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ORIGINAL PAPER

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Post-collisional sediment budget history of the Alps: tectonic versus climatic control

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Abstract Based on the sediment budget of the Eastern, Swiss and Western Alps since the Oligocene the regional tectonic evolution has been identified as the dominant factor. It is superimposed on the influence of both regional and global climate change and global sea-level change. During late Pliocene and Pleistocene times, climate became the dominant factor because of cyclic glaciations. The early post-collisional history of the Alps is characterized by a doubling of sediment discharge rates around the Rupelian/Chattian boundary. This increase is attributed to isostatic re-adjustment either after large-scale thermal reorganization of the lithosphere related to slab break-off, or to crustal thickening as continental crust became subducted. From Middle Oligocene to Late Miocene times, the overall trend of sediment discharge rates in the entire Alps was modified only during relatively short-lived phases. These are characterized by an increase in Aquitanian (ca. 23–21 Ma) and late Burdigalian times (ca. 18–16.4 Ma), and a decrease in early to middle Burdigalian (21–19 Ma) and Langhian to Serravalian times (16.4–12 Ma). An important, still ongoing period of uplift, reflected by rapidly increasing sediment discharge rates, started in latest Miocene times in the Swiss and Western Alps and affected the Eastern Alps some 2 million years later. The reason for this uplift is not clear, but deep-seated lithospheric processes appear to be likely.

Keywords Alps · Climate · Sediment budget · Tectonic events · Tertiary

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Introduction

High mountain ranges are generally created by the collision of continental lithosphere (e.g., Molnar and England 1990). Collisional processes lead to crustal thickening, followed by isostatic uplift, erosion, and the formation of relief (e.g., Beaumont et al. 1996; Tucker and Slingerland 1996). Denudation rates accelerate until a steady state of crustal thickening, denudation, and relief is reached (Ahnert 1970; Tucker and Slingerland 1996). The mass of the erosional products represents integrated denudation rates with low spatial, but high temporal resolution.

Denudation rates have been shown to be proportional to relief in many settings, among other parameters such as precipitation, erodibility (lithology), and vegetation cover (Einsele 1992). The reconstruction of the ancient relief of an orogen and surface uplift through time has turned out to be very difficult and imprecise (Mercier et al. 1987; Fielding 1996) because no direct method of determination exists for Alpine-type mountain ranges.

The rates of denudation in a global scale are directly related to climate by a great number of factors (see Hay 1996), and thus a discussion of the basic causes of climate change will benefit from a better understanding of the causes of mountain uplift and the rates of denudation (Summerfield and Hulton 1994). Moreover, there is an ongoing discussion whether the tectonically induced uplift of mountain ranges essentially forced the climate system into the glacial mode (Raymo et al. 1988; Raymo and Ruddiman 1992), or if global cooling and repeated glaciations forced uplift of the mountain ranges (Molnar and England 1990). In this respect, the reconstruction of the denudation history of young mountain ranges contributes to the perspectives of global climatic change.

Aim of this study

This study of the Alps (Fig. 1), one of the most intensively studied mountain ranges in the world, is intended to evaluate the causes of mountain uplift. Because of the

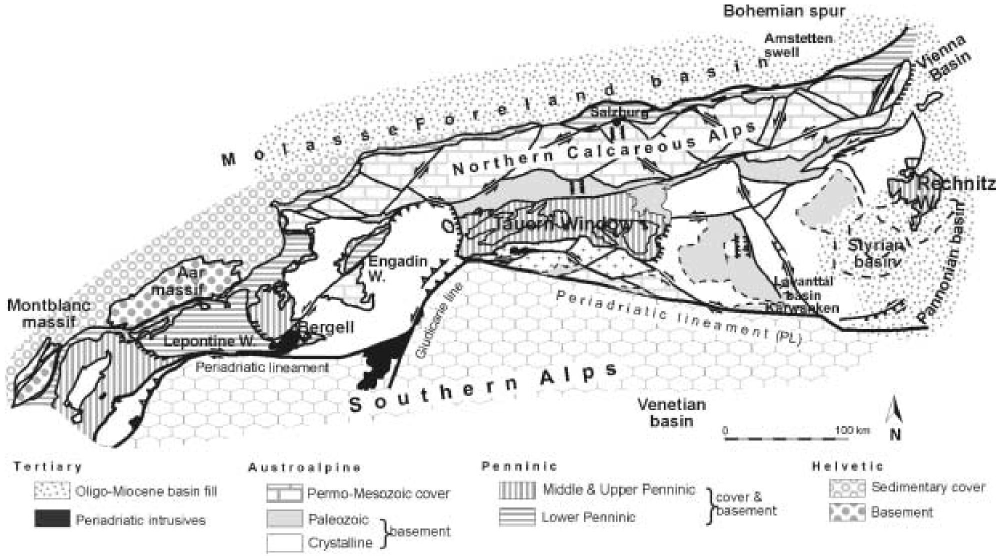

Fig. 1 Structural sketch map of the Swiss and Eastern Alps

limited size of the Alps, consequences for climate change can only be expected on a regional scale. The aim of the study is to show that a temporal resolution of Alpine bulk denudation rates of up to 1 million years is sufficient to relate their changes to either climatic or tectonic causes.

Previous work

England (1981) was the first to compare the thickness of missing hanging wall rock, deduced from metamorphic isograds, with bulk Alpine-derived sediment volumes of several surrounding basins. Guillaume and Guillaume (1982, 1984) recalculated the sediment budget of the Alps, whereas Hay et al. (1992) differentiated Alpine-derived sediment volumes according to time slices. Recently, Schlunegger (1999) and Schlunegger at al. (2001) calculated denudation rates in the Swiss Alps on the basis of sediment volumes in the Swiss molasse basin. A detailed data base for the Alpine sediment budget can be found in Kuhlemann (2000). The sediment budget calculations of these authors arrive at quite similar bulk volumes, but the estimates of the Alpine contribution to distal basins vary strongly. For a discussion of these different calculations see Kuhlemann (2000).

Complementary to denudation rates calculated from sediment budget data, thermochronologic data of exposed rock mirror cooling rates, which may be transformed to denudation rates if reasonable assumptions of the thermal gradient can be made (e.g., Mancktelow and Grasemann 1997). Distinct cooling events in the Alps are typically related to tectonic events (Ratschbacher et al. 1991; Blanckenburg and Davies 1995; Fügenschuh et al. 1997; Schmid et al. 1997; Frisch et al. 1999). However, thermochronologic data of exposed rock provide only local information, which has not yet been evaluated orogen-wide in terms of temporal changes of post-collisional Alpine denudation.

Methods and error sources

The budgets of the Eastern Alps, on the one hand, and of the Swiss and Western Alps, on the other hand, have been calculated separately. Both domains are separated by the meridian of the Alpine Rhine River and Lake Como in this study.

Our principal method was to compile from the literature the volume of sediments in all basins that received Alpine material. This was done by digitizing all available thickness maps of strata and base contour lines of sedimentary basins, as well as planimetry of geological profiles. The calculated volumes of sediment were then re-compacted to a porosity equivalent to the solid rock of the source terrain. If density data of the sedimentary basin fill was not available, it was calculated on the base of porosity data and seismic velocities. If such data were also lacking, the standard compaction curves of Daly et al. (1966), plus an additional 7% compaction because of the presence of ductily behaving grains (see Pittman and Larese 1991), were applied. The base data are discussed in detail by Kuhlemann (2000). The solid rock-equivalent sediment volumes of the basins were separated into formations of known stratigraphic range to achieve the best possible time resolution.

Similar sediment budget estimations (e.g., Hay et al. 1992) were already published earlier without limiting the possible errors. At present, a formally correct statistical error analysis is not feasible because there are a lot of factors influencing the final error bar of the estimated eroded sediment volume. On the other hand, without a rough appraisal on the known errors the result are less valuable. Here we present the first attempt to give a bounding box of errors of sediment volume calculations based on the estimated effects of the modifying factors. We are aware that the estimate given is not fully correct from a statistical point of view, but, at the present level of understanding and with the available data, it is hardly possible to work out a better (i.e., less uncertain) estimate. Most of the aforementioned modifying factors are obviously of methodical origin; therefore, we expect that several error sources may be reduced as further knowledge accumulates.

Our semi-quantitative error assessment (see the Appendix) may shed some light on the validity of the estimation and reveals constraints in further application of the derived data. We are convinced that our assessment, although with limited statistical validity, increases the practical value of the derived numerical results.

The transformation from relative stratigraphic to chronostratigraphic ages also represents a source of error that is not normally evaluated, which we try to assess here, too. Comparing ages attributed to stratigraphic boundaries during the last 10 years (Fig. 2, with references) gives a high divergence in the age estimates. If the reader prefers to assume that the accuracy of the most recent chronostratigraphic time scales represents an almost perfect estimate of an unknown "true" value, the calculated error for the stratigraphy can be ignored (see Fig. 3). With respect to the most commonly used stratigraphic timetables we refer to the chronostratigraphic charts of Berggren et al. (1995), Steininger et al. (1995), and Rögl (1996).

The estimated errors for separate basins and formations of the Eastern Alps reveals that, at a confidence level of 65% (1*F* error), major calculated changes of erosion rates and, thus, the reconstructed general trend, are reliable, whereas at a 95% level only three major features appear to be significant: the increased sediment discharges at 30, 17, and 5/3 Ma (see below). The other interpreted variations can only be supported by independent geological observations.

We conclude that while some smaller features of the varying sediment flux interpreted in this paper are insignificant from a statistical point of view because of the inherent errors of the method, the major rises and falls still persist in the case of selection of a more rigorous significance level. The computed relative error of the total sediment volume derived from the Eastern Alps is only 3.5% (1σ error), which indicates that the supposed statistical scattering in the contributions of the different basins is generally true. An addition of several maximum potential errors cannot be ruled out, but is extremely unlikely. Multiple errors are expected not to develop in a single direction during calculation, but tend to partly compensate each other, of course in an unknown way.

All details of these mass estimates have been documented by Kuhlemann (2000) and are not discussed in the frame of this paper, in order to concentrate on the implications of the results.

Data

Alpine-derived sediments are deposited in numerous basins of generally increasing distance to the orogen. The bulk volumes of Alpine origin, including the

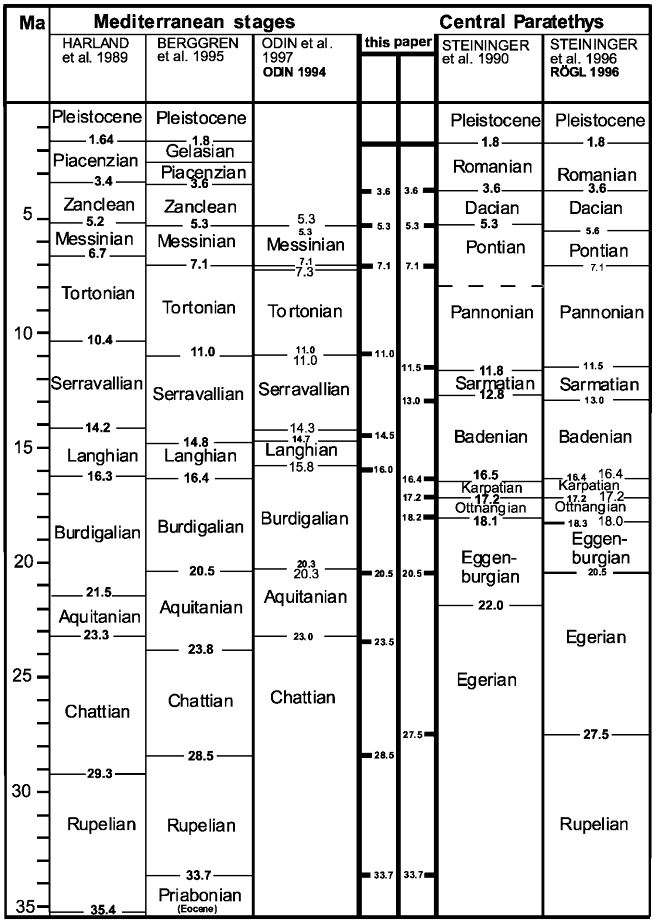

Fig. 2 From 1990 to 1996, the stratigraphic age determinations of Harland et al. (1989) and Steininger et al. (1990) have mostly been cited. After 1996, the stratigraphic tables of Berggren et al. (1995), Steininger et al. (1995) and Rögl (1996) are commonly cited and thus adapted for this paper. Precisely dated ages of stratigraphic boundaries in international Mediterranean reference profiles of Odin (1994) and Odin et al. (1997) are given for comparison

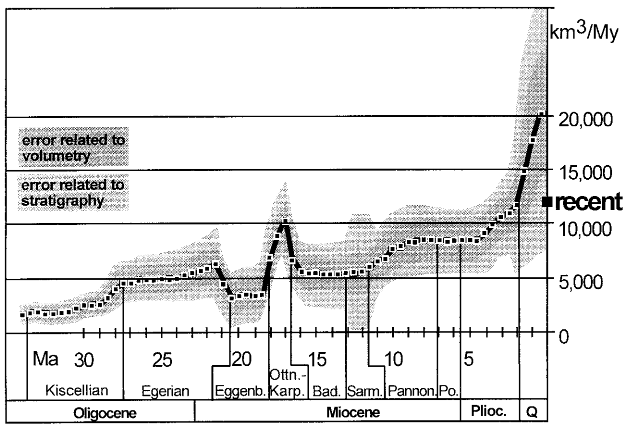

Fig. 3 Error envelope: (1σ error) of volume estimates of the Eastern Alpine-derived sediments, after Kuhlemann (2000). The error envelope is separated into a potential error related to volumetric calculations and an error related to the potential chronostratigraphic accuracy of the stratigraphy, as calculated from the varying length of periods in frequently cited time tables of the last 10 years

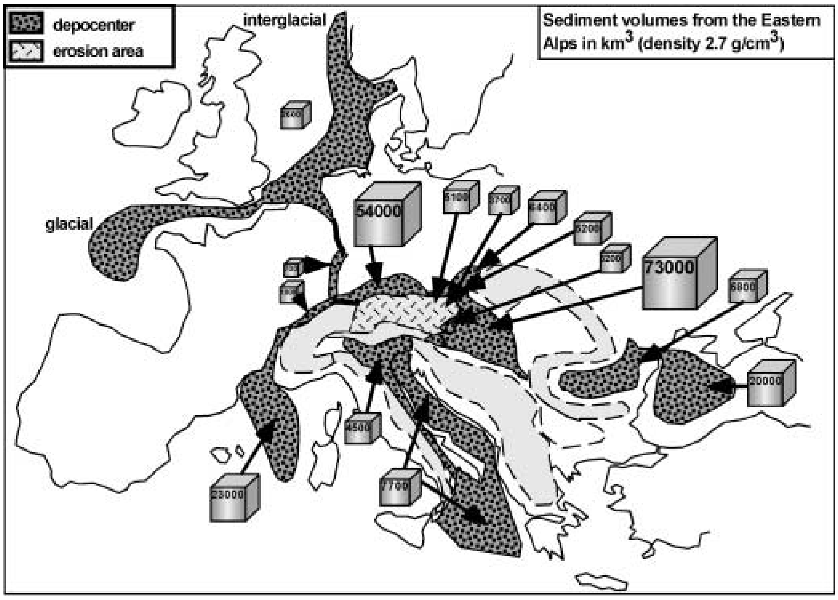

Fig. 4 Location of sedimentary basins supplied by the Eastern Alps

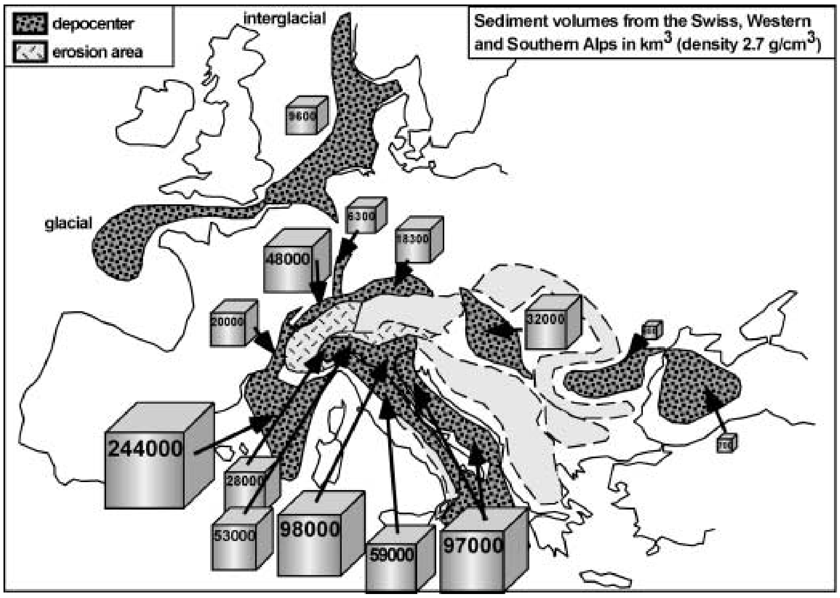

Fig. 5 Location of sedimentary basins supplied by the Swiss and Western Alps

estimated dissolved load, are summarized in Figs. 4 and 5.

The changing rates of Alpine sediment discharge, separated for the major basins of the Eastern Alps and the Swiss and Western Alps, respectively, is shown in Figs. 6 and 7. These curves are generated on the base of solid rock volumes. For a justification of these volumes, we refer to Kuhlemann (2000). To avoid artificial jumps at formation boundaries, we performed slight smoothing within the given volume and time span covered by the formation. All available semiquantitative and qualitative information has been used to achieve a maximum objectivity for this smoothing procedure, instead of the application of a mathematically correct, but still artificial smoothing function.

The sediment discharge rates achieved display mainly similar trends for the Eastern Alps and Western Alps, respectively, except for an increase of sediment discharge at ~11 Ma in the Eastern Alps, not expressed in the W. A time lag of 2–3 million years is observed for the latest Miocene/Pliocene drastic increase of sediment discharge between the western and eastern part of the Alps.

Discussion

Except for Alpine-derived sediment bulk volumes in major basins calculated by England (1981) and Guillaume and Guillaume (1982, 1984), Hay et al. (1992) were the first to separate bulk volumes according to formations

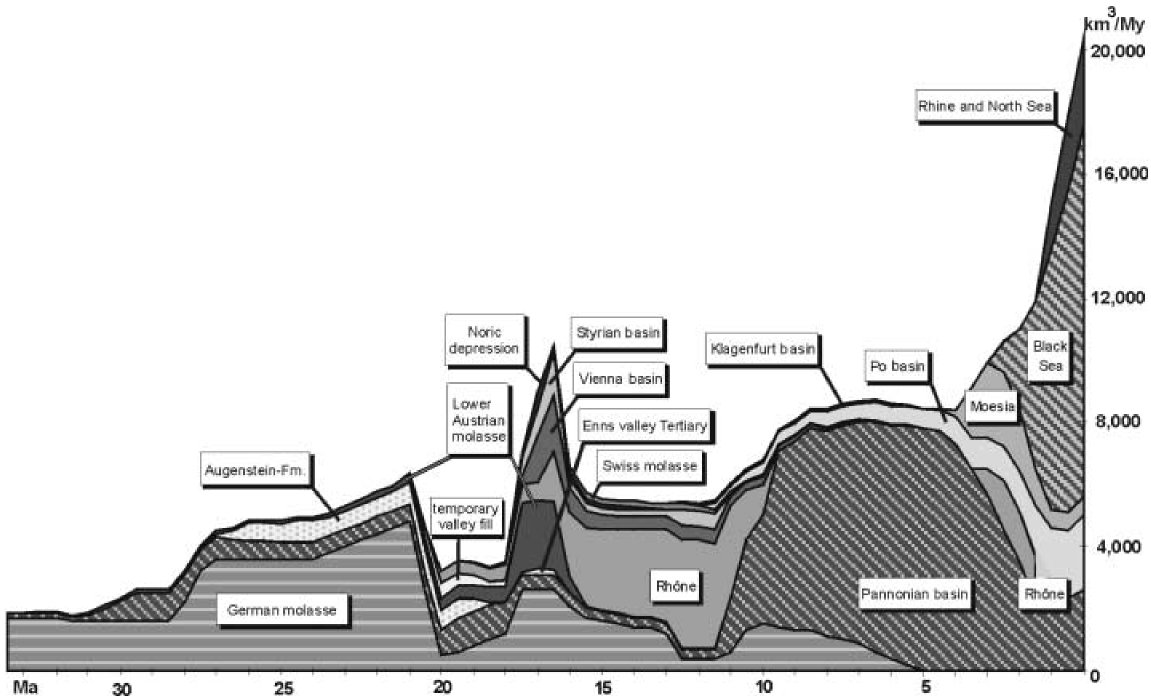

Fig. 6 Cumulative sediment discharge rates (solid rock) of the Eastern Alps since Oligocene times, differentiated for major sediment sinks. The small volumes deposited in the Slovenian, Lavanttal, and Inntal basins are included, but not differentiated in this figure. The volumes of formations are provided in the Appendix

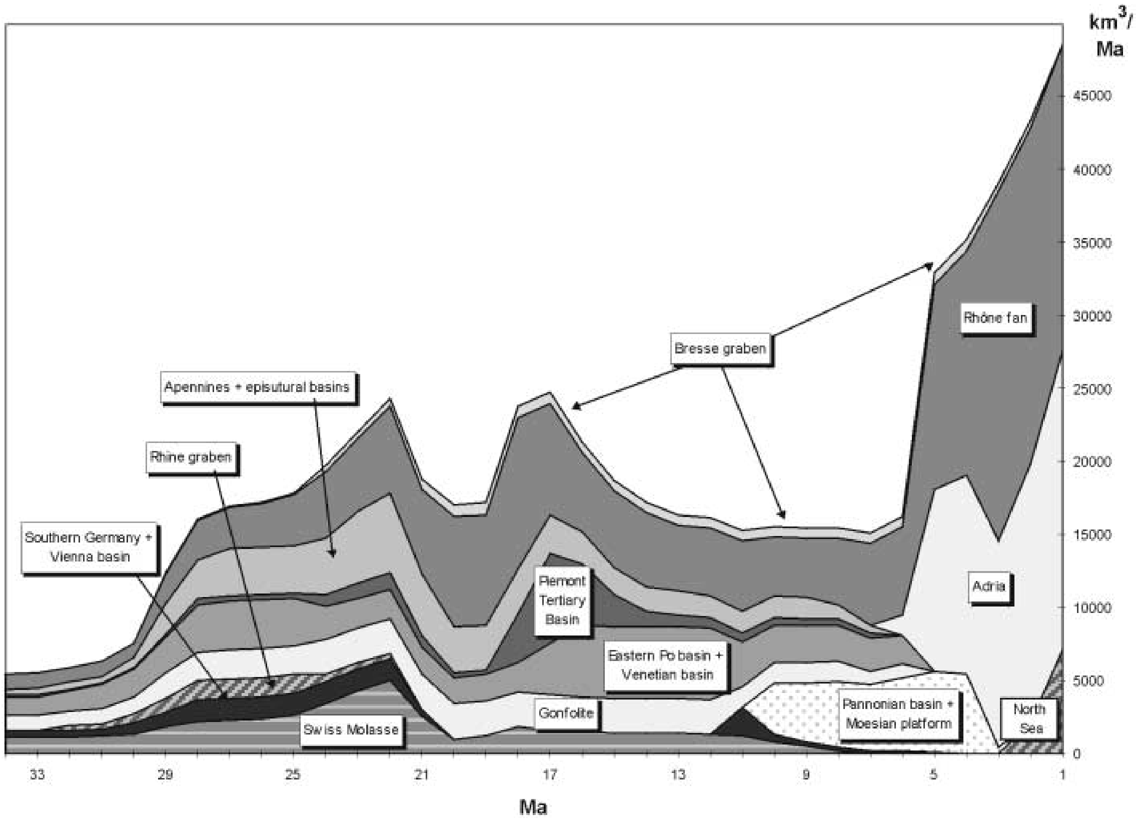

Fig. 7 Cumulative sediment discharge rates (solid rock) of the Swiss and Western Alps since Oligocene times, differentiated for major sediment sinks. The volumes of formations are further differentiated in the Appendix

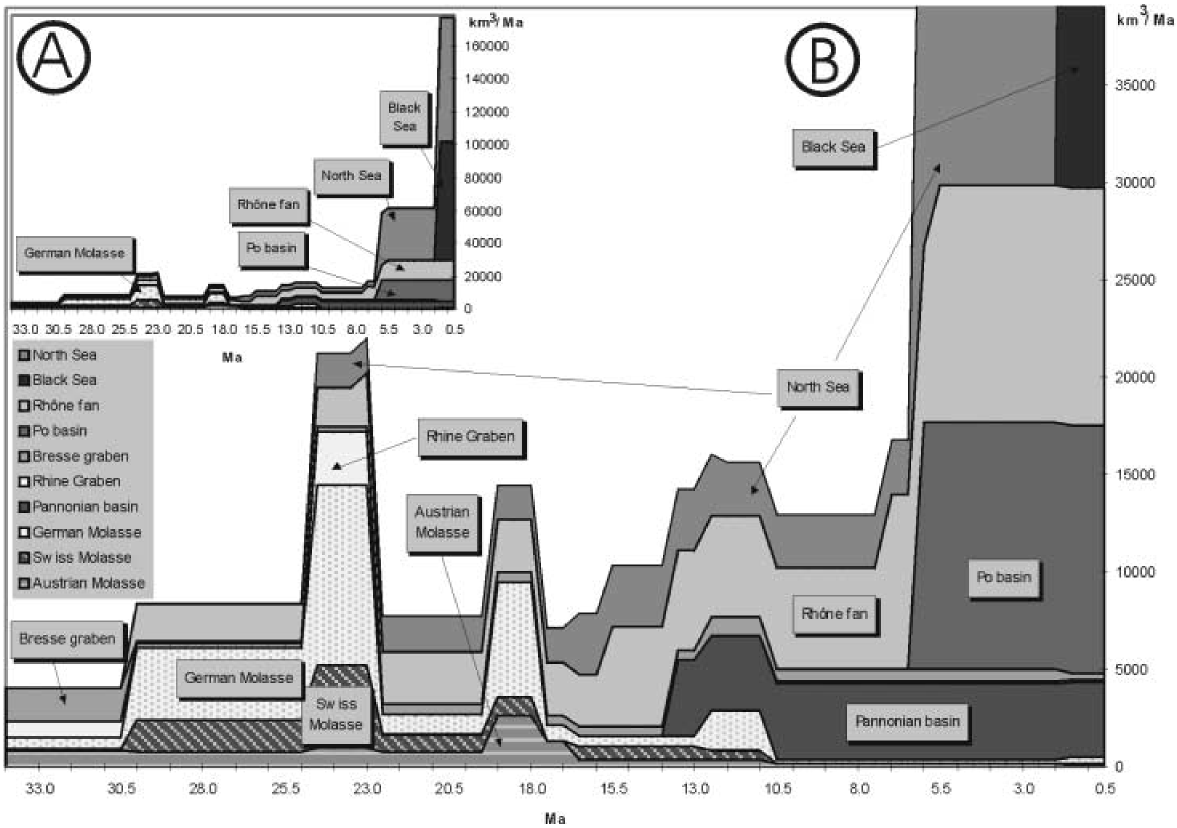

Fig. 8 Cumulative sediment discharge rates (solid rock) of the entire Alps since Oligocene times, differentiated for major sediment sinks, according to data of Hay et al. (1992). *A* The complete curve including whole amount of the latest Neogene and Plio-Pleistocene sediment volumes. *B* Only the lower part of the volume axis is shown in order to display Oligo-Miocene relative changes more clearly

and, thus, the time of deposition. We computed the data of Hay et al. (1992) in Fig. 8 to briefly discuss different trends. The trends for the Oligocene to the Late Miocene are quite similar, although Hay et al. register much stronger variations than we do. The very large difference of Plio-Pleistocene volume estimates is a result of highly divergent estimates of the relative Alpine contribution to the Danube fan in the Black Sea and the extensive export to the North Sea, assumed by Hay et al. (1992). For the Danube fan, we estimate 17% Alpine contribution, similar to Guillaume and Guillaume (1982, 1984), whereas Hay et al. (1992) assume 50%. For the North Sea, export of Alpine material can be excluded between ~20 and ~1.3 Ma (Kuhlemann 2000, and references therein). Large Pleistocene sediment volumes in the North Sea originate from Fennoscandia. During sea-level highstands (interglacial periods) these sediments are transported from the English Channel eastward into the North Sea by prevailing westerly winds and tidal pumping (Kuhlemann 2000, with references).

Potential controlling factors

Our basic strategy is to compare long- and short-term variations of the sediment budget with tectonic events, thermochronologic cooling rates, regional and global climate change, and possibly eustatic sea-level changes. Erodibility of exposed rock will also play an important role as lower plate (Penninic) metapelites became exposed during the Miocene (see Kuehni and Pfiffner 2001; Schlunegger et al. 2001; Kuehni et al. 2002). Other important factors such as vegetation coverage are a function of climate and altitude, and can hardly be reconstructed for the geological past. Altitude and relief evolution are also difficult to estimate for narrow Alpine-type mountain ranges. If climate change and variations of erodibility are of minor importance, the sediment discharge will, in turn, strongly depend on the relief (Einsele 1992). The importance of these various factors will be briefly discussed below.

Sea-level change

Global sea-level changes since Oligocene times have been studied in detail (e.g., Haq et al. 1988; Abreu and Anderson 1998). The effect of a sea-level rise at the foot of a mountain range is that river valleys would drown and create temporal accommodation space for sediments. In the case of a 100-m rise of the local base level, affecting a relief comparable to the recent Eastern Alps, an estimated volume of around 500 km^3 would accumulate in the valleys below the new base level along the northern and eastern margin of the Eastern Alps. Volumes in a similar range would additionally accumulate above the base level in the valleys by temporal aggradation, in order to establish equilibrium river profiles. This is of course a crude estimate because the ancient relief was always lower than today (Frisch et al. 1998), potentially increasing the sediment volume stored in the valleys. On the other hand, the glacially widened recent valleys provide more accommodation space than fluvially formed valleys would do. However, the solid rock volume of this unconsolidated river debris would range around 700 km^3, which is about 5% of the recent denudation rate per million years in the Eastern Alps (see Fig. 3). During periods of low sediment discharge rates in Miocene times, the potential effect may rise up to 10%, which is still within the error range.

If the sea-level drops, the temporarily deposited debris would be reworked relatively quickly. Such redeposition would temporarily increase the sediment discharge by up to 20% during large-scale changes of the global sea level, such as the rapid drop of up to 150 m (Haq et al. 1988) in earliest Chattian times. Short-term sea-level changes of 5th and 4th order cannot yet be resolved by the sediment budget method because of their short duration of less than 1 million years and the lack of basin-wide correlations of such cycles. Sea-level changes of the 3rd order, however, have a typical amplitude of 30–50 m within a complete, 2–3-million-year-long cycle in Tertiary times (Haq et al. 1988). The estimates of the amount of sea-level change is, however, under debate (e.g., Miall 1995). Changes of 1st and 2nd order have a duration of few to several tens of million years, which is too slow to be resolved by the sediment budget. Local or regional indications for apparent sea-level changes, decoupled from global sea-level changes, are known from major unconformities in most circum-Alpine basins. They indicate that, except for the extreme base-level drop in the Mediterranean in latest Miocene times (see e.g., Cita et al. 1978), regional tectonics were superimposed on global sea-level changes in basins close to or within the Alps.

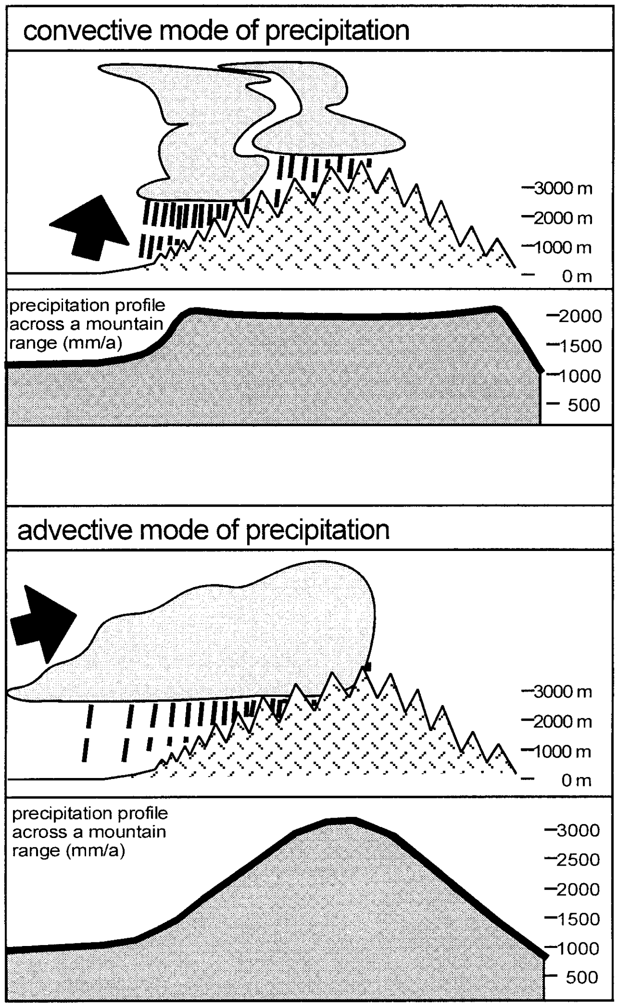

Fig. 9 Convective versus advective mode of precipitation and altitude-dependent variation of its amount across the Alps

Climate

The influence of climate change in the Alps since the Oligocene is separated here into (1) precipitation (amount, seasonality, intensity, regional distribution), and (2) temperature, which affects the type and density of vegetation and the intensity of chemical and physical weathering.

1. In the recent setting of the Alps, the export of dissolved load is generally proportional to the total amount of runoff because the amount of dissolved load is largely dependent on the lithology of the catchment (Einsele and Hinderer 1997). Strong seasonality of precipitation appears to drastically increase the mobilization of solid load on a regional scale (Schröder and Theune 1984). The short-term intensity of rainfall increases the mobilization of solid load by thunderstorms in local catchments. Fast advection of moist air over several days increases the mobilization of solid load in regional dimension, as monitored by the “century flood” of Lake Constance in 1987 (Wessels 1995). Advective orographic rainfall in mountains increases the amount of precipitation roughly linearly with altitude by a factor of up to three in the actual case of the Swiss and Eastern Alps (Fig. 9; Blüthgen and Weitschet 1980). Recent investigations of the annual precipitation in the Alps indicate that the curvature of topography is the predominant factor affecting its distribution (Frei and Schär 1998), but the actual precipitation pattern displays a mixture of both convective and advective precipitation. A weak meridional atmospheric circulation favors the convective mode of precipitation, which concentrates rainfall at altitudes of around 900 m above the base level at the margin of the mountain chain, whereas the amount of precipitation at the axis of the

orogen is slightly lower (Blüthgen and Weitschet 1980, p. 304ff). An advective mode of precipitation dominates in the case of atmospheric high temperature gradient, present in the west-wind zone during Pleistocene–Holocene times (Hay 1996). The increase of the thermal gradient increases the speed of S to N transport of latent and sensitive heat, rotated to zonal westerly winds by the Coriolis effect. This circulation pattern forces zonally moving cyclonal front systems to cross mountain belts and to the release much of their moisture. The quantification of precipitation in the Alps in post-Eocene times is problematic because paleofloral data are mostly derived from the surrounding basins and rarely from basin remnants within the mountains. Such data from basins adjacent to the Eastern Alps in Miocene times have shown that annual precipitation remained roughly constant at about 1,100–1,300 mm with a flat summer maximum and a fairly short minimum, probably during winter times (Bruch 1998). Seasonality, therefore, was of minor importance during Miocene times. Regionally drier conditions are observed in the western Swiss molasse in Aquitanian times (Konzalova and Berger 1991). The modern amount of precipitation in the Alpine foreland is in the range of about 800 to 1,000 mm/year. The intensity of rainfall in the geological past cannot be quantified. However, frequent hummocky cross stratification in middle Oligocene shore sands of the foreland basin (Diem 1986), as well as frequent tree-rafted pebbles in late Early Miocene intramontane fluvial environments, indicate episodic storm events (Kuhlemann 2000). The potentially most important factor of precipitation changes in the Alps is the transformation of the atmospheric circulation pattern from more convective to more advective rainfall. This change is mainly related to the thermal gradient between tropic and polar regions (Hay 1996), which stepwise increased after 14 Ma in the northern hemisphere, as indicated by the frequency of ice-rafted debris in the Arctic Ocean (Thiede et al. 1998). As a consequence of increasing temperature gradients in the vertical and latitudinal oceanic profiles, atmospheric circulation had to respond, although the regional mesoscale climatic differentiation of this response is not known (see Hay 1996). Mesoscale inverse climate modeling based on Middle Miocene paleoflora of NW Germany indicate weak meridional winds from southerly directions (Utescher et al. 1997).

2. The temperature control on physical weathering processes is important in areas without vegetation cover, coeval with mean annual temperatures below 0 °C. In these regions, physically weathered debris is easily mobilized by episodic events of strong precipitation, and downhill creeping is enhanced by solifluction. Temperature becomes even more important below annual average temperatures of about –5 °C, depending on the amount of precipitation, if high amounts of snow accumulate to form glaciers. Fast-moving, temperate valley glaciers appear to be the strongest agents of erosion in Alpine-type mountain ranges (Hallet et al. 1996).

For Neogene times, it is most important to know how much area of the mountain range was above the tree line and above the minimum altitude of permanent ice formation. This depends on the average annual temperature and the altitude of the mountains. Unfortunately, an estimate of the former altitude of the Alps is rather imprecise because no direct method of determination exists. According to paleoflora proxy-data, average annual paleo-temperatures in the East-Alpine foreland were in the range of 11 to 12 °C in late Miocene times (Bruch 1998), thus about 4 C higher than in modern times. This would mean that at around 8 Ma, the tree line on the northern flank of the Eastern Alps was located about 600 m above the recent tree line, at around 2,400 m, assuming a standard temperature decrease of 0.7 °C per 100 m altitude (Blüthgen and Weitschet 1980). The snow line would have ranged at around 3,400 m a.s.l., probably beyond the highest altitudes in the Eastern Alps at that time. Thus, potential glaciation of the Alps in late Miocene times was restricted to the highest massifs of the Swiss and Western Alps, if they were as high as today, which is also unlikely.

Regional climate in central Europe was not necessarily strictly linked to the global climatic signal. Temperatures on land appear to have decreased only slightly during Miocene times (Bruch 1998), and cooling of the world ocean between 15 and 14 Ma (Savin et al. 1975) appears to have influenced the Mediterranean and the Paratethyan realm only in a damped manner. However, changes of the Alpine sediment budget are not coeval with either global or regional climate change (Fig. 10).

Erodibility

The erodibility of exposed rock is primarily related to the degree of lithification. Unconsolidated clastic sediments are by an order of magnitude more erodible than lithified sedimentary rocks (e.g., flysch) in catchments of the southern Eastern Carpathians (Ichim and Radoane 1986, 1987). Metamorphic rocks such as paragneiss are three to five times less erodible than lithified flysch rocks in the latter example (Ichim and Radoane 1986, 1987). In the Swiss Alps, gneisses appear to be even more than ten times less erodible than the flysch units exposed in that region, at least in the scale of local catchments (Kuehni et al., submitted). In regional catchments with scales of hundreds and thousands of square kilometers, both the amount of sediment yield (Milliman and Meade 1983) and the differences of erodibility (Spreafico and Lehmann 1994) are reduced, resulting in the well-known scale effect for increasing catchment sizes (Milliman and Meade 1983). At the scale of a whole orogen, the erodibility decreases further because of this scale effect. Models suggest that the effect of

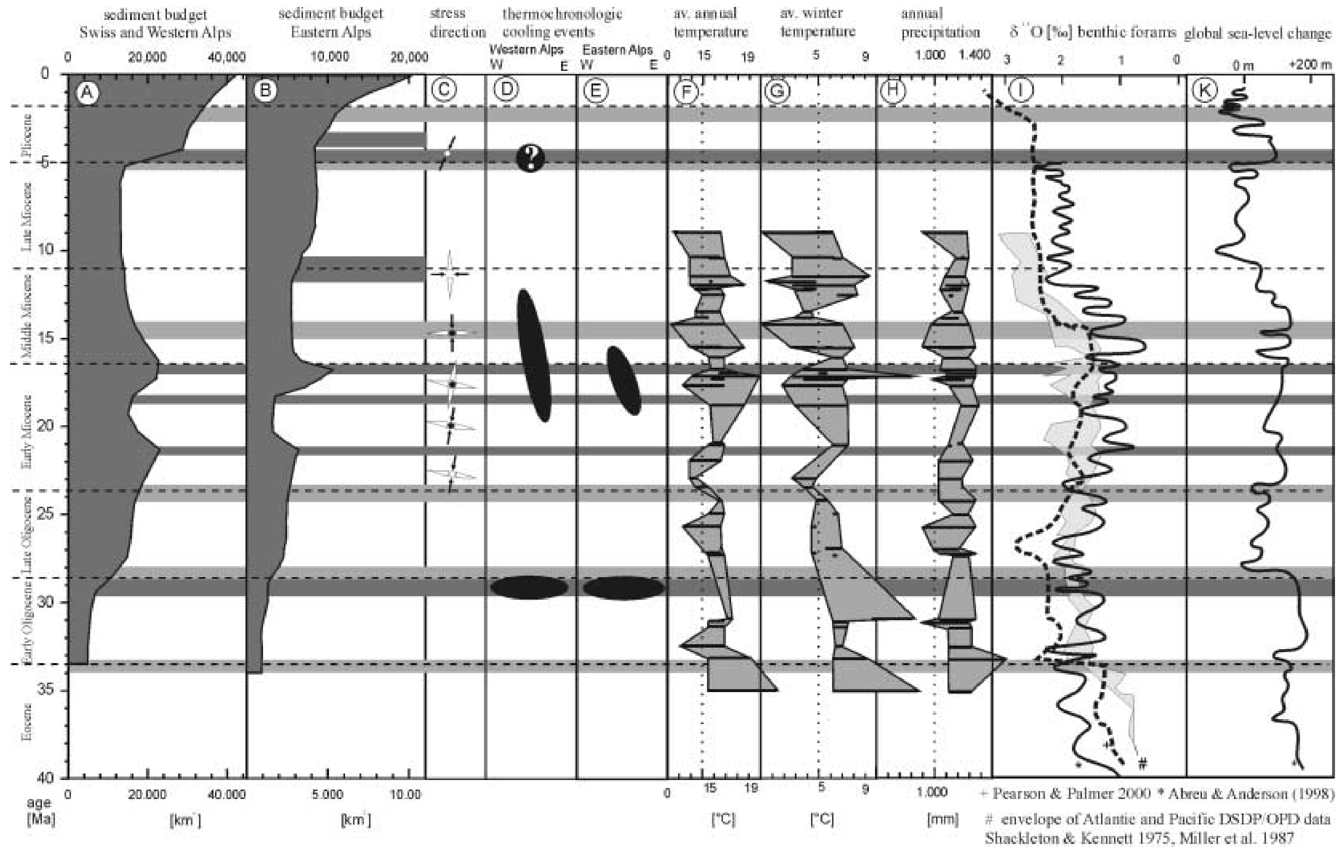

Fig. 10 Comparison of temporal variations of the Alpine sediment budget (*A*, *B*), changes of stress directions in the Eastern Alps (*C*, after Zeilinger et al. 1999), thermochronologic events in the Western and Swiss Alps as recorded by cooling age peaks of zircon and apatite fission track data (*D*, after Hunziker et al. 1992) and Eastern Alps (*E*, after Frisch et al. 1999), regional climate change in the North Alpine Foreland Basin, according to palynoflora (*F–H*, after Bruch 1998), global climate change, as recorded by the oxygen isotope composition of benthic foraminifera (*I*, after Shackleton and Kennett 1975; Miller et al. 1987; Abreu and Anderson 1998; Pearson and Palmer 2000), and global sea-level change (*K*, after Abreu and Anderson 1998). Important events in the sediment budget curves are marked in *dark gray*, events of climate change in *light gray*

lithological contrasts for erodibility is particularly high in strata with a low angle of dip, and weak folding and faulting (Tucker and Slingerland 1996). The Alps, however, are mainly characterized by steeply dipping and intensively folded and faulted strata. However, recent studies show that differences in erodibility have a strong influence on the formation of relief and the organization of the drainage pattern (Kuehni and Pfiffner 2001; Schlunegger et al. 2001).

In the Swiss Alps, nappes of sedimentary rocks were more widely exposed in Early Oligocene times, as deduced from the petrographic composition of molasse conglomerates and sandstones (Schlunegger et al. 1997b). In Miocene times, erodibility contrasts between low-grade schists (e.g., Bünden schists) and Austroalpine or Helvetic crystalline basement were more important because they occurred along the axis of the orogen and around exhuming tectonic windows (Schlunegger et al. 1997b; Kuehni and Pfiffner 2001). At the scale of nappes in these tectonic windows, erodibility contrasts affected regions of several 1,000 km^2 extent in axial position, where altitude and local relief typically reached a maximum (Ahnert 1984). In such cases, strongly contrasting erodibility potentially affects the exhumation geometry and the morphology, e.g., by a migration of the drainage divide (Schlunegger et al. 2001; Kuehni et al. 2002).

Potential controlling factors for changes of Alpine sediment discharge rates

Processes between 31 and 28 Ma

The increase of sediment discharge rates (see Figs. 6 and 7) occurred almost simultaneously with rapid regional overfilling of the molasse foreland basin and the corresponding facies change from marine to terrestrial environment (Sinclair 1997a) in the western part of the basin. Conglomeratic fan delta progradation started in the Swiss Alpine molasse at around 30 Ma (Schegg 1993; Schlunegger et al. 1996), or even at 32 Ma in the Eastern Swiss molasse, according to Kempf et al. (1999). In the westernmost part of the Eastern Alps conglomeratic deposition started somewhat later, within the earliest Chattian Baustein beds, according to sequence stratigraphic correlation in the molasse basin (Zweigel et al. 1998). In the western part of the Southern Alps, a facies change in Chattian times is documented by a rapid increase of grain size in marine mass flows (Gunzenhauser 1985). These changes mirror rapid formation of mountainous relief in the hinterland in this short period.

Judging from the Alpine sediment discharge in Chattian/Aquitanian times, which is about half of that observed in the Plio-Pleistocene period, it does not appear justified to assume almost Himalayan altitudes as proposed by Hay et al. (1992) and Hantke (1993), or altitudes formerly higher than now observed in the Bergell area (up to 3,500 m), as assumed by Jäger and Hantke (1984), and Giger and Hurford (1989). Such assumptions are also in conflict with empiric approximations of height limits of orogens, based on the recent relief of the Earth's major mountain chains (Ahnert 1970, 1984).

The Bergell area, situated at the boundary between Central and Eastern Alps, appears to represent a fairly stable region of maximum average altitude (Frisch et al. 1998) with steep local relief gradients allowing large boulders to travel from the exposed Oligocene intrusive body over several tens of kilometers southward down to sea level as early as in Chattian times (Jäger and Hantke 1984). These boulders are deposited as marine mass-flows of the Gonfolite Lombarda Formation in the central section of the Southalpine foreland basin (Lombardy). The large size of boulders, however, is a problematic argument for extreme altitudes or glacial transport, as assumed by Hantke (1993) because such boulders can also be transported by debris-flows, especially if supported by earthquake tremors (Beaty 1989). Nevertheless, because at least three global cool periods occurred in Oligocene times, separated by warmer climatic phases (Miller et al. 1987), periodic high mountain glaciation with a snowline at altitudes around 3,000 m cannot be ruled out.

One potential driving mechanism for the increased sediment discharge rates around 30 Ma is uplift caused by the increasing rigidity of the down-warped European foreland (Stockmal and Beaumont 1987). The European margin had been progressively thinned during Jurassic extension by normal faulting. Increasing rigidity of the European margin towards the north would enhance thickening of the crust by foreland thrusting, followed by uplift (see Beaumont et al. 1996).

Alternatively, uplift may be explained by the isostatic response of the Alps to slab break-off at around 32 to 30 Ma (after Blanckenburg and Davies 1995; Sinclair 1997b). There is, however, a time lag of about 2 million years before the response of strong surface uplift and subsequent formation of relief, but response times of such duration are frequently assumed in landscape evolution models (e.g., Tucker and Slingerland 1996). The model of Royden (1993) explains the moderate topography of the Carpathian and Apennine chain by the subsurface load of a dense lithospheric slab. The setting of the Carpathian chain is characterized by an eastward prograding slab break-off (Sperner 1996) and subsequent magma generation, younging from the Western Carpathians in middle Miocene times to the Eastern Carpathians in late Miocene times and the southeastern edge of the Carpathians in Quaternary times (Royden et al. 1983). Surface uplift in the Carpathian chain follows at 2 to 4 million years after the first magmatic pulse, as indicated by increased progradation of deltas in the Pannonian basin and overfilling of the foredeep basin (see Vakarcs et al. 1994). The setting of the Western Carpathians in middle Miocene times may be similar to the setting of the Alps in Oligocene times.

The large mid-Oligocene sea-level drop, recently dated by magnetostratigraphy at 30 Ma (Schlunegger et al. 1996), coincides in time with the increase of denudation in the Alps and may appear to be an important controlling factor. The regressive event unquestionably triggered extensive re-deposition and appears to have controlled, for example, the rapid environmental change from offshore to shore facies within the Baustein beds in the South German and Swiss molasse basin (Diem 1986; Zweigel et al. 1998). The synchronous regression, however, cannot explain the diachronous appearance of conglomerates (see above). If the regression was an important factor controlling the sediment discharge rates of the Alps, the following long-term transgression should have forced sediment deposition in the foreland to decrease, which is not observed.

Processes between 24 and 21 Ma

At least two explanations for the increase of the average sediment discharge rates in the Swiss and Western Alps have to be considered: (1) a decrease of precipitation, and (2) the relief increased by isostatic adjustment to enhanced thrust loading and crustal thickening.

1. Schlunegger et al. (2001) postulate, on the base of model experiments, that a decrease of precipitation in the western Swiss molasse (Konzalova and Berger 1991) might have forced the topography to adjust, resulting in vertical growth. Increased topography would, in turn, result in an increase of pebble size and sediment discharge. In the case of vertical growth and reduced precipitation, however, the relief requires more lag time to adjust and the reduced transport capacity of Swiss Alpine rivers would first result in a reduced sediment discharge. The decrease of precipitation in the western Swiss molasse might rather be a result of increased relief, if easterly winds would produce local lee effects. Unfortunately, regional proxy-data for predominant wind directions are not yet available.
2. Some increase of relief is indicated by a strong increase of the pebble size in the western part of the East Alpine molasse as well as in the Swiss molasse (Kempf and Matter 1999). On the other hand, the increasing pebble size may be explained by the advance of the thrust front. This is recorded by the acceleration of subsidence of the southern margin of the fore-

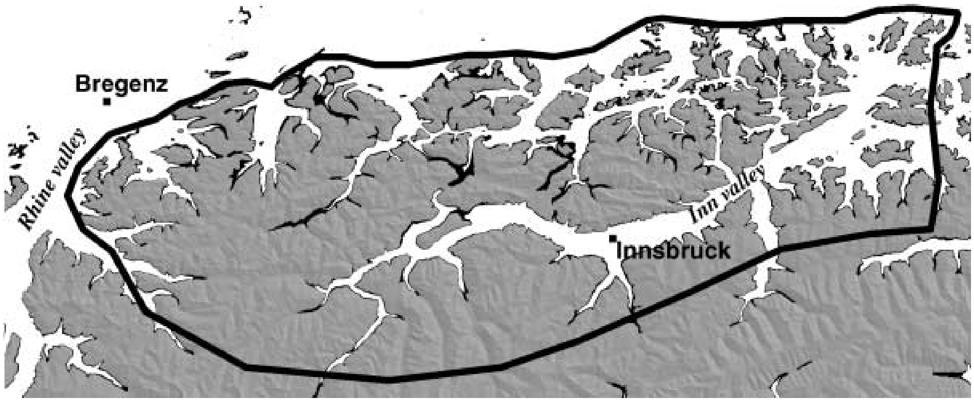

Fig. 11 Digital elevation model of the northwestern Eastern Alps, sketching the area affected by a rise of the base level by 700 m (*white*) and 800 m (*black*) above the altitude level of the Inn entering the Molasse foreland basin. The volume between the valley ottom and the white plain has been numerically calculated for the area *bordered in black* to estimate the potential temporary storage of debris in the course of a 700-m base-level drop

land basin, according to magnetostratigraphic data of Schlunegger et al. (1996) and Kempf et al. (1999). According to model experiments (Sinclair et al. 1991), an acceleration of the subsidence of the basin near the thrust front without a change of the basin width would increase the taper angle of the orogenic wedge and, thus, a relative rise in the axis of the Swiss Alps. A similar conclusion, which is enhanced crustal thickening in the axis of the Swiss Alps, is drawn by Schlunegger et al. (1997b) on the base of facies analysis of the foreland fans.

Processes between 21 and 20 Ma

The decrease in sediment discharge rates is coeval with the reduction of the thrust advance rate by more than a factor of three in the western part of the foreland (Homewood et al. 1986). This observation is in conflict with model predictions (Sinclair et al. 1991; Schlunegger 1999), which postulate vertical growth of topography as a consequence of decreasing thrust advance rates. In the easternmost low relief part of the orogen (Lower Austrian molasse to Vienna basin) thrusting continued until late Burdigalian times (Decker and Peresson 1996).

According to Frisch et al. (1998, 2000), a part of the plate convergence is compensated for by extension along the axis of the orogen, driven by gravity from the highly elevated Swiss and Western Alps towards the east. Extension probably reduced crustal thickness and lowered topography in the Swiss and Eastern Alps (Kuhlemann et al. 2001a). According to Schlunegger and Willett (1999), extension in the Swiss Alps had already started at ~25 Ma.

According to Zweigel et al. (1998), the reduction of foreland thrusting led to viscoelastic relaxation of the western part of the Eastern Alpine foreland basin. This caused uplift of a foreland bulge in the northern part of the basin with extensive reworking of unconsolidated sediment (Kuhlemann and Kempf 2002). Subsidence of several hundreds of meters, extrapolated to be around 700 m according to the curvature of the down-warped foreland (Zweigel et al. 1998), occurred at the thrust front. In the western part of the recent Eastern Alps, a volume of about 800 km^3 would temporarily accumulate in the valleys below the new base level, as calculated from a digital elevation model of the Eastern Alps (Fig. 11). Additional volumes should have accumulated in order to establish equilibrium river profiles. The solid rock volume of this unconsolidated river debris would range around 1,000 km^3.

For the Swiss Alpine foreland basin, flexural models, including broken plate models, are preferred (e.g., Sinclair et al. 1991). The migration of the flexural bulge towards more proximal sites, similar to the western East Alpine foreland, has recently been explained by the initiation of out-of-sequence underplating in the area of the Aar massif (Schlunegger et al. 1997b).

During this time, a marine connection developed at the front of the orogen between the Paratethys and the Western Mediterranean [Upper Marine Molasse or “OMM” group; “Burdigalian Seaway” of Allen et al. (1985) and Martel et al. (1994)] because of increased subsidence at the thrust front. The reduction of the flexural wavelength of the foreland could be explained by (1) thermal weakening of the overridden plate (Zweigel et al. 1998), (2) decreasing sediment discharge (Schlunegger 1999), or (3) a combination of steepening of the slope angle of the pro-wedge and decreasing sediment discharge (Sinclair et al. 1991).

Steepening of the average slope of the pro-wedge, as assumed by Sinclair et al. (1991), would increase the sediment discharge. According to Schlunegger et al. (1998), a reduction of the size of the N-drained catchment may have largely compensated this effect. Schlunegger et al. (1998) infer a reduction of the catchment size at ~20 Ma from increasing amounts of flysch sandstone pebbles from flysch units, formerly covering the Aar massif, at the expense of crystalline rocks (see also Matter 1964). However, a relative increase of flysch units contributing to the pebble spectrum of the foreland fans could also result from progressive erosional unroofing of flysch units below klippen of the Austroalpine crystalline hanging wall. A similar increase of flysch pebbles is observed in the molasse fans north of the western Eastern Alps because of erosional unroofing of the Northern Calcareous Alps and increasing exposure of the underlying flysch nappes. Here, there is no indication

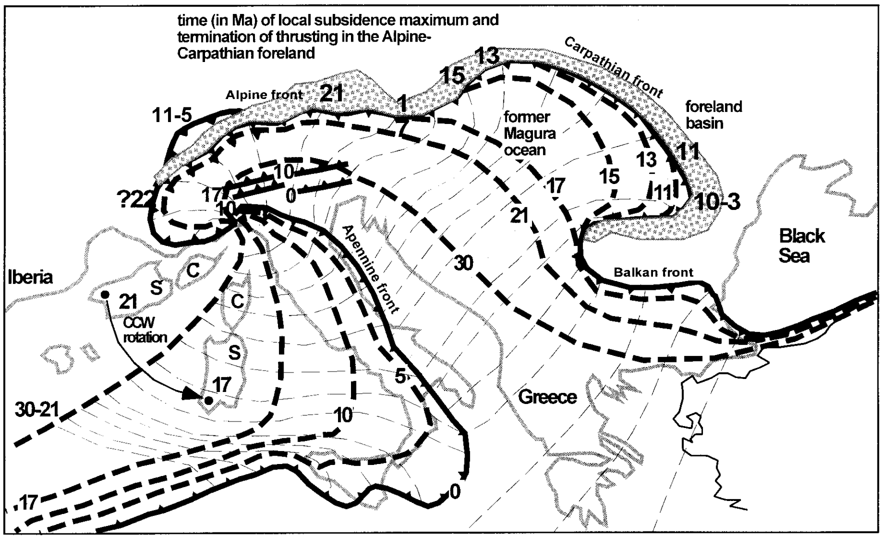

Fig. 12 Sketch map of the Mediterranean realm to indicate the timing of thrust propagation along the Alpine and Carpathian thrust front. *Hatched lines* indicate particle flow

of any shift of the drainage divide (Brügel 1998; Brügel et al. 2000).

Judging from the slightly decreasing sediment discharge rates calculated for the southern side of the orogen, northward movement of the drainage divide in the Swiss and western Alps has been of minor importance (Kuhlemann 2000). According to Kuhlemann et al. (2001b), the northward shift of the drainage divide happened at ~17 Ma. Recently, Eynatten et al. (1999) state that this shift occurred several million years later at ~15 Ma.

The main argument of Schlunegger (1999) for a northward shift of the drainage divide at around 20 Ma is the drop in sediment accumulation rates in the Swiss molasse basin to about a quarter of what he calculated for late Aquitanian times. His budget calculation, however, does not consider extensive export of sediment, mainly fine-grained material and most of the dissolved load, towards the Rhône fan (Kuhlemann 2000). Sedimentation of silty and particularly dissolved material in the molasse foreland basin was suppressed by the meso- to macrotidal environment and west-directed offshore currents (Allen et al. 1985), probably driven by dominant or more effective easterly winds. The assumption of easterly winds is not necessarily in conflict with the dominance of NE-directed nearshore tidal currents along the margin of the Bohemian massif (Faupl and Roetzel 1990), which would rather suggest a near-shore net eastward transport by tidal pumping.

A reduction of sediment discharge caused by exposure of more resistant lithologies is not supported by the pebble composition of the foreland fans (Matter 1964). In contrast, ophiolite pebbles (Dietrich 1969), K–Ar mica ages (Eynatten et al. 1999), and zircon fission-track ages (Spiegel et al. 2000) prove that higher Penninic ophiolites and easily erodible metaflysch rocks (Bünden schists) were exposed.

Processes between 18 and 17 Ma

The increase of sediment discharge rates in the Eastern Alps is stronger than in the Swiss and Western Alps. The eastern part of the Eastern Alps collided with the Bohemian spur, which initiated the rise of the Amstetten swell (Lemcke 1988), as well as a rise of the easternmost part of the Northern Calcareous Alps and especially the flysch nappes in front of them (Tollmann 1985). The uplift of this swell established a new westward directed drainage pattern in the foreland. The deepest part of the Molasse basin, situated in Upper Austria NE of Salzburg, became isolated and was filled up by increasing volumes of incoming sediment.

This sediment discharge pulse also coincides with up-doming and the formation of significant relief in the region of the later Tauern window. The rigid upper crust E of the Brenner fault broke into a number of tectonic blocks that started to migrate to the E along conjugate strike-slip faults that still dominate the tectonic pattern of the Eastern Alps (Frisch et al. 1998). Activity of this fault pattern and a phase of enhanced exhumation rates in the Penninic tectonic windows between 18 and 16 Ma is well known (Blanckenburg et al. 1989; Cliff et al. 1985; Dunkl and Demény 1997). A number of intramontane basins were newly formed along these faults (see Ratschbacher et al. 1991). A facies change in these interior basins from lacustrine to braided river environment with deposition of conglomerates of local provenance indicates the creation of a steep local relief east of the Tauern window, where before only minor relief existed (Frisch et al. 1998).

The principal reason for the up-doming and surface uplift event is less clear (Frisch et al. 1999). It is assumed that the roll-back of the Carpathian thrust belt in the rear of the retreating subduction of the remaining "Magura Ocean" (Fig. 12) temporally slowed down when approaching the Bohemian spur and the Moesian platform. This also slowed down northeastward propagation of the so-called ALCAPA (Eastern Alps and the Western Carpathians) and Tisza blocks in the rear of the thrust belt (see Tari and Horváth 1995). The slowing down of the northeastward movement of the ALCAPA block in the rear of the Carpathian flysch nappe pile temporally reduced early extensional processes in the Eastern Alps (Frisch et al 1998). The temporal reduction of lateral extrusion seems to have been compensated by vertical thickening in the Eastern Alps, followed by isostatic adjustment and surface uplift (Frisch et al. 1999, 2000). It is surprising that the Alpine sediment discharge responds nearly without a lag time to this tectonic event. Maybe the intense faulting during this time increased erodibility and fast subsidence along fault-controlled, newly forming dewatering lines that lowered the local base level, which lead to a more rapid formation of adjusted relief.

The passage of the Carpathian thrust belt into the remaining bay initiated a complex rotation pattern in the continental ALCAPA and Tisza blocks (Márton et al. 2000). Subsequently, accelerated extrusion is indicated by rapid exhumation of the Tauern core complex from middle to upper crustal levels (Genser et al. 1995; Frisch et al. 1998). The lateral extrusion is supported by an indentation of the Southern Alps (Ratschbacher et al. 1991).

In the Swiss and Western Alps, enhanced sediment discharge rates are also observed, which in analogy to the Eastern Alps, might be related to uplift of the Lepontine dome, or, alternatively, to differential uplift of the Aar massif (Schlunegger et al. 1997a).

Processes between 16 and 14 Ma

A significant and rapid reduction of the sediment discharge rates in the Eastern Alps is closely linked to crustal thinning as a far-field effect of strong extension in the Pannonian basin. Escape of continental fragments to the east, syn-rift sedimentation, crustal thinning, high heat flux, and volcanic activity within the Pannonian basin (Tari and Horváth 1995) show that gravitational collapse, lateral extrusion, and escape of East Alpine blocks and eastern South Alpine fragments reached a maximum (Royden et al. 1983). Space for extension was provided by accelerated roll-back of the subduction zone after the thrust belt had passed the gate between the Bohemian spur and the Moesian platform (Fig. 12; Sperner 1996). A fast shift of the depocenters in the Western and Eastern Carpathian foreland basins towards the E and a decline of accumulation rates were observed by Meulenkamp et al. (1996). It seems that, in Badenian times, the relief east of the developing Tauern window largely drowned in its own debris because of crustal thinning (Reinecker and Lehnhard 1999). The stagnation of sediment discharge rates in the Eastern Alps between 14 and 12 Ma at a low level records further continental extension.

During this time, sediment discharge rates of the entire Swiss and Western Alps record a slower reduction. The Swiss Alps experienced a phase of constructive growth, which was presumably balanced by extensional tectonics (e.g., Pfiffner 1986; Schmid et al. 1997; Schlunegger 1999). Coarsening and thickening-upward trends, as well as enhanced subsidence in the Swiss molasse fans (Schlunegger et al. 1996; Kempf et al. 1999), may record a regional effect of differential uplift of the Aar massif (see Schlunegger and Willett 1999).

A reduction of sediment discharge might result from an exposure of resistant rock lithologies, but, from 16 to 14 Ma, the amount of sandstone delivered to the north, at the expense of crystalline rocks and quartzites (Matter 1964), does not support this assumption. The pebble composition delivered to the south also gives no indication of changes of rock resistance in the catchment area.

The reduction may also be related to the declining relief of the Sesia-Lanzo zone of the Italian Western Alps, which provided a major source for the early Miocene Apennine flysch basins (Di Giulio 1999; Dunkl et al. 2001) and which is partly covered by Plio-Quaternary sediments of the Po plain.

Processes between 12 and 10 Ma

The slight increase in sediment discharge rates in the Eastern Alps is partly explained by the termination of E–W extension (Dunkl and Demény 1997) and subsequent minor uplift, recorded by a regional regression (Winkler-Hermaden 1957). This implies reworking of temporary deposits in the interior basins, which has been considered as cannibalism. The generally weak surface uplift trend is superimposed on stronger differential uplift of the Tauern range and the Karawanken chain in the SE part of the Eastern Alps, recorded by a drastic increase in pebble size. Uplift in the eastern Eastern Alps occurs coeval with the onset of thrusting and subsequent strong uplift in the eastern Southern Alps (e.g., the Dolomites), as recorded by the facies of the Venetian foreland basin (Massari et al. 1986).

The inversion of the western Swiss molasse basin between 11 and 10 Ma (Kaelin 1997), changing the drainage pattern to an easterly direction, is induced by folding and thrusting of the Swiss Jura mountains. This process appears not to have increased sediment discharge rates from the Swiss and Western Alps as a whole. Thrusting and uplift of the Jura mountains does not mean that the base level at the northern margin of the Swiss Alps changed substantially, if at all. Onset of thrusting in the Jura mountains coincides in time with a decrease of thrusting in the central section of the Southern Alps (Schönborn 1992).

Slightly enhanced rates of crustal uplift of the Aar massif (Pfiffner et al. 1997), possibly accompanied by surface uplift according to Schlunegger (1999), also has no visible effect on the sediment budget. It may be speculated that further reduction of relief of the Sesia-Lanzo zone compensated the differential uplift of the Aar massif.

Processes between 7 and 5 Ma

Sediment discharge rates from the Western and Southern Alps are poorly constrained because of very rough estimates of re-deposition during the Mediterranean desiccation. The missing effect of the dramatic drop of the base level on the sediment discharge may be explained by the short duration of the desiccation event. The duration of total desiccation has recently been precisely dated by Krijgsman et al. (1999) between 5.59 and 5.50 Ma. Although 90,000 years was sufficient to cut several hundred-meter-deep canyons into the margin of the orogen in the course of the largest south-trending rivers, this amount of time was too short to lower the base level of the tributaries and, thus, the relief of the largest part of the south-directed catchment remained unaffected by the Mediterranean desiccation. The volume eroded from these canyons is in the range of 50 km^3 each, and there not more than five prominent canyons documented in the Italian Alps (Finckh 1978).

In late Miocene times, ocean temperatures drop in the northern hemisphere (Miller et al. 1987; Thiede et al. 1998) and simultaneously Eastern European continental temperatures drop (Zubakov and Borzenkova 1990), but these had no consequences for the Alpine sediment budget. This may be explained by the relative aridity in the Alpine realm, especially on the southern flank (Van Dam and Weltje 1999).

Processes between 5 and 3 Ma

The sediment discharge rates from the Swiss and Western Alps record the strongest increase in their history since the 30 Ma event. It is important to note that the early Pliocene marine transgression flooded most of the Po basin and also the gorges formed during the Messinian desiccation. The uplift of the central Alpine sections at their southern front since 5 Ma may be in the range of a few to several 100 m because the Messinian canyons reach as deep as 600 m below the recent sea level (Finckh 1978).

The basic reason for this drastic increase of sediment discharge is not clear. The event is not yet recorded in the surface cooling pattern of large parts of the Alps, except for the external massifs and the Lepontine dome in the Swiss and Western Alps (Hunziker et al. 1992). Pliocene apatite fission-track cooling age from the external massifs, such as the Aar and Mont Blanc massifs, indicate differential accelerated uplift by rates of 0.5 mm/year at 6 to 4 Ma and another 4 km of denudation in the last 3 Ma, according to Michalski and Soom (1990). Similar cooling ages in the Ticino and Toce cores of the Lepontine dome, compiled by Schlunegger and Willett (1999), have not yet been interpreted as a signal of strongly enhanced uplift.

Pfiffner et al. (1997) noted the coincidence in time of accelerated uplift of the Aar massif and Jura folding, related to Adriatic lower crustal indentation (see also Schmid et al. 1997). On the other hand, folding and uplift of the Jura started at around 11 to 10 Ma (Kaelin 1997) and compression in the foreland declined in latest Miocene times (Marchant and Stampfli 1997), whereas uplift in the Aar massif accelerated (Michalski and Soom 1990), increasing the taper of the pro-wedge. It seems that, for unknown reasons, a late Miocene stage of lateral growth on the northern margin of the Swiss Alps has been stopped and that post-Miocene convergence has been mostly transformed into crustal thickening along the axis.

Recent motions of the Adriatic plate measured by VLBI-technique (Ward 1994) do not differ from Late Neogene convergence rates calculated by Homewood et al. (1986), Dewey et al. (1989), and Schmid et al. (1997) for the Swiss Alps, but it is important to note that strain rates decrease to the W. The African plate movement relative to Europe changed at 16.2 Ma from NE to NNW and at about 8.9 Ma from NNW to NW, coincident with tectonic reorganizations of the central Mediterranean (Mazzoli and Helman 1994). Although consequences of the changing direction of the moving Adriatic plate for the Alpine evolution are unclear, a further reduction of convergence in the Western Alps follows from the geometric setting (see Mazzoli and Helman 1994). This reduction might initiate de-eclogitization (possibly granulitization) of the crustal root of the Western Alps.

Recent literature underlines the importance of mineral transformations in the crustal roots in collisional belts. In the Himalaya–Tibet transect relatively light blueschist rocks of subducting cold and old continental crust isostatically support the High Himalayas (Henry et al. 1997). The Tibetan plateau is isostatically supported by relatively light granulite facies rocks whereas the intercalated suture zone is underlain by relatively heavy eclogite rocks and thus has a lower average altitude (Le Pichon et al. 1997). Alternative mechanisms for rapid uplift of the Tibetan plateau without compression in the upper plate are continental underplating (Zhao and Morgan 1985) and a hot upper mantle (Molnar et al. 1993). The latter mechanism cannot be applied to the Alps, according to the structure of the upper mantle (Panza et al. 1982). Underplating of Adriatic lower crust since the Late Miocene, and thus shortening and thickening, is clearly evident (Marchant and Stampfli 1997), but appears to have operated at relatively constant rates. P–T–t modeling of the Central Alpine section by Bousquet et al. (1997) demonstrates that a convergence rate of less than 4 mm/year would induce a transformation of eclogite into granulite in the uppermost crustal root. Once granulite has started to form, the induced uplift would increase denudation and subsequent further crustal uplift, decompressing the crustal root and thus accelerating the formation of granulite by a positive feedback.

Panza et al. (1982) record inversions of seismic velocities in the lower portions of the crustal root, which may indicate thermal weakening and perhaps the presence of fluids released during eclogite to granulite transformation. Computed seismic velocities of the root zone (Marchant and Stampfli 1997) may be interpreted in terms of rocks with a density typical of granulites rather than eclogites.

If the change of the plate movement direction at 8.9 Ma and the general tectonic reorganization of the western Mediterranean in Messinian times were a basic reason for an initiation of de-eclogitization of the Alpine crustal root, a time lag of about 2–3 million years before the onset of strong surface uplift and the subsequent formation of relief would be present.

Because of minor climate change in latest Early Pliocene times (Zubakov and Borzenova 1990), larger areas might have been uplifted to altitudes above the tree line, which would have increased denudation. The tree line may represent an important threshold value for denudation processes. Enhanced denudation, in turn, increases relief and induces subsequent isostatic uplift (Molnar and England 1990). Thus, granulite formation would have been increased by positive feedback. Because crustal thickening in the Alps is by far less important than in the Himalaya–Tibet profile because of the much smaller overall plate convergence and lesser amounts of subducted continental crust, the volume of eclogite formed during higher convergence rates, which could be transformed into granulite, is also of less volumetric importance.

The corresponding increase of sediment production in the Eastern Alps is much less strongly expressed and appears to have started in middle Pliocene times. Uplift has probably mainly affected the western parts. At the same time, fault-controlled local basin inversion is recorded in several Pannonian sub-basins (Vakarcs et al. 1994; Tari and Horváth 1995), indicating a reorganization of the regional stress field (Horváth 1995).

Processes between 3 and 0 Ma

The global late Pliocene temperature drop (Zubakov and Borzenova 1990; Thiede et al. 1998) coincides with a further increase of sediment accumulation rates. This is the first time that there is a clear correlation between a climatic signal and denudation rates. Since then, increasing glaciation has accelerated erosive processes in Alpine-type mountain ranges (Hallet et al. 1996). Further increase of sediment discharge rates in areas drained to the N (W) is mostly caused by increasing glaciation and deforestation of mountain regions, superimposed upon potential tectonically induced uplift.

Recent East Alpine denudation rates of about 0.017 mm/year are similar to late Pliocene denudation rates prior to glaciation (Kuhlemann 2000). This implies that a further increase of sediment discharge rates has been exclusively climatically driven. Recent denudation, however, is calculated from artificially modified rivers draining glacially over-deepened valleys. It is suspected that natural disequilibrium of the glacial relief, providing temporary sediment sinks, overcompensates the man-made increase in denudation and suggests a lower level of denudation than it would be expected in a natural equilibrium state of relief. Consequently, climatic change may not be the only reason for increased Pleistocene denudation; a minor tectonic component may be also involved.

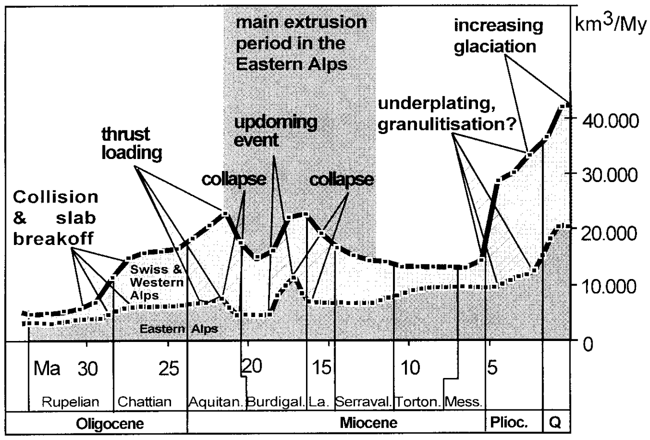

Fig. 13 Postulated main tectonic and climatic events controlling erosion rates in the Eastern Alps and the Swiss and Western Alps, respectively. For alternative interpretations of the Swiss Alps, see Schlunegger (1999) and Schlunegger et al. (2001)

Measurements of recent uplift rates of 1 to 1.5 mm/year in large parts of the Alps (BEV 1991; Kahle et al. 1997; Reinecker and Lehnhard 1999) indicate very young accelerated uplift. These measurements are mostly based on reference points (e.g., Aarburg/Switzerland and Horn/Austria), which appear to be slightly uplifted with respect to the geoid (Reinecker and Lehnhard 1999). The measured uplift rates are much higher than the calculated regional average Pleistocene denudation rates. A part of the uplift is caused by melting of the late Pleistocene ice cover, which is being isostatically compensated. Additionally, compensation of Late Pleistocene short-term clastic material export during deglaciation has to be considered, although the potential isostatic compensation effect of this load is probably an order of magnitude lower than that related to the ice melting. Both effects are difficult to quantify. Modeling of recent isostatic adjustment of the Swiss Alps because of deglaciation reveals uplift rates in the range of 1 to 2 mm/year, matching measured uplift rates with respect to Aarburg at the margin of the Molasse basin (Gudmundsson 1994). Because of the large uncertainty in estimating the flexural elastic compensation of the ice load, Gudmundsson (1994) stresses that the modeled uplift rates are maximum estimates and, rather, indicate that deglaciation is responsible for at least “some or even a large part of the observed uplift”.

Conclusions

Neither regional nor global climatic change fit in time to changes in the bulk Alpine sediment accumulation before latest Miocene times. Global sea-level change is of subordinate importance and can hardly be resolved by the sediment budget method. In contrast, the regional tectonic setting has been shown to have largely controlled the sediment production of the Alps in Oligo-Miocene times (Fig. 13).

In latest Miocene (Messinian) times, the regional tectonic, environmental, and climatic setting drastically changed: too fast to differentiate causes and effects. However, because the drastic increase in sediment discharge from the Swiss and Western Alps in Early Pliocene times is not coeval with that from the Eastern Alps, climatic forcing is unlikely. In latest Early Pliocene times, larger areas of the Swiss and Western Alps might have been uplifted to altitudes above the tree line, which may represent an important threshold value for increased denudation.

From late Pliocene times on, positive feedback of global cooling, enhanced precipitation, and tectonic uplift increased sediment discharge from the Alps. Special importance is attributed to the formation of temperate glaciers during glacial periods, which increased physical and chemical weathering. Over-deepening and over-steepening of the valleys by glaciers resulted in a relative uplift of mountain tops and crests after the melting of the ice load and subsequent isostatic adjustment.

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Appendix

A semi-quantitative approach to limit the errors of the sediment budget curve

In our approach, we suppose that the data derived from different sources are realizations of statistical variables. This is only partially true because these data mostly represent computed values of real measurements. The second assumption is that these “raw data” are independent. In many cases, namely if the basins are situated far from each other or formed at different times, this assumption is plausible. In other cases, such as the Pannonian basin, the Moesian platform and the Black Sea, this assumption is not valid, especially during overfilling of the Pannonian basin in Plio-Pleistocene times. On the other hand, the coupling is not too strong because these basins were supplied by other source terrains, which increases the independence of the basins from each other and, unfortunately, the significance of those individual basins in connection with the Eastern Alps. This potential effect of coupling is taken into account partially in another way, in that the errors of the individual data points were slightly overestimated. Further considerations are given below.

The error of the calculated thickness values of individual strata is difficult to estimate because in most of the cases only few independent data are available. The spread of our estimates is typically in order of 10%. Although it is formally not correct, in lack of a better approximation we use this value as an estimate on the error range of the input data.

Having kept in mind the limited validity of the aforementioned two assumptions, a relative estimated error percentage for each individual sedimentary basin and each time interval (0.5 million years) has been assigned. These relative estimates on error range from 5% to as high as 100%, whereas 50% is the typical value. The absolute errors are now calculated from the relative ones, and square-summed for the contributing basins for each individual time point (Fig. 2).

This type of error estimation contains only the errors from the volumetry, but does not contain the possible effect of the erroneous length of stratigraphic units in the geological time table, erroneous stratigraphic age determination of formations, and an error related to an artificially high stratigraphic resolution of 0.5 and 1 million years.

The transformation from a stratigraphic relative age to chronostratigraphic time scales inherits a potential, which we tried to assess. Ages attributed to stratigraphic boundaries during the last 10 years (Fig. 2, with references) show a high divergence. The difference between the duration of the same chronostratigraphic units displayed in Fig. 3 varies: the typical difference in their “estimates” is 30%, whereas the maximal difference reaches 80% in the case of the Aquitanian stage (Harland et al. 1989: 1.8 Ma duration, Berggren et al. 1995: 3.3 Ma duration). Here we treat this difference as an estimate on the error of the “measurement” of the duration, although the method of the data acquisition certainly did not formally follow all statistical guidelines.

To estimate the error of the length of stratigraphic units, the variability displayed by Fig. 2 is treated as a typical error range except for the periods shorter than 2 million years, where the small variability reflects lack of independent data rather than anomalously high precision. In these cases, an estimate of error of up to 40% results. Because the time span is in the denominator for the calculation, the relative errors are additive and increase the overall error of the volume calculation.

As was mentioned earlier, a severe source of error is related to the fact that only few basins are supplied exclusively from the Alps, which is a particular complication for late Miocene to recent sediments derived from the Eastern Alps (Kuhlemann 2000). This is still a minor problem as long as the basin is situated relatively close to the Alps and the main discharge is derived from this source terrain. In such cases, the potential error is estimated as 20 %, since the available provenance data (e.g., heavy mineral and pebble lithology composition) often allow a clear separation for each formation. In the case of a shallow marine, or even a tidally influenced environment, the potential error rises significantly because of mixing of fine- and medium-grained debris (see also Schlunegger 1999). In this case, the separation of source terrains is based on the relative amount of key minerals from the marine sediment, and the end member heavy mineral composition prior to and after the marine phase.

As the catchment size of the basin increases with increasing distance, the relative contribution from the Alps should decrease and may give rise to an unacceptably high error. In this case, only the recent, Holocene, and Late Pleistocene budget of local and regional semi-enclosed lake systems and the evaluation of large catchments with multiple sources allows the error to be limited. This actualistic approach has to be applied in the case of the Pleistocene Rhine catchment and the late Pliocene–Pleistocene Danube catchment (see Einsele and Hinderer 1997; Kuhlemann 2000). The error is estimated to be in the range of 30%.

The export and diffuse spread of dissolved material had to be estimated in several cases. The relative amount of dissolved load as compared with the solid load, represented by suspended load and bedload, is related to the areal extent of key lithologies such as carbonates, feldspar-rich basement rocks, and quartzites. Such key lithologies produce a characteristic relative amount of dissolved load, which has been extracted from recent river load measurements (e.g., Sommer 1980; Schröder and Theune 1984). For recent settings, the error for the absolute amount of dissolved load is in the range of 30%. The relative amount of dissolved load is influenced by the intensity of chemical weathering and, thus, by the climate, and can be estimated only very roughly. The potential error for estimates of the exported dissolved load may reach up to 50%.

Re-deposition is a major problem in the subalpine molasse because the restoration of imbricated molasse thrust sheets (e.g., Pfiffner 1986) is an important source of error (Schlunegger et al. 1997b). In the North Alpine foreland basin this potential error effects mainly the Oligocene and early Miocene sediment budget, whereas the South Alpine foreland basin suffered massive reworking in middle Miocene times (Schönborn 1992) and latest Miocene times (Messinian; e.g., Ryan and Cita (1978). Moreover, during thrusting of molasse thrust sheets the amount of immediate (<1 million years) redeposition is difficult to estimate.

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