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ORIGINAL PAPER

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Sedimentary tectonics and subsidence modelling of the type Upper Cretaceous Gosau basin (Northern Calcareous Alps, Austria)

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Abstract The Upper Cretaceous Gosau Group of the Austrian Northern Calcareous Alps records sedimentation and subsidence after Early Cretaceous thrusting. The Gosau basin in the Gosau-Russbach area is approximately 8 km wide and 10 km long. It is filled by more than 1000 m alluvial/shallow-marine deposits of the lower Gosau Subgroup (Upper Turonian–Lower Campanian). Facies and thickness changes within short horizontal distances suggest synsedimentary basin margin faulting. Extensional structures within the Triassic basement of the basin include fibrous gashes which indicate (W)NW–(E)SE directed extension of 6–18%. (W)NW-directed normal faults at the southeastern basin margin, a prominent SE-directed normal fault with a minimum fault throw of approximately 500 m at the NW basin margin, and dextral strike-slip at the southwestern margin suggest a pull-apart origin of the basin between NW/SE-trending, right-overstepping dextral strike-slip faults. Backstripped tectonic subsidence curves yield values of total subsidence of 700 m in approximately 6 Ma. Forward computer modelling based on extensional models results in stretching factors β between 1.09–1.15. Local extension along strike-slip faults is suggested as the main mechanism for basin formation.

Keywords Eastern Alps · Gosau Group · Late Cretaceous · Basin analysis · Strike-slip basin · Subsidence modelling · Normal fault · Extension

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Introduction

The Eastern Alps have a complex history of repeated extension and compression related to the movement of the African plate and several microplates such as the Austroalpine and the Adriatic plates against the European plate (e.g., Dewey et al. 1989; Channell et al. 1992). Convergence during the Cretaceous and from the Eocene onwards resulted in two orogenies, first during the Early to middle Cretaceous and then in the Tertiary. Cretaceous thrusting was restricted to Austroalpine units which formed the upper plate during Tertiary subduction and thrusting. Cretaceous displacements include W- to NW-directed shortening, ductile stacking and metamorphism of the Austroalpine basement (e.g. Ratschbacher 1986; Behrmann 1990; Genser et al. 1996), thin-skinned NW-directed thrusting and dextral shear along NW-striking tear faults in the cover nappes of the Northern Calcareous Alps (NCA; Linzer et al. 1995, 1997), and extensional faulting related to "orogenic collapse" in the central Austroalpine units (Krohe 1987; Froitzheim et al. 1994). The structural evolution of the cover nappes in the NCA also includes Late Cretaceous uplift followed by significant subsidence leading to the formation of the Gosau sedimentary basins. The Gosau Group unconformably overlies Early Cretaceous fold-and-thrust structures (Wagreich and Faupl 1994; Wagreich 1995). The Cretaceous kinematics of the NCA are poorly constrained by structural data and several subsidence mechanisms were put forward for the Gosau basins; these include compressional piggyback models (Eisbacher and Brandner 1995), as well as extensional and pull-apart models (Wagreich 1991, 1995; Neubauer et al. 1995; Willingshofer et al. 1999).

These basin models were the starting point for tectonic investigations in the Gosau-type area, which is characterized by moderate post-depositional Tertiary deformation. This paper provides structural and sedimentological evidence for a Late Cretaceous phase of pull-apart extension within the NCA and compares measured extension with results of subsidence modelling.

Cretaceous geodynamics and deposition of the Gosau Group

The fold-and-thrust belt of the NCA and the Austroalpine basement units originated as parts of a microplate which was situated between the Penninic Ocean to the north and the Adriatic Plate to the south (Channell et al. 1992). Cretaceous deformation resulted both from the closure of the Meliata–Vardar ocean which left an Early Cretaceous suture zone within the Austroalpine units (Decker et al. 1987; Thöni and Jagoutz 1993) and subsequent middle to Late Cretaceous subduction of the Penninic Ocean below the Austroalpine units (Winkler 1988; Decker 1990). West-directed movement of the Austroalpine microplate and (S)E-directed oblique subduction of the Penninic Ocean below the NCA are documented by Early to Late Cretaceous thrust directions recorded in the Austroalpine basement units and in melanges of the subducted South Penninic Arosa and Ybbsitz units (Winkler 1988; Ring et al. 1988; Decker et al. 1993). The NCA were situated at the northern leading edge of the Austroalpine upper plate at that time (e.g., Wagreich 1995). Cretaceous deformation of the NCA was characterized by dextral transpression resulting in combining NW-directed folding and thrusting and dextral strike-slip faulting along NW-striking transfer faults (e.g., Eisbacher and Brandner 1995; Linzer et al. 1995, 1997). A minimum of 60% NW/SE-directed shortening was reconstructed from balanced cross sections (Eisbacher et al. 1990; Linzer et al. 1995). Comparable amounts of shortening during the Early to middle Cretaceous are also reported from within the Austroalpine basement (Behrmann 1990).

From Late Turonian onwards, the Gosau Group marks a new depositional cycle which post-dates both Cretaceous folding–thrusting in the NCA and ductile deformation–metamorphism in the Austroalpine basement units. The Gosau Group rests unconformably on folded and faulted Permo-Triassic strata of the NCA. Widespread erosion and the deposition of karst bauxites give evidence for a significant period of sub-aerial exposure in Middle Turonian time (Faupl and Wagreich 1992).

Basin analysis of the Gosau Group indicates a twofold subdivision of the basin fill (e.g., Wagreich and Faupl 1994; Sanders et al. 1997). The lower Gosau Subgroup (LGS; Upper Turonian–Campanian) comprises a diachronous succession of continental to shallow marine sedimentary rocks. Deposition in the NCA started in small, partly connected basins during the Late Turonian to Coniacian (Summesberger and Kennedy 1996) and was characterized by distinctive facies and thickness changes within short horizontal distances. The LGS basins have been interpreted as fault-bounded extensional and/or pull-apart basins (Wagreich 1988, 1995, 1998; Wagreich and Faupl 1994; Sanders 1998) with different subsidence paths, diachronous facies, and short basin inversion events (Wagreich 1991; Wagreich and Faupl 1994). Sequence stratigraphic analysis (Sanders et al. 1997; Sanders 1998) revealed the importance of tectonically enhanced topography on the geometry of stratal packages of the basin fill. Gosau basins display considerable similarities to strike-slip basins in a broad transform zone, such as small, rapidly subsiding depocenters, intervening structural highs, diachronous trangressions, phases of uplift and inversion, facies, grain size and thickness changes within short distances, and prominent basin bounding faults (e.g., the basins of the Californian Continental Borderland; Christie-Blick and Biddle 1985). These similarities are the consequence of a comparable geotectonic position of the basins on continental margins with oblique subduction and strike-slip faulting.

The upper Gosau Subgroup (UGS; Santonian/Campanian–Eocene) comprises deep-water deposits which record an NCA-wide deepening event (Wagreich 1993, 1995). Sedimentation overstepped formerly separated basins (Wagreich and Faupl 1994). Subsidence during the deposition of the UGS was interpreted as a result of subduction and/or underthrusting, leading to tectonic erosion (Wagreich 1995) or underthrusting of Austroalpine units (Willingshofer et al. 1999).

Stratigraphy and sedimentary infill of the Gosau basin

The Late Cretaceous Gosau basin in the the Gosau area (Upper Austria) and near Abtenau–Russbach (Salzburg) is the type area of the Gosau Group (Fig. 1). A reconstruction of the basin geometry by restoring Tertiary faulting results in an original basin of the LGS approximately 8–10 km wide and 10 km long. If similar Cretaceous deposits in the area of Abtenau are included (Jarnik and Wagreich 1993), the composite Late Cretaceous basin extended at least over 25 km. The basin fill comprises approximately 1000 m of Upper Turonian to lowermost Campanian terrestrial and shallow-water sediments of the LGS, which are unconformably overlain by more than 1200-m-thick deep-water deposits of the UGS (Figs. 2, 3). The UGS clearly seals older basin bounding structures of the LGS, as similar turbidite facies are found on former hangingwall and footwall blocks (Fig. 3) and deep-water deposits of the UGS onlap Triassic strata (Wagreich 1988).

The lithostratigraphic and sedimentary evolution of the basin have been discussed by Wagreich (1988) and Sanders et al. (1997). Up to 350-m-thick red alluvial conglomerates (Kreuzgraben Formation; see Fig. 3) of Late Turonian age forming the base of the LGS are

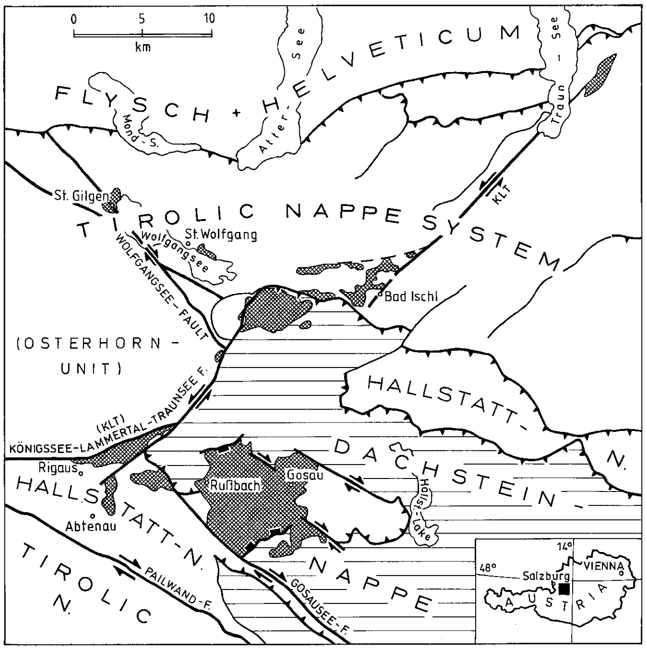


Fig. 1 Tectonic setting of the Gosau basin at the type locality Gosau-Russbach in the Northern Calcareous Alps (NCA). Upper Cretaceous sediments of the Gosau Group (*cross hatched areas*) unconformably overlie folded and thrusted Triassic to Lower Cretaceous strata of the Dachstein and Hallstatt Nappe

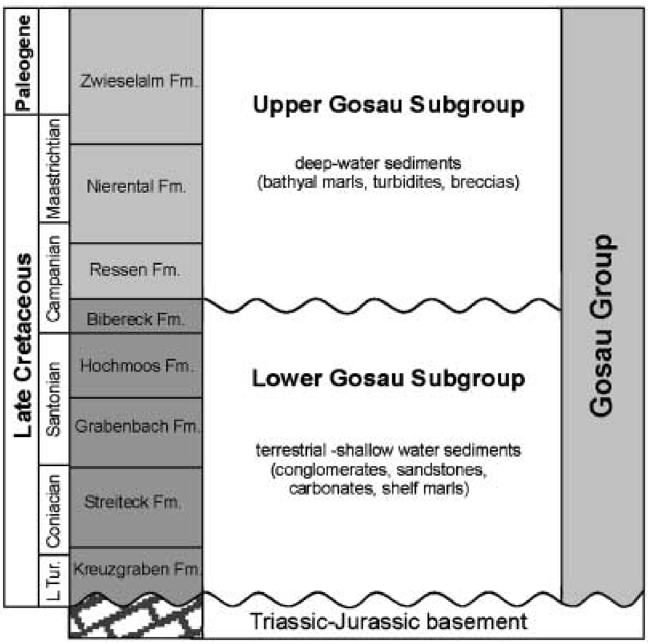


Fig. 2 Lithostratigraphy of the Gosau Group in the Gosau-Russbach area, based on Plöchinger (1982) and Wagreich (1988; no absolute timescale implied)

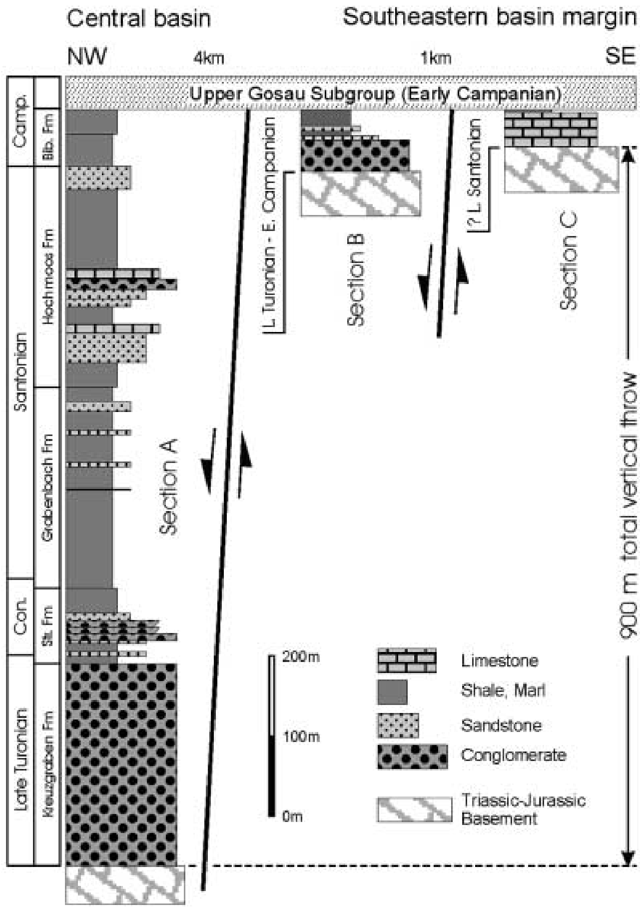
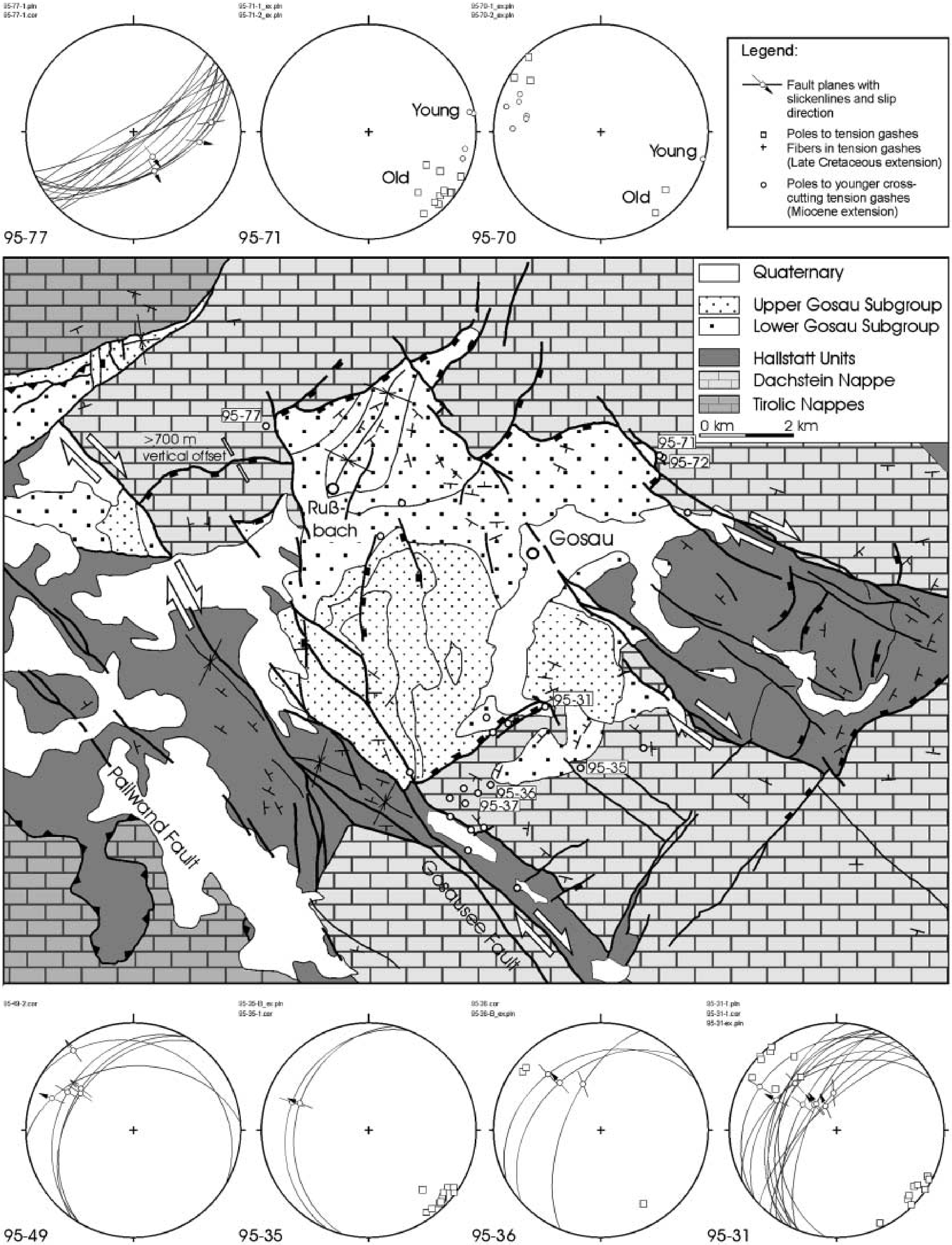


Fig. 3 Lithostratigraphic sections of the lower Gosau Subgroup (LGS) from the center (section A) and the SE margin (sections B and C) of the Gosau basin. Thickness changes from ca. 1000 m in the basin center to only 30 m at the margin indicate significant synsedimentary normal faulting. All sections are unconformably overlain by Lower Campanian sediments of the upper Gosau Subgroup (UGS) providing an upper time limit for normal faulting. *Str. Fm* Streiteck Formation, *Bib. Fm* Bibereck Formation

overlain by a transgressive succession of shallow-marine marls and backstepping coarsening-upward fan-delta paracycles of the Upper Turonian to Coniacian Streiteck Formation. Conglomerates of the Kreuzgraben Formation record progradation and retrogradation of alluvial fans (Wagreich 1988, 1998). Foraminiferal assemblages suggest water depths of approximately 150–300 m at maximum flooding in Early Santonian time (Grabenbach Formation; Wagreich 1988). Storm-influenced shelf and near-shore sediments of up to 500 m, including rudist bioherms (Hochmoos Formation), fill the basin in Santonian to Early Campanian times (Bibereck Formation).

Sedimentary thicknesses of the LGS are less along the SE basin margin (e.g., section B; see Fig. 3). Thirty to 50 m of alluvial sediments (Kreuzgraben

Fig. 4 Interpreted tectonic map of the surrounding of Gosau (see Fig. 1 for location). Structural plots (Schmidt net lower hemisphere projections) show normal faults and poles to tension gashes attributed to Late Cretaceous extension and normal faulting


Young
Old
Young
Old
95-77
95-71
95-70
Legend:
Fault planes with slickenlines and slip direction
Poles to tension gashes
Fibers in tension gashes (Late Cretaceous extension)
Poles to younger cross-cutting tension gashes (Miocene extension)
Quaternary
Upper Gosau Subgroup
Lower Gosau Subgroup
Hallstatt Units
Dachstein Nappe
Tirolic Nappes
0 km
2 km
95-77
>700 m vertical offset
95-71
95-72
Ruß-bach
Gosau
95-31
95-35
95-36
95-37
Pailwand Fault
Gosausee Fault
95-49
95-35
95-36
95-31

Formation) are unconformably overlain by 30 m of Upper Santonian to Lower Campanian shallow-water deposits. The strong thickness reduction from 1000 to 80 m within a horizontal distance of only 3 km and the facies change from marls to sandstones are probably due to the presence of synsedimentary normal faults. Further to the south up to 30 m of Upper Santonian neritic bioclastic limestones (Untersberg Formation) mark a Late Santonian/Early Campanian transgression onto a cliffed coast near a fault scarp.

Tectonic setting of the Gosau-type location

The Upper Turonian to Eocene sediments of the Gosau Group at the type locality unconformably overlie thrust and strike-slip fault contacts between Triassic to Jurassic strata of the Dachstein and Hallstatt Nappe (Lammertal- and Hallstatt Unit; Fig. 4). Structural data show that most of the outline of the present basin follows major faults of both Cretaceous and post-Eocene age. To the SW, the NW-striking dextral Pailwand and Gosausee fault system forms the present basin boundary with respect to the Lammertal-Hallstatt Unit. Similar dextral strike-slip faults form the NE margin of the basin (Fig. 4). The NW and SE margins of the basin correspond to major normal faults.

The post-depositional tectonic overprint in the Gosau area is minor as compared with other sites within the NCA. Eocene to Miocene thrusting resulted in gentle folding and in the formation of rare bed-scale duplex and ramp-flat structures indicating minor NW- and N-directed shortening (Peresson and Decker 1997). Faulted Eocene sediments of the UGS give evidence for Late Eocene to Oligocene reactivation of the Cretaceous NW-striking dextral Lammertal-Gosausee Fault (Fig. 4). The youngest structures recorded are related to Miocene NE-striking strike-slip faults (Königssee-Lammertal-Traunsee Fault; Fig. 1; Decker and Jarnik 1993; Peresson and Decker 1997) and Miocene E/W-directed co-axial extension (E/W-dipping extensional faults and fibrous tension gashes; Decker et al. 1994).

Cretaceous extension in the Gosau region

Structures indicating a pronounced NW/SE-directed extensional event affecting the Triassic basement around the Gosau basin are map-scale NW- and SE-dipping normal faults including those at the NW and SE basin margin, NE-striking fibrous calcite-filled extension gashes, and NE-striking gashes filled with fine-grained red or gray siliciclastic and calciarenitic sediment (Fig. 5). These structures yielded dateable nannofossil assemblages (Table 1) and are systematically crosscut and offset by Miocene extensional structures.

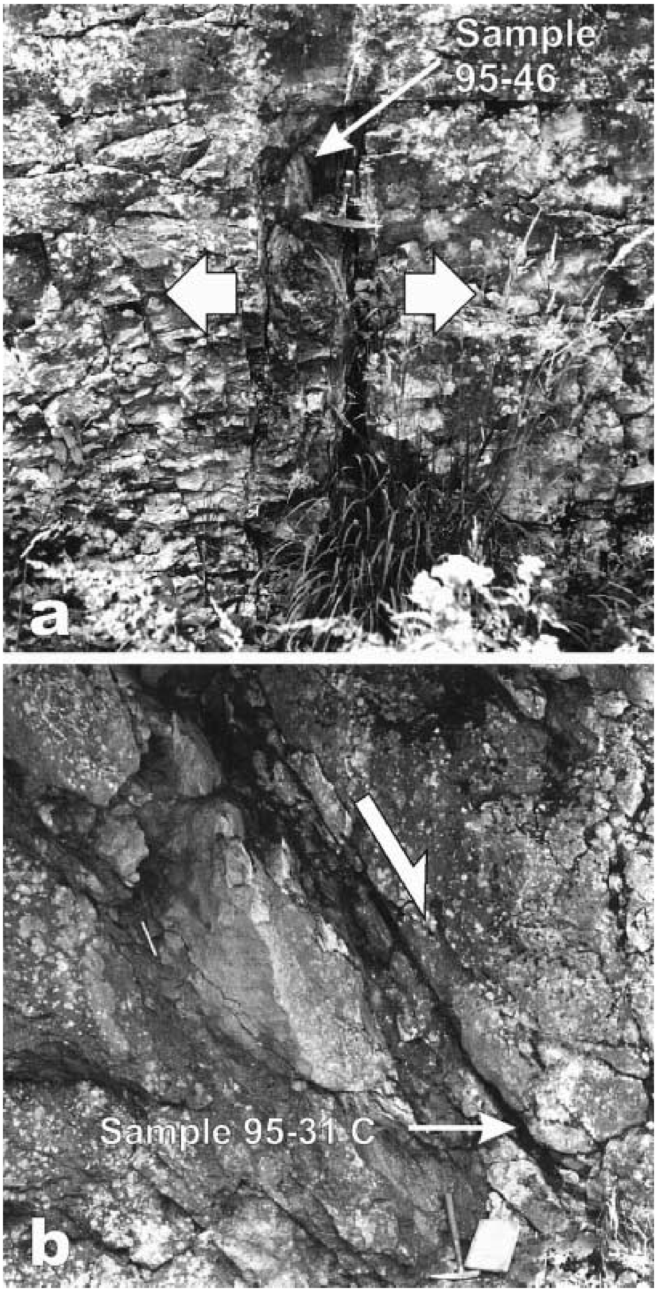


Fig. 5 **a** Tension gash in Upper Triassic Dachsteinkalk filled by Upper Cretaceous red marly limestone (station 95–46; compare Tables 1, 2). **b** Northwest-directed normal fault in Upper Triassic Dachsteinkalk at the southeastern basin margin with red micritic siltstone of Santonian–Campanian age along fault plane (station 95–31; compare Tables 1, 2)

The normal faults at the basin margins show stratigraphic offsets of the order of several hundred meters. At the NW margin, more than 700 m of vertical throw along a planar normal fault dipping 70° to SE is estimated from the displaced contact between Middle and Upper Triassic carbonates of the Bodenberg (Fig. 4). At the SE margin, a major planar normal fault offsets Rhaetian bioclastic limestones comprising black peb-

Table 1 Nannofossils, foraminifera, and interpreted stratigraphic ages of sediment-filled tension gashes. See Table 2 for site location and orientation of gashes

Outcrop/ sample no.		Species	Interpreted age
95/31C	Red micritic siltstone along NW-directed normal fault	*Stradneria crenulata* *Micula decussata* *Eiffellithus turrisseiffellii* *Lucianorhabdus cayeuxii* *Rucinolithus sp.* *Orastrum sp.* *Calculites sp.* *Arkhangelskiella sp.*	Santonian–Early Campanian
95/31E	Red micritic siltstone in tension gash	*Eiffellithus eximius* *Prediscosphaera cretacea* *Arkhangelskiella sp.* *Glaukolithus sp.* *Stradneria crenulata*	M. Turonian–Santonian
95-46	Red marly limestone in tension gash	*"Globotruncana" (Rosita sp.)* *Dorothia pupoides*	Turonian–Campanian
95/74	Red micritic siltsone along NW-striking dextral fault	*Watznaueria barnesae*	Late Jurassic–Cretaceous

bles on top of the Dachsteinkalk, indicating a vertical offset of ca. 500 m. For the SE basin margin, major thickness changes of the LGS across the fault from several hundred meters in the hangingwall to only 80 m in the footwall prove that faulting occurred contemporaneously with the deposition of the LGS. Sediment thicknesses suggest an approximate total offset of the base of the LGS of approximately 900 m (Fig. 3). The fault is sealed by Lower Campanian turbidites of the UGS (Ressen Formation; Figs. 3, 5). Minor NW-directed faults in outcrops along the SW basin margin show very peculiar fault morphologies with red siltstone and clay infills and thick layers of polyphase calcite cements (station 95–31, Table 2). These features and an apparent lack of synkinematic calcite mineralization are regarded as indicators that the faults originated close to the surface. Horizontal extension due to normal faulting at the basin margins adds up to approximately 250 and 325 m for the displacement along the NW and SE boundary faults, respectively. For the 9-km-wide LSG basin, this corresponds to ca. 6% of NW/SE-directed basement extension (Fig. 6).

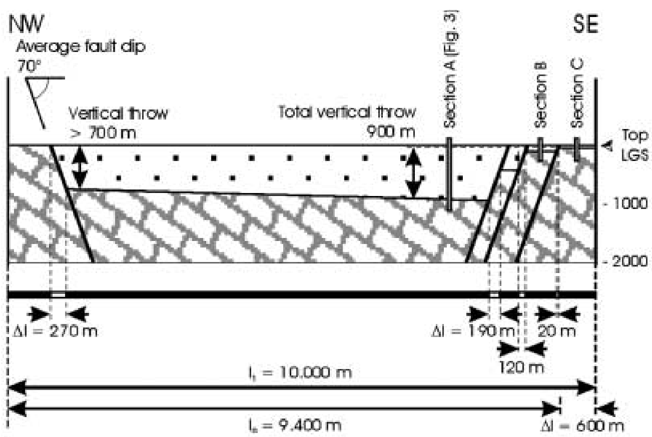


Fig. 6 Schematic cross section through the LGS basin. Planar normal faults at the NW and SE basin margin account for ca. 6% horizontal extension in the section plane. The vertical offsets have been estimated from offset markers for the NW margin and from thickness variations of the LGS for the SE margin, respectively (compare stratigraphic sections in Fig. 3). Fault dips of ca. 70° and planar fault geometries are indicated by outcrop observations

Table 2 Sampled sediment infill in tension gashes and faults. Columns refer to outcrop numbers, easting/northing according to Austrian BMN coordinates, sample numbers, and orientation of tectonic structures. *Fp* fault plane; *lin* slickenline; *Ex* extension gash with extension direction perpendicular to the gash). Results are summarized in Tables 1 and 3

Outcrop No.	Y_{M31}	X_{GKM}	Sample No.	Orientation	Results
95–31	464.900	268.300	95-31-A	Fp 292/68 lin 320/62 normal	–
95–31	464.900	268.300	95-31-B	Fp 304/65 lin 316/58 normal	–
95–31	464.900	268.300	95-31-C	Fp 304/65 lin 316/58 normal	Nannofossils (Table 1)
95–31	464.900	268.300	95-31-E	Gash with irregular margins	Nannofossils (Table 1)
95–35	465.400	267.275	95-35-A		–
95–35	465.400	267.275	95-35-B		–
95–35	465.400	267.275	95-35-C	Fp 246/86 lin 336/12 dextral	–
95–46	462.800	266.500	95-46	Ex 350/80	Heavy minerals (Table 3) Foraminifera (Table 1)
95–70	467.300	273.100	95-71	Ex 312/70	–
95–70	467.300	273.100	95-72	Ex 326/80	Heavy minerals (Table 3)
95–74	467.975	272.450	95-74	Fp 042/76 lin 314/03 dextral	Nannofossils (Table 1)

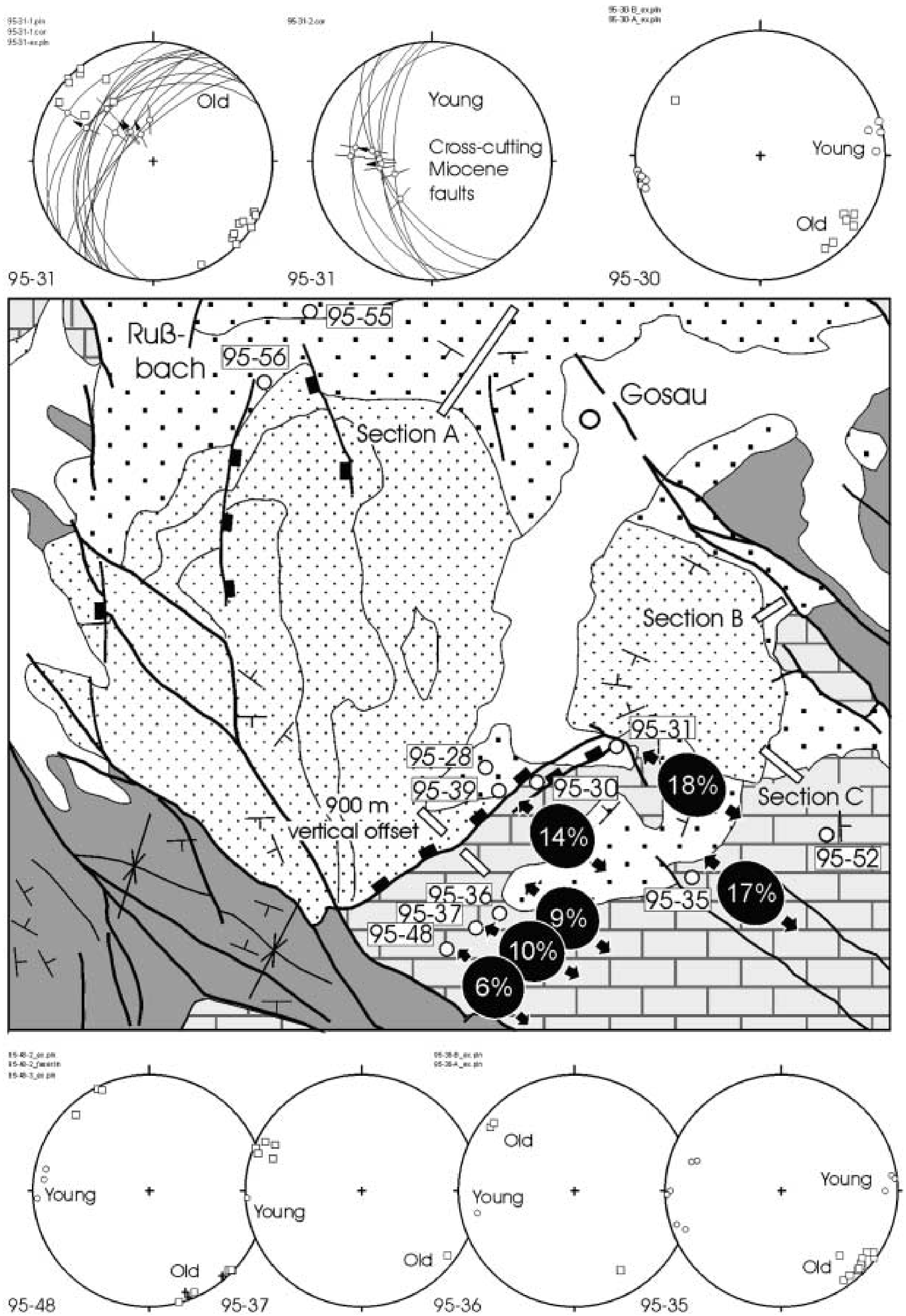


Fig. 7 Orientations of tension gashes measured in the Triassic basement of the LGS. Northwest/southeast-directed coaxial extension with finite strain between 6 and 18% is compensated by fibrous and sediment-filled tension gashes. Systematic cutting of the NE-striking gashes by younger N/S-striking gashes and W-directed normal faults (station 95–31). The biostratigraphic dating of sediment-filled gashes (Table 1) indicate Cretaceous deformational ages. See Fig. 4 for legend

Northeast-striking calcite-filled extension gashes in limestones of the Dachstein Nappe indicate significant coaxial extension of the basement parallel to the slip of the normal faults at the basin boundaries (Fig. 7). Crosscutting relationships show that these structures both post-date Jurassic neptunian dikes, which can readily be discerned due to their infill of pure red micritic and crinoidal limestones, and pre-date N-striking Miocene calcite-filled tension gashes (Fig. 5). Northeast-striking extensional structures are virtually absent from sediments of the LGS indicating that the brittle extension only affected the basement (Fig. 8). Several biostratigraphically dated fillings of tension gashes by nannofossils and foraminifera indicate a Turonian–Campanian age for their development (Tables 1, 2). These data are corroborated by heavy mineral spectra from sandstone and siltstone dykes which are rich in stable minerals such as tourmaline and zir-

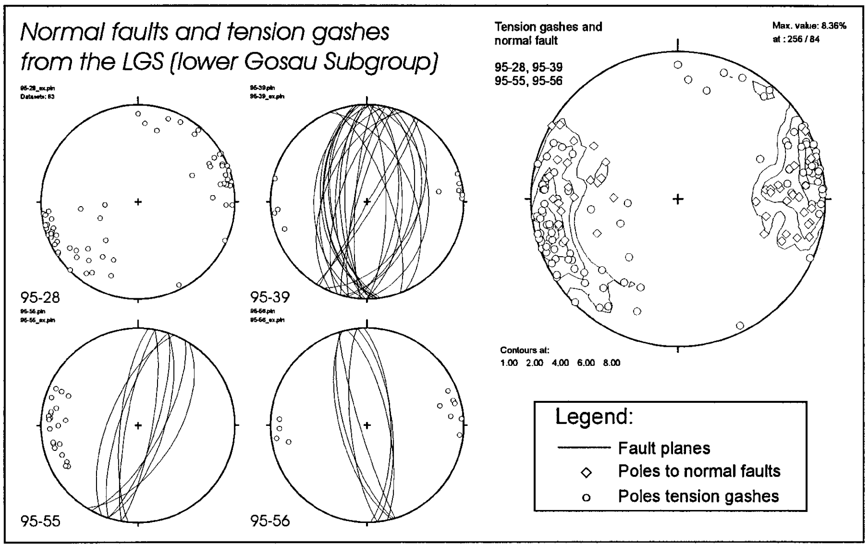


Fig. 8 Orientation of normal faults and tension gashes measured in the lower Gosau Subgroup. East/west-directed extension is related to Miocene deformation, whereas the absence of NW/SE-directed extensional structures, which are present in the Triassic basement (Fig. 5), indicate their Cretaceous age

con without chrome spinel (Table 3). Similar spectra are known from the Kreuzgraben and Streiteck formations (Wagreich 1988), indicating that the filling of the gashes occurred synchronously to the main LGS phase of subsidence.

Northeast-striking tension gashes with fibrous calcite and tension gashes filled with micritic siltstones and marlstones account for approximately 6–18% of coaxial NW/SE-directed extension in the Triassic basement of the SE basin margin (Fig. 7; Tables 1, 2). Adding these values to the extensional strain of the basin boundary normal faults reveals ca. 12–24% finite extension of the basement across the Gosau basin.

NW-striking wrench faults (Pailwand-Gosausee Fault)

Dextral strike-slip faults form both the SW and NE basin margin and transect the LGS basin in the vicinity of Gosau. These faults also comprise the present boundaries between the Dachstein Nappe and Hallstatt units near Hallstatt and Lammertal (Fig. 9). The normal faults described in the previous section partially link up with or terminate against dextral strike-slip faults indicating a kinematic linkage of both fault systems. Evidence for dextral slip along the NW-striking faults is supported by micro- and medium-scale slickensides mapped in outcrops along the faults (Fig. 9).

Late Early Cretaceous deformational ages for one of these dextral faults (Pailwand Fault, Fig. 9) have been determined by K–Ar and Rb–Sr dating of fine-grained illite in fault gauges (Kralik et al. 1987). The radiometric data revealed ages of 99–104 and 99± 7 Ma, respectively. Late Cretaceous fault slip is also indicated by red micritic siltstone infills along the dextral fault at the NE margin of the LGS basin, which are very similar to the infills of tension gashes and normal faults described previously. One sample from a dextral fault revealed Upper Jurassic–Cretaceous nannofossils (station 95–74; Fig. 9; Tables 1, 3).

The age data obtained from the Gosau region conform with previously published age interpretations by Linzer et al. (1995, 1997) who interpreted NW-striking dextral faults as Early to Late Cretaceous tear faults linked to NW-directed thrusting; however, data from the Gosausee Fault cutting through Eocene sequences of the UGS (Fig. 9), and regional comparison, prove that parts of the dextral faults have been reactivated during the Eocene to Oligocene as NW/SE-trending dextral strike-slip faults (Peresson and Decker 1997).

Table 3 Heavy mineral spectra of Cretaceous sediment-filled neptunian dykes compared with the mean heavy mineral composition of the Kreuzgraben Formation (16 samples; Wagreich 1988) forming the basal sequence of the LGS. The samples are similar with respect to the predominance of stable heavy minerals (zircon, tourmaline, rutile) plus apatite and low contents of garnet and chrome spinel. *95-46* Red marly limestone; *95-71, 95-72* red and gray calcarenite

Sample no.	Zr	Tu	Ap	Ru	Ga	Ep	Sta	Cr	Re
95-46	30	6	38	14	6	2	1	+	3
95-71	2	38	54	1	2	–	–	–	3
95-72	8	27	51	3	3	–	+	–	6
Kreuzgraben Formation	24	17	37	7	10	–	–	2	3

Subsidence analysis and forward subsidence modelling

Quantitative subsidence analysis has been applied to the LGS succession (Fig. 10a) to quantify tectonic subsidence and to compare the latter with calculated results derived from forward subsidence modelling. Standard backstripping techniques (Steckler and Watts 1978; Bond and Kominz 1984) were used incorporating an Airy model for isostasy to correct for sediment loading, which seemed to be a reasonable simplifica-

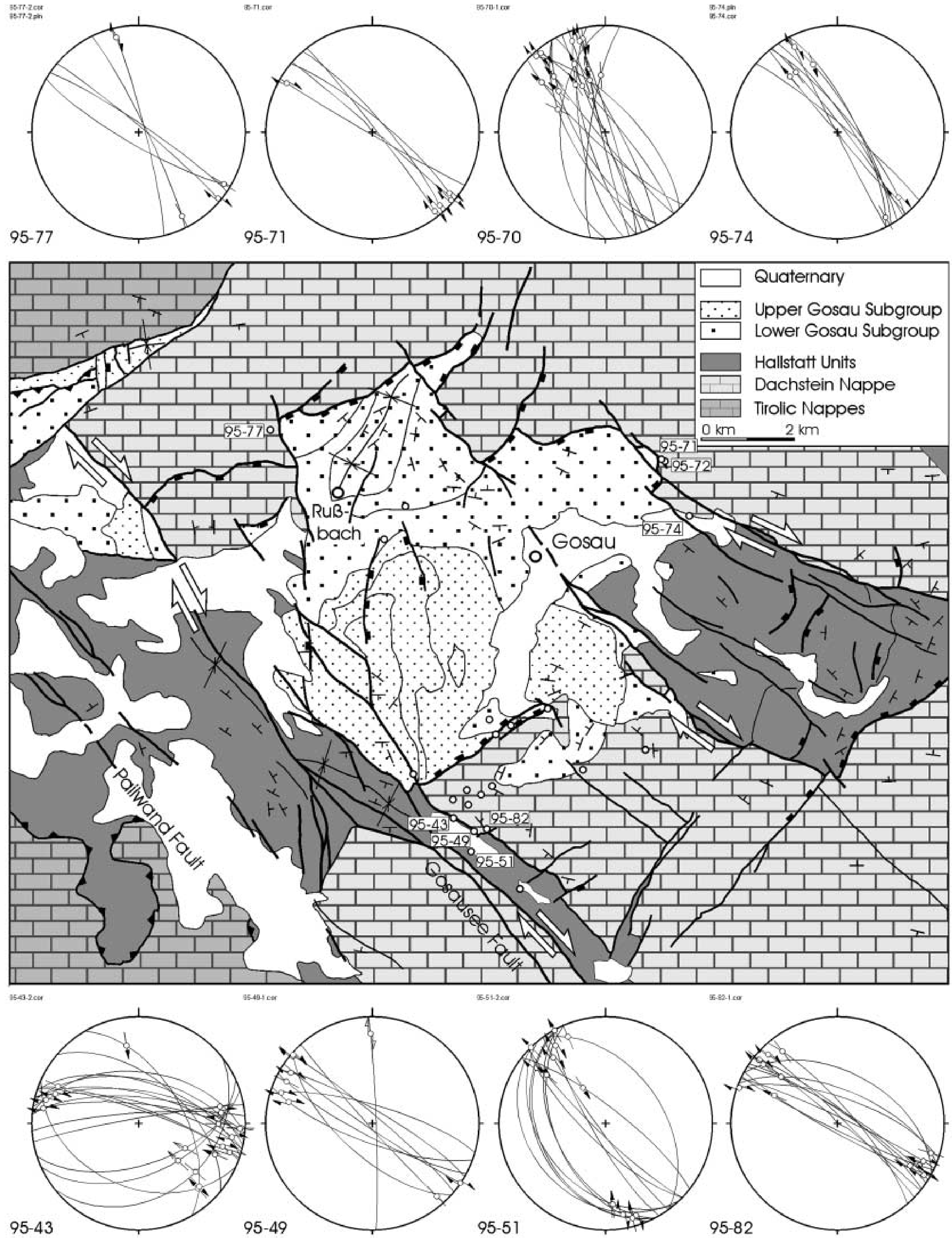

95-77
95-71
95-70
95-74
Quaternary
Upper Gosau Subgroup
Lower Gosau Subgroup
Hallstatt Units
Dachstein Nappe
Tirolic Nappes
0 km
2 km
95-77
95-71
95-72
95-74
Ruß-
bach
Gosau
Pailwand Fault
Gosausee Fault
95-43
95-82
95-49
95-51
95-43
95-49
95-51
95-82

Fig. 9 Interpreted tectonic map of the surrounding of Gosau (see Fig. 1 for location). Structural plots (Schmid's net lower hemisphere projections) show dextral strike-slip faults constraining the kinematics of the NE and SW basin boundary faults. Cretaceous deformational ages are indicated by the isotope dating of fault gauges of the Pailwand fault (Kralik et al. 1987) and by regional kinematic comparison. See Fig. 4 for legend

tion based on the fault system geometry around the basin. No correction for eustatic sea-level changes was applied. Paleobathymetric estimates are based on facies reconstructions and foraminiferal assemblages (Wagreich and Faupl 1994). Chronostratigraphic correlations are based on Wagreich (1992) and Summesberger and Kennedy (1996) using the timescale of Gradstein et al. (1995). Backstripping was performed by the SUBGOS program (Wagreich 1991) based on equations of Bond and Kominz (1984), including a correction for the pore space filled by cementation during the compaction process. Empiric decompaction parameters for standard lithologies are taken from Sclater and Christie (1980) and Karner et al. (1987).

Figure 10b shows the backstripped tectonic subsidence curve for the central part of the Gosau basin. The tectonic subsidence for the LGS totals up to 700 m during a time interval of ca. 6 Ma. Higher subsidence rates at the beginning of the deposition correspond to the sedimenation of coarse alluvial deposits. In the Early Santonian the rate of sediment supply was outpaced by the rate of subsidence and the basin deepened a minimum water depth of 150 m. During the Late Santonian tectonic subsidence declined and subsidence due to the increasing sediment load predominated. The tectonic subsidence rate declined to zero only approximately 6 Ma after basin formation, and a short phase of uplift occurred during the Late Santonian to Early Campanian, followed by rapid subsidence of the UGS (Wagreich 1993, 1995).

The subsidence of the Gosau pull-apart basin resembles the two-stage subsidence history of extensional basins (McKenzie 1978), although the time interval involved is a magnitude less than that for normal extensional basins. The recorded subsidence is characteristic for small pull-apart basins, where the thermal anomaly disappears largely during stretching due to lateral heat flow out of the narrow basin (e.g., Pitman and Andrews 1985; Cloetingh et al. 1992). The amount of thermal subsidence may have also been reduced because extension was more or less confined to the brittle part of the crust and did not involve the subcrustal lithosphere (thin-skinned pull aparts, e.g., Karner et al. 1987).

According to these considerations the subsidence of the Gosau pull-apart basin was modeled by a modified pull-apart model (Fig. 10c) adapted from Pitman and Andrews (1985), in which lateral heat flow accounts

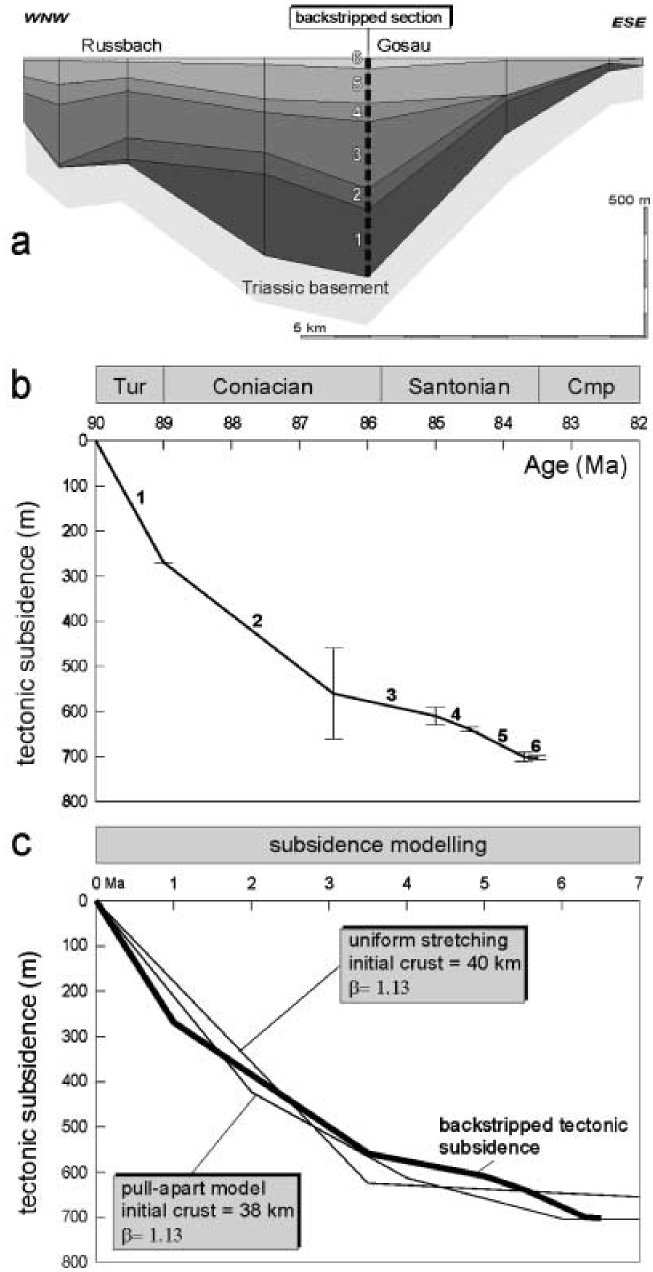


Fig. 10 **a** Restored WNW–ESE stratigraphic section through the Gosau basin below the UGS. Note strong thickness changes and the position of the backstripped section in the basin center. *Numbers* refer to lithological units used for backstripping. **b** Backstripped tectonic subsidence curve for the lower Gosau Subgroup of the central Gosau basin. *Error bars* indicate range of waterdepth estimates, timescale after Gradstein et al. (1995). **c** Modeled subsidence curves for the lower Gosau Subgroup, using uniform stretching (McKenzie 1978; Hellinger and Sclater 1983) and pull-apart models (Pitman and Andrews 1985). Modelling parameters: initial lithospheric thickness 125 km; initial crustal thickness 40 km; asthenospheric temperature 1350 °C; thermal diffusivity 0.8×10^{-6} m^2 s^{-1}; crustal density 2800 kg m^{-3}; mantle density 3330 kg m^{-3}; thermal expansion coefficient 3.3×10^{-5} °C

for additional subsidence during finite extensional steps (compare Cloetingh et al. 1992). The effect of a thin-skinned extensional model was examined by a two-layer extensional model of the lithosphere, allowing different stretching values for the crust and the subcrustal lithosphere (Hellinger and Sclater 1983; Van Wees et al. 1998). Lateral heat flow is accounted for by the incorporation of a strongly reduced thermal time constant based on the fact that basin subsidence stopped only 6 Ma after extension. A strong uncertainty in the modelling process comes from the poor constraints for the intitial Late Cretaceous crustal thicknesses below the Gosau basins of the NCA, which is a crucial input parameter. Estimated crustal thicknesses of the Austroalpine unit after Early Cretaceous compression vary between 25 km (Behrmann 1990) and 60 km (Willingshofer 2000). For modelling, conservative thickened crust values of 35–40 km were applied.

The best fit to the observed subsidence of the central part of the basin was obtained for the Pitman and Andrews pull-apart model modified to include successive stretching events with decreasing stretching factors, summing up to a total stretching factor β of 1.09–1.13, depending on assumed intitial crustal thicknesses (Fig. 10c). Modelling indicates that a reasonable fit of modelled and observed subsidence cannot be achieved by applying significantly higher stretching values or higher crustal thicknesses. The alternative two-layer stretching model gives only reasonable good fits if a prolonged duration of rifting of approximately 3.5 Ma and a uniform stretching of the crust and the subcrustal lithosphere is applied (Fig. 10c). This and the smooth subsidence curve without a major initial subsidence phase argues against a thin-skinned pull-apart mechanism with higher crustal stretching factors. Stretching factors of approximately 1.1–1.15 from the two-layer extensional model are similar to both the β values of the Pitman and Andrews model (Fig. 10) and to the independently derived finite extension of 12–24% measured from tectonic analysis (Figs. 7, 6).

Discussion

Structural data from the Gosau basin point to a formation of the LGS basin as an extensional basin between interacting dextral strike-slip faults and normal faults. Given the regional distribution of Gosau deposits, e.g., north of the Gosau area (Wagreich 1998), a system of NW/SE-oriented dextral strike-slip faults seems to be the major controlling structure for Late Cretaceous basin formation in this area. The data from the Gosau basin thus modify or contradict previously presented models, which explained basin formation by compressional tectonics, e.g., synclinal subsidence along transfer faults, thrust loading, and the formation of piggyback basins on top of thrust sheets during continuing Late Cretaceous thrusting within the NCA (e.g., Eisbacher et al. 1990; Linzer et al. 1995; Eisbacher and Brandner 1995).

Structural evidence for extensional basin formation during the Late Turonian–Early Campanian is in agreement with the results of forward subsidence modelling. Forward modelling shows that the observed subsidence history and sedimentary thicknesses of the LGS can readily be explained by low finite stretching. Stretching values obtained from structural analysis (12–24%) are similar to results of forward subsidence modelling (9–15%), using a Pitman and Andrews (1985) pull-apart model. Extension seems to be largely confined to the small strike-slip dominated basins, as suggested by the onlap of deposits of the UGS onto the basement.

Gosau basins in more internal positions south of the NCA, such as the Kainach basin in Styria, were interpreted as extensional basins subsiding within a sinistral wrench corridor coeval to exhumation of the Gleinalm "dome" (Neubauer et al. 1995). Basin subsidence, especially initial subsidence of continental basins, was explained by Willingshofer (2000) as a result of extension of overthickened Austroalpine crust after Early Cretaceous stacking. Extensional collapse seems to be a likely explanation for subsidence in internal parts of the Austroalpine unit, whereas the position of the NCA near the northern, active margin of the Austroalpine microplate during this time argues against the presence of significantly overthickened crust below the NCA. Given the results from subsidence modelling for the LGS of the Gosau basin, extension of only moderately thickened crust of approximately 40 km seems to give reasonable fitting subsidence curves for the Upper Turonian–Lower Campanian basin infill. Local Late Cretaceous extension within the NCA seems to be a consequence of the interaction of dextral strike-slip faults rather than to record regional extensional collapse of overthickened crust.

Conclusion

The Gosau basin in the Gosau-Russbach area is one of the keys for unravelling the Late Cretaceous structural evolution and basin formation in the central Northern Calcareous Alps. The Gosau basin is approximately 8 km wide and 10 km long, was filled by more than 1000-m alluvial/shallow-marine deposits of the lower Gosau subgroup (Upper Turonian–Lower Campanian), and is unconformably overlain by deep-water sediments of the upper Gosau Subgroup:

1. Basin structures of the lower Gosau Subgroup are sealed by Lower Campanian turbidites. Strong reduction in the thickness of the lower Gosau Subgroup along the SE basin margin indicate a synsedimentary active normal fault.
2. NW- and SE-dipping normal faults with stratigraphic offsets of several hundred meters at the

basin margins, NE-striking fibrous calcite-filled extension gashes, and NE-striking gashes filled with biostratigraphically dated Upper Cretaceous sediments indicate NW/SE-directed extension during the Late Turonian–lowermost Campanian. Finite extension adds up to 12–24%.

3. Dextral strike-slip faults form both the SW and NE basin margin and are kinematically linked to the normal faults. Structural data therefore suggest a pull-apart origin of the basin between NW/SE-trending, overstepping dextral strike-slip faults.
4. Backstripped tectonic subsidence curves give values of 700 m in approximately 6 Ma. Forward subsidence modelling based on extensional and pull-apart models results in stretching factors between 1.09 and 1.15. Reasonable fitting curves are obtained for initial crustal thicknesses of approximately 40 km and argue against a strongly thickened crust below the Gosau basins of the NCA. Local extension along strike-slip faults is suggested as the main mechanism for basin formation of the lower Gosau Subgroup.

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