The Oligocene geologic and paleotopographic evolution of the Eastern Alps

Joachim KUHLEMANN, Wolfgang FRISCH, István DUNKL

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Abstract: The Oligocene palinspastic situation of the Eastern Alps is characterized by a ~30% less E-W elongated shape than today. The recent shape formed during Miocene lateral extrusion.

The topographic situation in Late Eocene to Early Oligocene time was characterized by the termination of marine sedimentation except for the Lower Inn valley and neighbouring areas to the north, minor uplift, and the formation of a paleosurface with a hilly relief in the Northern Calcareous Alps (NCA) and in the Paleozoic terrains east of the Brenner line. West of the Brenner line, a moderate relief already existed, supplying coarse-grained material to submarine foreland fans. In this region, the topmost, low grade-metamorphic Austroalpine units were mostly removed by mid-Oligocene time and the crystalline basement became widely exposed.

In mid-Oligocene time a chain of volcanoes developed along the Periadriatic Lineament and provided effusive and tuffaceous material to the headwaters of the Paleo-Inn, which followed an active tectonic line. West of the Brenner line, a high mountainous relief developed by this time, reaching maximum elevations in the Bergell area. In the NCA west of the Inn river a mountainous relief established at the same time.

In the eastern central Alpine zone a moderate relief developed in the course of mid-Oligocene uplift, but it declined until Early Miocene time. Petrologic and thermochronologic data indicate that only topmost Austroalpine units with phyllites, low-grade metamorphic Paleozoic rocks, and siliciclastic sandstones equivalent to the basal section of the NCA were exposed in the area east of the Brenner Line. The eroded material was deposited on the drowning paleosurface of the central and eastern NCA, which formed a continuous depositional area with the foreland basin. Situated on the toe of the advancing nappe pile of the Eastern Alps, these so-called Augenstein deposits represent a depositional unit in a piggy-back setting.

As surface uplift continued in the west but not in the east until Late Aquitanian time, the increasing W-E topographic gradient enhanced gravitational instability and formed a prerequisite for Miocene lateral extrusion of the Eastern Alps.

Zusammenfassung: Die palinspastische Situation der Ostalpen im Oligozän ist durch eine im Vergleich zu heute um ~30% verringerte Ost-West-Erstreckung gekennzeichnet. Die rezente Geometrie wurde im Miozän durch die ostgerichtete laterale Extrusion geformt. Die paläotopographische Situation im Späten Eozän bis Frühen Oligozän war, vom Unterinntal und benachbarten

Institut für Geologie und Paläontologie, Universität Tübingen, Sigwartstrasse 10, D-72076 Tübingen, E-mail: kuhlemann@uni tuebingen.de, frisch@uni-tuebingen.de, dunkl@uni-tuebingen.de

Gebieten im Norden abgesehen, durch das Ausklingen mariner Sedimentation gekennzeichnet. In der Folge entstand in den Nördlichen Kalkalpen (NCA) und dem paläozoischen Basement östlich der Brenner-Linie infolge leichter Hebung ein hügeliges Relief. In den Gebieten westlich der Brenner-Linie bestand zu dieser Zeit bereits ein mäßiges Gebirgsrelief, welches die submarinen Vorlandfächer mit geröllführendem Material versorgte. In dieser Region waren die höchsten austroalpinen, schwach metamorphen Deckeneinheiten im Verlauf des mittleren Oligozäns bereits erodiert und das kristalline Basement war weithin exponiert.

Im mittleren Oligozän entwickelte sich eine Vulkankette längs des Periadriatischen Lineaments und stellte im Bereich der Quelläste des Paläo-Inn, der einer aktiven Störung folgte, effusives und tuffitisches Material zur sofortigen Abtragung bereit. Westlich der Brenner-Linie entwickelte sich zu dieser Zeit ein Hochgebirgsrelief mit maximalen Höhen im Bereich des Bergell. In den NKA westlich des Paläo-Inn entstand zeitgleich ein Gebirgsrelief.

In den östlichen Zentralalpen entwickelte sich im Zuge der allgemeinen Hebung im mittleren Oligozän ein bergiges Relief, das aber bis zum Frühen Miozän abnahm. Petrologische und thermochronologische Daten zeigen, daß östlich der Brenner-Linie nur die höchsten austroalpinen Deckeneinheiten mit Phylliten, schwach metamorphen Paläozoika und siliziklastischen Äquivalenten der Kalkalpenbasis exponiert waren. Das Abtragungsmaterial wurde auf dem ertrinkenden Paläorelief der zentralen und östlichen NKA abgelagert, wo ein mit der Molassevortiefe zusammenhängender Sedimentationsraum entstand. Da die Ablagerung im vorderen Bereich des sich Europa annähernden ostalpinen Deckenstapels erfolgte, stellen diese sogenannten Augenstein-Sedimente einen Ablagerungszyklus in einer "Piggyback"-Situation dar.

Da weitere Oberflächenhebung bis ins Späte Aquitanium im Westen anhielt, im Osten aber ausblieb, erhöhte sich infolge des zunehmenden topographischen West-Ost-Gradienten die gravitative Instabilität des Orogens und erzeugte so die Ausgangssituation für die laterale Extrusion der Ostalpen im Frühen und Mittleren Miozän.

Keywords: Oligocene, Augenstein Deposits, Eastern Alps, Periadriatic Volcanic Chain, Paleotopography, Fission Track

Contents

1. INTRODUCTION

The Paleogene evolution of the Eastern Alps includes fundamental tectonic, paleogeographic and environmental changes. In this paper, we focus on the Oligocene evolution, during which a high mountainous topography was built up in the west of the Eastern Alps and an increasing topographic gradient formed a prerequisite for Miocene lateral extrusion towards the east (Ratschbacher et al., 1991). The aim of this review paper is to provide a holistic view of the Oligocene geodynamic and topographic evolution of the Eastern Alps. The original data is published in Frisch et al. (1998, 1999, 2000, 2001) and other papers of the Tübingen group, cited in more specific chapters.

Some aspects of the Eocene evolution are summerized in order to constrain initial conditions for Oligocene geodynamic changes. Northward migration of the Eastalpine nappe stack was accompanied by southward subduction along its northern margin (e.g., Wagreich & Faupl, 1994). The Northern Calcareous Alps (NCA) were located at the tip of the orogenic wedge, when accretion of the North Penninic Rhenodanubian flysch units started in Paleocene time (e.g., Egger, 1995). These units were deposited during the Cretaceous and the Paleogene in a trough between the margin of Stable Europe and the Eastalpine nappe stack (see Trautwein et al., this volume; Wagreich, this volume). Thrusting of the NCA onto the Rhenodanubian flysch nappes ceased in Middle Eocene time and terminated sedimentation in these flysch basins (Prey, 1965).

Deep water deposition including turbidites occurred within the latest Cretaceous and Paleocene section of the Upper Gosau Group of the NCA and was accompanied by differential, but generally decreasing subsidence (Wagreich & Faupl, 1994). The evolving deep marine environment at the tip of the orogenic wedge in Late Cretaceous time is attributed to tectonic erosion, which reduced the thickness of the orogenic wedge from below and caused subsidence (Wagreich & Faupl, 1994). The decrease of subsidence in the NCA is probably due to the termination of subduction erosion and the onset of accretion of the Rhenodanubian flysch nappes. Deep water deposition in most of the Gosau basins of the NCA terminated in Early Eocene time (Wagreich & Faupl, 1994). Local deposition of shallow water Nummulitic limestones of Middle to Late Eocene age followed at the northern margin of the central NCA (Darga, 1990). Redeposited fossiliferous limestone pebbles of Early and Middle Eocene age are frequently found in molasse sediments (Hagn, 1967, 1976, 1989), testifying for a widespread marine deposition in the western NCA.

In the later source region for the Augenstein formation, flysch deposition in Gosau basins, particularly the Krappfeld Gosau, terminated in latest Cretaceous time (Thiedig & Wiedmann, 1976). It was succeeded by a thin terrestrial sequence including tropical soil formation, and by thick mid-Eocene limestones with red algae and nummulites (Van Hinte, 1963; Rasser, 1994). Marine carbonate sedimentation in the Eastern Alps apparently ceased in late Middle Eocene time (Hagn, 1976). According to our knowledge, siliciclastic debris in these Eocene limestones is rarely found which indicates that few islands were scattered in a shallow tropical archipelago.

The Late Eocene evolution of the Eastern Alps is only locally documented by sediments. In the foreland basin, continuous flysch deposition is recorded in the Katzenloch and Deutenhausen beds (Hagn, 1978). In the Inn valley, after shallow water and also limnic deposition in Late Eocene time a pull-apart basin with local scarp deposits, subtropical shallow water facies and deep-water marls developed (Hagn, 1960; Ortner & Sachsenhofer, 1996; Ortner & Stingl, this volume). After a short inversion period, the northern part of the western NCA was also occasionally influenced by marine transgressions in Late Eocene time, which is testified by redeposited pebbles of shallow water facies equivalent to in situ deposits of the Inntal Tertiary (Hagn, 1989). Evidence for significant relief in the hinterland is lacking.

2. METHODS

Our approach uses own structural, thermochronologic, petrographic, geomorphic, and sediment budget data for a geodynamic reconstruction:

(1) Palinspastic restoration

The reconstruction of the pre-extrusion geometry (Frisch et al., 1998) is based on the rearrangement of brittlely behaving upper crustal blocks according to geometry and the sense of shear of important Miocene faults (see Ratschbacher et al., 1991; Frisch et al., 2000b). Due to imprecise knowledge of the amounts of displacement along these faults, a best possible fit of dismembered tectono-metamorphic units as well as facies belts in sedimentary units has been achieved.

(2) Petrography and provenance analysis

Petrography and geochemistry of pebbles and sands mirror the development of catchments and the unroofing of the source terrains in the Eastern Alps (Brügel, 1998). Despite of some transport and weathering selection, particularly the pebble composition can be used for a reconstruction of formerly exposed lithologies and tectonic units.

(3) Thermochronology and exhumation history

Zircon and apatite fission-track (FT) analyses have been performed both on orogenic debris of the foreland basin and on source rock units in the Eastern Alps (Brügel, 1998; Brügel et al., in press). The cooling history displayed by orogenic debris mirrors regional changes of exhumation rates of the upper crust and surface exposure of mid-crustal material, exhumed by means of tectonic denudation and indicated by a sudden and strong decrease of the lag time of FT cooling ages. Cooling ages of source rocks in the Eastern Alps reflect the local exhumation history.

(4) Paleosurface reconstruction

Paleosurfaces are common features in the eastern parts of the Eastern Alps (Frisch et al., 2000a, in press). Based on FT data and geomorphic arguments, we present new time constraints for the formation of the paleosurface in the central and eastern NCA which drowned under the Augenstein sediments.

(5) Facies and basin setting

We shortly summarise the Oligocene facies development of the foreland basin which mirrors changes of relief in the hinterland (Frisch et al., in press). Facies, petrography and depositional setting of Augenstein sediment remnants reflect the contrasting evolution of the eastern versus the western parts of the Eastern Alps.

(6) Sediment budget

The sediment budget of the Eastern Alps displays a regional integral of surface erosion. Changes of the sediment budget are a good approximation for the development of relief which then can be interpreted in terms of a tectonic scenario (Kuhlemann, 2000). These data enable to estimate an ancient regional average thermal gradient which is important for the interpretation of thermochronologic, mainly FT data (Kuhlemann, 2000).

3. RESULTS AND DISCUSSION

3.1. Palinspastic restoration of the Oligocene setting

E-W extension and the associated unroofing of the Tauern window represents a major part of the overall extension of the Eastern Alps. It was mainly tectonically exhumed in Early and Middle Miocene time by a 160-km E-W pullapart of rigid Austroalpine hanging wall segments, forming the tectonic lid of the Penninic contents of the window (Fig. 1; Frisch et al., 1998). Large-scale shear is indicated by discontinuities in mineral cooling patterns across important shear zones (Blanckenburg et al., 1989).

Retrodeformation of the NCA along the Inntal and Salzach-Ennstal faults results in a continuous belt of the lower nappes which are now separated by higher nappes (Frisch et al., 1998). South of the Tauern window, a restoration of the elongated segments of upper plate units with mesozoic cover and a 150 km retrodeformation of equivalent units which escaped eastward into the Pannonian basement during the Miocene (Bakony; Kázmér & Kovács, 1985) results in a straight course of the Periadriatic lineament necessary for Oligocene large-scale displacement. The lineament is now disrupted and blocked by the Giudicarie line due to protrusion of the Dolomites indenter (Frisch et al., 2000b). The total E-W stretching of the Eastern Alps is ~170 km or 50% since Oligocene time.

3.2. Petrography and provenance analysis

3.2.1. Foreland Basin

A clayey marine deep water facies existed in the foreland basin trough during most of Kiscellian (Rupelian) time (Kapounek et al., 1965). In Early Egerian (Chattian) time, the center of the foreland trough north of Salzburg was supplied by axial turbidites, from the west and from the east (Füchtbauer, 1967). During Early Egerian time a large submarine fan with frequent pebble-rich debris-flows developed N of Salzburg (Malzer et al., 1993). Pebbles of this submarine fan mirror supply from a polymict source equivalent to the Paleo-Inn (see below). Granitic marker pebbles deriving from the Austroalpine unit

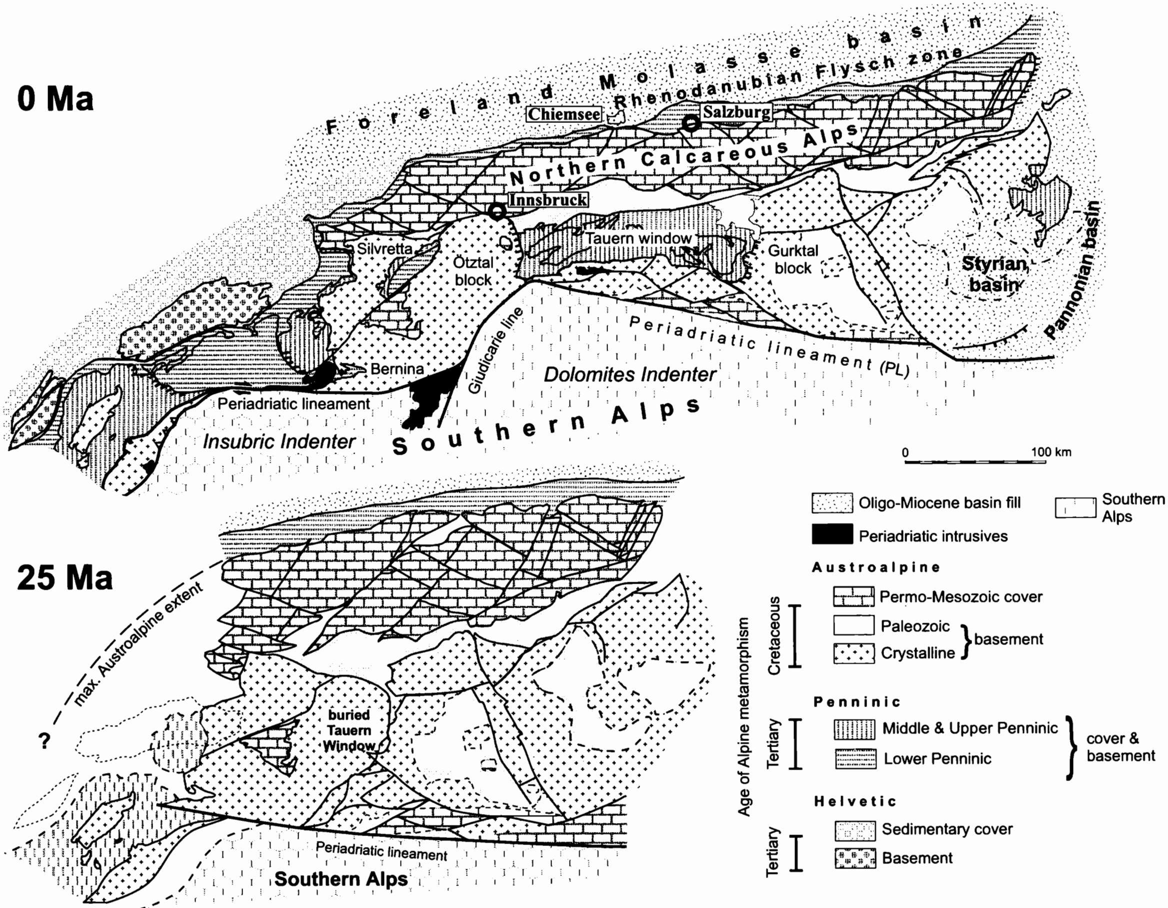

Fig. 1: Palinspastic restoration of the Eastern and Central Alps for the time before Miocene lateral extrusion after FRISCH et al. (2000b).

of the Bernina region are similar to those investigated by SKERIES & TROLL (1991) in polymict near-shore conglomerates which are equivalent to the debris flows deposited further to the east (LEMCKE, 1988).

The pebble composition of the foreland fans west of the Inn shows a remarkable change in mid-Oligocene (latest Kiscellian) time. In the Early Oligocene, pebbles are rare and consist of quartz with relics of phyllite in fold hinges, very small phyllites, dark carbonates (mainly dolomite), dark cherty limestones, dark cherts, and few quartzites. These lithotypes are typically observed in the low-grade metamorphic topmost Austroalpine units south of the NCA. Light coloured or brown carbonates mainly of Jurassic age, typical for the western NCA, are rare and limited to the westernmost fans (SCHIEMENZ, 1960; HAGN, 1978). Here, pebbles from the Rhenodanubian flysch zone also occur (HAGN, 1978).

In the Early Chattian deposits of the westernmost fans, light coloured or brown carbonates and brown sandy carbonates dominate whereas towards the east this NCA and flysch material is less dominant (SCHIEMENZ, 1960). The contribution from the Rhenodanubian flysch zone is increasing upsection.

These petrographic changes suggest that during Early Oligocene time only the westernmost NCA were exposed and that a low mountainous hinterland provided low-grade metamorphic Paleozoic material. Enhanced uplift rates in mid-Oligocene time increased the relief in the hinterland of these fans, and NCA as well as Rhenodanubian flysch units became widely exposed.

3.2.2. Inntal Basin

The Early Oligocene facies of the Inntal basin is charcterized by deep marine marls which grade upsection into turbidites (ORTNER & SACHSENHOFER, 1996; ORTNER & STINGL, this volume), which mirror progradation of the submarine prodelta of the Paleo-Inn. As proximal turbidites appear upsection, a predominance of quartz grains, schists and cherts is observed in thin section. In earliest Chattian time deposition of polymict conglomerates abruptly follows after a minor unconformity, containing low-grade metamorphic topmost Austroalpine debris as well as amphibolite-facies rocks of the crystalline basement, and NCA material (STINGL & KROIS, 1991). The pebble sizes and the amount of crystalline basement increase upsection, simultaneously to that observed in the westernmost fans of the East Alpine foreland basin.

These petrographic changes suggest that during Early Oligocene time most of the central Eastern Alps west of the Brenner Line were covered by low-grade metamorphic Austroalpine units. An uplift event in mid-Oligocene time increased the relief of the hinterland, and the crystalline basement became widely exposed.

3.2.3. Augenstein deposits

The Augenstein sediments are residual, mostly redeposited siliciclastic pebbly and sandy deposits which are widely distributed over the karst plateaus of the central and eastern NCA (13,000 km^2). The time of deposition is not exactly known, and both Oligocene (TOLLMANN, 1968) and Miocene ages (WINKLER-HERMADEN, 1957) have been proposed on the base of compositional correlations to foreland deposits. Depending on their true formation age, these sediments reflect the contrasting geodynamic setting between uplifting western NCA and subsiding central and eastern NCA.

The siliciclastic material is supposed to be deposited by braided rivers collecting their load from a source terrain south of the NCA (GÖTZINGER, 1913; WINKLER-HERMADEN, 1957). Most Augenstein remnants are reworked several times, and thus selective weathering potentially eliminated certain lithologies. Few autochthonous occurrences, however, provide information on the primary petrographic composition of these deposits (FRISCH et al., 2001). Pebbles of feldspar-bearing rocks have frequently been preserved in clayey matrix. Most pebbles, however, consist of polycrystalline quartz, quartzites, and of reddish to brownish quartz sandstones (Fig. 2). Other pebble lithologies are lydites, rhyolites, greenstones, and dark fine-grained carbonates. There are no coarse-grained marbles and no gneisses (amphibolite facies grade) among the pebbles (FRISCH et al., 2001).

The components nearly exclusively derived from weakly metamorphosed terrains up to greenschist facies grade. The lithologies are typical of Paleozoic terrains widely distributed in the eastern part of the Eastern Alps south of the NCA and of 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.

Towards the west, a potential facies transition of typical Augenstein deposits to Oligocene deposits of the Inntal basin deposits is indicated by the presence of high-grade metamorphic minerals such as reddish biotite in quartzites, and kyanite, staurolite and garnet as heavy minerals.

3.3. Thermochronology and exhumation history

3.3.1. Exhumation histories of source terrains

Apatite fission track studies were performed east of the Tauern window by GRUNDMANN & MORTEANI (1985), STAUFENBERG (1987), HEJL (1997), and REINECKER (2000) and in the Ötztal and Silvretta blocks by FLISCH (1986), FÜGENSCHUH (1995) and ELIAS (1998). Apatite fission track data from the Silvretta (FLISCH, 1986), the easternmost Ötztal block (FÜGENSCHUH, 1995) and the Gurktal block east of the Tauern window (HEJL, 1997) cluster around 30 Ma which indicates an important cooling event by that time and rather low rates of surface erosion since then. Local preservation of apatite cooling ages up to 60 Ma in the Brenner zone (FÜGENSCHUH, 1995) and the Gurktal block prove that bulk erosion did not exceed 3 km for the entire Tertiary epoch. Late Cretaceous and mid-Oligocene cooling age peaks are also present in mica age spectra (FRANK et al., 1987).

The age cluster around 30 Ma is also found in the apatite age spectra of Oligocene to Miocene molasse sands, suggesting an orogen-wide important cooling event in mid-Oligocene time (FRISCH et al., 1999). The apatite age spectra of distinct pebble lithologies such as red Buntsandstein and light coloured orthogneisses, sampled in Miocene fan deposits of the Paleo-Inn, indicate that the source terrain supplying 30 Ma apatite FT ages was located west of the Tauern window, whereas Late Cretaceous apatite ages mainly derive from the east and the north of the Tauern window (FRISCH et al., 1999). Cretaceous apatite fission track ages from clastic, non-volcanic material in Augenstein

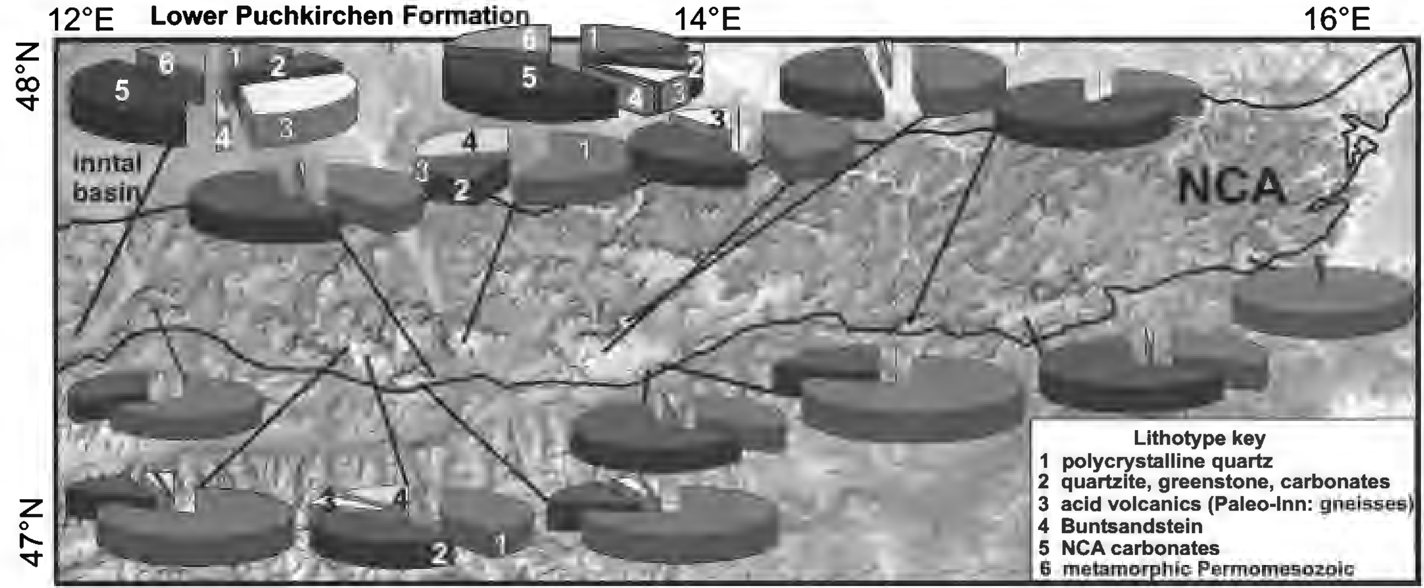

Fig. 2: Pebble compositions of Augenstein occurrences and Upper Oligocene strata of the Inntal Tertiary and the Lower Puchkirchen Formation (mod. after FRISCH et al., in press).

sediments show that the eroding rivers did not incise deeper than 2 km in the Paleozoic terrains east of the Tauern window, which supplied the central NCA in Oligocene time (see below; FRISCH et al., 2001).

3.3.2. Volcanic activity

In sands of the upper Angerberg beds of the Inntal basin, deposited in Late Oligocene time, a distinct and pronounced 30 Ma FT age cluster has been found in zircons (Fig. 3). The apatite FT age spectra in this sample is dominated by Late Cretaceous to Eocene cooling ages (Fig. 3). This apparent contradiction is explained by an important contribution of zircons deriving from the Periadriatic volcanic chain, which capped the well-known intrusive bodies lined up along the Periadriatic Lineament (FRISCH et al., 1999;

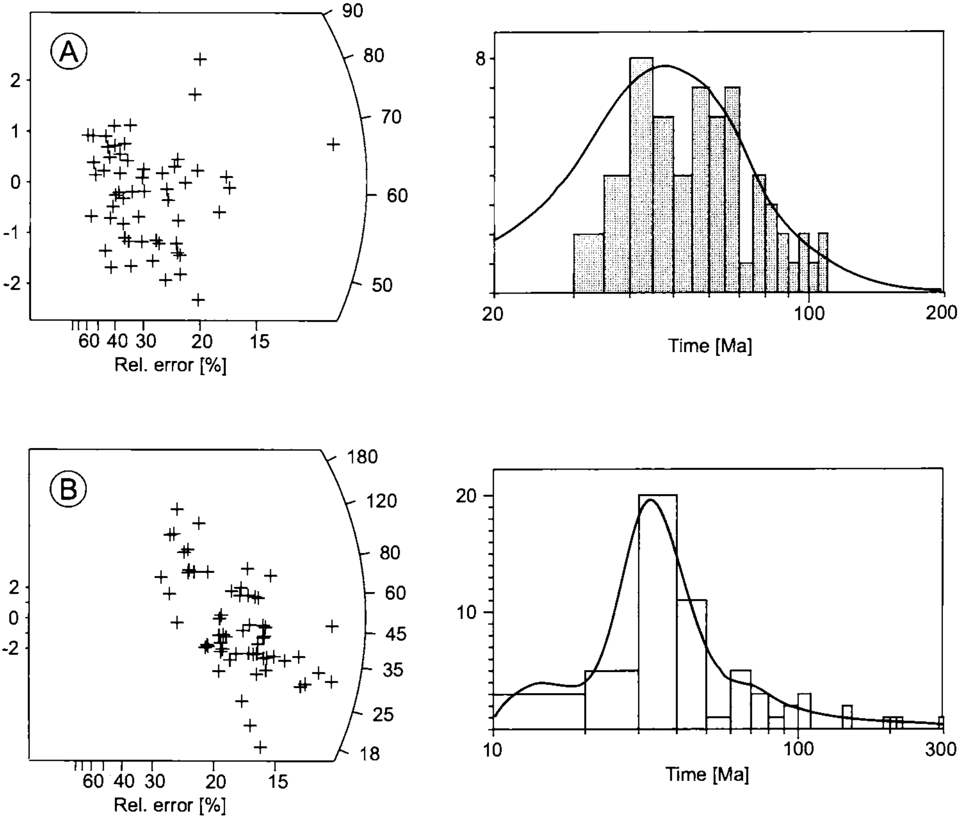

Fig. 3: Apatite and zircon fission track age clusters from the Upper Angerberg beds (Chattian) of the Inntal Tertiary, showing both detrital apatite grains (A) and dominantly volcanic zircon grains (B) origin (mod. after FRISCH et al. (1999). The data are shown as histograms and radial plots.

BRÜGEL et al., 2000). Due to lack of volcanic apatites in this sample, the apatite FT ages reflects detrital origin from the eroding basement. This interpretation is also supported by the clearness and the euhedral shape of the zircon crystals (see also GIGER & HURFORD, 1989; DUNKL & NAGYMAROSY, 1992; DUNKL et al., in press). Periadriatic volcanic pebbles are relatively rare in the pebble spectrum (MAIR et al., 1996) as compared to the relative amount of volcanic zircons in the heavy mineral spectrum (FRISCH et al., 1999). We interpret this in terms of easy destruction of the mostly tuffacous volcanics, whereas the resistant zircon crystals rather mirror the importance of volcanic material in the sediments. Volcanic or subvolcanic pebbles of Periadriatic origin are rare but always present in the pebble spectrum of the Paleo-Inn in the Oligocene Angerberg Formation and in the Miocene foreland fans (BRÜGEL, 1998). K-Ar ages of these subvolcanic pebbles indicate that the headwaters of the Paleo-Inn extended as far south as to the Adamello magmatic body, which most likely contributed volcanic pebbles of mid-Eocene to Early Oligocene age (BRÜGEL et al., 2000).

3.3.3. Volcanic zircons in Augenstein sediments: depositional age

The so-called Augenstein deposits consist of terrestrial sandstones and conglomerates rich in polycrystalline quartz. Despite their negligible preserved volume, these deposits provide important information of the paleogeography and exposed lithoterrains of the hinterland (see below) during the early depositional phase. As stated above, the time of Augenstein deposition is uncertain, probably during Oligocene to early Miocene time. FRISCH et al. (1998) argued that around 30 Ma, after an uplift impulse possibly related to slab breakoff (BLANCKENBURG & DAVIES, 1995), the advent of coarse pebble material in the Molasse zone west of the Inn river and in the central and eastern NCA happened simulaneously.

A 33 Ma old volcanogenic zircon population of Periadriatic origin from Augenstein sediments of a western NCA plateau (Steinernes Meer) shows that this is the maximum depositional age (FRISCH et al., in press). The lack of this volcanogenic signal in sandstone samples further to the west (Wilder Kaiser) and to the east (Dachstein) might either indicate a diachronism of Augenstein deposition or delayed transport of volcanic zircons due to backcutting of the headwaters of north-trending rivers.

3.3.4. Partial annealing of fission tracks in apatite of Augenstein sediments: thickness estimate

The Augenstein sediments probably formed a continuous sediment sheet covering the central and eastern NCA (WINKER-HERMADEN, 1957). We assume that the Augenstein sediments displayed a maximum thickness in the Dachstein region, since the only relevant autochthonous deposits of tightly cemented and compacted sandstones occur in this region (FRISCH et al., 2001).

Apatite fission track length distributions of samples from the Dachstein show shortened tracks, indicating a post-sedimentary mild thermal overprint (Fig. 4; FRISCH et al., 2001). 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 (HUFNAGEL et al., 1981) and a mean surface temperature around 16° C (BRUCH, 1998) results in burial

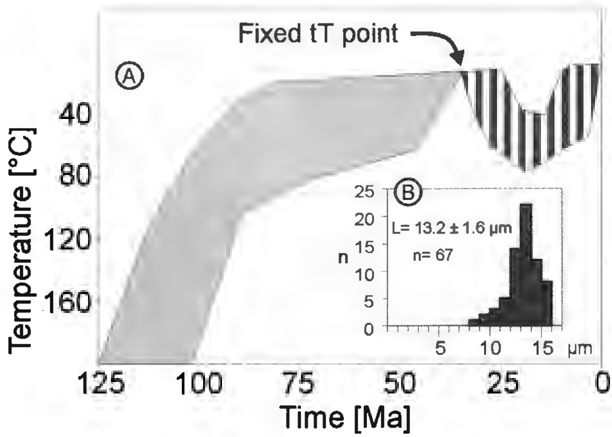

Fig. 4: Results of thermal modelling (A) based on apatite fission track length distribution (B), for a bulk of >50 combined Buntsandstein samples (mod. after Frisch et al., in press). The shaded time-temperature bands represent the envelopes of acceptable modelling paths and display the probably burial history (A). The model was forced to accept a fixed onset of sedimentation of the Augenstein deposits (vertical stripes) at 33 Ma.

of >1.3 km, possibly of ≥2 km (Frisch et al., in press). This thickness implies tectonic subsidence which is important for the geodynamic setting in Oligocene time.

3.4. Paleosurface reconstruction

Remnants of paleosurfaces, mostly attributed to the Miocene or Oligocene epoch, are common features in the eastern part of the Eastern Alps both in the central crystalline zone and the NCA (see Winkler-Hermaden, 1957; Frisch et al., 2000). They have been interpreted in terms of (i) a one-phase uniform peneplained paleosurface, which was tectonically dismembered in later time (Lichtenecker, 1926) or (ii) a polycyclic piedmont benchland formation with several periods of tectonic quiescence, in which planation surfaces of limited extent formed, and repeated phases of uplift (e.g., Götzinger, 1913; Seefeldner, 1926; Winkler-Hermaden, 1957; Riedl, 1966; Langenscheidt, 1986). Several authors correlated paleosurface remnants in the Austroalpine basement zone south of the NCA and east of the Tauern window with the NCA plateaus and defined different and numerous levels with downward younging ages. 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, 1926; Ratschbacher et al., 1991; Frisch et al., 2000).

Because termination of sedimentation of nummulite-bearing limestones in the central and eastern NCA occurred during Late Eocene time (Darga, 1990) and because of the time constraints from volcanic zircon fission track data (see above), the formation of a paleosurface prior to the deposition of the Augenstein sediments is restricted to Late Eocene to Early Oligocene time (Frisch et al., in press). It reflects erosion after the Eocene orogenic movements in the NCA, followed by tectonic quiescence. This paleosurface, termed "Dachstein paleosurface" by FRISCH et al. (2000), probably had a hilly character. Paleo-highs may have been present in the eastern part of Wilder Kaiser (see MUTSCHLECHNER, 1953) and the Leoganger Steinberge (see STINGL, 1990), where no remnants of paleosurfaces are preserved but where Augenstein sediments fill previously formed fissures (see above).

Paleosurfaces preserved in crystalline areas like the Nock surface appear to have formed in Early Miocene time (FRISCH et al., 1999; REINECKER, 2000), but a decline of relief certainly already characterized the Late Oligocene period. Frequently red clays are observed at the base of Late Burdigalian conglomerates (e.g., THIEDIG, 1970; WAGREICH et al., 1996; ZEILINGER et al., 1999) which were deposited in fault-bound basins in the course of lateral extrusion (RATSCHBACHER et al., 1991).

3.5. Facies and basin setting

3.5.1. Foreland Basin

In the foreland basin Early Oligocene deposits are typically of clayey or marly composition (e.g., LEMCKE, 1988). In the western Bavarian Molasse, sandy turbidites and mud-supported layers with small pebbles are locally observed (HAGN, 1978; FISCHER, 1979). Turbidite deposition in the Inntal basin starts during Early Oligocene time. A drastic change of facies is observed in Early Chattian time, when conglomerate deposition started and the Swiss and the western Bavarian foreland basin turned from marine to terrestrial environment (LEMCKE, 1988). The eastern deep marine foreland trough started to be supplied from the southwest with sandy turbidites and mud-supported pebbly mass-flows (ROBINSON & ZIMMER, 1989; MALZER et al., 1993). Apart from the axial supply, few small Alpine submarine fans developed at the southern margin of the eastern molasse trough (KOLLMANN, 1977; MALZER, 1981). The pebble size of all fans increased during Chattian time and conglomerates almost exclusively built up the proximal part of the fans in the Subalpine Molasse (LEMCKE, 1988).

An important indication for a weak and differentially subsiding European foreland east of the meridian of Chiemsee is deduced from the foreland basin facies. An almost fixed position of the coastline during deposition of the Late Oligocene-Early Miocene Puchkirchen Formation (LEMCKE, 1988) and apparent water depths of probably more than 1 km (WAGNER, 1996), despite of increasing sediment supply (KUHLEMANN, 2000), indicates stronger tectonic subsidence in this section than further to the west. The deepest marine environment is located in the area north of Salzburg, since a submarine fan further east turns to westerly directions (MALZER, 1981).

3.5.2. Augenstein deposits

The above mentioned facies change suggests that the discharge of pebbles to the Augenstein depositional area started in mid-Oligocene time. The pebbles of the Augenstein sediments have mainly diameters up to a few centimeters, whereas in few localities in the very south of the NCA plateaus pebbles of 10 or 20 cm diameter occur. Most pebble residuals of loose Augenstein deposits are well-rounded, sometimes displaying a polished surface, which indicates a long-distance or long-term transport by rivers. The rareness of fine-grained material in many localities, however, appears to be the result of multiple redeposition. Most fine-grained material has been washed into local karst sinkholes, whereas the pebbles remained on the karstified plateaus. Creeks of sufficiant transport capacity to transport pebbles are rare on the karst plateaus. A part of the fine-grained material has been multiply redeposited in cave systems (LANGENSCHEIDT, 1986).

We recognize less indications for braided river plain deposits as previously stated (e.g., WINKLER-HERMADEN, 1957). Moderately sorted coarse sandstones in the autochthonous occurrences indicate relatively constant transport conditions. 40° northward dipping bedding planes, interpreted in terms of leeward dipping foresets of sand bodies (Kufstein Plateau, Dachstein), indicate a channel depth of more than 0.5 m. Another autochthonous occurrence (Augensteindlgrube, Dachstein) displays less sorting and small-scale amalgamation of channel fills, which could be interpreted in terms of local deposition by a small braided river system. Further to the north, small pebbles are becoming rare. The presence of low energy environments and swamps with clayey sediments and reducing Eh-conditions is indicated by pseudomorphs of goethite after pyrite and markasite (see BAUER, 1954).

The overall setting of the Augenstein deposits suggests local deposition of conglomerate-bearing channel fills close to the southern margin of the deposition area, probably interfingering with fine-grained meander belt deposits. Towards the north, meandring rivers with a low transport capacity approached the coast of the Molasse Sea, possibly located south of the Alpine front. The Augenstein deposits represent the terrestrial margin facies of the foreland basin. Since Oligocene Augenstein deposition on the NCA occurred during ongoing progradation of the East Alpine nappe stack, deposition occurred in a piggy-back setting.

The initial reason for the Oligocene onset of subsidence in the central and eastern NCA is unknown. Subduction erosion appears to be unlikely, since accretion of Helvetic units continued until mid-Oligocene time east of Salzburg. Equivalents to the Inn valley Tertiary, including Oligocene molasse sediments, have been drilled on top of a lower NCA nappe (Vordersee 1; STEININGER et al., 1986). Further accretion of Subalpine molasse units continued until 17 Ma at the the eastern end of the NCA (WAGNER, 1996).

In Late Oligocene time, the Dachstein area was located south of the region of maximum foreland subsidence, according to palinspastic restorations of FRISCH et al. (1998). Thus, a relative maximum of subsidence of the upper plate as compared to regions west and east of the Dachstein area is likely. Further loading by the mass of sediments typically increases subsidence (e.g., STECKLER et al., 1988), which also applies for the Augenstein deposits.

3.6. Denudation-accumulation budgets

3.6.1. Budget of Augenstein deposits

The balance of erosion and deposition in regional catchments such as the Augenstein deposits and their source regions provides information on the sediment retaining capability of the semi-enclosed basin, which potentially provides additional environmental evidence.

If an average erosion rate of 0.05 mm/a (Frisch et al., 1999; Kuhlemann, 2000) over 10 Ma of Augenstein deposition is assumed for a source area of ~16,000 km², then a volume of 8,000 km³ was eroded in that time span. Since carbonate rocks were rare in the source area, the volume of dissolved material is estimated to have been around 15%, according to similar recent catchment settings in the Alps (Einsele & Hinderer, 1997), i.e., 1,200 km³. If we assume that about 70% of the remaining 6,800 km³ of bedload and suspended load were deposited on top of the central and eastern NCA, and that 30% were transported into the marine Molasse basin further north, a total volume of of 4,760 km³ (solid rock) would contribute to the Augenstein deposits.

The equivalent uncompacted volume with an average pore volume of 25% would be in the order of 6,350 km³ (Kuhlemann, 2000; Frisch et al., in press). This in turn is equivalent to an average sediment thickness of ~500 m, if spread over ~13,000 km² of the central and eastern NCA (see above). If we consider the irregular thicknesses of the Augenstein sediments due to a buried paleorelief and differentially higher subsidence in the central NCA with a local maximum up to 2 km thickness, this estimate appears to be realistic. At the eastern margin of the NCA thicknesses of Augenstein deposits were probably negligible and had been removed before Late Burdigalian time, since Augenstein sediments are not present in the Vienna Basin, where a mountainous relief has been sealed by Karpatian sediments (Tollmann, 1985).

This estimate of 4,760 km³ of volume deposited on the NCA may appear to be relatively high, as this is more than half of the volume eroded in the hinterland. It has, however, to be considered that before Miocene lateral extrusion of the Eastern Alps the NCA had a north to south extent of about 50 km (Frisch et al., 1998). For most of this distance rivers were probably meandring through vegetated, swampy lowlands, which were able to retain a large part of the suspended load and most of the bedload.

3.6.2. Budget of East Alpine Periadriatic volcanics

The budget of plutonic and volcanic material in an orogen and the timing of its generation provides information on the thermal gradients in the lithosphere. Here, only the volcanic contribution to the sediment deposition is estimated in order to separate this volume from material provided by erosion of the uplifting Eastern Alpine source terrains.

Most volcanic material of the Periadriatic volcanic chain in the Eastern Alps except for the feeder channels was removed by erosion until Early Miocene time (Frisch et al., 1998; 1999; Kuhlemann, 2000). The overall volume of Periadriatic volcanic rocks exposed in the southwestern part of the Eastern Alps is estimated to have been in the range of 3,000 km³ and may have covered up to 5 to 10% of the entire area of the Eastern Alps (Kuhlemann, 2000). The estimate is based on the areal distribution of Oligocene intrusive rocks and Oligocene dikes close to these plutons (Purtscheller & Mogessie, 1988; Brügel et al., 2000). Dykes in a distance of more than about 20 km north of the Periadriatic lineament, formerly thought to belong to the Periadriatic magmatic cycle (Beccaluva et al., 1983), turned out to be Permo-Triassic in age according to K-Ar dating (Zöldföldi et al., 1999).

3.6.3. Sediment budget of the entire Eastern Alps

Changes of sediment supply to basins adjacent to the Eastern Alps in post-Eocene time generally match variations of rates of tectonic processes already known from structural and geochronologic studies. A strong and persistent increase in sediment supply by more than 100% is observed in Late Oligocene time (Fig. 5; KUHLEMANN, 2000). This increase is coeval with a phase of global cooling (SAVIN et al., 1975), an eustatic sea-level drop (HAQ et al., 1988, ABREU & ANDERSON, 1998) and an important tectono-magmatic event, related, e.g., to slab breakoff (BLANCKENBURG & DAVIES, 1995). Due to the persisting high level of sediment discharge until Aquitanian time, this 3rd order eustatic sea-level drop cannot be the reason for enhanced erosion, since the following period is characterized by a 2nd order sea-level rise (see HAQ et al., 1988). Climate change as a direct reason is more difficult to exclude, since the entire Chattian period represents a relatively cool period (see SAVIN et al., 1975). In Aquitanian time global temperatures increase coeval with a further increase of sediment discharge. This implies that causal coupling of surface erosion and climate change in Oligocene-Early Miocene time was not of importance. Instead, thrust loading due to continuing convergence and thickening of the orogen is

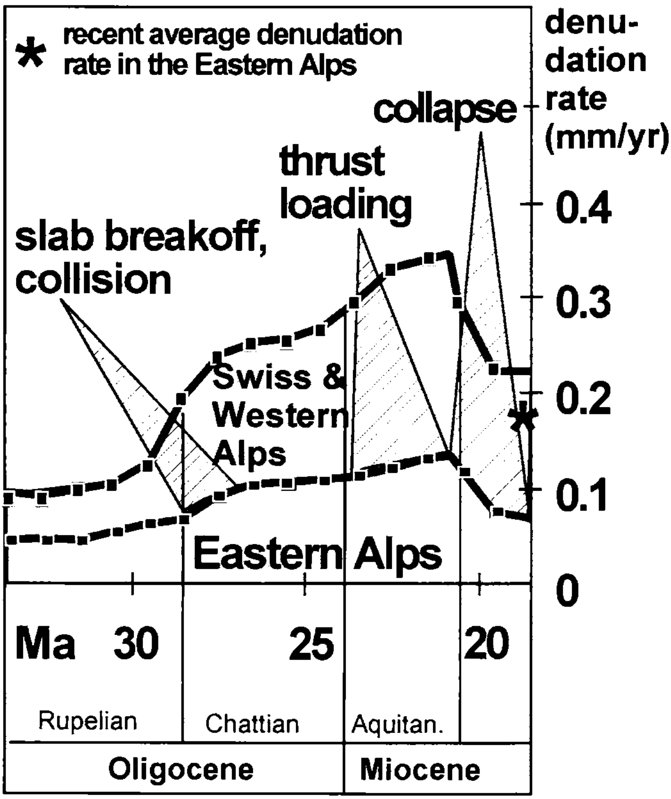

Fig. 5:
Oligocene to Early Miocene average denudation of the Eastern Alps, according to sediment budget calculations of KUHLEMANN (2000). The proposed geodynamic events represent one of several other possible controlling factors, and reflect our preferred interpretation.

assumed (KUHLEMANN, 2000). Regional climate evidence from palynoflora displays relatively constant precipitation in the range of 1000 to 1300 mm/a around the Eastern Alps from Oligocene to Middle Miocene time (BRUCH, 1998). Dryer conditions have been reported from the western Swiss molasse during Aquitanian time (KONZALOVA & BERGER, 1991).

Since increasing sediment discharge indicates the development of relief (EINSELE, 1992) and East Alpine sediment discharge was significantly lower in Late Oligocene than in recent time, it appears unlikely that the Oligocene relief was higher than today. This conclusion holds also for the Swiss Alps (SCHLUNEGGER et al., in press; KUHLEMANN, 2000) and is supported by a comparison of Late Oligocene and recent pebble sizes in the lower Inn valley. It is therefore not justified to assume almost Himalayan altitudes for a part of the the Swiss Alps in Oligocene-Early Miocene time, as proposed by HAY et al. (1992) and HANTKE (1993). The drop of sediment discharge after 21 Ma is interpreted to result from a relief collapse in the course of lateral extrusion (FRISCH et al., 1999; KUHLEMANN, 2000). Alternative explanations for the drop of sediment discharge in terms of exposure of less erodible rocks and a reduction of precipitation are presented by SCHLUNEGGER et al. (in press) for the Swiss Alps, but these factors do not apply for the Eastern Alps.

4. GEODYNAMIC EVOLUTION

The Eocene orogeny terminated marine sedimentation throughout the Eastern Alps and resulted in uplift, erosion and partial peneplainization (Fig. 6).

The geographic and topographic situation in mid-Oligocene time is interpreted to have been characterized by a hilly landscape in the eastern parts of the Eastern Alps, whereas in the southwestern parts a moderate relief already existed. These different relief domains supplied low to moderate amounts of sediment, respectively, to the foreland basin. The southwestern part of the Eastern Alps occasionally supplied small pebbles. Large parts of the western NCA, except for their southwestern part, were not yet emerged. We explain the relatively low to moderate relief in terms of a hidden load of a dense lithospheric slab which was still attached to the orogenic root. In the eastern parts of the Eastern Alps only topmost Austroalpine units with phyllites, low-grade metamorphic Paleozoic rocks, and siliciclastic rocks equivalent to the basal section of the NCA were exposed. In the western parts of the Eastern Alps these tectonic units were also still present in large areas, but some crystalline basement was already exposed.

Early Periadriatic magmatic activity had concentrated in the Adamello region (VILLA, 1983). In mid-Oligocene time Periadriatic volcanic activity strongly increased, which maybe related to slab breakoff and subsequent magma generation according to BLANCKENBURG & DAVIES (1995). A volcanic chain developed along the Periadriatic lineament (e.g., BORSI et al., 1979), probably expelling several thousands of km^3 of mainly tuffaceous material in the reach of rivers draining to the north (Figs. 6, 7). Increased surface erosion during early Chattian time, as indicated by a doublication of sediment discharge, suggests increasing relief. We relate both the magmatic paroxysm and prominent uplift in the Alps to the detachment of the dense subducting slab from the orogenic root zone (see also SINCLAIR, 1997) and to crustal stacking in the course of continent-continent collision.

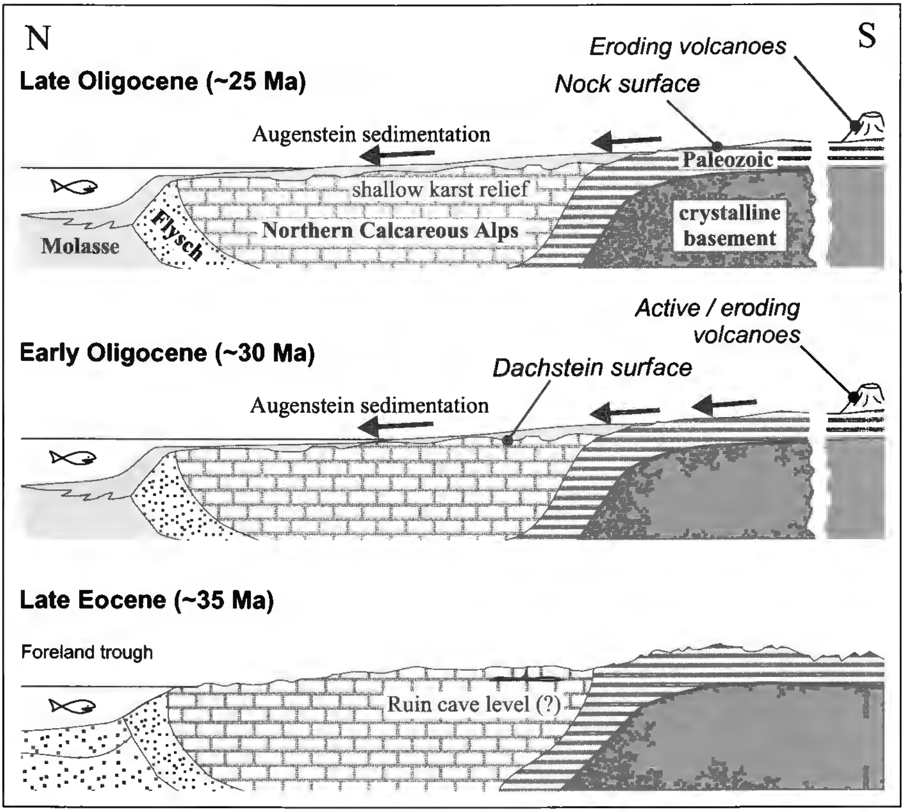

Fig. 6: Schematic N-S section of the Dachstein area and the low grade metamorphic terrains of the Eastern Alps between Late Eocene and Late Oligocene time.

Conglomerate fans developed in a foreland basin which rapidly turned from marine to terrestrial facies west of the Chiemsee area. East of the Chiemsee, the foreland basin remained in an underfilled deep marine environment, despite of increasing sediment supply. Subsidence occurred especially in the central NCA in the immediate south of the strongly subsiding foreland sector (Figs. 6, 7). The eastern NCA experienced minor subsidence, whereas the NCA west of the Inn were uplifted. In the central and eastern NCA, subsidence enabled terrestrial deposition of Augenstein sediments, sealing the Dachstein paleosurface. These piggy-back deposits represent the terrestrial marginal facies of the foreland basin. The facies of the Augenstein deposits comprise local conglomeratic channels at the southern margin of the NCA, which entered a vast coastal plain with rivers probably meandering northward to the coast of the Molasse Sea near the Alpine front.

During Chattian time a mountainous relief established in the western Eastern Alps, displaying increasing altitudes towards the SW. The Bergell area, situated in the southwestern corner of the Eastern Alps, was probably part of the highest region of the

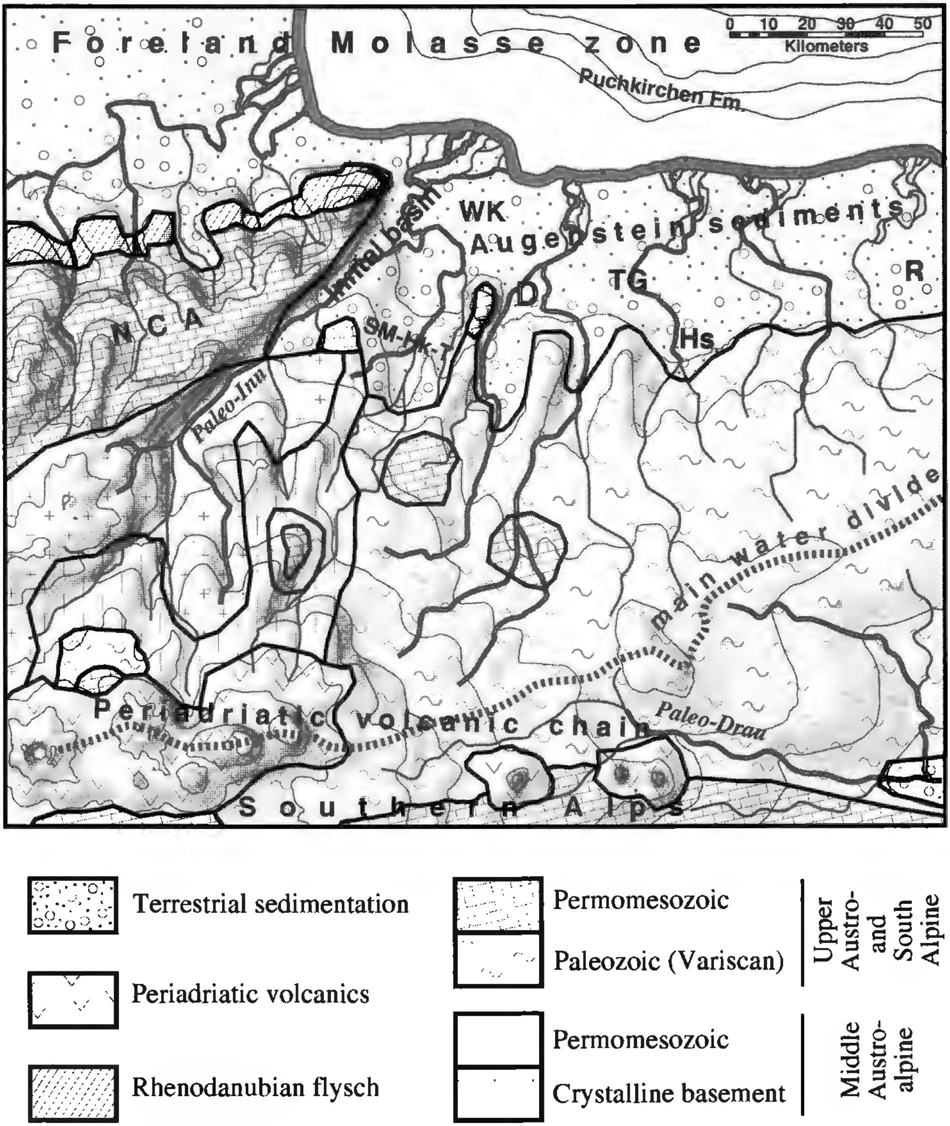

Fig. 7: Paleogeography and paleogeology of the Eastern Alps in Late Oligocene time (mod. after FRISCH et al., in press). The palinspastic restoration is taken from Fig. 1. Sketch shows different source areas for Augenstein and Inntal Tertiary sediments, but also transitional situation for Steinernes Meer and Wilder Kaiser. NCA, Northern Calcareous Alps. WK, Wilder Kaiser; SM-Hk-T, Steinernes Meer – Hochkönig – Tennengebirge; D, Dachstein; TG, Totes Gebirge; Hs, Hochschwab; R, Rax.

Alps at that time (WAGNER et al., 1979; GIGER & HURFORD, 1989; BERNOULLI et al., 1993). This area served as a triple point of regional drainage divides during Oligo-Miocene time (BRÜGEL, 1998), similar as today. In the western parts of the Eastern Alps (Ötztal Alps, Silvretta, Bernina) the topmost Austroalpine units became largely removed by continuous erosion, and the crystalline basement became widely exposed. In the eastern central Alpine zone the moderate relief, which developed in the course of a short-term uplift event in Early Chattian time, started to decline.

Important further surface uplift in the Swiss Alps started not before Aquitanian time, affecting also the western margin of the Eastern Alps (KUHLEMANN, 2000). This uplift increased the east-west topographic gradient in the Eastern Alps and created gravitational instability (FRISCH et al., 1998).

The headwaters of the Paleo-Inn river, which were funneled by a valley forming along the sinistral Inntal fault, carried large volumes of volcanic material from the Periadriatic volcanic chain towards the northeast and drained even areas south of the Periadriatic lineament, like the Adamello region (BRÜGEL, 1998; BRÜGEL et al., 2000). Although the catchment of the Paleo-Inn has undergone important reorganisation during Late Miocene time (BRÜGEL, 1998), basic features of this river system came into existence already in mid-Oligocene time. This differs much from most of the Eastalpine river systems, which developed mainly during lateral extrusion in late Early to mid-Miocene time (see BRÜGEL, 1998; FRISCH et al., 1999).

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