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Late orogenic rebound and oblique Alpine convergence: new constraints from subsidence analysis of the Austrian Molasse basin

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ABSTRACT

Subsidence analysis of 16 wells in the Austrian Molasse basin documents major spatial and temporal changes in tectonic subsidence. The timing of main tectonic subsidence phase shifted from early Oligocene in the western part of the peripheral foreland to the early Miocene in the eastern part. These temporal and spatial changes in tectonic subsidence reflect a change from oblique dextral to sinistral convergence between the Alpine nappe stack and its foreland. The main phase of sediment accumulation was retarded to the early Miocene and led to the infill of the basin and a major second, sediment load driven phase of basement subsidence. Sediment accumulation rates in the basin reflect the build-up of topography in the Alpine mountain chain. Since approximately 6 Ma a pronounced regional uplift of the entire Molasse basin has taken place, marking the transition from lateral extrusion to orthogonal contraction within the Alpine-Carpathian system and deep-seated changes in geodynamic boundary conditions, likely delamination of previously thickened lithosphere.

INTRODUCTION

Foreland basins develop in response to the bending of an elastic lithosphere due to loading by the advancing orogenic wedge and/or additional loads, as e.g. slab pull forces and thickened mantle lithosphere, operating on the lithosphere (Beaumont, 1981; Royden, 1993). Modeling of foreland basins so far has mostly only focused on the constructive stage of basin evolution, with relatively minor attention for their late-stage inversion of subsidence, as observed in the Austrian Molasse basin.

The Austrian Molasse basin provides a detailed stratigraphic response, from the late Eocene onwards, to the configuration of the Eastern Alpine orogenic wedge, allowing to place time constraints on the main young tectonic phases of the Alpine orogen. This is particularly important, as data on the timing of brittle deformation phases within the Alps are difficult to assess in the absence of related sediments. There are almost no other data on the uplift history of the Eastern Alps, apart from limited geodetic data on the present stage (e.g., Meurers, 1992) and exhumation histories from fission track data (Grundmann and Morteani, 1985; Staufenberg, 1987; Hejl, 1997). Below we will demonstrate that the stratigraphic record of the Austrian Molasse basin provides important constraints on magnitudes and causes of vertical motions within and adjacent to the basin.

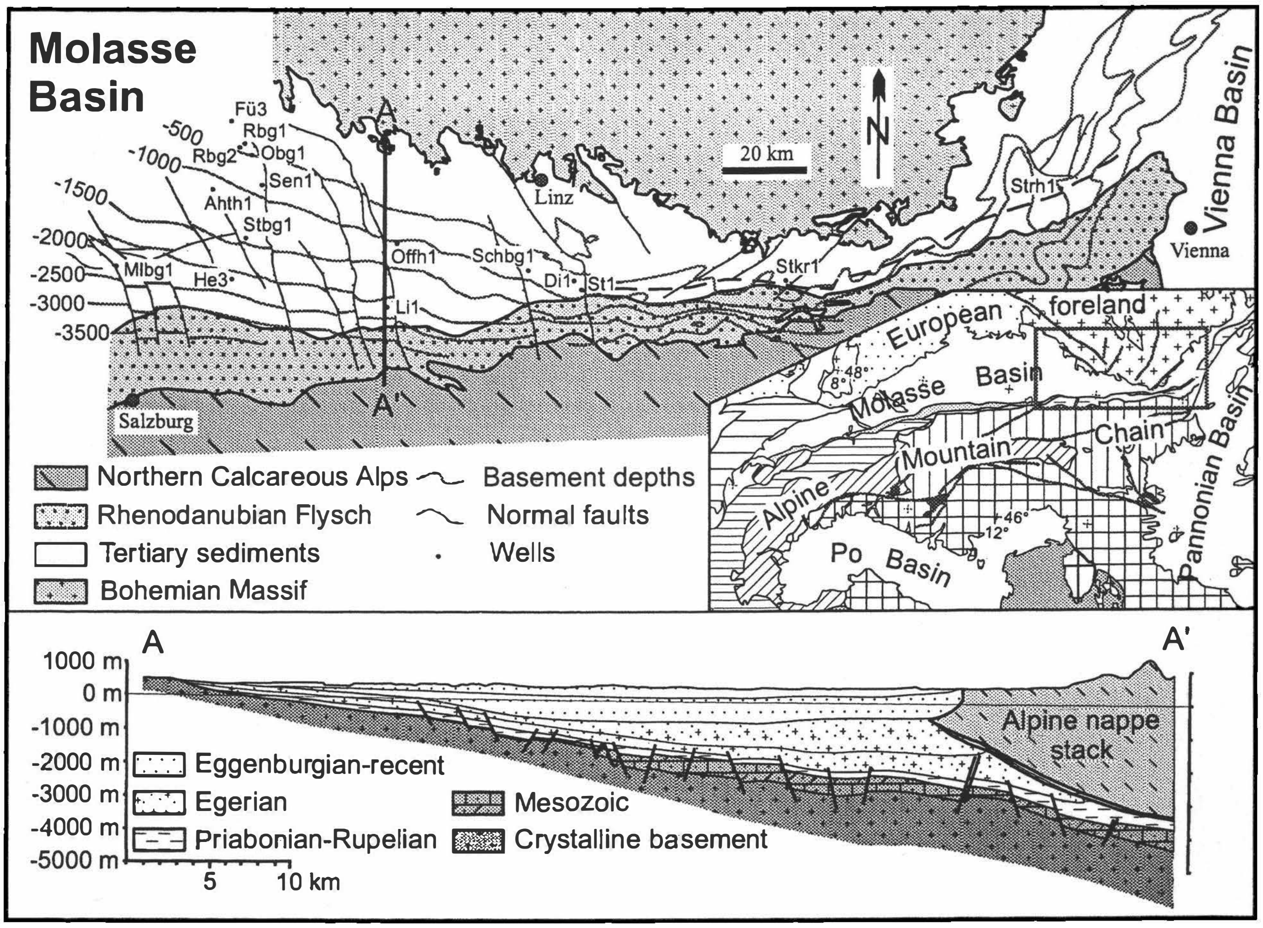

Fig. 1: a) Tectonic map of the Molasse basin and its surroundings, showing basement depths and location of analyzed wells. Inset shows setting of the investigated basin in the Alpine arc. b) N-S section displays the basin geometry and main depositional units of the basin.

STRATIGRAPHIC FRAMEWORK

The Molasse basin of the Alps (Fig. 1) is a classical foreland basin developed in response to the loading of the southern margin of the European plate after the final continent-continent collision (Lemcke, 1984; Bachmann et al., 1987; Wessely, 1987; Malzer et al., 1993). The Austrian Molasse basin displays strong lateral changes in shape with a decrease in width from about 150 km in the German Molasse basin to less than 10 km at the spur of the Bohemian Massif (Fig. 1). To the east the basin widens again and changes its strike from E-W to NE-SW. Also the basement depths of the basin at its southern margin decrease from about 3500 m in the west to about 500 m in the east. In the same direction the ages of the oldest Molasse strata get increasingly younger (Malzer et al., 1993). The overriding Alpine nappe complex comprises structurally upwards units derived from the outer shelf to slope of the European continental margin, followed by the Flysch nappes, and finally the Austro-Alpine complex in an upper plate position. The youngest sediments of these units are of lower Eocene ages. Reflection seismic profiles and well data support a post-Eocene shortening of more than 200 km (Wagner et al., 1986).

The Molasse sequence started in the Late Eocene with the subsidence of the European plate, with a deepening towards the south (Lemcke, 1984; Bachmann et al., 1987; Malzer et al., 1993). Sediments range from terrestrial to shallow marine clastics and limestones to marls of a deeper shelf. In the Latdorfian (early Oligocene), the basin subsided quickly to water depths of several hundreds of meters and dark shales to marls of a restricted basin were deposited. They are overlain by the Rupelian (32-28 Ma) sequence of light chalky marls, overlain by banded marls and then silty shales to marls. These marls pass into sandstones and conglomerates towards the south, that were derived from the rising Alps. Along the northern rim of the present basin and the spur of the Bohemian Massif terrestrial sediments prevailed. In the Egerian (28-20.5 Ma), the basin configuration remained essentially the same with terrestrial to shallow marine conditions along the northern margin. In the southern part of the basin thick turbiditic fans were shed into the basin. At the same time the southernmost part of the basin was overridden by the advancing nappe complex, incorporating also Molasse sediments (Malzer et al., 1993).

With the Egerian (20.5-18 Ma) the orogenic wedge reached essentially its present position and the basin axis shifted to the north. The basin also shows a transgression to the north and the spur of the Bohemian Massif shows a first major phase of subsidence. The main sediments were still sandy to silty shales and marls, only the turbiditic influence decreased. In the Ottnangian (18.0-17.2 Ma), the basin shallowed progressively and finally the sea regressed to the east of the Bohemian Massif at the end of this stage. From the Karpatian to the Pannonian terrestrial sediments were deposited in the basin west of the Bohemian Massif, which can be divided into several lithozones (Unger, 1989). These represent bodies of different sediment sources and transport directions and are also divided by erosional gaps. Only close to the Vienna basin marine ingressions into the Molasse basin occurred up to the Sarmatian. In the Pannonian, a change from mainly W-directed to E-directed transport occurred. After the Pontian mainly erosion of the sediments took place, induced by the uplift of the Molasse basin. This uplift is documented in the present elevation of the shallow marine sediments of the late Ottnangian of about 550-600 m above sea-level.

SUBSIDENCE ANALYSIS

Subsidence analysis of the Molasse basin was carried out for 16 wells together with an evaluation of seismic sections. We used the stages for the central Paratethys for the stratigraphic correlation and the absolute time scale of Steininger et al. (1996) for the Miocene to Pleistocene, and that of Cande and Kent (1992) for older stages. Most of the time markers used are sequence boundaries that are biostratigraphically tied to the stages of the central Paratethys (see also Jin et al., 1995). Sediments were decompacted accounting for lithology-dependent vertical fluid escape during decompaction with the program package PDI (IES, Jülich). We used program defined lithologies that match the observed lithologies. Missing stratigraphic sections were reconstructed from adjacent well data, seismic profiles, and geological maps. These eroded sections are less than about 200 m in most wells. For the easternmost wells no reconstruction of missing sections was made due to the widespread erosion of the youngest strata in this area.

Along the northern margin of the basin shallow marine sediments allow us to obtain relatively well constrained water depths. Also to the west, during the Egerian, a deep marine basin (Puchkirchen basin) graded into shallow marine to terrestrial sediments (Lower Freshwater Molasse), pointing to an increase in water depths from the N to the S and from the W to the E. The subsequent terrestrial sediments range from the Karpatian to the late Pannonian/early Pontian (7.1 Ma). In the Vienna basin, close to the east, marine conditions prevailed up to the Sarmatian and changing transport directions in the Molasse basin point to very low east-west topographic gradients and low elevations up to this time span. We, therefore, conclude that major surface uplift of the basin commenced only in the Pontian.

Backstripping of the sediments to reconstruct the basement shape due to tectonic loading was carried out for a local isostatic model. The inferred general shape of the tectonic subsidence curve and the timing appear to be rather insensitive to assumptions on the flexural properties of the foreland plate. Subsidence curves corrected for eustasy (Haq et al., 1987) display only minor differences to uncorrected curves of both basement and tectonic subsidence and are largely well within uncertainties in water depths (Fig. 2).

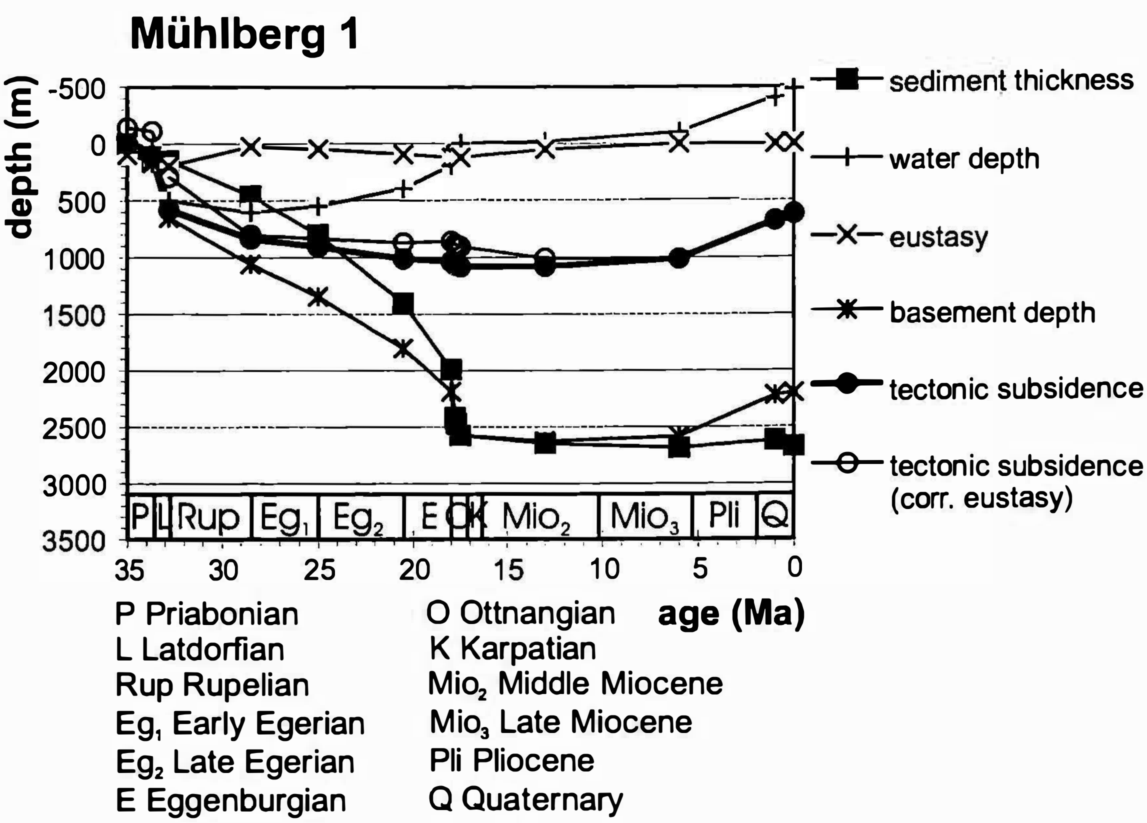

Fig. 2: Geohistory diagram displaying sediment thicknesses, basement subsidence, tectonic subsidence, water depths, and eustasy in time for well Mlbg 1 (Fig. 1a). Tectonic subsidence for local isostasy with a mantle density of 3,300 kgm^{-3}, sediment densities as calculated by the decompaction procedure.

SUBSIDENCE PATTERNS

Along a N-S section in the western part of the Austrian Molasse basin all wells show similar temporal subsidence evolutions (Fig. 3). Subsidence started in the Late Eocene. In the early Oligocene, the basin strongly subsided to greater water depths and reached already large fractions of the maximum amounts of tectonic subsidence. The basement subsidence curves display for this time slice decreasing subsidence rates, followed by an increase in the Ottnangian. Basement subsidence is mainly driven by sediment loading and thus mainly reflects changing sediment accumulation rates. Only in the Ottnangian minor tectonic subsidence occurred. Basement depths and the amount of tectonic subsidence are well defined for the end of the Ottnangian, as paleowaterdepths are tightly constrained by the transition from marine to terrestrial conditions. After the Ottnangian subsidence rates decreased strongly. Subsequently, uplift to the present observed depths occurred with similar, only slightly decreasing amounts away from the orogen along the whole profile normal to the trend of the basin. The estimated tectonic uplift is in the order of 500 m, leading to a reduction of the present tectonic subsidence to about a half of its maximum values in the southern part of the basin and to net uplift in the peripheral part of the basin. The total amount of uplift since the Ottnangian/Karpatian is well constrained by the available data. The exact timing is more uncertain, with evidence for a major uplift beginning at the end of the concordant sedimentation in the Pontian.

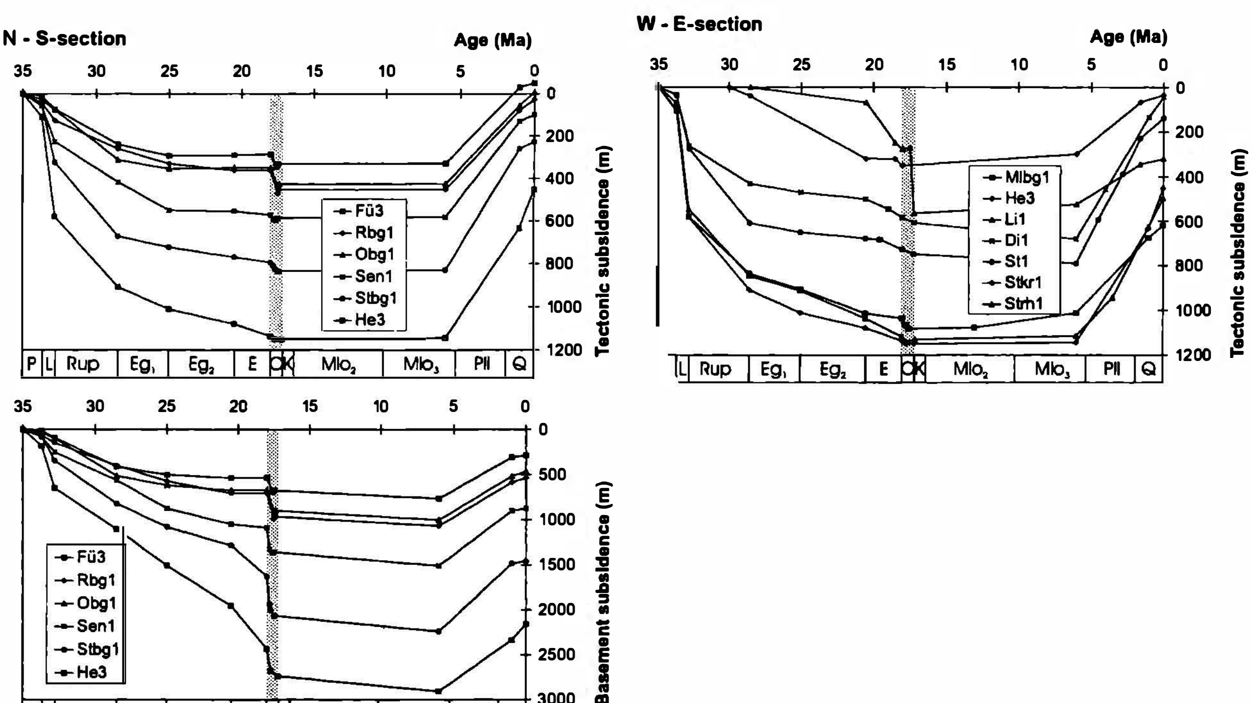

Fig. 3: Temporal evolution of subsidence in time. For stratigraphic stages, see Fig. 2. a) Tectonic and basement subsidence for N-S profile. b) Tectonic subsidence for E-W profile (for location of wells, see Fig. 1a).

Parallel to the Alpine front the basin displays marked differences in its subsidence history (Fig. 4). Towards the east, initial subsidence is retarded, occurring only in the late Egerian east of the spur of the Bohemian Massif. There, tectonic subsidence rates strongly increased in the Eggenburgian and Ottnangian, leading to the formation of the present eastern Austrian Molasse basin and the N-S trending spur of the Bohemian Massif. The subsequent tectonic uplift occurred along the whole strike of the basin, decreasing towards the east from about 600 m to 200 m. At the spur of the Bohemian Massif, tectonic subsidence was almost completely reversed.

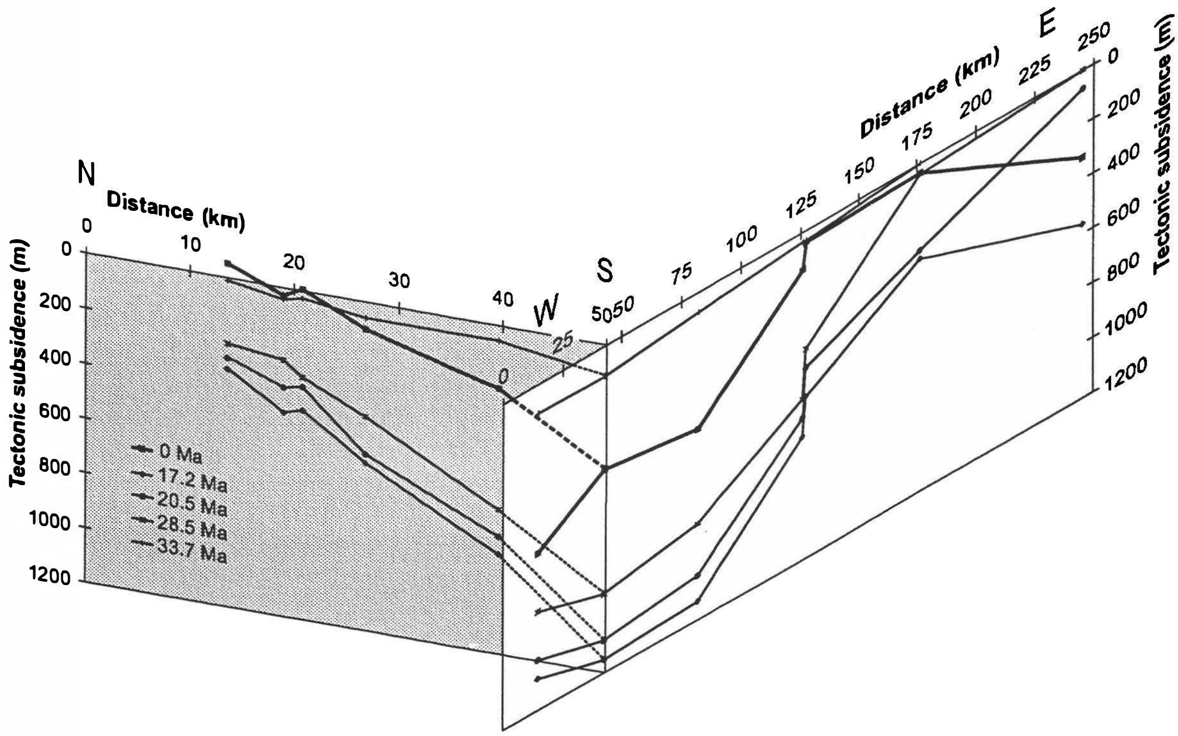

Fig. 4: Spatial view of tectonic subsidence for different time slices.

CONSTRAINTS ON MECHANISMS FOR LATE CENOZOIC VERTICAL MOTIONS

The subsidence patterns record several sharp transitions that appear to reflect three major temporal changes in the geodynamic evolution of the orogenic belt.

Stage 1. Onset of foreland subsidence and its linkage with the internal Alpine orogen. The onset of subsidence during the Eocene may represent initial stages of flexural loading of the European continental crust by the advancing Alpine nappe complex and thickening of the Alpine nappe complex (Fig. 5a). Detailed work in the Eastern Alps revealed a kinematic path of dextral transpression during overthrusting of thinned continental outliers and the southern margin of the European continental lithosphere (Kurz et al., 1996; Genser et al., 1996). These basement rocks are presently exposed within the Penninic Tauern Window, and show a general WNW-directed transport direction up to the metamorphic peak, that has been dated at between about 30 and 20 Ma. Subsidence in the western part of the Austrian and the Swiss and German Molasse basin appear to record, therefore, the collisional coupling of the European continental margin and the evolving Alpine nappe stack in the late Eocene to early Oligocene.

Stage 2. Full coupling of internal orogen with Molasse basin. In the late Early Miocene (Eggenburgian to Ottnangian) strong tectonic subsidence commenced in the eastern part of the Austrian Molasse basin. This stage coincides with the transition from WNW-directed contraction to eastwards directed lateral extrusion of central sectors within the Eastern Alps (Ratschbacher et al., 1991). The extruding wedge was bound by sinistral strike-slip faults that reach up to the foreland basin along its northern sector. Displacement along these faults led to progressive loading of more eastern parts of the foreland, whereas the preceding WNW-directed transport was subparallel to the strike of the Austrian Molasse basin. Lateral extrusion is associated with gravitational collapse of upper sectors within the Alpine nappe edifice and tectonic unroofing of metamorphic core complexes (Ratschbacher et al., 1991; Kurz and Neubauer, 1996). Sediment accumulation rates increased in the Early Miocene and peaked during the Ottnangian. As the basin configuration remained essentially the same, accumulation rates reflect sediment input rates and creation of topography in the adjacent mountain belt. The timing of extension and the formation of metamorphic core complexes in the internal zone are constrained by cooling ages of the uplifting metamorphic Tauern dome at between about 22 and 14 Ma. As this tectonic phase has led to the construction of strong topographic gradients, ongoing convergence between the European and Adriatic plates was likely largely compensated by orogenic thickening and lateral extrusion. The changes in displacement paths are also expressed in changing paleostresses directions and regimes in frontal parts of the Alpine nappe edifice (Decker et al., 1993).

Stage 3. Final uplift. Several mechanism, leading to either changes in the load configuration or the mechanical state of the flexed plate, may contribute to the late stage uplift of central and northern sectors of the Eastern Alps, comprising the Molasse basin. These include (for resulting subsidence/uplift patterns see Fig. 6): (1) Viscous relaxation of the flexed plate, reducing the flexural wavelength, would lead to uplift of peripheral parts of the basin, and subsidence of the internal parts (e.g., Beaumont, 1981). This is in contradiction to the observed uplift pattern with the highest amount of uplift at the orogenic front and only slightly decreasing amounts towards peripheral parts. Changes in loading can be either due to superficial processes, as (2) erosional or tectonic denudation of central sectors of the Alps, the former possibly enhanced due to climatic changes. The resulting uplift patterns resemble the observed ones, but especially for low effective elastic thicknesses (EET), as appropriate for the Molasse basin (compare observed and calculated basement profiles), uplift should vanish in peripheral parts of the basin and would also give stronger gradients. Additionally, judging from apatite fission track data (Grundmann and Morteani, 1985; Staufenberg, 1987; Hejl, 1997), denudation rates in this time span high enough to bring about the unloading required for the observed uplift, are only reached in a few places in the internal part of the Eastern Alps. Deep-seated processes leading to unloading can be either (3) slab break-off or (4) distributed delamination or convective removal of mantle lithosphere. Slab break-off, simulated by dropping previously applied end loads (vertical shear stresses and/or bending moments), leads to either negligible repercussions on the peripheral basin for low EETs or additional subsidence in the basin for large EETs due to shallowing of the peripheral bulge that is related to the end loads.
Therefore, we conclude that the late stage wide-spread uplift of the entire Alpine realm including the northern peripheral foreland basin is most likely explained by distributed delamination and/or convective removal of overthickened lithosphere and northward spreading of the mechanical decoupling between mantle and crust of the subducted lithosphere, enhanced by erosional unloading. This late-stage major change in the geodynamic boundary conditions of the Alpine system is also expressed in its present gravimetric state (Lyon-Caen and Molnar,

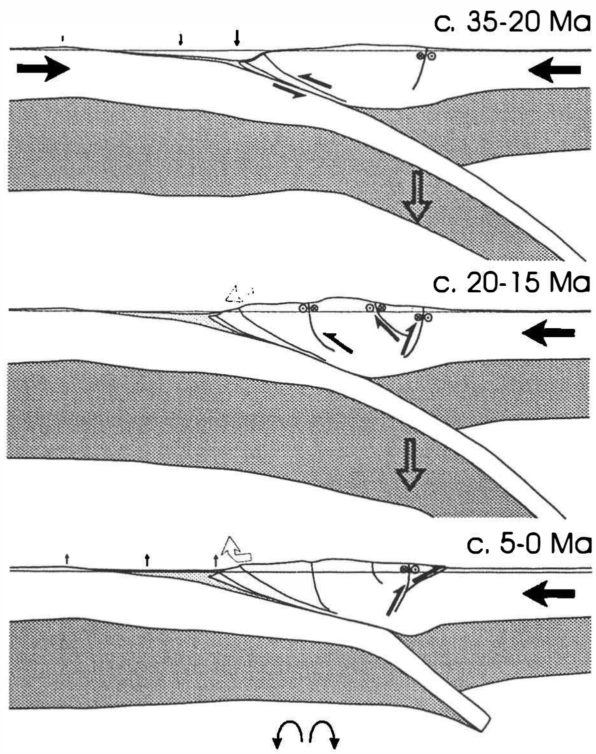

Fig. 5: Proposed model for three-stage evolution of the eastern sector of the Alpine Molasse basin. a) Rapid initial foreland basin formation due to loading by the advancing Alpine nappe stack of the subducting southern margin of the European plate. b) Coupling of lower European plate and frontal orogenic wedge. Compensation of ongoing convergence by vertical thickening, leading to increasing sediment supplies to the foreland basin, and lateral extrusion (out of plane). c) Widespread uplift due to delamination and/or convective removal of thickened lithosphere and minor erosional unloading.

1989). Recently, a number of studies have shown that the lithosphere in the cores of Alpine orogens is relatively weak (Okaya et al., 1996; Cloetingh and Burov, 1996), promoting the development of mechanical decoupling between upper crustal flexure and mantle lithosphere. Supporting evidence comes from modeling that resulted in unusual low effective thicknesses of the Northalpine Molasse basin. Values range between c. 25 km in the west and 10 km close to the investigated area (Andeweg and Cloetingh, 1998). Very low values were also reported from the mountain core (Okaya et al., 1996) and the western sectors of the Pannonian basin (Sachsenhofer et al., 1997). The timing of the mechanical decoupling appears to reflect major thermal relaxation following rapid exhumation of mechanically weak crust in the Early Miocene (Genser et al., 1996).

The onset of late Molasse basin uplift and similar uplift of the Styrian basin and western part of the Pannonian basin (Sachsenhofer et al., 1997) occurs at the time of a major reorganization of the external stress field at 6-5 Ma, recently recorded in the central European realm (e.g., Horvath and Cloetingh, 1996; Peresson and Decker, 1997). Such changes in stress acting on weak, decoupled lithosphere, caused by delamination, could provide an effective mechanism for regional rapid vertical motions of the crust. Lithospheric delamination is also inferred from the 6-5 Ma onset of alkaline volcanism in the western part of the Pannonian basin, the Po basin, and the northern foreland of the Alps (e.g., Embey-Isztin et al., 1993).

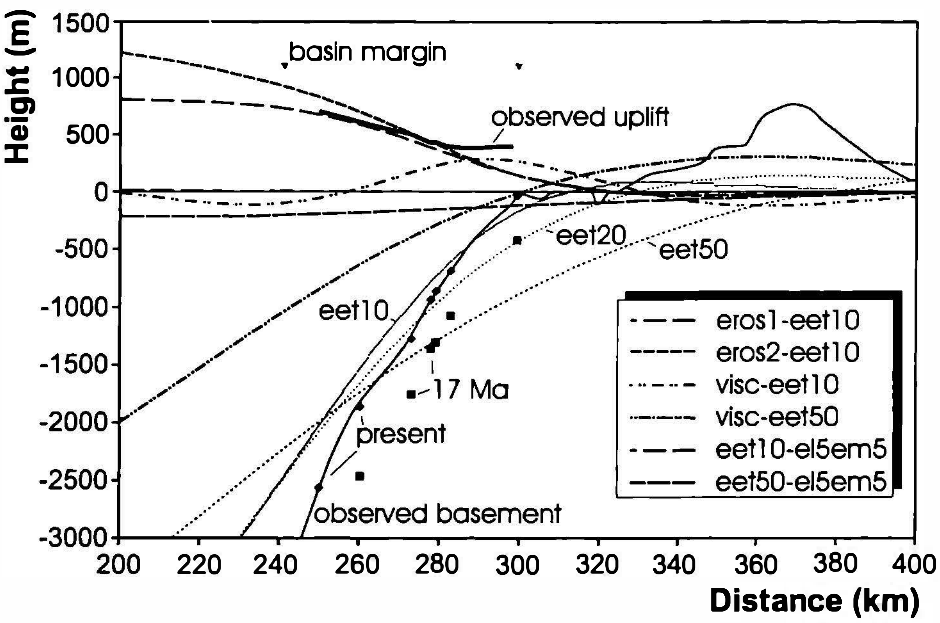

Fig. 6: Observed uplift pattern and basement depths in comparison to modeled basement profiles (for effective elastic thicknesses (EET) of 10, 20, and 50 km, respectively) and uplift/subsidence patterns for different scenarios: (1) Erosional unloading in orogenic wedge by 1 km (eros1-eet10) and 2 km (eros2-eet10), respectively, for a flexed plate with an EET of 10 km; (2) viscous relaxation (visc) of plates with initial EETs of 10 and 50 km, respectively; (3) dropping of an initially applied vertical shear force of $5 \cdot 10^{12}$ N/m and a bending moment of $5 \cdot 10^{16}$ N at the end of the plate (0 km) for plates with EETs of 10 and 50 km, respectively.

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