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Subduction tectonic erosion and Late Cretaceous subsidence along the northern Austroalpine margin (Eastern Alps, Austria)

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Abstract

The Late Cretaceous to Early Tertiary subsidence history of the Northern Calcareous Alps (NCA) records the effect of two independent basin formation mechanisms at the northern leading margin of the Austroalpine unit. The terrestrial to shallow-marine sediments of the Lower Gosau Subgroup were deposited mainly within small, fault-bound basins during a phase of strike-slip faulting from the late Turonian onwards. After a short period of uplift, deformation and erosion of 1 to 3 Ma, renewed rapid subsidence followed. During this period the whole NCA subsided into bathyal to abyssal depths. The characteristics of this second evolutionary phase are: (1) a short period of uplift and erosion, followed by strong subsidence of the whole NCA with tectonic subsidence rates up to 700 m/Ma; (2) sedimentation of turbidites and hemipelagites (Upper Gosau Subgroup) (3) northward tilting of the depositional area; (4) elimination of an accretionary wedge north of the NCA as the main source for the sediments; and (5) a pronounced migration of the subsidence event from the northwest to the southeast from late Turonian/Santonian to the Maastrichtian. These features can be explained by a model of subduction tectonic erosion along the northern margin of the Austroalpine unit, a part of the Adriatic microplate. Tectonic erosion, as compared to recent analogues and fore-arc modelling, may be due to the collision and oblique subduction of an oceanic swell or ridge of the Penninic plate beneath the overriding Austroalpine unit with the NCA on its leading northern margin.

1. Introduction

The orogenic evolution of the Alps is the result of the complex interplay of movements and collisions of the African and European plates and intervening microplates. These motions are caused by spatially and temporally distributed episodes of rifting, opening, and closing of oceanic domains between continents and continental fragments. Within the Mesozoic to Cenozoic history of the Eastern Alps two peaks of orogenic deformation can be recognized, controlled by strong convergent movements of the African and

European plates and collisions of microplates (e.g., Ring et al., 1988; Dewey et al., 1989; Chanell et al., 1990): (1) the “Eoalpine” event, starting during the Late Jurassic/Early Cretaceous with Early to Middle Cretaceous thrusting and metamorphism; and (2) the “Mesoalpine” to “Neoalpine” deformations beginning in the Late Eocene, including a Neogene phase of lateral extrusion (Ratschbacher et al., 1991a). In the Austroalpine realm, which formed the leading northern margin of the Adriatic microplate within the segment of the Eastern Alps during the Cretaceous and Palaeogene, the sediments of the

Gosau Group were deposited in the time interval between these two tectonic pulses. As a consequence, the sedimentary evolution and subsidence history of these basins exemplify the complex tectonic evolution of the Austroalpine unit during this time and enable speculations concerning processes during Late Cretaceous to Early Tertiary plate convergence.

This paper presents a new geodynamic model for the tectonic evolution of the leading margin of the Austroalpine unit during the Late Cretaceous and Palaeogene based on a basin analysis of the Gosau Group of the Northern Calcareous Alps (NCA). The geodynamic history of the more southern Late Cretaceous basins of the Austroalpine unit, such as the Kainach Gosau basin, probably reflects extensional collapse in close relationship to the uplift and unroofing of metamorphic domes in a sinistral wrench corridor (Krohe, 1987; Ratschbacher et al., 1989; Neubauer and Genser, 1990; Ratschbacher et al., 1991b; Neubauer et al., 1992, 1995-this issue). The subsidence history of the Gosau basins of the NCA suggests a more complex evolution as a

consequence of the interplay of subduction, oblique overthrusting, subhorizontal extension, and tectonic erosion (Wagreich, 1993; Wagreich and Faupl, 1994). Processes of subduction tectonic erosion account for particular features of the geodynamic evolution of the NCA during the Late Cretaceous and can be compared with models from recent erosional plate margins (e.g., von Huene, 1986; Ballance et al., 1989; von Huene and Lallemand, 1990).

2. Geological setting

The sediments of the Gosau Group of the NCA (Figs. 1, 2) comprise erosional remnants of the former extensive, locally up to 2500-m-thick Late Cretaceous to Early Tertiary sedimentary cover of the nappe complex of the NCA (Faupl et al., 1987). During the Late Cretaceous, these sediments were deposited near the northern active margin of the Austroalpine domain (Winkler, 1988; Faupl and Wagreich, 1992a), which itself was a part of the Adriatic microplate. This roughly

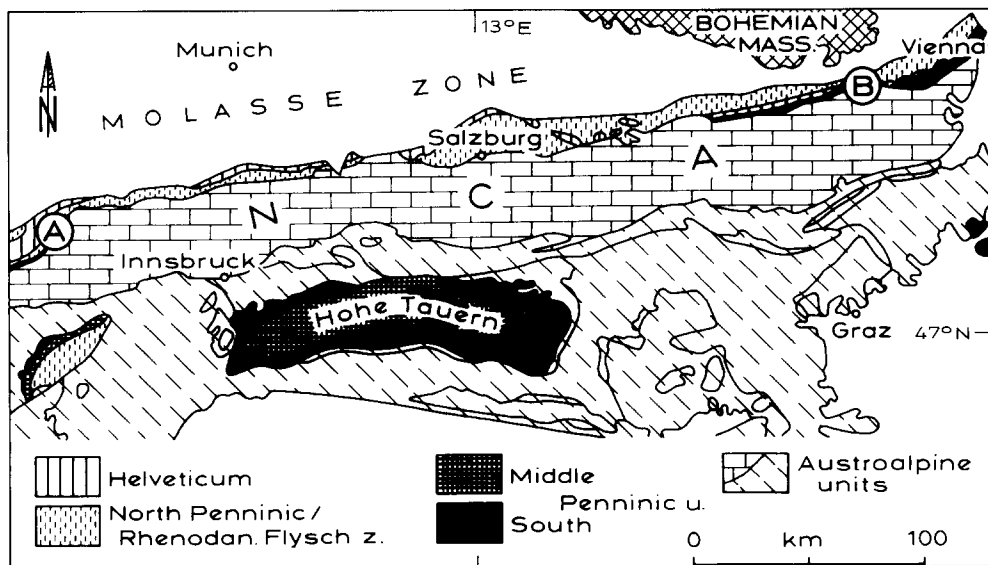


Fig. 1. Generalized tectonic map of the Eastern Alps, depicting units of the lower plate (Helvetic, North Penninic and Middle Penninic units) during Cretaceous convergence, remnants of the South Penninic oceanic plate (A = Arosa/Walsertal zone, B = Ybbsitz zone/Kahlenberg nappe), and the upper plate, the Austroalpine composite unit. The Northern Calcareous Alps (NCA) with the Gosau Group as their cover formed part of the leading margin of the upper plate during the Cretaceous.

east–west-trending margin was characterized by subduction of the northerly and westerly situated Penninic oceanic domain during the Cretaceous. South- to oblique southeastward-directed subduction of the South Penninic oceanic plate seems probable according to the existence of an accretionary wedge to the north of the NCA (Faupl and Wagreich, 1992a). Especially the sedimentary and structural evolution of the South-Penninic Arosa and Walsertal zones (A in Fig. 1) at the

northwestern margin of the NCA (Ring et al., 1988; Winkler, 1988) and the Ybbsitz zone (B in Fig. 1) to the east (Decker, 1990; Homayoun and Faupl, 1992; Schnabel, 1992) give evidence of the evolution of the South Penninic Ocean and accretionary processes at the northern margin of the Austroalpine unit.

The evolution of the active northern margin of the Austroalpine unit started with the onset of subduction, which is dated as Early Cretaceous

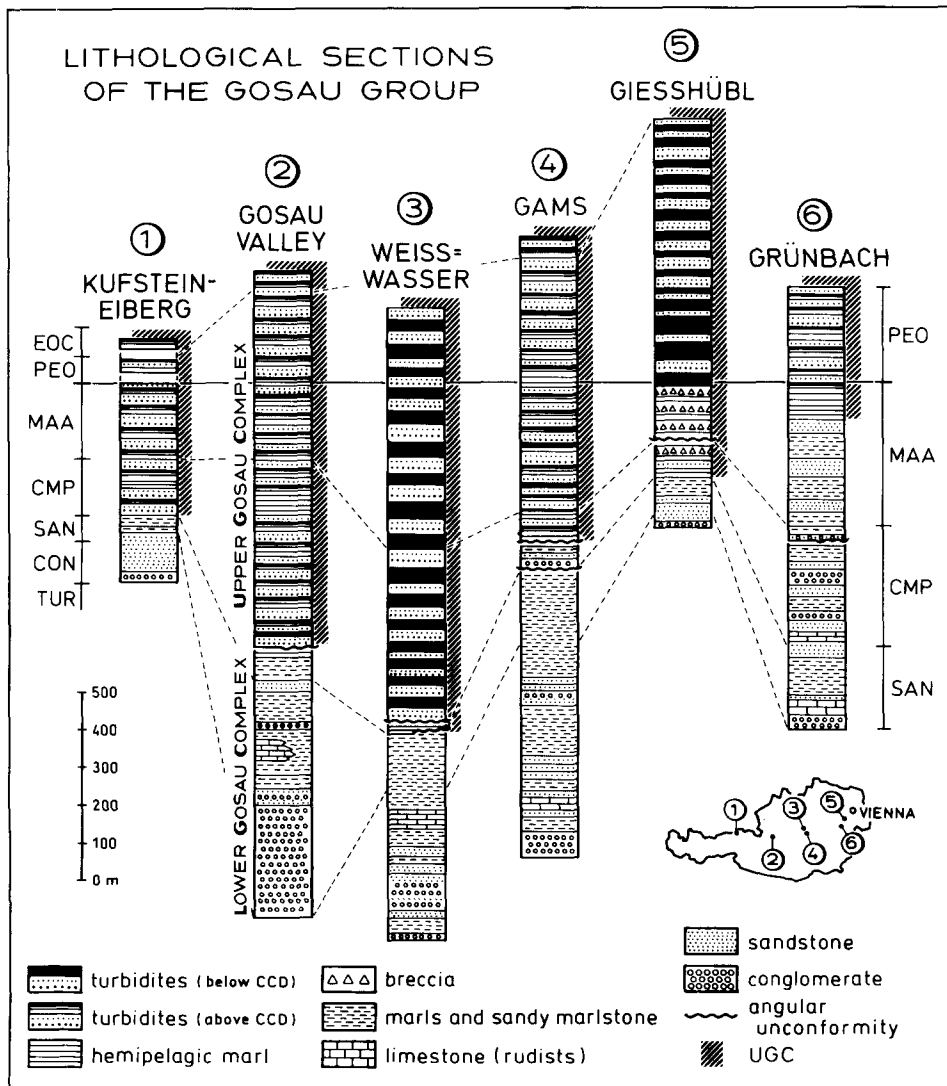


Fig. 2. Schematic stratigraphic columns of selected localities of the Gosau Group of the Northern Calcareous Alps, indicating the sediments of the Lower Gosau Subgroup (= Lower Gosau Complex) and the Upper Gosau Subgroup (= Upper Gosau Complex), and major angular unconformities.

by the occurrences of siliciclastic flysch and breccias on top of pelagic sequences of the South Penninic Ocean (e.g., Winkler, 1988; Decker, 1990). Subduction was accompanied by accretion of oceanic material within a complex accretionary wedge along the northern margin of the Austroalpine unit until the late Turonian/Santonian. During the late Aptian–Cenomanian interval, detrital chrome spinel in sediments of both the Austroalpine NCA south and the South Penninic units north of the wedge proves the emergence and erosion of slices of oceanic crust (Poher and Faupl, 1988) within the accretionary wedge due to continued underplating (e.g., Winkler, 1988; Faupl and Wagneich, 1992a; Homayoun and Faupl, 1992). Detrital glaucophanitic amphiboles and rare lawsonite in sediments of Cenomanian–Turonian age along the whole length of the NCA (Winkler and Bernoulli, 1986; Winkler, 1988; Faupl and Wagneich, 1992b) are evidence for coeval exhumation of subduction-related high-*P* metamorphic rocks within the accretionary wedge.

The NCA originated as a nappe complex of the Upper Austroalpine unit by top-to-northwest (Eisbacher et al., 1990; Linzer et al., 1995—this issue) and/or top-to-north (e.g., Tollmann, 1987; Frank, 1987) decollement of its basement and overthrusting of the originally northern Middle and Lower Austroalpine tectonic units during the Early and Middle Cretaceous. During the deposition of the Gosau Group, the NCA were therefore already situated near the northern Austroalpine leading margin of the Adriatic microplate, receiving coarse “exotic” detritus from the Penninic–Austroalpine accretionary wedge north of the NCA (e.g., Poher and Faupl, 1988; Faupl and Wagneich, 1992a, fig. 3).

From the Late Eocene onwards renewed compression within the orogenic wedge and thrusting onto the European passive margin resulted in a complex deformation and rearrangement of the elements of the former Penninic–Austroalpine active margin (e.g., Behrmann, 1990; Neubauer and Genser, 1990). Later strike-slip faulting in the context of lateral extrusion and tectonic escape (Ratschbacher et al., 1989, 1991a; Neubauer and Genser, 1990; Decker et al., 1993) further complicated the tectonic evolution of the Eastern

Alps. Therefore, pre-Late Eocene structures within the NCA are largely obliterated due to polyphase reactivation during younger extensional and compressional phases (Decker et al., 1993).

3. Sedimentology of the Gosau Group

The Gosau Group of the NCA comprises two sedimentary complexes, often separated by a distinct angular unconformity. The lower part of the succession, the Lower Gosau Subgroup (LGS; Wagneich and Faupl, 1994), consists of terrestrial freshwater to shallow-marine sediments of late Turonian to Campanian/Maastrichtian age (Fig. 2). Coarse, locally up to 400-m-thick alluvial-fan and braid-plain sediments at the base discontinuously overlie older sedimentary strata of the NCA. Karst bauxites, freshwater limestones and coal seams are also widespread deposits at the beginning of this cycle. Sediments of brackish to marine fan-deltas and braid-deltas indicate a slow transgression of the sea. Whereas local systems of alluvial fans and fan-deltas prevailed during the early history of basin formation, a more widespread open-marine shelf transport system dominated during the Santonian. The former basins still represented depressions acting as sediment traps on the shelf (Wagneich, 1988). Marine sedimentation is characterized by thick marls with sandstone intercalations. Storm-influenced sedimentation is very common in these shelf environments. Typically open-marine, highly diversified and plankton-rich microfaunal assemblages (Butt, 1981; Wagneich, 1988) as well as rich Tethyan macrofaunas suggest, that the greater part of the NCA (except the southeastern region) was already covered by a shallow sea during the Santonian. Macrofossils and foraminiferal faunas give evidence of varied water depths up to a maximum of about 150 m (Wagneich, 1988).

Provenance studies on pebbles and heavy minerals point to the existence of “exotic” source areas both to the north and to the south of the NCA during the deposition of the LGS (Faupl et al., 1987). Pebbles of acid and basic volcanic rocks, serpentinites, and chrome spinels in the

heavy mineral fractions, are major components delivered from these source terrains outside of the NCA. Chrome spinel derived from the northern source area gives evidence of the erosion of ophiolites north of the NCA up to the Santonian. These ophiolites have been obducted within the Penninic–Austroalpine accretionary structure, that consisted of oceanic and continental basement slices (e.g., Winkler, 1988; Pober and Faupl, 1988).

A detailed basin analysis in the areas of Gosau and Gams–Weißwasser (for locations see Figs. 2 and 5) indicates the existence of rather small, elongated depocentres during the sedimentation of the LGS, which were characterized by high sedimentation rates. The widths of these basins are in the range of a maximum of 10 to 15 km and basin lengths do not exceed 30 km. Strong lateral thickness changes of individual formations within horizontal distances of a few kilometres at the margins of the depocentres (Wagneich, 1988), and 5–25-m-thick, repetitive coarsening- and thickening-upward cycles (Wagneich, 1989) within alluvial-fan and fan-delta deposits testify to the importance of tectonic control on basin evolution.

The sedimentation of the LGS is terminated by a diachronous phase of deformation, erosion and exhumation of sediments of the LGS and uplift of basement rocks in the greater part of the Gosau basins (Faupl et al., 1987). Where the duration of this tectonic pulse could be constrained biostratigraphically, a short time interval of only 1 to 3 Ma was deduced (Wagneich, 1988). The thickness of eroded sedimentary rocks is estimated to be more than 300 m in the southern part of the Weißwasser area and more than 500 m in the eastern part of the Gams area, indicating local basin inversion and exhumation of fault-bound blocks during the early Campanian. Other parts of the NCA remained more or less stable with only minor erosion such as in the central part of the Gosau Valley area.

The following deposition of the Upper Gosau Subgroup (UGS) records a sudden, distinctly diachronous deepening of the whole NCA resulting in continuous deep-water sedimentation up to the Early to Middle Eocene. Bathyal marls, mass-flow breccias, and sediments of laterally confined slope

aprons and small turbidite fans (e.g., Faupl, 1983; Faupl et al., 1987; Ortner, 1992) are the dominant facies associations within the greater part of the NCA from the Campanian onwards. Bathymetric interpretations based on foraminiferal faunas rich in planktonics indicate bathyal water depths between 500 and 2500 m for the deposition of marls and marly limestones of the Nierental Formation and coeval turbidite formations (Butt, 1981; Wagneich, 1988). In the northern parts of the NCA turbidites were deposited below the local calcite compensation level, as indicated by non-calcareous hemipelagic mudstones in the turbidite-rich sections of Muttekopf, Kössen, Weißwasser and Lilienfeld–Gießhübl (Faupl, 1983; Faupl et al., 1987; Ortner, 1992). This tendency of northward deepening is in accordance with palaeocurrent data from turbidites, slump folds and mass flow deposits, which point to a north-dipping palaeoslope that existed from the Campanian to the mid-Eocene (Faupl et al., 1987). From the late Campanian onwards deep-water sediments are known from every Gosau locality from the western NCA (Muttekopf, Ortner, 1992) to the Gießhübl area at the eastern margin of the NCA (Faupl et al., 1987). As a consequence, it can be concluded that the whole NCA except its southeastern margin was covered by deep-water sediments during that time (Wagneich and Faupl, 1994). Extremely plankton-rich foraminiferal assemblages in carbonate-rich hemipelagites (Butt, 1981) and an early Campanian radiolarian bloom give evidence for oceanic water masses and a Tethys-wide upwelling event (Kuhnt et al., 1989). These facts speak against sedimentation of the UGS in small basins divided by shallow-water or erosional areas as suggested in the models of Leiss (1990) and Moussavian et al. (1990).

The sediments of the UGS clearly onlap onto the basin margins and stable areas of the LGS. A palaeogeographic restoration of the Campanian to Maastrichtian of the NCA shows significant facies differences within only a few kilometres of horizontal distance between sections dominated by thick deposits of mass flows and “proximal” turbidites and those dominated by thinner hemipelagic sediments (Wagneich and Faupl,

1994). This suggests the existence of several deep-water slope depressions filled by turbidites between small submarine structural highs characterized by deep-water hemipelagic deposition, resembling the bathymetric situation of slope basins along active/transform continental margins, e.g., such as the offshore basins of the Californian Continental Borderland (Teng and Gorsline, 1989).

The clastic material of the UGS was derived only from source terrains to the south of the NCA. Due to continued exhumation and progressive erosional unroofing of Austroalpine basement complexes, metamorphic minerals such as chloritoid and, in younger parts of the sections, garnet and staurolite dominate the heavy mineral spectra (e.g., Faupl and Wagneich, 1992a). Chrome spinel, which is still of some significance in sandstones of the UGS, e.g., in the Weißwasser area, was delivered from remnants of an older Tethys suture zone south of the NCA (Pober and Faupl, 1988; Faupl and Wagneich, 1992a, fig. 4). A provenance from metamorphosed Palaeozoic serpentinites can be excluded according to the geochemical data of the chrome spinels (Pober and Faupl, 1988, p. 661).

4. Subsidence history

A general overview of the subsidence history of the Gosau Group of the NCA, including backstripped basement and tectonic subsidence curves for major Gosau localities, was given in Wagneich (1991). This paper deals mainly with the geodynamic evolution of the UGS and therefore concentrates on data from continuous deep-water sections of the Gosau Group.

4.1. Backstripping method

Tectonic subsidence curves were constructed for several sections of the Gosau Group using standard backstripping methods (Steckler and Watts, 1978). Composite sections for the central basin areas, representing depocentres especially for the LGS, were used. Thickness and lithology

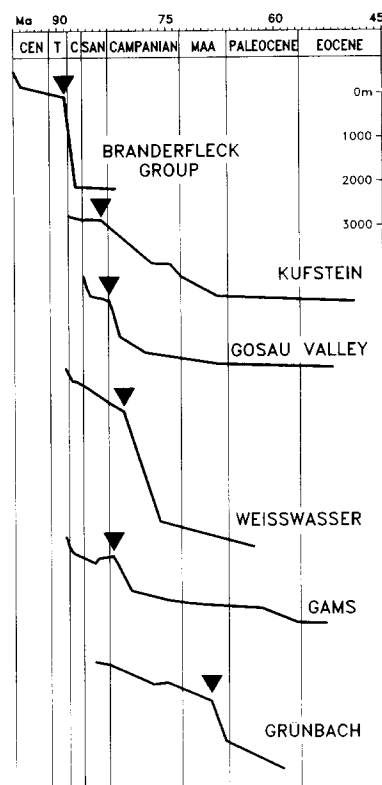


Fig. 3. Tectonic subsidence curves for selected localities of the Gosau Group and the Branderfleck Group of the Northern Calcareous Alps. Normal backstripping procedures have been applied. For sections and locations see Figs. 2 and 4. Time scale after Harland et al. (1989). Triangles mark diachronous onset of deepening attributed to a phase of subduction tectonic erosion.

data of individual formations and members used for the construction of the curves shown in Fig. 3 were taken from my own observations (Fig. 2 and Appendix) and published sections (Branderfleck Group–Stoffelmühle section: Weidich, 1984; Kufstein–Eiberg section: Ibrahim, 1976; Gosau Valley area: Wagneich, 1988; Gams: Kollmann, 1964, and Wagneich, unpubl. data; Weißwasser: Faupl, 1983). Decompaction of individual lithologies (sandstone, mudstone, nannofossil ooze, limestone), a crucial point in the backstripping procedure for Alpine sections, was calculated by assuming a simplistic exponential model of compaction based on empirical porosity curves (Wildi et al., 1989; Loup, 1992). The effect of cementa-

tion was taken into consideration by recompacting the sediment only up to the average content of cement known from thin section modal analysis. Although this method gives only a rough estimate of the complex compaction–cementation history of the Gosau sediments, it forms a base for systematic comparison of the subsidence curves.

Palaeobathymetric estimates are based on sedimentological and faunal evidence, especially the bathymetric distribution of both planktonic and benthonic foraminifera (e.g., Butt, 1981; Kuhnt et al., 1989; Wagreich and Faupl, 1994). For deep-water sediments, minimum values of depositional water depths were used. Short-time sea-level variations were not incorporated into palaeobathymetric estimates, although the long-term curve of Haq et al. (1987) was used as a reference level. Tectonic and basement subsidence curves were generated by a computer program (SUBGOS, available from the author) based on similar programs by Wildi et al. (1989).

4.2. Tectonic subsidence

The resulting curves for tectonic subsidence record multiphase, segmented subsidence paths for most of the investigated Gosau sections as well as for the Branderfleck Group (Fig. 3). A two-phase subsidence history is typical for the major Gosau localities of the middle and eastern parts of the NCA, such as the type area of the Gosau Valley, Weißwasser, Gams, and Grünbach (for details see Wagreich, 1991).

The first subsidence phase of the Gosau Group coincides with the deposition of terrestrial to shallow-water sediments of the LGS. The onset of subsidence is highly diachronous from late Turonian (e.g., Gams) up to Santonian–Campanian (Grünbach, Fig. 3). The initial basin formation is attributed to a rapid and short-lived subsidence event of several hundreds of metres of tectonic subsidence of only about 1 Ma duration (first steep part of curves in Figs. 3 and 4), characterized by the sedimentation of coarse alluvial and fan-delta sediments at the base of most of the Gosau sequences. This resulted in the

formation of local, partly underfilled basins (Pitman and Andrews, 1985), because sedimentation could not keep up with rapid initial subsidence rates. Therefore, the basins deepened very rapidly from subaerial environments to open marine shelf depths within the first 1 to 2 Ma. Tectonic subsidence rates as high as 600 m/Ma can be reconstructed for this phase (Fig. 4).

After this event the tectonic subsidence rates decreased constantly to almost zero (horizontal part of curves of the Gosau Valley area and Gams in Figs. 3 and 4), resulting in a regressive tendency and filling of the basins with prograding shallow-marine sediments. Prolonged basement subsidence during this time interval is mainly a consequence of the isostatic response to the load introduced by the sediment itself.

After a short time interval of rock uplift and erosion resulting from deformation of the basins of the LGS, the second subsidence phase shows a distinct, regular shift in time from the west to the southeast of the NCA. Subsidence started in the western NCA not later than in the Santonian and reached the southeastern parts as late as the Maastrichtian (Fig. 5). If the partly contemporaneous sedimentation of the Branderfleck Group of the northernmost parts of the western NCA (Weidich, 1984) is also considered as a result of this event, the subsidence into bathyal to abyssal depths started in the northwestern units as early

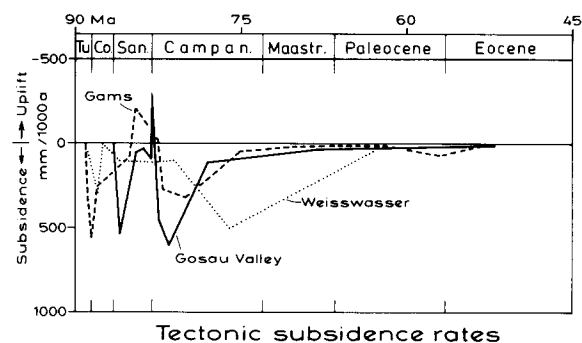


Fig. 4. Rates of tectonic subsidence for sections of the Gosau Group in the Gosau Valley, Gams and Weißwasser area. Two subsidence cycles, corresponding to the deposition of the Lower and the Upper Gosau Subgroup, are separated by uplift up to 300 m.

as in late Turonian/early Coniacian times (Fig. 3). The deepening from neritic to bathyal or even abyssal depths below the local CCD occurred in a time interval of 1 to 3 Ma (Wägreich, 1988, 1991). Tectonic subsidence rates as high as 700 m/Ma are reconstructed for this event. Depth profiles for the late Campanian along N–S-trending palaeogeographic reconstructions, e.g., along a section from Weißwasser to south of Gams, give evidence of a northward tilting of the NCA. Therefore, the highest subsidence rates and the deepest parts of the basins occurred in the northernmost tectonic units of the NCA (Kössen, Weißwasser, Gießhübl area), whereas the southeasternmost units such as the Grünbach area remained stable (Faupl et al., 1987). After this event the subsidence decreased slowly, and the NCA were characterized by bathyal to abyssal sedimentation up to the Early to Middle Eocene.

5. Basin models

Data on sedimentology, basin geometry, and subsidence of the Gosau Group of the NCA strongly suggest that the LGS and the UGS should be considered as individual and genetically different steps in the evolution of Late Cretaceous basins in the NCA. This is demonstrated by the segmented subsidence curves with an intervening phase of uplift and deformation. Therefore, inde-

pendent models are suggested for basin formation and subsidence.

5.1. Lower Gosau Subgroup

The first peak of subsidence at the beginning of the deposition of the LGS is attributed to the formation of basins along SE–NW- to E–W-striking strike-slip or oblique-slip faults (Wägreich, 1988, 1991). Most of these basin margin faults were reactivated during Tertiary compressional and extensional events, and therefore, their reconstruction is based mainly on facies mapping, palaeocurrent patterns, and pronounced changes of thicknesses of formations. At the southern margin of the Gosau Valley area, Wägreich et al. (1993) found Cretaceous extensional features such as tension gashes and Neptunian dikes related to pull-apart extension along a dextral strike-slip fault.

The Late Cretaceous component of strike-slip faulting in the NCA geometries seems to be a consequence of dextral transpressional deformation of the Austroalpine unit (Ring et al., 1988; Linzer et al., 1995-this issue). Transpression is interpreted to be the result of oblique subduction below the leading margin of the Austroalpine unit by Faupl and Wägreich (1992a). Individual blocks probably subsided in a complex strike-slip-dominated tectonic setting. Whereas a pull-apart basin origin was inferred for the depocentre

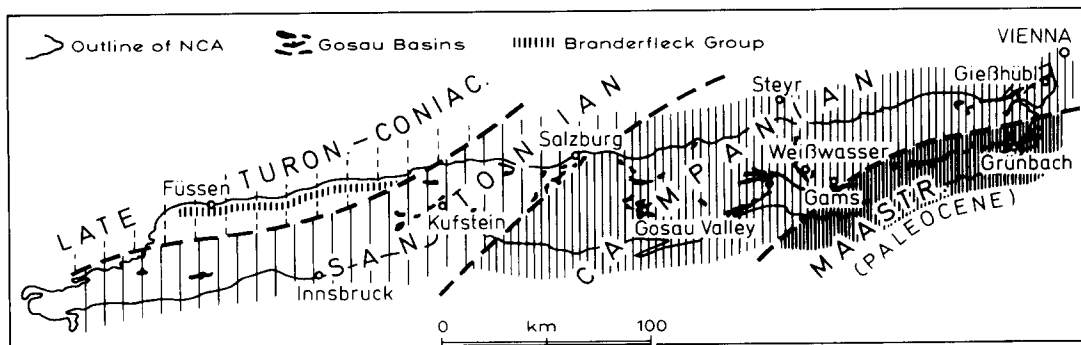


Fig. 5. Isolines of the onset of the second subsidence phase ascribed to subduction tectonic erosion. The significant time shift from the northwest to the southeast of the NCA is interpreted as a consequence of oblique collision and overriding of an oceanic swell or ridge. Isolines are drawn from the subsidence paths of the basins of the Gosau Group and the Branderfleck Group (cf. Fig. 3 and Wägreich, 1991).

of the LGS of the Gosau Valley (Wägrich et al., 1993), the existence of other geometries like fault-wedge or ramp depressions in the sense of Mann et al. (1983) cannot be excluded for other areas of the NCA. Cretaceous extensional structures in the Gosau Valley area (Wägrich et al., 1993) and the lack of evidence for continuous thrusting during the deposition of the LGS (e.g., growing anticlines, progressive, syntectonic internal unconformities or syndeformational rotations; e.g., Anadón et al., 1986) argue against synclinal/transfer fault/piggyback basin models for the Gosau Group recently suggested by Leiss (1990) and Eisbacher et al. (1990).

The sudden subsidence of small, fault-bound basins within such an overall transpressional regime could have been induced by short-lived orogen-parallel extension of thickened Austroalpine crust, which resulted from the Lower to Middle Cretaceous crustal shortening and nappe stacking in the Austroalpine unit (e.g., Frank, 1987; Behrmann, 1990; Neubauer et al., 1992). Preliminary forward modelling of subsidence (Wägrich et al., 1993) indicates similarities to the subsidence histories of pull-apart basins (Pitman and Andrews, 1985; Cloetingh et al., 1992) and collapse basins on overthickened crust (Seguret et al., 1989). Both are characterized by a large amount of initial isostatic subsidence and the lack of significant thermal subsidence. The maximum amount of crustal extension during this phase can be estimated by considering extensional subsidence models by Hellinger and Sclater (1983) and Pitman and Andrews (1985). Basin modelling for the Gosau Valley area (initial tectonic subsidence about 450 m, total tectonic subsidence about 500–530 m after 5 Ma) with standard values for lithospheric parameters (Hellinger and Sclater, 1983, table 1) and incorporating crustal values in excess of 25 km (Behrmann, 1990) result in extensional values of about 5 to 15%. These values are in accordance with measured extension from the Gosau Valley area (Wägrich et al., 1993).

5.2. Upper Gosau Subgroup

The interpretation of the second subsidence phase of the Gosau Group is problematic regard-

ing common sedimentary and subsidence models for extensional (e.g., McKenzie, 1978; Hellinger and Sclater, 1983), extensional pull-apart (e.g., Pitman and Andrews, 1985; Cloetingh et al., 1992) and compressional flexural basins (e.g., Jordan, 1981; Flemings and Jordan, 1990). Each of these three traditional end-member models fail to explain the intrinsic characteristics of the UGS: (1) the short-lived event of uplift and deformation preceding a short time interval of rapid subsidence; (2) the time lag of subsidence of about 15 to 20 Ma between the west and the southeast of the NCA; and (3) the northward tilting of the whole NCA.

Extensional and pull-apart models are not able to explain the stepwise deepening of the whole NCA into bathyal or even abyssal depths unless unreasonable amounts of extension are assumed, for which no structural evidence exists in the Gosau basins and the underlying nappes of the NCA. Forward subsidence modelling according to physical models given by McKenzie (1978) and Hellinger and Sclater (1983) based on data from the Weißwasser section (initial tectonic subsidence of more than 2000 m in about 8 Ma, "thermal" subsidence of more than 700 m in 10 Ma) results in theoretical extensional values of more than 100% to 150% (according to applied crustal and lithospheric thicknesses). Such high amounts of (crustal) extension within the NCA during the Late Cretaceous can be excluded according to recent structural analysis by K. Decker (pers. commun., 1994), although bulk E–W stretching of up to 100% was suspected for the Austroalpine unit in the Late Cretaceous by Behrmann (1990) based on the evolution of basement complexes. Although the segmented subsidence curve could be a result of basin formation and basin deformation at releasing and restraining bends of strike-slip faults, this mechanism fails to give an explanation for widespread subsidence into bathyal–abyssal depths and for the elimination of the accretionary prism along the whole length of the NCA as indicated by the lack of "exotic" detritus from the north in the sediments of the UGS.

Models of compressional basin subsidence due to overthrusting and flexural subsidence as a re-

sult of thrust loading and stacking of nappes from south-southeast to north-northwest of the NCA (Leiss, 1990) result in the assumption of unrealistic high crustal loads to account for total tectonic subsidence values of up to 3000 m. According to simple loading models of an elastic lithosphere (Jordan, 1981) a thrust load 20 km wide and 10 km thick would only produce a maximum subsidence adjacent to the load of about 1000 to 1400 m, depending on the assumed flexural rigidity of the lithosphere and sediment and mantle densities, respectively. There is no evidence for the existence of such an additional crustal load upon the nappes of the NCA during the Late Cretaceous. The application of a foreland flexural type of basin fill model (Flemings and Jordan, 1990) for the Gosau basins as suggested by Leiss (1990) would also predict that the deepest parts of such a basin should have been adjacent to the theoretical load in the south-southeast of the NCA, close to north-northwestward-moving thrust sheets of the tectonically higher nappe systems of the NCA. This is the opposite palaeobathymetric situation to the observed facies distributions, which place the deepest parts of the basin in the northern NCA (Butt, 1981; Faupl et al., 1987; Wägrich and Faupl, 1994). In addition there is no proof by structural or sedimentological data for synsedimentary compression and thrust movement within the NCA during the continuous Late Cretaceous to Early Tertiary deposition of the Gosau Group, apart from the distinct and short-lived deformational phase between the sedimentation of the LGS and the UGS.

6. Model of subsidence due to tectonic erosion

As a consequence of the inability of traditional basin-forming models to explain the subsidence history of the UGS, a new model involving deepening of the whole NCA due to subduction tectonic erosion is suggested (see also Faupl, 1991; Wägrich, 1991). Tectonic erosion of frontal parts of the overriding plate during subduction of oceanic crust is now recognized as one end-member stage of recent active plate margins in contrast to active margins characterized by accre-

tionary processes (e.g., Moore et al., 1986; von Huene, 1986; Ballance et al., 1989; von Huene and Lallemand, 1990). Reports about a phase of tectonic erosion within ancient active margins now being part of Alpine-type fold-and-thrust belts are, however, very rare and poorly constrained, based largely on P - T - t data on the evolution of metamorphic basement complexes (Frank, 1987; Polino et al., 1990).

Processes of subduction erosion of parts of the accretionary wedge and fore-arc/arc basement slices along active margins are recognized mainly from seismic lines indicating major unconformities and gaps in accretion and sediment accumulation, and from large-scale gravity failure along the slope at non-accretionary margins. Short-lived, sudden subsidence events of the fore-arc wedge and adjacent regions of the overriding plate and a landward retreat of the margin front are ascribed to processes of subduction erosion at these margins. Studies of modern trenches characterized by subduction of positive topographic features of the downgoing oceanic plate such as seamounts and mid-oceanic ridges (e.g., Lallemand and Le Pichon, 1987; Ballance et al., 1989; Collot and Fisher, 1989; Lallemand et al., 1989; Nelson and Forsythe, 1989; Collot et al., 1992) and modelling of the behaviour of accretionary wedges during ridge subduction (Lallemand et al., 1992) led to a geodynamic model for subduction tectonic erosion and subsidence along active plate margins. The impinging topographic high produces a landward shifting and deforming swell within the accretionary wedge, followed by gravitational failure and collapse of the fore-arc after the overriding of the seamount (Lallemand and Le Pichon, 1987; Collot and Fisher, 1989; Ballance et al., 1989; von Huene and Lallemand, 1990; Lallemand et al., 1992; Osmaston, 1992).

During the ongoing subduction of a topographic high, subduction erosion is not only confined to the accretionary prism but may also affect basal parts of the continental crust of the overriding plate by erosionally thinning the upper plate from below (subcrustal or basal erosion of von Huene and Lallemand, 1990). This results in a distinct succession of uplift, erosion, trenchward tilting, and subsidence of the whole fore-arc

and the adjacent plate margin. Prolonged subsidence of the whole plate margin up to several kilometres during 10 to 20 Ma is largely the consequence of isostatic accommodation due to crustal thinning and the replacement of light continental crust by more dense oceanic crust (Langseth et al., 1981; Birch, 1986).

7. Evidence for tectonic erosion within the NCA

Many of the observed peculiarities of the UGS can be explained by applying models of the behaviour of overriding plates during the subduction of topographic highs on the oceanic plate such as seamounts or aseismic ridges. The event of deformation and uplift within the NCA is therefore attributed to the beginning of the subduction of the leading edge of a topographic high (e.g., Gardner et al., 1992). The duration of this phase, i.e. 1–2 Ma, is similar to that observed during the deformation and subsidence of accretionary prisms as a result of seamount subduction (Ballance et al., 1989; von Huene and Lallemand, 1990). This deformation is followed by rapid subsidence into bathyal to abyssal depths as a consequence of basal erosion. As an additional hint the basement subsidence curves for the Miocene to recent history of the erosive Japan margin are comparable in shape, magnitude, and duration to those of the UGS, e.g., the Gosau Valley and the Weißwasser areas (Fig. 6). Basement subsidence rates of 300 to 700 m/Ma at the beginning of the deposition of the UGS have about the same size range as those observed at the Japan Trench (320 m/Ma) and the lower slope off Peru (400–500 m/Ma) during the onset of tectonic erosion (von Huene and Lallemand, 1990).

Trenchward tilting of the frontal portion of the overriding plate after tectonic erosion is observed at the active margin off Puerto Rico (Birch, 1986) and at erosional surfaces along the Japan and Peru margins (von Huene and Lallemand, 1990). This corresponds to the asymmetric northward deepening of the NCA during the Campanian–Maastrichtian (Faupl et al., 1987). Tilting of the NCA is accompanied by a drastic change in the palaeotransport system: material derived from the

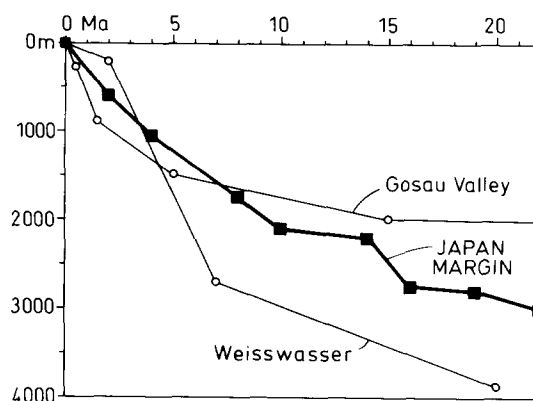


Fig. 6. Basement subsidence of the Japan margin (modified after von Huene and Lallemand, 1990) and basement subsidence of the Upper Gosau Subgroup of the Gosau localities Gosau Valley and Weißwasser. Magnitudes and durations of the subsidence of the UGS are comparable to that caused by Neogene tectonic erosion along the Japan margin.

former accretionary prism north of the NCA, which is typical for the LGS, is missing from sediments of the UGS. This can be ascribed to the elimination of the accretionary prism by subduction during tectonic erosion.

The pronounced diachronicity of the subsidence event showing a regular time shift from the northwestern part of the NCA to the southeastern parts (Fig. 5) can be explained by the overriding of an oblique, approximately SW–NE-trending topographic high on the oceanic South Peninsular plate (Fig. 7). Oblique subduction resulted in an southeastward younging of the onset of deformation and subsidence from late Turonian/early Coniacian to Maastrichtian, a time shift of about 10 to 15 Ma over a distance of about 400 km. Comparable migration rates of the locus of collision have been reconstructed for the collision of the highly oblique seamount chain of the Louisville Ridge at the Tonga Trench (180 km/Ma, Ballance et al., 1989) and a similar shift has been reported for the subduction of the Nazca Ridge off Peru (von Huene, 1986; von Huene and Lallemand, 1990) and the collision of the actively spreading Chile Ridge with the Peru–Chile Trench (Nelson and Forsythe, 1989; Murdie et al., 1993).

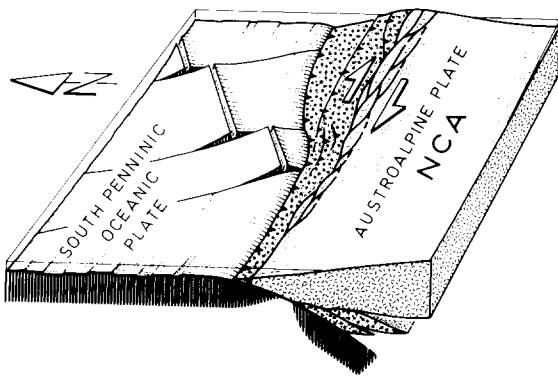


Fig. 7. Dynamic model of tectonic erosion for the NCA and the Penninic–Austroalpine active margin during Campanian/Maastrichtian times. Oblique collision and subduction of a dissected ridge on the South Penninic oceanic plate caused trenchward tilting and subsidence of the NCA due to sub-crustal erosion in the west, whereas in the east of the collision site, accretion was still dominating.

8. Discussion

The application of a model of subduction tectonic erosion to the Late Cretaceous evolution of the northern Austroalpine margin raises questions, among others, about the nature of the topographic high, plate convergence rates, and the magnitude of tectonic erosion necessary to account for the subsidence of the NCA. Although no direct evidence for the kind of the topographic high exists, the diachronous collision and subduction of an oblique spreading ridge of the South Penninic Ocean is a likely cause for the change from an accretionary to an erosive margin during the Late Cretaceous. The lack of signs of significant magmatic or thermal activities within the upper plate (e.g., DeLong et al., 1978; Hibbard and Karig, 1990) suggests that this former spreading ridge may have been inactive by that time.

An estimate of the size of the corresponding crustal wedge removed during tectonic erosion can be computed by considering the total amount of subsidence within the NCA after the sedimentation and deformation of the LGS. Neglecting effects of isostatic compensation due to the replacement of continental crust by high-density oceanic lithosphere and the lack of data about

the detailed configuration (e.g., geometry of the palaeoslab) of the Penninic–Austroalpine active margin, the total subsidence of the NCA gives a minimum value for the crustal material eroded during the Campanian–Maastrichtian (von Huene and Lallemand, 1990). A palaeobathymetric NW–SE cross-section for the late Campanian/Maastrichtian in the area of Weißwasser–Gams (for localities see Fig. 5) gives a minimum width of the Late Cretaceous NCA of about 60 to 80 km with maximum water depths up to 3000 m in the northwest (Weißwasser area, Faupl, 1983) and neritic environments in the southeast (Faupl et al., 1987; Wagreich and Faupl, 1994). As a result, erosion of a minimum crustal wedge of a cross-sectional area of about 90 to 120 km² is calculated to account for the given subsidence. This magnitude can be compared with that of the Neogene tectonic erosion along the Peru margin in the Lima basin area, where von Huene and Lallemand (1990) reported erosion of a cross-sectional area of about 290 km². Given a time interval of about 14 Ma (Campanian–middle Maastrichtian, time scale of Harland et al., 1989) for the subsidence to reach the southern part of the investigated cross-section in the eastern part of the NCA, an apparent plate convergence rate of about 4 to 6 mm/a is calculated, although this figure gives only a rough estimate of plate convergence because of great uncertainties regarding the actual subduction direction and the width of the NCA in the Late Cretaceous.

The evolution of the northern Austroalpine active margin from accretion during the Early Cretaceous to subduction tectonic erosion in the Late Cretaceous bears similarities to the polyphased fore-arc evolution recorded in the Hikurangi accretionary prism of New Zealand (Ferriere et al., 1992). Structural data from this accretionary prism indicate an evolution from a Neogene accretionary stage to a phase of tectonic erosion, subsidence and fore-arc basin sedimentation of about 16 Ma, to renewed accretion in recent times. Phases of accretion are accompanied by compressional deformation and seaward-directed thrusting, whereas, during times of subsidence and tectonic erosion, an extensional tectonic regime prevails.

9. Conclusions

The Penninic–Austroalpine active margin was characterized by accretion during the Early Cretaceous. Mid-Cretaceous thrusting in the Austroalpine unit was followed by the development of strike-slip basins of the Lower Gosau Subgroup within the Northern Calcareous Alps, probably as a consequence of orogen-parallel extension. From the late Turonian/Santonian onwards the former accretionary margin changed step-by-step to an erosive stage as evidenced by the subsidence history of the Branderfleck Group and the Gosau Group of the NCA and the elimination of the accretionary wedge. The change in the behaviour of the active margin is attributed to the collision and subduction of an oblique, SW–NE-trending topographic high, which created a wave of uplift, deformation and subsidence that migrated through the NCA from the northwest to the southeast.

Coeval with the tilting of the NCA due to subduction tectonic erosion of frontal parts of the Austroalpine unit during the Santonian–Campanian, cooling ages of metamorphic minerals indicate exhumation and unroofing of the Austroalpine basement complexes to the south of the NCA (e.g., Frank, 1987; Behrmann, 1990; Neubauer et al., 1995–this issue). Processes of subduction erosion were probably dominant during the whole interval of deep-water sedimentation of the Gosau Group until the Middle to Late Eocene, as there is no evidence for the formation of an accretionary prism during that time. During the Late Eocene, plate collision and thrusting related to a major shift in the motions of the African and European plates (e.g., Ring et al., 1988; Dewey et al., 1989; Decker et al., 1993) terminated the sedimentation of the Gosau Group in the NCA, marking the final closure of the Penninic Ocean and collision of the Adriatic microplate with the southern passive margin of the European plate.

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Appendix

Input data and calculated backstripped subsidence for composite sections of the Gosau Group of the Gosau Valley (Wagreich, 1988), Gams (Wagreich, unpubl. data; Kollmann, 1964), and Weißwasser (Faupl, 1983; Wagreich, unpubl. data). Time scale modified after Harland et al. (1989). Th = thickness of lithological unit, PWD = palaeowaterdepth, Lithology (proportions of sandstone/mudstone/nannofossil ooze/limestone), St = backstripped tectonic subsidence, Sb = backstripped basement subsidence; cement proportion 15%.

	Time (Ma)	Th	PWD	Lithology	St	Sb
Gosau						
1	86.5–86.0	300	0	0/.8/.2/0	268	448
2	–85.5	80	150	.6/.1/.3/0	453	692
3	–84.5	250	50	.3/.3/.4/0	495	908
4	–83.8	120	15	.3/0/.6/.1	511	1001
5	–83.1	100	50	.4/0/.4/.2	575	1129
6	–83.0	30	10	.8/0/0/.2	548	1119
7	–82.5	60	200	.3/.1/.6/0	772	1384
8	–81.5	30	800	.2/.4/.4/0	1372	2006
9	–78.0	400	1000	.6/.2/.2/0	1730	2613
10	–68.0	400	1000	.1/.2/.7/0	1990	3108
11	–52.0	300	1000	.5/.2/.3/0	2072	3365
Gams						
1	89.0–88.8	70	0	/1/0/0	64	106
2	–88.5	200	15	.5/.3/0/.2	231	397
3	–88.0	100	30	.3/.4/.3/0	358	584
4	–85.0	250	100	.1/.4/.5/0	585	987
5	–84.5	20	30	.9/.1/0/0	479	898
6	–82.5	50	15	.8/.2/0/0	432	899
7	–82.0	15	150	.1/.5/.4/0	569	1049
8	–80.0	1	800	0/0/1/0	1203	1689
9	–75.0	25	1000	.1/.3/.6/0	1412	1917
10	–72.0	60	1000	.2/.4/.4/0	1484	2016
11	–70.0	70	1000	.8/.2/0/0	1515	2087
12	–66.5	30	1000	.1/.3/.6/0	1553	2141
13	–62.0	25	1000	.1/.6/.3/0	1596	2189
14	–57.0	300	1200	.7/.3/0/0	1923	2696
15	–53.0	40	1200	.1/.8/.1/0	1948	2749
Weißwasser						
1	89.0–88.0	240	30	.5/.3/.2/0	289	433
2	–87.5	50	15	.2/0/0/.8	292	465
3	–86.0	100	50	.3/0/.7/0	435	669
4	–83.0	100	300	.2/0/.8/0	778	1071
5	–81.0	10	500	0/.3/.7/0	974	1273
6	–76.0	0	3000	1/0/0/0	3471	3771
7	–63.0	1000	3000	.4/.3/.3/0	4037	4935

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