Evolution of the Alpine foreland basins

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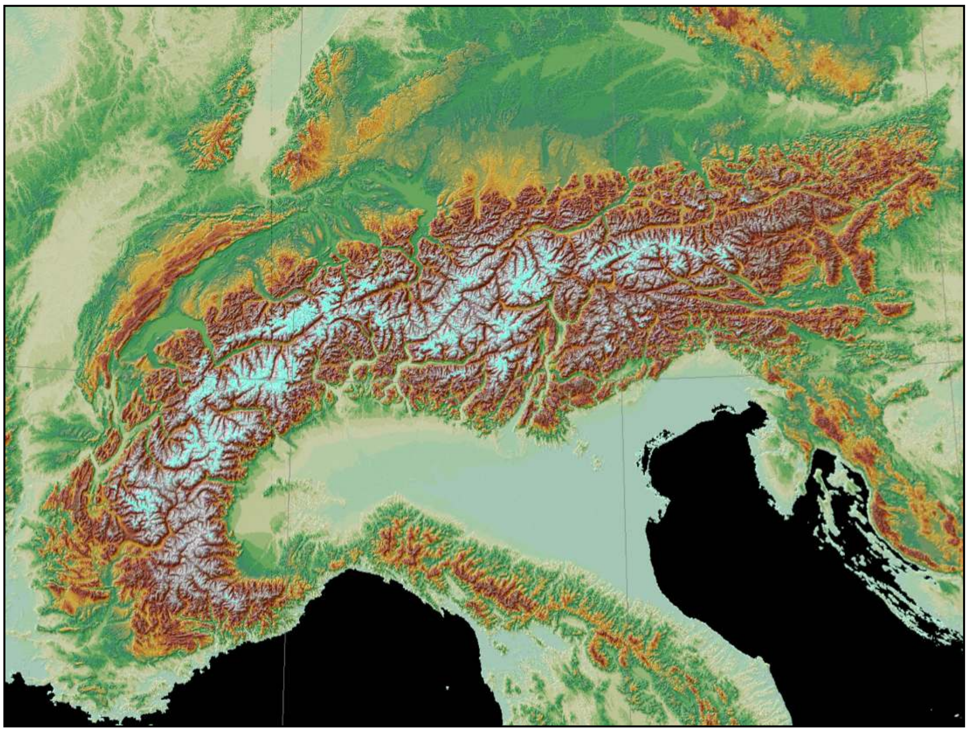
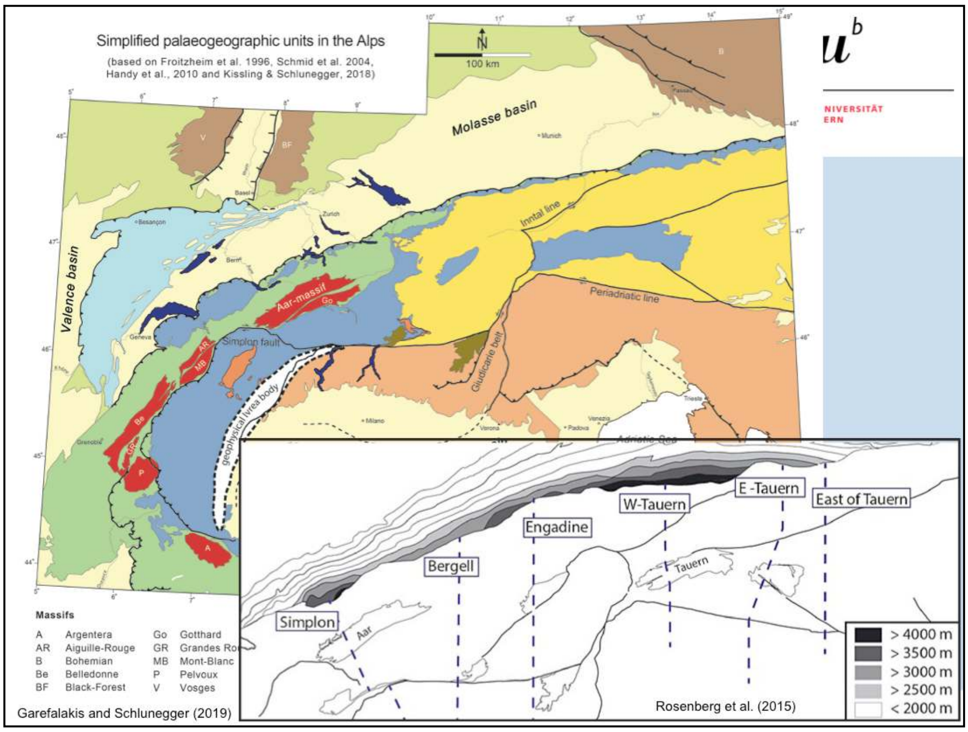
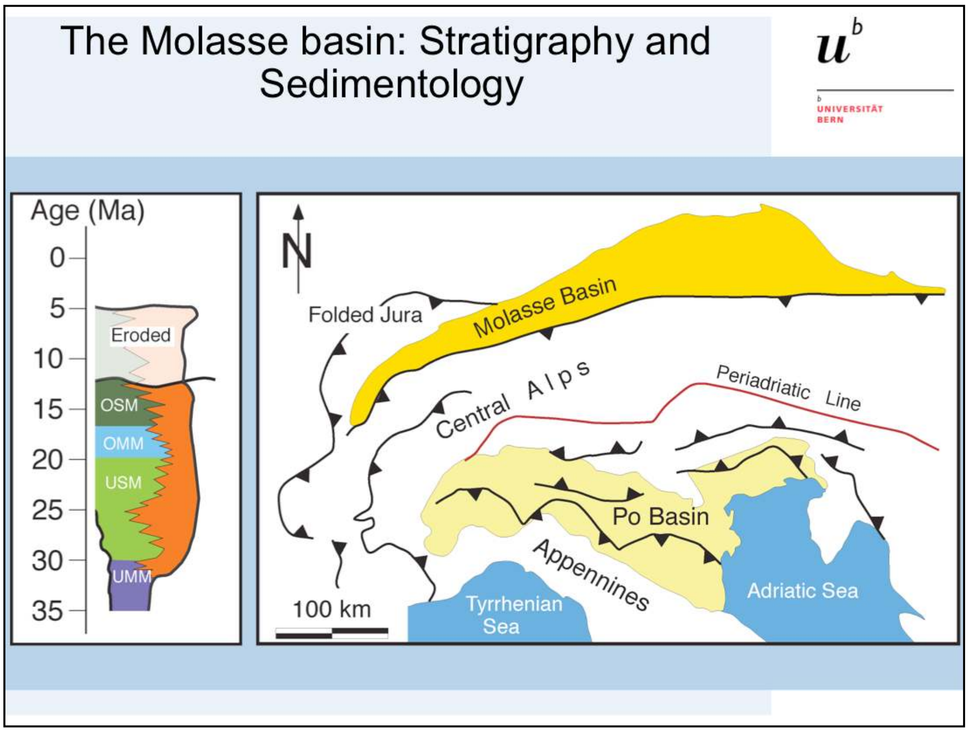


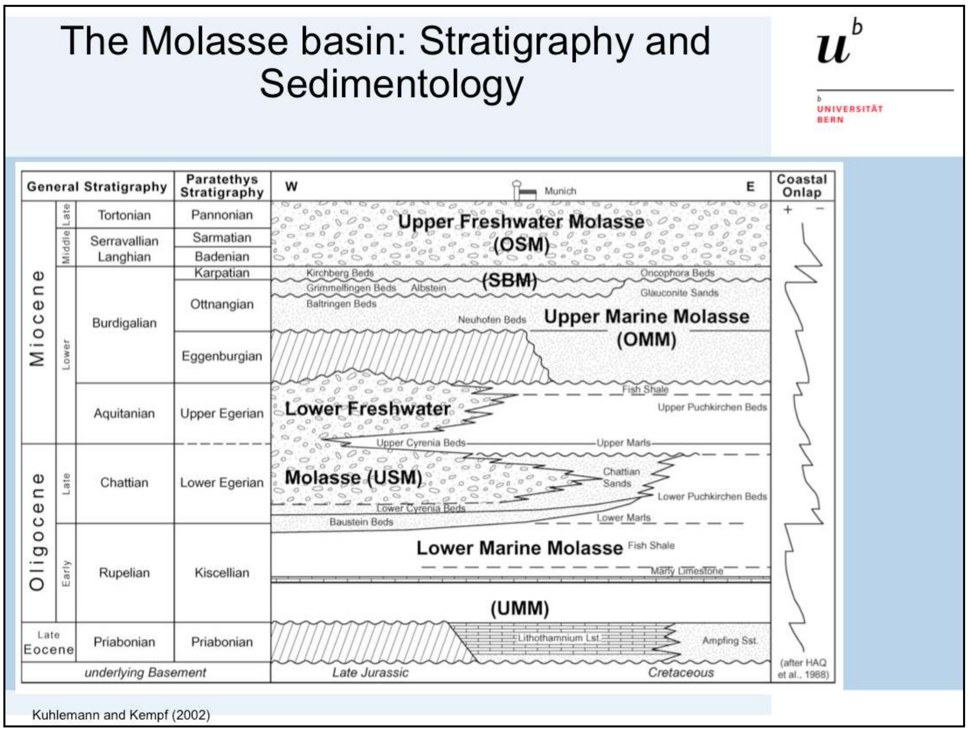
The European Alps are bordered by two foreland basins situated on the northern and the southern sides (Molasse and Po basins). While the Molasse basin in the north has been dissected by streams and thus displays a substantial local relief, the Po basin on the southern side is mainly flat. This suggests that the Molasse basin experiences uplift and erosional recycling, while the Po basin still subsides and acts as sedimentary trough. This then leads to the question about the timing and the mechanisms leading to the uplift and erosion of the Molasse basin, which will be one aspect to be discussed.



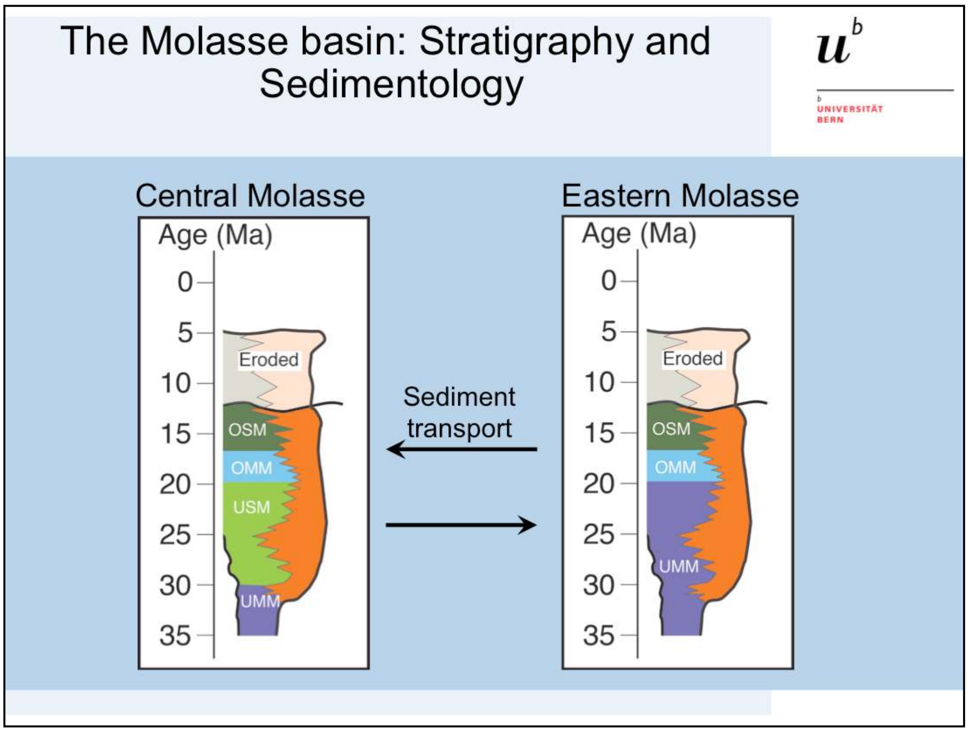
The Molasse basin itself shows distinct along-strike differences. It is a broad > 100 km-wide basin in the east, from where it narrows to a few tens of kilometers to the west. In cross-sections, the foreland plate dips towards the SE at a relatively steep angle in the west, while the dip angle of the plate underneath the Eastern Molasse basin is shallower. The bordering Alps themselves also display along-strike differences in architectural style: the Eastern Alps have still maintained their orogenic lid made up of the Austroalpine sedimentary cover nappes, while this unit has largely been eroded in the west, and high-grade rocks are exposed particularly in the Lepontine area in the Central Alps.



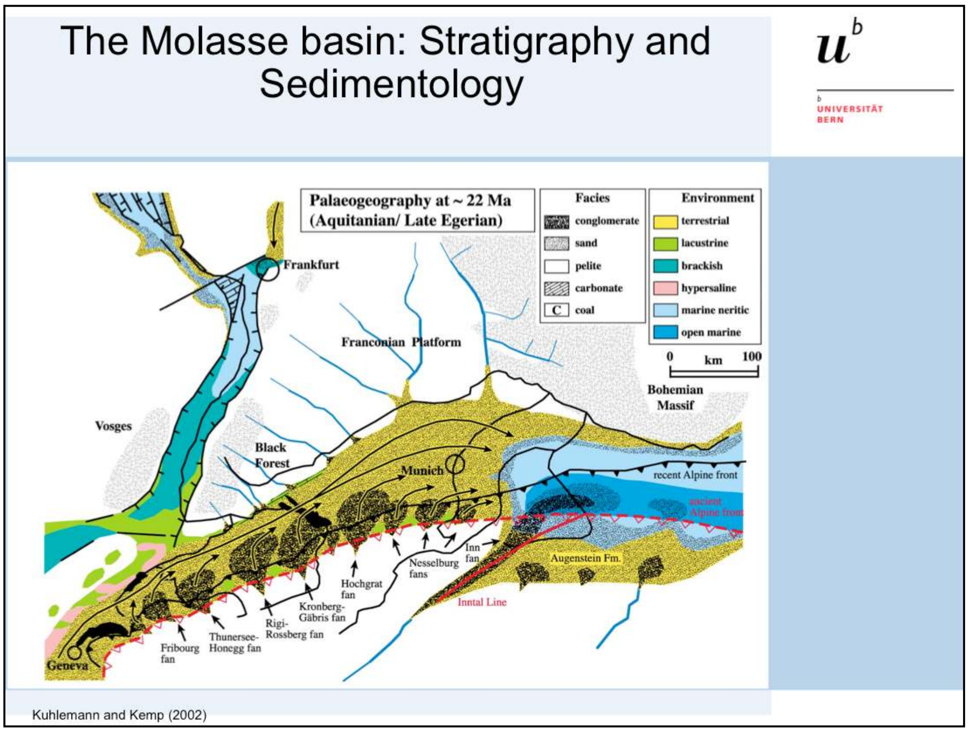
The stratigraphy of the Molasse basin can be categorized into two large-scale shallowing- and coarsening-upward sequences, at least in its central part. The first megasequence starts with Flysch-type sedimentation of the North Helvetic Flysch and the Lower Marine Molasse group (UMM). The sequence ends with the fluvial deposits of the Lower Freshwater Molasse group (USM). This first megasequence thus includes the shift from the underfilled to the overfilled stage of foreland basin evolution, which occurred at 30 Ma. The second megaseqeunce follows upon the Burdigalian transgression at 20 Ma and includes the shallow marine deposits of the Upper Marine Molasse group (OMM) and the terrestrial sequences of the Upper Freshwater Molasse group (OSM). The youngest preserved sediments in the central Molasse basin are c. 14 Ma old, but Cederbom et al. (2011) could show that sedimentation continued until c. 5-10 Ma. At that time, the basin was uplifted, and the previously deposited material was eroded and recycled.



The basin fill discloses a different stratigraphic architecture farther to the east, where the first regressive sequence and the shift from basin underfill to overfill at 30 Ma is not recorded. Instead, deep marine and turbidtic sedimentation prevailed until c. 20 Ma, when shallow marine conditions stared to establish across the entire basin (Upper Marine Molasse, OMM).

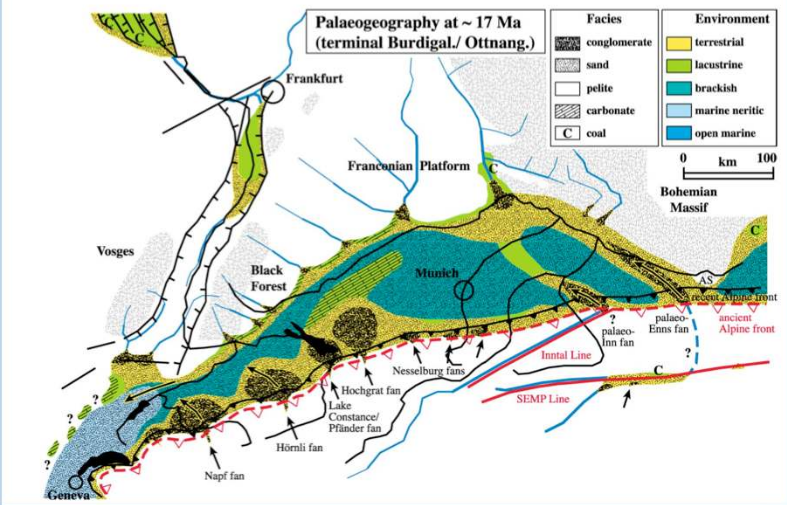


In comparison, while the central Molasse basin became overfilled at 30 Ma when terrestrial sedimentation started, the Molasse basin in the east maintained its underfilled Flysch-type character when deep marine deposits accumulated until c. 20 Ma. This was also the time period (30-20 Ma) when sediment transport occurred from the Central Molasse towards the Eastern Molasse basin. The situation then changed at 20 Ma: The Molasse basin in the east became shallower, and a peripheral sea with strong tidal currents occupied the entire basin on the northern margin of the Alps. Also at 20 Ma, the direction of sediment transport changed towards the opposite direction, i.e., from the east to the west.



The paleogeographic maps by Kuhlemann and Kempf illustrate the situation: Terrestrial conditions established in the Central Molasse basin at 30 Ma and remained so until 20 Ma, while deep marine conditions prevailed in the Eastern Molasse basin.

The Molasse basin: Stratigraphy and Sedimentology



Kuhlemann and Kempf (2002)

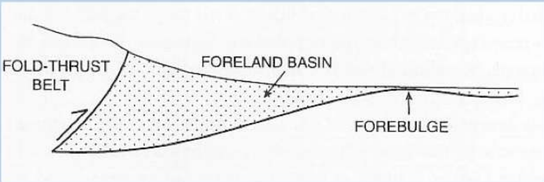
After 20 Ma, the basin became successively filled in the east, and discharge directions shifted towards the west.

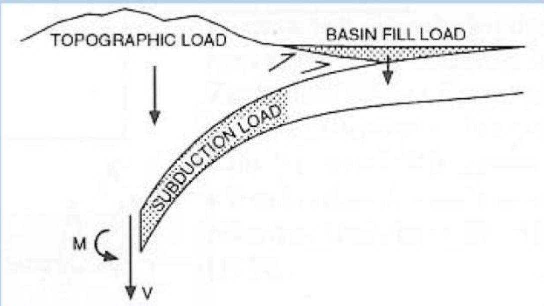
The Molasse basin: Stratigraphy and Sedimentology

- Stratigraphic change from Flysch to Molasse stage at 30 Ma
- Reversal of drainage direction at 20 Ma, paired with the transgression in the Central Molasse and a shallowing-up in the Eastern Molasse
- Uplift and erosion of the Molasse basin starting at 5-10 Ma

The first order changes in the Molasse basin thus include (i) the shift form basin underfill to overfill at 30 Ma in the central part while deep marine sedimentation prevailed in the east, (ii) the reversal of the drainage direction at 20 Ma, paired with the transgression in the Central Molasse and a shallowing-up in the Eastern Molasse, and (iii) a period of uplift and erosion of the entire Molasse basin starting at c. 5-10 Ma. There is growing evidence that these changes were driven by lithospheric scale processes and related changes in the loading underneath the Alps, which will be discussed in the following.

Mechanisms of foreland basin formation





$$\alpha = \sqrt[4]{\frac{4D}{(\rho_m - \rho_{w/s})g}}$$

$$\text{Basin width} = \frac{\pi}{2}\alpha$$

$$\text{Basin depth} = \frac{V \times \alpha^3}{4D}$$

D: Flexural rigidity

V: Load

Turcotte and Schubert (1982); DeCelles and Gilles (1996)

The allocation of the loading and changes thereof is not obvious, at least for stratigraphers. In this context, the formation of accommodation of a foreland basin can occur in response to thrusting leading to topographic loads. Alternatively, slab load forces, or subduction loads, can lead to a bending moment and/or to a vertical downwarping of the foreland plate. In addition, horizontal forces can also cause a buckling of the plate and the formation of a trough. Accordingly, multiple mechanisms are capable to form a flexural trough and thus a foreland basin.

Conceptual investigations have shown that the wavelength of a flexural basin depends on the flexural strength and thus on the flexural rigidity (D) only, while the amplitude of the deflection and thus the depth of a basin depends on both the flexural rigidity and the magnitude of the applied loads (V).

Thrusting, loading, erosion, and stratigraphic responses

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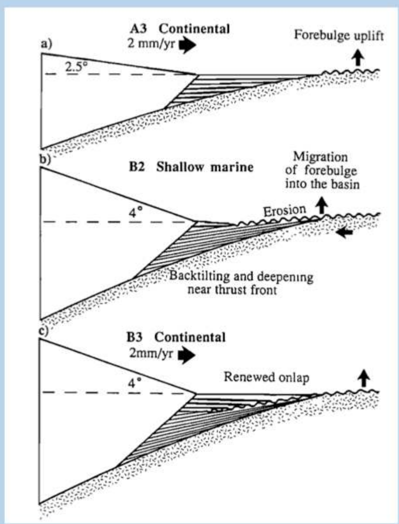
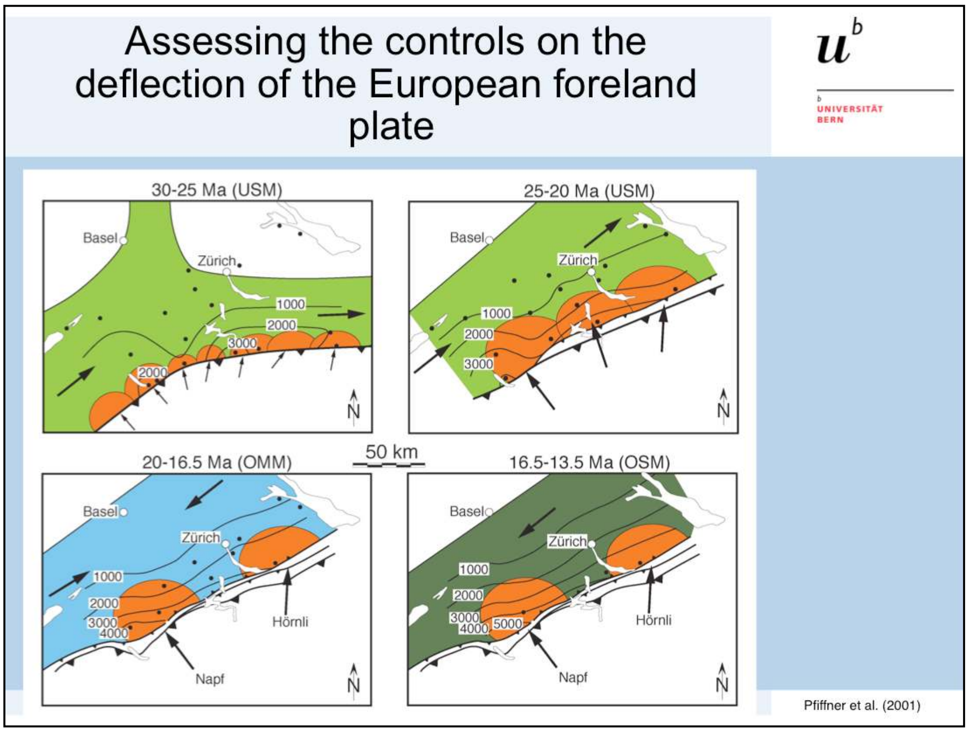


- *Lower Freshwater Molasse:* Large erosional unloading results in a redistribution of loads from the orogen to the foreland
- *Upper Marine Molasse:* Orogenic loading in the Aar massif results in a downwarping of the plate and in a marine transgression
- *Upper Freshwater Molasse:* Continued erosional unloading causes a regression

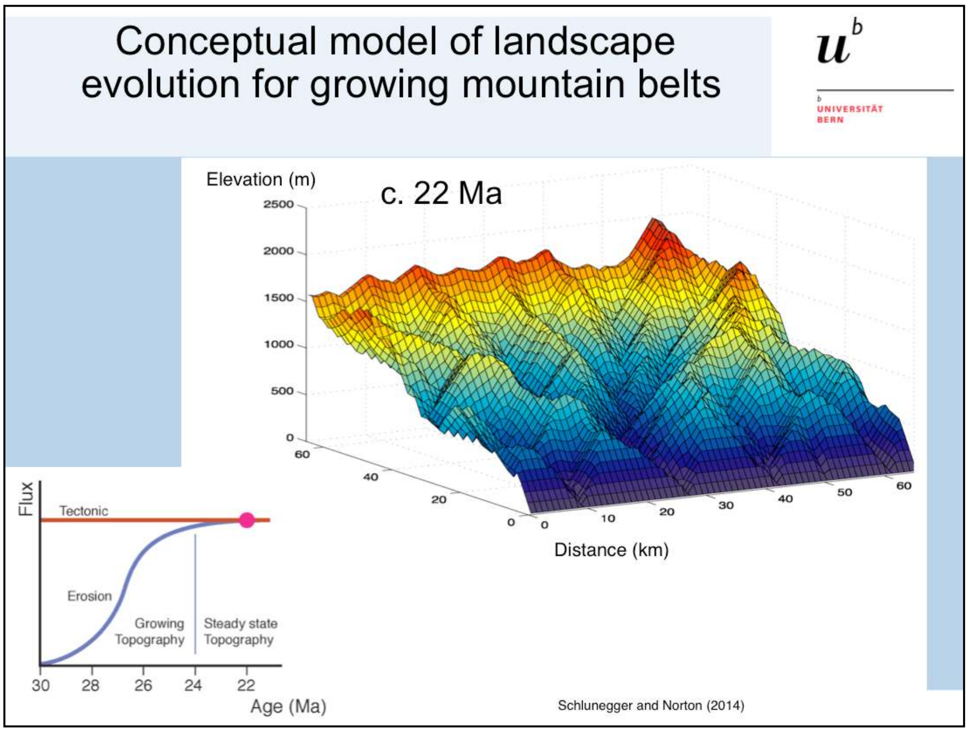
Sinclair et al. (1991)

Changes in topographic loading and related stratigraphic responses have conventionally been applied by nearly all stratigraphers (e.g., Jordan and Flemings, 1990; Sinclair et al., 1991; Jordan and Flemings, 1991; Schlunegger et al., 1997, and many more) using a model that links thrusting and erosion in the orogen with the flexural response of the adjacent foreland basin. Such a model has been employed to explain, for instance, the Burdigalian transgression in the Central Molasse basin.

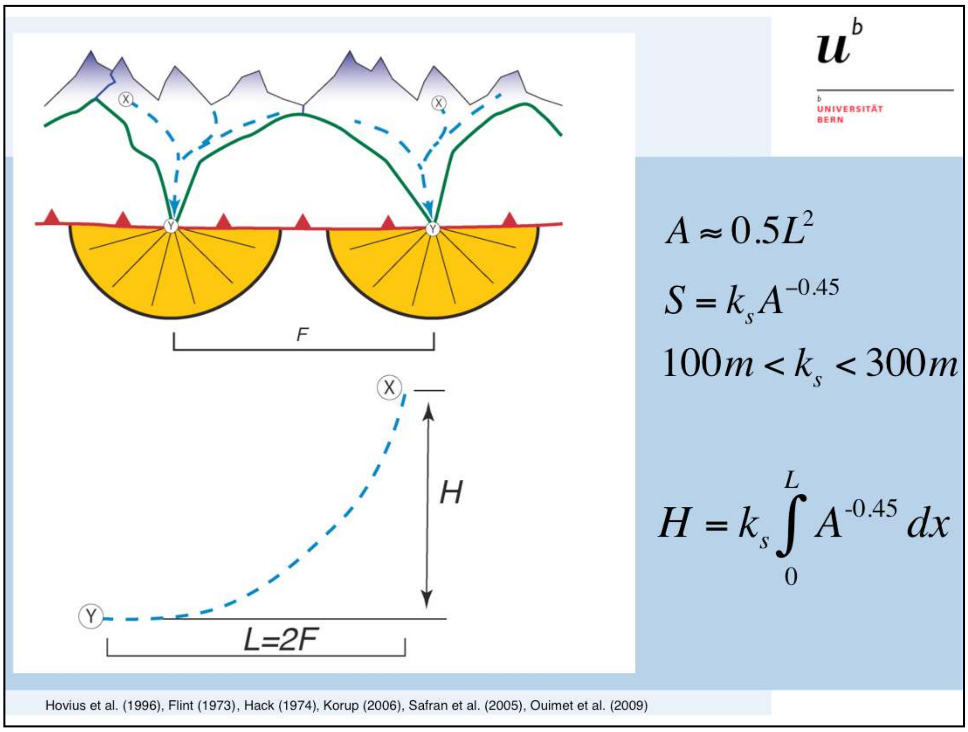


As a first step, we wanted to determine whether we have to primarily consider changes in the surface loading for the deflection of the foreland plate, as has usually been inferred by stratigraphers, or whether we need to consider slab loads. Here, we employed information preserved by the stratigraphic record particularly from the Central part of the Molasse basin. The restoration illustrates (i) locations where stratigraphic data is available (black circles), (ii) the conglomerate fans situated the proximal basin border, and (iii) the cumulative thickness of deposited material as isopachs. We can make three major observations: (i) a reduction in the number of fans through time paired with a larger spacing between the fans and a broader width of the fans; (ii) the flexural wavelength of the basin remained stationary while the amplitude of the deflection increased. This suggests that the loading was increasing as well, either through the formation of a larger topography, or through a greater contribution of slab loads.

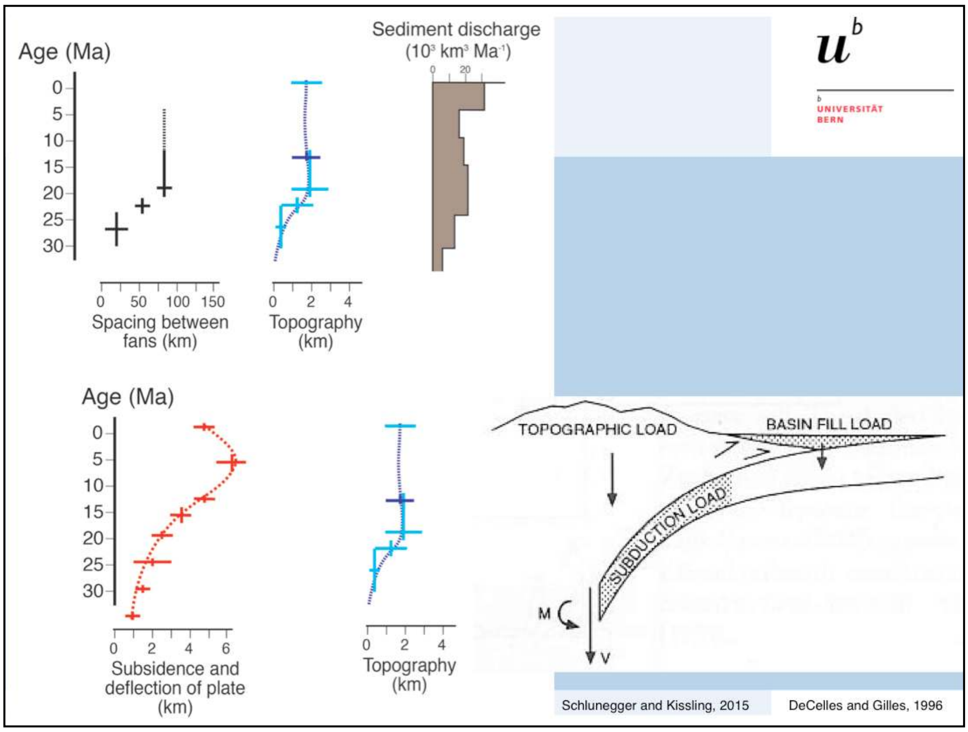
We used some basic principles from geomorphology to test the hypothesis whether a larger topography, and thus greater topographic loads, can be invoked to explain the increasing deflection through time. In this context, the spacing between individual fans bears key information to reconstruct how the surface topography in the adjacent Alps might have changed.



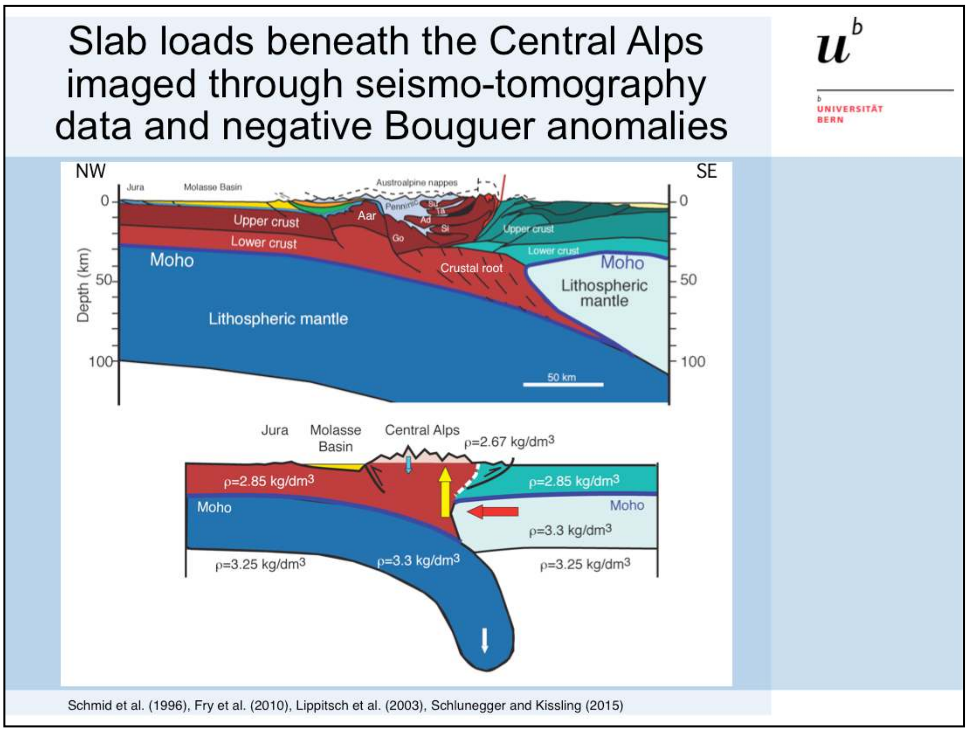
This example illustrates, from a theoretical point of view, how a landscape can evolve for the simplest case of a uniform block uplift at a constant rate, and for the consideration of advection (erosion rates proportional to slope and water discharge) and diffusion (erosion rates proportional to the curvature of the surface topography) as erosional processes in channels and on hillslopes (Tucker and Slingerland, 1997). The model predicts that streams respond through the combination of (i) headward erosion, (ii) cannibalization and (iii) enlargement of the drainage basin of competitive streams. Headward erosion continues until the drainage divide has been reached. At that point, the landscape has reached a steady state where crustal uplift is fully compensated by surface erosion. In the foreland basin, we expect a decrease in the number of fans, an increase in the spacing between individual fans and an increase in the supply rates of sediment until the topographic steady state has been reached.



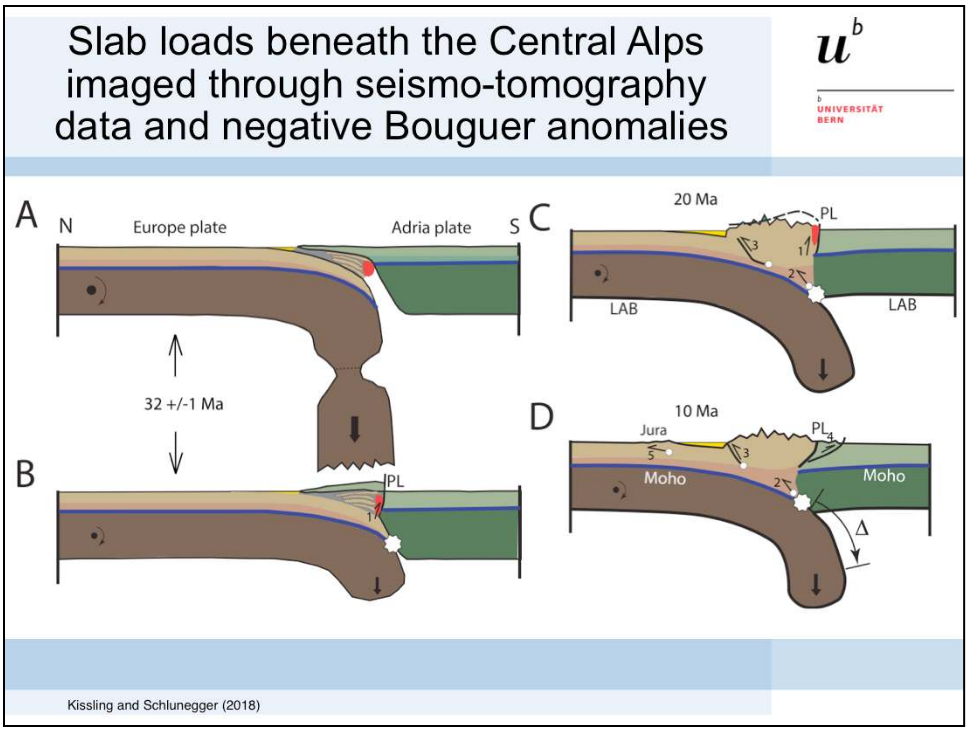
The model set up presented before and particularly the advection part of the fluvial erosional component base on Flint's and Hack's laws in geomorphology, which predict that the spacing between streams (F) and thus alluvial fans, the lengths of streams (L), the upstream size of the drainage area (A) and the stream gradient at any point along the stream (S) are closely related to each other. This allows, through the integration of the channel gradient, to estimate the elevation of the drainage divide and thus to reconstruct the drainage basin relief (H).



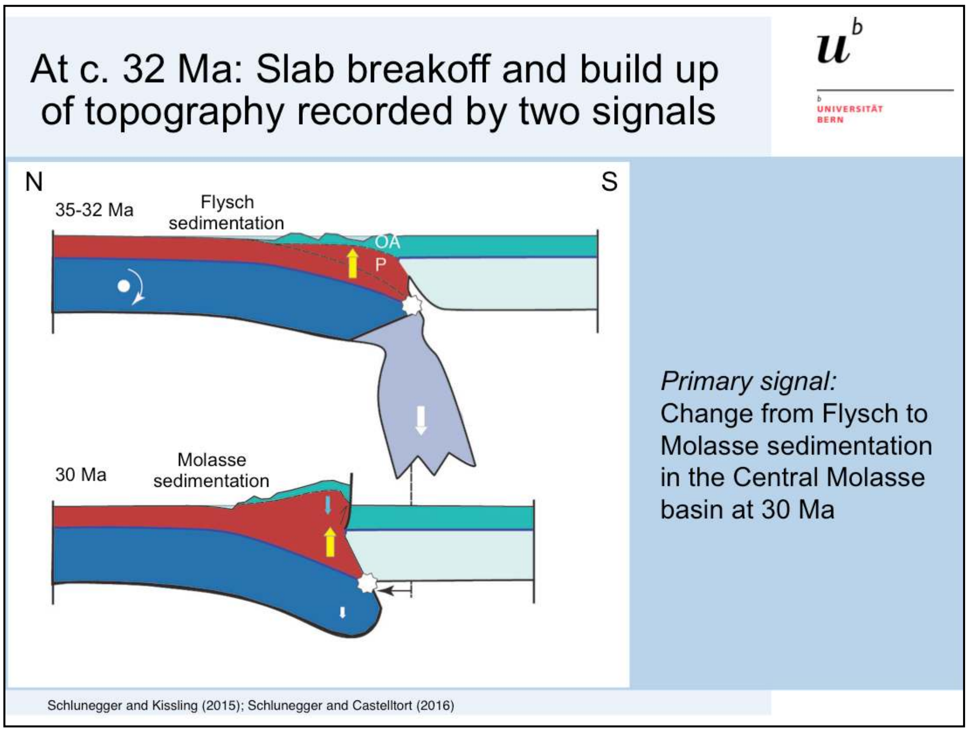
The evolution of the spacing between the alluvial fans in the Molasse basin can thus be used to infer a scenario of how the topography has grown through time. This is corroborated by independent data on a paleoaltimetry estimate in the Alps at 15 Ma (dark blue cross, Campani et al., 2012) through measurements of the lapse rate in the stable isotope records. These reconstructions show that the Alpine topography was rising between c. 30 and 20 Ma, and that this rise was also accompanied by a increase in the erosional flux, as sediment budgets (Kuhlemann et al., 2001) reveal. After 20 Ma, however, the elevation has remained nearly stationary, but the deflection of the basin continued. This implies that changes in topographic loads alone cannot be invoked to explain the large scale formation of accommodation space in the Molasse basin and that slab loads need to be considered as well.



Seismo-tomography investigations have disclosed the continuation of the subducted lithospheric mantle of the European plate beneath the Central Alps. This allowed then the reconstruction of a simplified geological-geophysical model of the Central Alps together with assignments of density values to the different units. Accordingly, the large-scale downward bending of the European plate appears to be driven by vertically directed slab load forces, while the low-elevated topography has been maintained by the buoyancy of the crustal root that is made up of accreted lower crustal material (causing the negative Bouguer anomaly). Because slab load forces appear to have exerted the major control on the large-scale subsidence pattern of the Molasse basin, the subduction and loading history of the European lithospheric mantle appears to exert a large control on the evolution of the Molasse basin.

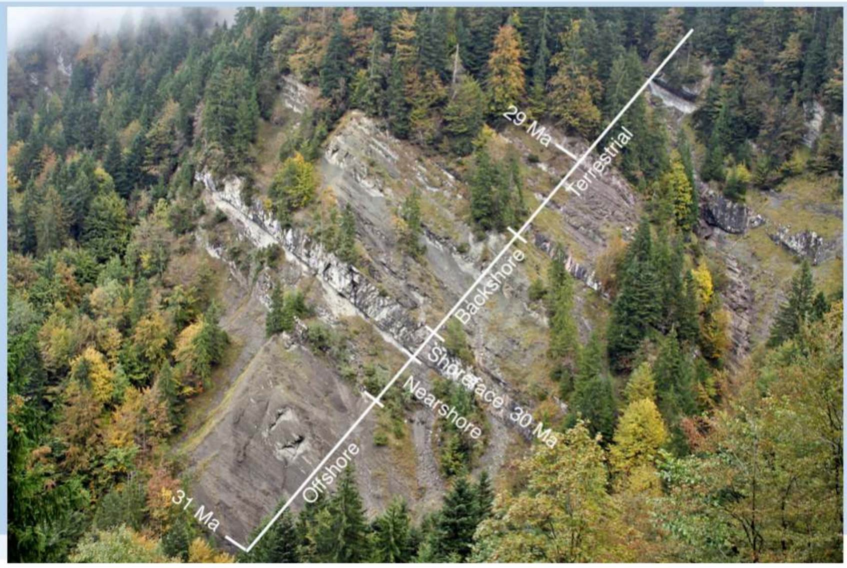


The subduction history of the European lithospheric mantle has been reconstructed by Kissling and Schlunegger (2018) based on palinspastic restorations of previous authors, e.g.., Schmid et al. (1996) and Handy et al. (2010). This reconstruction shows that prior to 32 Ma, the European continental lithosphere started to enter into the subduction channel, while the oceanic lithosphere slab was still attached to the European plate, thereby bending the plate and forming a deep Flysch trough at the tip of the Adritatic continental plate. The differences in densities between the heavy and subducted oceanic lithosphere and the buoyant continental crust resulted in strong tension stresses at the interface between both plate segments. The consequence was that the oceanic lithosphere slab broak off at c. 32 Ma, resulting in a rebound of the European continental plate and initating the creation of the incipient Alpine topography.

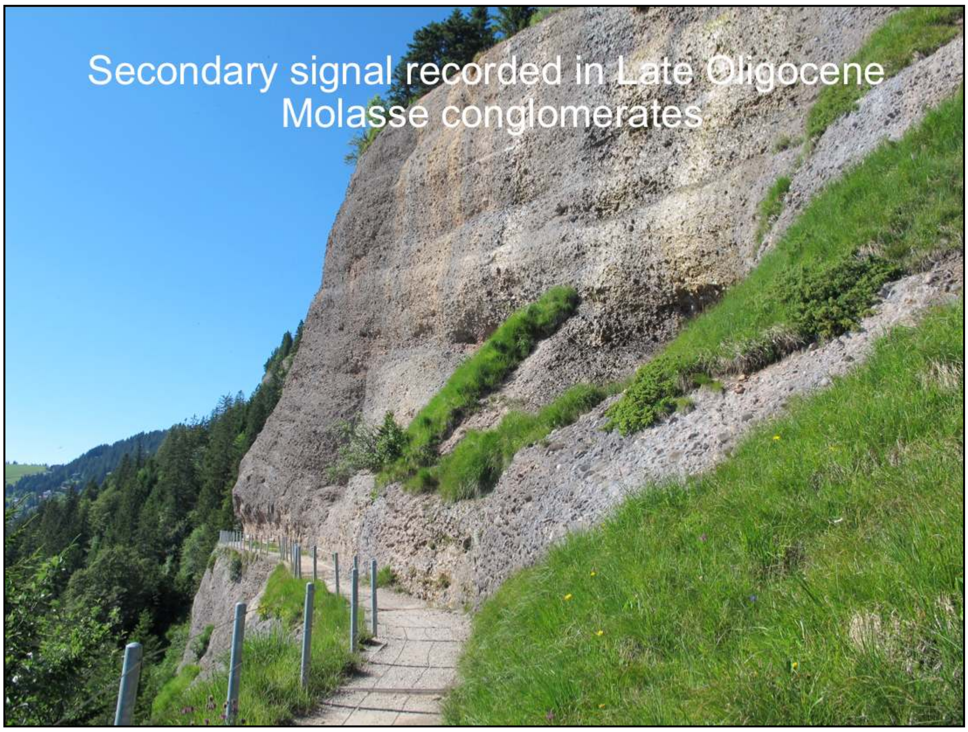


The inferred occurrence of slab breakoff is recorded by two major signals in the Central Molasse basin. First, the rebound of the European plate resulted in a shallowing of the Molasse basin, which records a change from deep marine Flysch sedimentation to terrestrial and shallow-marine Molasse-type environments. Slab rebound also caused the formation on an incipient topography, thereby promoting surface erosion and increasing the erosional mass flux to the basin. Sinclair (1997) proposed that the combination of these mechanisms resulted in the shift from basin underfill to overfill in the north, while deposition of submarine coarse-grained Confolite Conglomerates, indicating steep topographic slopes, continued in the south (Bernoulli et al., 1991).

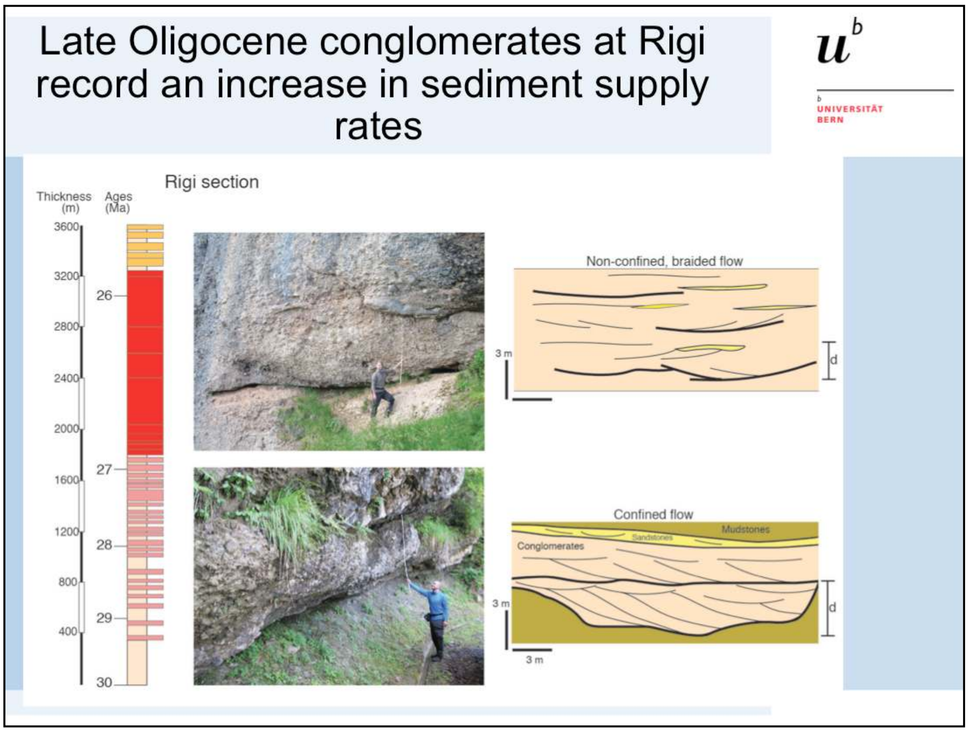
Primary signal: Change from Flysch to Molasse sedimentation at 30 Ma



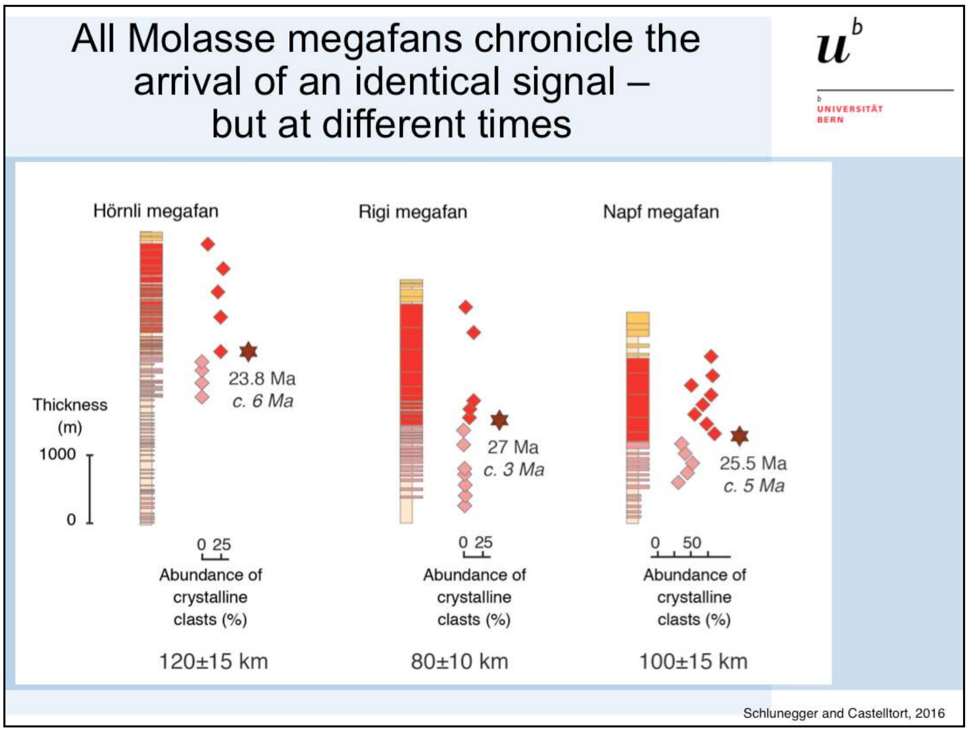
The arrival of the first sedimentary signal, i.e., the change from Flysch to Molasse sedimention, is nicely exposed along the Marbach section (Schlunegger et al., 1996) close to Bern, where magnetostratraphy dating constrained the shift from basin underfill to overfill at 30 Ma. There, the section includes the facies changes from offshore marls to terrestrial fluvial sandstones with pedogenetic marls, and it includes all sedimentological recorders of a continuous regression such as nearshore storm deposits, shoreface beach sandstones and backshore marls with washover sandstone splays and coal beds.



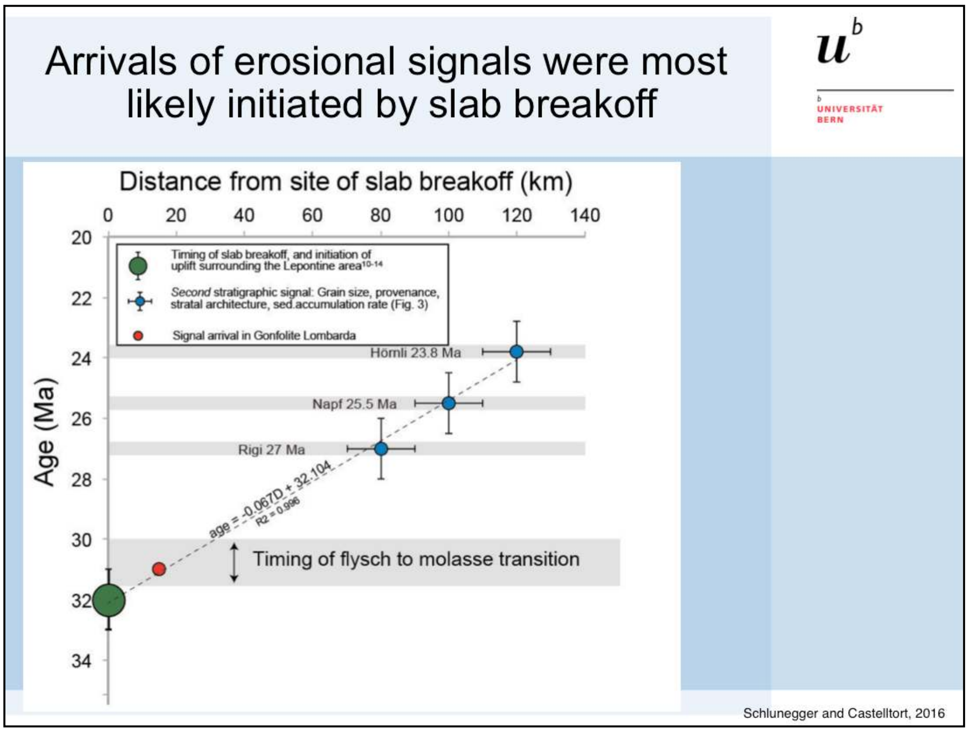
There is also a secondary signal in response to slab breakoff, which we infer from the patterns of conglomerate deposition in the Central Molasse basin. We interpret that this secondary signal was a secondary pulse of large material fluxes to the basin, which we infer from the stratigraphic architecture of fluvial conglomerates.



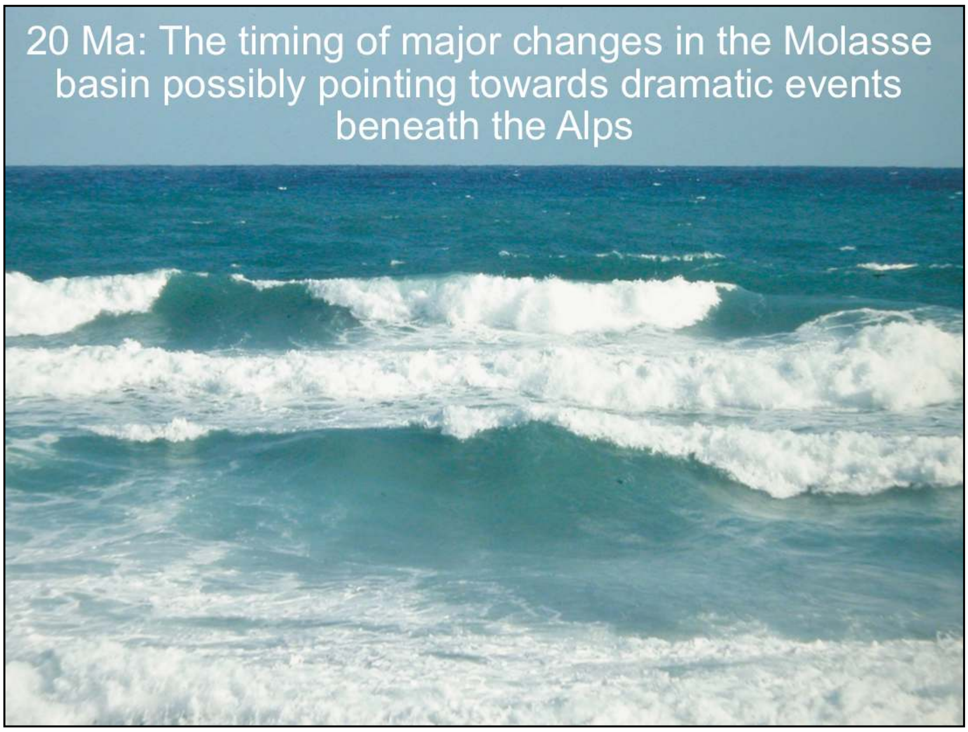
I exemplify the arrival of the secondary signal at the example of the Rigi conglomerates, situated in the Central Molasse basin adjacent to the orogen front. The corresponding suite is c. 4000 m thick and was deposited between 30 and c. 26 Ma as magnetopolarity chronologies imply (Schlunegger et al., 1997). The section starts with alternated conglomerates and mudstones, which were deposited by streams that were laterally bordered, and thus constrained, by floodplains. At 27 Ma, the sedimentation pattern changed significantly, and amalgamation of coarse-grained conglomerate beds start to dominate the sedimentation pattern. These deposits usually form within an environment where braided channels accumulated coarse-grained material on steep alluvial fans, where sediment fluxes are high. The change from constrained to braided channels thus records the arrival of a sedimentary pulse.



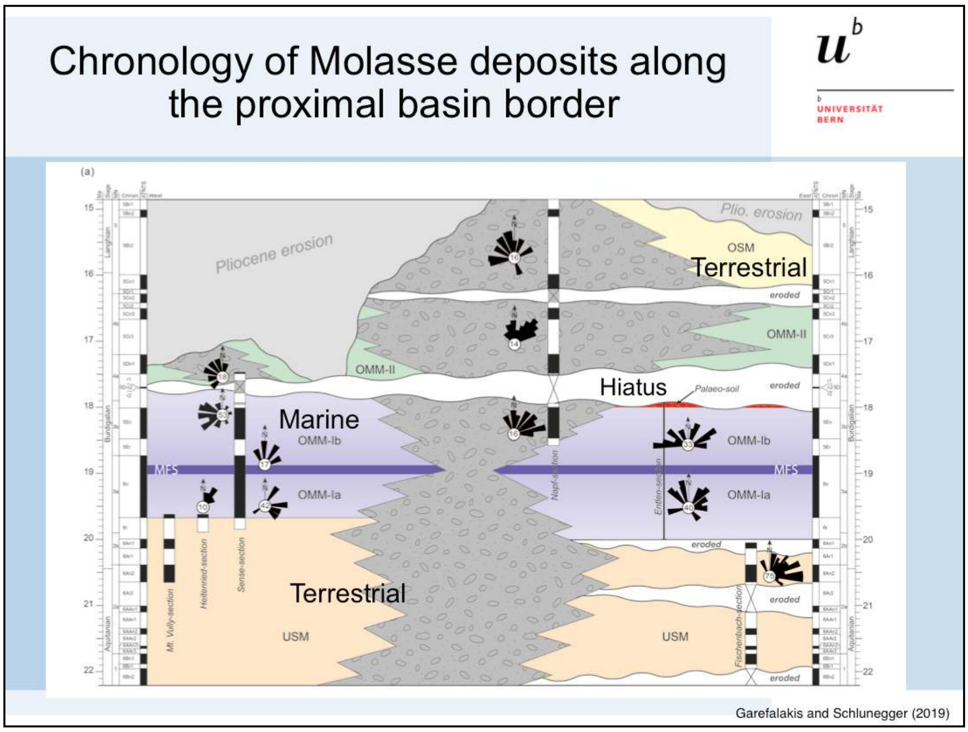
Identical stratigraphic architectures where fluvial conglomerate deposits coarsen up-section are observed at least at three sites within the Central Molasse basin where the material sources were situated in the Central Alps. However, the inferred arrival of a secondary sedimentary pulse occurred at different times (27 Ma at Rigi, 25 Ma at Napf, and 24 Ma at Hörnli) and thus with a different delay in comparison with the arrival of the first sedimentary pulse at 30 Ma.



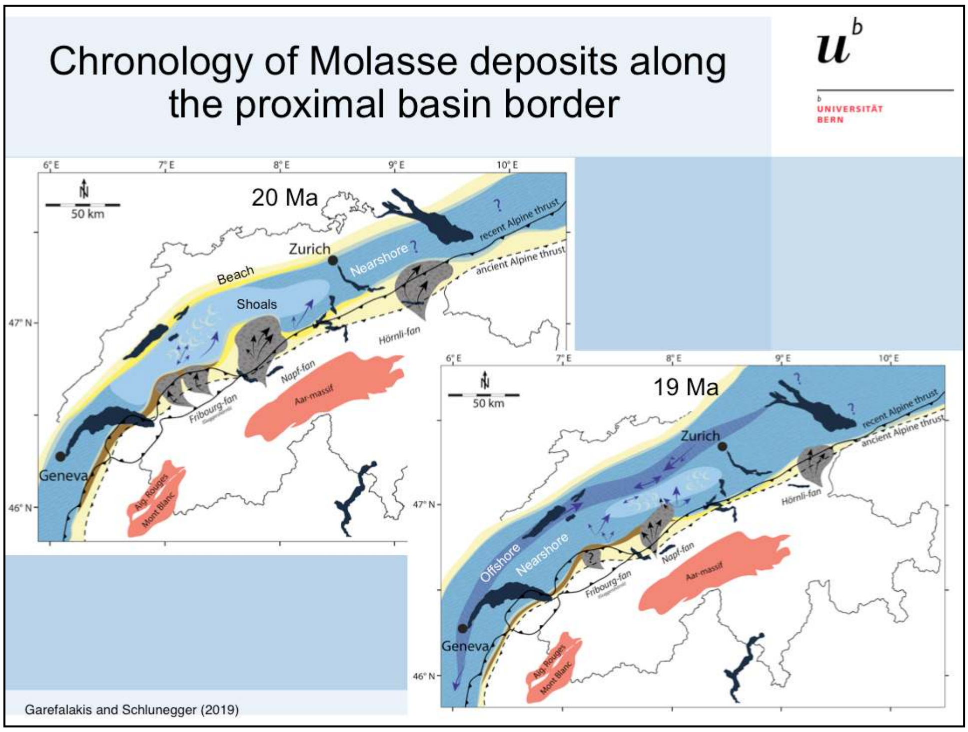
We then plotted the arrival time of the secondary signal recorded in the Molasse conglomerates as a function of the distance from the site where slab breakoff was considered to have occurred. Despite the large uncertainties particularly in the distance between the Central Alps, the site of slab breakoff and the material source, the points fall on one line where the age intercept corresponds to the timing of slab breakoff. Accordingly, the stratigraphic signals in the Central Molasse basin characterized by (i) the change from basin underfill to overfill at 30 Ma, and (ii) the subsequent shifts in sedimentation patterns from an alternation of mudstones and conglomerates to amalgamations of conglomerate beds are likely to represent surface recorders of deep-seated, lithospheric-scale processes.



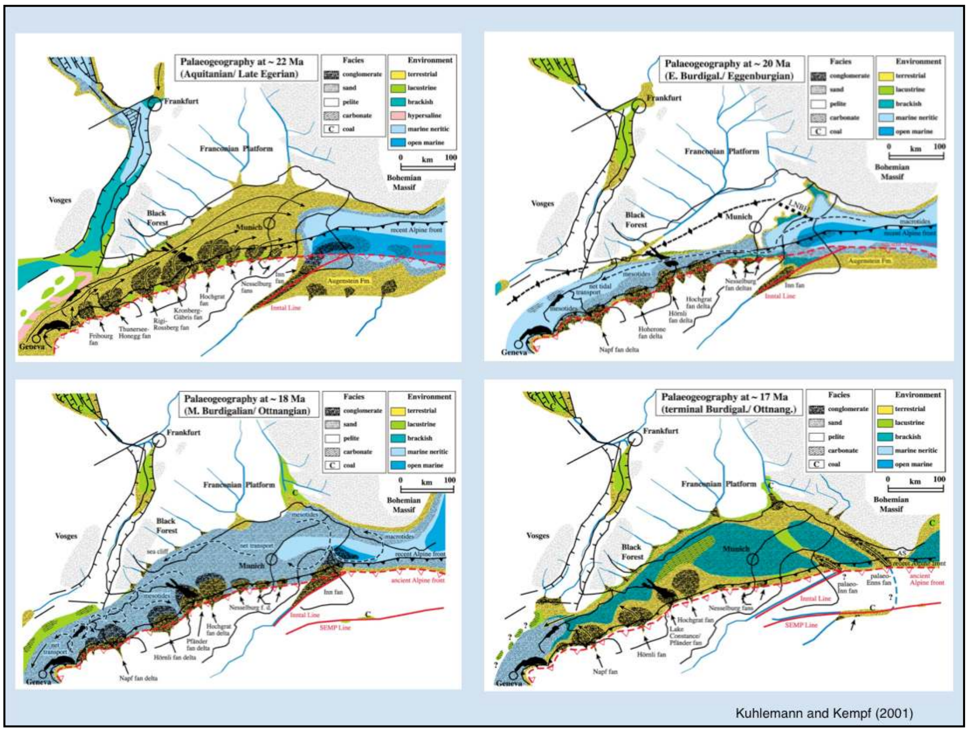
The Burdigalian was the second time period when major changes were recorded in the Molasse basin. First, shallow marine conditions established within the entire Molasse basin across Switzerland, Germany and Austria. In addition, and probably most important, the drainage within the basin changed in the opposite direction within a time span of less than 2 Ma.



This diagram, what stratigraphers refer to as Wheeler diagram, shows the facies relationships for the Central Molasse basin within a temporal framework over a distance of c. 100 km along strike. The chronology has been established through numerous magneto- and biostratigraphic work (Keller, 1989; Schlunegger et al., 1996; Jost et al., 2016). First, there are multiple time intervals of now sedimentary records, referred to as hiatus. These coincide in time when global sea level was lowered, which thus caused a phase of erosion and non-sedimentation in the Molasse Basin. More relevant, however, is the detailed record of a shift in paleoflow direction. During USM times when terrestrial conditions prevailed, the discharge was directed towards the NE. The same discharge pattern is also recorded by the 20 Ma-old shallow marine sediments. At the time when the peripheral sea had its largest water depth, which was the case at 19 Ma (MFS=maximum flooding stage), the discharge directions started to change towards the N, and from 18 Ma onward paleodischarge mainly occurred towards the NW and thus in the opposite direction. This means that the basin axis tilted from a NE to a SW orientation. This inferred change in the tilt direction of the basin axis is corroborated by the direction of the marine transgression. At 20 Ma, marine conditions started earlier in the east, from where the marine ingression progressed towards the west. This implies an eastward tilt of the basin axis. The second transgression after 18 Ma started earlier in the west and then progressed towards the east,



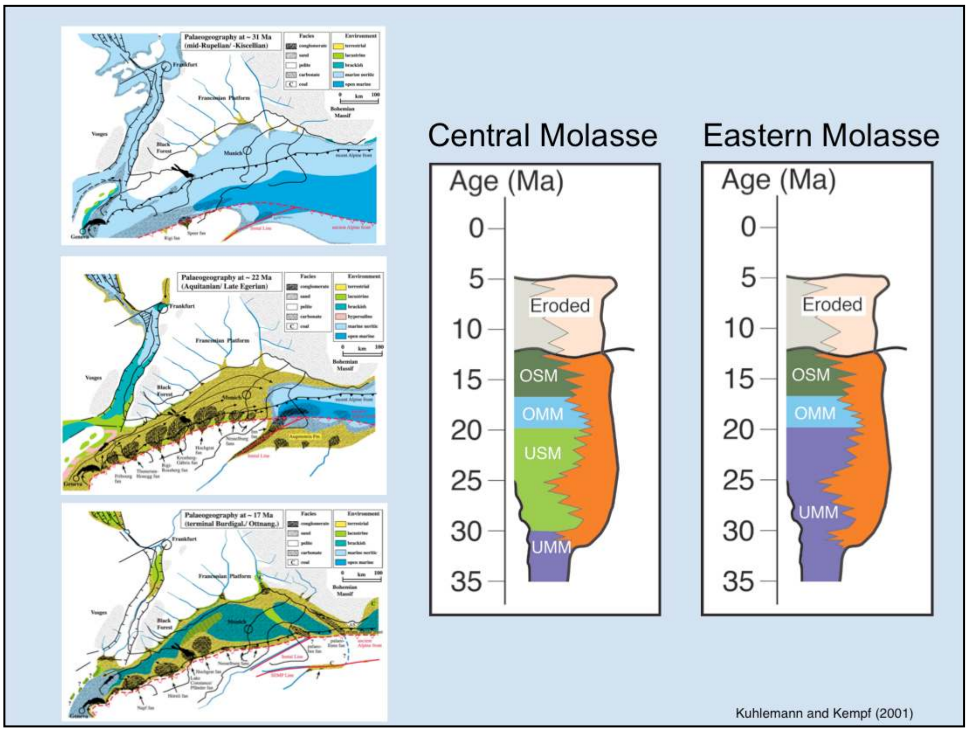
The establishment of the Burdigalian seaway in the Central Molasse basin was not only associated with a drainage reversal within less than 2 Ma, but the transgression was also associated with a widening and deepening of the basin both at proximal and distal locations, as new mapping shows. This even resulted in offshore marine conditions with water depths > 50 m close to the distal basin border.



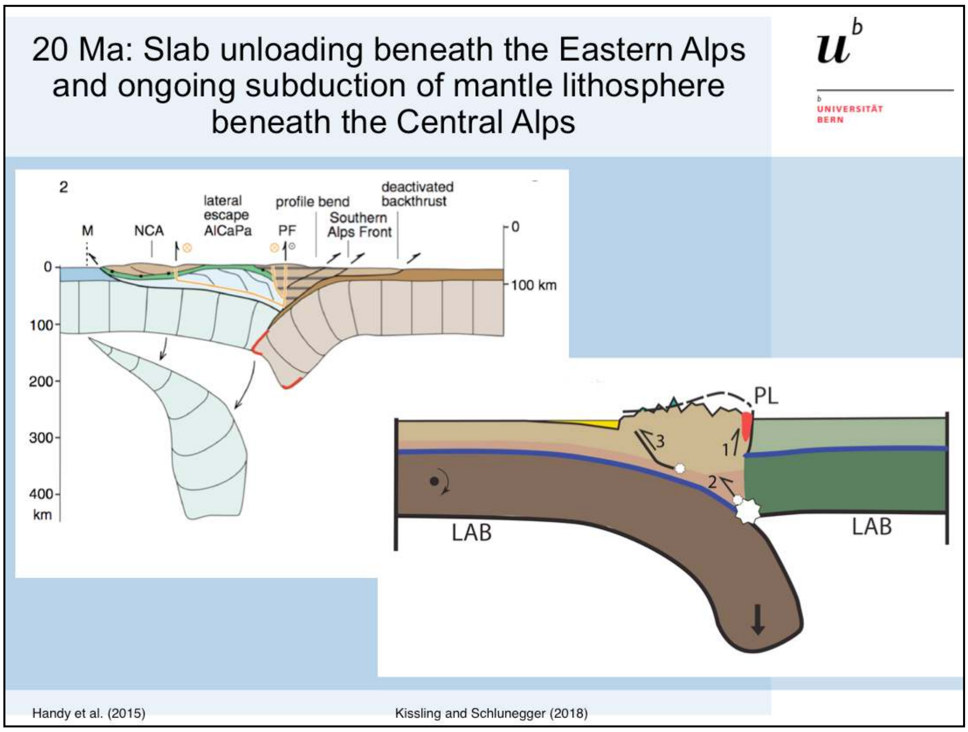
Kuhlemann and Kempf (2001)

At a broader scale, but with less resolution both in space and time, the Central and Easter Molasse basin showed nearly opposite trends in their stratigraphic records between 30 and 20 Ma, and even thereafter. At 30 Ma, a phase of plate unloading, most likely through slab breakoff beneath the Central Alps, resulted in a rebound of the foreland plate and large erosional fluxes to the Central Molasse, giving way to overfilled conditions. In the Molasse basin east of Munich, however, underfilled conditions still prevailed. Provided that slab loads were responsible for the large scale deflection pattern of the European foreland plate, then the basin configuration prior to 20 Ma implies that some of the European oceanic lithosphere was still attached to the European plate in the east, thereby downwarping the plate beneath the Eastern Alps and resulting in an east-directed tilt of the basin axis.

At 20 Ma, however, a period of foreland plate downwarping beneath the Central Alps most likely caused the widening and deepening of the Molasse basin in its central part, while a mechanism of rebound and plate unloading beneath the Eastern Alps has to be invoked to explain the shift from Flysch type to shallow-marine Molasse type of sedimentation in the eastern segment of the Molasse Basin. Plate unloading underneath the Eastern Alps versus plate loading beneath the Central Alps could have resulted in a differential westward tilt of the basin axis, which could explain the reversal of the drainage direction.

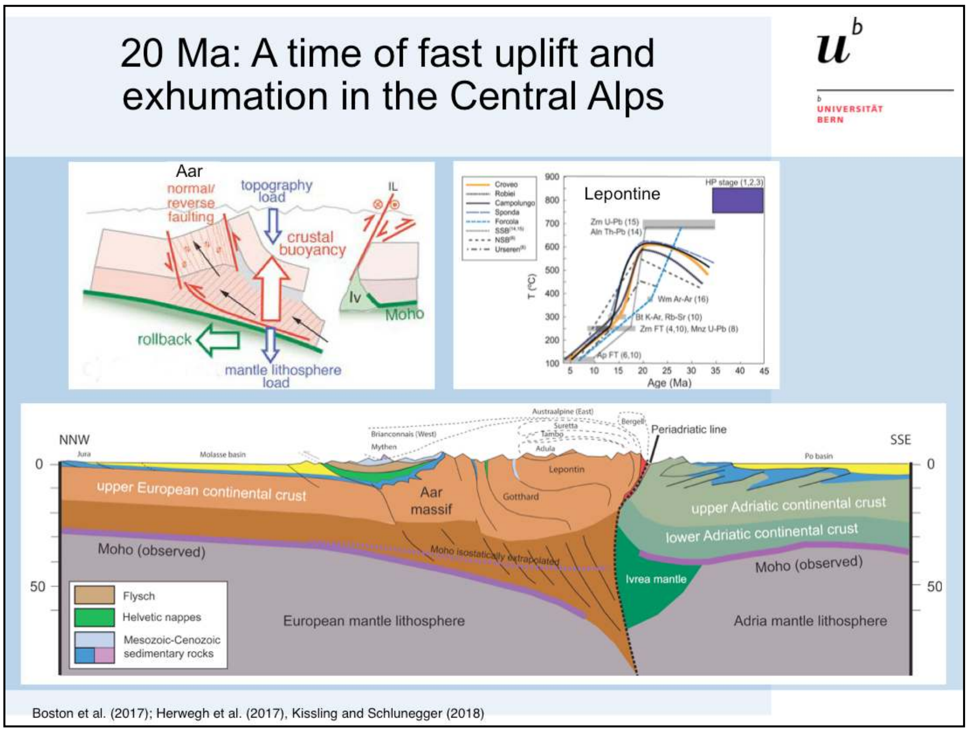


In summary, while sedimentation in the Central Molasse was characterized by a shift from basin underfill to overfill at 30 Ma, and then again by a period of marine sedimentation at 20 Ma, the Eastern Molasse maintained its Flysch type of sedimentation prior to 20 Ma. At that time, the basin experienced a phase where deep marine conditions changed to shallow marine environments. These shifts in sedimentation patterns were also associated by a reversal in the drainage direction, which occurred within a short time span of < 2 Ma.

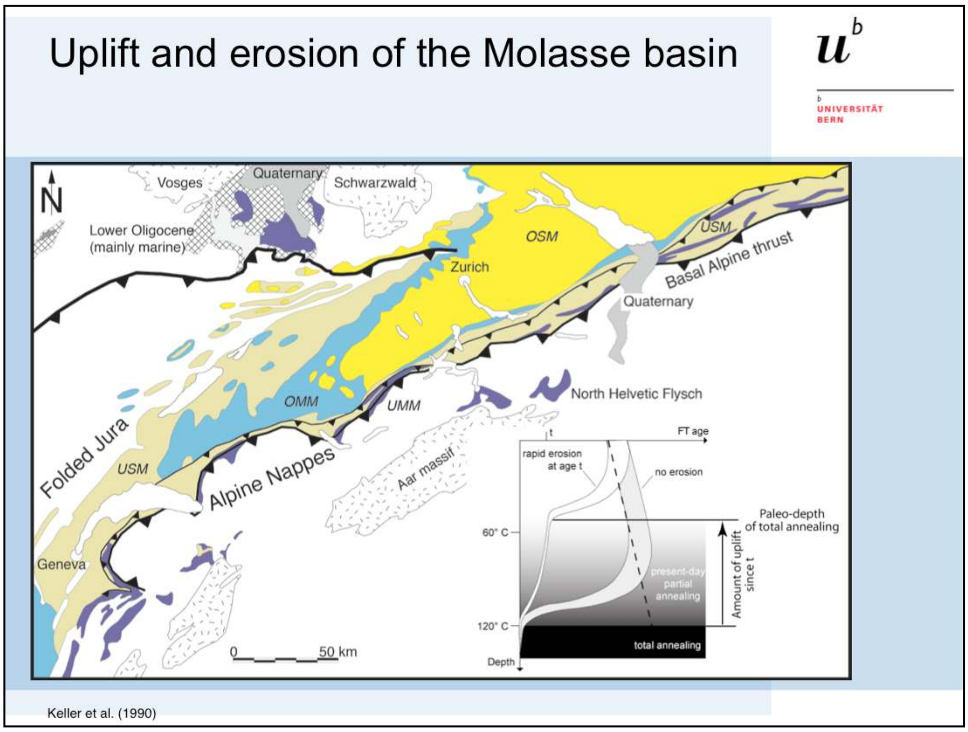


It is possible, per perhaps very speculative, to relate the along-strike differences in basin evolution paired with the reversal of the drainage direction to contrasts in subduction mechansims between the Central and Eastern Alps. While ongoing subduction of the lithospheric mantle of the European plate could have resulted in a widening and deepening of the Central Molasse basin, a period of slab unloading beneath the Eastern Alps could be invoked to explain the shallowing-upward trend in the Easter Molasse basin. The result was a possible westward tilt of the foreland plate and a reversal of the drainage direction. I note, however, that this interpretation is only preliminary and is still work in progress.

In this context, it was also proposed that slab unloading beneath the Eastern Alps allowed the Adriatic plate to subduct towards the north. If this mechanism is valid, then the Eastern Molasse basin changed its position relative to the subduction direction and became a retro-foreland basin at 20 Ma, while the Central Molasse still continued to operate as a pro-foreland basin. I expect differences in basin geometry, subsidence patterns and facies belts along strike and across the basin. The consequences on the evolution of the basin have not been elaborated yet and are awaiting the results of ongoing research.

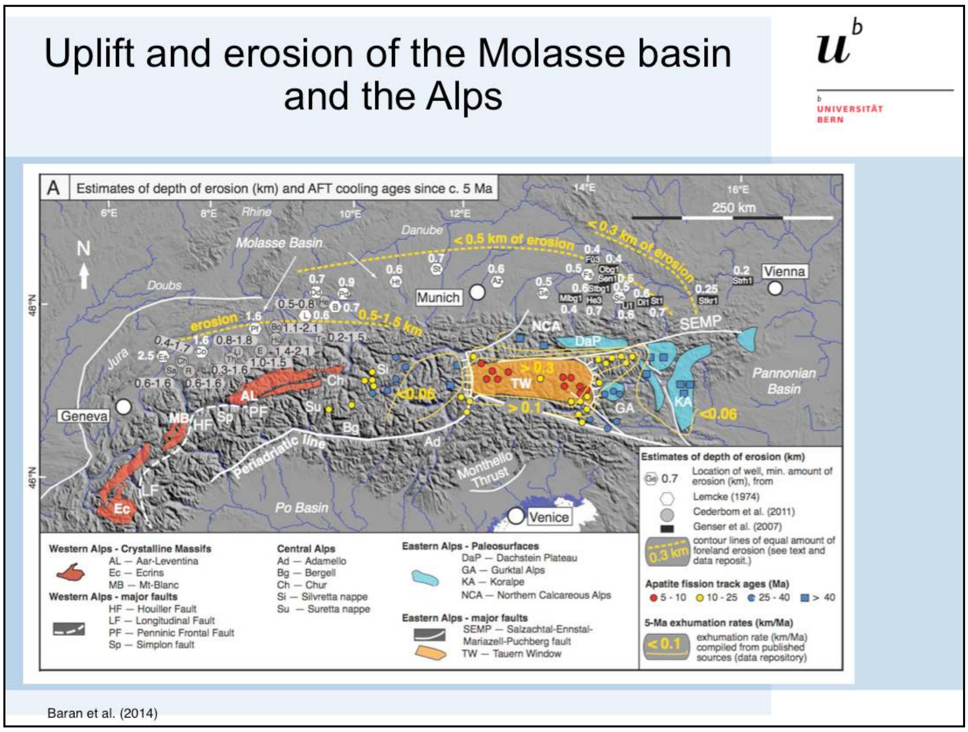


The time at 20 Ma was indeed characterized by drastic events. In the Lepontine area, exhumation rates occurred at their highest rates within a very short time interval of less than 5 Ma. Also at 20 Ma, the Aar massif experienced a phase of rapid uplift and exhumation. At the same time, sediment supply rates to the Molasse basin decreased, and the Southern Alps became deformed after 18 Ma. It is not fully clear, yet, how these signals have to be linked, and how the basin response has to be embedded in this geodynamic framework. I predict that research investments focusing on the 20 Ma-old time period would be much awarding.

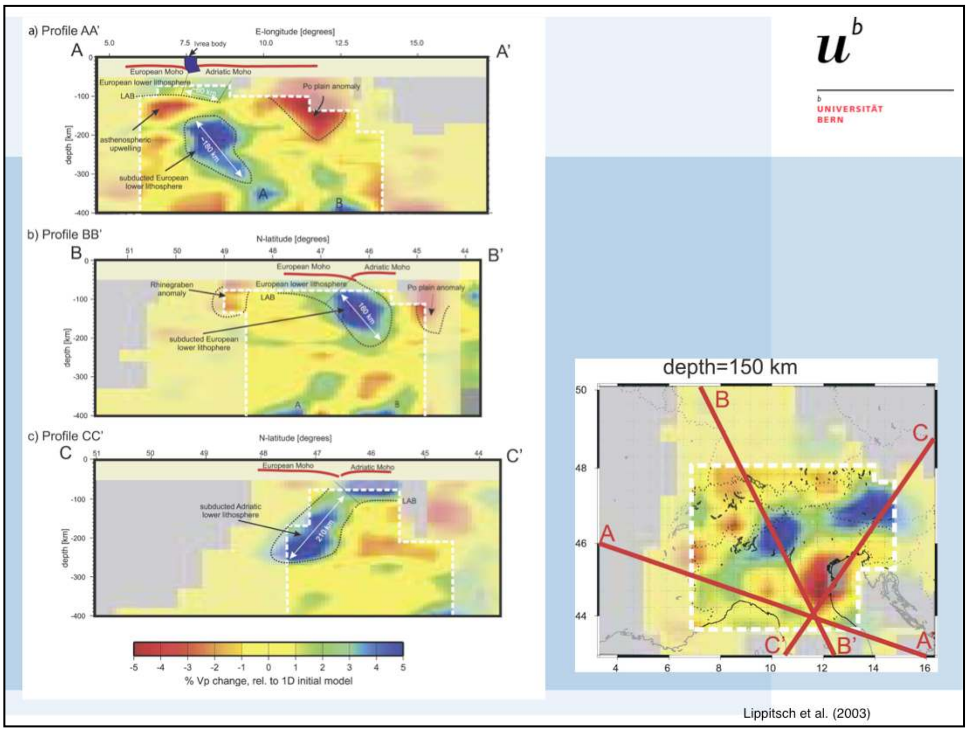


The current exposure pattern of Molasse units shows a distinct peculiarity, where successively older sedimentary groups are exposed towards the west. This implies that the basin has been in the state of uplift and erosion, and that the amount of erosion is likely to be larger in the west compared to the northeast. The first-order question to address here includes (i) the timing of uplift and erosion, and (ii) the amount of erosional recycling.

This problem has been addressed by Charlotte Cederbom (Cederbom et al., 2004; 2011) through the application of fission track ages measured on detrital material in boreholes. Fission track ages of apatite grains that are deposited in a sedimentary basin will reflect the temperature history of the provenance regions until they are heated above c. 60°C. In the depth interval where partial annealing takes place (i.e., between 60°C and 120°C), apatite fission track ages become successfully younger and finally converge to 0 Ma at 120°C where total annealing resets all fission tracks. If the sedimentary deposits are then exhumed from the depth where total annealing takes place, to a shallower depth with zero annealing, then the fossil partial annealing zone and particularly the paleo-depth of total annealing is preserved. In case that the geothermal has not changed, then the difference between the modern depth of total annealing and the paleo depth corresponds to the magnitude of uplift and exhumation. The apatite fission track ages just at the depth of the exhumed paleo-depth of total annealing is the time when basin inversion started. The



In her PhD work, Ramona Baran (Baran et al., 2014) compiled various datasets including the Cederbom et al. (2004; 2011) estimates about the timing and the amount of uplift in the central part of the Molasse basin, and estimates about the amount of erosion in the German and Austrian segments of the basin (Lemke, 1974). The latter datasets are mainly based on maturity estimates. She also included fission track ages from the Alps in her analyses and reconstructed contour lines of uplift and erosion since 5-10 Ma. She found a center of highest erosion in the Central Alps and the adjacent Molasse basin, from where the amount of erosional recycling decreased farther east. She interpreted that this pattern might be explained by a phase of plate unloading beneath the Western Alps, possibly in response to slab tearing. This process has been inferred based on seismo-tomography datasets presented by Lippitsch et al. (2003). However, this hypothesis is strongly contested in the scientific literature.



Most of the hypotheses about lithospheric controls on the evolution of the Molasse basin are based on the results of seismo-tomography investigations by Lippitsch et al. (2003) that have had a major impact on how the evolution of this basin can be framed in a geodynamic context. In particular, the third hypothesis where slab unloading beneath the western Alps explains the pattern of exhumed Molasse sediments is based on the inferred slab tear seen in cross section A (Western Alps). Likewise, the second hypothesis that slab unloading beneath the Eastern Alps exert a strong control on the drainage reversal at 20 Ma bases on the inferred northeastward dip of the lithospheric mantle slab, suggesting that this material is part of the Adriatic plate. This requires that the European slab had to be removed before the subuduction of the Adriatic slab was possible. The possible timing of 20 Ma depends on the amount and the history of shortening in the Southern Alps in relation to the length of the subducted Adriatic lithospheric mantle slab (section C) and has been addressed by Ustaszewski et al. (2008) and Handy et al. (2015). Finally, the timing of slab breakoff at c. 32 Ma is consistent with the length of the subducted European lithospheric mantle slab and the amount and chronology of thrusting and shortening of the Central Alps (section B).

Summary

- Signals of lithosphere-scale processes are likely to be visible in the Molasse basin
- Processes in deep Earth are likely to be preserved on the surface, however the details have not been fully identified yet
- It will be a challenge, but likely possible, to deconvolve surface and lithospheric signals from the stratigrapahic records