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# The Dachstein paleosurface and the Augenstein Formation in the Northern Calcareous Alps – a mosaic stone in the geomorphological evolution of the Eastern Alps

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**Abstract** The central and eastern areas of the Northern Calcareous Alps (NCA) are characterized by remnants of the Dachstein paleosurface, which formed in Late Eocene (?) to Early Oligocene time and is preserved with limited modification on elevated karst plateaus. In Oligocene time, the Dachstein paleosurface subsided and was sealed by the Augenstein Formation, a terrestrial succession of conglomerates and sandstones, which are only preserved in small remnants on the plateaus, some in an autochthonous position. Thermochronological data suggest a maximum thickness of the Augenstein Formation of >1.3 km, possibly >2 km. The age of the Augenstein Formation is constrained by the overall geological situation as Early Oligocene to earliest Miocene. Fission track age data support an Early Oligocene age of the basal parts of the formation. The source area of the Augenstein Formation consisted predominantly of weakly metamorphic Paleozoic terrains (Greywacke Zone and equivalents) as well as the Late Carboniferous to Scythian siliciclastic base of the NCA to the south of the depositional area. To the west, the Augenstein Formation interfingered with the Tertiary deposits of the Inntal. Sedimentation of the Augenstein Formation was terminated in Early Miocene time in the course of the orogenic collapse of the Eastern Alps. The Augenstein sediments were eroded and redeposited in the foreland Molasse zone. From Pannonian times (~10 Ma) on, the NCA and the denuded Dachstein surface experienced uplift in several pulses. The Dachstein paleosurface has been preserved in areas, in which thick limestone sequences allowed subsurface erosion by cave formation and thus prevented major surface erosion.

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## Introduction

The Northern Calcareous Alps (NCA) are part of the (Upper) Austro-Alpine mega-unit of the Eastern Alps and consist of a sedimentary succession ranging from Late Carboniferous to Eocene times. This succession is dominated by Middle and Late Triassic platform carbonates, which are together 2–3 km thick and are the prime determinant of the landscape in the NCA. A large part of the central and a minor part of the eastern NCA is characterized by karst plateaus, mostly between 1,800 and 2,500 m in elevation, some of more than 100 $km^2$ extent (Fig. 1). The plateaus are developed on limestone sequences, mostly the Late Triassic Dachsteinkalk, whereas the widespread dolomites (mainly Late Triassic Hauptdolomit) are generally not plateau-forming (for approximate location of the Hauptdolomit/Dachsteinkalk boundary, see Fig. 1b).

The karst plateaus represent parts of a paleosurface, which carries scarce remnants of Tertiary conglomerates and sandstones of the Augenstein Formation. There is a long-lasting debate about the mode and significance of the paleosurface in terms of monophase versus polyphase formation and its pre- or post-Augenstein age. Also controversial are the age and the relation of the Augenstein Formation to its basement, i.e., primary versus redeposited. This paper describes and characterizes the Augenstein Formation and its relation to the plateau surfaces. The results are of importance for the reconstruction of the geological and geomorphological evolution of the central and eastern NCA in the Neo-Alpine history, i.e., during Oligocene to Recent times. Our model for the evolution of the paleosurface and the Augenstein Formation is based on geomorphological observations,

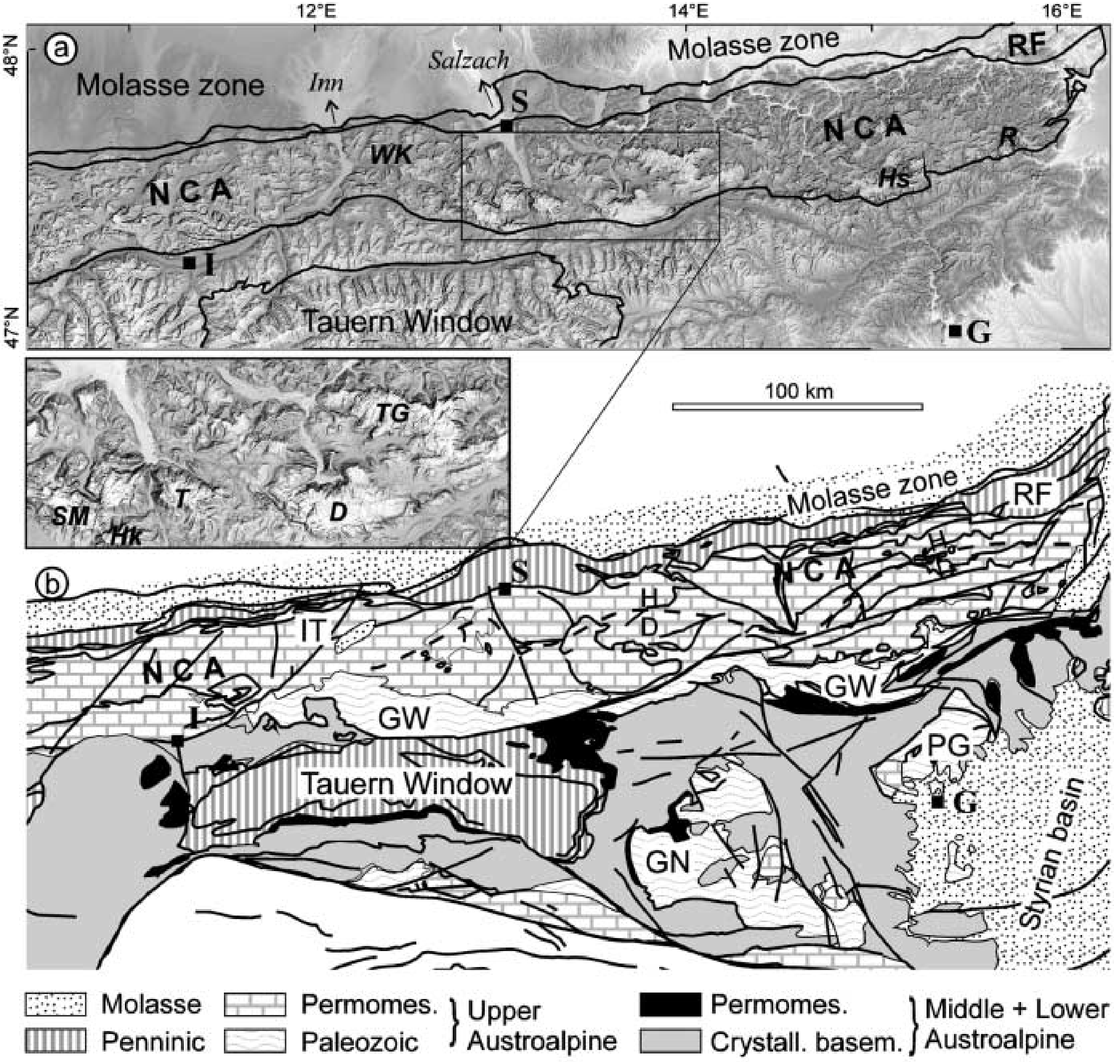



**Fig. 1** **a** Digital elevation model of the Northern Calcareous Alps (NCA) and adjacent areas, enlargement shows central NCA. Plateaus with paleosurface remnants mentioned in the text: *D* Dachstein; *Hk* Hochkönig; *Hs* Hochschwab; *R* Rax; *SM* Steinernes Meer; *T* Tennengebirge; *TG* Totes Gebirge. *WK* Wilder Kaiser (no plateau). **b** Geological sketch map of the Eastern Alps. *Dashed line* in NCA separates Dachsteinkalk (*D*) and Hauptdolomit (*H*) facies zones. *RF* Rhenodanubian flysch zone; *GW* Greywacke Zone; *PG* Paleozoic of Graz; *GN* Gurktal nappe. *G* Graz; *I* Innsbruck; *S* Salzburg

sedimentological analysis, and thermochronological studies.

After a short evaluation of existing concepts on the Augenstein sediments and the karst paleosurface(s), we examine the composition of the Augenstein sediments and their geological source units. Zircon and apatite fission-track data are used to obtain information about the tectonothermal situation in the source area and to sketch a more precise picture about the exposed material. The age of the Augenstein Formation is discussed on the basis of geological and geochronological constraints, and the thickness of Augenstein sediments is estimated by mass calculation and apatite fission-track data. Finally, the evolution and uplift history of the karst plateaus are sketched and attempts on cave dating reported because cave formation in the karst massifs is related to their uplift history.

## Previous concepts

Remnants of ancient planation surfaces, mostly attributed to the Miocene or Oligocene epoch have since long been recognized in the eastern part of the Eastern Alps (Fig. 1; see Winkler-Hermaden 1957). In the Northern Calcareous Alps (NCA), the elevated karst plateaus form striking and significant geomorphological features, which only occur in their central and eastern parts. The western part of the NCA – which embraces the area west of the Inn river water gap – completely lacks plateaus and, in contrast, is exclusively characterized by acute crests and ridges. This is considered to be because of its different geological and geomorphological evolution in Oligocene and Neogene times. Brügel (1998) and Frisch et al. (1998, 2000) showed that the western NCA were already a mountainous and eroding area in Late Oligocene times, when the NCA further east were an area of sediment accumulation.

There are mainly two lines of thoughts concerning the interpretation of the elevated plateau surfaces. (1) The idea of the “Rax landscape” (Lichtenecker 1924, 1926; after the Rax plateau, see Fig. 1a) is that of a one-phase uniform peneplained paleosurface, which was tectonically dismembered in later time. (2) This contrasts to the idea of polycyclic piedmont benchland (Piedmonttreppe) formation with several periods of tectonic quiescence, in which planation surfaces of limited extent formed, and repeated phases of uplift (Götzinger 1913; Seefeldner 1926; Winkler-Hermaden 1957; Langenscheidt 1986). Winkler-Hermaden correlated paleosurface remnants in the Austro-Alpine basement south of the NCA and east of the Tauern window (Fig. 1) with the NCA plateaus and defined six levels with downward younging ages. Tollmann (1986) denied the existence of the “Rax landscape” arguing that a single, continuous paleosurface, as defined by Lichtenecker (1924), did not exist. Generally, a Miocene formation age was attributed to the paleosurface remnants of the higher levels.

The concept of polycyclic planation surface formation does not take into account that there was considerable Neogene (mainly Early to Middle Miocene) block segmentation along a prominent, mainly strike-slip fault pattern and subsequent differential uplift (Lichtenecker 1924, 1926; Ratschbacher et al. 1991; Frisch et al. 2000).

The Augenstein Formation consists of sandstones and conglomerates rich in polycrystalline quartz. It was deposited by rivers collecting their load from a source in the south (Simony 1851; Götzinger 1913; Winkler-Hermaden 1957). Most authors attributed a Miocene age to the Augenstein Formation (e.g., Winkler-Hermaden 1957, with references therein). However, from the fact that pebble material of the Augenstein Formation (among other material) is also contained in uppermost Early Oligocene to earliest Miocene molasse strata (upper Deutenhausen and Puchkirchen Formations), Tollmann (1968) concluded that Augenstein sedimentation embraced the same time-span. These formations were deposited in the marine part of the Molasse basin in front of the central and eastern NCA (see Fig. 7; Malzer et al. 1993). Frisch et al. (1998) came to the same result from a different line of reasoning. They argued that, after an uplift impulse probably triggered by slab break-off after continental collision (Blanckenburg and Davies 1995), coarse pebble material appeared in the Molasse zone at ~30 Ma (late Early Oligocene), and correlated this event with the advent of coarse clastic material in the central and eastern NCA (the Augenstein Formation), which formed a part of the Molasse sedimentation area at that time. The uppermost limit for the age of the Augenstein Formation is the late Early Miocene (~Ottnangian at 18 Ma) period, when fault-bounded longitudinal depressions formed south of the NCA, thus cutting the possibility of sediment supply from the south (Frisch et al. 2000).

Lichtenecker (1924) introduced the term “Augenstein landscape” in order to describe the flatlands or hilly landscape formed by the accumulating sediments of the Augenstein Formation. The thickness of the Augenstein Formation was estimated by Winkler-Hermaden (1957) to be several hundred meters. The Augenstein landscape is completely destroyed today. Only scattered and very small remnants of Augenstein occurrences exist, many of them not in their original position. All authors agree that “Augenstein landscape” and “Rax landscape” are successive landforms (Winkler-Hermaden 1957). Ganss (1939), Riedl (1966) and Louis (1968), however, argued for autochthonous Augenstein occurrences, meaning that the surface, on which the Augenstein sediments were deposited, is preserved in places. According to Riedl (1966), the “Rax landscape” represents a denuded karst surface, which was modeled by corrosive boundary effects between the hard rock/Augenstein sediment interface. He considered its age to be younger than the Savic tectonic phase, i.e., post-Oligocene.

To the west of the Augenstein depositional area, the Late Eocene to Oligocene sediments of the Inntal (“Unterinntal-Tertiär”, see Tollmann 1985; short: “Inntal Tertiary”) was partly synchronously deposited with the Augenstein sediments. It displays marine facies in Early Oligocene and terrestrial facies in Late Oligocene times. Late Oligocene conglomerates contain material supplied by the Paleo-Inn River (Krois and Stingl 1991; Skeries and Troll 1991; Mair et al. 1996; Brügel 1998; Frisch et al. 1999).

## Composition and source of the Augenstein Formation

Although the preserved volume of the Augenstein Formation is negligible, its petrographic composition is an important testimony of the Oligocene paleogeographic situation. Because we only observe the very basal parts of the Augenstein Formation, the following description of its sandstones and pebble contents cannot necessarily be extended to the higher parts of it. Augenstein occurrences are widely distributed over the karst plateaus thus indicating an overall coverage of the central and eastern NCA. There is a limited number of occurrences in clearly autochthonous position, where sandstone and conglomerate are attached to the underlying limestone. In several instances, these autochthonous occurrences are bound to negative karst features, where they have been protected from erosion. The majority of occurrences, however, are allochthonous, i.e., there are local accumulations of loose pebbles on the plateau surface. In several places,

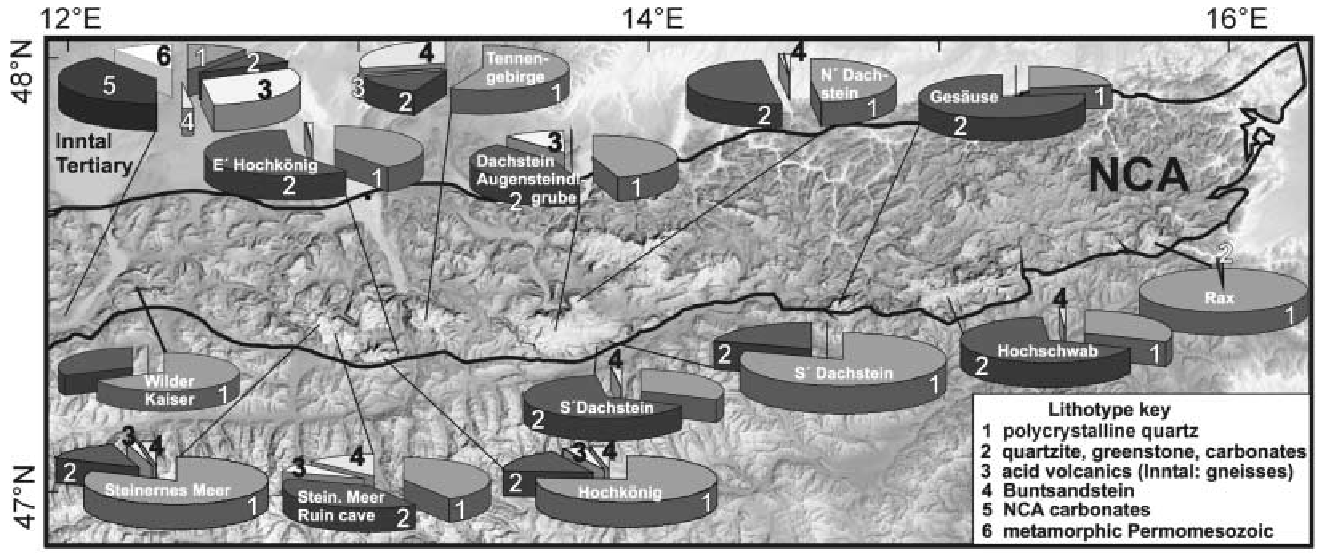



**Fig. 2** Pebble compositions of Late Oligocene strata of Inntal Tertiary (Krois and Stingl 1991) and Augenstein occurrences

reddish-brown soils had formed by weathering of the Augenstein material (Solar 1964) and were typically intermixed with it. The soils indicate subtropical climate as it prevailed until Middle Miocene times (Bruch 1998).

In the locality of Augensteindlgrube (central part of Dachstein plateau, see Fig. 11), sandstones show poor to moderate sorting, small-scale amalgamations of channel fills with normal, sometimes reverse grading, and cross-bedding. Grains are subangular to well rounded. Imbrication of fine pebbles at Augensteindlgrube and leeward dipping foresets in another autochthonous occurrence of the Dachstein plateau indicate river transport from S to SSE. Cathodoluminescence shows that the quartz grains are overwhelmingly derived from metamorphic rocks and rarely from volcanic rocks. Plutonic quartz is absent.

We also studied the components of the conglomerates in the field and by thin section microscopy from a number of occurrences in the central NCA. The pebbles have mostly diameters up to a few centimeters, in some localities pebbles of 10–20 cm diameter occur. The components nearly exclusively derive from weakly metamorphosed terrains up to greenschist facies grade. The lithologies are typical of (1) Variscan Paleozoic terrains widely distributed in the eastern part of the Eastern Alps south of the NCA, and (2) the post-Variscan siliciclastic base of the NCA. These lithologies have their present counterparts in the Greywacke Zone, the Paleozoic of Graz, and the Gurktal nappe, on the one hand, and in an imbricate zone along the southern margin of the NCA, on the other (Fig. 1). The Variscan terrains consist of an Ordovician to Early Carboniferous volcano-sedimentary sequence. The post-Variscan base of the NCA embraces Late Carboniferous to Early Triassic (Scythian) strata. In the westernmost Augenstein occurrences, lithologies that are suggested to have suffered metamorphism of greenschist or even amphibolite facies grade and to pertain to the Middle Austro-Alpine Permo-Triassic cover sequence also occur.

Polycrystalline quartz pebbles are the predominating components in the Augenstein conglomerates (Fig. 2). They derive from phyllites, which are widespread in the Paleozoic sequences and in which they form nodules precipitated from material mobilized by pressure solution. In a number of polycrystalline quartz pebbles, remnants of schist, otherwise completely destroyed, are enclosed in fold hinges. The frequency of the quartz pebbles shows that phyllites and other low-grade schists were widespread in the source area, as it is the case in the present counterparts.

Other pebble lithologies are quartzites, sandstones, conglomerates, lydites, rhyolites, greenstones, and mostly black carbonates (Fig. 2). The quartzites are very variable and can be correlated with lithologies both in the Variscan and post-Variscan series. Those from the Variscan sequence are often gray to black, massive or banded; some contain chloritoid. White, partly greenish (phengite-bearing) quartzites are well known from Middle Austro-Alpine Permo-Scythian sequences. Red quartzites and metasandstones can easily be correlated with the typical Early Triassic Buntsandstein formation in the western part of the NCA (in the central and eastern NCA the Buntsandstein facies is replaced by the Werfen schist facies). They are frequent in Augenstein occurrences in the western part of their distribution area, which is closest to the possible source areas (Fig. 2). In one of the western occurrences (Steinernes Meer) quartzite containing reddish-brown biotite and some garnet was also found. The reddish color in biotite is caused by high Ti contents, which indicate temperatures above the greenschist facies range. This quartzite most likely derives from the Middle Austro-Alpine unit.

The quartz-rich pebbles frequently show crystal-plastic deformation of quartz, polygonization, strain-induced grain boundary migration and rotation recrystallization, in line with metamorphic temperatures >~300 °C (Passchier and Trouw 1996). Grain boundary area reduction fabrics (coarse-grained recovered fabrics) typical of higher (amphibolite-facies) grade quartz assemblages with according crystal growth are generally missing.

Fine conglomerate and sandstone pebbles of grayish-brown appearance with clastic white mica can be correlated with Late Carboniferous to Permian (post-Variscan) rocks of the NCA base. Lydites (black cherts) are characteristic of the Variscan sequence. They are very fine-grained and show practically no mineral growth, probably because of growth inhibition by frequent iron oxide and graphite pigment. Rhyolites, some with granophyric texture, are the only feldspar-bearing acid lithologies. Deformed metarhyolites ("porphyroids") form an important and characteristic horizon in the Variscan sequence, but rhyolites are also widespread in the Permian sequence. Despite them being mentioned in the literature (e.g., Louis 1968) and a thorough search, we did not find gneiss components.

Greenstones (massive or schistose) are widespread in the Variscan sequence, where they experienced different grades of deformation. Black carbonate rocks are typical within the mostly Devonian carbonate series of the Variscan sequence. Light carbonate pebbles are rare in the Augenstein sediments but can be derived from the same source. The carbonate pebbles are generally fine-grained, thus showing only weak or even no metamorphic overprint. A contribution of Mesozoic carbonate pebbles from the Upper Austro-Alpine cover sequences is therefore possible. There are no coarse-grained (amphibolite facies grade) marbles among the pebbles.

As far as it can be judged from index minerals, fabrics and mineral behavior, metamorphic temperatures of the components of the Augenstein conglomerates remained below ~500 °C, which is in line with the known metamorphic grade of the preserved counterparts of the source rock sequences. The only likely exception are the biotite quartzites. From the lack of gneisses, which are the most widespread lithology in the crystalline basement of the Middle Austro-Alpine unit, amphibolites, micaschists and coarse-grained marbles or other typical amphibolite-facies grade rocks, we conclude that the Middle Austro-Alpine crystalline basement (Fig. 1b) was not a source terrain for the basal Augenstein sediments.

Heavy mineral concentrates show a predominance of the stable phases zircon, tourmaline, and rutile, which are present in practically all studied samples. Kyanite was only found in the westernmost occurrences (Wilder Kaiser, Steinernes Meer), where garnet and hornblende are also present in a part of the samples. Garnet and hornblende were also found in the eastern NCA (Hochschwab). Apatite, anatase, ilmenite, epidote, tremolite, and magnetite are present in variable amounts. Since many of the heavy minerals are likely to have been recycled from the Paleozoic and Scythian quartzites, they do not necessarily reflect the zonation of Alpine metamorphism in the source area. However, the concentration of kyanite and garnet in the westernmost occurrences may reflect a contribution of Middle Austro-Alpine rocks, which partly experienced Eo-Alpine (Cretaceous) metamorphism exceeding greenschist facies.

## Provenance study by fission-track dating

Fission-track (FT) dating was performed on clastic zircon and apatite crystals from Augenstein sandstones, and on pebble populations from conglomerates (Table 1). Apatite fission-track length distributions were studied in order to reveal the thermal history of the Augenstein sediments (see later section). Because there is only very weak thermal overprint, which led to limited track shortening in apatite, both zircon and apatite ages can be used for provenance studies of the sediments.

Age spectra from clastic zircons or apatites from sandstone yield integrated information about the tectonothermal situation in the source area during sedimentation ("single grain dating"; Hurford et al. 1984). If pebble populations are studied, i.e., groups of pebbles of a distinct lithotype from one outcrop, then the fission-track age spectra give litho-specific and thus considerably more differentiated information about the hinterland, such as the distribution of lithologies and their geodynamic state at the time of erosion and sedimentation ("pebble population dating"; Dunkl et al. 2001).

The studied samples derive from the western part (Dachstein, Steinernes Meer, Wilder Kaiser; Fig. 1a) of the area where Augenstein sediment remnants are found. Because the Augenstein remnants are always basal parts directly deposited on the Dachstein paleosurface, the studied strata represent the oldest part of the Augenstein sediments.

### Zircon fission-track data

Three pebble population samples were taken for zircon fission-track dating (Table 1). Two Buntsandstein pebble samples show very wide zircon FT age ranges with the majority of ages between 300 and 100 Ma (Fig. 3a, b). For one of these samples it is possible to distinguish two age groups by the $\chi^2$ age method (Brandon 1992; Fig. 3c). The zircon crystals of the younger (Jurassic) cluster derive from a region that was affected by a Mesozoic thermal event, probably

**Table 1** Results from fission-track dating in Augenstein sediments (pebble population and sandstone samples). For localities, see Figs. 1 and 11. *D*, Dachstein; *Cryst.*, number of crystals. Track densities ($\rho$)=measured tracks×$10^5$/cm$^2$; *N*, number of tracks counted. $P(\chi^2)$, probability obtaining $\chi^2$ value for *n* degrees of freedom (where *n*=no. of crystals–1). Zircon ages calculated using dosimeter glass CN2 with $\zeta_{CN2}$=127.8±1.6. Apatite ages, CN5 with $\zeta_{CN5}$=373±7

| Locality | Sample no. | Lithology | Cryst. | Spontaneous | | Induced | | Dosimeter | | $P(\chi^2)$ | FT age |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $\rho$s | (Ns) | $\rho$i | (Ni) | $\rho$d | (Nd) | (%) | (Ma±1 s) |
| Zircon ages | | | | | | | | | | | |
| D-Nied. Gjaidst. | K-2–1 | Buntss. 39 pebb. | 50 | 193 | (6,553) | 33.4 | (1,128) | 4.97 | (4,899) | <1 | 182±11 |
| Steinernes Meer | K-14 | Buntss. 95 pebb. | 50 | 160 | (5,452) | 24.7 | (843) | 4.54 | (8,928) | <1 | 180±11 |
| Steinernes Meer | K-10 | Quartzite 37 pebb. | 50 | 101 | (4,769) | 41.5 | (1,955) | 4.96 | (4,899) | 1 | 77±3 |
| D-Augensteindlgrube | K-32F | Sandstone | 60 | 80 | (5,586) | 27.3 | (1,913) | 4.54 | (8,928) | <1 | 83±5 |
| Steinernes Meer | K-25–96 | Sandstone | 50 | 95 | (3,898) | 32.7 | (1,344) | 4.54 | (8,928) | <1 | 85±4 |
| Steinernes Meer[a] | K-32 | Sandstone | 50 | 97 | (3,772) | 42.8 | (1,670) | 4.54 | (8,928) | <1 | 64±7 |
| Wilder Kaiser | K-36 | Sandstone | 55 | 136 | (4,906) | 30.8 | (1,117) | 4.54 | (8,928) | <1 | 126±14 |
| Apatite ages | | | | | | | | | | | |
| D-Nied. Gjaidst. | K-2–1 | Buntss. 39 pebb. | 50 | 11.9 | (1,761) | 13.1 | (1,935) | 5.17 | (10,168) | 31 | 87±4 |
| Steinernes Meer | K-14 | Buntss. 95 pebb. | 35 | 11.0 | (1,574) | 12.7 | (1,819) | 5.17 | (10,168) | 82 | 83±3 |
| Steinernes Meer | K-10 | Quartzite 37 pebb. | 50 | 4.45 | (1,558) | 7.03 | (2,460) | 5.17 | (10,168) | 73 | 61±2 |
| Steinernes Meer | K-25–96 | Sandstone | 50 | 6.3 | (2,161) | 8.76 | (3,004) | 5.17 | (10,168) | 0 | 69±3 |

[a] Sample is from Leoganger Steinberge, a western extension of Steinernes Meer tectonic block

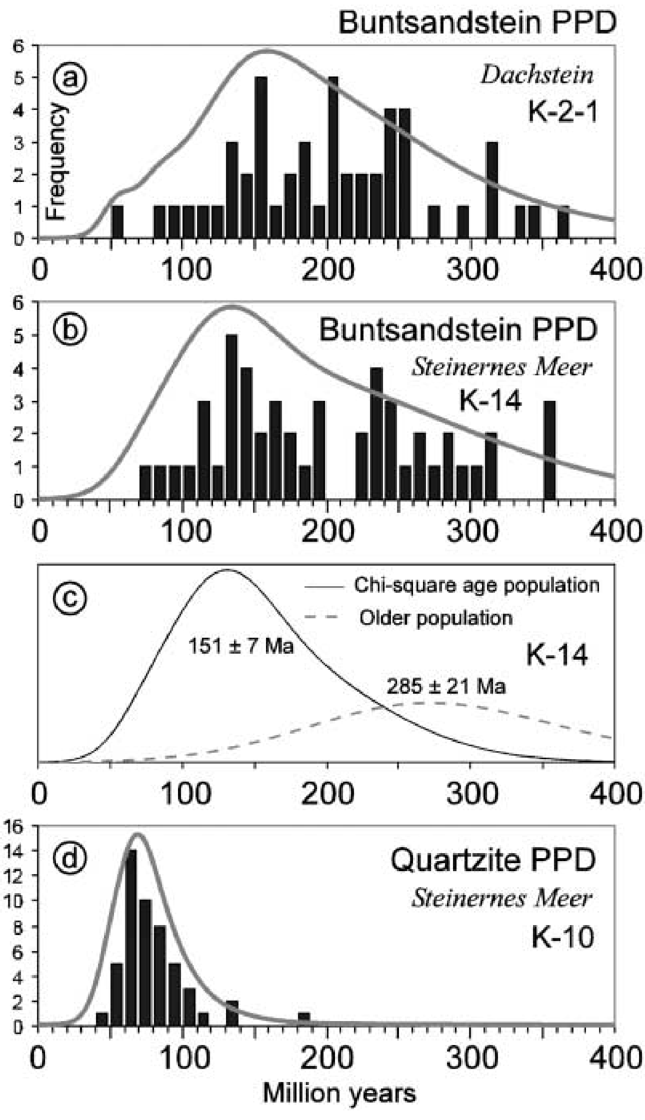



**Fig. 3** Zircon fission-track age spectra of Augenstein pebble population samples (see also Table 1). *Bold gray lines* represent age spectra calculated according to Hurford et al. (1984). **c** Separation of data in diagram **b** into two populations

because of crustal thinning in the Austro-Alpine realm. The older (Permian) cluster represents typical Late Variscan ages. Both thermochronological age groups are known from the westernmost part of the Austro-Alpine crystalline basement of the Eastern Alps (Thöni 1981; Flisch 1986) and from clastic material in the Rhenodanubian flysch zone (Eynatten 1996; Trautwein 2000). Because the age spectra derive from Buntsandstein pebbles, some eroded extension of the basal parts of the western NCA, which had not been overprinted by the Cretaceous metamorphic event above ~250 °C, was supplying material into the Augenstein sediments.

In contrast, a pebble population sample of white, sometimes greenish quartzite gives a narrow age distribution indicating a uniform source (Fig. 3d). These quartzites are likely to represent facies equivalents of the Buntsandstein in areas that experienced somewhat higher temperatures (>300–350 °C) during Cretaceous metamorphism. The typical white, and due to phengite also greenish "Skythquarzit" lithologies occur in the Middle Austro-Alpine realm, which is widespread in the area south of the NCA, and are likely to have been widely distributed in this region during sedimentation of the Augenstein Formation. For these units, mica K/Ar ages of ~95–70 Ma and zircon FT ages of ~80–65 Ma are typical (Frank et al. 1987; Dunkl et al. 1999).

The zircon FT age spectra of the Augenstein sandstone samples are rather variable (Fig. 4), thus indicating different sources. A great part of the single grain

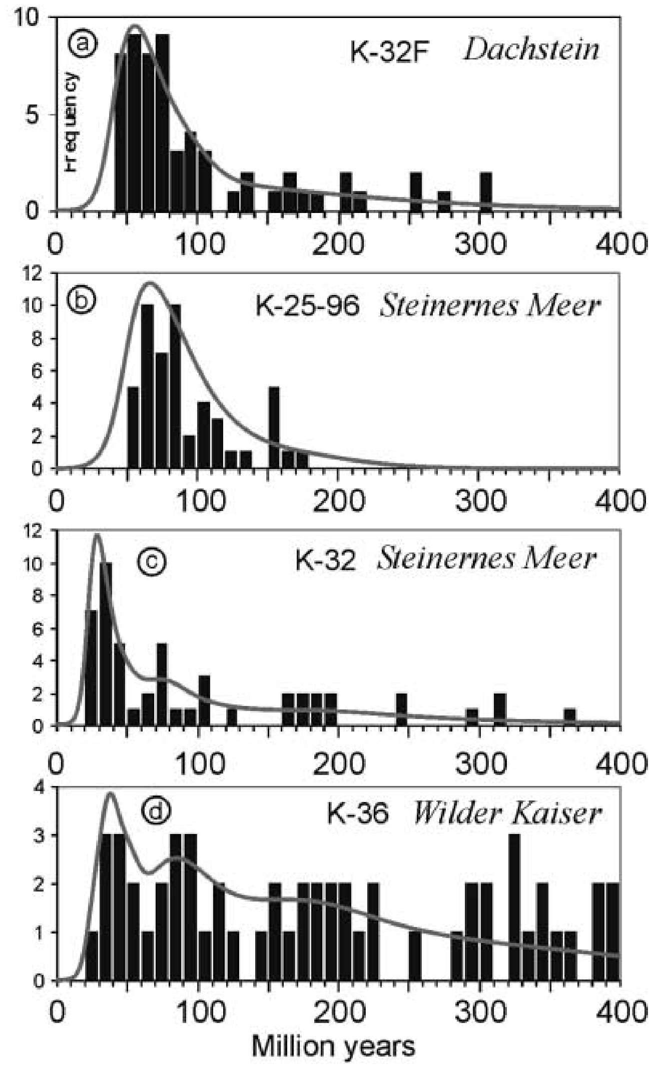



**Fig. 4** Zircon fission-track age spectra of Augenstein sandstone samples (see also Table 1). *Bold gray lines* represent age spectra calculated according to Hurford et al. (1984)

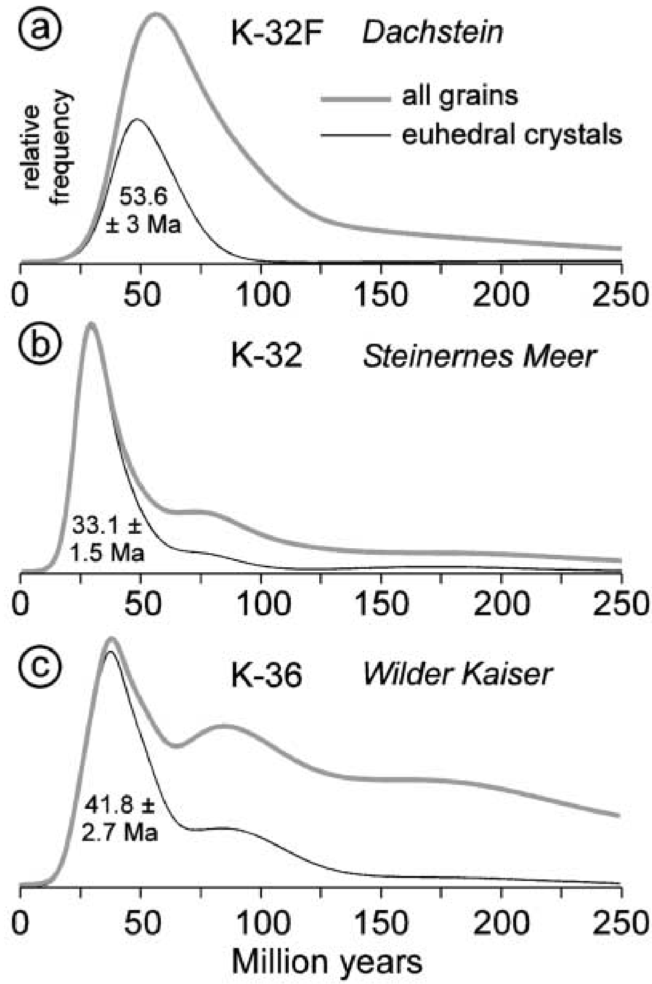



**Fig. 5** Age spectra of the bulk population (*bold gray lines*) and of euhedral zircon crystals (*thin lines*) from sandstone samples shown in Fig. 4. Euhedral grains indicate volcanic contribution

ages cluster around 80 Ma, which means that the Middle Austro-Alpine zone with, for instance, the widespread Scythian quartzites were supplying the (western) Augenstein sediments. The Jurassic and Late Variscan age groups are present in variable amounts. The Cretaceous and older age groups from the sandstone samples correspond to the age groups from the quartzite and Buntsandstein pebbles (Fig. 3). Besides polycrystalline quartz pebbles, both lithologies are the most frequent components in the Augenstein conglomerates.

Two zircon samples from sandstone yield young and sharp FT age peaks (Fig. 4c, d). This youngest age group is characterized by clear, colorless, euhedral zircon crystals (Fig. 5b, c). The crystals are slightly zoned or homogeneous and show a remarkable integrity of the edges and crystal faces. The age and the crystal character testify to a volcanic source. In the case of the sample from the Steinernes Meer block (Table 1; Fig. 5b), the age of the euhedral crystals (33.1±1.5 Ma) is identical to the age of the pronounced peak of activity of the main Periadriatic magmatism in Oligocene times (~33–30 Ma; Borsi et al. 1979; Blanckenburg and Davies 1995). Frisch et al. (1998, 1999) and Brügel et al. (2000) showed that the Periadriatic intrusive bodies presently exposed on the surface were topped by volcanic edifices in Oligocene times, which are completely eroded today. Andesitic and dacitic pebbles of this volcanism are found in Molasse sediments and the Inntal Tertiary (Mair et al. 1996; Brügel 1998). This volcanic material was only transported to a part of the Augenstein sediments in the western Augenstein area, which was in the reach of the supplying volcanoes (see below).

The volcanogenic grains in the sample from Wilder Kaiser gave a Late Eocene age of 41.8±2.7 Ma (Fig. 5c). This population is suggested to derive from an early volcanic period, which is known from tuffs and tuffites in the Apennines and the Pannonian basin

(Dunkl 1992; Fantoni et al. 1999) or could represent volcanic equivalents to the Periadriatic Adamello intrusion, which yielded similar ages (Villa 1983). Brügel et al. (2000) reported andesitic pebbles with similar K/Ar ages in the Molasse zone. The lack of the very characteristic 30-Ma-old group, which is widespread in Peri-Alpine sediments of Oligocene age, may indicate that the sample is older than the 33–30 Ma old volcanic episode or that it had a catchment area, which did not reach the volcanic edifices (see discussion below and Fig. 7).

The sample from the Dachstein (Fig. 4a) also contains a euhedral zircon population (Fig. 5a). These grains are not always colorless, but partly brownish. This may be caused by the higher age (53.6±2.7 Ma) and the resulting higher density of radiation damage. The grains may be volcanogenic. Van Couvering et al. (1981) reported early Paleogene FT ages from tuffites in flysch sequences. However, we cannot exclude that this contribution in the Dachstein sample is derived from an Austro-Alpine orthogneiss or an intrusive body that underwent Early Tertiary cooling.

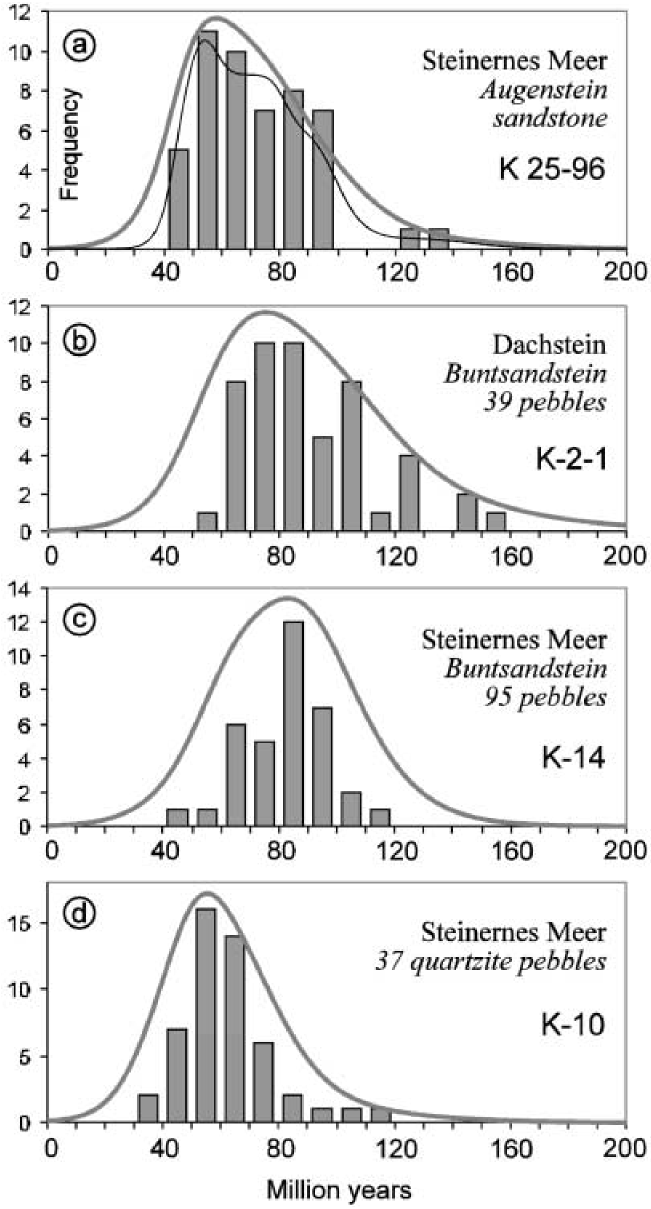



**Fig. 6** Apatite fission-track age spectra of **a** sandstone and **b–d** pebble population samples (see also Table 1). *Bold gray lines* represent age spectra calculated according to Hurford et al. (1984). *Thin line* in **a** was computed using 0.5 standard deviation

## Apatite fission-track data

Apatite single grain ages have been studied in a sandstone sample from Steinernes Meer (Fig. 6a). The single-crystal ages range from 100–40 Ma. Pre-Tertiary apatite FT ages are not known so far from the Eastern Alps, so the Cretaceous ages represent a missing link in the exhumation history of the orogen. They derive from a high structural level in the Austro-Alpine nappe stack, which is eroded today. The source rocks belong to a belt that suffered a Cretaceous thermal overprint.

The failed $\chi^2$ test indicates a composite character of the apatite age distribution in the sandstone sample. Two clusters are separate when the probability density plot is calculated with 0.5 standard deviation (Fig. 6a). This is confirmed by the pebble population samples, in which the apatite age distributions are differentiated according to distinct lithologies (Fig. 6b–d). White quartzite and Buntsandstein pebbles show that they derived from different areas with different cooling histories. The Buntsandstein pebble samples give significantly older ages than the quartzite pebble sample.

These two age groups refer to the two main tectonometamorphic groups of the Austro-Alpine nappe pile reflecting the diachronous metamorphic history of the Upper Austro-Alpine zone with the NCA and the Greywacke Zone and equivalents, on the one hand (ages from submicron sized neomorphic mica ca. 145–95 Ma; Kralik et al. 1987), and the Middle Austro-Alpine zone with crystalline basement and cover sequences along the central axis of the Eastern Alps, on the other (mica ages ~95–70 Ma; Thöni 1981; Frank et al. 1987). The Buntsandstein and quartzite pebble population samples for zircon and apatite ages (Figs. 3 and 6) are in perfect mutual agreement taking into account the different closure temperatures during cooling for the two mineral species.

The rather narrow age distributions and the passed $\chi^2$ tests for the pebble population samples indicate shallow, areal erosion, limited catchment areas without deeply incising valleys, and moderate relief. The incision depth of the valleys was significantly less than the depth of the upper boundary of the apatite partial annealing zone (~2 km).

## Source areas and age of Augenstein sediments

The source area of the Augenstein Formation has long been considered to have been situated to the south of its depositional area (Götzinger 1913; Fig. 7). The regions to the north and east are impossible as source areas, because they were occupied by the marine basins of the Molasse zone and the Intracarpathian region. To the west, the Paleo-Inn River shielded any transport of material from the mountainous western NCA or the basement areas further south (Fig. 7; Brügel 1998; Frisch et al. 1998). To the south, Paleozoic terrains are still widespread and tectonically superimpose the crystalline basement of the Austro-Alpine mega-unit. These Variscan Paleozoic terrains formed the basement of the NCA. Isolated remnants of the NCA are still preserved in this region (Fig. 1b). Indications of sediment transport from southern directions (see above) are in line with the overall paleogeographic situation.

On the basis of the pebble content, the heavy mineral spectra and the zircon and apatite fission-track data, we propose a scenario for the paleogeological and paleogeomorphological situation during Augenstein sedimentation (Fig. 7), which is based on the palinspastic reconstruction of Frisch et al. (1998). These authors showed that the Eastern Alps had a considerably shorter E–W extent prior to the prominent Early to Middle Miocene lateral extrusion process, which led to more than 50% E–W stretching and exhumation of the Penninic windows in Middle Miocene times at ~14 Ma (Brügel 1998). Our reconstruction considers large parts of the central and eastern parts of the Eastern Alps south of the NCA to have been continuous terrains of the weakly metamorphosed Variscan sequences and its post-Variscan siliciclastic cover. Mesozoic carbonates were rare in the area because the overwhelming part of this cover sequence had been detached and took the position of the NCA. Remnants of the Late Carboniferous to Early Triassic siliciclastic base of the NCA were probably more widespread in the area. This area contributed to the Augenstein Formation to its north, on the one hand, and to the Paleo-Drau River system to its east, on the other (Benedek et al. 2001). The Paleo-

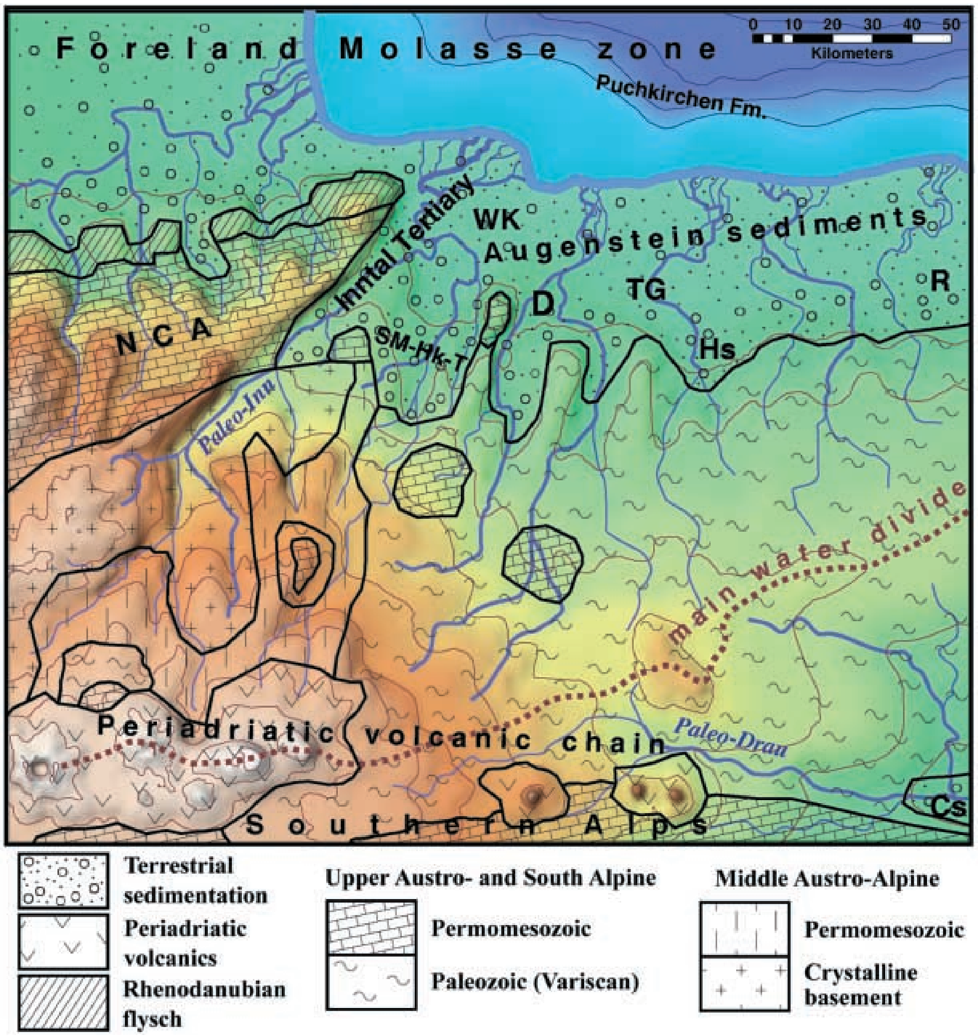



**Fig. 7** Paleogeography and paleogeology for the time of Augenstein deposition in Late Oligocene time. Palinspastic restoration for the time before Miocene E–W extension after Frisch et al. (1998). Sketch shows different source areas for Augenstein and Inntal Tertiary sediments, but also transitional situation for Steinernes Meer and Wilder Kaiser. *Abbreviations* as in Fig. 1a. *Cs* Csatka formation

Drau delivered conglomerates and sandstones to the Late Oligocene to Early Miocene Csatka formation, preserved today in the Bakony mountains in Hungary. The pebble compositions and the fission-track ages in the Csatka formation also suggest a source area made up of Paleozoic to Scythian rocks of the Upper Austro-Alpine unit as well as of Periadriatic volcanics (Benedek et al. 2001).

As is shown in Figure 7, the source area of the Augenstein sediments is considered to have formed an intermediate-relief scenery for the following reasons:

1. There was a general topographic gradient from mountainous areas west of the Eastern Alps (with elevations certainly surpassing 2,000 m in Late Oligocene time) towards the marine Intracarpathian basin to the east (Frisch et al. 1998, 2000). The source area for the Augenstein sediments was situated between the mountainous region and the basin, therefore, it appears plausible that it displayed an intermediate relief. An Alpine relief for the west of the Eastern Alps is demanded from pebble material transported into the Molasse basin over large distances by the Paleo-Inn River system (Brügel 1998).
2. Fission-track ages from the Paleozoic sequences show limited erosion during Tertiary times (Hejl 1997; Reinecker 2000). From thermal modeling based on apatite fission-track data, we conclude a moderate exhumation impulse in the Gurktal mountains, which were part of the Augenstein source area during Late Oligocene to earliest Miocene times (Reinecker 2000). This exhumation period was followed by the stabilization of a hilly paleosurface with paleosoils, which is preserved in remnants (Nockfläche; Exner 1949). Frisch et al. (2000) attributed an Early Miocene age to paleosurface and paleosoil formation, which was interrupted by the ca. 18-Ma tectonic event, during which fault-bounded valleys dissected the paleosurface. Samples from the Greywacke Zone (Grundmann and Morteani 1985; Staufenberg 1987) and from the crystalline basement E of the Gurktal mountains (Hejl 1997) gave pre-Oligocene apatite FT ages, reflecting erosion of <2 km since then.
3. The apatite fission-track ages from clastic material in the Augenstein (see preceding section) and the Csatka (Benedek et al. 2001) Formations also show that the eroding rivers did not deeply incise in the source area. The fission-track ages are generally distinctly higher than the sedimentation age and therefore indicate that the clastic material derived from an area with only moderate uplift rates.

To constrain the lower limit of the Augenstein sedimentation period, the fission-track data give valuable support. The 33-Ma-old volcanogenic zircon population of a sample from the western Steinernes Meer block (locality: Leoganger Steinberge; Table 1) shows that this is the maximum age of the sediment in this place. There are basically two lines of reasoning:

1. The 33-Ma-old zircons have been carried by air and/or rivers to the sediment, thus this sediment has the same age or is slightly younger. The other samples (Dachstein, Wilder Kaiser), which do not show this young volcanogenic zircon population, are older than 33 Ma and thus did not receive this material. Diachronic ages between ~35 and 30 Ma can therefore be assumed for the sedimentation of the basal Augenstein sediments. Ages >35 Ma appear unrealistic because thrusting in the NCA ceased in Middle to Late Eocene time and the formation of the Dachstein paleosurface requires several million years.
2. The 33-Ma-old zircons were transported by rivers to the sediment because volcanoes were in the reach of the river that supplied the Steinernes Meer area (Fig. 7). The Dachstein and Wilder Kaiser samples do not show this zircon population because their feeding rivers did not reach the young volcanoes, as suggested for the Dachstein area in Figure 7. They also may have been deposited on hills, which received sediment material only later, when greater parts of the volcanic sources were already destroyed, as suggested for the Wilder Kaiser area (see Fig. 7). In this scenario, all samples are younger than 33 Ma. As mentioned above, the ~30-Ma uplift impulse makes it likely that no substantial amounts of coarse clastic material were distributed before that time. This is at least the message from the foreland molasse sediments. Our reconstruction is in line with a scenario in which only one of the western Augenstein rivers (supplying Steinernes Meer area) reached the volcanoes, which were positioned in the far distance.

Farther east, the water divide between the Augenstein rivers and the Paleo-Drau River trended towards the ENE so that the volcanoes along the Periadriatic lineament were out of the reach of the Augenstein rivers (Fig. 7). To test this hypothesis, zircon FT data from the eastern NCA are needed: if the second scenario is true, there should be no young volcanogenic zircons in the eastern Augenstein occurrences. To the west, Augenstein sedimentation interfingered with the Inntal Tertiary in Oligocene times. The terrestrial sediments of the Inntal Tertiary (?late Early to Late Oligocene) received pebbles (e.g., gneisses; Fig. 2) from the Middle Austro-Alpine crystalline basement, which is not contained in the Augenstein sediments. However, the quartzites with Late Cretaceous zircon FT ages (Steinernes Meer) and frequent garnet as a heavy mineral in some of the western Augenstein occurrences (especially Wilder Kaiser) indicate that the westernmost Augenstein area shared Middle Austro-Alpine units with the Inntal Tertiary in its source terrains, where Scythian quartzites and garnetiferous basement schists were exposed. Western Augenstein occurrences and conglomerates of the Inntal Tertiary have also frequent Buntsandstein pebbles in common, indicating a source in the western part of the Eastern

Alps (see above). Moreover, the terrestrial sediments of the Inntal Tertiary contain pebbles and single-grain zircons from the Periadriatic volcanic chain (see Fig. 7; Mair et al. 1996; Brügel 1998).

We have no geochronological evidence for the upper limit of Augenstein sedimentation, but from the exhumation history of the source area and from the formation of the Nock paleosurface with soils it can be shown that sediment supply must have ceased in Early Miocene time. The main mass of the Augenstein sediments was probably deposited in the time span between ~30 and 21 Ma. A sediment mass calculation for the Eastern Alps showed that there was a drastic drop in sediment supply at 21 Ma because of the onset of the collapse of the orogen (Kuhlemann 2000). This event probably led to sudden subsidence in large areas of the Eastern Alps, and also in the Augenstein source area. Erosion ceased and red soils formed on the Nock paleosurface. The sketched scenario allows a period of 9–10 Ma, locally possibly even a slightly longer period, for the Augenstein sediments to accumulate. It also gives time for erosion of Augenstein sediments on the southern and eastern margins of their depositional area (Vienna Basin, Ennstal), where late Early Miocene sediments directly overlie the pre-Tertiary basement.

## Sediment thickness estimate

The Augenstein Formation probably formed a continuous sediment sheet as a cover of the central and eastern NCA and sealed a karstic paleosurface, which formed a hilly landscape (Louis 1968). Thus, thickness of the Augenstein sediments will have varied over short distances. We assume that the Augenstein sediments displayed their maximum thicknesses in the central NCA (e.g., Dachstein massif), but became much thinner in the eastern NCA. This conclusion is based on two considerations. (1) The sizes of the catchment areas of the Augenstein rivers and their relief decreased from W to E (Fig. 7), following the general topographic trend in the Eastern Alps, so that the sediment load of the Augenstein rivers must also have decreased from W to E. (2) From geological reasoning, destruction of the Augenstein sediment sheet occurred from Early Miocene through Pannonian time at ~10 Ma (Frisch et al. 1998). In the Vienna basin, which is a pull-apart structure with strong subsidence in Karpatian and Badenian time (Rögl and Steininger 1984), no Augenstein sediments are known at the interface between the NCA basement and the Miocene basin fill, although numerous drill holes should document their existence. In contrast, NCA material was eroded and deposited along the western margin of the Vienna basin from Karpatian time onwards (Kapounek and Papp 1961). Both observations show that the present eastern margin of the NCA was largely bare of Augenstein sediments already in late Early Miocene time. In contrast, in the central NCA, Augenstein material was eroded and redeposited in large conglomeratic fans in the Molasse zone in Middle Miocene time (Nördliche Vollschotter; Lemcke 1988). This overall situation speaks in favor of a thicker Augenstein sediment sheet in the western part (central NCA) than in the east.

Moreover, thickness of Augenstein sediments must have rapidly died out towards the southern margin of the NCA, where the Augenstein rivers entered from their erosional area into the sedimentation area.

### Sediment mass balance

An indirect and only very rough thickness estimate can be performed by a mass estimation of eroded rock in the source areas. The volume of rock, which has been removed in the source areas during the ~10 Ma of Augenstein deposition, has been distributed into the Augenstein sediments and the marine Molasse basin to its north. Dissolved material was transported into the Molasse basin, whereas the suspended load was probably deposited in both depocenters.

If an average erosion rate of 0.05 mm/year (Frisch et al. 1999; Kuhlemann 2000) over 10 Ma is assumed for a source area of ~16,000 $km^2$, then a volume of 8,000 $km^3$ was eroded in that time span. The suggested erosion rate is in line with the apatite fission-track data. Because carbonate rocks were rare in the source area, the volume of dissolved material is estimated to have been ~15%, according to similar recent catchment settings in the Alps (Einsele and Hinderer 1997), i.e., 1,200 $km^3$. From the composition of conglomerates in the marine Puchkirchen Formation, we assume that ~70% of the remaining 6,800 $km^3$ was deposited by rivers on top of the central and eastern NCA with a surface of ~10,000 $km^2$, and 30% transported into the marine Molasse basin further north. For the Augenstein Formation, this results in a total volume of solid rock of 4,760 $km^3$ and an equivalent of uncompacted Augenstein sediment with an average pore volume of 25% in the order of 6,350 $km^3$ (see also consistent values in Kuhlemann 2000). This, in turn, is equivalent to an average sedimentation rate of 0.063 mm/year and an average sediment thickness of 635 m. If we take the irregular thicknesses of the Augenstein sediment sheet into consideration as outlined above, we may conclude that, in the western parts, thicknesses will have surpassed 1 km over large areas and attained accordingly higher values above depressions of the underlying paleosurface.

### Thermal modeling of apatite fission-tracks

The apatite fission-track length distributions of the Buntsandstein pebble sample from the Dachstein massif and the quartzite pebble sample from the Stein-

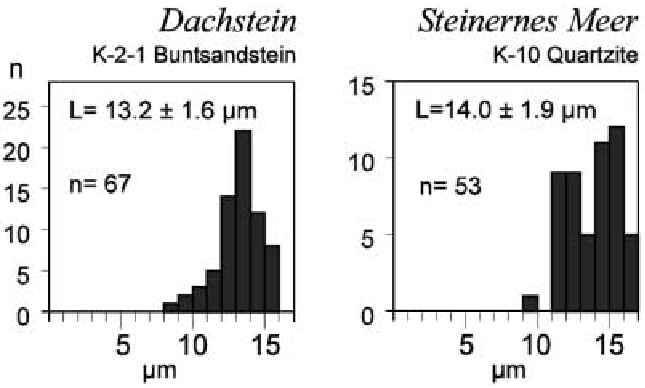



**Fig. 8** Fission track length distributions of two apatite samples (see Fig. 6)

ernes Meer show shortened tracks, but the length distribution curves have different character in the two samples (Fig. 8). Using the apparent ages and the track-length distributions, thermal modeling was performed on these samples to reveal their thermal history (Fig. 9). The AFTSolve program (Ketcham et al. 2000) was used with the annealing kinetics of Laslett et al. (1987). The diameters of the etch pits were small and usually uniform in the majority of the dated apatite grains. Therefore we suppose a fluorine-rich chemical composition for the choice of the modeling algorithms.

The time of sedimentation was chosen to be Early Oligocene, ~35–30 Ma on the grounds discussed above. This allows the insertion of an "invariable" point to the time–temperature path because, at that time, the sediment was at surface temperature. Thermal modeling proves that initial cooling from the total annealing zone of the Buntsandstein sample (apparent apatite FT age 87 Ma; Table 1) occurred prior to 110–100 Ma (Fig. 9a). The quartzite sample, in contrast, derived from a unit that underwent the very typical ~80 Ma (mica) cooling event in the Austro-Alpine realm (Fig. 9b), which is in line with the zircon FT ages from the same sample (Fig. 3d; see above).

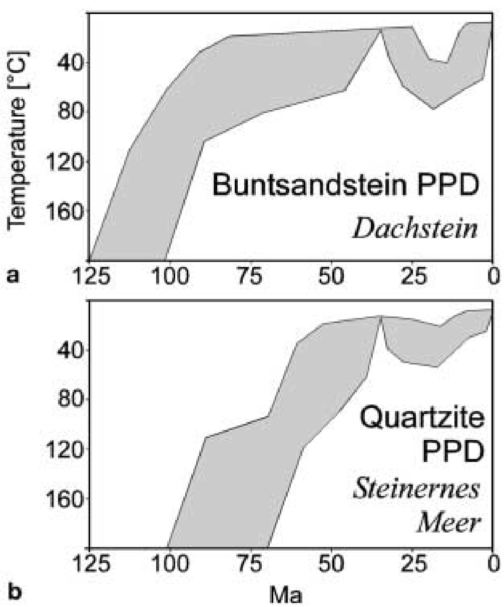



**Fig. 9** Results of thermal modeling based on apatite fission-track data for same samples as shown in Fig. 8. The *shaded* time–temperature bands represent the envelopes of acceptable paths using the AFTSolve program of Ketcham et al. (2000)

The general shortening of the tracks in the Buntsandstein sample from the Dachstein plateau indicates a post-sedimentary mild thermal overprint (Figs. 8a, 9a). Because of the low temperature and the lack of $T_{max}$ indicators (the sediment is free of organic material), we cannot expect precise time and temperature estimates. However, the maximum post-sedimentary temperature consistently exceeded ~50 °C in a series of modeling runs using different annealing kinetics and time of maximum temperature. It is difficult to estimate the geothermal gradient above the subsiding, karstified and highly permeable limestone substratum. A realistic geothermal gradient of 20–25 °C/km and a mean surface temperature of ~16 °C (Bruch 1998) results in burial of 1.36–1.7 km for $T_{max}$=50 °C, and of 1.76–2.2 km for $T_{max}$=60 °C. This thickness estimate is in line with the degree of compaction observed in thin sections of sandstone from the same region. There is a high amount of ductile (mostly argillaceous) grains and pressure solution of quartz.

The quartzite sample clearly shows less intense post-sedimentary thermal overprint (Fig. 9b). This indicates different thermal/burial histories over the Augenstein sedimentation area, a hilly substratum causing strong thickness variations, or, simply, a more marginal position of the quartzite sample. The quartzite sample was taken near the southern margin of the NCA, where much lower sediment thicknesses are presumed (see above).

## Features of the Dachstein paleosurface

It was shown above that the terms "Augenstein landscape" and "Rax landscape" were defined in the literature as successive landforms for the situation during Augenstein sedimentation and after removal of the Augenstein sediments (Lichtenecker 1924, 1926). According to this concept, the "Rax landscape" has been shaped by continuing erosion and karstification so that the present surfaces of the karst plateaus reflect the post-Augenstein situation. This concept was largely based on the idea that the present Augenstein occurrences are generally allochthonous.

However, examination of the Augenstein occurrences reveals that a limited number of them are clearly in an autochthonous or para-autochthonous position (see above). In several places, compact Augenstein sandstones and conglomerates are in primary contact to their carbonate basement and firmly connected and cemented to it (Fig. 10a, b). The autochthonous Augenstein occurrences are generally preserved in concave forms of the underlying karst surface. They are always of very local appearance, many occurrences have only sizes of few meters in diameter. The allochthonous occurrences, in contrast, are found as loose gravels, often scattered over a larger area.

The autochthonous occurrences are clear evidence that the pre-Augenstein paleosurface is preserved in places. This view is strongly supported by the existence of paleosurface remnants as they are evident from topographic features (Fig. 10c). Especially on the Dachstein plateau, Ganss (1939) already mapped coherent areas that are evidently paleosurface remnants, although today they are in a tilted position (Fig. 10d). This fact leads to the conclusion that the pre-Augenstein paleosurface can be reconstructed for larger parts of most karst plateaus, e.g., in the Dachstein massif (Fig. 11). To avoid confusion with other concepts, we proposed the term "Dachstein paleosurface" for the hilly, karstified surface that formed prior to Augenstein deposition (Frisch et al. 2000).

We attribute an Early Oligocene (pre- ~30 Ma), possibly also Late Eocene age to this surface. The (deep-water) marine sedimentation of the Late Cretaceous to Early Tertiary Gosau Group in the NCA terminated in the Early Eocene, the tectonic emplacement of the NCA on top of the Rhenodanubian flysch was completed in Middle to Late Eocene times (see Tollmann 1985). This gives a time frame for post-Gosauic deformation of the NCA, surface exposure and erosion, and paleosurface modeling. We consider the period between ~40 and 30 Ma as the maximum frame for the formation of the Dachstein paleosurface.

The Dachstein massif shows the paleosurface remnants best and allows the reconstruction of the surface in some detail (Fig. 11). Its central part is a flat-lying, hilly plateau ~2,000 m high (Fig. 10c,d). Augenstein occurrences, several of them in an autochthonous or para-autochthonous position, are frequent in the central part but are also found in the western part of the Dachstein massif. In contrast, the western part is rugged and does not exhibit features of a plateau at all, but it shows well-preserved remnants of the Dachstein paleosurface, which experienced a northward tilt of ~10° (Fig. 10d), similar to the paleosurface in the Hochkönig massif (Fig. 10f). Autochthonous Augenstein occurrences are found at different elevations. From this and the geomorphologic features, it is clear that post-Augenstein faulting and block segmentation dissected the paleosurface. Differential uplift and tilt brought the segments into different positions. Vertical throws of faults can be in the order of several hundred meters (Fig. 10d), horizontal displacements in the kilometer-scale.

In the central Dachstein massif, we consider most of the actual surface to represent the paleosurface only moderately modified by surface erosion and glacier modeling (Fig. 10d). The present picture of the flat-lying surface is probably similar to that of the paleosurface, although modification to a certain extent occurred without doubt.

**Fig. 10** **a** Outcrop situation at Augensteindlgrube, Dachstein, showing stratified sandstone and fine conglomerate in autochthonous position. **b** Augenstein conglomerate, cemented to the basement of Dachstein limestone, Steinernes Meer. **c** Totes Gebirge (*background left*, NNE) and Dachstein massif showing large extent of moderately modified Dachstein paleosurface, tilted in the western Dachstein massif (*background right*, SSW). **d** Tilted remnants of Dachstein paleosurface in western Dachstein massif indicated by *arrows*, and flat-lying part of Dachstein paleosurface in central Dachstein massif (*right*); *dashed line* indicates approximate location of fault separating tilt block from flat part; NNE is to the *right*. **e** Sheared stalagmite–stalactite figure, Mammut cave, Dachstein massif. **f** South-dipping neotectonic normal fault, Hochkönig; view to the W, Dachstein paleosurface remnants tilted to the right (N) are visible in background. **g** 3-m-high stalagmite in Eisriesenwelt cave, Tennengebirge. For localities, see Figs. 1 and 11

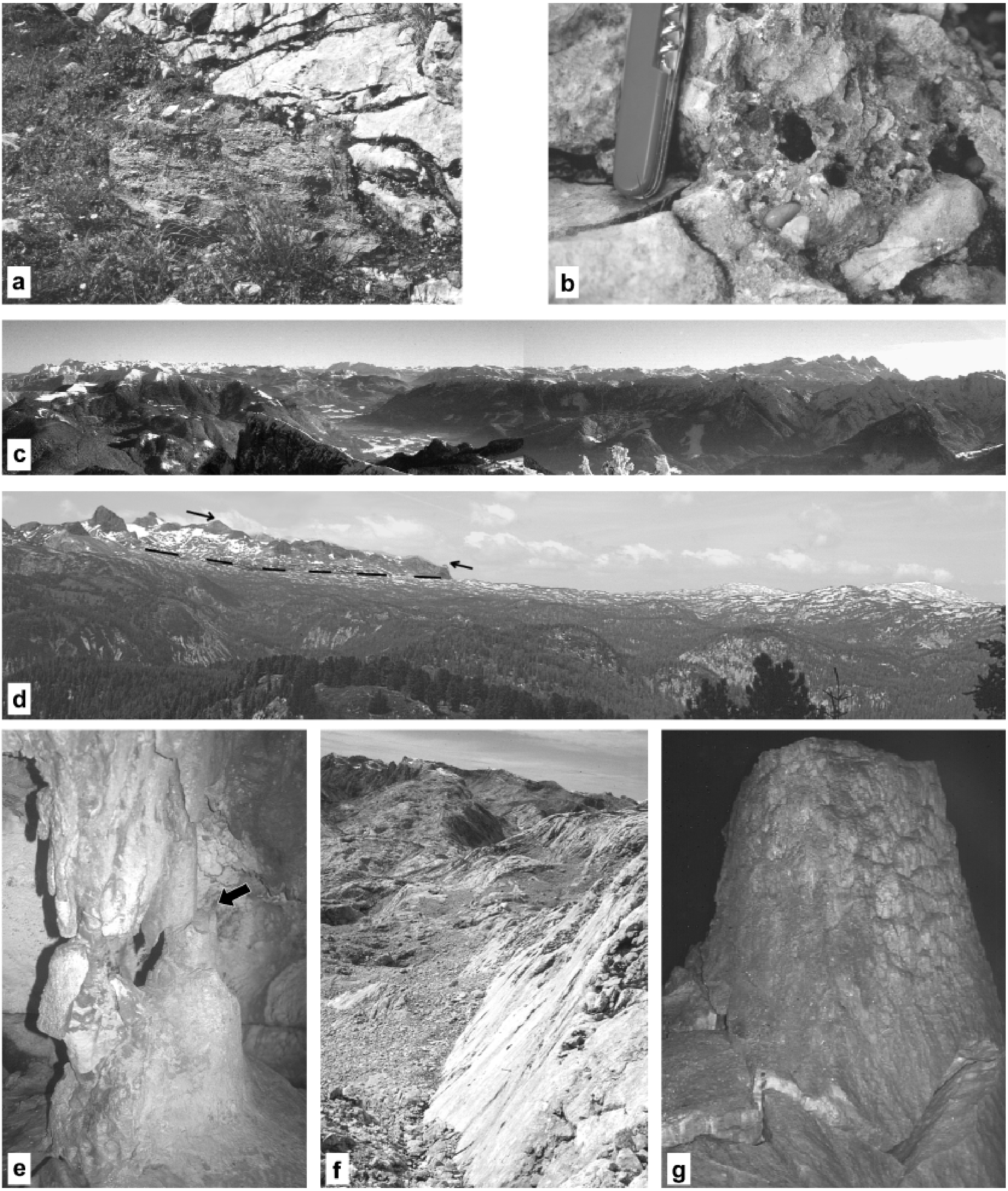
An evaluation of the autochthonous occurrence at Augensteindlgrube in the central Dachstein plateau (Fig. 10a) revealed slight and identical tilt of bedding in both the underlying Dachstein limestone and the Augenstein sandstone (Fig. 12a). NNE-trending joints affect the sandstones and pebbly components of fine-grained conglomerates. If bedding is rotated back to horizontal, the steeply inclined joints become vertical indicating that jointing occurred prior to tilting. The joints indicate ESE–WNW extension, which may be correlated with the overall E–W extension during the Miocene lateral extrusion process in the Eastern Alps (Frisch et al. 1998). From the Mammut (=mammoth) cave at the northern margin of the Dachstein massif, an interconnected stalactite–stalagmite figure has been sheared along a normal fault, displacing the top part towards 265° for 4.5 cm (Figs. 10e and 12a).

As in the western Dachstein massif, a northward tilt of about 10° is also obvious in the Hochkönig massif, which shows normal faulting with a spacing of >100 m (Figs. 10f and 12b). The normal faults were probably antithetically formed to tilting, but reactivated in post-glacial time. Fresh exposure of the fault planes forming scarps up to 20 m high show only limited glacier shaping and karstification by karren formation.

Tennengebirge, Hagengebirge, and most of the Totes Gebirge (Figs. 1a and 10c) are flat-lying plateaus with moderate modification of the Dachstein paleosurface and a number of mostly allochthonous Augenstein occurrences.

## History of the Dachstein paleosurface

Two circumstances enabled the Dachstein surface to survive in remnants so that a reconstruction of the surface can be performed over wide areas. (1) The paleosurface subsided and was sealed by the Augen-




stein sediments, then successively denuded. (2) During succeeding uplift, erosion largely acted subterraneously as documented by the huge cave systems and thus prevented complete destruction of the paleosurface.

Sealing and far-reaching denudation of the Dachstein paleosurface by the Augenstein sediments took about 20 Ma, from ~30 to ~10 Ma. In the Pannonian stage at ~10 Ma, most of the Augenstein material even in the central NCA had been removed and rede-

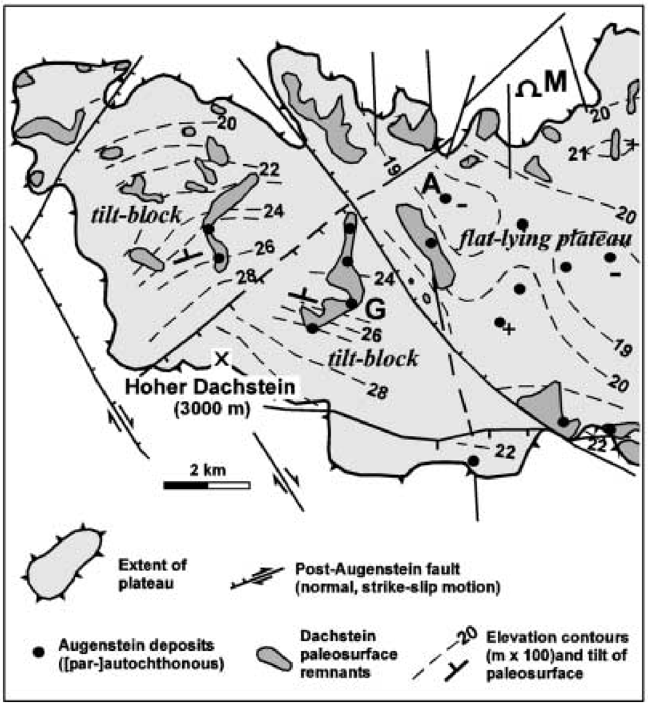



**Fig. 11** Dachstein paleosurface in western and central Dachstein massif. Two tilt blocks and paleosurface remnants characterize the western part, a flat-lying, erosion-modified paleosurface the central part. Shown are locality Augensteindlgrube (*A*), Niederer Gjaidstein (*G* sample locality for thermal modeling), and entrance to Mammut cave (*M*)

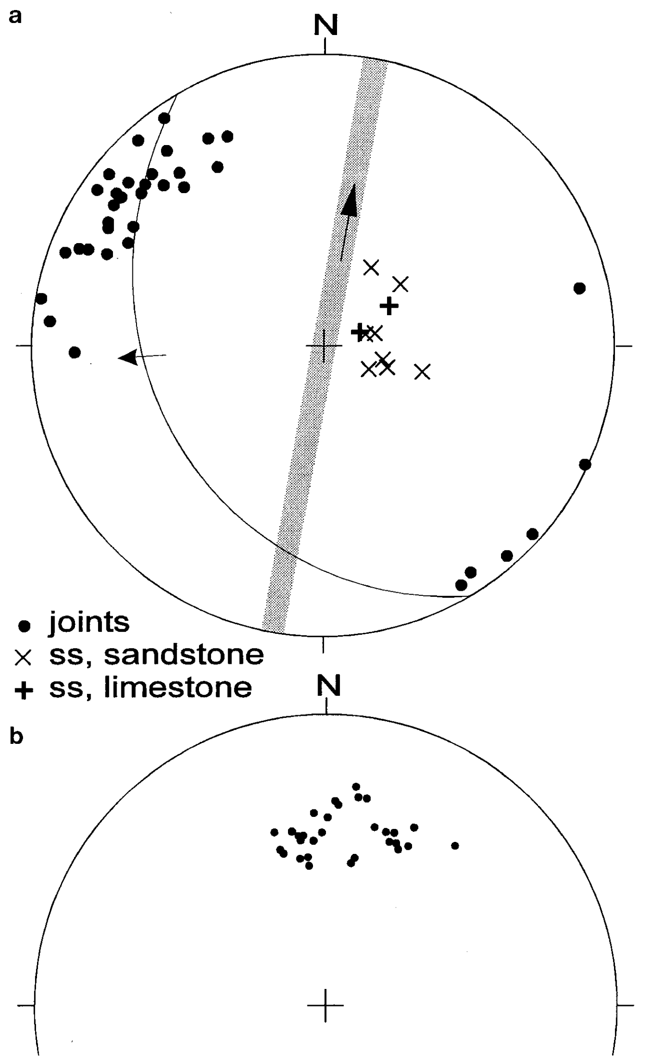



**Fig. 12** **a** Stereogram (lower hemisphere) showing structural data of Augenstein sandstone/conglomerate and Dachstein limestone at Augensteindlgrube and of speleothem in Mammut cave, Dachstein massif (for localities, see Fig. 11). Augensteindlgrube: *gray bar* shows trend of karst fissure (010°) in which Augenstein sediment is preserved. *Crosses* Poles to bedding planes of limestone and sandstone, respectively. *Dots* Poles to extensional joints in sandstone. *Great circle and arrow* Fault-slip data of sheared speleothem in Mammut cave (Fig. 10e). **b** Poles to neotectonic normal faults in Hochkönig tilt block (Fig. 10f). Data collected from three faults

posited in the Molasse trough, and NCA pebbles appeared in molasse conglomerate fans in substantial amounts for the first time (Steininger et al. 1986; Brügel 1998; Frisch et al. 1999). We therefore consider the time span from 10 Ma to present to be reserved for final surface uplift of the central and eastern NCA. All NCA massifs with plateaus contain large volumes of caves. These caves are not randomly distributed but organized in three levels in most of the massifs of the central NCA (Fischer 1990). This shows that uplift was not a continuous process but occurred in pulses. The pulses were interrupted by stages of tectonic quiescence, during which the horizontal cave tracts formed, adjusted to the respective drainage level. The horizontal levels are interconnected by vertical shafts that formed during and after the uplift pulses and are partly still actively forming.

The three cave levels are the Ruin, the Giant, and the Source cave level. The Ruin cave level is partly destroyed by surface erosion and is usually situated very close to the Dachstein paleosurface. It remains unclear whether this level formed during the late stages of denudation from the Augenstein cover or already during formation of the Dachstein surface in pre-Augenstein, i.e., earliest Oligocene time.

The Giant cave level contains the largest caves in the NCA with gallery lengths of many tens of kilometers in individual systems (Fischer 1990). This level is generally positioned 300–800 m below the Dachstein paleosurface. We suppose that this cave system formed in Late Miocene time, after a first significant uplift pulse of the central and eastern NCA. The karst plateaus, at that time, were still densely forested so that favorable conditions for cave formation prevailed.

The Source cave level is the lowest one. These caves are still active as shown by karst sources they discharge; their mouths are close to the valley bottoms. During Pleistocene time, active cave formation must have been minor because the ice cover restricted plant cover on the plateaus during most this time. We therefore suggest that formation of the Source cave system had already started in Pliocene time.

If we take an average of 2,000 m of uplift in 10 Ma for the Dachstein paleosurface, an average uplift rate of 0.2 mm/year results. The discontinuous uplift history, however, implies much higher uplift rates during the tectonically active periods. To get a clue for the timing of the uplift pulses, we tried to date cave material by the U/Pb method on speleothems and with cosmogenic nuclides on quartz material that had been washed in.

## Attempts of dating cave material

### U/Pb dating on speleothems

U/Pb dating was tried on speleothems (dripstones) from Mammut cave (sample 1) in the Dachstein massif and from Eisriesenwelt cave (sample 2) in the Tennengebirge (Fig. 1). Both caves belong to the Giant cave level. In both cases we tried to sample material that formed at an early stage of cave history. The gallery, in which sample 1 was taken, is inclined and dry. It is cut by vertical, water-bearing shafts that belong to the active cave system. Sample 2 was taken from the outer parts of a huge stalagmite with about 2 m diameter at the bottom and about 3 m height (Fig. 10g). The stalagmite grew on top of a layer of washed-in Augenstein material. No active speleothem formation was observed around the sampling site.

U and Th isotope concentrations were measured (Table 2). The Pb isotope contents were below the detection limits. The very low U concentrations are caused by the adjacent and overlying very pure limestones. Although the two samples derived from different mountain massifs and were 35 km apart, the results are virtually identical. In sample 1, The $^{230}Th/^{234}Th$ ratio is somewhat high for the small amount of detritus contained. In sample 2, all U and daughter Th species are in secular equilibrium with each other, which ascertains an age of >0.5 Ma. The perfect isotopic equilibrium of $^{234}U$ and $^{238}U$ in both samples suggests that they are even older than 1.5 Ma. Although U/Pb dating was not successful, the results show that the speleothems formed in pre-Quaternary time with high probability. This is in line with the suggested Late Miocene formation age of the Giant cave level.

**Table 2** U contents and U and Th isotope ratios in speleothems from the Giant cave level in the Northern Calcareous Alps

| Sample | U (ppm) | $^{234}U/^{238}U$ | $^{230}Th/^{234}Th$ | $^{230}Th/^{232}Th$ |
|---|---|---|---|---|
| 1 | 0.05734 | 1.001±0.005 | 2.2811±0.23 | 435 |
| 2 | 0.04175 | 0.9994±0.007 | 1.1318±0.07 | 1371 |

### $^{26}Al$, $^{10}Be$ dating on quartz

Washed-in Augenstein quartz gravel was sampled in the Eisriesenwelt cave from the same locality where the giant stalagmite occurs, and another locality in a blind side-gallery of the same cave system. Augenstein material is cemented by calcite and connected with the cave bottom or the cave walls. Deposition of the Augenstein material in the cave occurred earlier than the formation of the giant stalagmite, which was growing on Augenstein material.

The basis of the dating technique is that quartz exposed to cosmic rays at the ground surface accumulates $^{26}Al$ and $^{10}Be$ at known ratios (Nishiizumi et al. 1986). If this sediment is then redeposited in a cave, production of the two radionuclides ceases. Because $^{26}Al$ has a mean-life (1 Ma) shorter than the mean-life of $^{10}Be$ (2.2 Ma), the ratio of $^{26}Al:^{10}Be$ will decrease over time. Because the initial ratio of the radionuclides is known, their ratio in the cave sediment would record the time of burial. The reason that quartz is taken for dating is that the production rates of $^{26}Al$ and $^{10}Be$ are well known.

The criteria for the success of the technique are that (1) the quartz sediment was exposed at the ground surface prior to burial for long times; (2) the sediment was buried quickly; and (3) the sediment has been shielded from cosmic rays by at least 10 m of rock. Conditions (2) and (3) were certainly met within our samples. Condition (1) creates a question mark, because we do not know how long the Augenstein material was exposed before it was washed into the cave.

The quartz material had high background alumina concentrations, which means that the maximum detectable age may be only 2–3 Ma, depending on the initial exposure of the grains prior to cave deposition. It turned out that the $^{10}Be$ concentration of 7,800±3,900 atoms per gram quartz was too low, i.e., too close to the detection limits, so that the value cannot be trusted with confidence. The sample either came from a quickly eroding site, or it had been buried too long for the cosmogenic isotopes to survive. In the latter case, an age of >2 Ma for the deposition in the cave can be suggested. This would be in line with the results from speleothem dating.

## Synthesis and conclusions

Together with previous results, the study of the Dachstein paleosurface and the Augenstein Formation led to insights into, and conclusions for, the post-Eocene evolution of the Northern Calcareous Alps (NCA; see Fig. 7).

1. The western NCA, i.e., the part west of the (Paleo-) Inn River, had a different evolution than the central and eastern NCA. The western NCA formed a mountainous range since at least Late

Oligocene times and supplied local rivers with pebble material, which was transported into conglomerate fans along the southern margin of the terrestrial Molasse (Brügel 1998; Frisch et al. 1998), which formed an overfilled basin in this section. In contrast, the central and eastern NCA subsided and were superposed by a psephitic to psammitic sequence: the Augenstein Formation. In front of the subsiding part of the NCA, the Molasse zone formed a marine, underfilled trough, which caught up clastic material from the Paleo-Inn and from the Augenstein rivers (Late Oligocene/earliest Miocene Puchkirchen formation). The coastline between the terrestrial Augenstein Formation (which is a molasse sediment) and the marine Molasse was probably positioned in the northern part of the NCA. The Eastern Alps south of the NCA also displayed clear geomorphological differences between the mountainous western part and the eastern part with intermediate elevations and moderate to intermediate reliefs.

2. The Augenstein Formation sealed a paleosurface, which is defined as the Dachstein paleosurface, and which is preserved with limited modification on the elevated karst plateaus in the central and eastern NCA (Frisch et al. 2000). The Dachstein paleosurface was a single, probably hilly surface formed in Late Eocene to Early Oligocene time. The present remnants are found in different elevations (mostly between 1,800 and 2,500 m) and were tilted in some fault-bounded blocks (reaching ~3,000 m elevation on the upper margin of the tilt blocks of Hochkönig and Dachstein). The Dachstein paleosurface has been fragmented prior to or during uplift: the individual blocks have been differentially uplifted. The different elevations of the Dachstein paleosurface remnants are therefore a tectonic feature and not the product of polycyclic benchland formation. The Dachstein paleosurface is only preserved on top of karstified (mostly Triassic) limestone. It is not preserved where thick dolomite formations dominate the Triassic sequence. In the limestone areas, erosion during uplift of the paleosurface was mainly by subsurface karstification so that surface erosion remained a minor factor.
3. The Augenstein Formation was deposited by rivers from Early Oligocene to earliest Miocene times, probably between ~30 and 21 Ma. Locally, Augenstein sedimentation may have started a few million years earlier. The thickness of the Augenstein Formation was probably highly variable. The highest thickness may have been reached in the Dachstein region in the central NCA, where thermal modeling suggests a thickness of at least 1.3 km. Thicknesses near the present eastern margin of the NCA were probably much lower. The depositional area of the Augenstein Formation passed into the Oligocene strata of the Inntal Tertiary to the west, which displayed terrestrial facies in Late Oligocene time with similar thicknesses (Ortner and Sachsenhofer 1996) and was supplied by the Paleo-Inn River from erosion areas in the west of the Eastern Alps.
4. The Paleo-Inn River carried crystalline material from the Middle Austro-Alpine basement in the western part of the Eastern Alps as well as material from the Periadriatic volcanic chain into the Inntal Tertiary and further on into the marine foreland Molasse zone (Skeries and Troll 1991; Brügel 1998). In contrast, the Augenstein rivers nearly exclusively eroded weakly metamorphic Paleozoic (Variscan) and Late Carboniferous to Scythian (post-Variscan) sequences. The pebbly components can be derived from the Greywacke zone and its equivalents preserved in the eastern part of the Eastern Alps, as well as from the siliciclastic base of the NCA. Fission-track data suggest that not only the highest Austro-Alpine level, the Upper Austro-Alpine unit, but also Middle Austro-Alpine Permomesozoic rocks (e.g., Scythian quartzites) were sampled by the Augenstein rivers. Indications for Middle Austro-Alpine material (including heavy minerals indicative of high greenschist to amphibolite facies) are mainly found in the western parts of the Augenstein area. According to our paleogeological reconstructions (Frisch et al. 1998, 1999), such lithologies were exposed rather in the westernmost part of the Augenstein source area than further east. Also, red quartzites and sandstones of the Buntsandstein facies, which are characteristic for the Scythian epoch in the western NCA, are mainly found in the western Augenstein occurrences.
5. The Augenstein sediment sheet was removed from the top of the central and eastern NCA between Early Miocene and Pannonian time. Uplift of the denuded Dachstein paleosurface was performed in the last 10 Ma. According to the arrangement of giant cave systems in three levels in the limestone massifs carrying the Dachstein paleosurface remnants, we conclude that uplift occurred in pulses, interrupted by periods of tectonic quiescence. Dating of cave material was not successful but indicates that the middle (the Giant) cave level is of pre-Pleistocene age. According to our reconstruction, the oldest (and highest) caves (the Ruin level) should have formed in Late Miocene time, if not even during formation of the Dachstein paleosurface. Probably also the Giant cave level formed in Late Miocene times, leaving the Pliocene to Quaternary period for the formation of the lowest (the Source) cave level. Post-Pleistocene normal faulting reveals recent or sub-recent tectonic activity.

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