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ORIGINAL PAPER

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Growing folds and sedimentation of the Gosau Group, Muttekopf, Northern Calcareous Alps, Austria

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Abstract Analysis of the three-dimensional geometry of Upper Cretaceous clastics in the Muttekopf area (Northern Calcareous Alps, Austria) indicate fold and fault structures active during deposition. Coniacian continental to neritic sedimentation (Lower Gosau Subgroup) was contemporaneous with displacements on NW-trending faults and minor folding along NE-trending axes. From the Santonian onwards (sedimentation of the deep-marine Upper Gosau Subgroup) the NW-trending faults were sealed and large folds with WSW-trending axes developed. The direction of contraction changed to N–S after the end of Gosau deposition in the Danian (Paleocene). Synorogenic sedimentation patterns indicate continuous contraction from the Coniacian to the Late Maastrichtian/?Danian. Therefore, large-scale extension as observed in the central part of the Eastern Alps cannot be documented in the western parts of the Northern Calcareous Alps. A combination of subduction tectonic erosion for the frontal parts and gravitational adjustment of an unstable orogen after nappe stacking for the internal parts possibly accounts for the different development of Gosau basins in the frontal and trailing regions of the Austroalpine wedge.

Keywords Synorogenic sedimentation · Progressive unconformities · Upper Cretaceous · Deformational history · Northern Calcareous Alps

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Introduction

Synorogenic sedimentary successions deposited in fold and thrust belts record the growth of large-scale structures. Several studies, especially in the Spanish Pyrenees, defined the geometries of growth strata deposited on top of evolving anticline–syncline pairs, and clarified their relationship to the regional thrust geometry (Fig. 1; Riba 1976; Anadon et al. 1986; Deramond et al. 1993; Ford et al. 1997; Hardy and Ford 1997; Suppe et al. 1997). Progressive unconformities in synorogenic sediments record the time of structural activity during periods of active folding. Thus the growth of the large anticline–syncline systems in the fold and thrust belt of the Pyrenees has been reconstructed (see Puigdefabegras and Souquet 1986; Puigdefabegras et al. 1992; Meigs 1997).

In this study, the three-dimensional geometry of Upper Cretaceous clastics in the Muttekopf area has been established by mapping at a scale of 1:10,000 (Ortner 1990; Haas 1991); marker beds were traced on aerial photographs (scale approximately 1:5,000). Unconformities within the Upper Cretaceous succession have been related to distinct phases of folding, and as newly deposited sediments have been involved in ongoing shortening, changing directions of shortening are documented. Changing directions of contraction are also documented using small-scale brittle structures.

Geological setting

Upper Cretaceous/Lower Tertiary sediments that rest on top of the Austroalpine orogenic wedge in general are termed Gosau Group and are divided into two subgroups (Faupl et al. 1987; Wagreich and Faupl 1994): (1) Turonian to Lower Campanian terrestrial to deep neritic sediments of the Lower Gosau Subgroup,

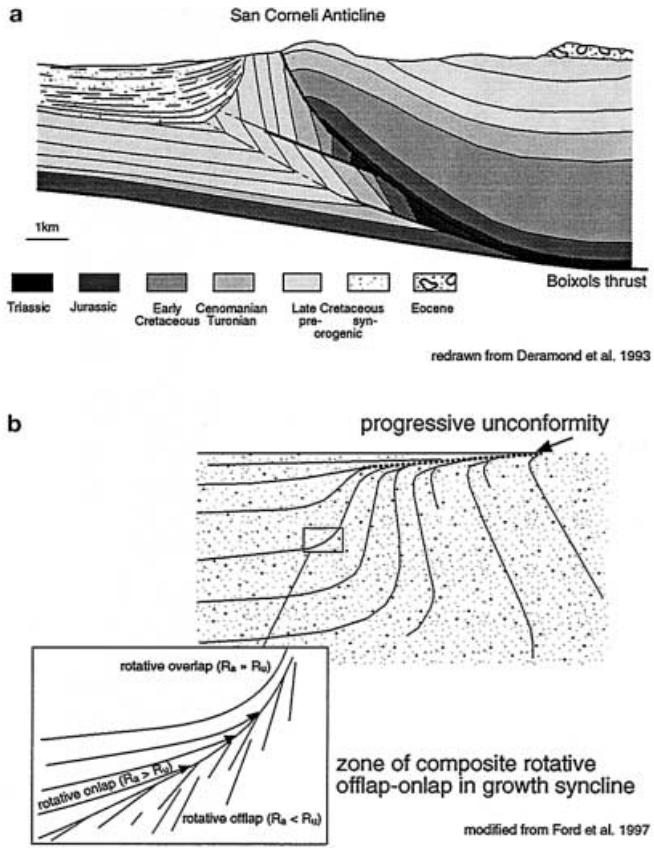

Fig. 1 **a** Example of an anticline–syncline system with synkinematic sediments. Progressive unconformities in the sedimentary wedge relate to the activity of the thrusts in the core of the anticline. **b** Nomenclature of unconformities found in synkinematic sediments. *Ra* Rate of deposition, *Ru* rate of uplift due to folding

and (2) Upper Santonian (in the western Northern Calcareous Alps) to Santonian–Maastrichtian (in the eastern Northern Calcareous Alps) turbiditic successions and mass flow breccias of the bathyal to locally abyssal realms of the Upper Gosau Subgroup, deposited on an approximately north-dipping slope towards the contemporaneous Flysch basin in the north.

Contractional deformation in the Northern Calcareous Alps (NCA) started in the latest Jurassic to Early Cretaceous, when the Austroalpine deposition domains evolved from a passive continental margin setting to an active margin setting (Channell et al. 1992a; Wagreich and Faupl 1994). After a first (pre-Gosau) deformational event, thin-skinned sedimentary cover nappes of the Northern Calcareous Alps formed a W–NW-vergent stack of nappes. While frontal units of the Austroalpine experienced continued Late Cretaceous contraction, internal units were exhumed and uplifted (Ratschbacher et al. 1989; Eisbacher et al. 1990; Froitzheim et al. 1994, 1997; Fügenschuh 1995; Neubauer et al. 1995). With some exceptions regional-scale structures sealed by Late Cretaceous Gosau deposits are NW- or NE-verging (Ortner 1994; Eisbacher and Brandner 1996; Schweigl and Neubauer 1997; Ortner and Reiter 1999), whereas structures overprinting Gosau deposits are N–NNE-directed (e.g., Eisbacher and Brandner 1996; May and Eisbacher 1999). The change in structural vergence is also accompanied by rotational movements of the Northern Calcareous Alps around vertical axes, indicated by diverging Jurassic to Cretaceous paleopoles in the Northern Calcareous Alps (Mauritsch and Becke 1987; Channell et al. 1992a), the Southern Alps and the Middle Austroalpine units (Förster et al. 1975; Channell et al. 1992b). However, it is not yet clear when the direction of contraction changed in the Northern Calcareous Alps.

Upper Cretaceous synorogenic succession of the Muttekopf area

Upper Cretaceous clastic sedimentary rocks in the Muttekopf area rest on the Upper Triassic Hauptdolomit Formation of the Inntal Nappe, one of the thrust sheets of the NCA, which in turn overlies the Lechtal Nappe (Fig. 2). The Muttekopf Gosau deposits are preserved in the core of the large WSW–ENE-trending Muttekopf–Sinnesbrunn syncline (Niederbacher 1982), which displays a south-dipping northern limb, and a vertical to northerly overturned southern limb. The southern limb is cut by a thrust fault that locally also forms the southern limit of the Gosau Group outcrop (Fig. 2, locality 8).

Sedimentation of the Lower Gosau Subgroup in the Muttekopf area began in Coniacian time with deposition of conglomerates in a braided river system and a superimposed alluvial fan, documented by up to 300-m-thick breccias and conglomerates (Haas 1991; Ortner 1994). Thick alluvial fan deposits are restricted to the easternmost part of the Gosau outcrops (Platteinwiesen of Fig. 2). The alluvial fan deposits are overlain by a thin unit of conglomerates with well-rounded clasts, interpreted as a transgressive lag at the base of the overlying "*Inoceramus* marl unit" (Haas 1991). Conglomerates resting unconformably on the Hauptdolomit Formation are widespread at the base of the Gosau deposits and possibly are related to a relative sea level rise. The silt- to sandstones of the "*Inoceramus* marl unit" contain a variety of marine fossils (including *Cladoceramus undulatoplicatus*), that are of Early Santonian age (Ampferer 1912; Leiss 1988, 1990).

The Upper Gosau Subgroup rests unconformably on the "*Inoceramus* marl unit" and consists of marls, sandstones, breccias, and conglomerates. Turbiditic deep-water deposits (below CCD, Ortner 1994) are organized in three fining upward megacycles up to about 300 m thick. Each megacycle is composed of three turbidite facies associations:

1. In the megabreccia association a thick megaturbidite (Johns et al. 1981) forms the base of the proximal part of the megacycles.

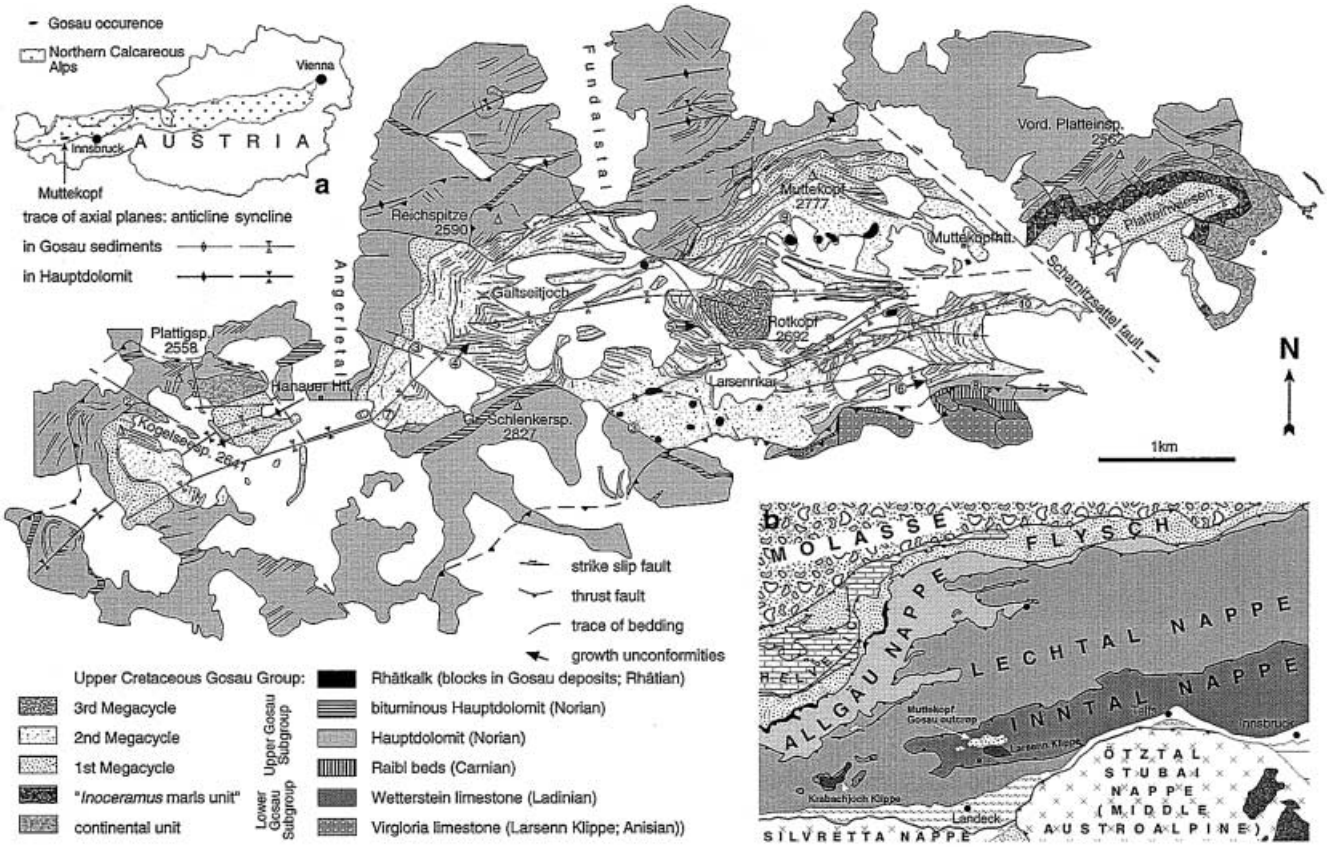

Fig. 2 Geological sketch of the Muttekopf area. *Numbers in circles* indicate localities referred to in text. *Inset a* Position of the investigated area in the Northern Calcareous Alps, *inset b* tectonic units in the vicinity of the investigated area. Krabachjoch Klippe and Larsenn Klippe form the Krabachjoch nappe unit

2. In the thick-bedded turbidite association sandstone beds up to 40 cm thick with full or incomplete Bouma sequences alternate with thick turbiditic marls (up to 15 m). In many cases conglomerate or breccia layers grade into the sandstone beds.
3. In the thin-bedded turbidite association sandstone beds up to 10 cm thick with Bouma Tb or Tc intervals alternate with dark, laminated marls, that are up to 30 cm thick. Thick breccia beds are intercalated with the marls and sandstones.

The lithofacies associations grade into each other, but each megacycle has different heavy mineral and clast associations, and shows different sediment transport directions (Ortner 1990, 1994).

The age of the deposits of the Upper Gosau Subgroup in the Muttekopf area is poorly constrained. The turbiditic marls locally contain corroded nannoplankton and rare foraminifera. The onset of deep-water sedimentation was dated with microfossils by Dietrich and Franz (1976) as late Santonian. Two recently collected nannofossil samples from the lower and upper part of the first megacycle yielded an age of CC17 (*Micula decussata*, *Lucianorhabdus cayeuxii*, *Lucianorhabdus cayeuxii* ssp. B, *Calculites obscurus*, *Lithastrinus grilli*; Late Santonian to Earliest Campanian) or younger. The base of the second megacycle has an age of Early Campanian to Early Maastrichtian (CC18) or younger, whereas the upper part of the second megacycle has an age of Late Campanian to Early Maastrichtian (CC21–23a; *Broinsonia parca*, *Arkhangelskiella cymbiformis*; M. Wagreich, personal communication, 1993–1995). The third megacycle was dated by planktonic foraminifera into the Late Maastrichtian to Danian (Oberhauser 1963) and by nannoplankton as Late Maastrichtian (Lahodinsky 1988).

Geometry of the Gosau Group

Structures sealed by Gosau Group sediments

The analysis of structures in the Hauptdolomit Formation sealed below Gosau sediments shows that the approximately WSW–ENE-trending fold axis of the Muttekopf–Sinnesbrunn syncline in the Hauptdolomit varies considerably in plunge. North of the Muttekopf area, approximately N–S-trending fold axes in the limbs of the syncline can be reconstructed upon back rotation of the Gosau beds into a horizontal position (Fig. 8). N–S-oriented fold axes predate formation of the Muttekopf–Sinnesbrunn syncline.

Thick deposits of the Lower Gosau Subgroup are restricted to the eastern part of outcrop. The NW-

trending Scharnitzsattel fault (Fig. 2) forms the border of the thick succession of the Lower Gosau Subgroup to the west. The lateral offset across the fault documented by an offset bituminous marker bed of the Hauptdolomit Formation (Fig. 2) is 1.6 km. However, there must have been an additional vertical component that lowered the northeastern block and accounts for the different thicknesses of the Lower Gosau Subgroup on both sides of the fault. A growth triangle occurs along a fault parallel to the Scharnitzsattel fault in the alluvial fan and *Inoceramus* marl deposits SSW of the Vordere Platteinspitze (locality 1 of Fig. 2). As the strata in this area dip subvertically, the map view serves as a cross section. Another conglomerate wedge in the alluvial fan facies was deposited along an active NW-trending fault northeast of the Kogelseespitze (locality 2 of Fig. 2). This suggests that NW-trending faults were active in the Early Santonian or earlier, synchronous with sedimentation of the Lower Gosau Subgroup in the Muttekopf area.

West of the Scharnitzsattel fault, the Lower Gosau Subgroup is restricted to the core and the northern limb of the syncline, while on the southern limb of the syncline it is absent due to onlap against the evolving northern limb of an anticline. Such an onlap can be observed south of Plattigspitze (see Fig. 4) and west of the Große Schlenkerspitze (Figs. 2 and 3). On the northern limb of the syncline, an unconformity truncates bedding of the Hauptdolomit Formation and the Lower Gosau Subgroup is parallel to the basal unconformity (Fig. 4). West of the Große Schlenkerspitze, the sediments onlap the northern and southern limb of the syncline and are thus restricted to the core of the syncline (Fig. 3).

The fold axis for the Lower Gosau Subgroup is parallel to fold axes reconstructed for the Hauptdolomit Formation, except that fold axes in the Hauptdolomite plunge more steeply to the west or east, because of earlier folding along N–S axes.

Relationship between Upper Gosau Subgroup and underlying sequences

In the Platteinwiesen area (Fig. 2), the Upper Gosau Subgroup overlies the Lower Gosau Subgroup conformably. The fold axes constructed for the Lower and Upper Gosau Subgroup in this area are identical and no angular unconformity between the two units can be observed. However, in the western part of the area, an unconformity between the Upper and Lower Gosau Subgroup locally truncates Lower Gosau Subgroup strata on the northern limb of the syncline (Fig. 3, foreground). In other places, onlap on the northern (Fig. 4) and the southern limb is observed (Fig. 3). Since total depositional thickness west of the Scharnitzsattel fault is much smaller, folding there is recorded by unconformities. It is inferred that minor folding during the Early Santonian was continuous.

In most parts of the area Upper Gosau Subgroup directly overlies the Hauptdolomit Formation. In the northern, gently dipping limb of the Muttekopf–Sinnesbrunn syncline, the Upper Gosau Subgroup generally rests on the Hauptdolomit Formation without angular unconformity. In the southern, subvertical limb, the difference in dip angle between Hauptdolomite and Gosau deposits can be up to 90° (e.g., at Larsennkar; Fig. 2), but generally the Gosau sediments onlap the Hauptdolomit Formation with an angular unconformity of about 55° (N of the Große Schlenkerspitze, Fig. 3), of about 30° (W of the Parzinnspitze), and 34° (south of Hinteres Alpjoch, Fig. 5). Thinning of the first and second megacycle towards the south can be interpreted as a rotative onlap onto the northern limb of an evolving anticline.

At the Larsennkar (locality 3 in Fig. 2), subhorizontal megabreccias of the second megacycle overlie subvertical beds of Hauptdolomit. This contact is a progressive unconformity (see Fig. 1 for terminology used to describe growth structures), where the younger strata of the second megacycle overlap and bury the older strata of an evolving anticline. This geometry is also seen in Fig. 3.

In locality 3 of Fig. 2, NW-trending strike-slip faults offset both the Hauptdolomit and the first megacycle, but are not seen within the second megacycle. The fault zone continues southeast of the Große Schlenkerspitze, where the megabreccias of the second megacycle are in sedimentary contact with the Hauptdolomit. Therefore the fault was sealed by sediments of the second megacycle.

Unconformities within the Upper Gosau Subgroup

In the Muttekopf–Sinnesbrunn syncline, the thickness of the Upper Gosau Subgroup in the southern limb is less than in the northern limb. This is both due to onlap of Gosau deposits on Hauptdolomit Formation towards the south and to angular unconformities within the second megacycle.

A well-exposed angular unconformity within the second megacycle is present at the western flank of Galtseitjoch. It disappears on the northern limb of the syncline (locality 4 of Fig. 2; Schlenkerkar unconformity of Fig. 3 and Ortner 1994). The unconformity can be traced 1.5 km to the east, where it is cut by a younger fault (locality 5 in Fig. 2). Near the core of the syncline, sediments below the unconformity are tilted and truncated (rotative offlap). Further towards the steep limb of the syncline, deposits below the unconformity are tilted, onlapped, and overlapped (Fig. 3). The sedimentary units typically have a wedge-shaped geometry due to continuous folding and tilting of subjacent deposits (Fig. 3). The development of the unconformity corresponds to a period when the rate of uplift due to folding was higher than the rate

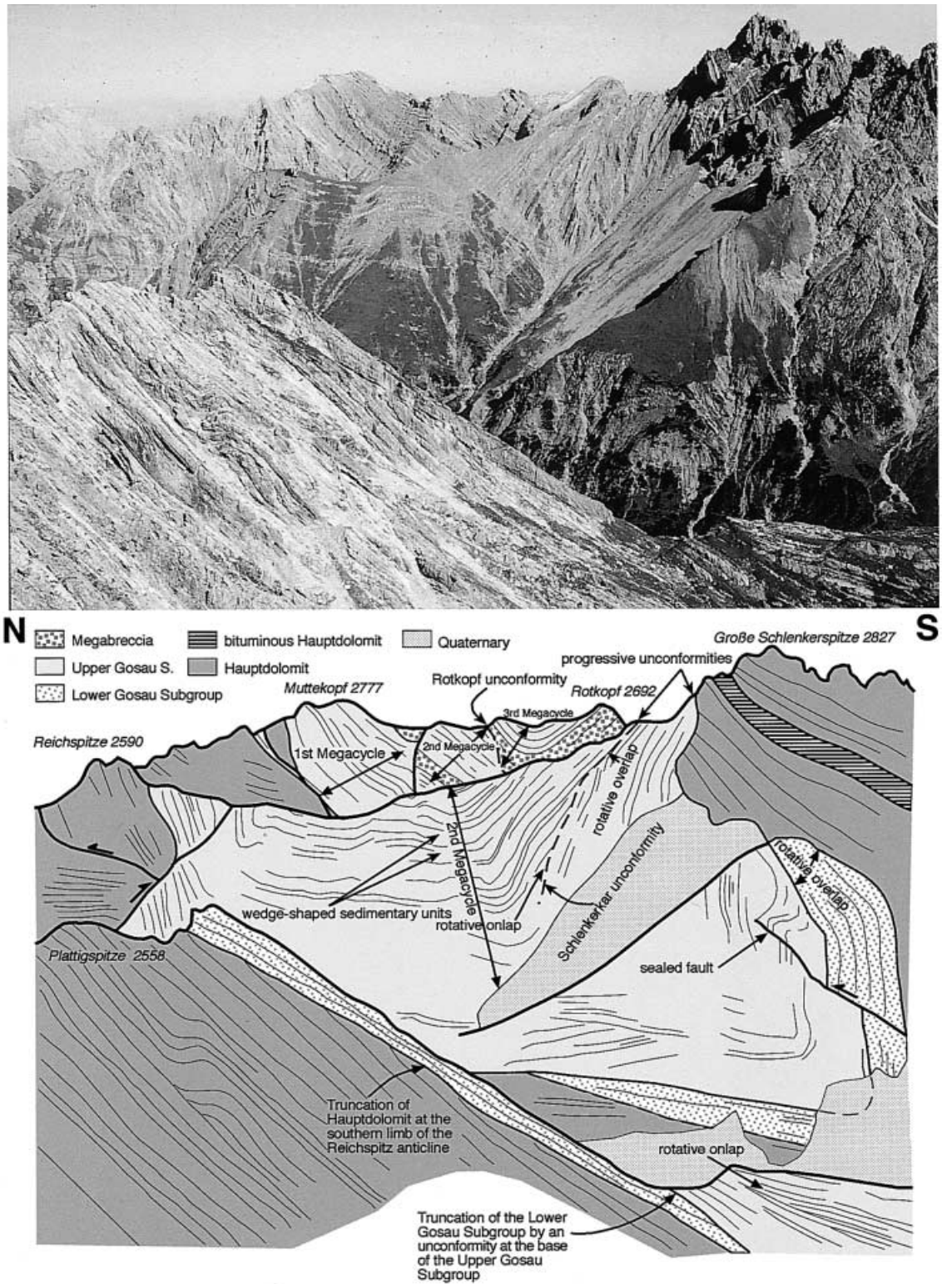

Fig. 3 View from the Kogelseespitze to the east. Progressive unconformities are generally restricted to the southern limb of the syncline; only in the foreground is onlap on the northern limb of the syncline observed

of deposition (Fig. 1). Later the relationship was reversed, with rotative onlap corresponding to an accumulation rate higher than the rate of uplift due to folding; rotative overlap corresponds to an accumulation rate much higher than the rate of uplift due to folding (Fig. 1).

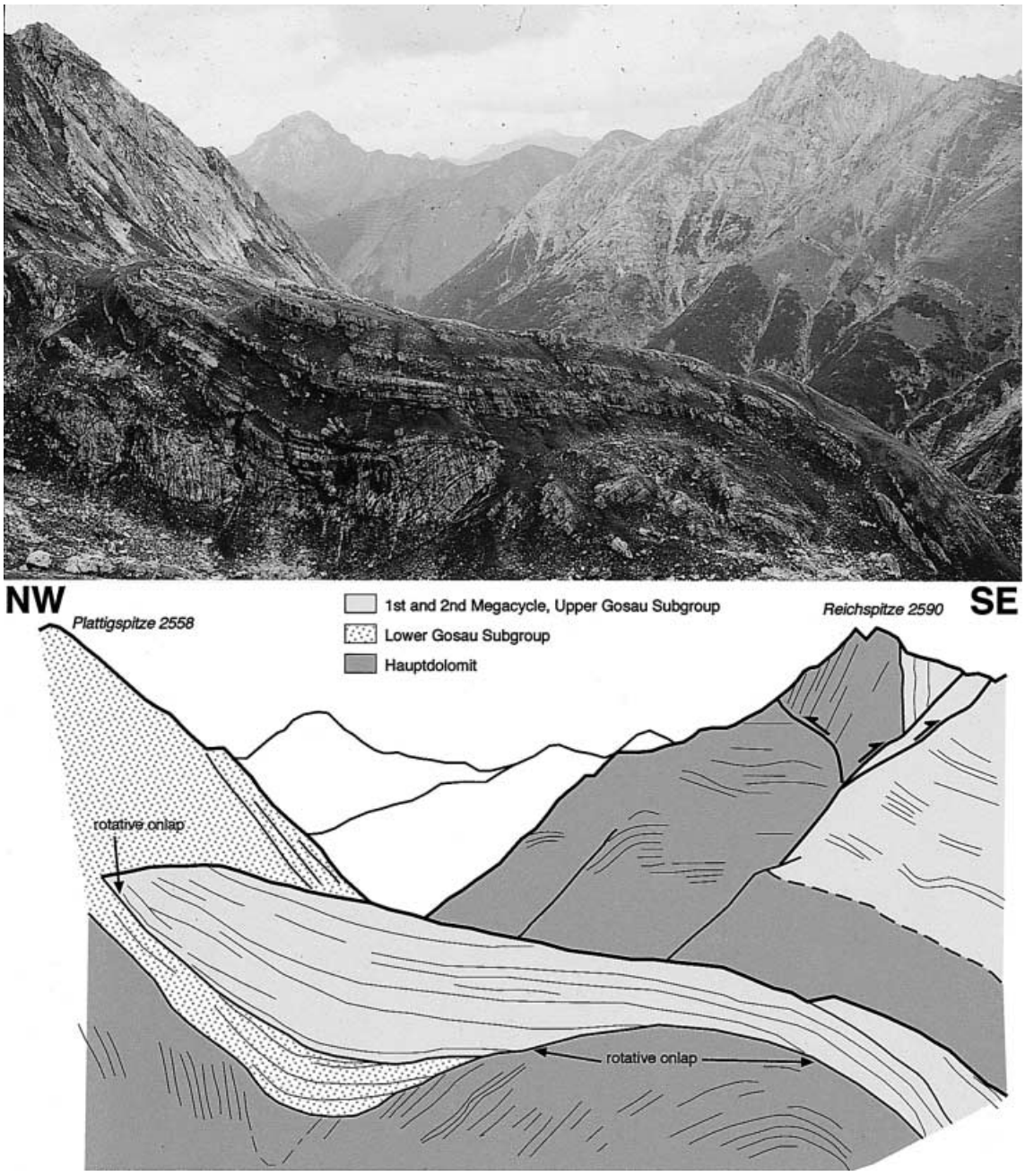

Fig. 4 View from the Kogelseepitze to the northeast. A syncline with NE-trending axis is sealed by deposits of the Lower Gosau Subgroup. The Upper Gosau Subgroup onlaps the southern and northern limb of the syncline

Another progressive unconformity within the second megacycle is found near the southern margin of Gosau deposits south of the Hinteres Alpjoch (locality 6 in Fig. 2 and Fig. 5; Alpjoch unconformity). The unconformity disappears to the west, where the Gosau deposits onlap the Hauptdolomit Formation. It is near a zone of intense folding associated with a thrust fault at the southern margin of the Gosau outcrop (locality 8 of Fig. 2). The top of the intensely folded zone is sealed by Gosau sediments approximately of the same age as those overlying the Schlenkerkar unconformity (Schlenkerkar unconformity of Fig. 5), indicating that folding took place during sedimentation.

Sediments of the third megacycle are separated from the second megacycle by the Rotkopf unconformity (Fig. 6; Wopfner 1954). This unconformity cuts progressively deeper into strata of the second megacycle towards the west. In a N–S transect, the Rotkopf unconformity truncates sediments of the second megacycle that had been tilted to the north, perhaps also due to ongoing folding. A decameter scale and originally north-vergent fold is sealed by breccias of the third megacycle (Fig. 6).

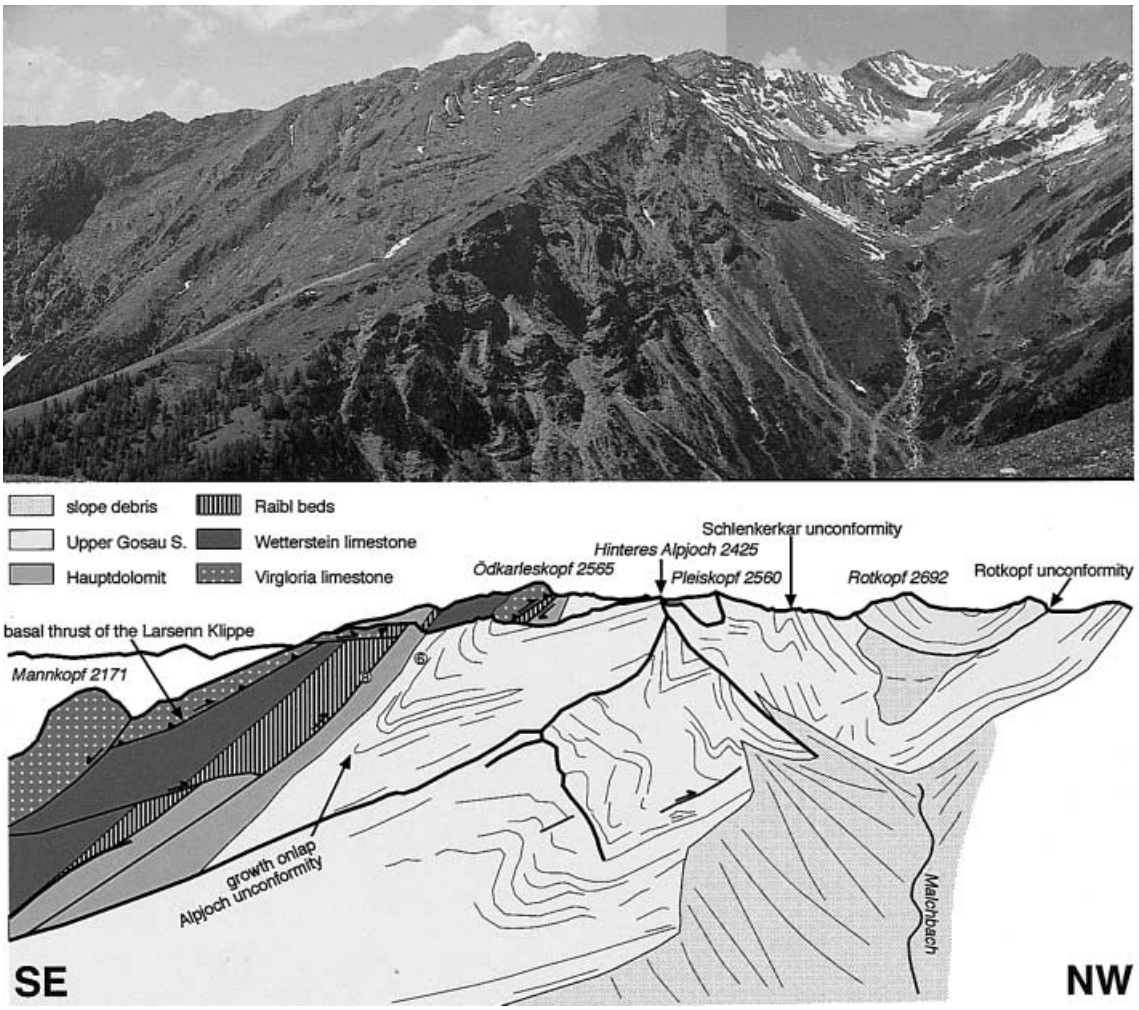

Fig. 5 View from the Platteinwiesen to the west. The Schlenkerkar unconformity has sealed the folded Gosau deposits. The folds in this area formed by bed parallel simple shear connected to displacement along the thrust fault immediately to the south of the Gosau deposits. The Alpjoch unconformity on the southern margin of the Gosau outcrop is related to this thrust fault as well. Activity of the basal thrust of the Larsenn Klippe predates the thrust fault; however, the upright sedimentary series of the Klippe was thrust on overturned rocks of the Inntal Nappe. *Numbers in circles* indicate localities referred to in text and Fig. 2

Fold axes within the Upper Gosau Subgroup

Hectometric folds at the southern margin of the eastern part of the Gosau outcrop in sediments of the first megacycle and in the lower part of the second megacycle all display WSW-trending fold axes with a mean trend of 252° (Fig. 7). The upper part of the second megacycle and the third megacycle display fold axes with a mean trend of 93° (Fig. 7).

Soft sediment deformation

Slumping is common in the Upper Cretaceous succession of the Muttekopf area and ranges from small-scale, asymmetric ball and pillow structures at the base of conglomerate beds to rolls in conglomerates, pinch-and-swell structures and boudinage of coarse clastic beds several meters thick. In thin-bedded sandstone–marl multilayers isoclinal folding and slides associated with small ramp-flat structures were observed. Intensely slumped intervals display chaotic mixtures of disrupted beds with the top and bottom of the slumped interval being flat.

Generally, the axes of slump folds (Wopfner 1954) are parallel to the fold axes of large-scale folds calculated from the same sediment package (Fig. 7). However, slump folds from the upper part of the second and the third megacycle trend more southeasterly than the large-scale fold axes do. The dip of the slope thus deduced ranges from northwest to northeast.

In the intensely folded area along the southern margin of the Gosau outcrop, hectometric NNW-ver-

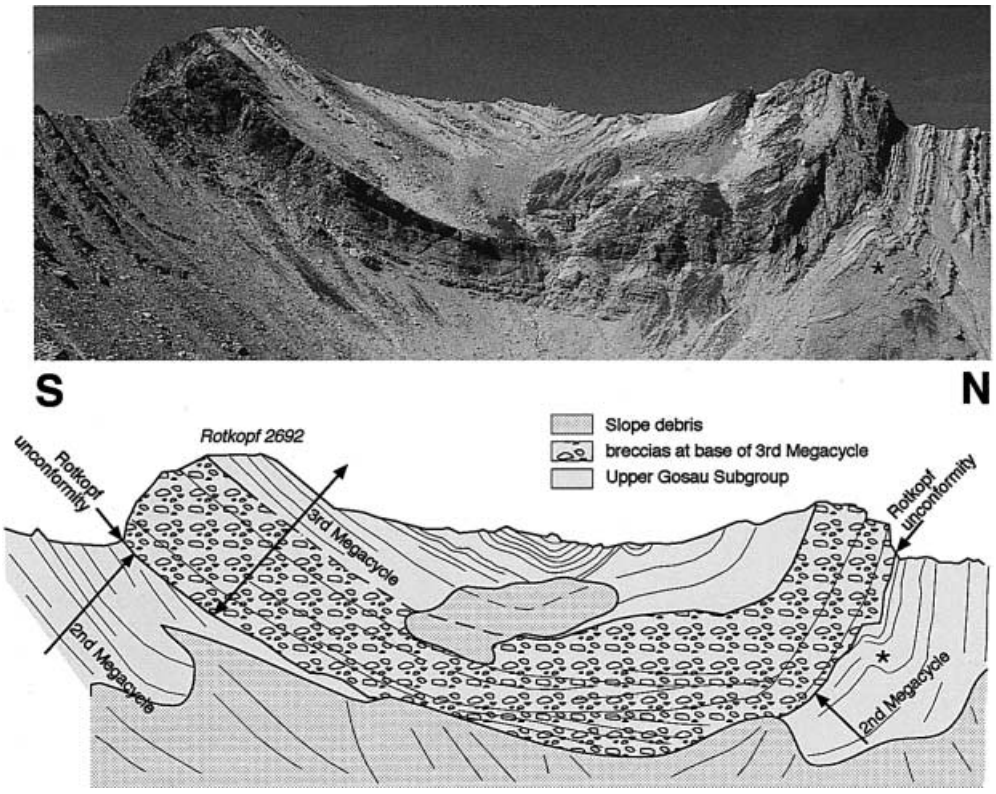

Fig. 6 View of the Rotkopf unconformity from the southeast. Sediments of the second megacycle are truncated after they were tilted to the north. *Star* marks a fold sealed by breccias of the third megacycle

gent folds developed in front of thrust faults (Fig. 5). In both limbs of the folds, conglomerate beds are commonly offset along small NNW-directed thrust faults, which developed from asymmetric ball-and-pillow structures that disappear inside the bed. Metric folds in the gently dipping limbs of the large-scale folds show small thrust faults analogous to the faults described above. In the subvertical limbs of the small-scale folds, subhorizontal thrust faults that offset the bottom of the bed also disappear inside the bed. This indicates top-to-the-NNW layer parallel simple shear associated with folding prior to lithification (locality 8 of Fig. 2 and Fig. 5).

Brittle deformation

Fault planes and lineations related to fault displacements were measured at four stations. Slip sense was deduced from calcite fibers and synthetic Riedel shears (Hancock 1985; Petit 1987). Cross-cutting relationships between faults gave an indication of the relative age for different fault populations. The orientation of the paleostress tensors was calculated using the right dihedra method (Angelier and Mechler 1977).

In the core of the Muttekopf–Sinnesbrunn syncline near Hanauer Hütte (Fig. 2, location 7), brittle deformation developed continuously from soft sediment deformation. Soft sediment deformation along faults is displayed by marls dragged into sandstone or conglomerate beds along faults, and by the absence of calcite fibers and development of shear zones rather than discrete faults. Brittle deformation is characterized by fault planes with calcite fibers. A direction of shortening was calculated from fault data sets measured in the steep southern limb of the syncline, after rotating the beds back from a subvertical position to a dip of 35° to the NNW around the regional fold axis, when the faults reach a conjugated geometry. The fault data sets indicate NNW–SSE-oriented shortening (Fig. 8a). Lineations on the thrust fault along the southern margin of the Gosau outcrop in the Hauptdolomit also indicate top-to-the-NNW movement (Fig. 8d). In the intensely folded area north of the thrust fault, folding is accompanied by extension parallel to the fold axis as documented by ductile shear zones and brittle fault planes (Fig. 8c).

A second stage of deformation is represented by subhorizontal faults cutting the folded sediments of the second megacycle near the locality Muttekopf peak of Fig. 2. Most fault planes display top-to-north movement (Fig. 8b). The Scharnitzsattel fault and parallel faults were reactivated with dextral sense of movement and, near the Scharnitzsattel fault, this deformation was compensated by dextral slip on parallel planes and sinistral slip on conjugated fault planes (Fig. 8c). This N–S compression postdates folding with ENE–WSW fold axes in the Muttekopf area.

During a third stage of deformation, NE–SW compression reactivated older thrusts active during the first brittle deformational event. During this phase, the steep thrust fault along the southern margin of the

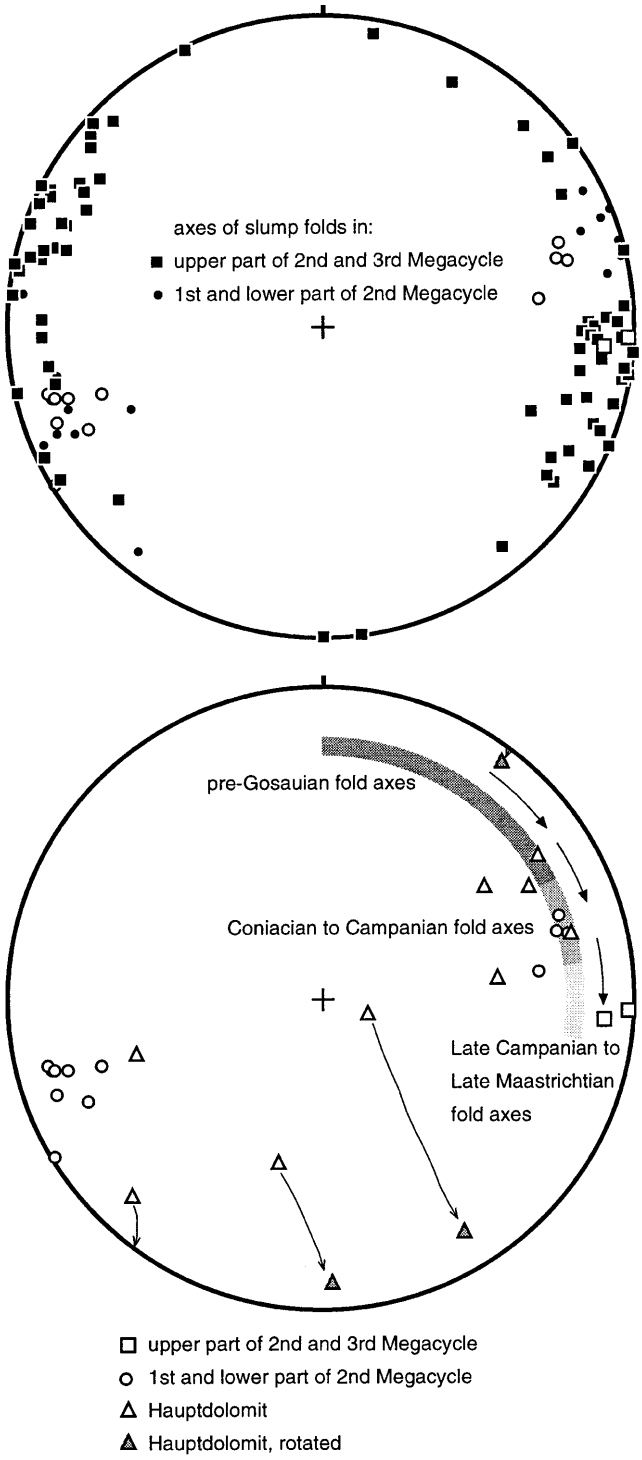

Fig. 7 Fold axes of large-scale folds and slump folds in the investigated area. All slump fold axes were rotated with the bedding planes into a horizontal position around the regional fold axis. Note change in orientation of fold axes in progressively younger sediments

Gosau outcrop was active as a sinistral strike-slip fault (locality 8 of Fig. 2 and Fig. 8d), and minor thrusts in the core of the Muttekopf–Sinnesbrunn syncline display top-to-the-NE movement (Fig. 3; Fig. 8a–c).

Interpretation of the fold growth sequence

The progressive unconformities in the southern limb of the Muttekopf–Sinnesbrunn syncline indicate growth of an anticline to the south of the Gosau outcrop area in late Santonian/Campanian time (Fig. 9b). East of the Schlenkerspitze (Fig. 2), this deformation was compensated by both thrust faulting and folding. A thrust fault along the southern margin of the Gosau deposits (Fig. 2, locality 8; Fig. 5) brought the Larsenn Klippe into the vicinity of the Gosau deposits. The northward tilting of sediments of the second megacycle sealed by the third megacycle could be related to minor growth of the anticline to the south of the Gosau deposits during late Campanian/early Maastrichtian time (Fig. 9c). Growth of the adjacent Reichspitz anticline located to the north postdates Gosau sedimentation; it probably occurred during Tertiary times. Fold growth of the Reichspitz anticline during the Upper Santonian as indicated by rotative onlap was minor (Fig. 9b).

Discussion

The style of Late Cretaceous sedimentation in the Muttekopf area is comparable to other clastic deep-water deposits. Megaturbidites and progressive unconformities are well-documented from the Eocene Hecho Group in the southern Pyrenees (e.g., Labaume et al. 1985) and are interpreted to be a consequence of erosion and deposition on the growing folds of the southern Pyrenees (e.g., Poblet et al. 1998). Megaturbidites there were probably triggered by collapse of slope deposits after seismic events or oversteepening of slopes due to folding. In the Muttekopf area, the presence of megaclasts derived from Triassic carbonates calls for the existence of a major fault scarp in the vicinity of the outcrop as preserved today.

Most of the sediments in the Muttekopf are part of the second megacycle. This megacycle can be used to illustrate the relationship between fining upward megacycles and folding. The megacycle begins in a time when the rate of deposition was high relative to fold growth leading to onlap and overlap of sediments onto the growing fold. The megabreccias also overlap the fold (Fig. 9). Subsequently, the relationship between rate of deposition and fold growth reversed, and the progressive unconformity developed. The drop in rate of deposition might indicate that most of the deposits that became subject to erosion because of uplift and tilting due to folding were removed by that time. Above the unconformity, renewed onlap and overlap indicates a new rise in rate of deposition relative to fold growth. A new megacycle should begin, but this is not observed (Fig. 9). A shift in fold growth from adjacent to more distant folds in the south might be responsible for increasing sediment input. As

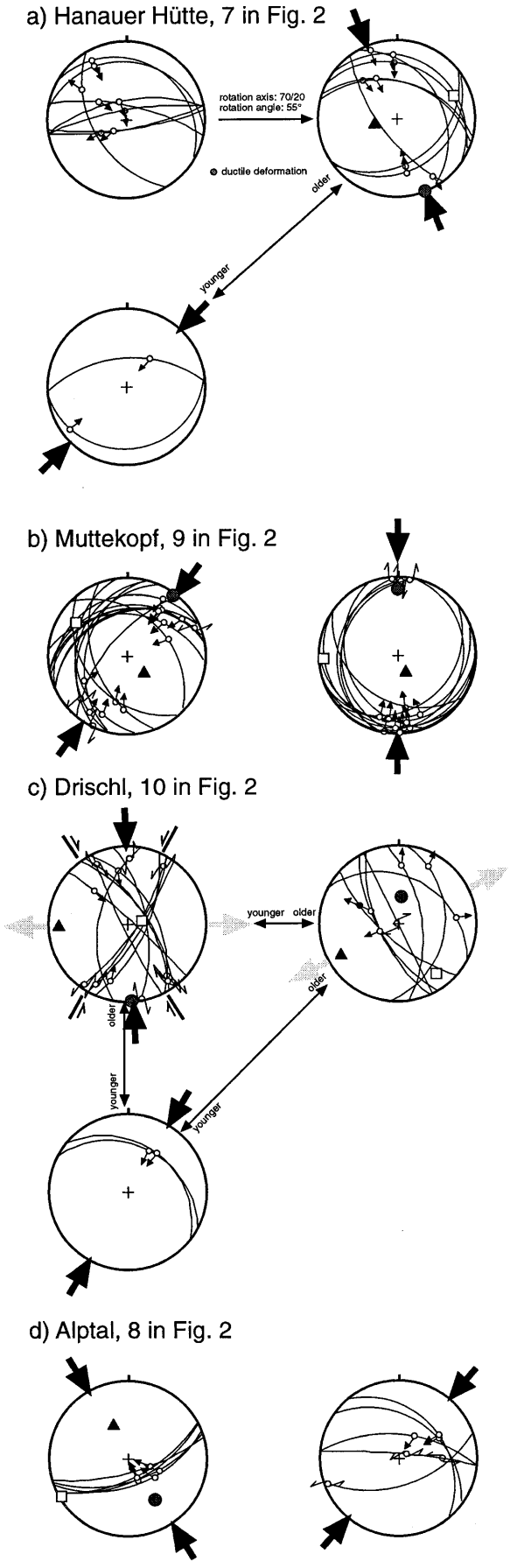

Fig. 8a–d Brittle displacements on faults at four stations. Relative age relationships are indicated by *double arrows*. *Large black* and *gray arrows* indicate the direction of contraction and extension, respectively. The orientation of the paleostress tensor is indicated by following symbols: *gray circle* σ_1, *white square* σ_2 and *black triangle* σ_3 (inversion of data: right dihedra method; Angelier and Mechler 1977)

shown by this discussion, the development of the fining upward megacycles was entirely controlled by fold growth.

In the Muttekopf area the growth of an anticline to the south of the Gosau outcrop is documented by several progressive unconformities. In the Lower Gosau Subgroup and the lowest part of the Upper Gosau Subgroup, unconformities are found on both limbs of the syncline (Figs. 3, 4, 9), whereas in the upper part of the Upper Gosau Subgroup they are restricted to the southern limb. The geometries of the unconformities, together with the evidence from early soft sediment and brittle deformation, indicate that the Gosau Group of the Muttekopf area was deposited during a time interval of continuous shortening. Activity along NW-trending transfer faults was restricted to the time of deposition of the Lower Gosau Subgroup (?Coniacian–Early Santonian), as these faults are sealed by the Upper Gosau Subgroup.

Fold axes in the Gosau strata display a progressive change from NE–SW-trending axes, that parallel fold axes in the Hauptdolomite Formation, to E–W-trending fold axes in sediments of the third megacycle. Progressive unconformities suggest that folding was active during deposition, and that only deformation that was contemporaneous with or younger than the deposits was recorded in the structural geometry. Deformation in the sediments documented by fault planes also reveals change of shortening from a NNW–SSE direction in sediments of the second megacycle (Lower Campanian to Lower Maastrichtian) to a later N–S direction. Younger faults indicate NE–SW compression.

The NW-trending high-angle faults and folds with NE-trending axes were active during deposition of the Lower Gosau Subgroup and became inactive during the Santonian; they were then sealed. At the same time the large fold structures with ENE-trending axes were initiated and began to grow. In areas where old structures continued to grow, fold axes did not change. If this is true regionally (see Froitzheim et al. 1994; Eisbacher and Brandner 1996), the change in the direction of compression together with the abandonment of NW-trending faults might indicate a change in the direction of convergence and therefore the end of oblique subduction. Alternatively, the progressive change in direction of compression might be related to an anticlockwise rotation of the western Northern Calcareous Alps (Mauritsch and Becke 1987) in the Late Cretaceous during persistent N–S oriented contraction.

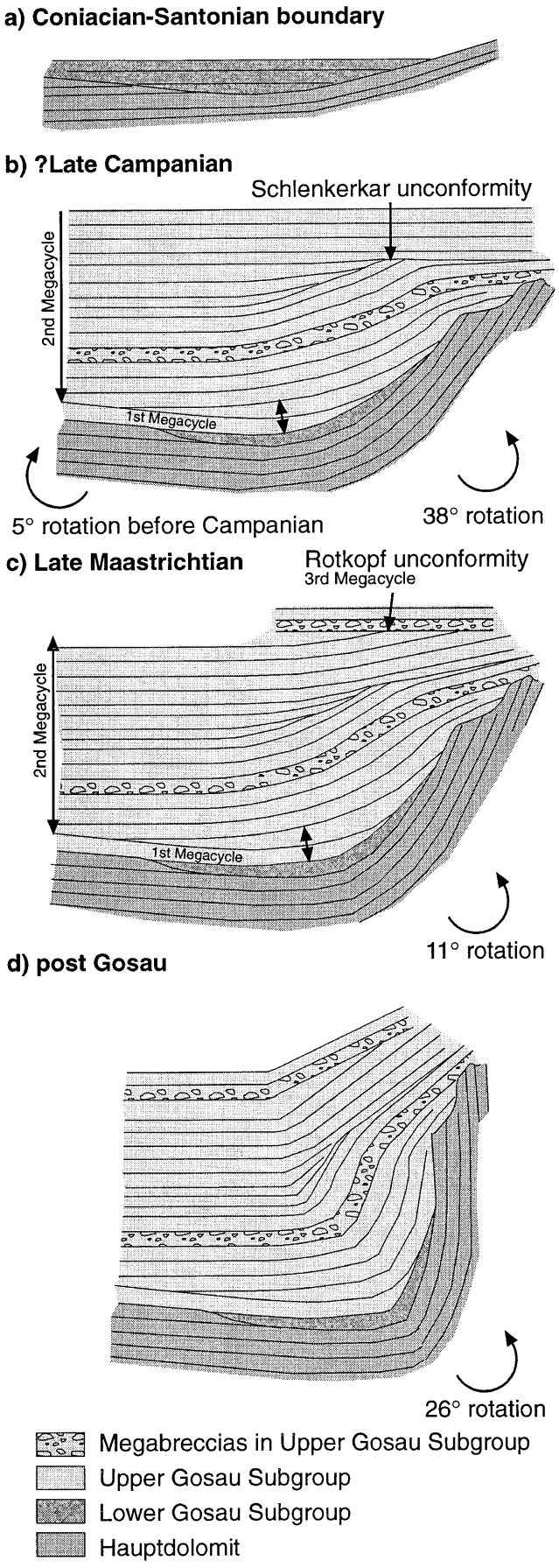

Fig. 9a–d Sequential restoration of the Muttekopf–Sinnesbrunn syncline based on a cross section Schlenkerspitz–Reichspitze (Fig. 3). Rotation angles refer to changes in dip of the limbs of the syncline between the single stages of contraction

Models for Gosau basin formation

Basement nappes of the Middle Austroalpine complex of Eastern Switzerland and the Tyrol were deformed by three tectonic events (Froitzheim et al. 1994, 1997; Fügenschuh 1995):

1. Albian to ?Campanian top west to northwest thrusting and nappe imbrication related to subduction of the South Penninic ocean (Trupchun phase) ended sedimentation on top of the basement units that lasted until Turonian time.
2. Late Campanian to Paleocene top-to-the-ESE extension caused thinning of overthickened crust (Ducan–Ela phase).
3. Late Eocene and younger top north thrusting was related to subduction of the Middle and North Penninic units (Blaisun phase).

The Trupchun phase in the Middle Austroalpine units can possibly be parallelized with the early N–S-trending axes of gentle folds and with the initiation of the folds with NE–SW-trending axes that are sealed by the Gosau sediments in the Muttekopf area and other areas of the Northern Calcareous Alps (Eisbacher and Brandner 1996).

The Ducan–Ela phase cannot be identified in the investigated area. Structural studies in other parts of the western Northern Calcareous Alps have not revealed regional structures related to this extensional event (Eisbacher and Brandner 1996; Weh 1998; May and Eisbacher 1999). In the investigated area the Late Campanian to Paleocene time seems to have been a period of relatively continuous fold growth and thrust faulting.

The folds with E–W-trending fold axes might be related to the Blaisun phase, as they postdate sedimentation in the Muttekopf area. Progressive brittle deformation also documents N–S shortening postdating folding and NE–SW shortening postdating N–S shortening, which is related to Tertiary lateral extrusion in the Eastern Alps (Ratschbacher et al. 1991; Peresson and Decker 1997). However, the timing is not tightly constrained.

The Ducan–Ela extension (Upper Campanian – Maastrichtian) as described from the Middle Austroalpine units is clearly connected to the formation of Gosau-age basins to the southeast (Neubauer et al. 1995; Froitzheim et al. 1997). However, the reason for Gosau basin formation in the Northern Calcareous Alps is not yet clear, and a relation to normal faults was discussed by Wagreich (1988), Ortner (1994), and Sanders (1998), and to strike-slip-faults by Eisbacher and Brandner (1996). Active folding during deposition

of the Gosau Group, as observed in the investigated area, was not described previously, but might be a important factor in many Gosau basins, as intraformational angular unconformities are present in several Gosau basins (e.g., Ruttner and Woletz 1956; Faupl 1983; Wagreich 1986, 1988). Only Niederbacher (1982) and Leiss (1988, 1990) presented models of continuous folding during sedimentation of the Gosau Group. In many Gosau basins progressive unconformities were probably not described because of poor outcrop conditions. Several models were put forward to explain contemporaneous extension in the internal part of the orogen (Middle Austroalpine) and shortening in the frontal part (Northern Calcareous Alps) and have been reviewed by Froitzheim et al. (1997): they include gravitational adjustment, subduction rollback, and tectonic erosion.

The last possibility was discussed by Polino et al. (1990) and by Wagreich (1993, 1995) for the Alps and provides a mechanism for strong and diachronous subsidence of the frontal Northern Calcareous Alps after a short period of uplift and erosion combined with (local) folding. Erosion at the lower side of the upper plate causes subsidence, and replacing light continental crust of the upper plate with heavy oceanic crust from the lower plate causes additional subsidence. However, these effects are observed in the frontal part of the orogenic wedge. Since this model does not account for extension and basin formation on top of the internal Middle Austroalpine. Subsidence in the central Alpine units probably was triggered by gravitational adjustment of an unstable orogenic wedge (Wagreich 1995).

Conclusions

1. The Lower Gosau Subgroup of the Muttekopf area was deposited contemporaneously with movements on NW-trending faults that probably represent tear or transfer faults complementary to NW–SE contraction. These faults were sealed by the Upper Santonian succession of the Upper Gosau Subgroup, but were reactivated later as dextral strike-slip faults.
2. Between the Coniacian and Maastrichtian, folding and thrusting was active in the investigated area, and is documented by several progressive unconformities in the Lower and Upper Gosau Subgroups, respectively (Fig. 9). Growing anticlines were active to the south and north of the Muttekopf–Sinnesbrunn syncline, but the northern anticline was abandoned shortly after onset of deposition of the Upper Gosau Subgroup and became again active in the Tertiary.
3. In the investigated area the direction of shortening progressively changed through time (Fig. 8):
   - NW–SE-directed shortening created NE–SW-trending folds sealed by Gosau deposits;
   - NNW–SSE-directed shortening created WSW–ENE-trending folds until early Campanian/early Maastrichtian time;
   - N–S-directed shortening created W–E-trending folds in late Campanian/late Maastrichtian time; and
   - NE–SW-directed shortening as documented by faults that postdated Gosau deposition.
4. The change from NW-directed thrusting together with activity of NW-trending tear faults to NNW-directed thrusting associated with growth of the large fold structures probably indicates the end of oblique convergence between the Austroalpine and Penninic units.
5. The Gosau Group of the Muttekopf area was deposited synchronously with thrusting and fold growth.

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