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Crustal thickening and crustal extension as controls on the evolution of the drainage network of the central Swiss Alps between 30 Ma and the present: constraints from the stratigraphy of the North Alpine Foreland Basin and the structural evolution of the Alps

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ABSTRACT

The combined information about sedimentary petrography from the North Alpine Foreland Basin and structural geology from the Alps allows a qualitative reconstruction of the drainage network of the central Swiss Alps between 30 Ma and the present. This study suggests that crustal thickening and crustal thinning significantly controlled the location of the drainage divide. It also reveals the possible controls of crustal thickening/thinning on the change of the orientation of the drainage network from across-strike between 30 and 14 Ma to along-strike thereafter.

Initial crustal thickening in the rear of the wedge is considered to have formed the drainage divide between north and south at 30 Ma. Because the location of crustal thickening shifted from east to west between ≈30–20 Ma, the catchment areas of the eastern dispersal systems reached further south than those of the western Alpine palaeorivers for the same time slice. Similarly, the same crustal dynamics appear to have controlled two phases of denudation that are reflected in the Molasse Basin by petrographic trends. Uplift in the rear of the wedge caused the Alpine palaeorivers to expand further southward. This is reflected in the foreland basin by increasing admixture of detritus from structurally higher units. However, tectonic quiescence in the rear of the wedge allowed the Alpine palaeorivers to cut down into the Alpine edifice, resulting in an increase of detritus from structurally lower units. Whereas uplift in the rear of the wedge was responsible for initiation of the Alpine drainage systems, underplating of the external massifs some 50 km further north is thought to have caused along-strike deviation of the major Alpine palaeorivers.

Besides crustal thickening, extension in the rear of the wedge appears to have significantly controlled the evolution of the drainage network of the western Swiss Alps. Slip along the Simplon detachment fault exposed the core of the Lepontine dome, and caused a 50-km-northward shift of the drainage divide.

INTRODUCTION

Foreland basin stratigraphies contain a record of the denudational and tectonic history of the bounding mountain belt, because the depositional histories of these basins are mainly controlled by lithospheric and surface processes within the evolving orogenic wedge (Jordan, 1981; Tucker & Slingerland, 1996). Sediment accumulation rate patterns in foreland basins provide information that allow reconstruction of the evolution of crustal thickening in adjacent orogens (e.g. Burbank *et al.*, 1986; Jordan *et al.*, 1993; DeCelles & Mitra, 1995; Schlunegger *et al.*, 1997a). Similarly, petrographic data from these troughs chronicle the denudational history of the bounding moun-

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tain belts (e.g. Eisbacher *et al.*, 1974; Lawton, 1986; DeCelles *et al.*, 1998; Frisch *et al.*, 1998). However, as revealed by Frisch *et al.* (1998), a successful reconstruction of the denudational mechanisms and the evolution of the drainage basin requires high-resolution stratigraphic data from the foreland basin and detailed structural information from the adjacent orogen.

The Oligo-Miocene Alps/North Alpine Foreland Basin (NAFB) system of central Switzerland is one of the best studied orogen/foreland basin systems. However, because direct physical stratigraphic, structural and geomorphic ties between the NAFB and the Alps have been removed by subsequent erosion, reconstructions of the Alpine drainage network for different time intervals have proven to be difficult. Previous studies either determined the catchment area and the spacing of the Oligo-Miocene Alpine palaeorivers (Speck, 1953; Gasser, 1968; Maurer *et al.*, 1982; Hurford, 1986; Giger & Hurford, 1989; Hovius, 1996), or estimated average erosion rates based on cooling paths of presently exposed rocks (Sinclair & Allen, 1992; Schlunegger *et al.*, 1997b).

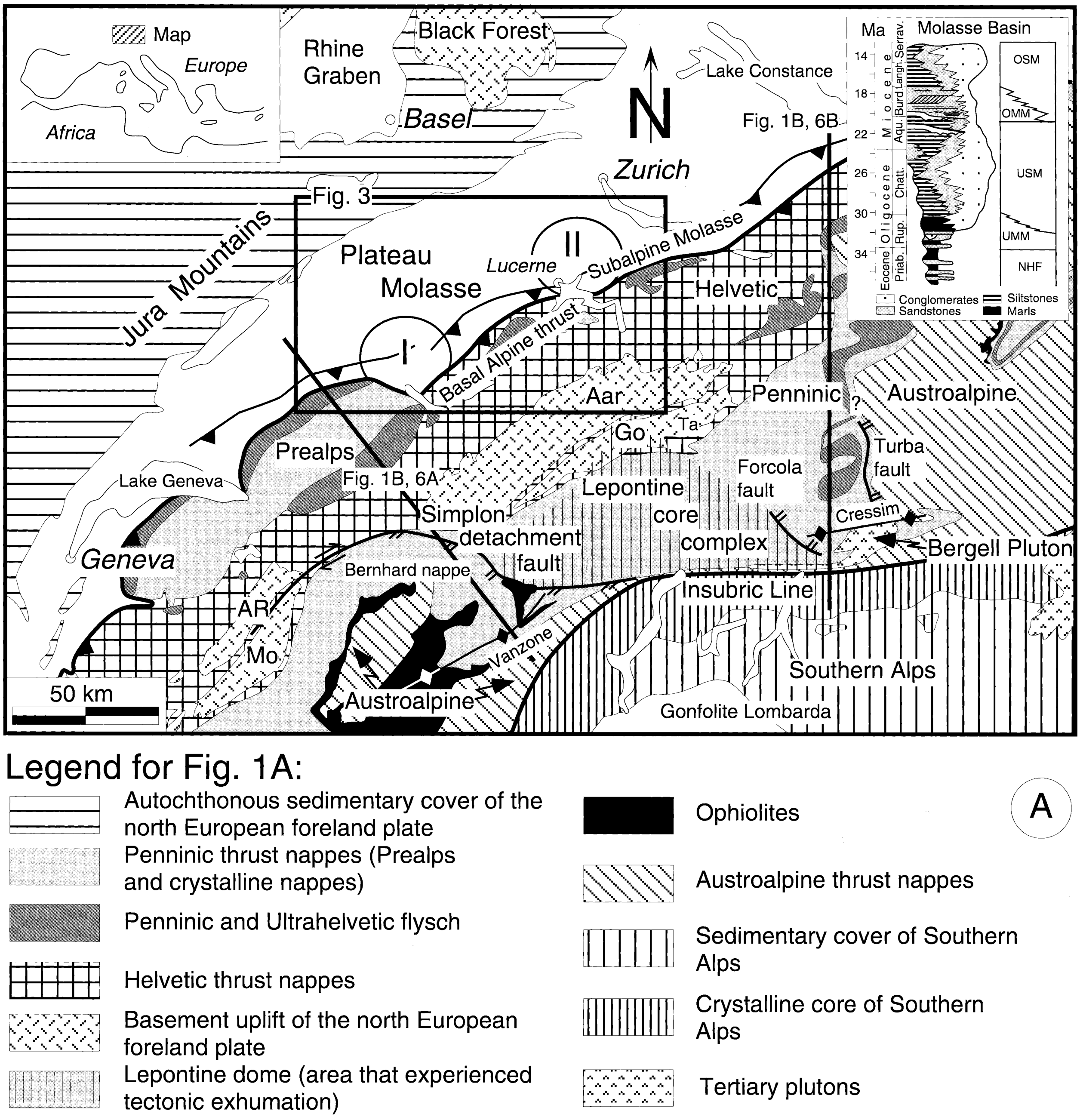
Here, we combine and synthesize information on the stratigraphic and structural evolution of the Alps/NAFB system to reconstruct the areal denudation history of the central Swiss Alps between 30 Ma and the present. We use the present-day Alpine architecture and the chronology of crustal extension and crustal thickening in the Alps coupled with published petrographic and sedimentological data from the central NAFB to: (i) determine the drainage network in the foreland basin, (ii) identify possible source terrains, (iii) reconstruct the drainage network in the erosional hinterland for different time intervals and (iv) discuss possible controls on the evolution of the Alpine drainage network. This study demonstrates that although drainage network systems in erosional hinterlands are never preserved in geological records, we are able to: (i) locate approximately the main drainage divides and reconstruct the courses of the main palaeorivers within reasonable bounds and (ii) estimate the size of the catchment areas for different time intervals if we integrate structural, thermochronological, stratigraphic and petrographic data.

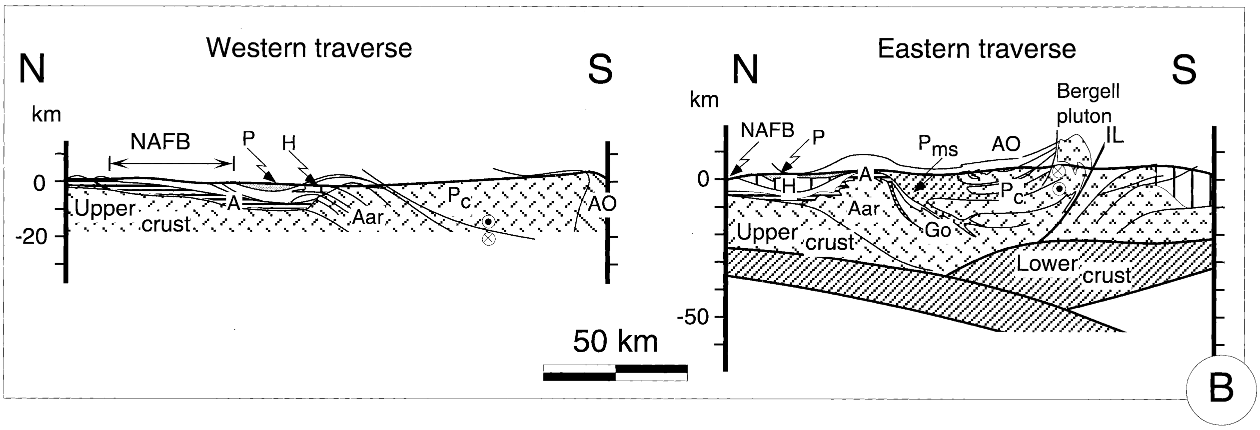
GEOLOGICAL SETTING

The Alps

The Alps form a doubly vergent orogen that consists of highly metamorphosed crystalline rocks in its core (Lepontine dome) and low-grade to unmetamorphosed thick-skinned and thin-skinned rocks in their external flanks (Fig. 1A; Schmid *et al.*, 1996). In the north, the present-day Alps comprise the external massifs (e.g. the Aar massif and its autochthonous–parautochthonous cover) and the Helvetic thrust nappes. They are structurally overlain to the south by the stack of Penninic and Austroalpine nappes (Fig. 1B). The sedimentary cover of the Penninic thrust nappes that form the Prealps (Fig. 1) was detached from its crystalline basement prior to 35 Ma (Schmid *et al.*, 1996). This latter unit is present south of the external massifs. The Penninic and Austroalpine nappes are separated from the south-vergent Southern Alps (Schönborn, 1992) by the E–W-striking Insubric Line that partly accommodated crustal convergence between the European and Apulian plates by steep S-directed reverse faulting and by strike-slip faulting (Schmid *et al.*, 1989). In the rear of the orogenic wedge north of the Insubric Line, the Penninic and Austroalpine nappes were folded (Vanzone and Cressim backfolds, Figs 1 and 2) due to S-vergent backthrusting along the Insubric Line between $\approx$30 and 20 Ma (Steck & Hunziker, 1994; Schmid *et al.*, 1996; Pfiffner & Heitzmann, 1997). Crustal thickening in the rear of the wedge was contemporaneous with E–W-directed crustal extension north of the Insubric Line (Mancktelow, 1992; Steck & Hunziker, 1994; Schmid *et al.*, 1997) that was accommodated by slip along the Simplon detachment fault in the west, and the Turba normal fault in the east (Figs 1 and 2). Situated at deeper structural levels and $\approx$20 km west of the Turba fault, NNW–SSE-striking, steeply inclined E-dipping normal faults reveal a systematic downthrow towards the east-northeast (Baudin *et al.*, 1993). The largest of these faults, the Forcola normal fault (Figs 1 and 2), has not yet been systematically investigated. According to Schmid *et al.* (1997), extension along the Turba and Forcola faults occurred prior to 30 Ma, and between 25 and 20 Ma, respectively. The amount of displacement along these faults is not known (Schmid *et al.*, 1997). However, the mechanical evaluation of stretching lineations suggests that a total of $\approx 80 \pm 40$ km of extension was accommodated by slip along the Simplon fault (Steck & Hunziker, 1994). Furthermore, cross-cutting relationships between the fault, temporally calibrated metamorphic fabrics and thermal models indicate that some 70 ± 35 km of ductile shear occurred between 25 and 15/10 Ma, and that $\approx 10 \pm 5$ km of brittle displacement took place

Fig. 1. (A) Geological map of the Oligocene to Miocene Swiss Molasse Basin and the adjacent Alpine orogen. Major tectonic units are labelled. The Prealps represent the sedimentary cover of the Penninic crystalline nappes. The Lepontine dome is indicated by a vertical hatch pattern. Inset (upper right): the stratigraphic scheme of the Molasse Basin (modified after Schlunegger *et al.*, 1996). External massifs: AR = Aiguilles Rouge massif, Mo = Montblanc massif, Aar = Aar massif, Go = Gotthard massif; I = deposits of the Honegg–Rigi palaeoriver, II = deposits of the Rigi–Höhronen palaeoriver. (B) Section across the present-day (left) western (Burkhard, 1988) and (right) eastern Swiss Alps (Schmid *et al.*, 1996). NAFB = North Alpine Foreland Basin, P = Prealps and flysch, H = Helvetic thrust nappes, A = autochthonous, Aar = Aar massif, P_c = Penninic crystalline nappes, AO = Austroalpine nappes, P_{ms} = Penninic metasedimentary nappes (schists and flysch), IL = Insubric Line, Go = Gotthard massif.


Map
Europe
Africa
Rhine Graben
Black Forest
Basel
N
Lake Constance
Fig. 1B, 6B
Zurich
Fig. 3
Jura Mountains
Plateau Molasse
Lucerne
II
I
Subalpine Molasse
Basal Alpine thrust
Helvetic
Aar
Penninic
Austroalpine
Go
Ta
Prealps
Lake Geneva
Fig. 1B, 6A
Lepontine core complex
Forcola fault
Turba fault
Cressim
Bergell Pluton
Simplon detachment fault
Bernhard nappe
Geneva
AR
Mo
Insubric Line
Vanzone
Southern Alps
Austroalpine
Gonfolite Lombarda
50 km
Ma
Molasse Basin
14
18
22
26
30
34
Miocene
Oligocene
Eocene
Serrav.
Langh.
Burd.
Aqu.
Chatt.
Rup.
Priab.
OSM
OMM
USM
UMM
NHF
Conglomerates
Sandstones
Siltstones
Marls
Legend for Fig. 1A:
Autochthonous sedimentary cover of the north European foreland plate
Penninic thrust nappes (Prealps and crystalline nappes)
Penninic and Ultrahelvetic flysch
Helvetic thrust nappes
Basement uplift of the north European foreland plate
Lepontine dome (area that experienced tectonic exhumation)
Ophiolites
Austroalpine thrust nappes
Sedimentary cover of Southern Alps
Crystalline core of Southern Alps
Tertiary plutons
A


Western traverse
N
S
km
0
-20
NAFB
P
H
A
Upper crust
Aar
Pc
AO
Eastern traverse
N
S
km
0
-50
NAFB
P
H
A
Pms
AO
Bergell pluton
IL
Aar
Pc
Go
Upper crust
Lower crust
50 km
B

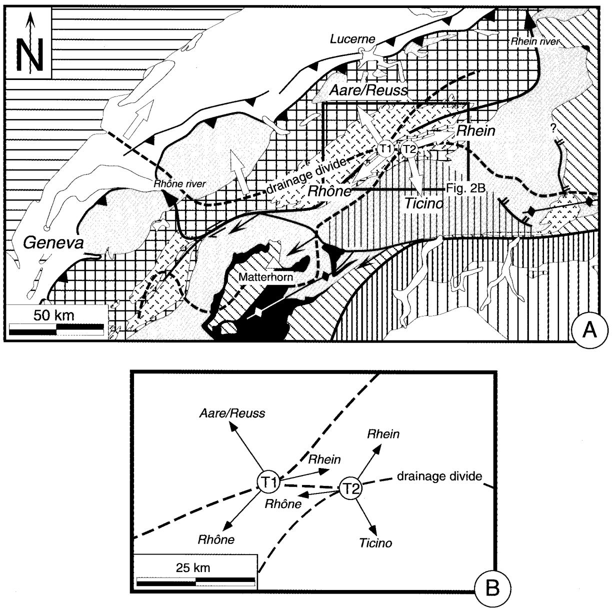


Fig. 2. Map showing the present-day Alpine drainage network. Note that the Aar and the Gotthard massifs separate the drainage network of the Aare/Reuss, Rhône, and Rhein rivers, and that of the Rhône, Rhein and Ticino rivers, respectively (A), resulting in the formation of two triple junctions (B). The map also shows the major tectonic structures. The Lepontine dome is indicated by a vertical hatch pattern. See Fig. 1 for legend and labels of the major tectonic structures. Note that for simplicity we did not differentiate the flysch units.

between 15/10 Ma and the present (Mancktelow, 1985; Grasemann & Mancktelow, 1993; Steck & Hunziker, 1994; Schlunegger & Willett, 1998). Structural and geochronological data as well as thermal models (Mancktelow, 1992; Grasemann & Mancktelow, 1993; Steck & Hunziker, 1994) suggest that slip along the Simplon fault is likely to have exhumed the high-grade crystalline core of the Penninic crystalline nappes that previously had experienced maximum temperatures of $>600\,^{\circ}$C (Lepontine dome, vertical hatch pattern, Figs 1 and 2). According to Grasemann & Mancktelow (1993) and Schlunegger & Willett (1998), maximum rates of extension occurred somewhen between 25 and 15 Ma. Using thermal models of cooling and erosion, the same authors suggest that extensional unroofing caused $\approx 50\%$ of the total exhumation of the Lepontine dome. Furthermore, fission track data imply that extensional slip along this fault is still active (Seward & Mancktelow, 1994).

The hangingwall of this fault consists of low- to medium-grade Penninic crystalline rocks, Penninic ophiolites and Austroalpine units (Figs 1 and 2). At present, the Simplon detachment fault dips » 15° towards the south-west. Palinspastic restorations of the western Swiss Alps (Burkhard, 1988) suggest that the angle of south-westward dip of this fault has been nearly constant in the geological past.

The external massifs underwent major exhumation during Miocene and Pliocene time. Pfiffner *et al.* (1997) reconstructed the exhumation history of the Aar massif (Figs 1 and 2) based on temporal calibrations of the annealing temperature of apatite and zircon fission track systems that were published by Michalski & Soom (1990). Pfiffner *et al.* (1997) concluded that exhumation of the Aar massif was heterochronous along-strike, starting prior to 20 Ma in the east and several million years later in the west. In the western part of this unit, a phase of maximum exhumation is interpreted to have been initiated at $\approx 15/10$ Ma (Pfiffner *et al.*, 1997). According to cross-cutting relationships between thrusts and the 25–20 Ma foliation in the Aar massif (Burkhard, 1988) this phase of maximum exhumation coincides with or post-dates the Grindelwald phase of deformation. This phase of deformation relates to an episode of basement uplift with a vertical displacement of ≈ 5 km (Günzler-Seiffert, 1941). The Grindelwald phase of deformation was coeval with thrusting and folding of the Jura Mountains and with the piggy-back displacement of the Molasse Basin (Pfiffner *et al.*, 1997).

The North Alpine Foreland basin

The peripheral North Alpine Foreland Basin (NAFB), located north of the Alps (Fig. 1), is interpreted to have formed as a mechanical response to the tectonic load of the evolving Alps (Homewood *et al.*, 1986; Sinclair *et al.*, 1991; Schlunegger *et al.*, 1997b). The sedimentological development of the North Alpine Foreland Basin can be described in terms of early deep-water sediments and later shallow-water/continental sediments which have been referred to as flysch and molasse in the classic Alpine literature (see discussions in Sinclair *et al.*, 1991; Sinclair & Allen, 1992). Comparisons between rates of exhumation in the Alps and preserved volume of sediment in the basin suggest that the Molasse represents the late overfilled stage of the evolution of the NAFB (Sinclair, 1997). The Molasse deposits are present in the northernmost part of the NAFB that has been referred to as the Molasse Basin (e.g. Matter *et al.*, 1980). The deposits in the Molasse Basin have been traditionally divided into four lithostratigraphic units, for which the conventional German abbreviations are used in this paper (Matter *et al.*, 1980): Lower Marine Molasse (UMM), Lower Freshwater Molasse (USM), Upper Marine Molasse (OMM) and Upper Freshwater Molasse (OSM). They form two shallowing- and coarsening-upward megasequences. The oldest megasequence comprises the Rupelian UMM, which is overlain by the Chattian and Aquitanian fluvial clastics of the USM. The second megasequence, with the transgressive Burdigalian at its base, consists of shallow-marine sandstones (OMM), which interfinger with major fan-delta deposits adjacent to the thrust front (Berli, 1985; Keller, 1989; Hurni, 1991; Schlunegger *et al.*, 1996). This megasequence is overlain by Langhian–Serravalian fluvial clastics of the OSM.

Along the southern border of the foreland basin, the Molasse deposits are present in a stack of S-dipping thrust sheets referred to as Subalpine Molasse in classic Alpine literature (Fig. 1). The Plateau Molasse, which represents the more distal part of the basin, is mainly flat lying and dips gently towards the Alpine orogen. Thrusting in the Subalpine Molasse was contemporaneous with sedimentation (Schlunegger *et al.*, 1997c; Kempf *et al.*, 1998).

In the central part of the Molasse Basin, which is the focus of this study (Fig. 1), transverse drainage systems with sources in the evolving Alps flowed into a NE-flowing axial drainage (Lac Léman palaeoriver) between 30 and 20 Ma, a shallow peripheral sea (Upper Marine Molasse) between 20 and 16 Ma, and a SW-orientated axial drainage between 16 and 14 Ma (Matter *et al.*, 1980; Berger, 1996). Two major transverse drainage systems, referred to as the Honegg–Napf and Rigi–Höhronen systems in this paper, were present in the central Molasse Basin (Fig. 1). They were active between 30 and ≈14 Ma (Honegg–Napf) and between 30 and ≈21 Ma (Rigi–Höhronen) according to magnetostratigraphic chronologies of fossiliferous sections (Schlunegger *et al.*, 1996, 1997a).

In the following chapters we discuss the geometrical relationships between the present-day drainage network and the lithotectonic architecture of the central Alps. This allows us to speculate about possible controls of movement along specific faults/thrusts (e.g. the Insubric Line, the Simplon fault) on the arrangement of the drainage network. In a following step we test the significance of controls of movement along these structures on the Oligocene to present-day Alpine exhumation by relating the sequence of Alpine deformation to the petrographic evolution of the Molasse Basin. Specifically, we use petrographic data from the NAFB as contraints on the location of the catchment area for different time intervals.

THE PRESENT-DAY DRAINAGE NETWORK OF THE CENTRAL ALPS

The present-day Alpine drainage network is divided into four segments (Fig. 2A). They are separated by two triple junctions that are located in the core of the Aar (T1) and the Gotthard (T2) massifs (Fig. 2A,B). These junctions separate the headwaters of the Aare/Reuss, Rhein and Rhône dispersal systems (T1), and those of the Ticino, Rhein and Rhône drainage systems (T2). The orientation of the water divide between the Ticino and Rhône/Rhein rivers parallels the major tectonic structures. In the footwall of the Simplon fault, the location of the drainage divide coincides with the northern border of the Lepontine dome that is interpreted to have experienced tectonic exhumation (Mancktelow, 1992; Grasemann & Mancktelow, 1993; Schlunegger & Willett, 1998). In the hangingwall of the Simplon detachment fault and east of the Forcola fault, however, the drainage divide between the Ticino and Rhône/Rhein dispersal systems partly follows the regional trend of the Vanzone (west) and the Cressim (east) backfolds (Fig. 2). The drainage divide between the Aare/Reuss and the Rhein river follows the boundary between the Penninic and Helvetic nappes. Approximately 80 km east of T1 in the area where no underplating of the Aar massif occurred (Pfiffner *et al.*, 1990), the course of the Rhein river changes to an across-strike direction and enters the Molasse Basin ≈100 km north-east of Lucerne (Fig. 2A). Similarly, the drainage divide between the Aare/Reuss and the Rhône rivers parallels the strike direction of the Aar massif. Approximately 30 km south-west of the eastern tip of Lake Geneva, the orientation of this drainage divide changes to an across-strike direction and crosses the Molasse Basin at a right angle.

Located north-west of the catchment area of the Ticino river (Fig. 2A), the source terrain of the Rhône river strikes NE–SW. It comprises the south-western part of the Aar and the Gotthard massifs, comprising low- to medium-grade granites and gneisses. In the south, it consists of ophiolites and low- to medium-grade Penninic and Austroalpine crystalline rocks that form the hangingwall of the Simplon fault (Figs 1 and 2). Further north, the catchment area of the Rhône river comprises the low-grade carbonates and shales of the Helvetic thrust nappes and the unmetamorphosed sandstones and carbonates of the Prealps. From the triple junction T2 located in the core of the Gotthard massif, the course of the Rhône river follows the steeply dipping Mesozoic sediments that separate the Aar and the Gotthard massifs (Fig. 2). At the south-western termination of the Aar massif, the direction of the Rhône river rotates in a clockwise direction by ≈10° as the river is trapped by the trace of the Simplon detachment fault. At the north-eastern termination of the Aiguilles Rouge and Mont Blanc massifs, the course of the Rhône river rotates again in a clockwise direction by 90°, after which the river discharges into Lake Geneva (Fig. 2).

The catchment area of the Rhein river comprises the medium- to low-grade Penninic crystalline nappes east of the Forcola fault, low-grade Penninic schists and flysch south-east of the Gotthard massif, and Helvetic sedimentary nappes in the north (Fig. 2A). The headwaters of this river are located in the core of the Aar and the Gotthard massifs. From there, the Rhein river follows the steeply dipping trace of the basal thrust of the Tavetsch massif (Ta, Fig. 1). This unit represents a tectonic sliver of mafic crystalline basement rocks that is located between the Aar and the Gotthard massifs. North-east of the Aar massif, the Rhein river flows along the trace of the basal Penninic thrust fault that separates the mainly flat-lying Penninic schists and flysch in the south from the steeply S-dipping Helvetic carbonates in the north. Further north-east, in the area where no underplating of the Aar massif occurred (Pfiffner *et al.*, 1990), the course of the Rhein river rotates anticlockwise by ≈90°, after which the river crosses the Helvetic thrust nappes and finally discharges into Lake Constance.

The catchment area of the Aare/Reuss drainage system consists of basement rocks at its southern border (Aar massif) and carbonates, sandstones and shales of the Helvetic and Penninic nappes. The courses of the Aare and Reuss rivers are predominantly orientated towards the north.

PALAEODRAINAGE NETWORK IN THE CENTRAL SWISS MOLASSE BASIN, AND PETROGRAPHIC CHARACTERIZATION

Methods

The reconstruction of the drainage network and the location of the facies belts of the Molasse Basin for different time intervals is based on a compilation of palaeogeographic maps that were published by Allen *et al.* (1985), Berger (1996) and Schlunegger *et al.* (1997d). Further reference is given in the figure captions. These authors constructed the palaeogeography of the Molasse Basin based on a compilation of petrographic (determination of the heavy mineral suites), sedimentological, magnetostratigraphic and seismostratigraphic data that were collected from outcrop and borehole sections and from seismic lines. The position of the thrust front and the palinspastic position of the stratigraphic sections of the thrusted Molasse at 25 Ma, 20 Ma and 16 Ma was taken from the sequential palinspastic restoration of the Alps described in detail by Burkhard (1988) and Schlunegger *et al.* (1997a) for the western and eastern parts of the study area, respectively. The results of conglomerate clast counts were compiled from Matter (1964), Stürm (1973) and Schlunegger *et al.* (1993, 1997a) to identify possible source terrains. In addition, conglomerate clast counts at three sites were carried out in the 30 Ma deposits of the Subalpine Molasse of central Switzerland to complete the petrographic dataset. The methodology for the conglomerate clast counts is described by Schlunegger *et al.* (1993), and for location maps refer to Schlunegger (1995) (Marbach section, three conglomerate beds).

Palaeocurrents from the eastern part of the study area were taken from Schlunegger *et al.* (1997a). Additionally, we collected ≈ 200 palaeocurrent data in the west to complete the analysis of dispersal direction. Palaeocurrents were determined from furrows, large-scale (> 0.5 m) trough cross-beds and imbricate clasts in the conglomerates. The teconic tilt in the Subalpine Molasse was removed in order to determine the palaeoflow direction at the time of deposition. In this paper we only consider the palaeoflow directions measured on conglomerates of alluvial megafans (Schlunegger *et al.*, 1997d) because they indicate the locations of the major drainage outlets at the mountain front, and therefore lack the regional compositional mixing that is likely to occur in an axial fluvial system.

Results

Drainage network of the central Molasse Basin

Despite the fact that the deposits of the various dispersal systems contain similar clast types and identical heavy minerals (except for the axial drainage, see below), they significantly differ in the relative abundance of the various components (e.g. Füchtbauer, 1959, 1964). Therefore, as revealed by numerous petrographic studies (e.g. Büchi & Schlanke, 1977; Maurer, 1983) the course and the position of the different dispersal systems in the Molasse Basin can be reconstructed within reasonable bounds. The evolution of the sedimentary dispersal systems of the central Swiss Molasse Basin is depicted on Fig. 3. It shows three stages of basin evolution. During the first stage, between 30 and 20 Ma, the axial tilt of the basin was towards the north-east (Berger, 1996). Three major dispersal systems were present during this time interval. The depocentre of the first system, referred to as the Lac Léman fluvial system, was located at the western end of the Molasse Basin ≈ 150 km south-west of the study area, from where it flowed eastward along the distal feather edge of the foreland basin (Fig. 3A,B). The course of this system (Berger, 1996) was determined by the presence of the key heavy minerals hornblende and blue amphibole in the sandstones that were not detected in the deposits of the transverse palaeorivers (Schlanke *et al.*, 1978; Mange & Oberhänsli, 1982; Maurer, 1983; Schlunegger *et al.*, 1997d). The longitudinal Lac Léman palaeoriver was fed by the second system, the transverse Honegg–Napf palaeoriver that originated in the central Alps and that entered the basin at the south-western border of the study area. The deposits of this palaeoriver were identified (Schlunegger *et al.*, 1993) by the occurrence of the heavy minerals apatite and epidote that were present in equal proportions (Honegg), or based on the predominance of epidote (Napf) (Füchtbauer, 1959, 1964; Maurer *et al.*, 1978; Maurer, 1983; Schlunegger *et al.*, 1993, 1997a,d). The third dispersal system, referred to as the Rigi–Höhronen palaeoriver, entered the basin ≈ 60 km further east (Stürm, 1973). The deposits of this palaeoriver are characterized by the predominance of the heavy mineral spinel (Rigi) or the occurrence of apatite and zircon in equal proportions (Höhronen; Schlanke, 1974; Schlunegger *et al.*, 1997d). Between 30 and 28 Ma, the Rigi–Höhronen palaeoriver was fed by the Beichlen palaeoriver that entered the basin in the centre of the study area, and that flowed eastward along the thrust front (Fig. 3A).

During the second stage of basin evolution, between 20 and ≈ 14 Ma, either no axial tilt was present (20–16 Ma) or the axial tilt of the basin was towards the south-west (16–14 Ma, Fig. 3C,D). The reason for the westward tilt of the basin is not known. The topographic axis of the basin was occupied by a shallow peripheral sea between 20 and 16 Ma (deposits of the Upper Marine Molasse Group, OMM; Fig. 3C) and an axial drainage after 16 Ma (Graupensand palaeoriver; Fig. 3D; Allen *et al.*, 1985; Berger, 1996; Schlunegger *et al.*, 1996). During the OMM time, SW-orientated transport of sediment occurred by strong tidal currents (Allen *et al.*, 1985). The presence of the heavy minerals topaz and andalusite in the tidal deposits of the OMM and in the

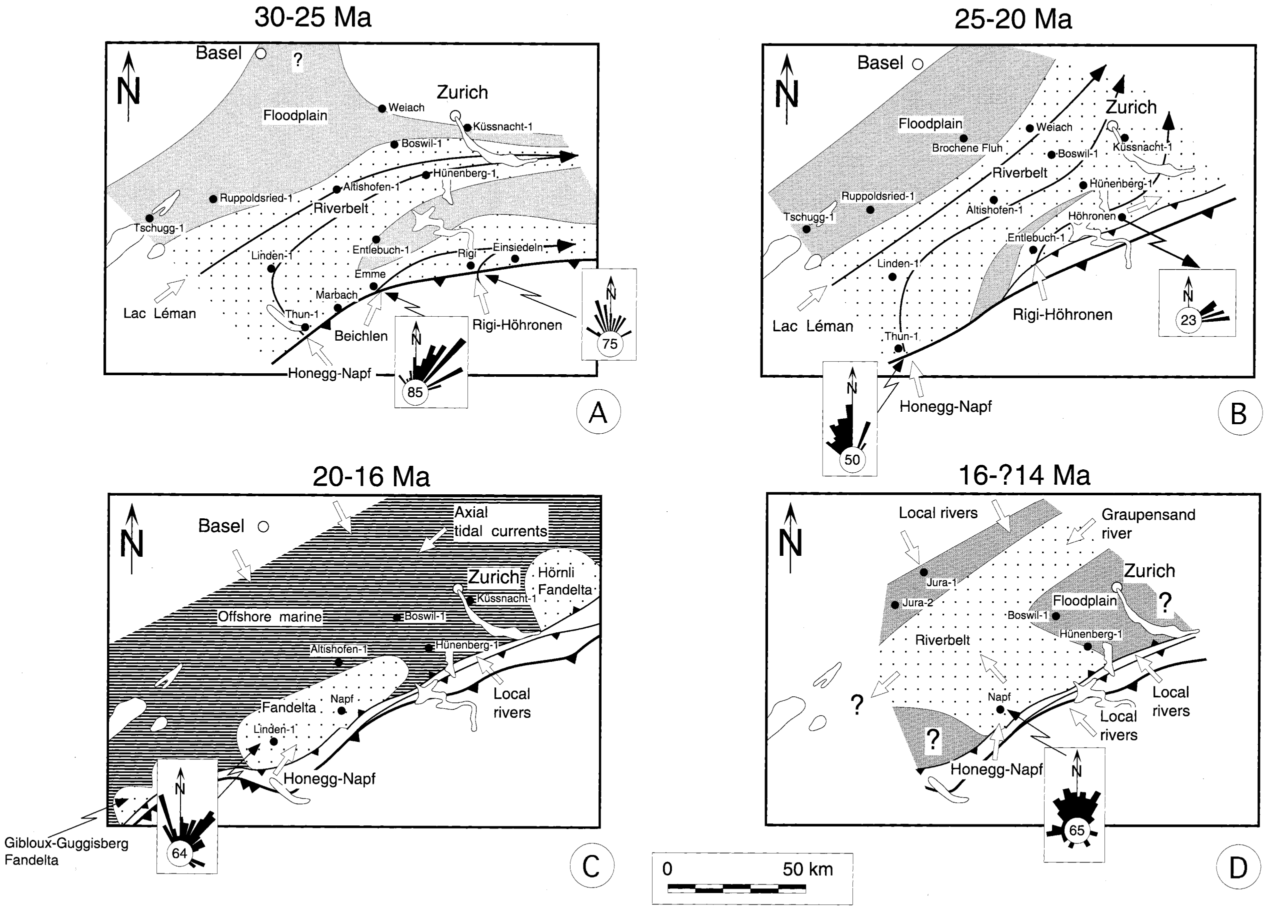


Fig. 3. Palaeogeographical map of the Molasse Basin for the time interval between (A) 30–25 Ma, (B) 25–20 Ma, (C) 20–16 Ma and (D) 16–?14 Ma and palaeoflow directions of the north Alpine palaeorivers. The stratigraphic and petrographic data for reconstruction of the map are taken from the following sections: Thun-1: Schlunegger *et al.* (1993, 1996), Linden-1: Schlunegger *et al.* (1993) and Maurer *et al.* (1978), Marbach: Schlunegger *et al.* (1996), Emme: Mägert (1998), Rigi: Stürm (1973) and Schlunegger *et al.* (1997a), Einsiedeln: Schlunegger *et al.* (1997b), Höhronen: Schlunegger *et al.* (1997a), Entlebuch-1: Vollmayr & Wendt (1987), Althishofen-1: Maurer *et al.* (1982) and Schlunegger *et al.* (1997d), Hünenberg-1, Boswil-1 and Küssnacht-1: Büchi *et al.* (1965), Schlanke (1974) and Schlunegger *et al.* (1997c,d), Weiach: Schlunegger *et al.* (1997d), Ruppoldsried-1 and Tschugg-1: Schlanke *et al.* (1978), Jura-1 and Jura-2: Kälin (1993), Napf: Matter (1964), Schlunegger *et al.* (1996) and Kempf *et al.* (1998), and Brochene Fluh: Schlunegger *et al.* (1996). Additional information is taken from Allen *et al.* (1985), Berger (1996) and Mange (personal communication 1995).

sandstones of the Graupensand palaeoriver indicate erosion of the Bohemian massif located ≈350 km north-east of the study area (Allen *et al.*, 1985). The transverse Rigi–Höhronen palaeoriver was deactivated by 21 Ma, and the Honegg–Napf palaeoriver was the only Alpine system feeding the basin in the study area. Palaeoflow directions (Fig. 3C) and geological maps (Haldemann *et al.*, 1980) indicate that the fan axis of the Honegg–Napf palaeoriver was orientated towards the north-east.

The last stage of basin evolution, between 14 Ma and the present, was characterized by uplift and erosion of the Molasse Basin. Similarly, at ≈15 Ma, shortening and deformation of the Jura Mountains, located north of the Molasse Basin, was initiated (Pfiffner *et al.*, 1997). A drainage divide that runs across-strike and separates the western from the eastern part of the basin was established north-east of Lake Geneva (Fig. 2).

Conglomerate clast composition

The conglomerate poplulation of the Beichlen dispersal system, which was active between 30 and ≈28 Ma according to magnetopolarity-based chronologies (Schlunegger *et al.*, 1996), is dominated by siliceous limestone and dolomite clasts with admixtures of sandstone and crystalline clasts (Fig. 4). The conglomerates of the Honegg–Napf palaeoriver, which was active between 27 and 14 Ma, comprise the whole petrographic spectrum from crystalline to sedimentary clast types (Fig. 4). Between 30 and 23 Ma, the conglomerate composition of the Honegg–Napf palaeoriver changed towards a higher percentage of crystalline clasts. During the same time interval, the percentage of siliceous limestone and dolomite clasts decreased, and the relative contribution of sandstone clasts increased (Fig. 4). At 20 Ma, however, the relative abundance of crystalline

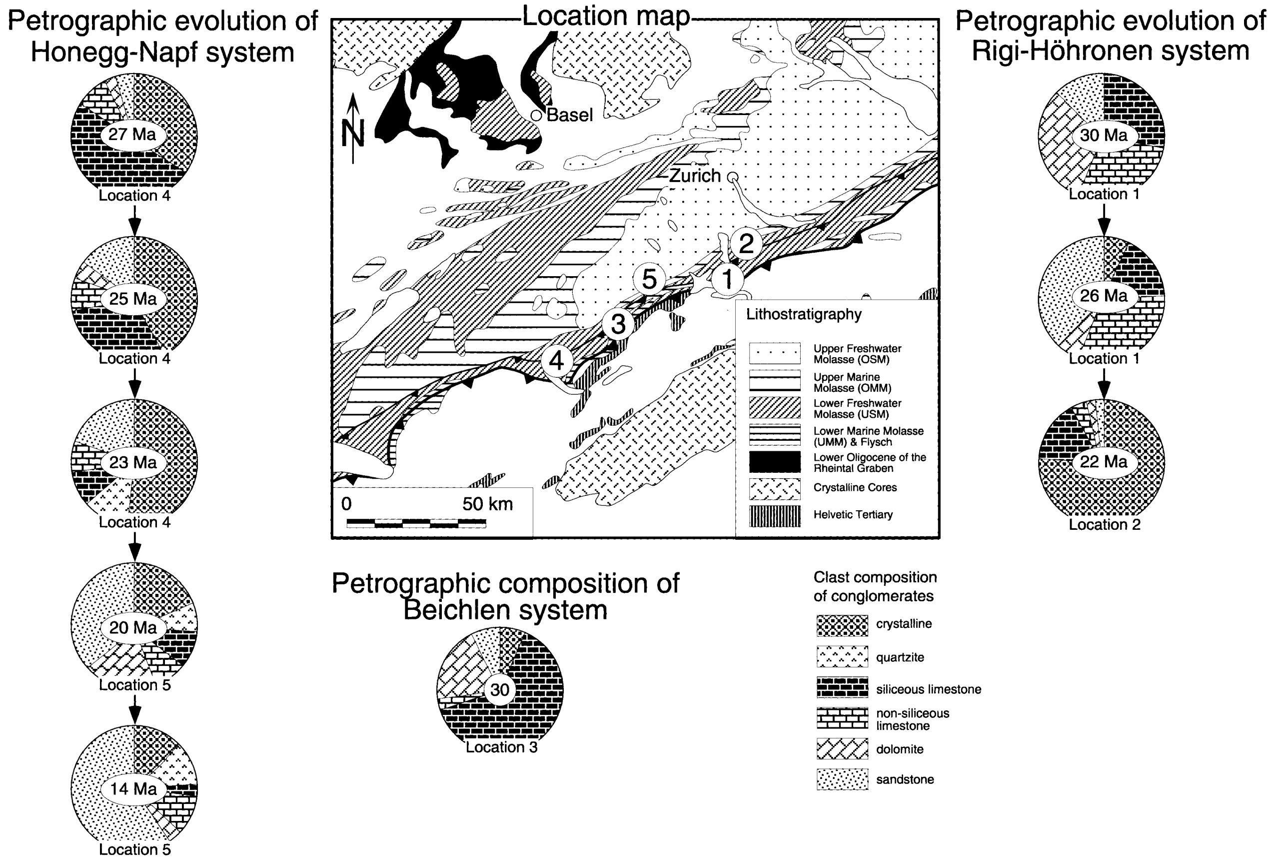


Fig. 4. Evolution of the conglomerate suites of the analysed palaeorivers and map showing the locations of the conglomerate clast counts. The petrographic data are taken from Schlunegger *et al.* (1997a) for the sites of sections 1 and 2 (Rigi and Höhronen section), Schlunegger *et al.* (1993) for the sites of section 4 (Thun-Prässerebach section) and Matter (1964) for the sites of section 5. The petrographic data of section 3 are presented in this paper (for location maps refer to Schlunegger, 1995). The conglomerate clast composition at these sites is thought to be representative of the petrofacies of the Honegg–Napf, the Beichlen and the Rigi–Höhronen palaeorivers. The numbers in the circles represent ages at which the conglomerates were deposited (see Schlunegger *et al.*, 1996, 1997a for chronological data).

clasts started to decrease, and sandstone clasts became a predominant component between 20 and 14 Ma. Note that after 25 Ma, greenschist-grade quartzite clasts appeared in the conglomerates of the Honegg–Napf palaeoriver (Fig. 4).

The conglomerate clast population of the Rigi–Höhronen palaeoriver changed significantly between the late Oligocene and early Miocene (Fig. 4). At 30 Ma, the conglomerate clast population is characterized by equally distributed dolomite, sandstone, siliceous limestone and other carbonate clasts. At 26 Ma, the first crystalline clasts (red granites) appeared, and dolomite clasts became less abudant. By the early Miocene, crystalline clasts became the predominant components of the conglomerates. The contribution of siliceous limestone clasts remained at $\approx$20–25%, whereas the admixture of other clast types is insignificant.

DISCUSSION

Provenance of the Alpine palaeorivers

Reconstruction of the provenance of the detritus in sedimentary basins is difficult because the hinterlands have been significantly modified by subsequent erosion. This is certainly the case for the Alps of central Switzerland. Nevertheless, because in the west (i) the major lithotectonic units are still preserved to some extent (Spicher, 1980), (ii) the exposed Penninic rocks are petrographically distinct and (iii) remnants of Austroalpine rocks (the orogenic lid of Schmid *et al.*, 1996) are present in the study area, reasonable inferences can be made about the provenance of the deposits of the central Swiss Molasse Basin. Based on comparative petrographic studies between clast types in the conglomerates of the Beichlen and the Honegg–Napf systems and the present-day lithologies in the hinterland, Speck (1953), Füchtbauer (1959, 1964), Matter (1964), Gasser (1967, 1968) and Schlunegger *et al.* (1993) concluded (Fig. 5) that (i) the sandstone clasts were most likely derived from North Penninic and Ultrahelvetic flysch nappes that underlay the Prealps and probably formed the Alpine front in the Oligocene and Miocene [note, for example, the present-day frontal position of the Subalpine flysch, or that of the Wägital flysch (Spicher, 1980)], (ii) the ?Liassic (Gasser, 1968) siliceous limestone clasts were possibly eroded from the Prealps and (iii) the crystalline

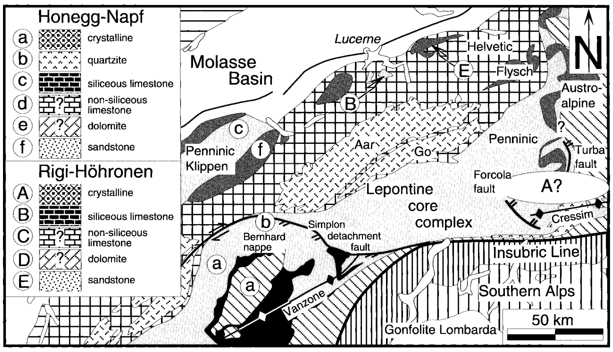


Fig. 5. Provenance map of the various clast types in the conglomerates of the Honegg–Napf and Rigi–Höhronen palaeorivers. The reconstruction of the source terrane of the clast types is based on comparative petrographic studies between the clast types and the preserved source units in the Alps. The sections in the Alps that expose rocks with petrographic similarities to the clasts in the Molasse Basin are labelled with circled lower and upper case letters. The source of the nonsiliceous limestone and dolomite clasts is not known. See text for reference list, and see Fig. 1 for legend. Aar = Aar massif, Go = Gotthard massif.

clasts are likely to have been derived from the crystalline core of the Austroalpine and from the upper Penninic nappes. However, because no thermochronological data are available from the detritus of the Honegg–Napf palaeoriver, a precise distinction between Penninic and Austroalpine nappes as catchment areas is not possible (e.g. Frisch *et al.*, 1998). The source areas of the ?Triassic dolomite clasts and the nonsiliceous limestone clasts are not known because comparative petrographic studies between possible source rock lithologies and the clasts have not yet been carried out. However, the hinterland of the greenschist-grade quartzite clasts that are only present in the conglomerates of the Honegg–Napf fan after 25/24 Ma (Schlunegger *et al.*, 1993) can be precisely located in the Bernhard nappe that is part of the hangingwall of the Simplon fault (Fig. 5). No detritus was derived from the external massifs during deposition of the Molasse Basin as indicated by thermochronological data (Michalski & Soom, 1990).

Despite major uncertainties in the lithotectonic architecture of the Alps during the Oligocene and Miocene, the determination of the provenance of the clast types (Fig. 5) reveals that the catchment area of the Beichlen and Honegg–Napf dispersal systems was located in the hangingwall of the Simplon fault and in the area of the Prealps. The petrographic evolution of the Honegg–Napf palaeoriver reveals three stages of drainage basin development: During the first stage, between 30 and 25 Ma, the relative abundance of crystalline clasts increased from $<10\%$ to $\approx 50\%$ at the expense of detritus from the Prealps. This change in the conglomerate clast composition suggests that the area of major denudation of the Honegg–Napf palaeoriver expanded southward from the area of the Prealps into the region that was occupied by the Penninic and Austroalpine crystalline nappes (Fig. 1B), or that this palaeoriver was downcutting the Alpine orogen to its crystalline core. We prefer the first interpretation because the petrographic shift towards predominance of crystalline clasts is associated with an increase in the contribution of red and green granites from initally $<5\%$ prior to 25 Ma to $>20\%$ after 25 Ma (Schlunegger *et al.*, 1993). These clast types are interpreted to have been derived from the crystalline core of the orogenic lid (Austroalpine nappes; Füchtbauer, 1959, 1964). This interpreted shift of the area of major denudation does not preclude some erosional unroofing in the rear of the wedge as indicated by cooling ages (Hurford, 1986). Indeed, as soon as the oldest part of an orogen, in this case the rear of the Alps north of the Insubric Line (Schmid *et al.*, 1996), was exposed above sea-level, it started to be eroded and dissected. Nevertheless, the petrographic data suggest that between 30 and ≈ 25 Ma, exhumation rates were presumbly highest at the tip of the orogen.

At the beginning of the second stage, at 25 Ma, the heavy mineral suite of the sandstones of the Honegg–Napf palaeoriver shifts towards predominance of epidote (Schlunegger *et al.*, 1993). The epidote was presumably derived from the ophiolites that separate the Austroalpine and the Penninic nappes (Fig. 1). Alternatively, it may have been derived from the granites of the Austroalpine nappes as suggested by the presence of abundant epidote in red and green granite clasts in the conglomerates (Füchtbauer, 1964). After 25 Ma, greenschist-grade quartzites derived from the Bernhard nappe, located in the footwall of the Austroalpine nappes, appeared (Fig. 1; Schlunegger *et al.*, 1993). The appearance of quartzite clasts post-dates by 0.5 Myr the shift of the heavy mineral suite towards predominance of epidote (Schlunegger *et al.*, 1993, 1996). Consequently, the post-25 Ma petrographic evolution implies that the interpreted phase of southward expansion of the Honegg–Napf palaeoriver was succeeded by a period of downcutting. The increasing abundance of flysch clasts during the third stage, between 20 and 14 Ma, suggests that the location of major erosional denudation shifted further north, leading to enhanced exhumation of the Penninic lid. Indeed, because the sedimentary cover of the Penninic nappes were detached from its crystalline basement and thrusted further northward during nappe emplacement prior to 35 Ma (Schmid *et al.*, 1996), any petrographic shift towards predominance of Penninic/Ultrahelvetic sedimentary clasts indicates a northward shift of the location of major erosional denudation.

The determination of the source terranes of the conglomerates of the Rigi–Höhronen palaeoriver (Fig. 5) is guided by the occurrence of siliceous clasts, the presence of clasts of red granite and polymict conglomerates that are referred to as Mocausa Conglomerates, the occurrence of low-grade crystalline clasts, and by geochemical analysis of radiolarites (Müller, 1971; Stürm, 1973). According to the petrographic data of Stürm and Müller, the erosional hinterland of this palaeoriver system was most likely the Prealps (siliceous limestone, radiolarite and Mocausa Conglomerate clasts), the Austroalpine crystalline nappes (red granites and low-grade crystalline rocks) and the Penninic crystalline nappes (low-grade crystalline rocks). The source terrane of the dolomite clasts is not known. The petrographic evolution that is characterized by the occurrence of predominantly clasts from the Prealps prior to 27 Ma, the first appearance of Austroalpine crystalline rocks at 26 Ma (red granites) and the predominance of low-grade crystalline clasts (?Austroalpine and/or ?Penninic nappes) in the early Miocene (Fig. 4) suggests that the drainage system of the Rigi–Höhronen palaeoriver evolved by southward expansion prior to 27 Ma, followed by downcutting of the Alpine edifice (Fig. 1B). Alternatively, this petrographic evolution can be interpreted as the result of erosional downcutting from the sedimentary cover of the orogenic lid to its crystalline basement. We prefer the first interpretation for the following reasons. First, erosion and deposition of Austroalpine red granites post-dates the first appearance of siliceous limestone clasts and radiolarite clasts derived from the Prealps by >0.5 Myr (Stürm, 1973; Schlunegger *et al.*, 1997a). Second, the northern tip of the Austroalpine crystalline nappes was located south of the tip of the Prealps according to structural restorations (Pfiffner, 1986). This implies that because the Prealps are overthrust by the Austroalpine nappes (Fig. 1), the stratigraphic succession of clasts as outlined above reflects a southward expansion of the catchment area of the Rigi–Höhronen palaeoriver. Note that the drastic shift towards predominance of crystalline clasts in the conglomerates of the Rigi–Höhronen palaeoriver at $\approx$24–22 Ma (Fig. 4) contrasts with the continuous increase of Penninic crystalline clasts recorded in the contemporaneous deposits of the Honegg–Napf palaeoriver.

The petrographic data suggest that the catchment area of the Beichlen and Honegg–Napf palaeorivers is almost identical with that of the present-day Alpine Rhône river (Figs 2 and 5). As outlined above, its southern source terrane consists of the erosional remnants of Austroalpine nappes, and the ophiolites and the Bernhard nappe that form the hangingwall of the Simplon fault. The southernmost border of the source terrane of the Rhône river nearly coincides with the 20 Ma Vanzone backfold. The source area to the north consists of sedimentary nappes (Helvetic nappes and the piggy-back stack of the Prealps) that form the footwall of the Simplon fault. Prior to 15 Ma, however, the Helvetic nappes were completely covered by the Ultrahelvetic flysch, the North Penninic flysch and the Prealps as indicated by the absence of Helvetic clast types (Matter, 1964).

The headwaters of the Rigi–Höhronen palaeoriver comprised the area that surrounds the Forcola normal fault as well as the Penninic schists and flysch nappes. If this conclusion is correct, then the headwaters of the Rigi–Höhronen palaeoriver can be located in a similar or at least comparable region as the catchment area of the present-day Rhein river (Figs 2 and 5).

Reconstruction of the evolution of the drainage network of the central Swiss Alps between 30 Ma and present: source rock lithologies and tectonics

In the following section, we reconstruct the evolution of the drainage network of the central Alps between 30 Ma and the present. We determine the location of the drainage divides for different time intervals. This reconstruction is guided by the configuration of the present-day drainage network (Fig. 2) and by the stratigraphic, petrographic and tectonic data from the Alps/Molasse Basin system. However, a complete discussion of the evolution of the drainage network requires information about sequential restorations of the orogen. In this paper we use the palinspastic reconstructions of Burkhard (1988) and Schmid *et al.* (1996) for the western and the eastern part of the study area (Figs 1 and 6A,B), respectively. These restorations were performed using (i) cross-cutting relationships between thrusts/faults and temporally calibrated metamorphic fabrics, (ii) cooling ages and an average geothermal gradient of $\approx 30\,^{\circ}\mathrm{C\,km^{-1}}$ (e.g. Schlunegger & Willett, 1998) to estimate exhumation rates and (iii) data about the ages when maximum P–T conditions were reached. Combining and synthesizing the sedimentological and structural information from the Alps/NAFB system as outlined above we discuss and reconstruct a qualitative forward model that relates the evolution of the major Alpine structures and their overlying units to the petrographic and sedimentological evolution of the Molasse from 30 Ma to the present.

Situation between 30 and 25 Ma

The configuration of the Alpine drainage network between 30 and 25 Ma is depicted in Fig. 7. The Penninic and Austroalpine nappes have already been emplaced (Burkhard, 1988), enhanced backthrusting along the Insubric Line was initated prior to 30 Ma in the eastern Swiss Alps (Cressim backfold) and continued between 30 and 25 Ma in the same area (Fig. 6B). In the southwestern Swiss Alps, backfolding of the rear of the wedge (Vanzone backfold) was initiated prior to 25 Ma, and SW-directed slip of the hangingwall of the Simplon detachment fault started at $\approx$25 Ma (Fig. 6A). Also at 25 Ma, the tip of the wedge was located $\approx$35 km and $\approx$25 km south of the present-day western and eastern Alpine front, respectively.

Shortly after 30 Ma, the phase of southward expansion of the Rigi–Höhronen system was succeeded by a period of downcutting, implying that its headwaters reached the hinge of the Cressim backfold near the Bergell pluton in the late Oligocene at 25 Ma (e.g. Schlunegger *et al.*, 1997a). This interpretation is supported by the palinspastic restoration of the eastern Swiss Alps (Fig. 6B), which

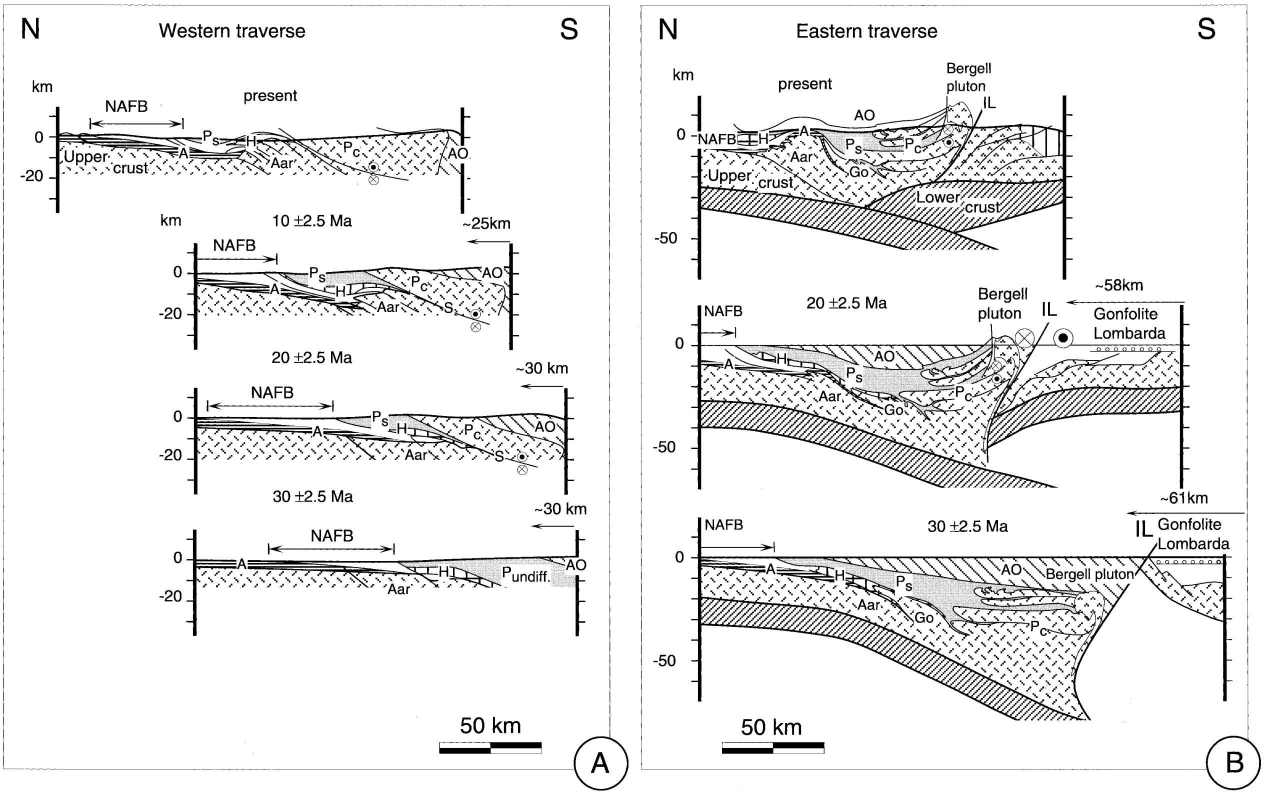


Fig. 6. Structural evolution of the Alps in (A) the west and (B) the east of the study area (Fig. 1). The sequential palinspastic restorations are taken from Burkhard (1988) and Schmid *et al.* (1996) for the western and the eastern transect, respectively. The sequence of motion along the major thrusts was assessed by these authors using cross-cutting relationships between structures and temporally calibrated metamorphic fabrics. A = autochthonous, Ps = Penninic sedimentary nappes and flysch nappes, Pc = Penninic crystalline nappes, P_{undiff} = undifferentiated Penninic and Ultrahelvetic units, H = Helvetic nappes, Aar = Aar massif, AO = Austroalpine nappes, IL = Insubric Line, NAFB = North Alpine Foreland Basin.

suggests that enhanced rates of backthrusting along the Insubric Line increased the topographic gradient between the NAFB and the hinge of the Cressim backfold. As a result, the catchment area of the Rigi–Höhronen palaeoriver expanded southward, causing first enhanced exhumation of the Prealps in the north (predominance of sedimentary clasts) and then the crystalline core of the Alps further south (appearance and predominance of Austroalpine and/or Penninic crystalline clasts after 26 Ma; Figs 6B and 7). However, between 30 and 25 Ma, the headwaters of the Honegg–Napf palaeoriver continued to expand southward from the area of the Prealps toward the hinge of the Vanzone backfold as indicated by the ongoing increase of crystalline clast types in the conglomerates. We interpret that the along-strike heterochroneity in the dynamics of the north Alpine palaeorivers was caused by the fact that backthrusting and backfolding were time transgressive from east to west (Burkhard, 1988; Schmid *et al.*, 1996; Fig. 6)

Situation between 25 and 20 Ma

Between 25 and 20 Ma, the tip of the wedge propagated ≈ 5–20 km (western and eastern part, respectively) further north-west from its position at 30–25 Ma, and the Austroalpine and Penninic nappes were passively emplaced as piggy-back units (Figs 6 and 8). Also between 25 and 20 Ma, extension along the Simplon detachment fault caused initial tectonic exhumation of the Lepontine dome (vertical hatch pattern, Fig. 8; Grasemann & Mancktelow, 1993; Schlunegger & Willett, 1998). Furthermore, S-vergent backfolding in the east and formation of the Cressim backfold was completed at 20 Ma (Fig. 6B), and formation of the Vanzone backfold due to S-vergent backthrusting in the west continued (Fig. 6A). Finally, exhumation of the eastern Aar massif was initiated during this time interval (Fig. 6B; horizontal hatch pattern on Fig. 8).

We interpret that ongoing backthrusting along the Insubric Line and the associated formation of the Vanzone anticline continued to increase the topographic gradient between the foreland basin and the rear of the wedge in the west (Fig. 6A). As a result, the Honegg–Napf palaeoriver continued to shift its location of major erosional denudation southward. However, this ongoing southward shift of the area of major erosion was associated with downcutting, as indicated by the fact that the first appearance of quartzites from the Bernhard nappe post-dates the abundant occurrence of Austroalpine clasts (Fig. 4).

As outlined above, we speculate that exhumation of the Lepontine dome caused a ≈ 50-km northward shift of the major drainage divide and a distinct separation of

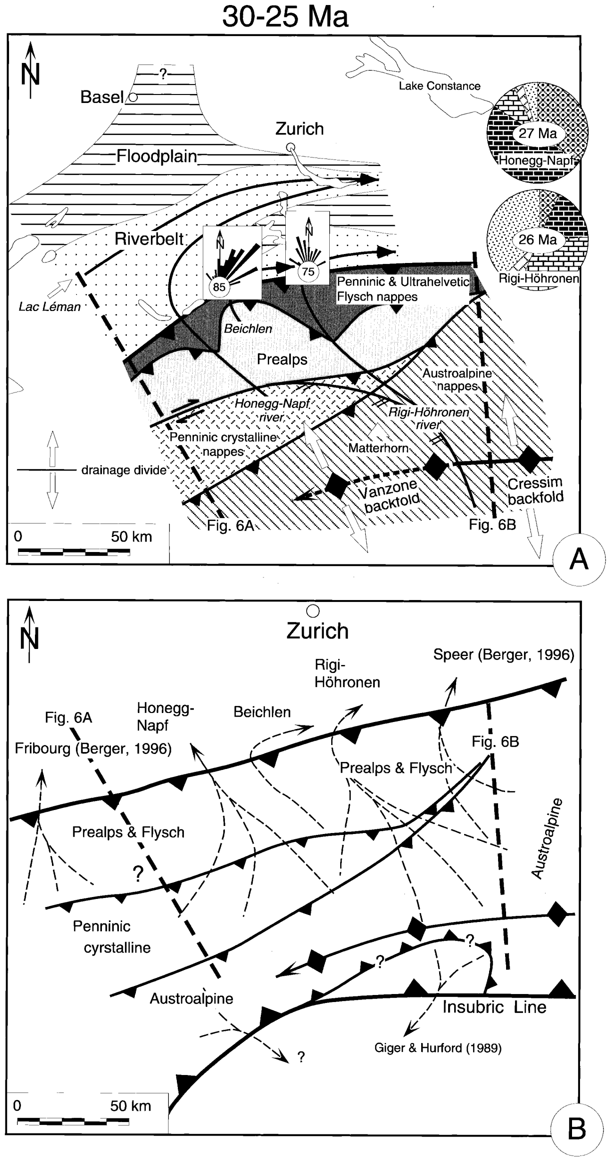


Fig. 7. (A) Palaeogeographical sketch showing the drainage network of the Alps/Molasse Basin between 30 and 25 Ma. Note that the Vanzone and Cressim backfolds are interpreted to have formed the drainage divide between north and south. See Fig. 3 for legend of the conglomerate clast composition. (B) Sketch of the Alpine drainage network between 30 and 25 Ma. The point of entry of the Fribourg and Speer palaeorivers into the basin is taken from Berger (1996). The source terrane of the Fribourg palaeoriver is not known. The determination of the catchment area of the Speer palaeoriver is discussed by Habicht (1945) and Frei (1979).

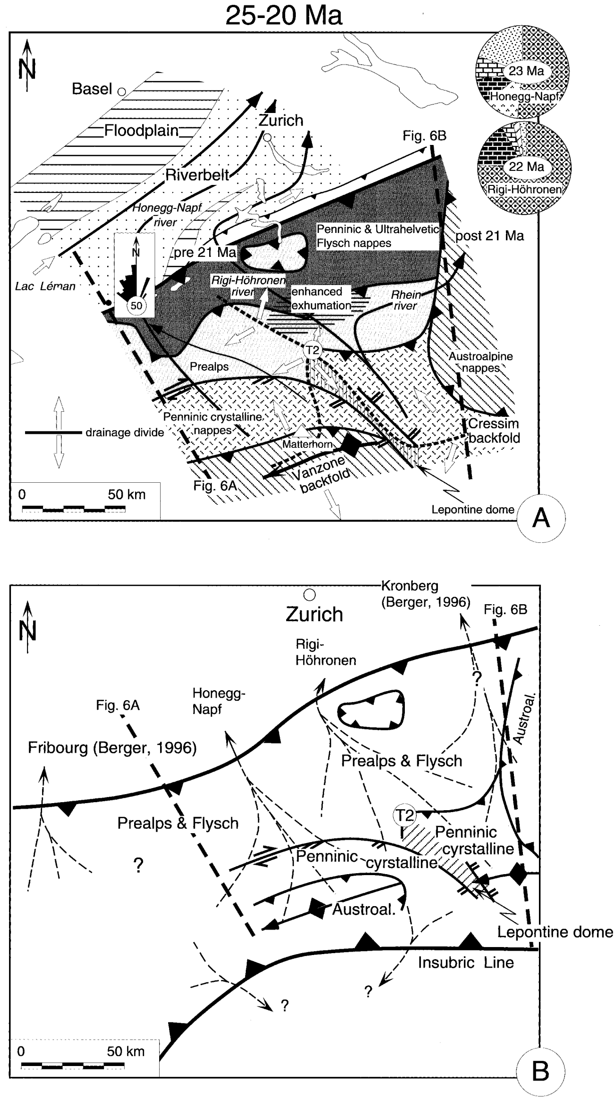


Fig. 8. (A) Palaeogeographical sketch showing the drainage network of the Alps/Molasse Basin between 25 and 20 Ma. Note that slip along the Simplon detachment fault caused a northward shift of the major drainage divide between the north and the south, and the formation of the triple junction T2. Initial exhumation of the Aar massif in the east is thought to have controlled the eastward deviation of the Rigi–Höhronen palaeoriver. See Fig. 3 for legend of the conglomerate clast composition. (B) Sketch of the Alpine drainage network between 25 and 20 Ma. The point of entry of the Fribourg palaeoriver into the basin is speculative (e.g. Berger, 1996), and determination of the source terrane of this palaeoriver is not known. See Fig. 8(A) for legend.

the catchment areas between the Honegg–Napf and the Rigi–Höhronen palaeorivers (formation of triple junction T2, Fig. 8). Indeed, because the Simplon fault dips towards the south-west (Fig. 6A), displacement along this fault is likely to have resulted in a northward shift of the major drainage divide provided that the rate of slip along the Simplon fault was significantly greater than the rate of erosion of the hanging- and footwall. Indeed, whereas the rate of slip was >1000 m Myr^{-1} according to 2D thermal models (Grasemann & Mancktelow, 1993), surface erosion rates were presumably ≤ 400 m Myr^{-1} as suggested by 1D thermal models of cooling and erosion (Schlunegger & Willett, 1998). Furthermore, whereas both palaeorivers carried similar clast types prior to ≈ 27 Ma (dolomites, siliceous limestones, sandstones), their post-27 Ma conglomerates significantly differ in terms of the first appearances of key clasts and the relative abundances of identical clast types (Fig. 4; Stürm, 1973; Schlunegger *et al.*, 1993). However, we think that because the detachment faults in the east dip towards the north-west, extension in this part of the orogen did not cause a N–S shift in the location of the major drainage divide. We think that extension and normal faulting in the catchment area of the Rigi–Höhronen palaeoriver between the Turba and Forcola normal faults is likely to have resulted in exposure of low-grade crystalline units in the rear of the orogenic wedge. As a result, this phase of deformation may have caused the drastic petrographic change between ≈27 Ma and ≈22 Ma in the conglomerates of the Rigi–Höhronen palaeoriver towards predominance of low-grade crystalline clasts (Fig. 4).

Initial exhumation of the eastern Aar massif and its overlying units (horizontal hatch pattern) is likely to have resulted in an eastward shift of the course of the Rigi–Höhronen palaeoriver (e.g. Schlunegger *et al.*, 1997a). This interpretation is supported by stratigraphic data from the Molasse Basin, as indicated by the first-appearance of detritus from the catchment area of the Rigi–Höhronen palaeoriver ≈70 km further east prior to 20 Ma (O. Kempf, personal communication 1996).

Situation between 20 and 16 Ma

Between 20 and 16 Ma, the tip of the orogenic wedge shifted ≈5–20 km (eastern and western part, respectively) further north-west (Fig. 9). Also between 20 and 16 Ma, additional slip occurred along the Simplon fault. According to 2D thermal models, rates of slip along the Simplon fault were greatest between 18 and 15 Ma (Grasemann & Manktelow, 1993). At 20 Ma, exhumation of the western part of the Aar massif and the Aiguilles Rouge and Mont Blanc massifs was initiated (Fig. 6A). In the east, the Aar massif experienced enhanced exhumation rates during this time interval (Fig. 6B).

We interpret that ongoing exhumation of the Lepontine dome by slip along the Simplon fault (Grasemann & Mancktelow, 1993) resulted in an ongoing north-westward shift of the drainage divide between the southern Alpine palaeorivers and the Honegg–Napf palaeoriver. This north-westward shift in the drainage divide is likely to have changed the configuration of the drainage basin of the Honegg–Napf palaeoriver. Indeed, a northward shift of the catchment area towards the region of the Penninic and Ultrahelvetic flysch nappes that covered the Aar massif at that time (Figs 8 and 9) is likely to explain the petrographic shift towards higher contribution of flysch clasts in the conglomerate clast population (Fig. 4). This scenario in turn would explain initiation of a phase of high exhumation rates in the Aar massif at that time (e.g. Pfiffner *et al.*, 1997).

Situation between 16 Ma and the present

Somewhere between 16 Ma and the present, shortening with a horizontal displacement of ≈25 km occurred in the Jura Mountains (Fig. 6A; Pfiffner *et al.*, 1997). Also

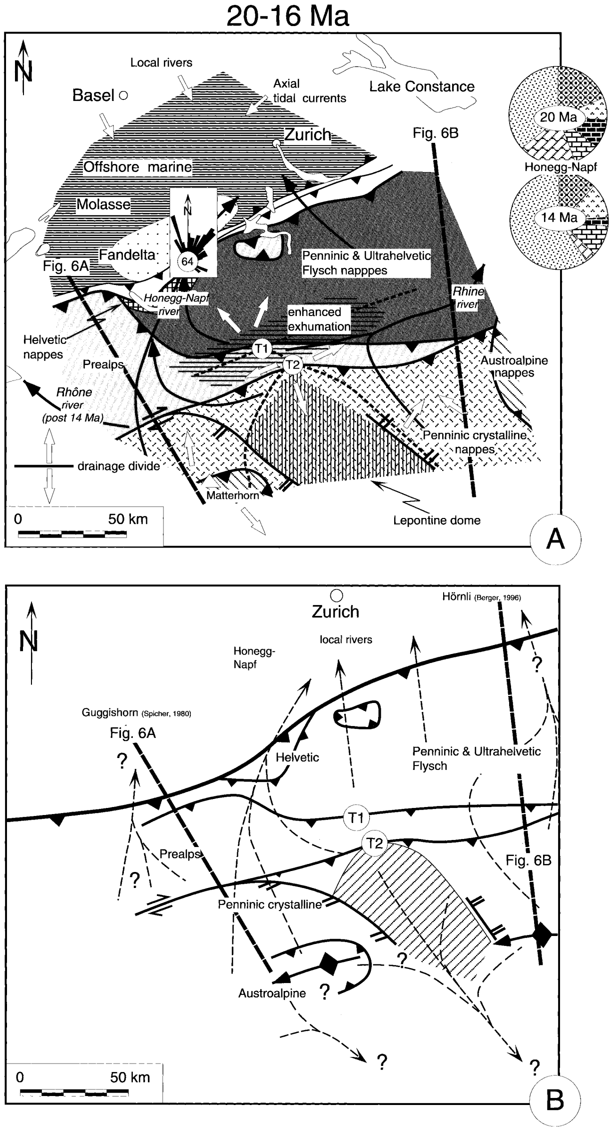


Fig. 9. (A) Palaeogeographical sketch showing the drainage network of the Alps/Molasse Basin between 20 and 16 Ma. Enhanced exhumation of the Aar massif in the west is thought to have controlled the formation of triple junction T1 and the westward deviation of the Honegg–Napf palaeoriver somewhere after 14 Ma. Because the planes of the Turba and Forcola normal faults dip towards the north-east, extension along these faults is interpreted not to have caused a northward shift of the drainage divide. See Fig. 3 for legend of the conglomerate clast composition. (B) Sketch of the Alpine drainage network between 20 and 16 Ma. The point of entry of the Hörnli palaeoriver into the basin is speculative. See Fig. 9(A) for legend.

during the last 16 Myr, the external massifs experienced enhanced rates of crustal thickening and exhumation as indicated by apatite fission track data and cross-cutting relationships between temporally calibrated metamorphic fabrics and structures (Michalski & Soom, 1990; Pfiffner *et al.*, 1997). Finally, the Molasse Basin started to be dissected and eroded (see above).

We propose that enhanced exhumation and the associated uplift of the external massifs significantly changed the course of the Honegg–Napf palaeoriver to the orientation of the Rhône river. This means that uplift of the western Aar massif is likely to have caused the formation of triple junction T1 and a westward deviation of the Honegg–Napf palaeoriver. Similarly, the 90° rotation of the course of the Rhône river at the north-eastern termination of the Mont Blanc and Aiguilles Rouge massifs suggests that uplift of these units controlled the change of the flow direction of this river.

The formation of the drainage divide that crosses the Molasse Basin at a right angle north-east of Geneva might be the result of Quaternary glaciation that caused Lake Geneva to form (e.g. Spicher, 1980). Alternatively, it might be linked to shortening in the Jura Mountains. According to Burkhard (1988) and Pfiffner *et al.* (1997), deformation of the Jura Mountains was probably caused by final convergence between the Adriatic and the European plates. The latter authors suggested that final crustal convergence and shortening in the core of the Alps was transferred to the Jura Mountains along a SE-dipping thrust. They concluded that slip along this thrust is likely to have translated and uplifted the Molasse Basin. If this hypothesis is true, then along-strike differential shortening in the Jura Mountains and differential slip along the hypothesized thrust plane beneath the Molasse Basin is likely to have caused (i) differential tilt of the basin (e.g. Lemcke, 1974), (ii) erosion and downcutting of Molasse deposits and (iii) the establishment of a water divide north of Lake Geneva provided that a lateral ramp exists on the fault. Indeed, the amount of shortening in the Jura Mountains increases between Basel and the area of Lake Geneva (Fig. 1), and then decreases further west (e.g. Steck & Hunziker, 1994; Laubscher, 1996).

CONCLUSIONS

The integration of stratigraphic and structural information in four dimensions as presented in this paper reveals that drainage networks are the result of complex interactions between lithospheric and surface processes that were modifying the topography. Specifically, this work suggests that lithospheric thinning by crustal extension in a compressional system is a major control on the location of the drainage divide and hence on the development of the drainage network. This aspect has been ignored in most previous studies. Finally this paper provides a basis for estimating the areas of individual catchments in the erosional hinterland. If this database is combined with maps of cooling rates that can be converted into exhumation maps, and with evaluations of the relative importance of tectonic vs. erosional exhumation (Grasemann & Mancktelow, 1993), we will be able to estimate the volumes of material that were supplied to the adjacent foreland basins.

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