Structural evolution of the central Northern Calcareous Alps : significance for the Jurassic to Tertiary geodynamics in the Alps

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Structural evolution of the central Northern Calcareous Alps: Significance for the Jurassic to Tertiary geodynamics in the Alps

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Key words: Extension, thin-skinned tectonics, collisional tectonics, accretionary wedge, peripheral foreland basin, submarine sliding, Northern Calcareous Alps

ABSTRACT

The geological and structural evolution of the central Northern Calcareous Alps (NCA), Eastern Alps, has been investigated in order to constrain the geodynamic setting and sequence of deformations. The central NCA comprise three nappe complexes with different lithologies and facies due to distinct Triassic to Cretaceous geodynamic evolution: (i) The Tirolic nappes with mainly Triassic shallow water deposits represent the footwall plate on which a Late Jurassic to Early Cretaceous peripheral foreland basin developed (Oberalm to Rossfeld formations) after the closure of the Meliata/Hallstatt ocean. (ii) The overlying Lower Juvavic nappes comprise Triassic continental slope and oceanic deposits, whereas (iii) the Upper Juvavic nappes include Triassic shallow water deposits of the assumed opposite shelf. The presence of Late Cretaceous to Paleogene Gosau basins allows division into pre-, syn- and post-Gosauian tectonic events: (1) Crustal extension in approximately N-S direction during Early Jurassic is documented by Neptunian dykes (D_1) and breccias. (2) Afterwards a top to NNE-NE emplacement of both Lower and Upper Juvavic nappes combined with formation of NW trending folds (D_2) occurred. The Upper and Lower Juvavic nappes west of the Salzach valley were thrust over the Tirolic nappes during middle Cretaceous, while Lower Juvavic nappes east of the Salzach valley were transported by submarine sliding processes from Late Jurassic to Early Cretaceous. Syn- to post-Gosau deformations were: (3) formation of Gosau basins within a transtensive wrench corridor mainly documented by syn-Gosauian orthogonally NNE and E trending extensional joints and dip slip faults due to subvertical extension (D_3); (4) syn- to post-Gosauian NE-SW shortening (D_4); (5) post-Gosauian NW-SE contraction (D_5). (6) Subsequent Neogene N-S contraction (D_6) and (7) a younger E-W contraction (D_7) affected the entire nappe pile along the northern margins of the Eastern Alps.

ZUSAMMENFASSUNG

Die geologische und strukturelle Entwicklung der zentralen Nördlichen Kalkalpen (NKA), Ostalpen, wurde untersucht, um ihre Geodynamik und Deformationsabfolge zu erfassen. Im Mittelabschnitt umfassen die NKA drei Deckeneinheiten mit unterschiedlicher Lithologie und Fazies, die verschiedene geodynamische Entwicklungen aufweisen. Die Tirolischen Decken, die hauptsächlich aus triassischen Flachwasserablagerungen bestehen, stellen die Liegendplatte dar, auf welcher sich nach der Schließung des Hallstatt/Meliata-Ozeans ein spätjurassisches bis frühkretazisches, peripheres Vorlandbecken (Oberalmer bis Rossfeld-Schichten) entwickelte. Die darüberliegenden Tiefjuvavischen Decken beinhalten Sedimente vom triassischen Kontinentalabhang und Ozeanbecken, während die Hochjuvavischen Decken aus Flachwasserablagerungen vom wahrscheinlich ursprünglich gegenüberliegenden Schelf bestehen.

Unterkretazische bis paläogene Gosaubecken erlauben eine prä-, syn- und postgosauische Einstufung der tektonischen Ereignisse: (1) Eine etwa N-S gerichtete Extension (D_1) im frühen Jura ist dokumentiert durch Liasspaltenfüllungen und Breccien (2). Danach erfolgte der Transport der Juvavischen Decken nach NNE bis NE, kombiniert mit einem NW-streichenden Faltenbau (D_2). Die Hochjuvavischen und Tiefjuvavischen Decken westlich des Salzach-Tales wurden in der mittleren Kreide über die Tirolischen Decken geschoben, während die Tiefjuvavischen Decken östlich des Salzach-Tales vom späten Jura bis in die Frühkreide durch submarine Gleitprozesse transportiert wurden.

Die syn- bis postgosauische Deformation führte zuerst zu einer Extensionsphase (D_3) mit NNE bis E streichenden Extensionsklüften und Abschiebungen, vermutlich innerhalb eines Seitenverschiebungskorridors. Dann kam es zu einer NE-SW-Einengung (D_4), gefolgt von einer NW-SE Einengung (D_5). Eine darauf folgende, neogene N-S-Einengung (D_6) mit E-W-Extension und eine jüngere E-W-Einengung (D_7) deformierten die gesamten, vorher gestapelten Deckeneinheiten entlang des Nordrandes der Ostalpen.

Introduction

The Northern Calcareous Alps (NCA) represent a cover fold-and-thrust belt along the northern margins of the Austroalpine nappe complex in the Eastern Alps (Fig. 1). The central NCA are built up of four major tectonic units (Tollmann 1976a, b; 1985). These include from footwall to hangingwall (Fig. 1, 2): (1) the Bajuvaric nappe complex, represented by only an narrow strip along the northern margins of the NCA; (2) the overlying Tirolic nappe complex includes a pre-Late Carboniferous basement exposed in the upper portion of the Greywacke Zone (Fig. 1); (3) the Lower Juvavic nappe complex with the so-called Hallstatt nappes and slices (e.g., Hallein unit) and (4) the Upper Juvavic nappe complex (e.g. Berchtesgaden and Dachstein nappes). The emplacement of the Northern Calcareous Alps onto the southern, stable European continental

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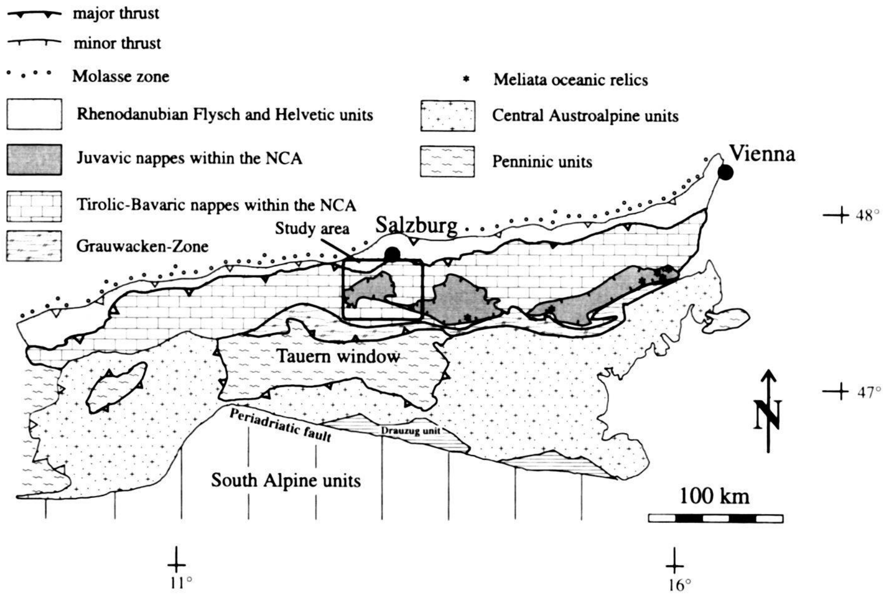

Fig. 1. The Northern Calcareous Alps (NCA) within the Eastern Alps. Note the distribution of the Juvavic nappes within the central and eastern part of the NCA.

margin sequences (Helvetic units and Molasse zone) and the Penninic Rhenodanubian Flysch zone occurred during Late Eocene to Early Miocene (Plöchinger 1980; Tollmann 1985; Decker et al. 1993; Linzer et al. 1995).

The stratigraphic succession of the central NCA ranges from the Permian to the Eocene and was interpreted to represent the northwestern passive margin of the Tethys, facing the Tethyan oceanic domain in the SE (Tollmann 1976a; Lein 1987; Haas et al. 1995). A key feature for this interpretation was the presence of Middle to Late Triassic pelagic Hallstatt limestones within Juvavic nappes, which were interpreted to have been emplaced from the south onto Bajuvaric/Tirolic nappe complexes containing Triassic shallow water deposits. The discovery of Middle Triassic and Jurassic bathyal sequences, Middle Triassic radiolarites and pelagic limestones, Jurassic shales and siliciclastic turbidites within the eastern NCA, corresponding to the oceanic Meliata sequences of the Western Carpathians (Kozur & Mostler 1992; Gawlick 1993; Mandl & Ondrejickova 1993), suggests more complex paleogeographic and tectonic relationships. The original paleogeographic position, transport distances and the time of thrusting are discussed by Tollmann (1985, 1987), Frank (1987), Channel et al. (1992) and Neubauer (1994), especially the nature of transport of the Juvavic nappes. Fischer (1969) was the first to postulate gravity processes for the emplacement of the Lower Juvavic nappes and slices in the areas of Salzburg. Plöchinger (1974, 1976, 1979, 1980), Schäffer (1976) and Tollmann (1981, 1987) postulated the transport of both Lower and Upper Juvavic nappes (e.g. Hallstatt, Dachstein and Berchtesgaden nappes) as large-scale olistostrome complexes over the Tirolic nappes during the Late Jurassic to Early Neocomian. The motor of the sliding was considered to be salt diapirism (Haselgebirge). The combined Tirolic/Juvavic nappe complex was interpreted to have only marginally been overprinted by the subsequent Cretaceous to Tertiary contraction and nappe stacking, which caused a tectonic overprinting of the orginally sedimentary contacts between Juvavic nappes and underlying units (Lein 1987; Tollmann 1987).

New structural data from western and eastern sectors of the NCA demonstrate a polyphase, internal deformation of the NCA indicated by: (1) the presence of Late Cretaceous to Eocene Gosau basins which overlie already deformed sequences; (2) the deformation of these Gosau sequences provides evidence for a post-Gosauian (late Eocene-Miocene), internal imbrication and thrusting of the NCA onto underlying, Penninic and European units (Tollmann 1985; Decker et al. 1993; Eisbacher & Brandner 1995; Linzer et al. 1995).

Metamorphic overprint within the area of investigation ranges from non-metamorphic in the northern sectors to low grade in the southern sectors. Investigations of the conodont colour alteration indices (CAI), carried out in the central part of the NCA by Gawlick et al. (1994), indicate diagenetic to low grade metamorphic conditions (CAI = 5–7) in some Juvavic nappes predating the nappe emplacement during the Late Jurassic to Early Neocomian. This pre-Neocomian age of a low grade metamorphism is in line with Late Jurassic, apatite fission track cooling ages found by Hejl & Grundmann (1989) within the Werfen and Lunzer Formations of the Tirolic nappe complex. Illite-crystallinity of Permoscythian and Carnian shales of different tectonic units in the central NCA shows an increase from diagenetic conditions (200±50 °C) in the northern and central part to anchimetamorphism (270–320 °C) in the South (Kralik et al. 1987, Fig. 2). The age of the anchimetamorphism documented by K-Ar and Rb-Sr model and isochron ages ranges between 103 and 141 Ma (Kralik et al. 1987).

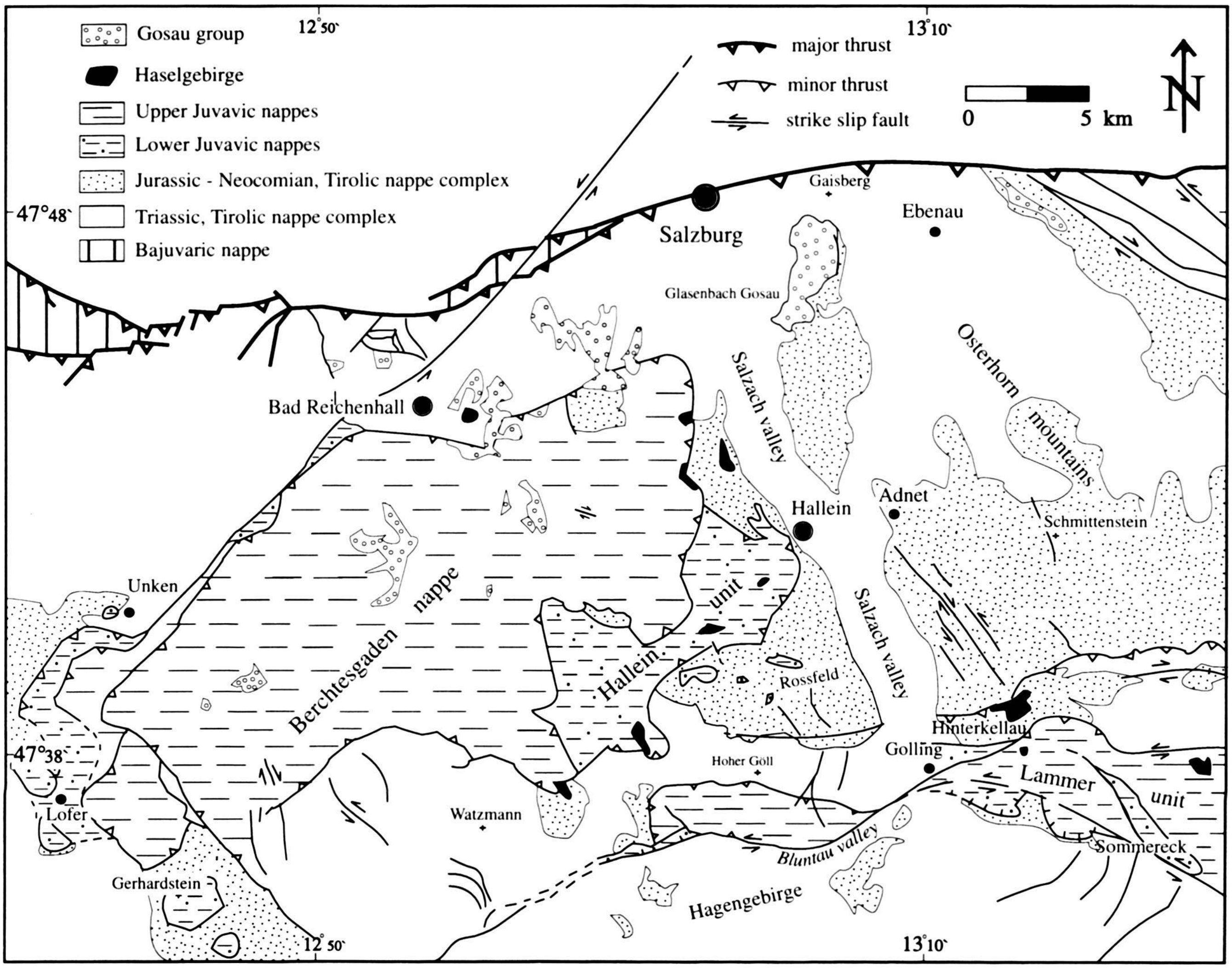

Fig. 2. Simplified geological map of the central NCA based on Ampferer (1927), Plöchinger (1982, 1987) and Prey (1969).

The aim of this study is to present structural data from the central part of the Northern Calcareous Alps in order to constrain the Jurassic to Neogene geodynamic evolution. Especially, we intend to demonstrate that the Lower Juvavic nappes west of the Salzach valley and the Upper Juvavic nappes were thrust over the Tirolic nappe during the Cretaceous and not during the Late Jurassic as suggested by previous interpretations.

The discussion is based on interpretation of geological maps (Ampferer 1927; Prey 1969; Tollmann 1973, 1976a, 1976b, 1985; Häusler & Berg 1980; Plöchinger 1980, 1982, 1983, 1987; Decker et al. 1994), on tectonic interpretation of sedimentary sequences (e.g., Gawlick 1991, 1992; Böhm et al. 1995) and on new structural data, to show the succession of tectonic events and their imprint on the sedimentary record.

Tectonostratigraphy of the central NCA

The Tirolic, Lower and Upper Juvavic nappes are different in sedimentary and structural thicknesses within the study area (see Fig. 3, 4).

The Tirolic nappe complex includes Permian to Scythian clastics and Middle and Upper Triassic carbonate platform sequences. These are overlain by pelagic Adnet limestones (Early Jurassic), Strubberg marls and breccias, radiolarite and basinal deposits of the Oberalm, Schrambach and Rossfeld Formations. The Lower Juvavic nappes consist mainly of Permian Haselgebirge and Triassic pelagic Hallstatt and Pötschen/Pedata limestones (slope to basin facies) and Upper Jurassic shallow water deposits (Fig. 3) that are mostly in a tectonic contact with salts and clays of the Haselgebirge Formation. The Upper Juvavic nappes are built up by Triassic carbo-

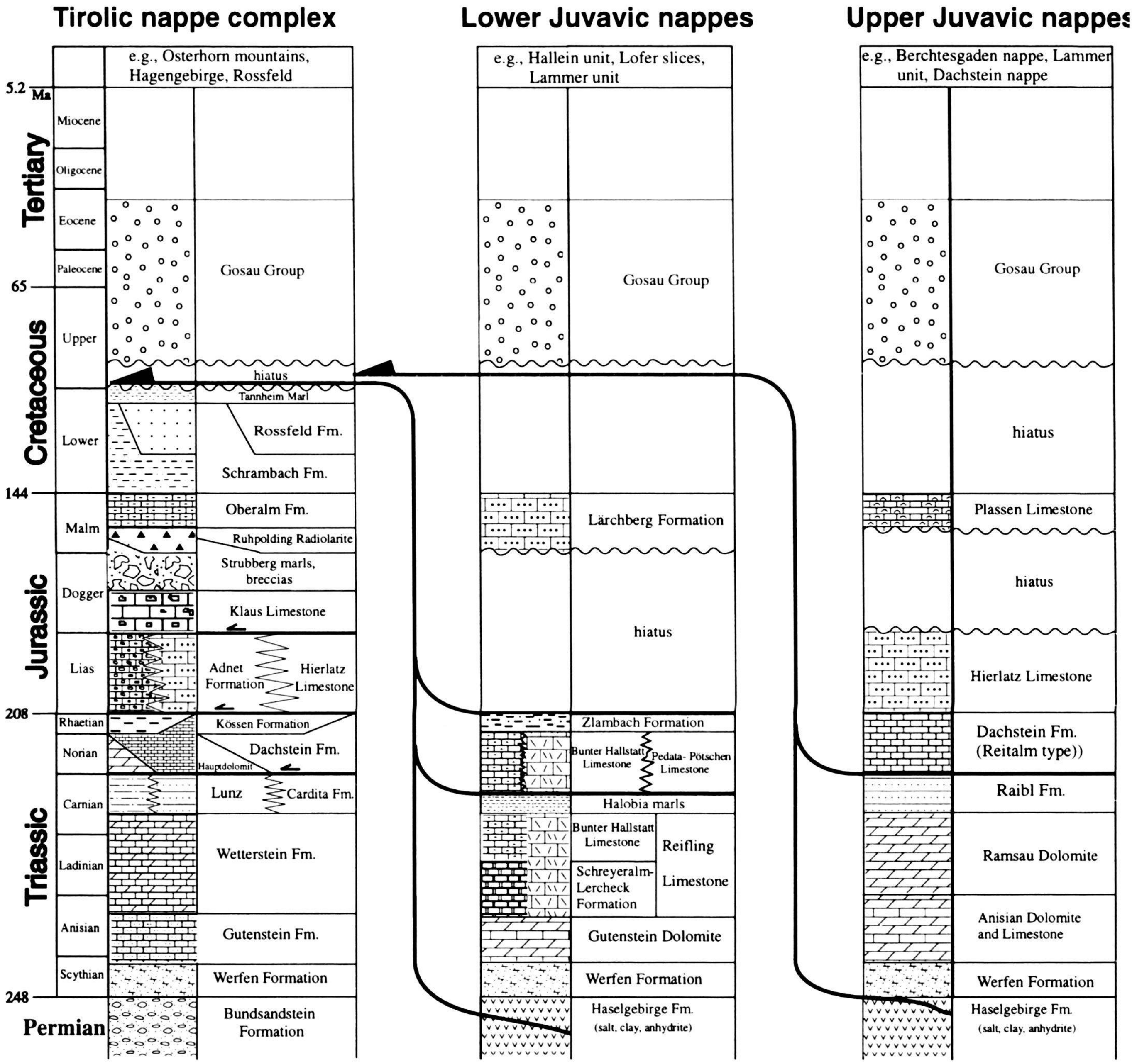

Fig. 3. Stratigraphy of the main tectonic elements of the central NCA with major decollement horizons.

nate platform deposits and relatively thin Jurassic formations (Fig. 3, 4). The uppermost unit is the Upper Juvavic nappe complex which is represented in the central NCA by the Berchtesgaden and Hohes Brett nappes in northern part of the Bluntau valley and by the Gollinger Schwarzer Berg nappe overlying the Lammer unit. In contrast to the Tirolic nappes from Dogger to Middle Cretaceous the Upper Juvavic nappes show only shallow-marine Late Jurassic Plassen Limestone between two great hiatus. Thus the reason to separate the Upper and Lower Juvavic nappe complexes from the Tirolic one is not only the higher tectonic position, but also the marked difference in sediment records, thickness and facies (Fig. 3).

Both the Tirolic and the Juvavic nappe complexes are discordantly overlain by Late Cretaceous to Middle Eocene Gosau Formations. Haselgebirge, Raibl, Lunz, Halobia, Kössen and Adnet Formations correspond to major decollement horizons.

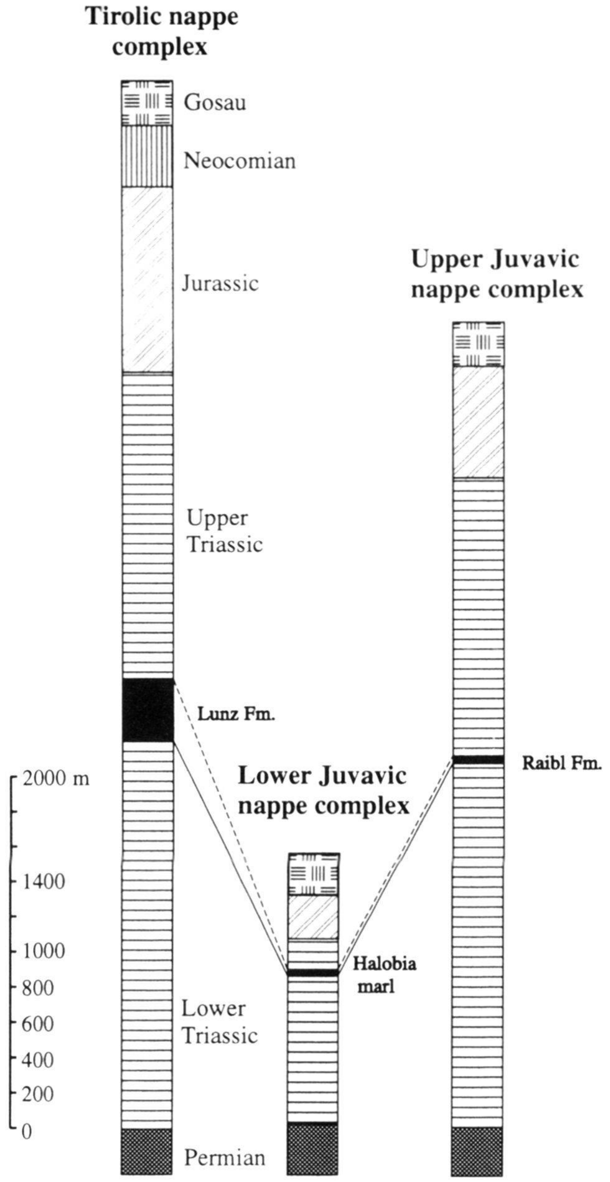

Fig. 4. Comparison of cumulative thickness within the main tectonic elements of the central NCA. Data from Plöchinger (1980).

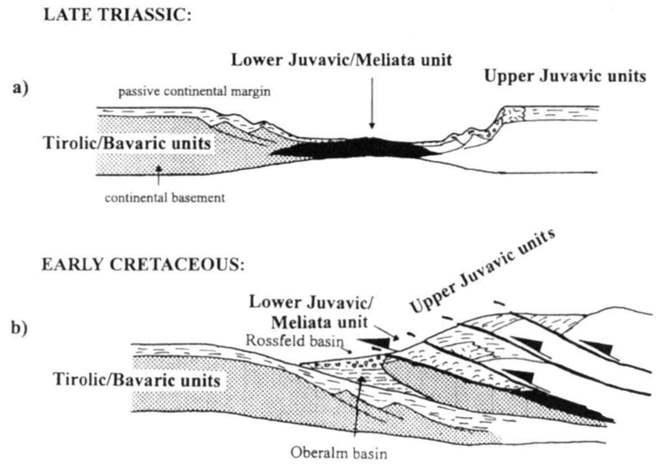

Fig. 5. Geological model for the possible paleogeographic origin of various nappe complexes within the central NCA during (a) Middle Triassic rifting and (b) or the emplacement of Juvavic nappes onto the Tirolic unit during early Cretaceous, causing flexural bending of the Tirolic units by thrust loading.

Paleogeography and geodynamic setting

It is well-known that a major part of the tectonic units within the NCA represent specific facies developments (e.g. Tollmann 1976a, 1985) that strongly vary from one nappe to the next ("facies nappe hypothesis", e.g. Tollmann 1973). This is obvious from the above given statements on the stratigraphy of formations exposed within the Tirolic, Upper and Lower Juvavic nappe complexes within the study area. For geodynamic interpretations, the occurrence of Middle Triassic and Jurassic Meliata oceanic sequences in the easternmost part of the NCA (Mandl & Ondrejickova 1993; Kozur & Mostler 1992; Gawlick 1993; Fig. 1) at the same tectonic level (position) as the Lower Juvavic nappe in the studied area is crucial. These relationships lead to the idea to separate the paleogeographic origin of Tirolic and Upper Juvavic Triassic shallow water deposits by Triassic deep water sequences of the Meliata/Hallstatt unit in between. The model is outlined in Figure 5a. It contrasts previous interpretations, e.g. of Fischer (1969), Schäffer (1976) and Tollmann (1981, 1985), where the Upper Juvavic nappe complex is in a paleogeographic position north of the Lower Juvavic nappe complex. But the main proof for this model is the cross section through the central NCA (Fig. 6, 7): The Upper Juvavic Berchtesgaden nappe overlies the Lower Juvavic Hallein unit, both overlying the Tirolic nappe complex; the thrust contacts are sealed by the Late Cretaceous Gosau sediments. Thrust contacts between Berchtesgaden nappe and Hallein unit indicate a transport of the Berchtesgaden nappe top to the NNE-NE. Also strataparallel fibrous slickensides within the underlying Tirolic nappe show the same transport direction. If we restore the original position of the three nappes in this cross section, we get the following paleogeographic order: The Tirolic nappe in the North, the Lower Juvavic nappe in the middle position and the Upper Juvavic nappe to the South.

Furthermore the Hoher Göll unit south of the Hallein unit acquires a Tirolic tectonic position because the Dachstein reef passes laterally into Kössen basin sediments (Plöchinger 1955; Gawlick 1996, pers. comm.) and it is overlain by Late Jurassic Oberalm conglomerates and limestones (Del-Negro 1972). Its neighbour in the south, the Hohes Brett nappe belongs to the Upper Juvavic nappe complex and is bounded by sinistral strike slip faults (Fig. 6) both to the N (Hoher Göll) and to the South (Bluntau valley).

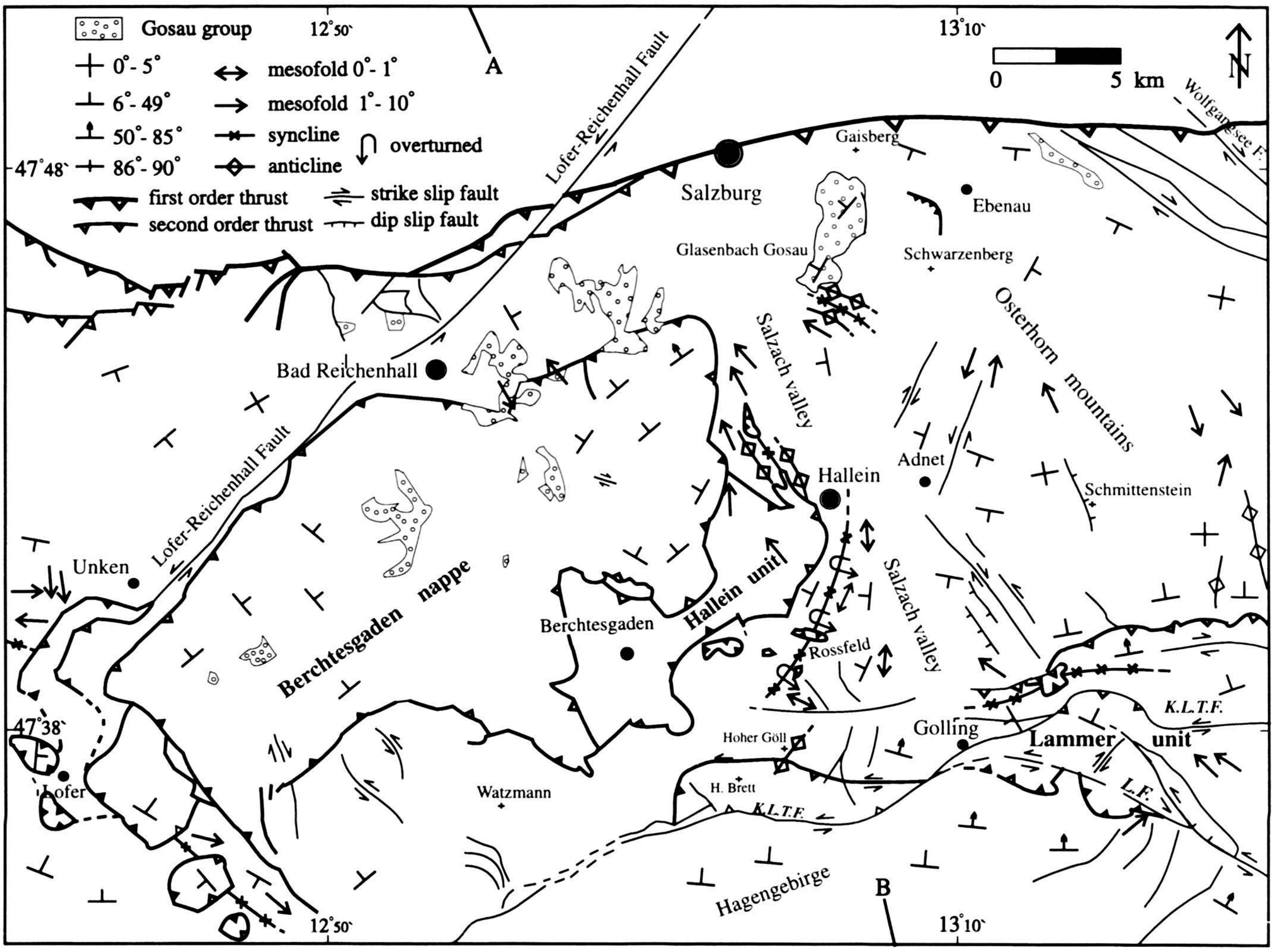

Fig. 6. Structural map of the central NCA. K.L.T.F. = Königssee – Lammertal – Traunsee fault, L.F. = Lammertal fault. A–B indicate the position of cross section of Fig. 7.

Obvious differences between Tirolic and Upper Juvavic units occur from the Permian to the Middle Cretaceous (compare Tollmann 1976a; Plöchinger 1980). The most representative are (Fig. 3, 4): (i) Lagoonal evaporites (Haselgebirge Formation) in the Upper Juvavic units vs. terrestrial Permian clastic sequences in the Tirolic units; (ii) thin, clastic Halobia Formation at the base of the Upper Triassic pelagic, basinal sequence of the Lower Juvavic units vs. thick, clastic beds of the Lunz Formation (Fig. 3) at the base of mainly shallow water deposits (e.g. Dachstein Limestone) in the Tirolic units; (iii) mainly Rhaetian reefs in the Tirolic in contrast to mainly Norian reefs in Upper Juvavic units; (iv) Late Jurassic basinal sequences (Oberalm Fm.) in the Tirolic units vs. shallow water Plassen Formation in the Juvavic units; and, the most significant one, (v) the transition from Late Jurassic basinal sequences to siliciclastic sequences of the Rossfeld Formation (see Faupl & Tollmann 1979), a feature that is not reported from the Juvavic units. These differences in facies and thickness between the sedimentary units of the Tirolic and Upper Juvavic nappe complexes are interpreted as the result of their different paleogeographic shelf position (Fig. 5a). The Lower Juvavic units are interpreted to represent the westernmost sedimentary outlier of the Hallstatt/Meliata oceanic seaway (Fig. 5a).

Another important aspect is represented by the continuous Upper Jurassic to Lower Cretaceous deposits of the Tirolic nappe complex where carbonate deposits of the Oberalm basin grade into thick siliciclastic deposits of the Schrambach and Rossfeld Formations. These coarsening upward sequences with Tirolic and Juvavic components are interpreted as a clastic wedge deposited within a peripheral foreland basin in a contractional regime (Fig. 5b). A synorogenic origin of the Rossfeld Formation was already postulated by Faupl & Tollmann (1979). The siliciclastic detritus of the Rossfeld Formation comprises volcanic quartz, feldspar, apatite and other

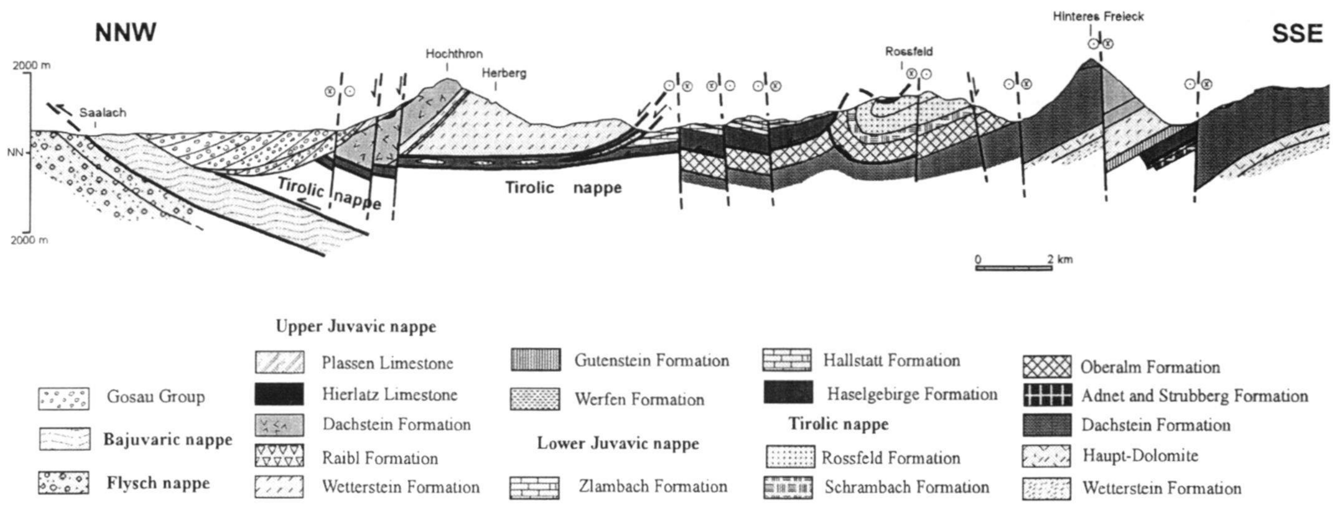

Fig. 7. Cross section through the central Northern Calcareous Alps.

components of volcanogenic rocks (Schweigl & Neubauer 1997). After a short sedimentary hiatus in the late early Cretaceous, caused by the Austrian tectonic phase (see Tollmann 1985), the deformed sequences were discordantly overlain by Gosau sediments (shallow water to basin facies).

Analysis of map-scale structures

The large-scale structure is dominated by thrusts, strike-slip faults and folds (Fig. 6). Lower Juvavic nappes occur in three isolated exposure areas between the Tirolic and Upper Juvavic nappes (Fig. 2): (1) Lofer-Unken-Reichenhall area, (2) Hallein unit and (3) Lammer unit including the Bluntau valley.

The structural map and the cross section (Fig. 6, 7) show a very important feature of pre-Gosauian kinematics of the central NCA: The Upper Juvavic Berchtesgaden nappe overlies the Lower Juvavic Hallein unit, both overlie the Tirolic nappe system and the thrusting contacts are sealed by the late Cretaceous Gosau sediments.

To the south, the Lower Juvavic Hallein unit is limited by the Tirolic Göll unit (Fig. 2) and in the northwest by the Upper Juvavic Berchtesgaden nappe. The Middle and Upper Triassic facies of the Upper Juvavic Berchtesgaden nappe and of the Hohes Brett and the Tirolic Göll slices are quite similar: lagoonal and reef facies. Therefore, the discussion, if the Göll nappe belongs to the Tirolic or Juvavic nappe complex, is still going on. Fischer (1969) and Plöchinger (1980, 1987) put it to the Juvavic nappes, while Del-Negro (1972), Gawlick (1995 pers. comm.) and the authors put it to the to the Tirolic nappe complex. However, the Hohes Brett nappe is bounded by strike slip faults both to the N and to the S (Fig. 2, 5a).

Large, upright folds on km-scale, with fold axes trending NW to WNW, are exposed in the western part of the Tirolic nappe within the Osterhorn mountains, north- and southwest of Hallein and in the Lammer unit (Fig. 6). Geological mapping on a 1 – 25,000 scale revealed that these folds are discordantly overlain by the Glasenbach Gosau sediments (Fig. 6). These folds are, therefore, older than Late Cretaceous. The youngest folded formations (Oberalm limestone), which are of Late Jurassic age, form a lower time marker for the formation of these folds. The macrofolds are accompanied by mesofolds on metre- to dekametre-scale with subhorizontal fold axes (see next chapter). Similarly oriented mesofolds occur in the Lammer valley and in the Rossfeld-Hallein area within the Tirolic nappe.

A southeasterly overturned syncline on kilometre-scale, the Rossfeld syncline, is oriented NE-SW to NNE-SSW (Fig. 6, 8). Originally it has also been oriented NW, but a drag caused by the incoming thrust mass of the Berchtesgaden nappe changed its orientation. This interpretation explains the gradual change of orientation of the macro- and mesofolds from NE-SW to NW-SE going from the Rossfeld to the North. These fold structures are tectonically overlain by Lower Juvavic slices (Fig. 8), as already known since Plöchinger (1976). The fold structures have to be middle Cretaceous or younger, because the youngest folded sediments belong to the Rossfeld Formation. The youngest beds of the Rossfeld syncline are Aptian in age. Furthermore, underlying Tirolic units of the Berchtesgaden-Rossfeld area, e.g. Rossfeld sandstones and Schrambach marls show strata-parallel fibrous slickensides which indicate a thrusting top NNE to NE. A further important consequence of these relationships is that thrusting of the Lower Juvavic nappes over the Tirolic nappes in the central NCA occurred after the Neocomian. North of the Rossfeld area, the macro-

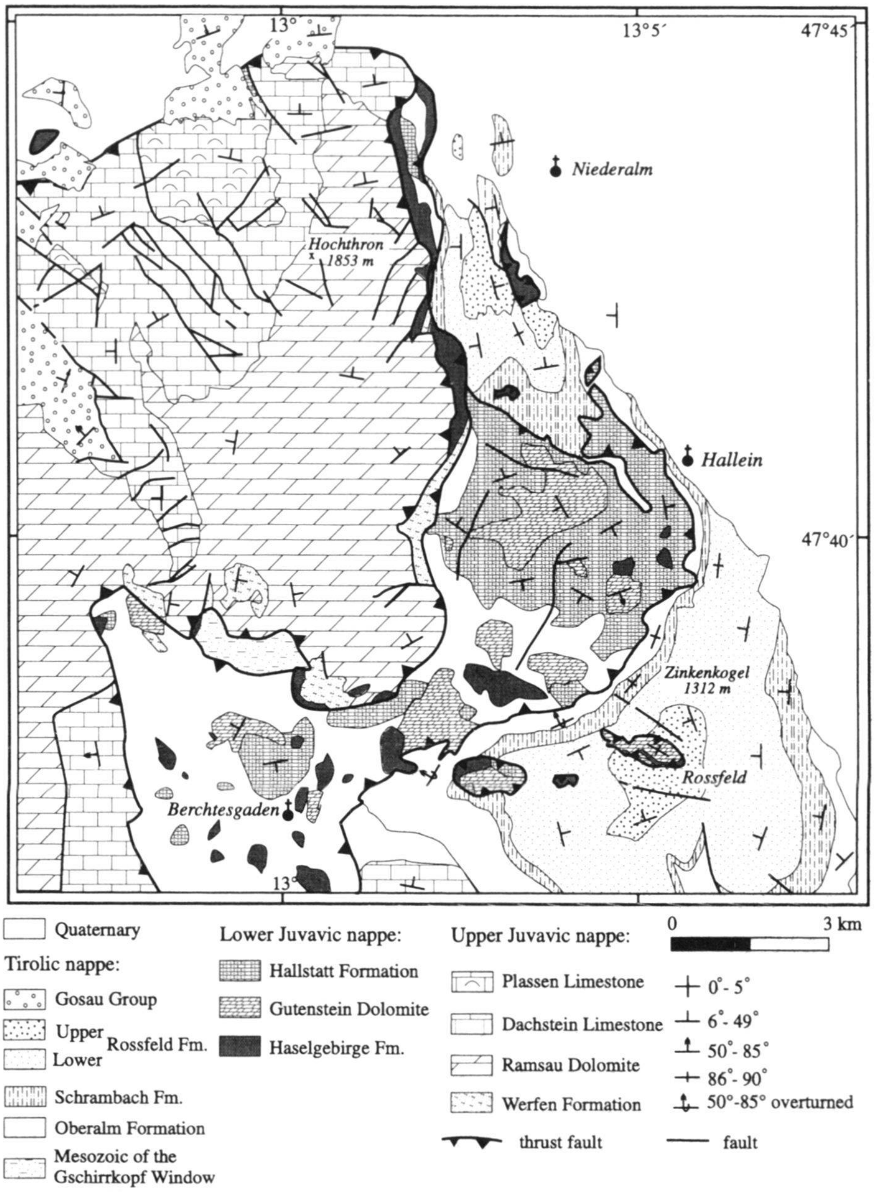

Fig. 8. Geological map of the Berchtesgaden-Rossfeld area based on Prey (1969). Note that the Rossfeld syncline with Neocomian sediments is discordantly overlain by Lower Juvavic nappes, and that the thrust contact between Tirolic and Upper Juvavic nappes is sealed by Gosau deposits.

folds within the Tirolic nappes gradually change to NNW-SSE orientations (Fig. 6). They are accompanied by m-scaled, NW to NNW trending mesofolds.

Syn- to post-Gosauian, map-scale and metre-scaled dip-slip faults are widespread in the whole study area, especially in the Osterhorn mountains and Rossfeld area. They mainly trend ENE and NNW respectively and display offsets from some meters up to 10 meters. One of the major dip slip faults passes through the Schmittenstein (Fig. 6).

The Osterhorn mountains are also characterized by some post-Gosauian NE-directed thrusts within the Tirolic nappe complex, e.g. near the locality Schwarzenberg some kilometres southeast of Salzburg (Fig. 6). NE-directed thrusts are often kinematically linked with WSW-NNE to SW-NE oriented sinistral strike-slip faults, e.g. the Schwarzer Berg thrust near the Königsee–Lammertal–Traunsee fault (Decker et al. 1994). Decker et al. (1994) suggested a shortening of about 2 km along this fault. The E-trending Königssee–Lammertal–Traunsee fault (K. L. T. F.) itself produced a displacement of 5 to 15 km (Decker et al. 1994).

The Neogene N-S and E-W contraction have left mainly strike-slip faults and thrust structures. The Juvavic slices and nappes of the Lammer unit are thrust over the Tirolic Strubberg Formation and Dachstein Limestone in the south. The northern boundary of the Lammer unit complex is represented by the Königssee–Lammertal–Traunsee strike-slip fault and by

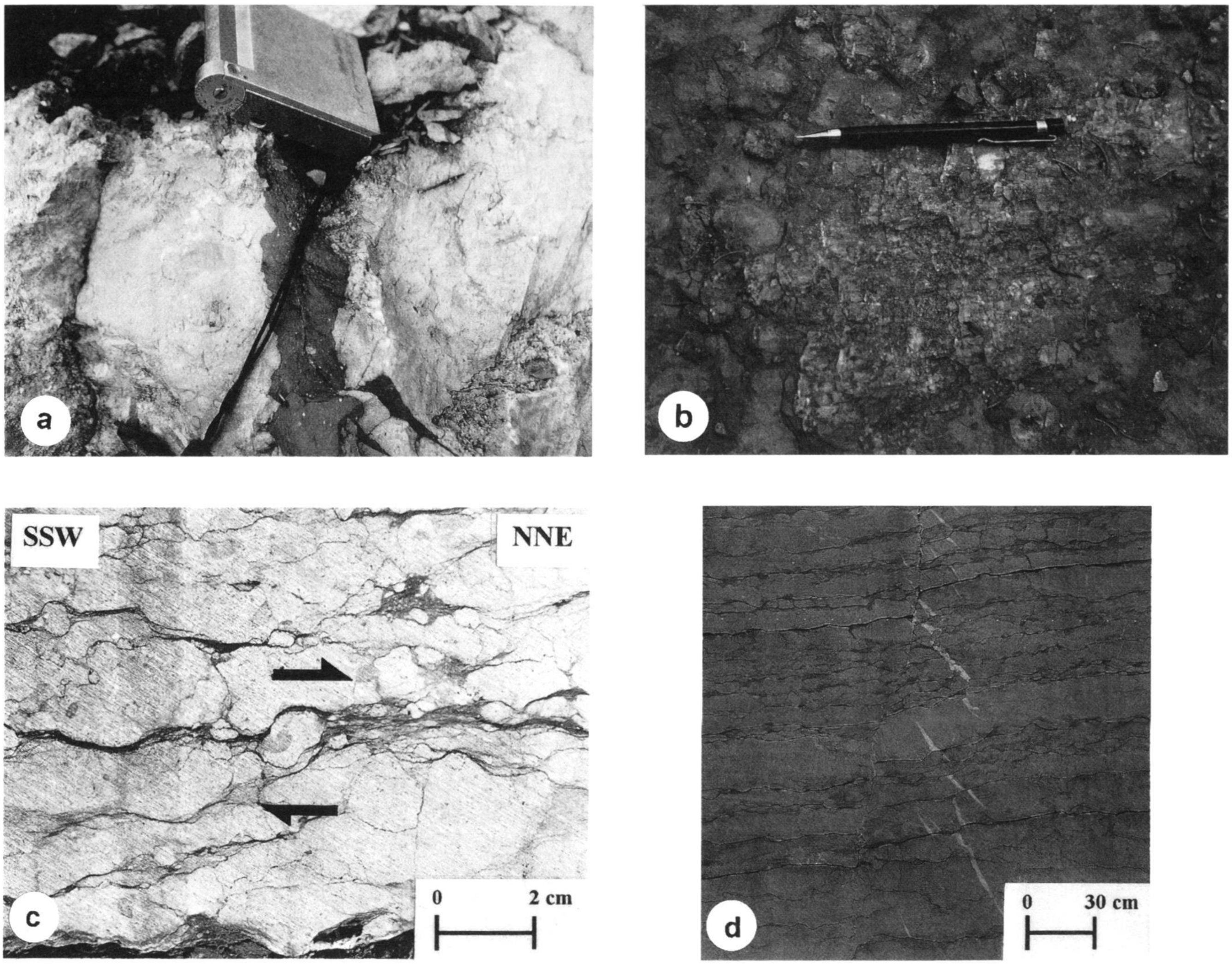

Fig. 9. Representative examples of deformation structures within the central NCA: a) Neptunian dyke filled with Hierlatz limestone, Adnet. b) Strata-parallel fibrous slickensides in the Adnet formation, Adnet. c) Semiductile deformation in the Adnet formation with σ-porphyroclast, shear bands and stylolithes, Adnet. d) Dip slip fault (D_3) cuts structures of the D_2-event, Adnet formation, Adnet.

the Gollinger Schwarzer Berg thrust, which separate the Lammer unit from the Tirolic Osterhorn mountains.

Thrust faults indicating a transport top to the N are situated north of the Lammer unit (Fig. 6). In the southern part of the Lammer unit thrust faults and their outcrop-scale structures show backthrusting to the S.

Another important fault system of the Salzburg area are NW-SE oriented, dextral strike-slip faults (e.g., the Wolfgangsee fault and faults in the NE and SW of the Osterhorn mountains, Fig. 6). NW-SE oriented strike-slip faults are also sinistral (e.g. faults W of the Watzmann, Fig. 6), which offset Jurassic beds. In contrast to the interpretations of Linzer et al. (1995) new investigations along the Lammer fault showed a further sense of movement. Paleostress data and Riedl planes of different outcrops at the entrance of the Lammer valley near Golling indicate only an activation during a NE-SW contraction (see also Fig. 14a), which proves a sinistral movement along this fault. Fischer (1969) postulated a sinistral offset of 30–40 km for the Lammer fault, based on the sinistral offset of the Upper Juvavic reefs. Outcrops in the central and the eastern Lammer valley demonstrate two displacement events, a sinistral and a dextral activation of the about NW-SE oriented Lammer fault.

Oberalm limestones and Schrambach marls of the Unken area expose many open to tight, metre to dekametre-scaled folds of two generations (see also Häusler & Berg 1980). The first fold generation trends E (90° ± 20°) and the second generation trends S (180 ± 20°). Both fold generations must be younger than Late Jurassic.

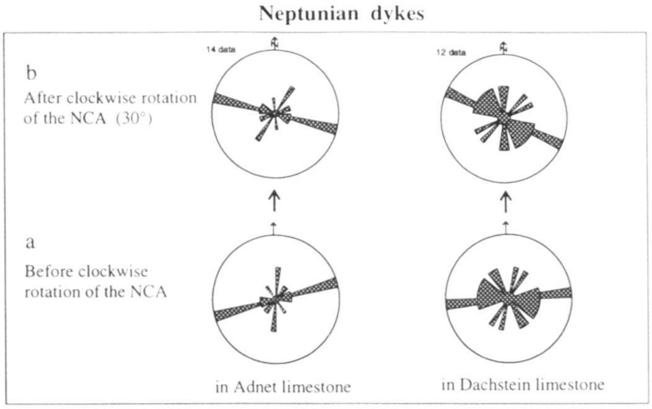

Fig. 10. Orientations of Neptunian dykes in Adnet (area of Adnet) and Dachstein limestones (area S of Lofer). a) Orientation before clockwise rotation of the NCA (≥ 30°); b) orientation after rotation.

Structural field data

Structural work followed methods described in Ramsay & Huber (1983, 1987), Hancock (1985) and Groshong (1988) for semi-brittle to brittle rheologic conditions. Inhomogeneous data sets of fault-slip analysis were separated into homogeneous data sets by the following methods: field observations on the relative chronology of deformation phenomena; graphical computation of P-T-axes (Turner 1953); graphical separation method after Hoeppener (Hoeppener 1955); and the direct inversion method (Angelier & Goguel 1979). For paleostress tensor determination computations of P-T-axes were used (Turner 1953) as well as the right-dihedra method (Angelier & Mechler 1977) and the direct inversion method (Angelier & Goguel 1979), which gives the ratio of the principal stress axes (R-value). The computer versions of Delvaux (unpublished), Ratschbacher et al. (1994) and Wallbrecher & Unzog (unpublished) were used for computation. Stereographic projections are in Schmidt net, lower hemisphere. The paleostress plots were produced with the programme of Delvaux.

Structural investigations within the central part of the NCA revealed a sequence of eight distinct deformation events, based on overprint criteria: (1) N-S extension evidenced by Neptunian dykes of Early to Middle Jurassic age within the Tirolic nappe complex (D_1); (2) pre-Gosauian NNE-SSW to NE-SW shortening due thrusting and folding (D_2); (3) syn- to post-Gosauian mutually orthogonal, about N and E trending extensional joints and dip slip faults due to subvertical compression (D_3); (4) post-Gosauian NE-SW shortening (D_4); (5) post-Gosauian NW-SE contraction (D_5); (6) Neogene N-S contraction combined with E-W extension (D_6); (7) Late Miocene E-W contraction (D_7) and post-Miocene N-S extension

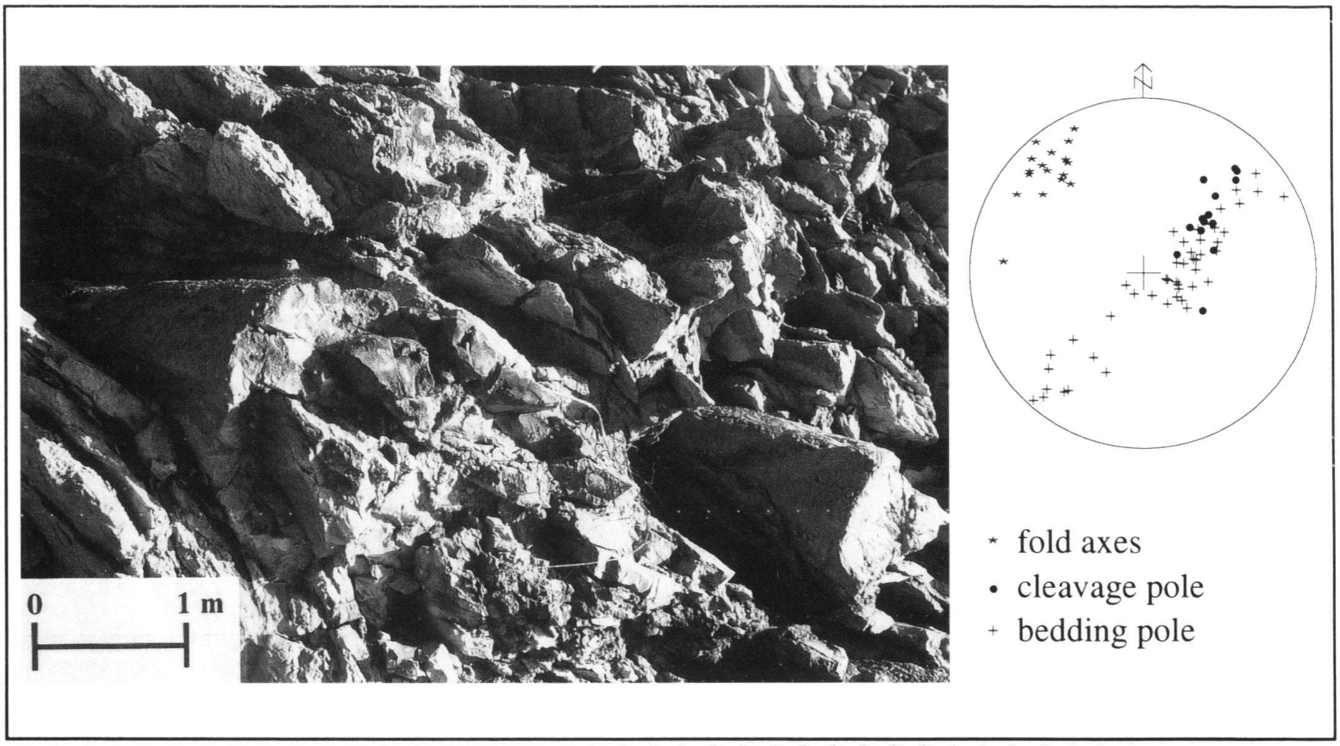

Fig. 11. Tight folds in the Schrambach marl (D_2-deformation) with Schmidt plot, Leube quarry, NE of Hallein.

Tab. 1. Some representative paleostress data of D_2-, D_3- and D_4-deformation stages: S.O.R. = Schrambach, Oberalm, Rossfeld Formations; n = number of data; $R = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. For localities see Fig. 12.

Outcrop	Formation	Sigma 1		Sigma 2		Sigma 3		R-value	n
		azimuth	dip	azimuth	dip	azimuth	dip		
Strataparallel fibrous slickensides (D2-deformation):									
1	Rossfeld	43	14	230	76	134	1	0.5	10
2	Adnet	22	37	112	1	203	53	0.59	17
3	S. O. R.	66	16	224	73	334	6	0.5	10
4	Oberalm, Lias	18	27	284	48	125	30	0.52	18
69	Oberalm	16	7	108	21	270	68	0.17	10
Dip slip faults (D3-deformation):									
5	Gosau	100	68	265	21	357	5	0.1	10
6	Gosau	185	61	64	16	327	24	0.75	7
7	Hallstatt	67	74	264	15	173	4	0.46	7
8	Hallstatt	92	68	306	19	212	11	0.75	11
9	Hallstatt	137	86	316	3	46	0	0.4	10
10	Oberalm	197	52	345	33	86	16	0.67	27
11	Oberalm	7	68	107	4	198	22	0.5	9
12	Oberalm	21	64	173	23	268	11	0.59	7
13	Lias limest.	131	85	26	1	296	5	0.4	7
14	Schrambach	181	69	83	3	352	21	0.33	7
15	Schrambach	253	60	67	30	158	3	0.83	7
16	Schrambach	19	74	260	8	168	14	0.5	8
17	Rossfeld	127	85	9	3	279	5	0.5	9
18	Rossfeld	336	78	144	12	234	2	0.15	20
19	Rossfeld	322	84	59	1	149	6	0.4	25
20	Dachstein	240	80	353	5	84	11	0.5	8
21	Wetterstein	318	76	100	11	192	8	0.53	8
22	Wetterstein	285	75	179	5	87	14	0.33	8
23	Werfen	189	83	283	0	13	7	0.17	7
24	Werfen	185	81	63	5	332	8	0.5	7
25	Gosau	340	61	157	29	247	1	0.5	7
NE-SW contraction (D4-deformation):									
26	Gosau	229	9	135	25	337	63	0.5	7
27	Gosau	57	58	214	30	310	10	0.67	7
28	Gosau	69	8	175	63	335	26	0.8	7
29	Hallstatt	67	12	199	72	334	13	0.4	7
30	Hallstatt	58	23	225	66	326	5	0.5	7
31	Hallstatt	51	6	309	64	144	25	0.18	12
32	Oberalm	214	12	72	75	306	9	0.47	17
33	Oberalm	39	21	183	65	304	14	0.9	10
34	Oberalm	55	24	269	62	151	14	0.33	19
14	Schrambach	59	23	271	64	154	12	0.0	10
35	Schrambach	225	16	117	47	328	39	0.0	16
36	Schrambach	226	37	73	50	327	13	0.5	7
37	Rossfeld	66	12	332	18	188	68	0.28	11
38	Rossfeld	40	34	203	55	304	8	0.62	13
18	Rossfeld	33	9	125	15	273	72	0.33	7
39	Dachstein	238	15	122	58	336	27	0.5	16
40	Wetterstein	33	11	136	48	294	40	0.75	9
21	Wetterstein	224	14	28	76	133	3	0.5	9
22	Wetterstein	202	17	99	35	314	50	0.06	10
23	Werfen	59	29	315	23	192	52	0.67	7

Tab. 2. Some representative paleostress data of D_5-, D_6- and D_7-deformation stages: n = number of data; $R = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. For localities see Fig. 12.

Outcrop	Formation	Sigma 1		Sigma 2		Sigma 3		R-value	n
		azimuth	dip	azimuth	dip	azimuth	dip		
NW-SE contraction (D5-deformation):									
6	Gosau	323	14	140	76	233	0	0.5	8
41	Gosau	134	19	256	57	34	26	0.5	14
25	Gosau	308	16	205	37	56	49	0.47	10
31	Hallstatt	321	4	86	83	231	6	0.38	13
42	Oberalm	314	26	185	52	57	26	0.5	7
34	Oberalm	158	11	310	77	66	6	0.71	8
43	Lias limest.	350	12	189	78	81	4	0.4	7
13	Lias limest.	346	20	245	28	108	55	0.5	8
44	Schrambach	131	33	9	39	246	33	0.5	10
36	Schrambach	117	32	316	57	212	9	0.5	10
35	Schrambach	147	3	259	82	57	7	0.79	14
45	Rossfeld	115	0	25	67	205	23	0.5	16
46	Rossfeld	150	9	43	61	245	28	0.31	7
47	Rossfeld	308	1	217	46	39	44	0.33	7
48	Wetterstein	135	7	36	52	230	37	0.43	9
49	Wetterstein	303	8	201	56	38	33	0.5	10
21	Wetterstein	308	11	39	4	149	78	0.12	9
23	Werfen	118	17	209	2	306	73	0.0	10
N-S contraction (D6-deformation):									
50	Gosau	348	4	241	77	79	13	0.67	7
51	Gosau	187	8	86	53	284	36	0.11	8
52	Gosau	198	24	67	56	299	23	0.5	12
53	Hallstatt	177	2	274	71	87	19	0.5	14
7	Hallstatt	348	6	257	5	123	82	0.4	13
9	Hallstatt	22	18	264	56	122	28	0.89	10
54	Oberalm	176	18	25	70	268	9	0.8	11
32	Oberalm	167	26	356	63	259	4	0.4	7
34	Oberalm	8	12	223	76	99	8	0.5	7
55	Lias limest.	18	41	177	47	279	11	0.62	8
56	Schrambach	13	23	277	15	158	62	0.5	7
16	Schrambach	191	6	54	82	282	6	0.33	9
57	Wetterstein	356	16	128	67	261	16	0.33	8
24	Werfen	173	7	270	45	77	44	0.5	7
58	Werfen	8	78	143	8	234	8	0.1	7
59	Dachstein	169	18	59	47	274	38	0.5	7
E-W contraction (D7-deformation):									
5	Gosau	88	37	183	7	282	52	0.1	7
53	Hallstatt	266	15	167	29	19	57	0.57	11
9	Hallstatt	98	11	197	39	355	49	0.79	10
60	Oberalm	79	10	210	75	347	11	0.11	10
61	Lias limest.	281	53	55	28	157	22	0.51	7
62	Schrambach	90	30	308	46	196	20	0.75	9
63	Schrambach	89	16	339	50	191	35	0.5	9
47	Rossfeld	81	13	322	66	175	21	0.53	11
64	Rossfeld	273	20	177	17	51	63	0.5	8
65	Rossfeld	269	1	1	68	178	22	0.9	11
66	Dachstein	93	24	197	29	331	51	0.5	11
57	Wetterstein	89	0	182	84	360	6	0.78	9
48	Wetterstein	265	16	92	74	355	2	0.52	11
49	Wetterstein	93	10	352	48	191	40	0.54	9
67	Werfen	267	8	7	50	171	38	0.51	8
68	Rossfeld	252	40	51	48	153	10	0.49	9
25	Gosau	97	13	190	14	327	71	0.5	7

(D_8) documented by dip slip faults. Deformations D_4 to D_7 are evidenced by strike slip faults with fibrous slickensides and Riedel planes, by thrusting, often with ramp-flat geometries, by en-echelon tension gashes, by ductile shear zones and by open to tight folds.

Deformation stage D_1: The N-S extension in the Tirolic nappes is well documented by synsedimentary ESE, sometimes NE trending extensional veins in the Adnet and Dachstein Limestones which are filled with red Liassic to Dogger sediments (Fig. 8, 9a), referred to as Neptunian dykes (e.g. Böhm et al. 1995). Considering the clockwise (≥ 30°) rotation of the NCA during Late Jurassic (Channel et al. 1992, Linzer et al. 1995) the original orientation of the Neptunian dykes (Fig. 10) indicates approximate N-S extension during Early Jurassic. The Neptunian dykes are widespread in the whole area of Salzburg. Their width ranges from millimetres to centimetres in the Adnet limestone, and from decimetres to meters in the Dachstein limestone. The Neptunian dykes are offset by

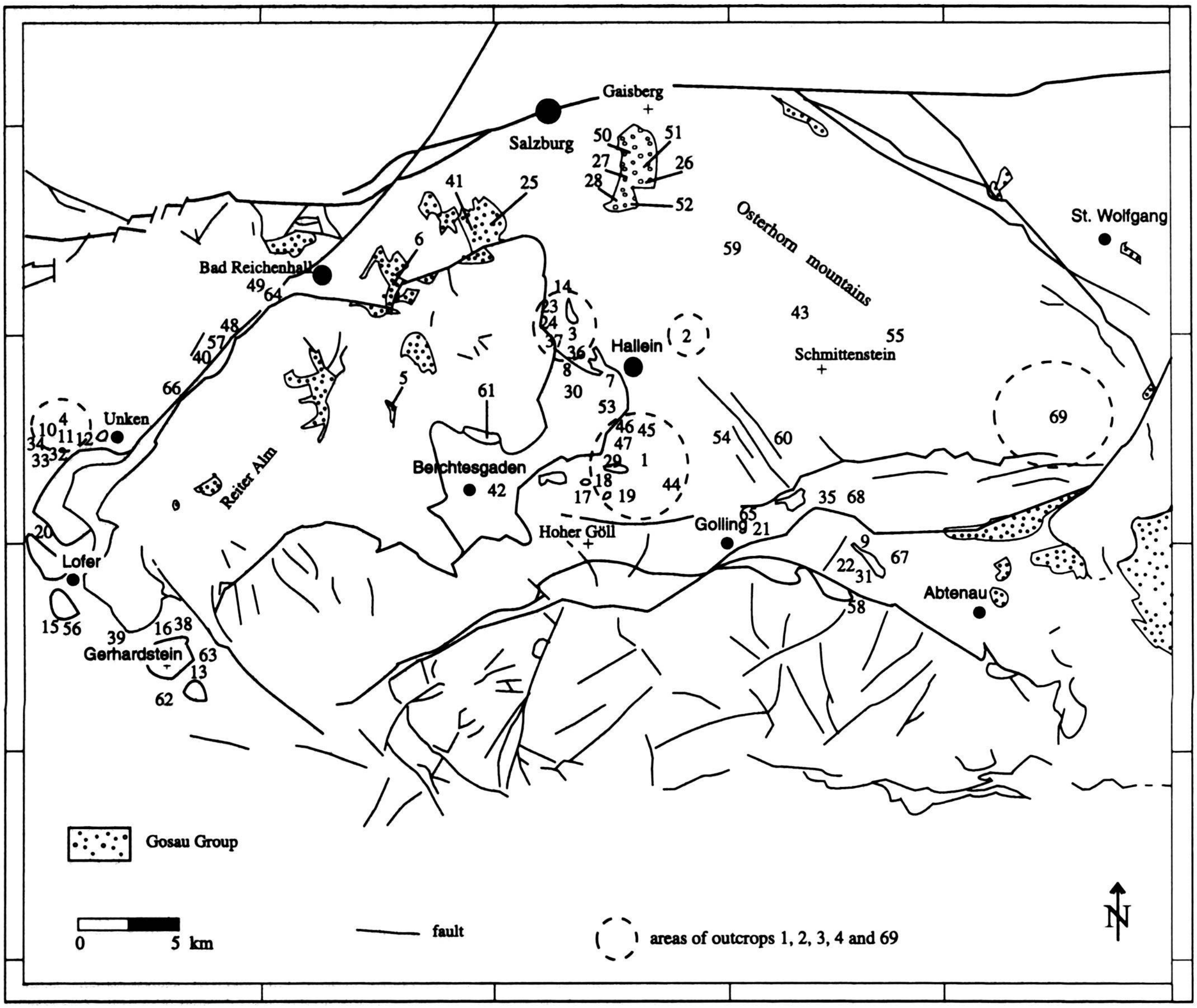

Fig. 12. Localities of the outcrops with data presented in Table 1 and 2.

thrust planes of the D_2-deformation. Another indication of extension in the Early to Middle Jurassic are gravity flows, like the Adnet Scheck (a mass flow unit), the Strubberg breccia (Gawlick 1992) and the Schwarzenbergklamm breccia within beds of the Tirolic nappe complex (Fig. 3).

Deformation stage D_2: NNE- to NE-directed thrusting of the Juvavic nappe complex over the Tirolic nappe complex is proved by strata-parallel fibrous slickensides (Tab. 1), stickolithes, S-C-fabrics, σ-porphyroclasts and oblique stylolites in red nodular, strongly semiductilely deformed Adnet Limestone (Fig. 9b, c). In the quarries of Adnet these structures are cut by a steep dip slip faults (Fig. 9d), which has been reactivated as strike-slip fault of the NE-SW contraction (D_4 deformation). Strata-parallel fibrous slickensides and some stylolithes are also present in marls, limestones and sandstones of the Rossfeld, Schrambach, Oberalm and Hallstatt Formations, e.g. in the Hallein-Rossfeld area. The Gosau sediments show no strata-parallel fibrous slickensides. In the Osterhorn mountains we found strata-parallel fibrous slickensides (Tab. 1) in Jurassic limestones, which indicate not only top NNE thrusting, but also a younger top to the ESE thrusting. Other structures, indicating NE-SW oriented shortening, are upright folds and other dm- to m-scaled folds in Triassic and Jurassic sediments, which are discordantly overlain by Gosau sediments. In a quar-

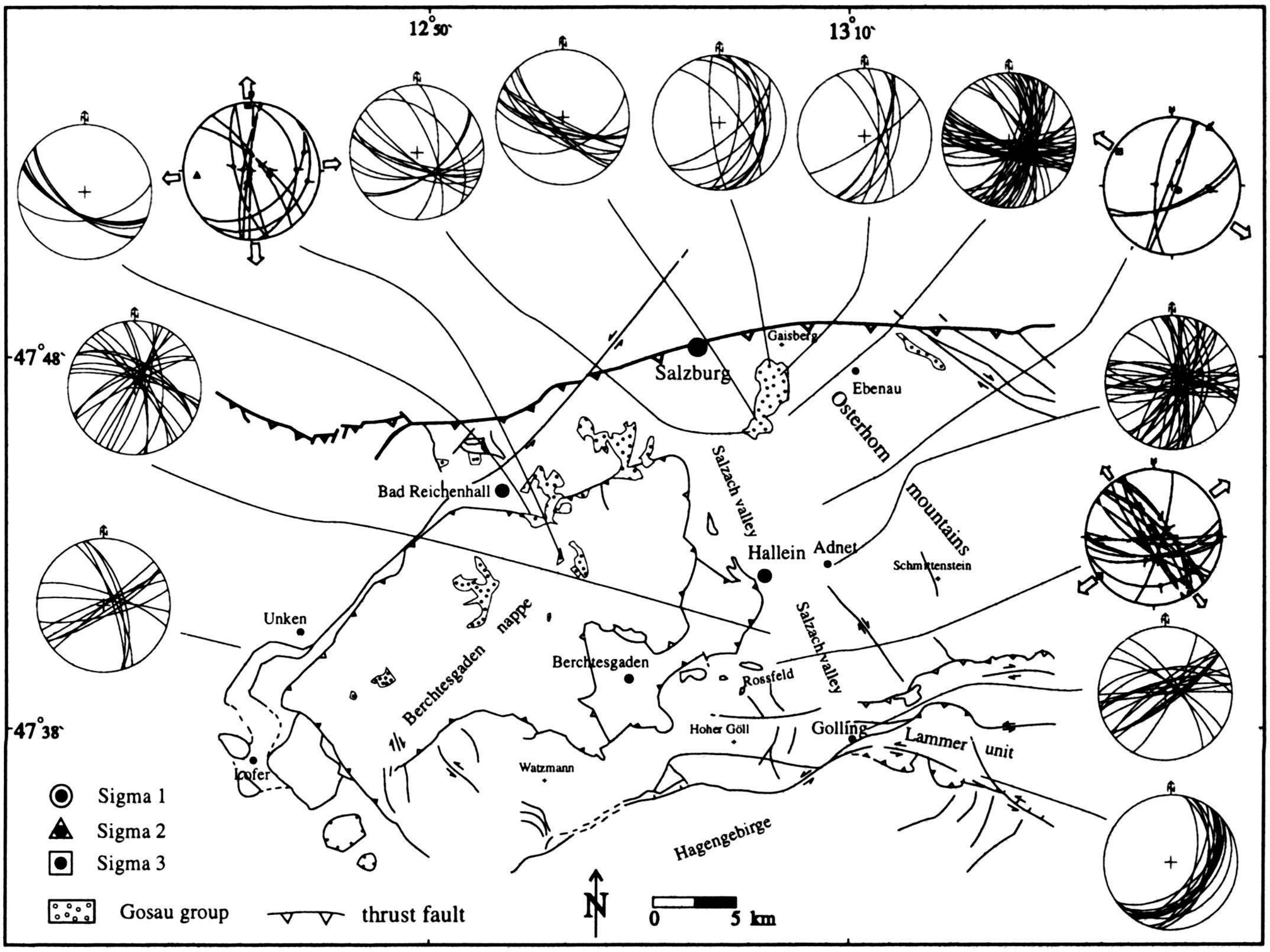

Fig. 13. Mineralized extension veins as kinematic indicators of the orientation of extensional strain and Schmidt plots with dip slip faults and orientation of principal stress axes. Note similar orientations both in pre-Gosau and Gosau Formations.

ry N of Hallein such mesofolds show a planar axial cleavage not related to folding (Fig. 11). The Berchtesgaden nappe (Upper Juvavic) only shows tectonically overprinted contacts with the underlying Tirolic nappe. Fault striae and Riedel planes show a displacement top NNE to NE. The underlying Tirolic beds show NW-SE oriented mesofolds and strata-parallel fibrous slickensides indicating a nappe transport to the NNE. These deformation structures (D_2 deformation) are cut by steep, conjugated dip-slip faults (D_3 deformation), which were partially reactivated by syn- to post- Gosauian transpressive events.

Deformation stage D_3: The third deformation event is characterized by NNE and E trending extensional joints (chocolate table structure), combined with conjugated dip-slip faults. Sigma and R-values of the dip-slip faults are shown in Table 1, localities of all sites are indicated on Figure 12. This pattern implies a subvertical orientation of σ_1; σ_3 orientations mainly vary between SW and NW. The joints, filled with white sparite, range from mm- to cm- scale in width. The structures linked to this kinematic phase can be observed in the whole Salzburg area (Fig. 13). In some outcrops the E-W oriented joints are crosscut by the N-trending joints or both joint sets are partly activated as dip-slip faults. Furthermore, within the Gosau, Oberalm, Adnet and Rossfeld Formations along the Salzach valley occur dekametre-scale dip-slip faults trending N to NW and with offsets of some metres. In the quarries of Adnet the dip-slip faults cut structures of the D_2 deformation (Fig. 9d). Often, the dip-slip faults are reactivated by subsequent deformation stages (D_4 to D_7) as strike-slip faults.

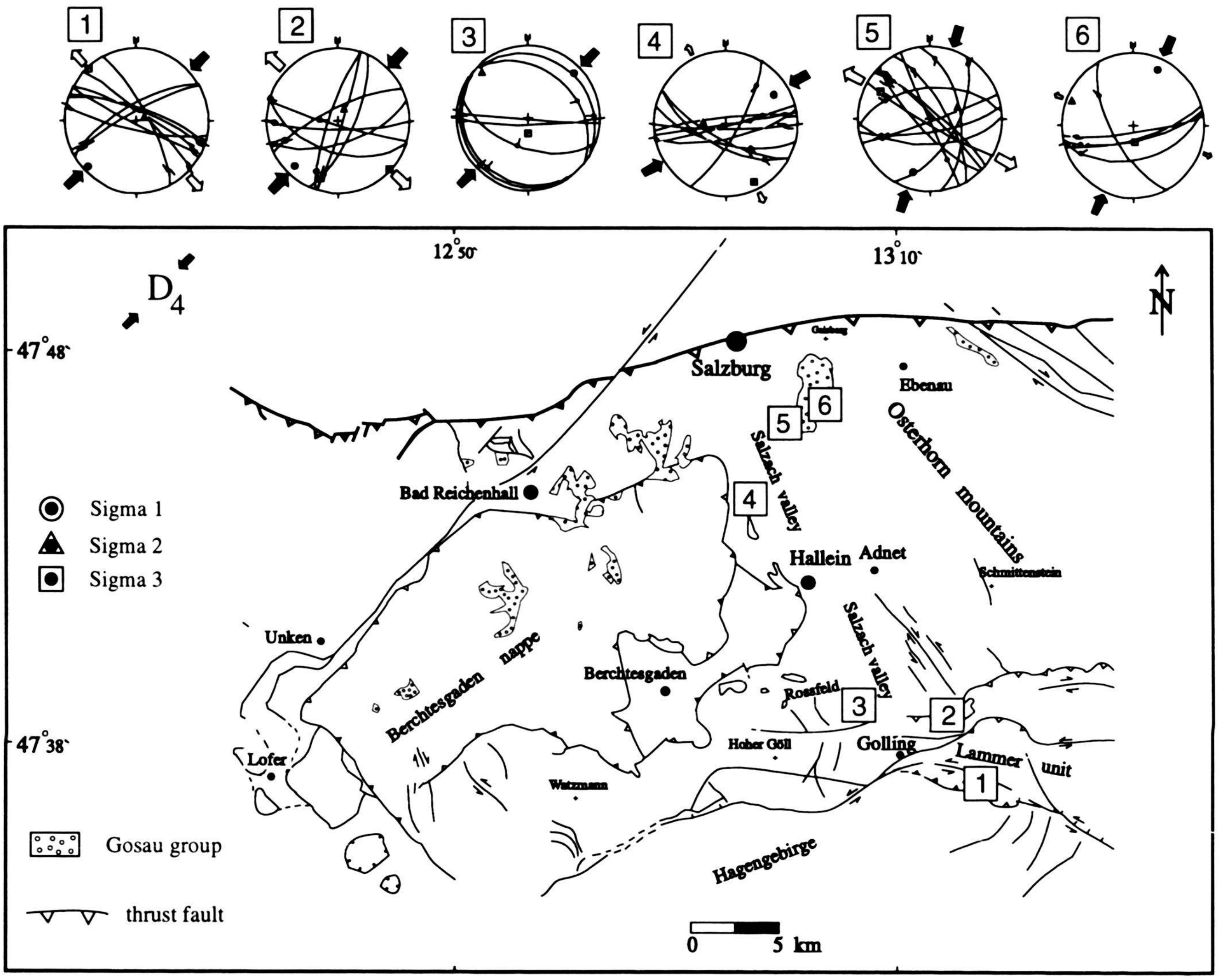

Fig. 14. Schmidt plots with faults and orientation of principal stress axes calculated by the right-dihedra method: a) The stress field of D_4 deformation is characterized by strike-slip, dip-slip and thrust faults while b) D_5 deformation presents strike slip and thrust faults.

Deformation stage D_4: This deformation, with NE-SW contractional structures, is characterized by newly formed or reactivated strike-slip faults with fibrous slickensides (Fig. 14a, Tab. 1). Orientations of σ_1 trend subhorizontally NE, and the orientation of σ_3 is subvertical, resp. NW trending. Dip-slip faults of the D_3 event were reactivated as strike-slip faults. E of Ebenau and in the Lammer unit some small-scale top to the NE thrusts occur. Thrusts with ramp-flat geometries top to the SW can be observed within Oberalm, Dachstein and Wetterstein Formations of the Rossfeld area, the Göll unit and south of Bad Reichenhall.

Deformation stage D_5: The NE-SW contraction (D_4) is overprinted by fault sets indicating NW-SE oriented contraction. σ_1 is NW-SE oriented and σ_3 subvertical to NW-SE (Fig. 14b, Tab. 2). This deformation shows mainly strike-slip faults. Some small-scale thrusts top to the NW occur within Schrambach, Oberalm and Hauptdolomite Formations of the Hallein area and Osterhorn mountains.

Deformation stage D_6: This event includes N-S oriented σ_1 and E-W extension with R ratios around 0.4 (Fig. 15a, Tab. 2). The deformation is generally represented by major E-W to SW-NE striking, sinistral strike-slip faults, i.e. the Königssee–Lammertal–Traunsee and Lofer–Reichenhall faults (Fig. 6). Dip-slip faults occur together with the strike-slip faults. These faults, also present in Eocene sediments of the Gosau Group, fit well into the Miocene N-S contraction and E-W extension formed during lateral extrusion of the Eastern Alps (e.g. Ratschbacher et al. 1991, Decker et al. 1993, 1994). Similar

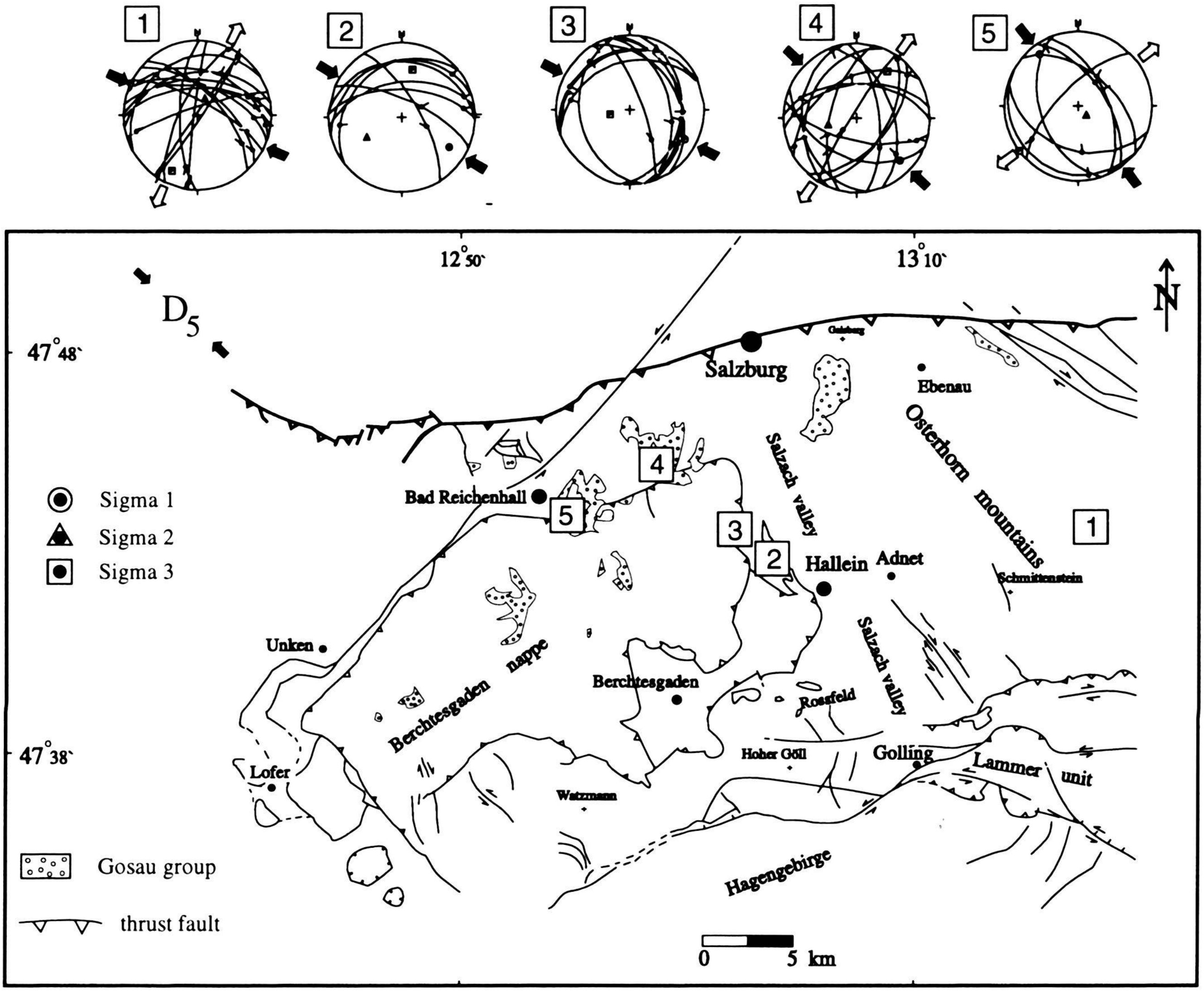

Fig. 14b. For explanation see previous page.

fault patterns are recorded in the Molasse zone (Decker et al. 1993), which forms, therefore, a good time marker. Several fault sets of older deformation events were reactivated by D_6.

Deformation stage D_7: A young E-W contractional event, depicted by σ_1 trending subhorizontally E-W and by σ_3 subhorizontal N-S with R around 0.5 (Tab. 2, Fig. 15b). The D_7 event is evidenced by strike-slip faults, dip-slip faults and N-S oriented mesoscale folds. It overprints the D_6 event. This deformation preferentially reactivated large-scale strike-slip faults of the preceeding N-S contraction, i.e. the Lofer-Reichenhall, the Lammer, the Wolfgangsee and the Königssee–Lammertal–Traunsee faults (Fig. 6). Decker et al. (1993) put this E-W contraction in the Late Miocene because it affected the Oligocene Molasse of the western Eastern Alps and it postdates the lateral extrusion. Similar young E-W compressional events, reactivating major strike-slip faults (e.g. Salzach–Enns–Mariazell–Puchberg (SEMP fault) have been reported from the eastern part of the NCA (Nemes 1995).

Deformation stage D_8: This deformation displays σ_1 subvertical and σ_3 subhorizontal N-S (Fig. 16). It is documented by dip slip faults and probably by some E-W trending extensional joints which we relate to the D_3 event. The relative age is quite clear because these dip-slip faults overprint strike-slip faults of the D_7 deformation in the Lammer unit and southeastern Osterhorn mountains, and because they cut about N trending dip-slip faults formed during the D_3 deformation northeast of Golling (Fig. 16).

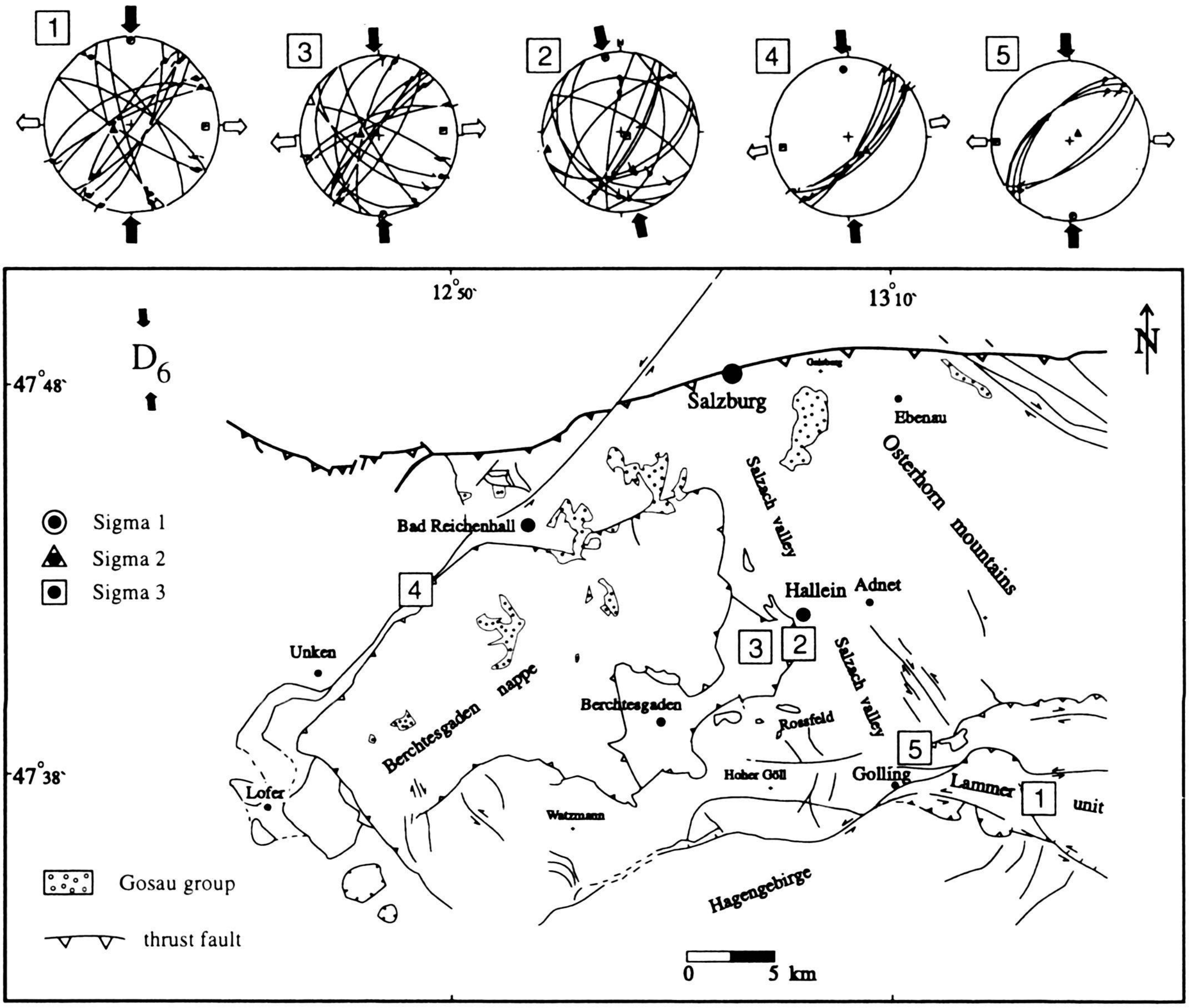

Fig. 15. Schmidt plots with faults and orientation of principal stress axes calculated by the right-dihedra method: a) Strike-slip, thrust and dip-slip faults dominate D_6 deformation, while b) D_7 is characterized by strike-slip and thrust-faults.

Discussion

The analysis of the main geological features and structures of the central sectors within the NCA reveals evidence that makes it necessary to change some geodynamic concepts. The most important difference to previous interpretations is that final thrusting of the Juvavic nappes onto the Tirolic nappe complex postdates deposition and predates subsequent deformation of Neocomian formations. Only small slices of Juvavic material have been transported by olistostromes into Tirolic basins from Middle to Late Jurassic. Therefore, the present nappe structure of the central NCA cannot be related to Jurassic gravitational emplacement of olistostromes preserved within Late Jurassic marly sediments of the Tirolic nappe complex as suggested before (e.g. Tollmann 1981, 1987). This is well proved by the the tectonic superposition of Lower Juvavic slices over the Neocomian Rossfeld syncline (Fig. 6, 8). Another important proof are strata-parallel fibrous slickensides in the underlying Neocomian sediments of the Rossfeld-Berchtesgaden area, that indicate a top to NNE to NE thrust direction (Tab. 1). A key feature is presented by the tectonic arrangement of major units in Figure 7: The Upper Juvavic Berchtesgaden nappe lies over the Lower Juvavic Hallein nappe and both over the Tirolic nappe and the thrust contacts were sealed by Gosau sediments. This implies an original

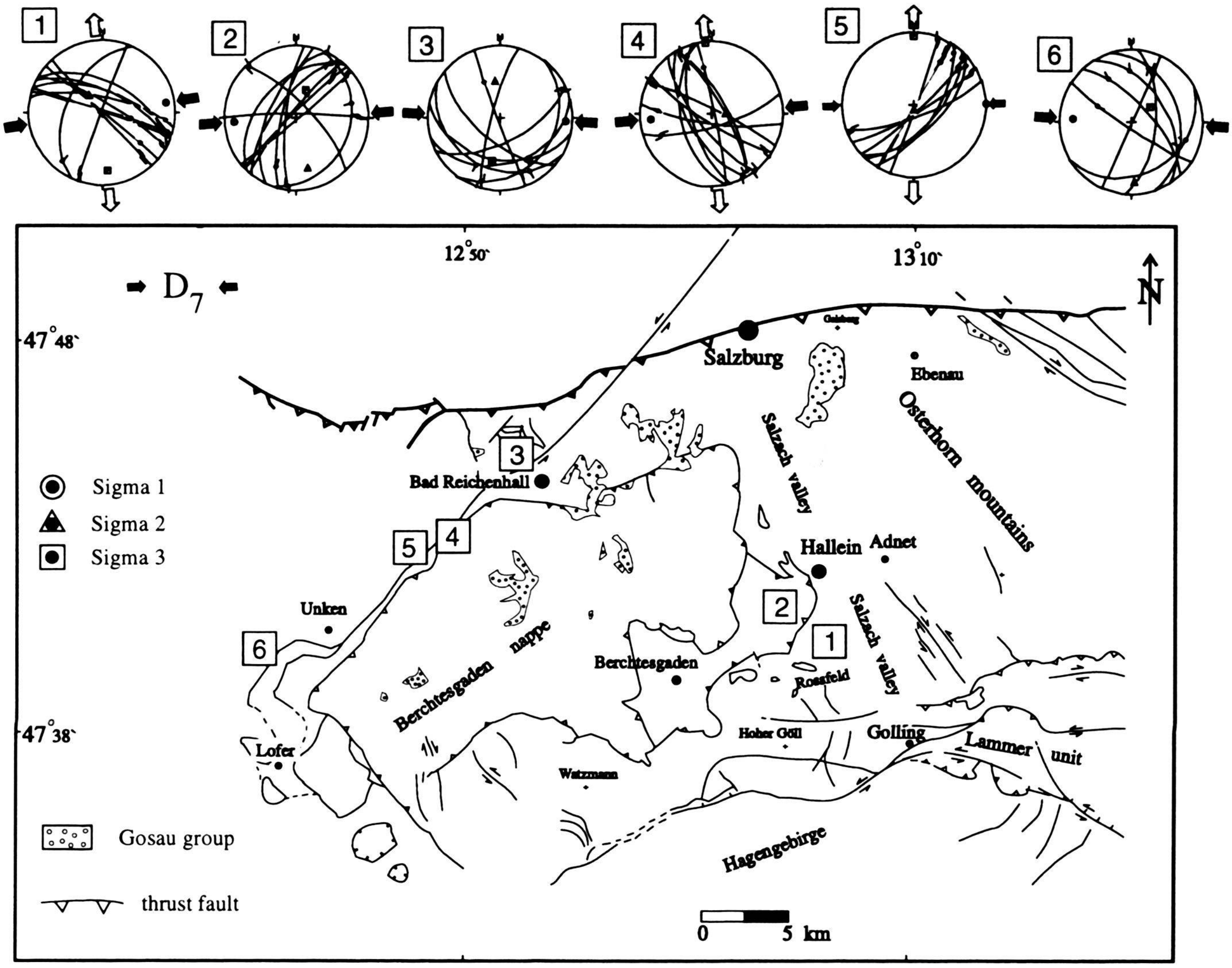

Fig. 15b. For explanation see previous page.

paleogeographic position, where the Tirolic nappe is situated in the North, the Lower Juvavic nappe in the middle and the Upper Juvavic nappe in the South (see Fig. 5a, b). These relationships indicate that the entire nappe structure of the Juvavic nappe complex (with Lower and Upper Juvavic nappes), except some Juvavic slices within the Lammer unit, must be tectonic in origin, and not sedimentary. In the Lammer unit sedimentary slices of Lower Juvavic material occur within olistostromes of the Strubberg and Oberalm Formations (Plöchinger 1955, 1979; Tollmann 1987; Gawlick 1992, 1996). The paleontological and sedimentological proofs for this interpretation are: there are two well-known Lower Juvavic slices (interpreted as olistolithes), the Kellauwand (Hinterkellau) slice, east of Golling and the Sommereck slice in the Lammer valley (Fig. 2). The first one is in a sedimentary contact with the surrounding Upper Jurassic sediments of the Tirolic nappes (Plöchinger 1983). The Sommereck slice shows a sedimentary contact to the underlying Jurassic, Tirolic material and consists of Pötschen limestone (Gawlick 1996). A sliding breccia virtually forms the contact to the underlying Strubberg Formation. Stratigraphical and paleontological data of Gawlick (1992, 1994) showed that the Gollinger Schwarzer Berg complex belongs to the Upper Juvavic nappes. We found only fault contacts between this complex and the surrounding Lower Juvavic and Tirolic sediments. This leads to the idea that the Schwarzer Berg complex was transported by thrusting like the Berchtesgaden nappe. The thrust contacts of the Berchtesgaden nappe to the underlying Tirolic nappes and the nappe itself is sedimentary, discordantly overlain by Gosau sediments (Fig. 6, 7), which means that the thrusting occurred

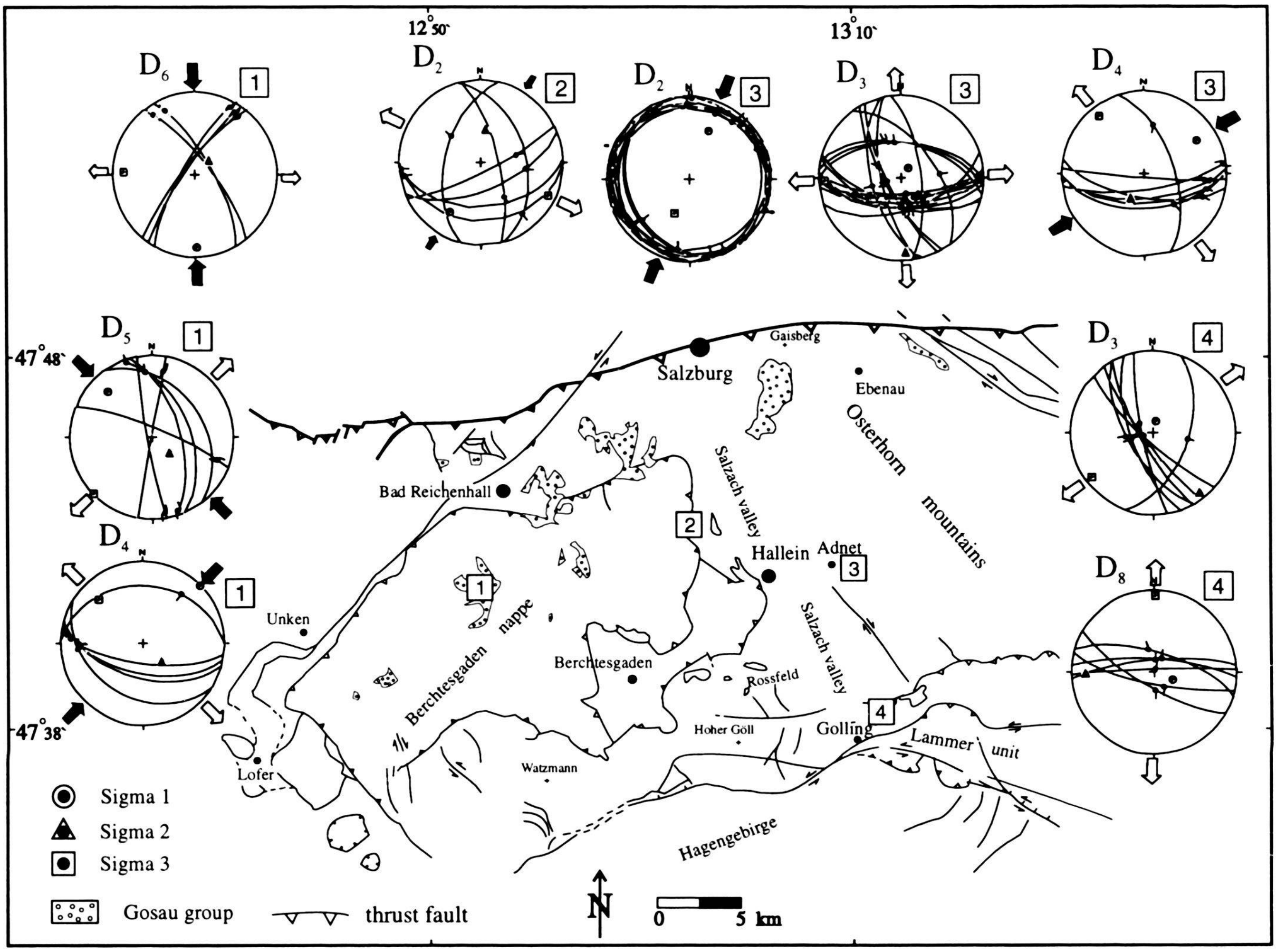

Fig. 16. Plots showing relative chronology of the deformation stages.

before the deposition of the Upper Cretaceous Gosau Group. No strata-parallel fibrous slickensides as in the underlying Tirolic units have been found in Gosau sediments. Rb-Sr and K-Ar ages of Permo-Scythian slates in the southern part of the central NCA between 103 and 141 Ma are interpreted by Kralik et al. (1987) as the result of heat transport due to long lasting crustal thinning combined with incipient thrusting at the Jurassic-Cretaceous boundary.

Our conclusion is that Upper Juvavic nappes and the Lower Juvavic nappes west of the Salzach valley were thrust over the Tirolic nappes. Most of the Lower Juvavic nappes and slices east of the Salzach valley were transported over Tirolic nappes by sedimentary processes sensu Tollmann (1987) and others (e.g. Plöchinger 1979) within mass flows (olistostromes). Gawlick (1991, 1992, 1996) demonstrated this for the Strubberg breccia in the Lammer valley and Plöchinger (1983) also found Lower Juvavic material in Oberalm conglomerates.

The NE-SW to NNE-SSW-oriented shortening occurred before deposition of the Gosau sequence. This contrasts interpretations from other areas where pre-Gosauian shortening is interpreted to have been NW-SE-oriented (e.g. Linzer et al. 1995; Eisbacher & Brandner 1995) and where NNE-SSW shortening postdates Gosau deposition. A Cretaceous, pre-Gosau nappe displacement top to the N to NE also affected the Greywacke Zone, the Gurktal nappe and the Permo-Mesozoic cover of the Middle Austroalpine, postdating a W to WNW-thrusting (Ratschbacher 1986; Neubauer et al. 1987, 1995). In the Plattengneis mylonite of the Middle Austroalpine Koralm unit early Late Cretaceous structures also show a thrusting top to the NNE (Frank 1987).

Our D_3-extension phase is most likely syn-Gosauian because it also affects basal Gosau beds. This is in line with models of an extensional formation of Gosau basins in a transtensional regime (e.g. Wagreich 1993, 1995). Post-Gosau defor-

Tab. 3. Summary of deformation event within the NCA worked out by different authors.

	Western NCA	Central NCA				Eastern NCA
Time	**Deformation phases after Channel et al. 1992; Eisbacher & Brandner 1995,**	**Deformation phases after Tollmann (1976, 1987), Plöchinger (1980, 1995)**	**Deformation phases after Ratschbacher et al. 1991, Linzer et al. 1995**	**Deformation phases after Decker et al. 1993, 1994**	**Deformation phases after Schweigl & Neubauer (this paper)**	**Deformation phases after Nemes et al. 1995**
Liassic	extension, scarp faults	extension, breccias			D_1: about N-S extension, breccias	
Dogger to Lower Cretaceous		sliding tectonics of the Juvavic nappes				
mid-Cretaceous	WNW-NW directed thrusting together with folding	thrust nappe formation, thrusting of Tirolic nappes over Bajuvaric nappes		D_1: σ_1 E-W, σ_3 subvertical; thrusting	D_2: N to NE thrusting of Juvavic nappes; σ_1 NNE-SSW, σ_3 subvertical	
Late Cretaceous	continuation of mid-Cretaceous deformation	continuation of mid-Cretaceous deformation	NW-directed thrusting and nappe stacking	continuation of mid-Cretaceous deformation		D_1: NW-directed nappe stacking; σ_1 NW-SE, σ_3 subvertical
Eocene	NNE-SSW contraction; strike slip, reverse faulting	thrusting of the NCA over the Helvetic and Flysch nappes	continuation of Late-Cretaceous deformation	D_2: σ_1 N-S, σ_3 subvertical; thrusting, folding	D_3: σ_1 subvertical, σ_3 E-W and N-S; extension	D_2: σ_1 N-S, σ_3 vertical or subhorizontal; thrusting and strike-slip faulting
Oligocene	NNW-SSE contraction; folding, thrusting				D_4: σ_1 NE-SW, σ_3 mostly subhorizontal NW-SE; D_5: NW-SE contraction	D_3: NE-SW compression; thrusting and faulting
Miocene	continuation of Oligocene NNW-SSE contraction	a) Further folding and imbrication of the NCA, thrusting over the Molasse b) NW-SE and NE-SW trending faults	a) NW directed thrusting; b) N-S contraction c) NE-directed extension d) clockwise rotation of the NCA	D_3: σ_1 N-S, σ_3 subvertical; D_4: σ_1 subvertical, σ_3 E-W; extension D_5: σ_1 E-W, σ_3 N-S;	D_6: σ_1 N-S, σ_3 trending E-W; D_7: σ_1 E-W, σ_3 N-S; both D6 and D7 show thrusts, strike slip faults, folds	D_4: E-W contraction, σ_3 N-S; strike slip and thrust faults
post-Miocene		continuation of Late Miocene faulting		D_6: σ_1 subvertical, σ_3 N-S; extension	D_8: σ_1 subvertical, σ_3 about N-S;	D_5: NW-SE compression; D_6: N-S directed extension

mation is interpreted as the final piggy-back emplacement of the NCA onto the European lithosphere. The emplacement is polyphase, too, and records changing deformation directions due to partitioning into orthogonal shortening relatively to the foreland, and orogen-parallel lateral transfer of the Central Alps towards the east (e.g. Ratschbacher et al. 1991).

Comparing these results with structural results of Ratschbacher et al. (1991), Decker et al. (1993, 1994) and Linzer et al. (1995), there are some differences (Tab. 3): the first event, early Jurassic extension (D_1), is not described in all three papers, but it is well known (e.g., Channel et al. 1992, Böhm et al. 1995). The second deformation corresponds neither to the second event (thrusting related N-S directed contraction) of Decker et al. (1993) nor to the NW thrusting in the western NCA (Eisbacher & Brandner 1995). The third and fourth deformation events (D_3, D_4) are not separately described in previous works. The post-Gosauian NW-SE contraction (D_5) is well documented by late Early Cretaceous to late Eocene NW-directed, dextral-transpressional stacking of nappes, described by Ratschbacher et al. (1991) and Linzer et al. (1995). N-S contraction (D_6) fits well with the third event (σ_1 subhorizontal N-S, σ_3 subhorizontal E-W) of Decker et al. (1993), but also with Miocene sinistral displacement along ENE to NNE trending strike-slip faults with offsets up to 15 km (Ratschbacher et al. 1991; Linzer et al. 1995). The deformation stage D_7 can be correlated with the fifth tectonic event (σ_1 subhorizontal E-W, σ_3 subhorizontal N-S) described by Decker et al. (1993).

The sense of movement along the Lammer fault (Fig. 6) contrasts with interpretations given by Linzer et al. (1995). Paleostress data of slickensides and Riedl planes of three outcrops along the ESE-WNW trending Lammer fault indicate not only a dextral but also an older and younger sinistral shear. This result is in line with the work of Fischer (1969), who postulated 30 km sinistral displacement of the Norian barrier reef (exposed within Upper Juvavic nappes) along the Lammer fault.

Because of missing basement sequences we suggest an origin of the Juvavic units of the NCA to the south of the present exposure of the Tirolic nappes. Possible origins could be within the eastern Southern Alps in Slovenia, where similar Juvavic units are in normal, sedimentary contact with a basement. On the other hand, the sediments of the Tirolic unit are connected with a basement, the uppermost portion of the Greywacke Zone exposed to the south of the NCA. The Juvavic units do not contain a basement on which these Permian to Triassic units were deposited. We assume that the Juvavic units were detached from their basement during late Lower Cretaceous decollement. Following evidence from the literature, Cretaceous nappe transport of the NCA was first towards NW (Ratschbacher 1986; Ratschbacher & Neubauer 1989; Ratschbacher et al. 1991; Linzer et al. 1995) and later directed towards NNE (Eisbacher & Brandner 1995). We did not find evidence for a NW-directed nappe transport in the Cretaceous.

Concerning the origin of tectonic elements exposed in the central NCA the following model is proposed: In the Triassic the Meliata/Hallstatt ocean (with Hallstatt and Meliata stratigraphic elements) separated the Upper Juvavic continental margin in the south from the Tirolic continental margin in the north (Fig. 5a). In the earliest Jurassic the Piemontais ocean opened and caused further tectonic instability. The Triassic carbonate platforms were destroyed, scarp faults (Channel et al. 1992) and Neptunian dykes (D_1) developed. The formation of basins within the Tirolic unit began, e.g. the Lammer through. During Middle/Late Jurassic the Hallstatt/Meliata ocean was closed and a major part of the Lower Juvavic material was subducted or incorporated in an accretionary wedge (Fig. 5b).

From Middle to Late Jurassic the former accretionary wedge was uplifted and moved northwards. So we can find Lower Juvavic and Meliata detritus in the Strubberg breccias and Lower Juvavic material in Oberalm and conglomerates (e.g. Plöchinger 1979; Gawlick 1992). Even Lower Juvavic nappes were tansported by submarine gravity flows into the Tirolic basins, e.g. Sommereck and Kellauwand slices. Gawlick (1992) found also some Upper Juvavic material in Strubberg breccias of Middle to Late Jurassic age. From the Lowermost Cretaceous onwards siliciclastic detritus arrived in the peripheral foreland basin. Volcaniclastic material in the Rossfeld formation indicates simultaneous volcanic arc activity in the hinterland (Schweigl & Neubauer 1997). During late Early and early Late Cretaceous the sediments (Tirolic units) were folded and overthrusted by the remaining Lower Juvavic nappes and the Upper Juvavic nappes.

The Gosau basins developed (D_3) in a transpressional regime (Wagreich 1995) and Gosau sediments transgressed the already assembled Tirolic and Upper Juvavic nappe complexes. NE-SW contraction (D_4) may relate to late Cretaceous sinistral shear along ENE trending ductile shear zones in the central Austroalpine areas as recorded by Neubauer et al. (1995). The final closure of the Piemontais through during late Eocene caused a NW-SE (D_5) contraction (Ring et al. 1989). Afterwards the deformation events D_6 and D_7 affected the central part of the NCA. The N-S contraction (D_6) corresponds to the lateral extrusion of the Eastern Alps (e.g. Ratschbacher et al. 1991). Decker et al. (1993) tentatively interpreted the E-W contraction (D_7) as a result of Africa's motion relative to Europe to the NW during Late Miocene.

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