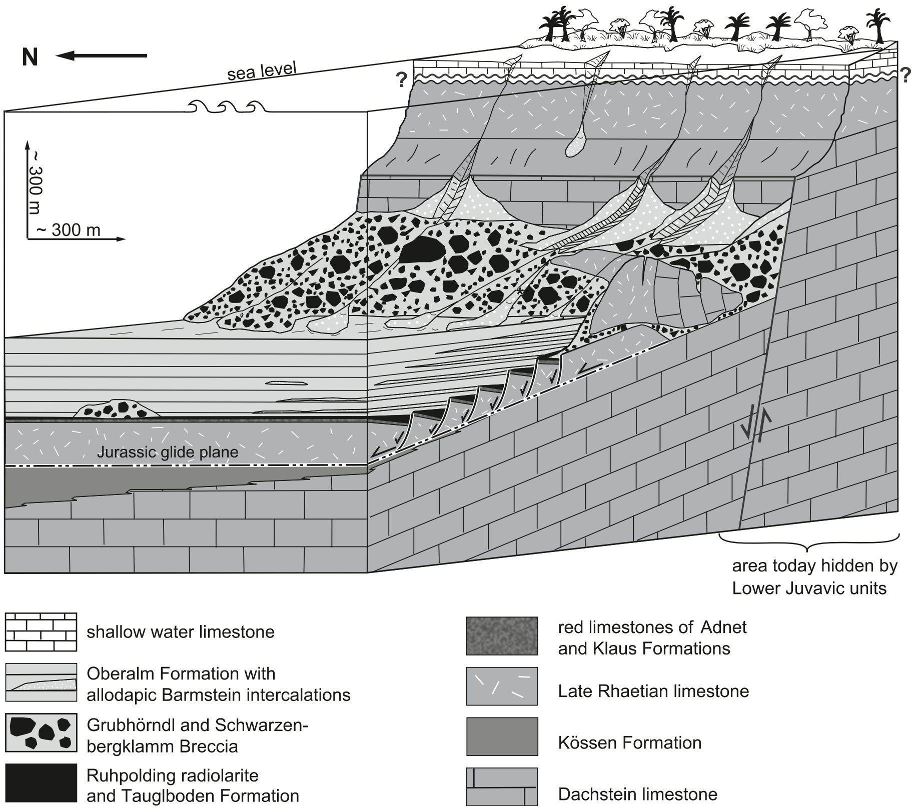


Fig. 12. Tentative reconstruction of the Grubhörndl and Schwarzenbergklamm breccias at the time of deposition of the Oberalm Formation in the Tithonian, giving an impression of the height of the fault scarp. The Grubhörndl breccia (Oxfordian) formed by collapse (and toppling, see text) of the footwall of a normal fault, is overlain by supra-fan lobes fed by a shallow water carbonate platform on top of the footwall. Both the carbonate platform and the normal fault are hidden below the Lower Juvavic nappe (see Fig. 2). The occurrence of Tithonian shallow water carbonates in the footwall is indicated by coarse bioclastic debris in Barmstein beds on top of the Grubhörndl breccia (star). Sub-aerial exposition in the footwall as shown is purely speculative.

tonically positioned on top of the Hallstatt unit, into the immediate vicinity of the present-day NCA, as is documented by ophiolithic detritus in Cretaceous synorogenic deposits of the NCA (e.g. Poper & Faupl 1988). Recent models of the NCA nappe stack that were inspired by the nappe structure described for the Austroalpine nappe system, including the NCA, in general (Schmid et al., 2004; Janak et al., 2004), are, however, not valid for the western NCA. For example, the Inntal thrust sheet represents the western continuation of the Tirolic unit (Tollmann 1976; Ortner et al. 2006). On top it carries several klippen of a tectonically higher thrust sheet, the Krabachjoch nappe, which is equivalent in facies to the underlying Inntal thrust sheet, but equivalent in tectonic position to the Lower Juvavic nappe (Tollmann 1976). This illustrates the non-cylindrical nature of the nappe edifice of the NCA on a large scale. In particular, remnants of the outer continental margin facing the Meliata Ocean are absent in the western NCA; but breccias are commonly found in Middle to Upper Jurassic post-rift sediments (e.g. Eisenspitze breccias, Achtnich 1982; Rofan breccias, Wächter 1987; breccias of the Thiersee syncline, Töchterle 2005). The redeposited material of these breccias consists entirely of debris from local sources. Away from the Hallstatt melange and related breccias, which can readily be explained by sliding from a thrust wedge, the genesis of locally sourced breccias of the western NCA needs an alternative explanation. Plate tectonic reconstructions of the Alpine realm show that the NCA were located in a zone of transform faulting (Weissert & Bernoulli 1985; Trümpy 1988; Channell et al. 1990). Hence, activity of strike-slip faults and formation of pull-apart extensional basins provides a good explanation for the repeated, but not contemporaneous shedding of coarse grained and locally sourced breccias (see above).

The studied area is in close proximity to the Hallstatt melange of the Lower Juvavic nappe and also to the locally sourced breccias within the Tirolic nappe, separated by an early Late Cretaceous thrust (Fig. 2). Cretaceous thrusting superimposed a tectonic unit influenced by the distant effects of Jurassic shortening, causing the gravitative emplacement of the Hallstatt melange (thrusting hypothesis 2) onto another tectonic unit mainly controlled by normal faults related to strike-slip faulting (strike slip hypothesis 3). Thus, Cretaceous thrusting reduced the distance between parts of the NCA that were controlled by different tectonic processes. Even given the evidence for a thrust related fill in southerly adjacent basins (see above), we prefer an interpretation that involves normal faults in a strike-slip scenario for the formation of the breccias of the Unken syncline.

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