The Molasse Basin:

Tectonics, sea level and basin dynamics
Contents
Abstract ........................................................................................................................................... 3
Introduction ...................................................................................................................................... 3
Geology ............................................................................................................................................ 5
   Stratigraphy .................................................................................................................................. 7
Basin Dynamics ................................................................................................................................. 9
   Permo-Carboniferous Basins (358.9 Ma – 252.2 Ma) ................................................................. 10
   Triassic Basin (252.2 Ma – 201.3 Ma) ......................................................................................... 10
   Jurassic Basin (201.3 Ma – 145 Ma) .......................................................................................... 11
   Cretaceous Basin (145 Ma – 66 Ma) ............................................................................................ 12
   Cenozoic Basin Evolution (66 Ma - today) ................................................................................ 12
Present-day Tectonics ..................................................................................................................... 14
Conclusion ....................................................................................................................................... 14
References ....................................................................................................................................... 16

List of figures
Figure 1: Overview of the Alps and the Molasse Basin: GeoMapApp ................................. 4
Figure 2: A: Overview of the Swiss-German Molasse Basin with contour lines of the base Tertiary sediments and major structures, B: N-S profile through the German Molasse Basin: Heidelbach et.al .......................................................... 4
Figure 3: Overview of the classification of the Molasse Basin: Véron .............................. 6
Figure 4: General Stratigraphy of the central NAFB: Kuhlemann et al ............................ 8
Figure 5: Overview of the geological era ............................................................................... 9
Figure 6: Overview of the basement in Permo-Carboniferous times, including main troughs: Bachmann et al ............................................................... 10
Figure 7: Overview of the basement in Middle Triassic times: Bachmann et al .......... 11
Figure 8: Overview of the basement with isopachs in Late Jurassic time: Bachmann et al ........................................................................................................................................ 12
Figure 9: Overview of the tertiary Transgression: Bachmann et al ................................ 13
Figure 10: Summary, showing the pattern of sediment discharge to the north, the stratigraphic architecture, the progradation of topographic axis, the palaeoclimat e and geodynamic events: Schlunegger et al. 2007 .......... 15
Abstract

The Molasse Basin is divided in the ‘Folded Molasse’ and the ‘Molasse Platform’. The evolution started with the Permo-Carboniferous Basin with his basement from the Variscan orogeny. In the Cenozoic Basin Evolution the last and dominant phase of the Molasse Basin-development occurred in the Oligocene and Miocene times with two shallowing- and coarsening upward megasequences. The Lower Marine Molasse (UMM) - Lower Freshwater Molasse (USM) sequence and the Upper Marine Molasse (OMM) - Upper Freshwater Molasse (OSM) sequence. The facies distribution was driven by tectonic processes of the Alpine thrust front and the impact of the Alpine uplift coupled with erosion and sedimentation.

Sediments found in the Alpine Foreland are shallow marine limestones overlain by turbiditic sandstones. Also marls and mudstones occurred. Alluvial fan deltas developed in the Oligocene and conglomerates, the so called “Nagelfluh”, were transported in the northern Alpine foreland. Two imposing fans were the Napf- and the Hörnli-fan in Switzerland. The todays uplift rate of the Alps is 1 mm/a and erosion is going on.

Introduction

The Molasse Basin represents the northern Alpine foreland basin and is located to the northern flank of the Alps. This Alpine foreland basin has a width of max. 130 km and a length of 1000 km. The Molasse Basin extends from west to the east about France, Switzerland, Germany and Lower Austria. The Lake Geneva (France) is the western end of this foreland basin, where the basin has a width of about 20 km. The width in the German part varies to the present-day maximum of 130 km in Bavaria and easterly from 10 km to 40 km. In the east it is linked with the Vienna Basin. The Molasse Basin is a typical peripheral foreland basin developed in Tertiary age atLate Eocene (55 Ma) to Late Miocene (5 Ma). The name of the Molasse Basin is due to the sediments of Tertiary age, the so-called “Molasse”. This Molasse is the debris of the rising Alps. The Molasse refers to the sediment charge formed as terrestrial or marine deposits in front of a rising mountain –here the Alps-. The Molasse developed due to rapid erosion while emergence of the mountain. The word “Molasse” is a word of Latin derivation “mollis” and means ‘weak and casual’. In 1779 the swiss natural scientist Horace-Bénédict de Saussure announced this definition for the sandstones of the alpine foreland basin.

The origin of the Alps began during the Lower Cretaceous (145 Ma – 66 Ma) with the continent-continent collision between the European plate and the Adriatic plate, also called “Apulia”. The orogeny of the Alps is vergent compressional and consist of thin-and thick-skinned mostly unmetamorphosed thrust sheets and high-grade metamorphic rocks at the external flanks (Schlunegger et al. 1997).
Figure 1: Overview of the Alps and the Molasse Basin: GeoMapApp

Figure 2: A: Overview of the Swiss-German Molasse Basin with contour lines of the base Tertiary sediments and major structures, B: N-S profile through the German Molasse Basin: Heidelbach et al.
In the Molasse Basin there are two different geological and geomorphological observed parts. The main part, 90 % of the basin, refers to the 'Unfolded Molasse' in the north, also called Molasse Plateau (Sinclair et al. 1991). The Molasse Plateau represents the distal part of the basin, which is flat dipping toward the Alpine orogen (Schlunegger et al. 1997, Pfiffner et al. 2002). The other part refers to the 'Folded and thrusted (subalpine) Molasse'. The subalpine Molasse, also known as "Molassezone" or "Faltenmolasse" is off the northern margin of the Alps in the southernmost parts of the Molasse Basin area (Véron 2005). This Subalpine Zone extends in a 10 km wide striation long of the northern margin of the Alps. The zone is limited by different tectonic units of the mountain range (Véron 2005). During thrusting by Alpine nappe tectonic the todays Subalpine Molasse sediments became incorporated into these nappe tectonic (Reinecker et al. 2010). After thrusting, the deposits are present in a stack of southward dipping thrust sheets (Schlunegger et al. 1997, Pfiffner et al. 2002). Thrusting in the Subalpine Molasse was contemporaneous with the sedimentation. The Subalpine Molasse build a thrust sheet.

The Molasse Basin is restricted along the northern margin (Swiss territory) by the Jura Mountains (Fig. 3). The Molasse sediments resume, along the transition from the foreland basin to the Jura Mountains, the folding and faulting of the Jura Fold Belt. This shows the young (Late Miocene) age of the fold belt deformation (Véron 2005). Also to the east of the Jura Mountains in central and western Switzerland the fold-and-thrust belt of the Jura Mountains is tectonically linked to the basin. In the northern part of Switzerland are remnants of Molasse sediments which are preserved in its synclines. Adjoin to the northeast of Switzerland, Molasse sediments onlap on the Mesozoic platform in the Swabian and Franconian Jura (German territory). In East Bavarian and Upper Austrian is the Bohemian Massif (Fig. 3) which borders the Molasse basin along faults. Some faults are covered by Molasse sediments. In Lower Austria a direction change took place, a major fault with SW-NE direction. This fault originated in the Neogen (23,03 Ma – 2,588 Ma) and is locally buried by Molasse sediments. In the east is the Waschberg Zone the overthrust of the Molasse zone and the Vienna Basin. This zone is also a part of the Folded Molasse (Véron 2005).
The sediments of the Subalpine Molasse are turbidites of the north Helvetic Flysch covered around the uppermost Helvetic nappes (Sinclair et al. 1991). Between the outward Plateau Molasse in the north and the Folded Molasse in the south the thickest deposits of this Foreland Basin are steeply tilted with in-imbricate thrust blocks of the Subalpine Zone. In the north, sediments of the Plateau Molasse are thin and pinch out into the Table Jura (Tafeljura) (Sinclair et al. 1991).

The Table Jura is the opposite of the High Chain Jura (Faltenjura) and extends to France, Switzerland and Germany, but mostly in Switzerland in Canton Jura, Canton Basel-Land and Canton Aargau. It is a tabular highlandscape with precipitous valleys. While tertiary age (65 Ma – 2,6 Ma) the rocks broke-up in slabs due to subsidence of the Upper Rhine Rift, resulting in NE-ENE orientated breaks.

In Late Eocene (55 Ma) the deposition of the Molasse sediments began with fluvial and shallow-marine sandstones, shales and carbonates (Sachsenhofer et al. 2006). During transition of Eocene to Oligocene (33,9 Ma – 23,03 Ma) a flexural down-bending of the foreland resulted due to thrust loading of the Alpine nappes. Together with a coeval sea-level rise, subsidence of the Molasse Basin and drowning of the former developed carbonate platform evolved from this (Sachsenhofer et al. 2006). In the Oligocene the southern margin of the Molasse basin was steep and the northern part was gently dipping. Near the southern margin, the tectonically active part, deposits of 2 km thickness were accumulated and on the northern part fine-grained pelagic and hemipelagic rocks were deposited (Sachsenhofer et al. 2006). The stratigraphic development of the North Alpine Foreland Basin began with the turbiditic deep-water sediments of the north Helvetic Flysch, named as the underfilled Flysch stage. After this stage the overfilled Molasse stage developed with shallow-water / continental sediments (Pfiffner et al. 2002). These developed Molasse sediments have a traditionally lithostratigraphic division.
**Stratigraphy**

The lithostratigraphy of the North Alpine Foreland basin is divided in five groups. The five groups are listed in ascending order:

1. North Helvetic Flysch (NHF)
2. Lower Marine Molasse (UMM),
3. Lower Freshwater Molasse (USM)
4. Upper Marine Molasse (OMM)
5. Upper Freshwater Molasse (OSM).

The stratigraphic groups form two shallowing- and coarsening upward megasequences (Pfiffner et al. 2002). The oldest sequence begins with the Lutetian to Priabonian (Eocene; 47.8 Ma – 33.9 Ma) NHF (Schlunegger et al. 1997). It’s a classic flysch sequence marked by a marine transgression and deposition of shallow marine limestones (10-50 m) overlain by turbiditic sandstones (2000 m) in the western part of the MB, for example in France, the area around Annot (Provence-Alpes) (Jourdan et al. 2013). Sediments described as allochthonous remnants in the Folded Molasse (Andeweg et al. 1998).

After this, one part of the first megasequence comprises the early Oligocene (33.9 Ma – 23.03 Ma) Lower Marine Molasse, the Rupelian UMM. The UMM is the transition from the “Flysch” to the “Molasse” stage. During this time (Oligocene) the sea transgressed to the north. In the southern part of the basin, which subsided rapidly, the sandstones reached thicknesses of 1200 m (Andeweg et al. 1998). Sediments were deposited in marine environment in the east direction (Carpathians). These sediments were fine grained sandstones, turbidites, deep water marls and mudstones. First fan deltas developed in the UMM sea, which was a narrow branch off the Tethys (Pfiffner et al. 2002, Schlunegger et al. 1997, Sinclair et al. 1991). The sedimentation was a transition of marine turbidites to coastal sediments (Jourdan et al. 2013). During Rupelian time the marine environment became more shallower (Kuhlemann et al. 2002).

The next part is the late Oligocene to early Miocene (23.03 Ma – 5.332 Ma) Lower Freshwater Molasse, the Chattian and Aquitanian fluvial clastic rocks of the USM and alluvial megafans of conglomerates (Nagelfluh) deposited at the tip of the Alpine wedge as well as marls (Schlunegger et al. 1997, Sinclair et al. 1991). At the boundary of the Rupelian to Chattian (28.1 Ma – 23.03 Ma) an eustatic induced regression took place with coupled basin subsidence at the same rate. Also little transgression and regression sequences induced thrusting of the marls about sandstones (Andeweg et al. 1998). The Subalpine Molasse evolved as southward dipping thrust sheets and due to the tectonic movements in the Central Alps, the thrust sheets were exposed to erosion (Schlunegger et al. 1997, Kuhlemann et al. 2002). In the western NAFB was a climatic change from more humid to semiarid conditions during the Chattian time. A drainage system which had their sources in the rising Alps, were transverse during these times, but turned orogen-parallel into a NE flowing axial submarine (UMM) or terrestrial (USM) drainage (Pfiffner et al. 2002).

The second megasequence started with the Burdigalian (20.43 Ma – 15.97 Ma) [Miocene] transgression and consists of deposited wave- and tide dominated shallow marine sandstones of the Upper Marine Molasse group (OMM). These deposits were
interfingered with major fan delta sediments adjacent to the Alpine thrust front (Schlunegger et al. 1997, Pfiffner et al. 2002). At this time width of deposition was 60 – 80 km. The transition from the USM to OMM was indicating form overfilled to underfilled basin conditions and the accommodation space formation occurred at higher rates than the sediment increased. The sediment decrease was accompanied by a reduction of the relief at the northern margin of the Eastern Alps (Kuhlemann et al. 2002). Two deltaic fans were the Napf- and the Hörnli-fan in Switzerland. Glauconitic sandstones, limestones and marls were deposited, underlain by a transgressive conglomerate in the area of Switzerland (Sinclair et al. 1991). This part of the second megasequence is overlain by the Serravalian (13,60 Ma – 11,608 Ma) accumulated fluvial clastic rocks of the Upper Freshwater Molasse (OSM). During this time the sea regressed for the last time and continental sedimentation started again. While these sediments were deposited the orogen-normal Alpine paleorivers drained into a southwestward flowing orogeny parallel drainage. The Napf- and Hörnli-fan formed forward and drained northwards into river systems (Sinclair et al. 1991). Sediments were derived from the Eastern Alps and transported in western direction (Kuhlemann et al. 2002). During the Langhian times a sediment decrease happened and in Serravalian time the sediment discharge increased in northern and western direction. Also a slowdown of subsidence occurred.

Figure 4: General Stratigraphy of the central NAFB: Kuhlemann et al.
The Molasse Basin went through four major evolutionary stages: Syn-rift phase, Epicontinental phase, Passive Margin phase and Alpine Foredeep phase (Véron 2005). The Syn-Rift phase were during the Carboniferous (358.9 Ma – 298.9 Ma) and Permian (298.9 Ma – 252.2 Ma). During these period narrow troughs formed along the ENE-WSW and WNW-ESE trends of the Variscan wrench faults, evincible in the Giftthal, Bodensee and Entlebuch troughs. In the Triassic (252.2 Ma – 201.3 Ma) and Middle Jurassic (201.3 Ma – 145 Ma) the Epicontinental deposits overstep the Variscan basement. In the Passive Margin phase in Middle Jurassic and Early Cretaceous (145 Ma – 66 Ma) transtensional and transpressional movements taken place correlated with Jurassic extensional events (Véron 2005, Burkhard et al. 1998).

![Figure 5: Overview of the geological era](image)
Permo-Carboniferous Basins (358.9 Ma – 252.2 Ma)

One part of the Variscan orogeny underlies the Molasse Basin. This part became uplifted and was subjected to erosion in Late Carboniferous. During Westphalian (315 Ma – 303.9 Ma) and Stephanian (303.9 Ma – 299 Ma) times the Variscides joined to a system of SW-NE striking grabens and troughs. This system began to subside in the Molasse Basin area (Bachmann et al. 1986). The subsidence is the result of the development of the Late Hercynian wrench-fault system with the Variscan fold belt and its European foreland.

Two troughs, containing Late Carboniferous sediments, are exposed in the Aar Massif. One of the troughs, the Giftthal trough, strikes NW-SE. The basement around the troughs was exposed to weathering and erosion during Permo-Carboniferous times. Rocks of this basement top zone are reddish and 1 to 10 m thick. This weathered zone has also Late Paleozoic clastics and red terrestrial cherts of the Late Permian age (Bachmann et al. 1986, Véron 2005).

Figure 6: Overview of the basement in Permo-Carboniferous times, including main troughs: Bachmann et al.

Triassic Basin (252.2 Ma – 201.3 Ma)

In the area of the Aar Massif carbonates, evaporates and marls of the Middle Muschelkalk time transgressed the basement. The Muschelkalk appears in three formations: Lower-, Middle- and Upper Muschelkalk with thicknesses lower and thicker as 50 m – 100 m. In the transgressive margin of the MB the Muschelkalk was built up of sandstones overlain by dolomites. During deposition in the Late Keuper
time the margin moved further in SE direction and the Keuper was overlaying the Muschelkalk (Bachmann et al. 1986).

**Jurassic Basin (201.3 Ma – 145 Ma)**

The change over of the basement to the Jurassic time is well documented in northeastern Bavaria. In the area of Lake Constance the isopachs tend to the SE and a possible opening for the newly formed South Penninic Ocean was reached. Transgression of the basin edges in S- and SE-direction took place in the Middle Jurassic (Dogger). In addition to the transgression the Aar Massif was flooded and the connection between the German Basin and the Tethys Ocean became enlarged. During the Late Jurassic (Malm) the Franconian Platform and the North German Basin were separated during the uplifted Rhenish-Bohemian Massif (Bachmann et al. 1986).
At the beginning of the Cretaceous a rapid shallowing of South German Shelf areas were caused due to eustatically regression. Continuing eustatically rising sea levels induced marine sedimentation and transgression from the south. Further regression caused deposition of carbonates, carbonate breccias and anhydrites as well as accumulation of the glauconitic Gault Sandstone of basement blocks from the Bohemian Massif due to uplift and erosion. In addition to the carbonates also predominant lithologies are limestones, marls and during Late Cretaceous series, sandstones (Bachmann et al. 1986). In the Lower Cretaceous the Alpine Orogenesis began.

During the Oligocene to Miocene subsidence of the Molasse Basin was active with inversion tectonics. In this earliest tertiary stage wrench tectonics were present in the German part of the MB. Further in the Miocene last deformations and thrust nappes happened with strong folding of the
southern margin of the MB, the Subalpine Molasse. The center and the northern margin of the basin displaced by continuous advance of the nappes in the north. In the Oligocene, especially in the Upper Rupelian (33.9 Ma – 28.1 Ma), the transition from the underfilled flysch to the overfilled molasse stage in the NAFB basin took place (Sinclair 1997). This was effected in the area of the Paratethys and the first megasequence, the Lower Marine Molasse, the Rupelian UMM was evolved. After a regression of the Paratethys and a contemporaneous backthrusting along the Insubric Line (Schmid et al. 1996) and advance of the orogenic wedge the Lower Freshwater Molasse (USM) were deposited (Schlunegger et al. 1997). The second megasequence started with the Upper Marine Molasse (OMM) coupled with a global sea-level rise in the Miocene. The NAFB was flooded and marine sediments were deposited. Also sands and clays were deposited basin wide. At the end of the Early Miocene during the Ottangian sea-level highstand a beach-cliff developed along the northern margin of the basin. In the Jurassic, limestone and siliclastic sediments were deposited (Grunert et al. 2010, Bachmann et al. 1986).

The Ottangian is a part of regressive / transgressive cycles starting in the Late Eggenburgian by a transgressive reestablishing of the Burdigalian Seaway, a marine pathway towards the Atlantic (Grunert et al. 2010). Further sediments were marked by brackish deposits due to completion of the seaways towards the Atlantic (Grunert et al. 2010). During the following Upper Freshwater Molasse (OSM) in the Late Miocene the sea finally retreated and the final filling stage of the basin was completed. The OSM is characterized by a fluvial environment and build up of alluvial fans along the southern basin margin (Kuhlemann et al. 2001). Mostly sandstones and marls are preserved in the basin. The sedimentation of the Molasse ended and the erosion of the deposits began since the end of the Late Miocene.

Figure 9: Overview of the tertiary Transgression: Bachmann et al.
The Cenozoic sediments are divided structurally into the Autochthonous Molasse and the Allochthonous Molasse. The Autochthonous Molasse rests relatively uninterrupted on the European basement. The Allochthonous Molasse, including the Imbricated Molasse, is composed of Molasse sediments, which are included in the Alpine thrusts and which were moved tectonically into and above the southern Autochthonous Molasse.

Present-day Tectonics

The Molasse Basin underwent characteristic units and evolutionary steps of a foreland basin, which are explained in the title ‘Basin Dynamics’ above. Two different approaches could be the explanation to the development of the North Alpine Foreland Basin. First approach refers to the autochthonous folding of the Jura nappe due to thrusting of the basement and wrench-faulting, and second approach deals with the distant push folding (“Fernschub”). The deformation of the Alpine foreland was over a basal décollement horizon (Mosar 1999). The tectonically activities today are reflected by earthquakes, ongoing uplift and out-of-sequence thrusts. The Alps have an uplift rate of 1 mm/a observed also in the Molasse basin (Salève area, France). The Earthquake hypocenters below the Foreland are evenly spread in a depth range of the upper crust at higher density above the brittle-ductile transition at 20 km (Mosar 1999). The reason for that is the presence of high-pressure fluids. The compression changes from N-S-orientation to NW-SE-orientation in the Vuache-Fault-System. The resulted deformation is measured by sinistral and dextral movements along NNE-SSW- and NW-SE-trending faults. The Vuache Fault system is one of the major tectonic fault zone that interconnects the Subalpine Chains to the Jura Mountains across the Molasse basin (Mosar 1999). Ongoing uplift is due to active thrusting along a thrust front and leads in the foreland basin to asymmetric subsidence, which results in a wedge-shaped basin-fill (Kuhlemann et al. 2001).

Conclusion

The sedimentary response in the Molasse Basin experienced three stages in the geodynamic evolution. In the first stage / megasequence (UMM) deep crustal processes led to crustal thickening. Crustal growth introduces an increase of crustal accretion and surface erosion. The transition from UMM to USM indicates a stratigraphic change from marine to terrestrial conditions. Figure 10 shows the increasing sediment discharge during this transition, because of the high subsidence rate of the Molasse Basin. The change of humid climate to continental climate conditions initiates the second stage to the OMM. This stage is the transition from overfilled to underfilled basin condition. It was suggested that the erosional decrease could be a possible deformation change of the orogen. The climatic control plays an important role in the third stage. More erosive conditions lead to an increasing sediment flux (Fig. 10) to the OSM. Two effects could be the reason for that: the active deformation shifts towards the orogenic central and a resulted flexural rebound of the foreland plate.
The evolution of the Molasse Basin depends on possible environmental effects. Weathering or other climate conditions and geodynamic events play an important role. Today it will be still discussed and new interpreted.

Figure 10: Summary, showing the pattern of sediment discharge to the north, the stratigraphic architecture, the progradation of topographic axis, the palaeoclimate and geodynamic events: Schlunegger et al. 2007
References


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