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Paleogeography and catchment evolution in a mobile orogenic belt: the Central Alps in Oligo–Miocene times

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Abstract

In this study, we reconstruct the surface evolution of the Oligo–Miocene Central Alps using geochronological, geochemical and petrographical methods on the foreland basin sediments of both flanks of the mountain range. Our model is illustrated in four sketch maps of different time slices between mid-Oligocene to Middle Miocene times. For each time slice, we try to (1) give a palinspastic reconstruction of the Central Alps, based on the post-collisional lateral extrusion model, (2) show which tectonic units had become exposed to the surface due to exhumation processes in the Central Alps, (3) describe the thermochronologic evolution of lithological units formerly exposed but completely eroded today, (4) differentiate the catchment areas of the paleo-river systems which delivered debris to the foreland basins, and (5) describe the position of the main drainage divide relative to the exposed tectonic units. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Central Alps; Oligo–Miocene; Fission track; Drainage pattern; Exhumation

1. Introduction

Sediments of a foreland basin reflect the evolution of the adjacent orogen in the hinterland. For example, geochronological studies on detrital minerals give evidence of the thermal evolution and consequently of exhumation processes of the hinterland (see e.g. Wagner et al., 1979). Pebble sizes point to the paleo-relief, and clast composition of conglomerates as well as heavy mineral fractions of sandstones reflect the lithologies exposed during the time of deposition. Petrographic and thermochronologic data from differ-ent dispersal systems of a foreland basin monitor changes of the drainage pattern, while comparing foreland basins of both flanks of an orogen may give information about the position of the main drainage divide. The masses of sediment in the foreland basins may reveal an estimate of the paleotopographic evolution (see e.g. Hay et al., 1992), though they cannot provide direct evidence for paleoaltitudes. Possibilities and errors of this approach are discussed in detail in Kuhlemann (2000) and Kuhlemann et al. (2001).

The aim of this study is to reconstruct the surface evolution and the drainage pattern of the Central Alps during Oligo–Miocene times by combining geochronological, geochemical and petrographical data from the northern and the southern foreland basins (Swiss molasse basin and Gonfolite Lombarda Group, respectively). In addition to the drainage pattern, we try

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to reconstruct and to differentiate exposed metamorphic domains of the hinterland during Oligo–Miocene times. Furthermore, our model attempts to incorporate the orogen-parallel lateral extrusion (Ratschbacher et al., 1991; Frisch et al., 1998), which decisively influenced the post-collisional surface evolution of the Alps. We present new thermochronological and geochemical data from sandstones and pebbles from the Swiss molasse basin and from sandstones of the Gonfolite Lombarda Group, whereas petrographic characterizations of the foreland basins and thermochronological data from pebbles of the Gonfolite Lombarda Group are compiled from the literature. Our results are illustrated in four sketch maps of different time slices. Estimations of the topographic evolution are based on the sediment accumulation curve of Kuhlemann (2000), which shows the sediment budget of the Central and the Western Alps since Oligocene times, separated for the north- and south-directed catchment.

2. Geological setting of foreland and hinterland

It is beyond the scope of this paper to give a detailed description of the geology of the Central Alps and the adjacent foreland basins. Our brief outline focuses on superimposed evolutionary trends. For more information, see e.g. Pfiffner (1986) and Matter and Weidmann (1992) for the Swiss molasse basin, Gunzenhauser (1985) and Gelati et al. (1988) for the Gonfolite Lombarda Group and Steck and Hunziker (1994) and Schmid et al. (1996) for the Central Alps.

2.1. Swiss Molasse Basin

Sedimentation in the Swiss molasse basin started in Oligocene times and lasted until ~ 11 Ma in the distal part of the basin (Pfiffner, 1986). The proximal part of the basin is composed of large fan systems containing conglomerates, sandstones and mudstones (Fig. 1). The sedimentary succession is characterised by two coarsening upward megacycles (e.g. Matter and Weidmann, 1992), indicating alternating shallow marine and alluvial conditions. Between 25–20 Ma, heavy mineral spectra of sandstones from different dispersal systems show an abrupt change from apatite/garnet

towards epidote dominance (Füchtbauer, 1964; Schlunegger et al., 1997; Kempf et al., 1999). Most authors attribute this epidote dominance to the onset of erosion of South Penninic ophiolites in the Central Alps (Renz, 1937; Dietrich, 1969). Sedimentation ages of the Swiss molasse basin are well-constrained by biostratigraphic and magnetostratigraphic studies (Berger, 1992; Kempf et al., 1997; Schlunegger et al., 1997). Nomenclature and stratigraphy used in this study are according to Schlunegger et al. (1997) and Kempf (1998).

2.2. Gonfolite Lombarda Group

In contrast to the northern Alpine foreland basin, outcrops of Oligo–Miocene clastic sediments on the southern side of the Central Alps are restricted to the small area of the Gonfolite Lombarda Group (Fig. 1). The base of the Gonfolite Lombarda sensu lato is formed by the mainly pelitic Chiasso Formation, representing deep marine, turbiditic slope sediments (Gunzenhauser, 1985) with Rupelian to Early Chattian sedimentation ages (Gelati et al., 1988; Rögl et al., 1975). The overlying Chattian to Aquitanian Como Formation is mainly composed of conglomerates deposited in a submarine canyon system (Bernoulli et al., 1993). The youngest part of the Gonfolite Lombarda—the conglomerates of the Lucino Formation—is often referred to as Burdigalian to Langhian (e.g. Gunzenhauser, 1985). Based on palynological studies, Giger and Hurford (1989) suggest a Middle Miocene age. Therefore, in accordance with Giger (1991), an age of around 15 Ma is taken for the Lucino Formation.

2.3. Central Alps

In the present-day Central Alps, three tectonic mega-units are exposed (Fig. 1): the Austroalpine upper plate represents the former northern margin of the Adriatic microplate. It was thrust over Penninic units which comprise both oceanic and continental crust. The Helvetic realm, as the lowermost mega-unit, represents the European continent.

Austroalpine units are characterized by a Cretaceous metamorphic event with metamorphic ages between 145 and 90 Ma (Frank et al., 1987), including high pressure metamorphism and a thermal peak at
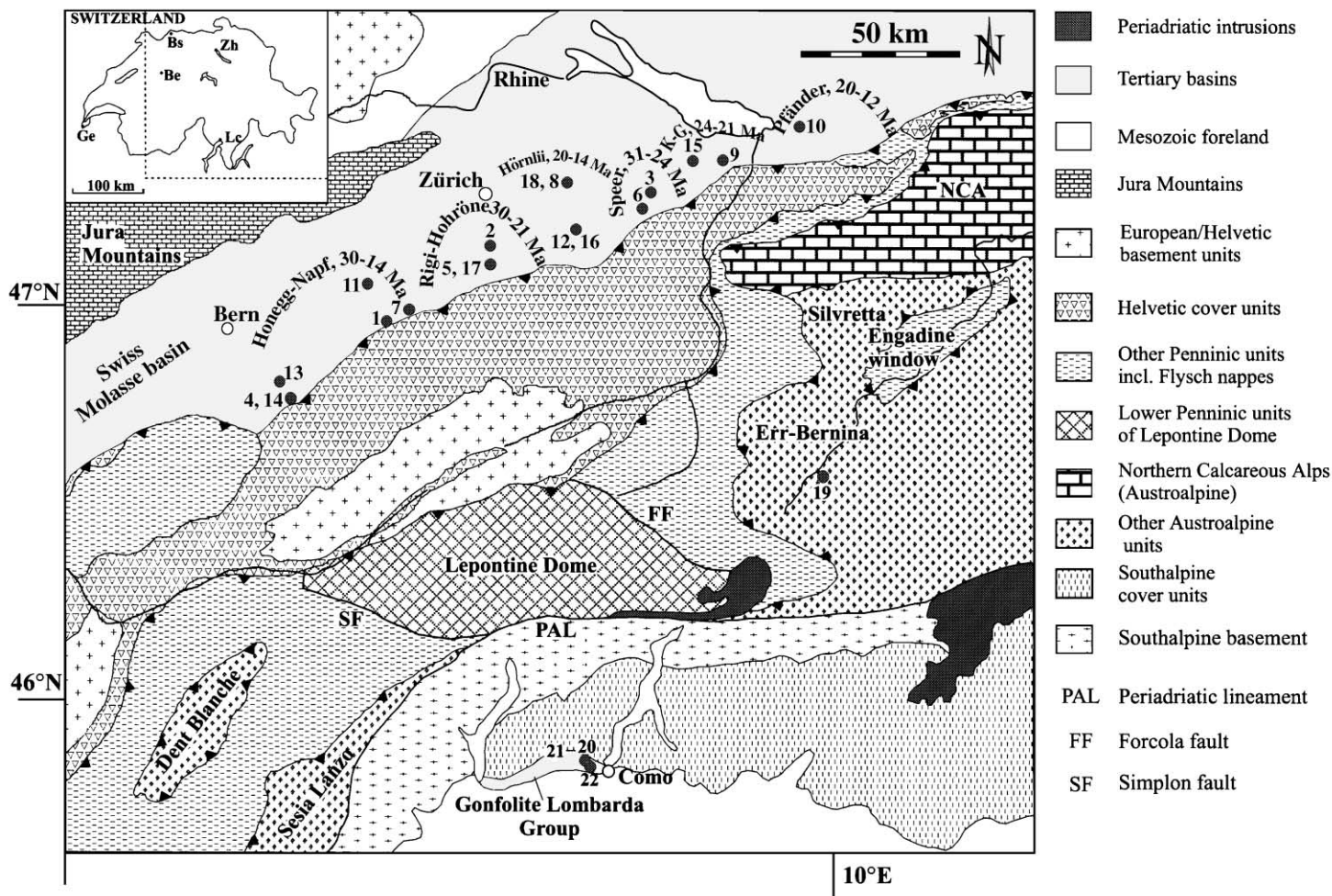
Fig. 1. Geological sketch map of the Central Alps and the adjacent foreland basins. To the north, the Swiss molasse basin with its different dispersal systems with time of activity, and to the south, the Gonfolite Lombarda Group are shown. Numbers refer to localities of samples dated by the Zr FT method. K–G = Kronberg–Gäbris fan. Inset: Ge = Geneva, Bs = Basel, Be = Berne, Zh = Zurich, Lc = Lucerne.

~90 Ma (Thöni, 1981). Cooling ages <90 Ma are characteristic for amphibolite-facies units of the Austroalpine realm (Frank et al., 1987). Austroalpine units exposed in the western part of the Eastern Alps show a general decrease of Cretaceous metamorphic temperatures from amphibolite and eclogite facies conditions in the southeast, to temperatures below greenschist facies conditions in the northwestern parts of the Ötztal and the Silvretta block (e.g. Thöni, 1981). This zoning is reflected by the mineral cooling ages, becoming increasingly older towards the northwest with pre-Alpine cooling ages prevailing in the Silvretta block (Flisch, 1986). While Austroalpine units of the Eastern Alps, with few exceptions, were not affected by Tertiary metamorphism, Austroalpine units of the Western Alps (Dent Blanche Nappe, Sesia Lanzo Zone) have been thermally overprinted in Tertiary times as evidenced by Tertiary cooling ages (Hurford et al., 1991).

The structure of the Central Alps is dominated by the Lepontine Dome, which was metamorphosed during the Tertiary Lepontine metamorphism (Jäger, 1973; Steck and Hunziker, 1994). Its hanging wall consists of Upper to Middle Penninic units with South Penninic ophiolites at the top of the sequence (e.g. Platta unit). These ophiolites are considered as source rocks for the detrital epidote of the Swiss molasse basin (Renz, 1937; Dietrich, 1969). Rocks belonging to the hanging wall of the Lepontine Dome have zircon fission track (Zr FT) cooling ages between 30 and 15 Ma (Hunziker et al., 1992) and a mid-Tertiary cooling rate in the range of 10 °C/Ma (Markley et al., 1998). The Lepontine Dome, in contrast, consists of Lower Penninic units with frequent Zr FT cooling ages younger than 15 Ma (Hunziker et al., 1992) and a mid-Tertiary cooling rate of up to ~80 °C/Ma (Hurford, 1986).

According to Meyre et al. (1998) and Frisch et al. (2000) the exhumation of the Lepontine Dome was mainly caused by the post-collisional lateral extrusion of the Alps. This extrusion period started around the Oligocene–Miocene boundary and led to an east–west stretching of the Central Alps of probably more than 100 km (Frisch et al., 2000). Two detachment faults bordering the Lepontine Dome have been attributed to the extension of the Central Alps: the Forcola fault to the east (active between ca. 25 and 18 Ma, Meyre et al., 1998) and the Simplon fault to the west (active between 19 Ma and the present, Mancktelow, 1985).

3. Dating of cooling ages in foreland basin sediments

The concept of dating detrital minerals from foreland basins was proposed by Wagner et al. (1979) and others as a promising tool to unravel the thermal and dynamic evolution of an orogen. Cooling ages from synorogenic clastic sediments reflect age patterns of the hinterland at the time of sedimentation. This in turn allows a distinction between different tectonic units exposed during earlier stages of the orogen and gives information about their geodynamic behaviour. Details about the early metamorphic history are often obscured by later thermal events in the present-day exposures of the orogen but may be well-preserved in the foreland basin sediments. Comparing cooling ages from detrital minerals from different parts of a foreland basin and from both sides of an orogen gives evidence about the geological structure of individual catchment areas and about the positions of the drainage divides.

In general, three different approaches can be pursued in dating cooling ages on foreland basin sediments: (1) Dating detrital minerals from sandstones gives an overview of the ages contained in exposures over a whole catchment area (e.g. Brandon and Vance, 1992). (2) Dating different minerals from pebbles in foreland basin conglomerates provides paleo-cooling paths, and the pebbles themselves yield petrographic information about possible lithotectonic units in the source area (Wagner et al., 1979). (3) Pebble population dating was proposed by Dunkl et al. (1998). For this method, a large number of pebbles (>50) of the same lithotype is collected from the same outcrop and processed together. The dating does not yield a single cooling age but an age distribution representing the whole lithological unit. A potential differential cooling behaviour of different lithological units can give additional information on the geodynamics in terms of exhumation in the hinterland.

All these approaches were pursued for the foreland basins of the Central Alps (Wagner et al., 1979; Giger and Hurford, 1989; Giger, 1991; von Eynatten et al., 1999; Spiegel et al., 2000). The mineral phases, according to the applied dating techniques, have different closure temperatures: $^{40}Ar-^{39}Ar$ and $^{40}K-^{40}Ar$ on white mica: 350 ± 50 °C (McDougall and Harrison, 1988; Purdy and Jäger, 1976), $^{40}K-^{40}Ar$ on biotite:

300 ± 50 °C (Armstrong et al., 1966), $^{87}Rb-^{87}Sr$ on biotite: 300 ± 50 °C (Jäger et al., 1967), zircon fission track (Zr FT): 240 ± 50 °C (Hurford, 1986) and apatite fission track: $120-60$ °C (Wagner and Reimer, 1972). This temperature range allows to monitor thermal processes concerning approximately the upper 12 km of the earth's crust, assuming a geothermal gradient of 30 °C/km.

4. Results and discussion: the paleogeographical evolution of the Central Alps on four sketch maps

4.1. Mid-Oligocene

Fig. 2(a) shows the paleogeological situation of the Central Alps at the beginning of the coarse clastic molasse sedimentation in mid-Oligocene times. Because Tertiary large-scale lateral extrusion started around the Oligocene–Miocene boundary, i.e. $7-8$ Ma later (Frisch et al., 2000), units today exposed in the Eastern and Western Alps (Ötztal and Silvretta block, Err–Berninia Nappe, Dent Blanche Nappe and Sesia–Lanzo Zone) were still situated in close neighbourhood. On the northern flank of the Central Alps, three large river systems delivered debris into the Swiss marine molasse basin: the Speer, Rigi–Hohröne and Honegg–Napf Rivers (Schlunegger et al., 1997; Kempf, 1998).
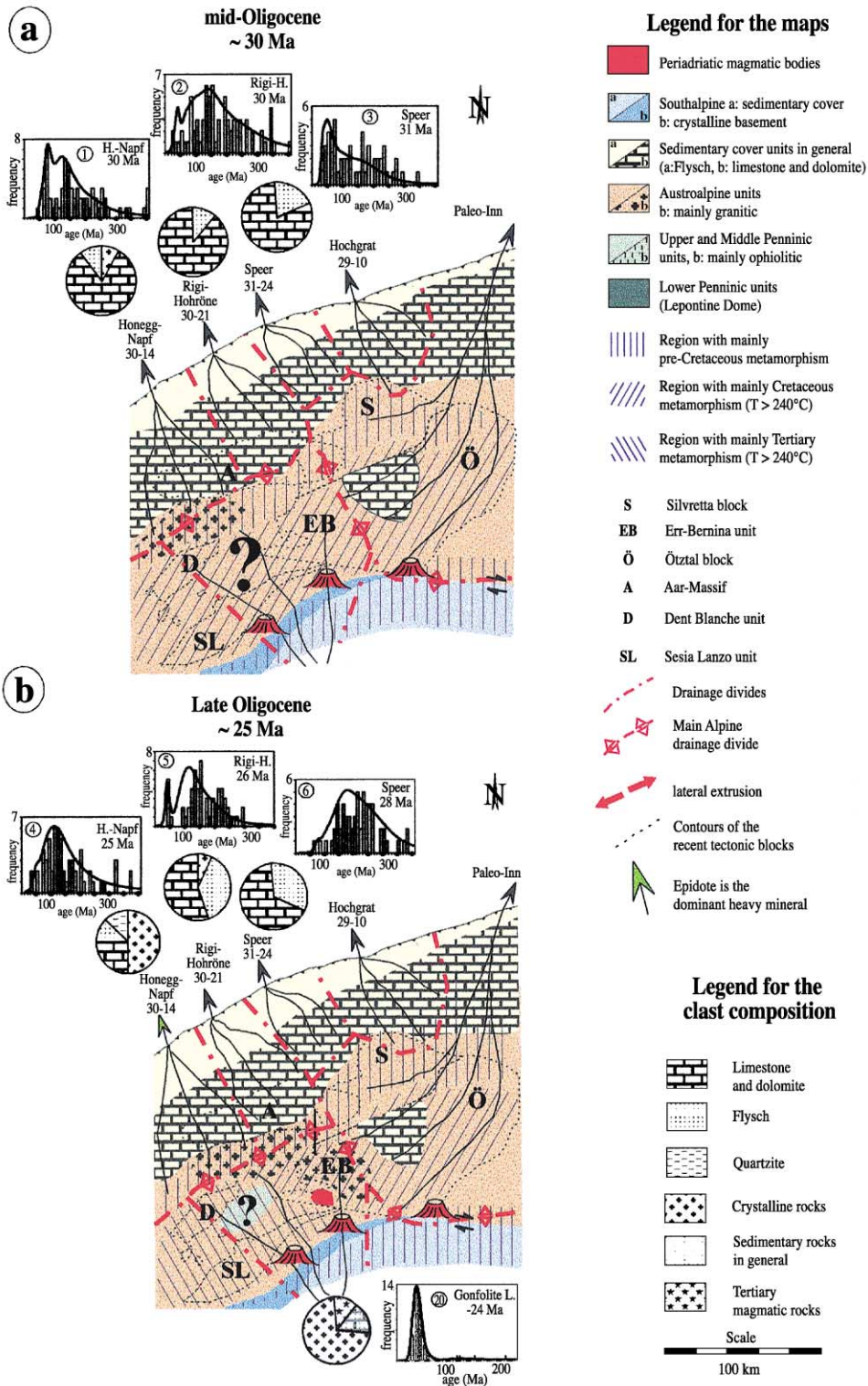
Zr FT age distributions from sandstones of these fans yield a typical Austroalpine pattern with a large range of Triassic, Jurassic and Cretaceous cooling ages. The badly constrained age groups around $50-40$ Ma of the Speer and the Rigi–Hohröne sandstones might be related to a volcanic event documented in the Penninic Schlieren flysch in the Swiss Alps (Winkler et al., 1990) or to the Eocene collision (see e.g. Schmid et al., 1996). The age distributions can be attributed to the recycling of flysch nappes, which in turn were fed from an Austroalpine source (Spiegel et al., 2000). The conglomerates of the Speer and Rigi–Hohröne fans contain exclusively flysch, limestone and dolomitic pebbles (Kempf, 1998; Schlunegger et al., 1998), whereas the Honegg–Napf fan additionally contains a small number of crystalline pebbles, mainly green granites (Schlunegger et al., 1998). Therefore, mainly sedimentary cover nappes and only few Austroalpine basement were
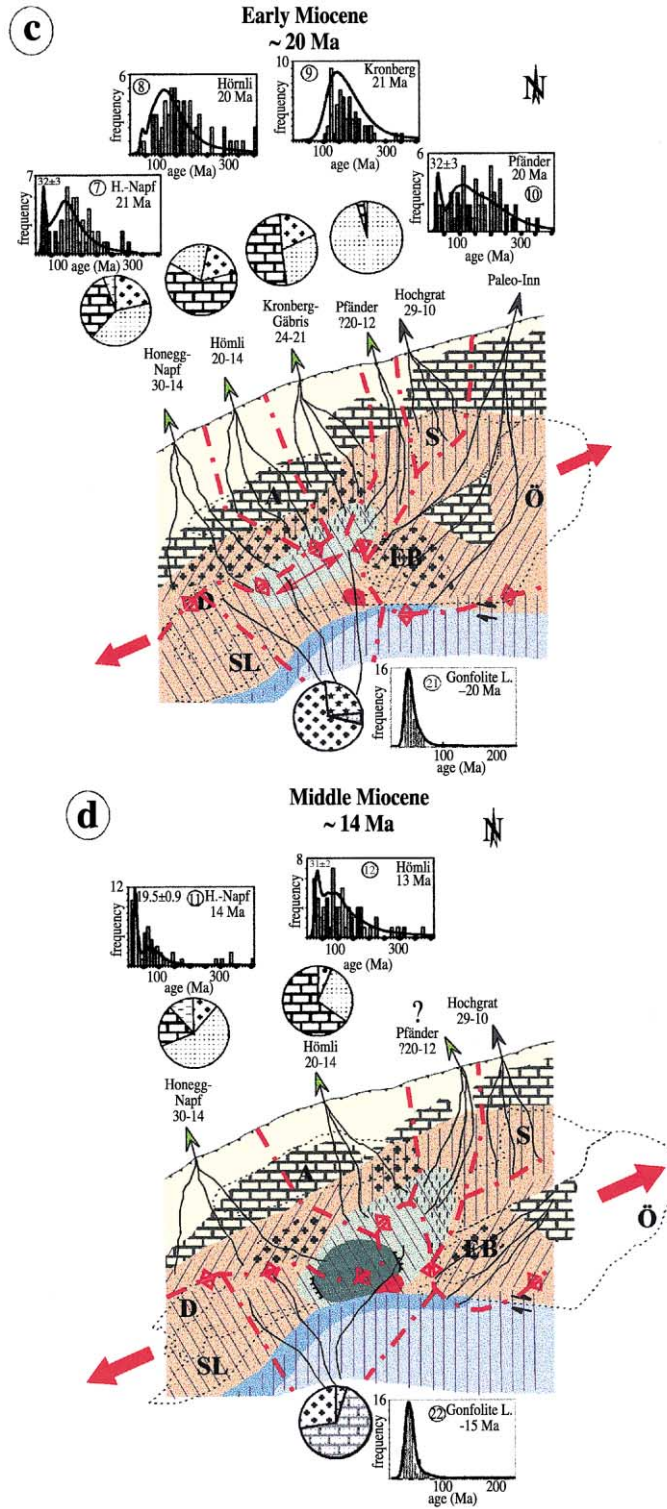
exposed on the northern side of the Central Alps. The interpretation that a great part of the zircons contained in mid-Oligocene molasse strata are recycled Austroalpine zircon crystals from an intermediate flysch source is corroborated by the fact that in younger sediments, the ages become older (see Fig. 2(b)). Rivers incising into exposed crystalline basement should supply zircons with increasingly younger ages according to the prograding exhumation of rocks. This trend becomes inverted when crystals were stored in flysch in an intermediate stage. The Tertiary cooling ages from the Speer and Rigi–Hohröne sandstones show that the exposed flysch was at least partly deposited during post-Cretaceous times.

On the southern flank of the Central Alps, Austroalpine basement as well as South Alpine basement and cover units were exposed (Giger, 1991). The Austroalpine basement was very probably affected by Alpine Cretaceous metamorphism, as indicated by some pebbles with Austroalpine provenance and Zr FT cooling ages between $60-55$ Ma (Giger, 1991). However, because no geochronological data from sandstones is available for this time slice, a reliable description of the age pattern of Austroalpine basement exposed in the south-draining hinterland is not possible. The Periadriatic lineament was topped by a volcanic chain completely eroded today (Giger, 1991; Ruffini et al., 1997; Brügel, 1998; Frisch et al., 1998; Brügel et al., 2000). These volcanoes delivered volcanoclastic material to the Gonfolite Lombarda Group (Giger, 1991) and to many other Peri-Alpine sedimentary units, e.g. the Apennines, Lombardian flysch, the Austrian molasse basin, Slovenian basin fragments and the Pannonian basin (Dunkl et al., 2000). In contrast, no detrital zircons or pebbles related to the Periadriatic volcanism were deposited in the Swiss molasse basin.

The clast compositions of the conglomerates show that the main drainage divide must have been situated mainly north of the exposed Austroalpine basement during mid-Oligocene times. In the easternmost part of the Central Alps, the main drainage divide, however, jumped towards the south in order to give way to the large catchment area of the paleo-Inn river (Brügel, 1998; Brügel et al., 2000).

The sediment accumulation curve shows an increase of the sediment supply after 30 Ma (Fig. 3). This increase and the onset of coarse clastic,
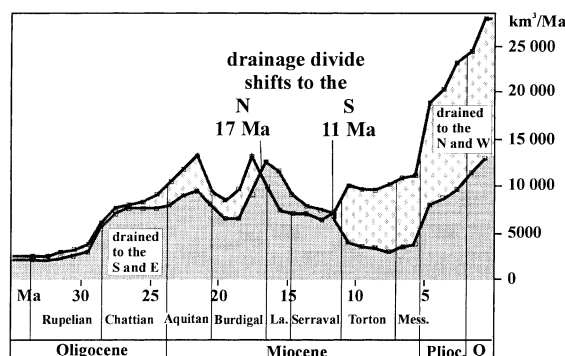
Fig. 3. Sediment budget since Oligocene times for the Central and Western Alps, separated for the north- and south-directed catchment after Kuhlemann (2000). A decrease of the sediment supply to the north at 17 Ma is coupled with an increase of the sediment supply to the south and vice versa at 11 Ma. These antagonistic changes are interpreted as shifts of the main drainage divide to the north and to the south, respectively.

conglomerate-rich sedimentation in the foreland basins reflects the development of a significant relief in the hinterland.

4.2. Late Oligocene (Fig. 2(b))

The same river systems as described before were still active during Late Oligocene times (Schlunegger et al., 1997; Kempf, 1998). Sandstones from these rivers again show Zr FT age distributions typical for an Austroalpine source (Spiegel et al., 2000). In the Honegg–Napf fan, heavy mineral composition of the sandstones changed at 25 Ma from apatite–garnet towards epidote dominance (up to 90% epidote, Schlunegger et al., 1997). While conglomerates of the Speer fan still comprised only pebbles from sedimentary cover nappes (Kempf, 1998), conglomerates of the Rigi–Hohröne fan contain some crystalline pebbles, mainly red granites (Schlunegger et

al., 1998). These red granites also occur in the Honegg–Napf fan, as well as green and white granites, rhyolites and granitic gneisses. A prominent feature of the Honegg–Napf fan at 25 Ma is the occurrence of green quartzites, which can make up as much as 10% of the conglomeratic components (Schlunegger et al., 1998).

According to Schlunegger et al. (1998) the Upper to Middle Penninic hanging wall of the Lepontine Dome became exposed at 25 Ma in the north-draining part of the Central Alps. Their model is based on two assumptions: (i) the sudden occurrence of epidote in the sandstones of the Honegg–Napf fan indicates the onset of erosion of ophiolitic rocks from the top of the Penninic sequence; (ii) the green quartzite pebbles of the Honegg–Napf fan were derived from the Middle Penninic Bernhard nappe, which contains similar quartzites in terms of petrography in the present-day exposure. Sr and Nd isotopic ratios, however, reveals a crustal-derived, granitic source rock for the detrital epidote (Spiegel et al., submitted). This indicates provenance from an Austroalpine source rock similar to the Lower Austroalpine metagranites as proposed by Füchtbauer (1964). Pebble population dating of the green quartzites yields a Zr FT cooling age of 111 ± 5 Ma (Table 1). The Middle Penninic nappes west of the Simplon line show Zr FT ages between ~ 25 and 20 Ma (Seward and Mancktelow, 1994) and a cooling rate in the range of 10 °C/Ma (Markley et al., 1998). Thus, a provenance of the green quartzitic pebbles from the Middle Penninic Bernhard nappe is not possible, i.e. neither the cooling age distribution or the heavy minerals of the sandstones nor the pebbles of the conglomerates point to an exposure of the Penninic hanging wall of the Lepontine Dome in the hinterland of the Swiss molasse basin in Oligocene times.

Based on petrographic criteria, the red and green granites of the molasse conglomerates have been

Fig. 2. Paleogeographic evolution of the Central Alps from mid-Oligocene times (a) to Middle Miocene times (d) with FT age distributions of detrital zircons from sandstones of the foreland basins and clast compositions of conglomerates. The probability density plots are computed according to Hurford et al. (1984), calculation of the young zircon age groups according to Brandon (1992), plotting by TRACKKEY (Dunkl, in press). Sedimentation ages of sandstones are at the right top corner; numbers in circles refer to sample localities (see Fig. 1). Nomenclature and stratigraphy of the Swiss molasse fans are according to Schlunegger et al. (1997) and Kempf (1998), stratigraphy of the Gonfolite Lombarda Group is after Gunzenhauser (1985), Rögl et al. (1975) and Giger and Hurford (1989). The Pfänder fan of the Austrian molasse basin is assumed to form an independent system only from ca. 20 Ma onwards (see Schiemenz, 1960). The drainage patterns of the Hochgrat and Paleo–Inn systems are modified after Brügel (1998) and Brügel et al. (2000). Clast compositions: Honegg–Napf and Rigi–Hohröne fan: Schlunegger et al. (1998), Kronberg–Gäbris and Speer fan: Kempf (1998) (with further references), Hörnli fan: Tanner (1944), Pfänder fan: Schiemenz (1960), Gonfolite Lombarda Group: Giger (1991), Longo (1968).

Table 1
Results of zircon FT dating on sandstones and pebbles

Sample code	Fan/location	Lithology	Sedimentation age (Ma)	Counted crystals	Spontaneous		Induced		$P\chi^2$ (%)	Dosimeter		Central age (Ma ± 1σ)
					ρ_s	n_s	ρ_i	n_i		ρ_d	n_d	
22	Gonfolite Lombarda	sandstone	∼15	59	131.2	4136	146.3	4624	0	6.31	12343	33.6 ± 1.5
21	Gonfolite Lombarda	sandstone	∼20	60	70.1	3622	83.3	4303	0	6.45	12377	32.2 ± 1.2
20	Gonfolite Lombarda	sandstone	∼24	53	143.9	4187	143.1	4163	0	6.51	12343	38.9 ± 2
10	Pfänder	sandstone	∼20	60	147.8	5903	42.3	1688	0	5.62	10784	119 ± 11
19	Bernina River	red granites PPD	recent	20	349.8	2586	138.7	1025	24	4.75	8926	70 ± 3
16	Hörnli	red quartzite PPD[a]	13	57	271.6	6804	53.2	1334	26	6.57	12343	193 ± 7
18	Hörnli	red granites PPD[a]	20	47	248.8	4633	77.9	1450	9	6.45	12377	119 ± 5
15	Kronberg–Gäbris	granite SP	24	25	284.2	3056	66.1	711	23	6.28	12343	155 ± 7
14	Honegg–Napf	quartzites PPD	25	40	260.3	4223	55.7	903	21	4.1	8926	111 ± 5
13	Honegg–Napf	rhyolites PPD[a]	26	63	262.7	6682	58.9	1498	6	6.45	12377	168 ± 6
17	Rigi–Hohröne	red granites PPD[a]	27	25	245.9	3069	57.9	722	39	6.45	12377	158 ± 7

PPD = dated according to the pebble population method (Dunkl et al., 1998), SP = single pebble dating. n = number of counted tracks, ρ = track densities (× 10^5 tracks/cm^2), $P(\chi^2)$ is the probability of obtaining χ^2 value for v degrees of freedom (where v = number of crystals − 1). Ages are calculated using dosimeter glasses CN-2 with ζCN-2 = 116 ± 2. Dating was performed according to the external detector method (Fleischer et al., 1964). Samples 19 and 14 were irradiated at the ANSTO reactor, Lucas Heights (Australia), the other samples were irradiated at the thermal neutron facility of the Riso reactor (Denmark).

   [a] Data from Spiegel et al. (2000).

attributed to a western prolongation of the granites exposed in the present-day Err–Bernina region (Matter, 1964). These granites belong to a calc–alkaline suite. They were intruded during Variscan orogeny and were overprinted in Triassic times (Jäger, 1973; Hunziker et al., 1992) and during Cretaceous Eoalpine metamorphism (Rageth, 1984; Spillmann and Büchi, 1993). Geochemically, they are characterized by low Ti, Sr and Ba, and high Rb contents (Rageth, 1984). In this study, we compared geochemistry and Zr FT cooling ages of red and green granitic pebbles from different molasse fans with petrographically

similar pebbles from the recent Bernina river near St. Moritz (Fig. 1 and Tables 1 and 2). This river drains the Lower Austroalpine Err–Bernina region. Especially the red granites reveal similar geochemical characteristics for recent and molasse pebbles (Fig. 4). This corroborates the provenance of the granitic molasse pebbles from a western prolongation of the Err–Bernina granites, which is completely eroded today.

A pebble population of recent red granitic pebbles derived from the Bernina region reveals a Zr FT age of 70 ± 3 Ma (Table 1), reflecting cooling after the

Table 2
Geochemical analysis of granitic pebbles from the molasse basin and from the recent Bernina river

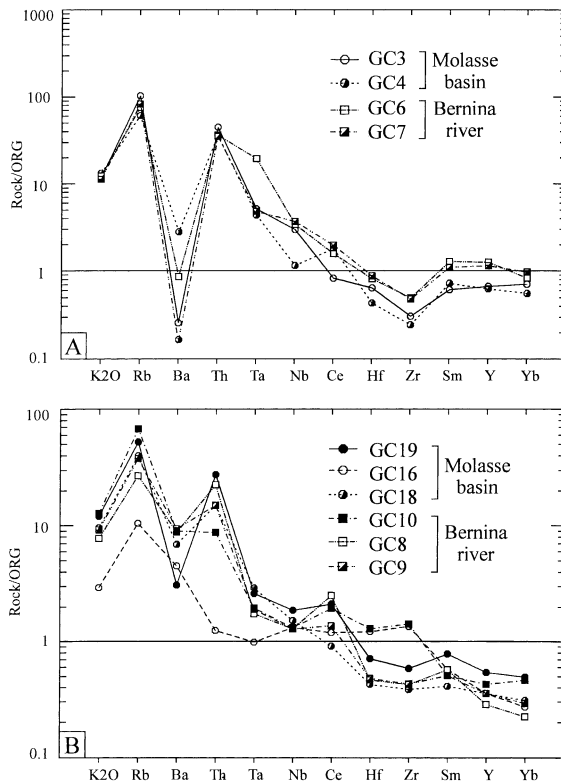| Code	Lithology	Fan/river	Sedimentation age (Ma)	K₂O weight (%)	Rb (ppm)	Ba (ppm)	Th (ppm)	Ta (ppm)	Nb (ppm)	Ce (ppm)	Hf (ppm)	Zr (ppm)	Sm (ppm)	Y (ppm)	Yb (ppm)
GC3	red granite	W molasse	21	4.75	403.8	23	38.83	3.60	29.61	32.01	5.82	105	5.55	47.62	5.69
GC4	red granite	Hörnli	13	5.32	233.6	149	31.18	3.07	10.17	42.87	3.91	84	6.50	41.63	4.47
GC6	red granite	Bernina	recent	4.95	289.5	52	29.58	13.64	32.88	55.39	7.35	169	11.51	86.46	6.67
GC7	red granite	Bernina	recent	4.52	323.1	16	32.22	3.38	36.55	53.87	7.87	164	9.87	81.72	7.79
GC16	green granite	K.G.	21	1.18	40.1	232	4.66	0.69	12.09	47.16	11.04	462	5.20	24.56	2.18
GC18	green granite	K.G.	21	3.83	155.8	343	13.27	2.05	14.71	35.26	3.86	131	3.70	25.67	2.48
GC19	green granite	Hörnli	20	4.85	206.1	160	21.47	1.83	18.24	60.17	6.44	200	7.04	38.60	3.96
GC8	green granite	Bernina	recent	3.12	104.5	431	17.19	1.22	10.85	73.92	4.20	145	5.15	19.34	1.80
GC9	green granite	Bernina	recent	3.69	146.0	468	11.90	1.33	10.96	46.85	4.33	147	4.59	24.61	2.34
GC10	green granite	Bernina	recent	5.10	257.9	463	7.86	1.37	12.53	45.84	11.67	485	4.60	27.91	3.72

Fig. 4. Ocean ridge granite normalized (ORG, see Pearce et al., 1984) geochemical patterns for granitic pebbles from different fan systems of the Swiss molasse basin (circles) and from the recent Bernina river, draining the Lower Austroalpine Err–Bernina region (boxes). 3a: green granitic pebbles, 3b: red granitic pebbles. See also Table 2.

thermal peak of Cretaceous metamorphism at ~ 90 Ma (Thöni, 1981). In contrast, two pebble populations of red granites from the molasse basin yield Zr FT ages of 119 ± 5 and 158 ± 7 Ma, similar to the ages of other pebble populations and single pebbles from the molasse conglomerates, which show exclusively Jurassic to Early Cretaceous Zr FT ages (Table 1). This age distribution is in line with the increasing temperatures of Cretaceous metamorphism from northwest to southeast, as is known from the Austroalpine Ötztal and Silvretta blocks (Thöni, 1981) when we assume continuous backward incision of the rivers towards the southeast. It also shows that the Cretaceous metamorphic gradient can be traced towards the west as the direct continuation of the Ötztal–Silvretta. This is corroborated by the exclusively Late Variscan

to Jurassic ^{40}K–^{40}Ar ages of white mica and biotite from pebbles of the molasse conglomerates (Spiegel et al., 2000) and by the absence of Cretaceous ^{40}Ar–^{39}Ar ages of detrital white mica from the molasse sandstones (von Eynatten et al., 1999). In conclusion, the eroded part of the Austroalpine basement in the Central Alps consisted of large areas, which experienced only weak or even no Eo–Alpine metamorphic overprint.

Zr FT age distributions of sandstones from the Gonfolite Lombarda Group reveal a different situation for the southern flank of the Central Alps. While Zr FT age spectra from the northern foreland show a heterogeneous distribution with predominantly Triassic, Jurassic and Cretaceous ages, sandstones from the southern foreland yield a very homogeneous distribution with a large majority of Zr FT ages clustering between 40 and 30 Ma (Fig. 2(b)). The few Zr FT ages >100 Ma are presumably derived from the Variscan basement of the Southern Alps, whereas for the ages between 40 and 30 Ma, three potential sources can be considered: (1) the Periadriatic magmatic bodies, i.e. the Bergell pluton and volcanoes of the Periadriatic volcanic chain; (2) Austroalpine basement thermally overprinted during Tertiary Lepontine metamorphism; (3) Penninic rocks from the hanging wall of the Lepontine Dome.

(1) The erosion of Periadriatic magmatic rocks is proven by frequent tonalitic pebbles derived from the Bergell pluton in Late Oligocene conglomerates of the Gonfolite Lombarda Group (Wagner et al., 1979; Giger and Hurford, 1989; Giger, 1991). (2) According to Giger (1991), pebbles with Austroalpine provenance have Late Variscan to Triassic biotite ^{40}K–^{40}Ar ages, Zr FT ages mainly between 38 and 33 Ma, while only a few pebbles yield Zr FT ages between 60 and 55 Ma (Giger, 1991). Thus, temperatures of Cretaceous metamorphism affecting the hinterland of the Gonfolite Lombarda Group probably were high enough to completely reset the Zr FT system (i.e. >200–250 °C) but too low to reset the biotite ^{40}K–^{40}Ar ages (i.e. < 300 °C). Zr FT ages of Austroalpine basement exposed on the northern flank of the Central Alps, in contrast, were only partly reset by Cretaceous metamorphism and unaffected by Tertiary metamorphism. (3) At ~ 24 Ma, gneiss pebbles with biotite ^{40}K–^{40}Ar ages and zircon and apatite fission track ages between 40–30 Ma occurred in the con-

glomerates of the Gonfolite Lombarda Group (Giger, 1991). Due to the high cooling rate and the young biotite ^{40}K–^{40}Ar ages, Giger (1991) attribute these gneiss pebbles to the erosion of the Penninic hanging wall of the Lepontine Dome. Austroalpine basement from the direct contact to the Bergell plutonic body, however, might show the same cooling pattern. In conclusion, it is clear, that Periadriatic magmatitic bodies and Austroalpine basement affected by Tertiary metamorphism largely contributed to the sediments of the Gonfolite Lombarda Group in Late Oligocene times. A Penninic gneiss contribution would also be in line with the geochronological data but cannot ultimately be proven.

The borderline between Austroalpine basement affected and unaffected by Tertiary thermal overprint must have roughly coincided with the main drainage divide, which was situated within the exposed Austroalpine units.

The sediment supply in the molasse basins continuously increased during Chattian and also during Aquitanian times, suggesting a continuously rising relief of the Central Alps (Kuhlemann, 2000, Fig. 3). This is in line with the data of Hay et al. (1992). Absolute elevations of 5000–7000 m in Late Oligocene times as proposed by Jäger and Hantke (1984) and by Hay et al. (1992), however, seem to be unlikely.

4.3. Early Miocene (Fig. 2(c))

The Oligo–Miocene boundary approximately marks the onset of lateral extrusion, which led to an east–west stretching in the range of 170 km for the Eastern Alps (Frisch et al., 1998) and of ~100 km for the Central Alps (Frisch et al., 2000), causing the tectonic denudation of the Tauern window and the Lepontine Dome. The enhanced exhumation of the hinterland should be reflected in the foreland basin sediments.

In the Swiss molasse basin, sediment discharge from the Speer and Rigi–Hohröne river systems ceased, and the Kronberg–Gäbris and Hörnli river systems became dominant (Schlunegger et al., 1997; Kempf, 1998). To the west, the Honegg–Napf river system persisted. For this time slice, zircons from sandstones of the Pfänder fan east of Lake Constance were also dated by the FT method (Table 1). The

Pfänder became an independent fan system only in Burdigalian times (Schiemenz, 1960). Conglomerates of all fans comprise crystalline pebbles in various amounts and sandstones of all fans contain epidote as the dominant heavy mineral.

Sr and Nd isotopic ratios of these epidotes point to a mantle-derived, basic source rock in all fan systems for the majority of the epidote (Spiegel et al., submitted). Therefore, we conclude that in Lower Miocene times, ophiolitic rocks from the very top of the Penninic nappe system became exposed over large areas of the Central Alps. These ophiolitic rocks were void of zircon, therefore, their erosion is not monitored by FT dating on detrital zircons from the foreland basin. This explains the Austroalpine age distribution of the Hörnli and Kronberg–Gäbris fan. In contrast, a ~30 Ma Zr FT age group appears in the age spectra of the Honegg–Napf and Pfänder fans. Zircons of this age can be derived either from Penninic nappes of the Lepontine area or from Periadriatic magmatic bodies. The majority of the young zircon crystals in the sediment are relatively small, rounded and rose-coloured, unlike those zircons derived from Periadriatic magmatitic bodies, which are mainly euhedral, clear and colourless (see Dunkl et al., 2000). We therefore conclude that the young zircon grains were derived from Penninic units of the Lepontine area underlying the ophiolitic rocks. This indicates that (i) the Honegg–Napf and the Pfänder system rooted in deeper structural levels than the other fans of the Swiss molasse basin and (ii) the Pfänder system must have had a rather narrow catchment area reaching far to the southwest, similar to the present Rhine river catchment.

On the southern flank of the Central Alps, Periadriatic magmatitic bodies, Penninic nappes, South Alpine basement and cover units, and Austroalpine units displaying Tertiary metamorphism were all exposed (Giger, 1991). This is reflected by the according pebble lithologies (Giger, 1991) and by a sandstone Zr FT age spectrum with ages clustering mainly between 40–30 Ma (Table 1). The number of South Alpine sedimentary pebbles increased, as compared to Late Oligocene times (Longo, 1968; Giger, 1991).

The main drainage divide was situated in the area of the Penninic units of the Lepontine region, but was still located north of the Periadriatic magmatic bodies,

since no zircons typical for Periadriatic intrusives occur in sandstones of the northern foreland basin.

Contemporaneously with the exposure of Upper to Middle Penninic units over large areas of the Central Alps (ca. 21 Ma), the sediment supply in the foreland basins was greatly reduced (Hay et al., 1992; Kuhlemann, 2000). This decrease of the sediment discharge indicates the collapse of the relief due to large-scale lateral extrusion processes.

4.4. Middle Miocene (Fig. 2(d))

In Middle Miocene times ($\sim$14 Ma), the Central Alps had nearly reached their present east–west extension (Frisch et al., 2000). Only the Honegg–Napf and the Hörnli river systems were still active, whereas sediment discharge from the Kronberg–Gäbris system into the Swiss molasse basin had ceased (Schlunegger et al., 1997; Kempf, 1998).

In sandstones of the Hörnli fan, a $\sim$31 Ma Zr FT age group appears, indicating that zircon-rich lithologies of the Penninic hanging wall of the Lepontine Dome had become exposed in the catchment area. In sandstones of the Honegg–Napf fan, a prominent Zr FT age group of $\sim$20 Ma points to an average cooling rate of $\sim$40 °C/Ma in the source region for Middle Miocene times (Spiegel et al., 2000), assuming a Zr FT closure temperature of $\sim$240 °C (Hurford, 1986). This cooling rate is too high to have its source in the hanging wall of the Lepontine Dome. Therefore, we conclude that in Middle Miocene times, the Lepontine Dome itself became exposed for the first time. At the same time the Penninic units of the Tauern window became exposed in the Eastern Alps (Brügel, 1998; Frisch et al., 1998). Both metamorphic domes of the Central and Eastern Alps were thus contemporaneously exhumed to the surface.

Conglomerates of the Honegg–Napf fan show a distinct increase of flysch pebbles as compared to Oligocene and Lower Miocene conglomerates (Schlunegger et al., 1998). According to Schlunegger et al. (1998) this is due to enhanced erosional denudation in the area of the Penninic and ultrahelvetic flysch nappes caused by a northward shift of the main drainage divide. Kuhlemann et al. (2001) also describe a shift of the main drainage divide towards the north at 17 Ma, based on an antagonistic change of the sediment budget on the opposite flanks of the Alps (Fig. 3).

However, the Zr FT data from the sandstones of the Honegg–Napf system suggest the exposure of Lower Penninic units from the Lepontine Dome in the catchment area. Therefore, the main drainage divide must at least locally have reached into the area of the Lepontine Dome, i.e. relatively far to the south. The increase of flysch pebbles in the conglomerates of the Honegg–Napf fan can also be explained by the uplift of the Aar massif during Miocene times (Michalski and Soom, 1990), which caused an enhanced erosion of tectonic units on top of it, including large flysch nappes.

In the southern foreland basin, the conglomerates of the Lucino Formation as the youngest part of the Gonfolite Lombarda Group were deposited at $\sim$15 Ma (Giger and Hurford, 1989). Compared to Early Miocene conglomerates, they show an increase of sedimentary pebbles with South Alpine provenance (up to 67%, Longo, 1968), reflecting the enhanced uplift of the Southern Alps. Moreover, South Alpine and Austroalpine basement, as well as Penninic units and Periadriatic intrusives were exposed in the south-draining part of the Central Alps (Giger, 1991). According to Giger (1991), the Lucino Formation contains pebbles which are similar to gneisses from the Lower Penninic Lepontine Dome in terms of petrography. No Zr FT ages are available from these pebbles. ^{40}K–^{40}Ar ages on biotite, however, are in the same range as ^{40}K–^{40}Ar ages from pebbles which are interpreted to have been sourced from higher levels of the Penninic nappe pile ($\sim$24–28 Ma, Giger, 1991). The exposure of the Lepontine Dome in the catchment area of the Gonfolite Lombarda Group should be reflected by a shift of the FT age distribution of detrital zircon towards younger cooling ages. No such shift occurred in the Zr FT age spectra of sandstones from the Lucino Formation (Fig. 2(d)), as compared to sandstones with Early Miocene sedimentation age (Fig. 2(c)). Because of the northward shift of the main drainage divide at 17 Ma, it seems unlikely that the whole exposure of the Lepontine Dome was drained towards the north in Middle Miocene times. We therefore conclude that the Lepontine Dome was not exposed during the time of deposition of the Lucino Formation. This implies either a sedimentation age older than 15 Ma for the Lucino Formation, or the first exposure of the Lepontine Dome can in fact be bracketed very precisely between 15 and 14 Ma.

After a short-lived enhancement in the course of updoming of the Lepontine core complex at around 17 Ma (Kuhlemann, 2000), the sediment supply has dropped again and persisted at the same level throughout Middle Miocene times (Fig. 3). The sediment accumulation data suggests that the relief of the Central Alps was greatly enhanced during Plio–Pleistocene times, reaching a maximum relief at the present time.

5. Conclusions

5.1. Paleogeography and surface evolution

In Mid-Oligocene times, the northern flank of the Central Alps was dominated by sedimentary cover nappes with only minor exposures of Austroalpine basement. To the south, a volcanic chain was situated in the region of the Periadriatic lineament. In Late Oligocene times, still only sedimentary cover units and Austroalpine basement were exposed on the north-draining side of the Central Alps, whereas rocks of the underlying Penninic mega-unit may have become exposed on the south-draining side. The post-collisional lateral extrusion of the Alps started around the Oligocene–Miocene boundary, causing the collapse of the relief and the exposure of Upper to Middle Penninic units over large areas of the Central Alps at 21–20 Ma. Finally, in Middle Miocene times, the Lower Penninic Lepontine Dome was exhumed to the surface, contemporaneously with the opening of the Tauern window in the Eastern Alps.

5.2. Metamorphism and thermal evolution

Austroalpine basement exposed during Oligo–Miocene times on the northern side of the Central Alps underwent temperatures ≤ 240 °C during Cretaceous metamorphism. The temperature pattern with a distinct gradient known from the Ötztal–Silvretta block was continuous towards the west, suggesting that the formerly exposed Austroalpine basement was the direct western prolongation of the Ötztal–Silvretta block. According to geochronological data, Cretaceous metamorphic temperatures in the Austroalpine basement exposed in the south-draining part of the Central Alps were slightly higher than in the north but still below ~ 300 °C. Tertiary Lepontine metamorphism did not affect the Austroalpine basement of the northern flank, but reached temperatures between ~ 240 and 300 °C on the southern flank.

5.3. Catchment areas and drainage pattern

Between 30–20 Ma the main drainage divide of the Central Alps migrated towards the south. Sedimentological studies imply a northward shift at 17 Ma (Kuhlemann et al., 2001), but despite this, the main water divide was still situated within the Lower Penninic basement nappes of the Lepontine Dome, as proved by geochronological data (von Eynatten et al., 1999; Spiegel et al., 2000).

Of all dispersal systems of the Swiss molasse basin, the Honegg–Napf fan in the western part of the basin rooted into the deepest tectonic units. It was the first fan to receive young zircons with Penninic provenance and the only fan that received debris from the Lower Penninic units of the Lepontine Dome. The headwaters of the Pfänder system of the western Austrian molasse basin also rooted in Penninic units of the Central Alps, indicating a southwest-elongated catchment area similar to the present Rhine river. The Pfänder system might therefore be called 'Paleo-Rhine.'

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