Facies of Molasse based on a section across the central part of the Swiss Plateau

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Summary of presentation and excursion guide given at the SASEG annual convention, Lucerne, Switzerland, June 2012

1. Introduction

The Canton of Lucerne and its neighbouring areas offer an excellent insight into the deposits of the Molasse Basin by providing a cross-section through the entire stratigraphic sequence from the Lower Marine Molasse to the Upper Freshwater Molasse, covering also the entire range of depositional environments from the proximal facies of the Subalpine Molasse to the distal facies in the North. The often excellent outcrops of the molasse in the Lucerne area were not only the target of many excursions (e. g. Matter et. al 1980) but they also inspired early generations of scientists: In his 1726 monography on the Pilatus, the Lucernese medical doctor and engineer, Moritz Anton Kappeler (1685 - 1769), provided the first correct genetic interpretation of the conglomerates (Nagelfluh) of the Rigi mountain and of the ripple-marks in the Luzerner Sandstein (Fig. 1), based on his observations of recent deposits in the Gulf of Naples – one hundred years before Charles Lyell, who in the Angloamerican literature is generally seen as the founder of actualism and thus of the modern geology (Trümpy 2003). The

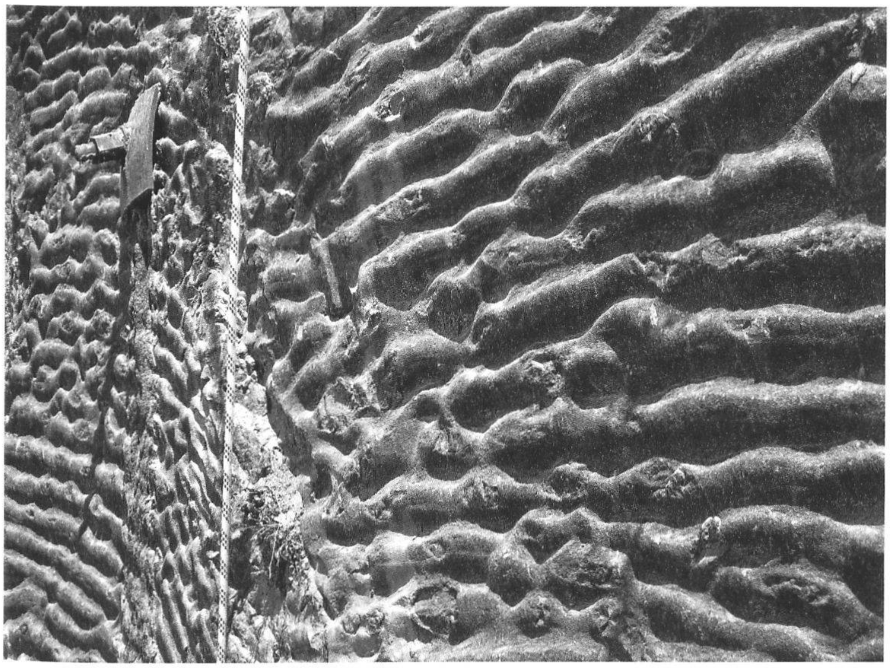

Fig. 1: Asymmetric wave ripples, flattended by the falling water table on a bedding plane in the former quarry Untergrund (Lucerne).

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Lucerne Molasse achieved fame also through the groundbreaking monographies of Kaufmann (1860, 1872), and only recently Schlunegger et al. (1997) reinterpreted the sequences of the Napf and the Rigi in the light of the alpine orogeny. The paper below sums up some of the important events in the Lower Freshwater Molasse, the Upper Marine Molasse and the Upper Freshwater Molasse. For a detailed description of the excursion stops see Keller (2000).

2. Overview

Stratigraphy

The stratigraphic overview in Fig. 2 explains the supergroup of the Molasse as the younger part of the sedimentary fill of the Alpine Foreland. The transition from the turbiditic sediments of the youngest and northernmost alpine Flysch-trough to the Molasse sedimentation took place at the base of the Lower Marine Molasse. The Molasse is characterized by two major sedimentary sequences, during which large alpine alluvial fans prograded. In Central Switzerland these are the alluvial fans of the Rigi-Rossberg in the Lower Freshwater Molasse and of the Napf fan in the youngest Upper Marine Molasse (St. Gallen Formation) and in the Upper Freshwater Molasse. Interestingly we find widespread lacustrine deposits at the basis of these fan sequences, indicating a temporary initial underfill of the Molasse Basin.

Tectonic development

The development of the tectonical history can best be explained at the example of the Rigi profile (Fig. 4). Kaufmann and Heim (1919), with their only limited knowledge of the stratigraphic relationships, saw in their «anticlinal theory» the Rigi still as the proximal sedimentary realm of the Miocene Upper Marine Molasse. Only the studies of Baumberger (1925, 1929) attributed the subalpine Molasse of the Rigi to the Oligocene, thus for the first time recognizing the unit as a Molasse-nappe dipping southwards towards the Alps. Due to the lack of deep data the real tectonic structure between the overthrust in the south and the monoclinal fold in the north is unclear until today: Trümpy (1979) interpreted the sequence as steep folds and imbrications while Burkhart (1990), with his first palinspastic reconstruction, interpreted it as a classical, well structured thrust belt, something that was also taken over by Schlunegger et al. (1997). Dipmeter measurement in the 2'300 m geothermal well of Weggis TH1 indicate a complex imbrication at the base of the mainthrust of the subalpine Molasse (Greber et al. 1994), a geometry hardly compatible with the previous interpretation of a well structured thrust belt. Keller + Lorenz AG / Geoform AG (2011) presented two entirely newly constructed geological-tectonical profiles, where the area between the monoclinal fold and the main thrust is presented as a simple triangle zone. In addition several, so far not known, Permo-Carboniferous troughs are shown (Fig. 5).

3. Lower Freshwater Molasse

The excursion gives a unique overview of the Molasse system from the Rigi in the South to St. Urban and Roggwil in the North, leading from the proximal facies of the Lower Freshwater Molasse to the distal facies.
In the overthrusted Molasse-nappe of the Rigi, the 3,000 m thick deposits of the Rigi-Rossberg-Fan represent the southernmost and most proximal facies realm. Well visible from a boat on Lake Lucerne is the westflank of the Rigi Mountain with its pronounced thick bands of conglomerates (Fig. 6), which are representing individual sedimentation lobes of the alluvial fan consisting of amalgamated, braided river deposits (Fig. 7). These rock bands carry the local name «Riginen». Individual conglomerate lobes are separated

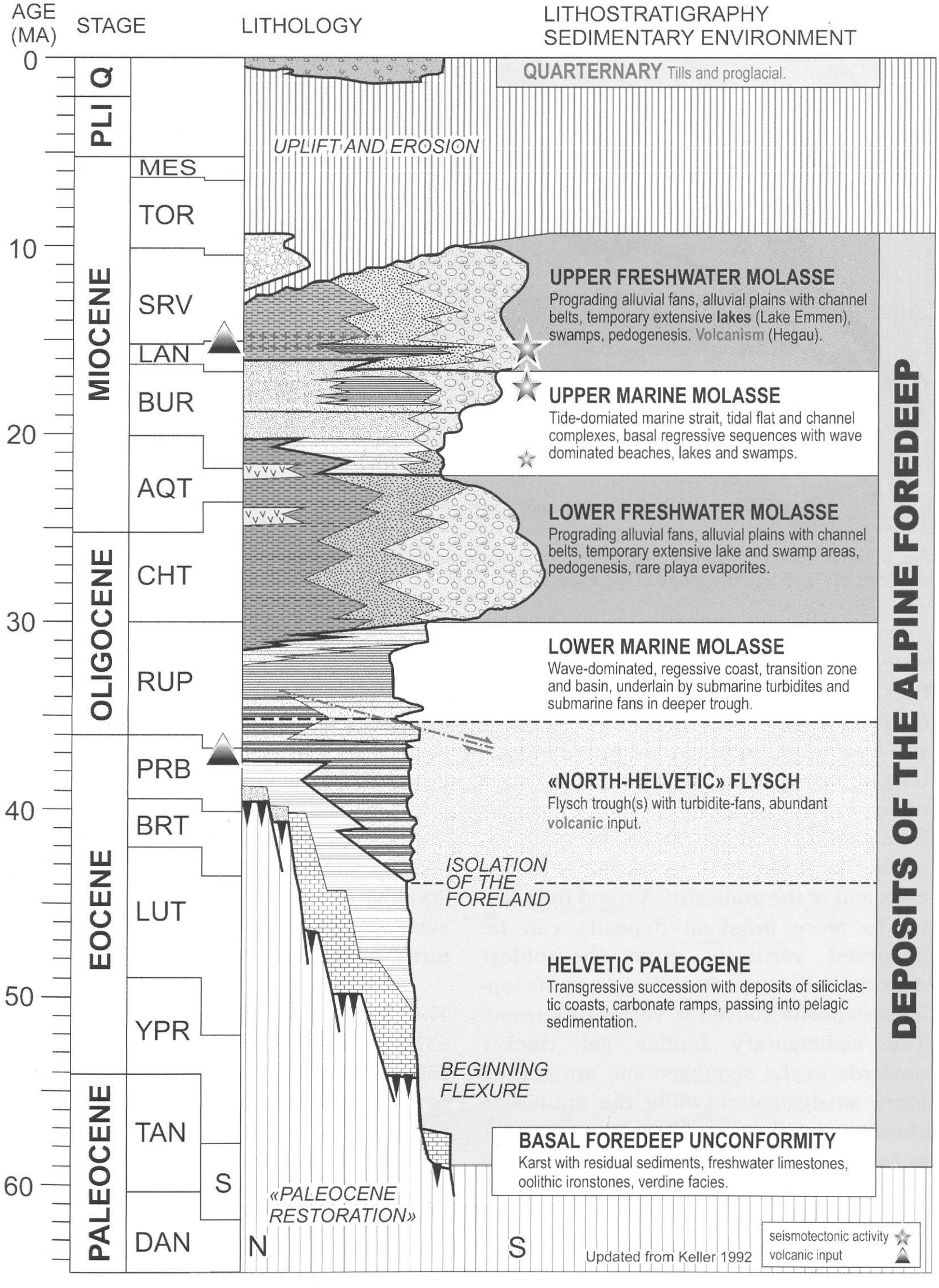


Fig. 2: Summary stratigraphic section of the Alpine foredeep (updated from Keller 1992).

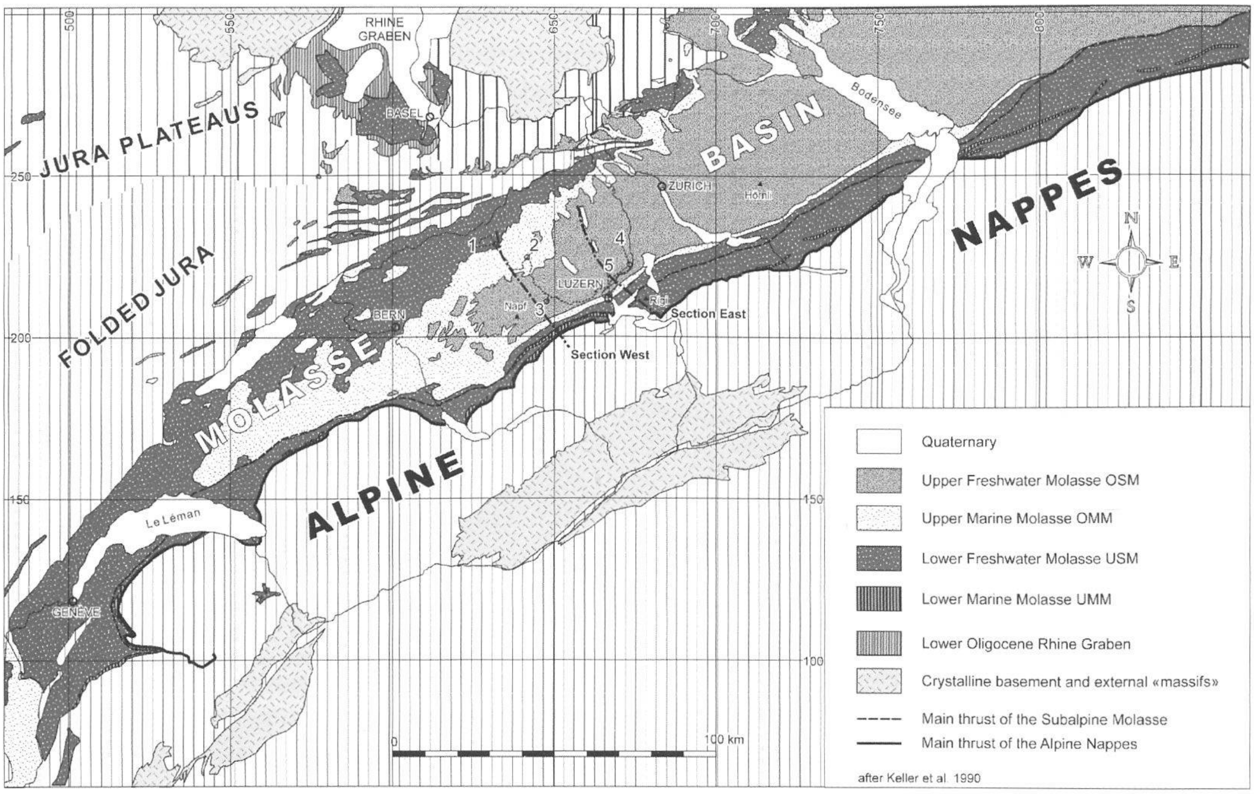
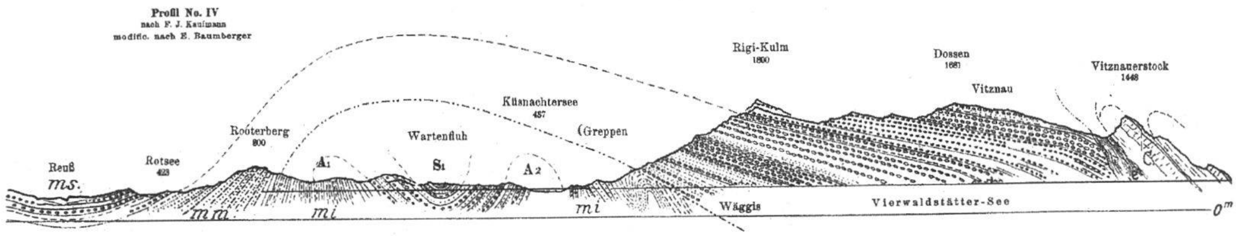


Fig. 3: Generalized geological map of the Swiss Molasse Basin (after Keller et al. 1990). Indicated are the sections of Fig. 5 and the stops of the excursion.

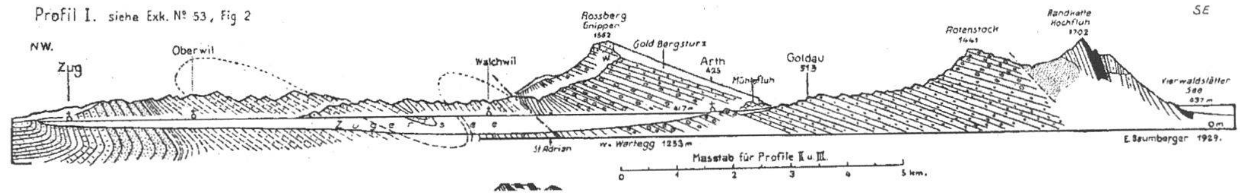
by stronger weathering, sandy-pelitic deposits from flooding periods, partly with soil formation. Within these up to several tens of meter thick conglomerate beds we observe from south to north a transition from proximal to distal fan deposits, accompanied by a decrease in thickness of the beds and of the grain size. A trend from distal to more proximal deposits can be observed vertically, from the oldest deposits at the base, near Weggis, to the topmost deposits above the village of Vitznau: The sedimentary bodies get thicker upwards in the sequence and are getting more amalgamated, while the grain size shows a coarsening upwards trend from 0.1 m to 1.9 m for the largest pebbles (Stürm 1973).

The intermediate facies belt of the «Deckensandsteine» - giving rise between Meggen and Küssnacht to a conspicuous landscape of pronounced bedding ribs - can be studied best at the roadside outcrops near Seeburg (outskirts of Lucerne, coordinates: 668‘850/210‘950). Here amalgamated stacked channel belts of sandy braided rivers can be observed with lateral sand bars and internal cross-bedding of megaripples. At the top and in an erosional contact the sequence is overlain by heterolithic, partially pedogenic flooding deposits. These are occasionally accompanied by several metre-thick structureless sheetflow conglomerates.

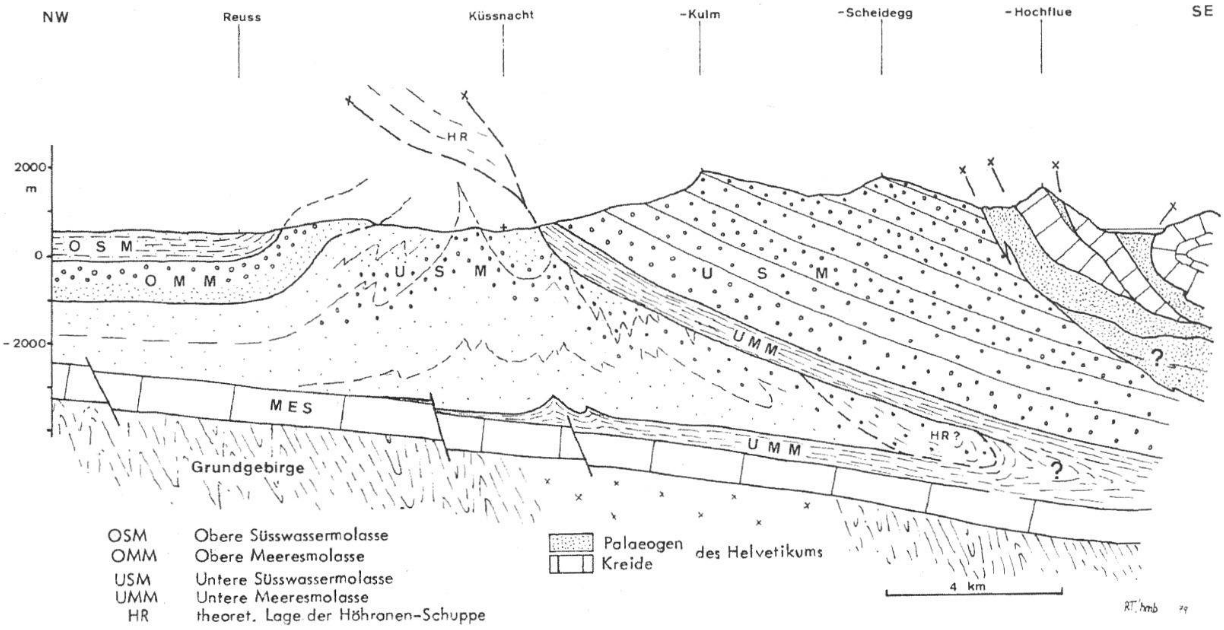
The marlpits at St. Urban LU (coord. 631’500/228'650) Roggwil BE (coord. 630‘100/230‘200) provide excellent outcrops of the distal facies of the Lower Freshwater Molasse. They are part of an axial mainstream system that drained to the ENE towards the Oligocene palaeocoast in the area of Munich. These outcrops give good examples of the sedimentary architecture for which Keller et al. (1990) established a simplified concept on the basis of regional lithofacies studies (see also Keller 1992, Platt &



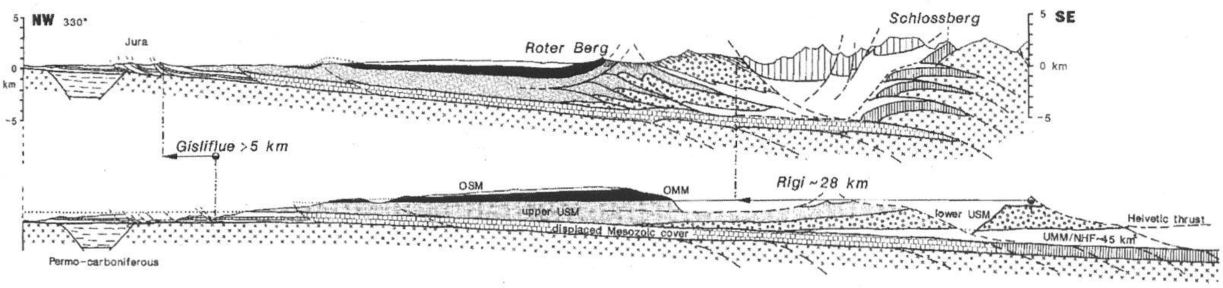
Heim 1919, after Kaufmann



Baumberger 1929



Trümpy 1979 (unpubl.)



Burkhard 1990

Fig. 4: Selection of different interpretations of Rigi-profiles from 1919 to 1990.

Keller 1992): The following architectural elements can be differentiated in the distal Lower Freshwater Molasse (Fig. 9): meander belt sandstone (MB), crevasse splays and channels (CS), levee sandstones and siltstones (LS), distal splay sandstones (DS), overbank fines, palaeosols and swamps (OPS) as well as subordinate lacustrine deposits (LAC) , especially in the western part of the basin. The summary facies model of Fig. 8 illustrates the sedimentary environments of the different architecture elements.

At the outcrop of the marlpit Roggwil (Fig. 10) the lower part shows the sandstones of a massive amalgamated meander belt (MB) with several crevasse channels and crevasse splays (CS). The crevasses channels show clear erosion of the underlying strata. Together with numerous distal splay (DS) these sandstones are lying in a matrix of pelitic, generally ochre to reddish coloured deposits of the floodplain with palaeosoils and swamps (UPS), the raw material used for brick manufacturing.

4. Upper Marine Molasse

The depositional environment of the Upper Marine Molasse was for a long time disputed, in spite of the fact that Speck (1945) had postulated a fossilized tidal flat area («versteinertes Wattenmeer») on the basis of trace fossils and sedimentary structures. On the evidence of «tidal sandwaves» Nio (1976) was able to prove for the first time the existence of strong tidal currents. Since then the Burdigalian seaway was seen as a tidal sea with meso- to macrotidal conditions (e. g. Homewood et al. 1986). A contradiction emerged, however, when two diploma geologists from Bern, Benkert (1984) and Hammer (1984) proposed on the basis of their sedimentological studies of the southern palaeocoast a microtidal regime, where the tidal amplitude was subordinate to the wave action.

This apparent contradiction was resolved by Keller (1989) after detailed sedimentolog-

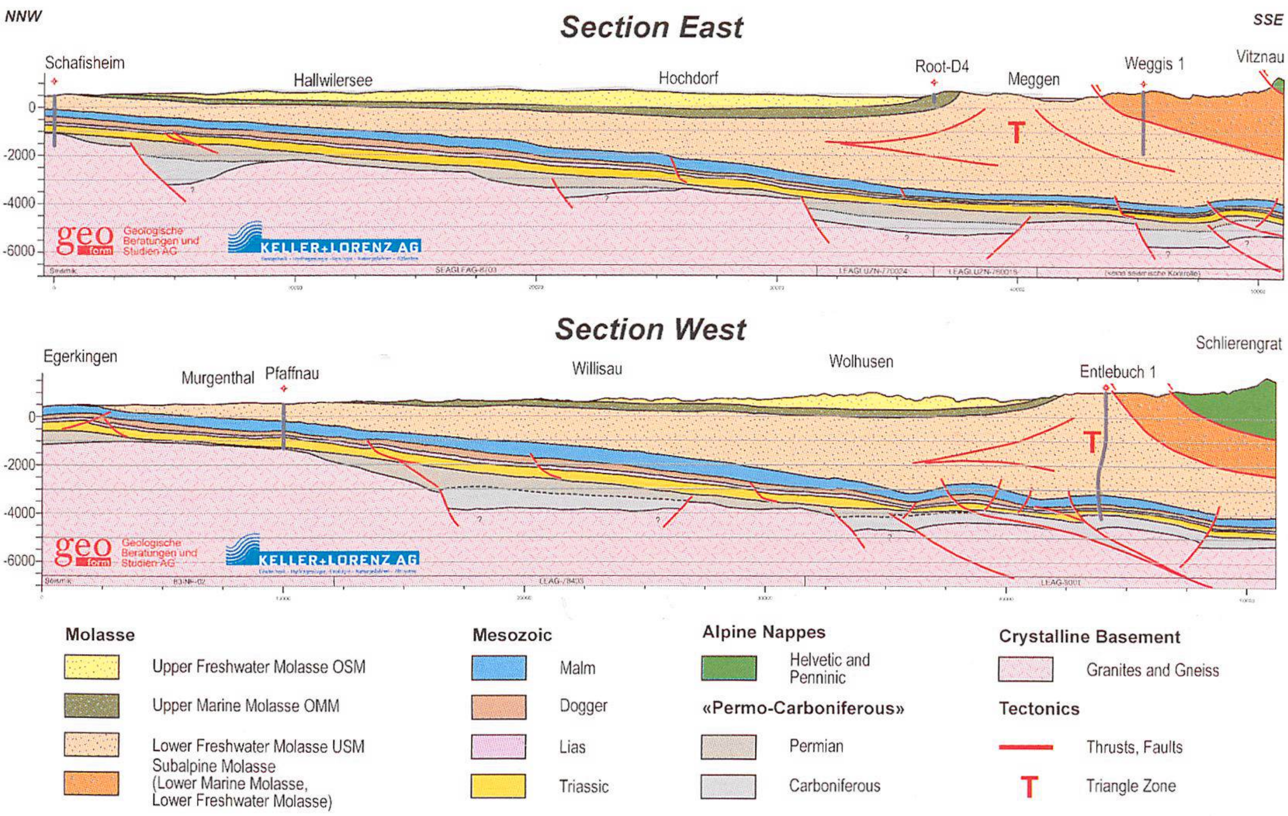


Fig. 5: Cross sections of the Molasse Basin of Central Switzerland (Keller + Lorenz AG / Geoform AG 2011).

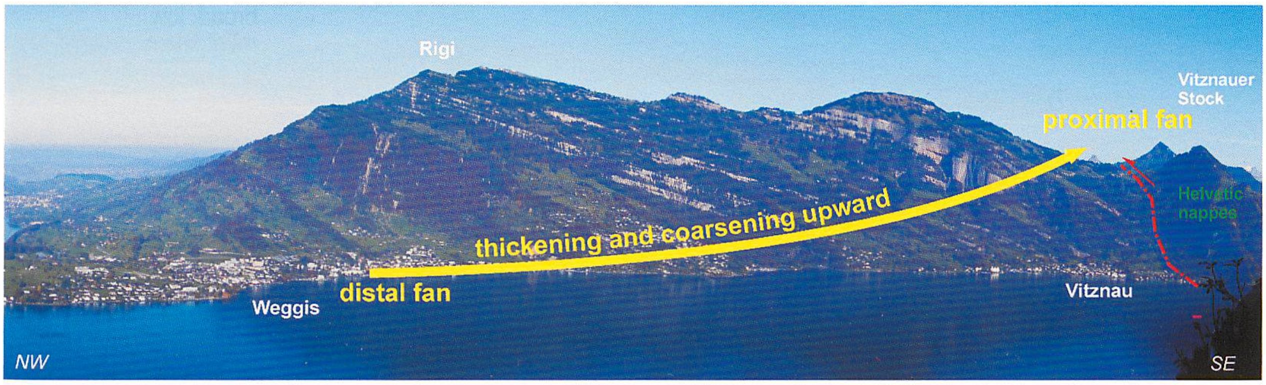


Fig. 6: View of the Rigi. The overthrusted Molasse-nappe consists of deposits of the Rigi alluvial fan of the Lower Freshwater Molasse. Clearly visible are the individual, northwards thinning depositional lobes («Riginen»), separated by stronger weathering flood deposits. From the older deposits in the north (Weggis) to the younger deposits in the south (above Vitznau) a clear coarsening- and thickening upwards trend can be seen, reflecting the prograding fan.

ical and lithostratigraphic analyses of the Upper Marine Molasse between Napf and Bodensee: In the course of the sedimentation in the narrow Burdigalian seaway, which linked the Mediterranean in the west with the Paratethys in the east, the palaeogeopgraphic and palaeohydrographic conditions changed repeatedly as a consequence of transgressive and regressive cycles. The influence of wave action, tidal currents and sediment input (deltas) and the resulting facies are shown in the ternary diagram of Fig. 11. At the base of the Upper Marine Molasse we find several regressive sequences, deposited under micro-tidal conditions and wave domination. The following transgression led to an increase of the tidal amplitude and the formation of standing tidal waves under meso-tidal conditions, similar to the present day situation in the Bay of Fundy (SE Canada), where the tidal amplitude has increased significantly with

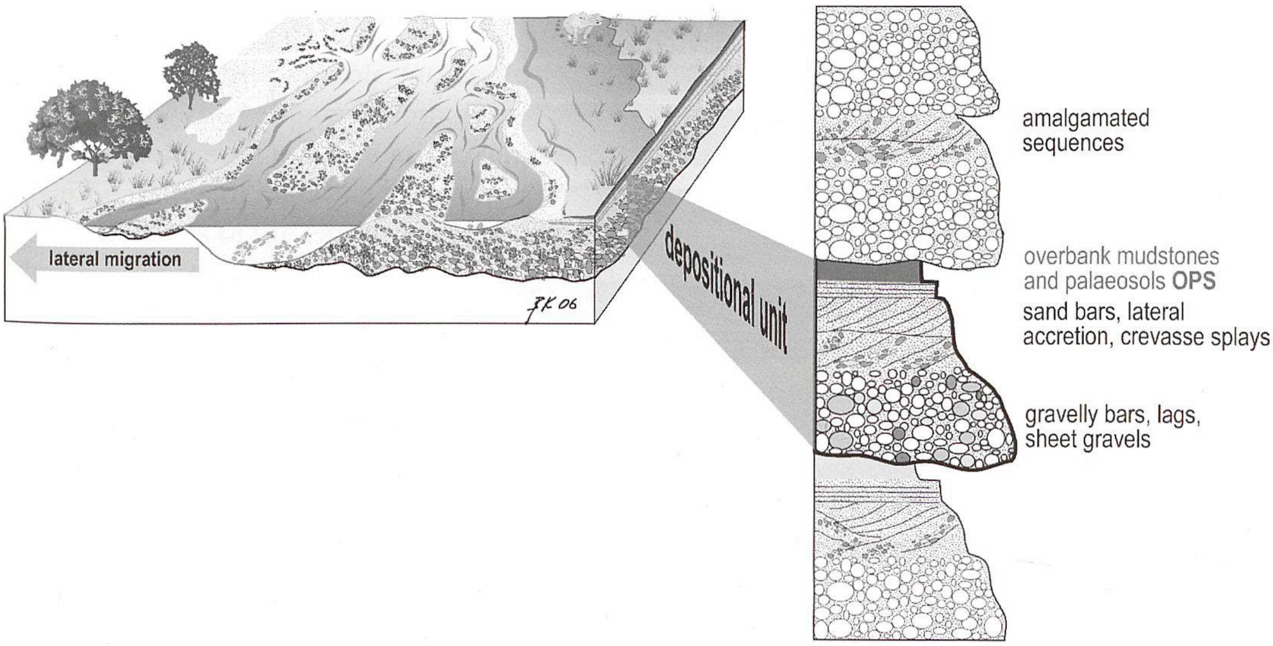


Fig. 7: Facies Model for the gravelly braided rivers of the proximal Lower Freshwater Molasse, and generation of fluvial sequences (Keller 2007).

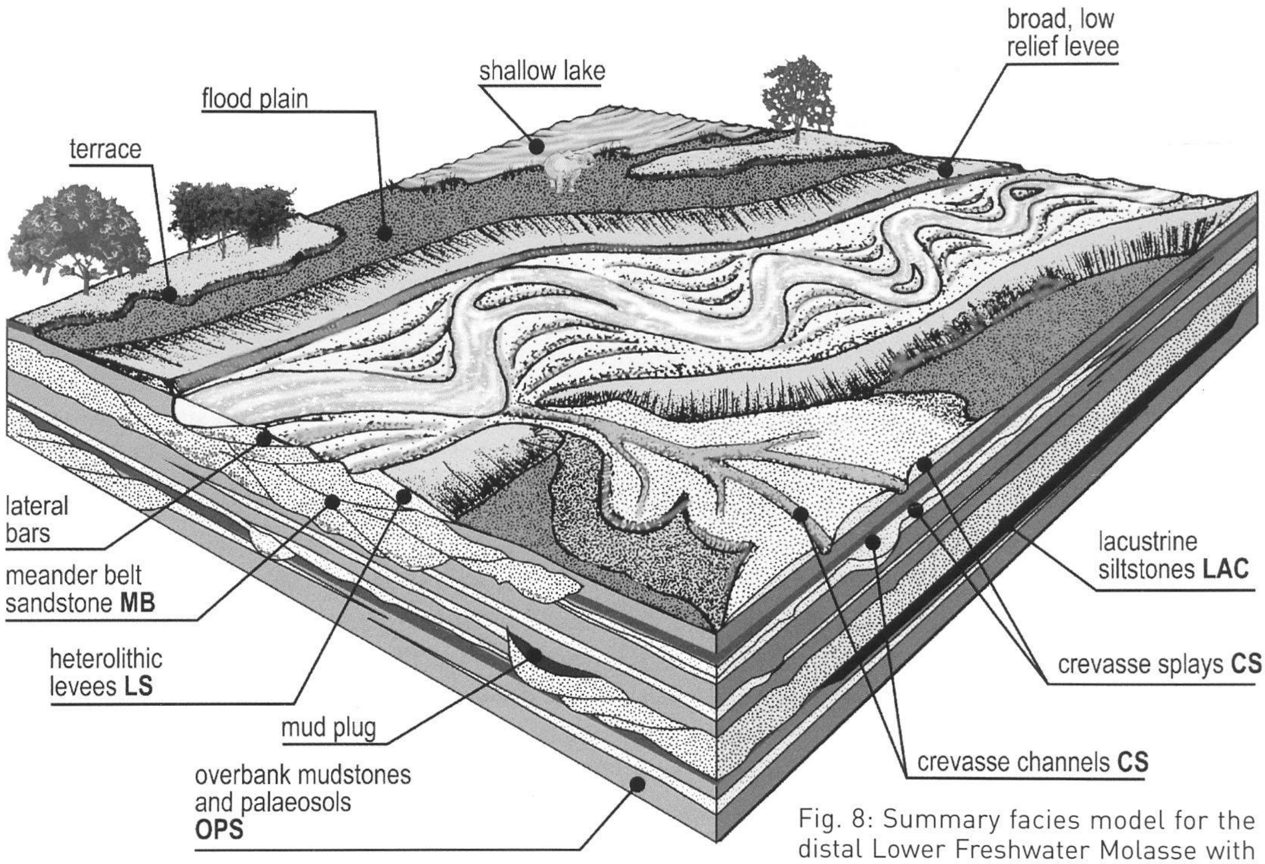


Fig. 8: Summary facies model for the distal Lower Freshwater Molasse with sinuous rivers (Platt & Keller 1992).

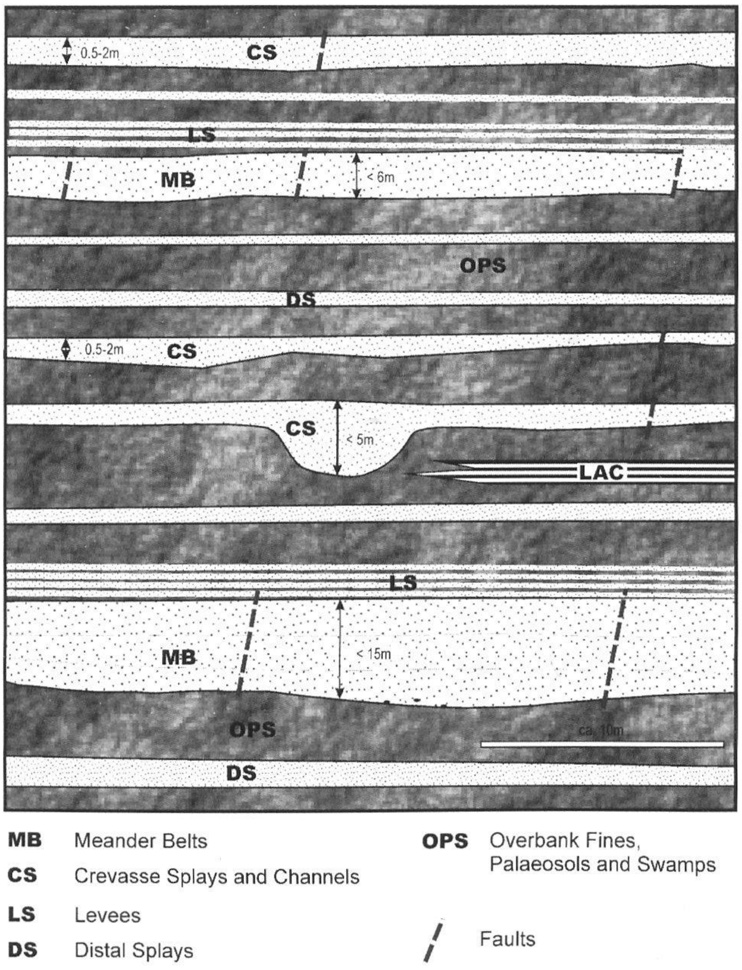


Fig. 9: Diagram of the principal architectural elements for hydrogeological purposes (Platt & Keller 1992).

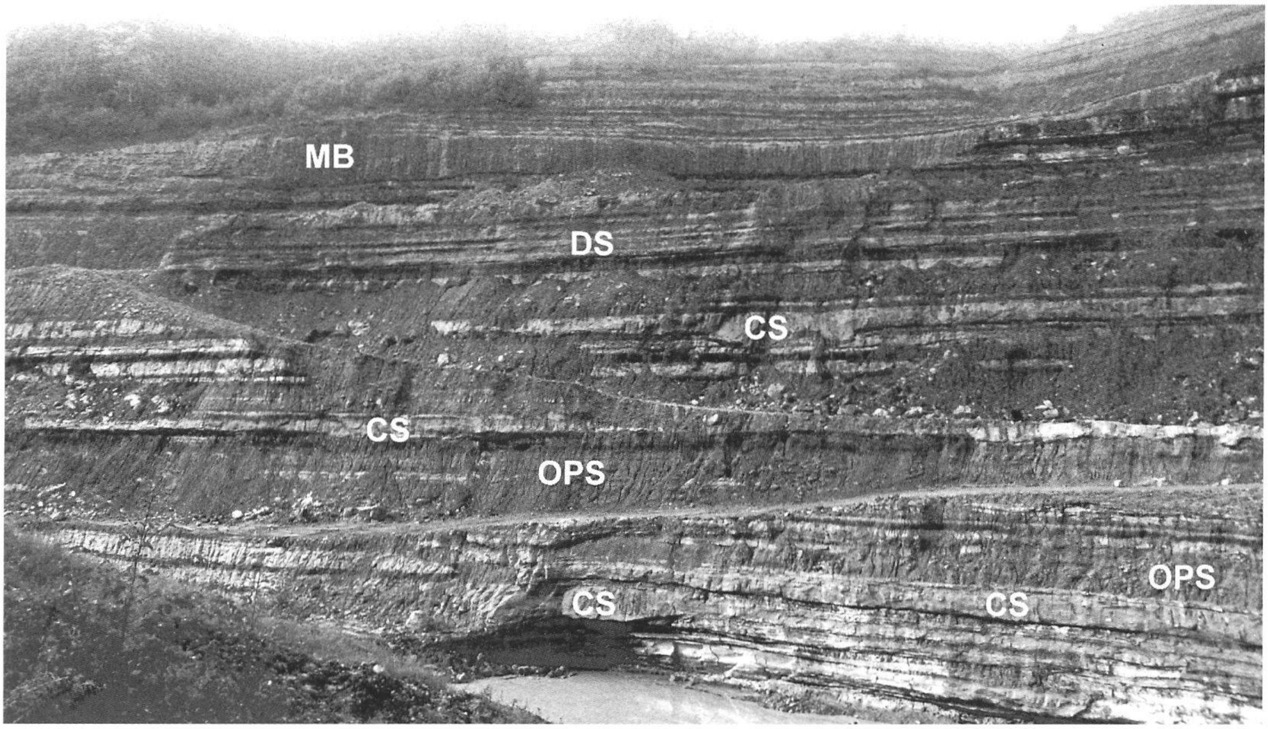


Fig. 10: Marlpit Roggwil showing the architectural elements (Fig. 8 and 9).

the Holocene sea level rise. Alternatively a falling sea level reduces the tidal amplitude and the tidal activity, leading to the deposition of a wave-dominated, mixed-energy facies. The individual wave dominated, mixed-energy and tide dominated parts of the section can be correlated between Napf and Pfänder ZH without problem (Keller 1989, Fig 11). With this first proof of a palaeohydrographically dynamic facies development during the sedimentation of the Upper Marine Molasse – i. e. the appearance and disappearance of standing tidal waves – the contradictions of the earlier static models of Homewood et al. (1986), Benkert (1984) and Hammer (1984) could be resolved plausibly. In addition, the new assumptions could be confirmed independently by the simulations of Bieg (2005).

The excursion visited two representative outcrops, one at the Lion Monument in Lucerne, showing the wave-dominated mixed energy case and the other at Schötz LU, representing the tide-dominated facies association. The wall of the abandoned quarry at the Lion Monument (coord. 666'250/212'700, detailed description by Keller 1990 und 2000) shows a conspicuous more or less parallel bedding, dipping today at about 50° to NNW due to a monoclinal fold. The mostly laminated sandstones can be attributed to the shoreface and foreshore sedimentary environments of the wave-dominated facies association. To the left above the Lion monument an interesting sequence of foreset-bundles can be observed (Fig. 12). They show the landward migration of a beach ridge: after the prograding phase, during the wave driven, dominant flood in landward direction (south) a first mud drape was deposited in the runnel. During the subordinate ebb current, current ripples in the opposite direction were formed. In slackwater phase of the low tide a second mud layer was deposited in the deeper part of the channel. This double mud layer and the current transport in the opposite direction with dominant high tide and subordinate low tide, document the tidal activity that is, however, masked in the laminated wave dominated beach deposits. This conspicuous tidal beach ridge was preserved only because it migrated after the erosional phase during a very severe hurricane into the erosional runnel that had been created during the hurricane (Fig. 13), thus - as a very rare event - being protected from the destruction by later, smaller events. Some 7 m to the left above the lion and above a sharp undulating erosional discordance, cross bedding of megaripples dominates, together with small current ripples with mud drapes. The features can be interpreted as the deposit of the overlaying tide-dominated facies association (see Fig. 11).

A cliff along the Luthern river near Schötz LU (coord. 640'830/223'600) represents deposits of the central part of the Burdigalian seaway. Three units can be observed (Fig. 14): The basal part consists of heterolithic wavy bedding with some storm sand layers and a thick, low-angle, inclined-bedded sandstone unit with abundant mud drapes, interpreted as a subtidal mixed flat. This part is overlain by some 3 m of cross bedding of 2D and 3D megaripples. The latter show lateral bundle sequences due to neap-spring tidal cycles, as described e. g. by Homewood (1981). Transport direction in this unit is generally NNW. This sequence originated under strongly asymmetric tidal currents – in this palaeogeographic context ebb currents – and has to be seen as the fill of a laterally migrating subtidal channel. Towards the roof, pronounced bundle sequences of 2D megaripples can be recognized – partly as form sets, above which further 2D and 3D megaripples are recognizable. Transport of this unit is oriented towards

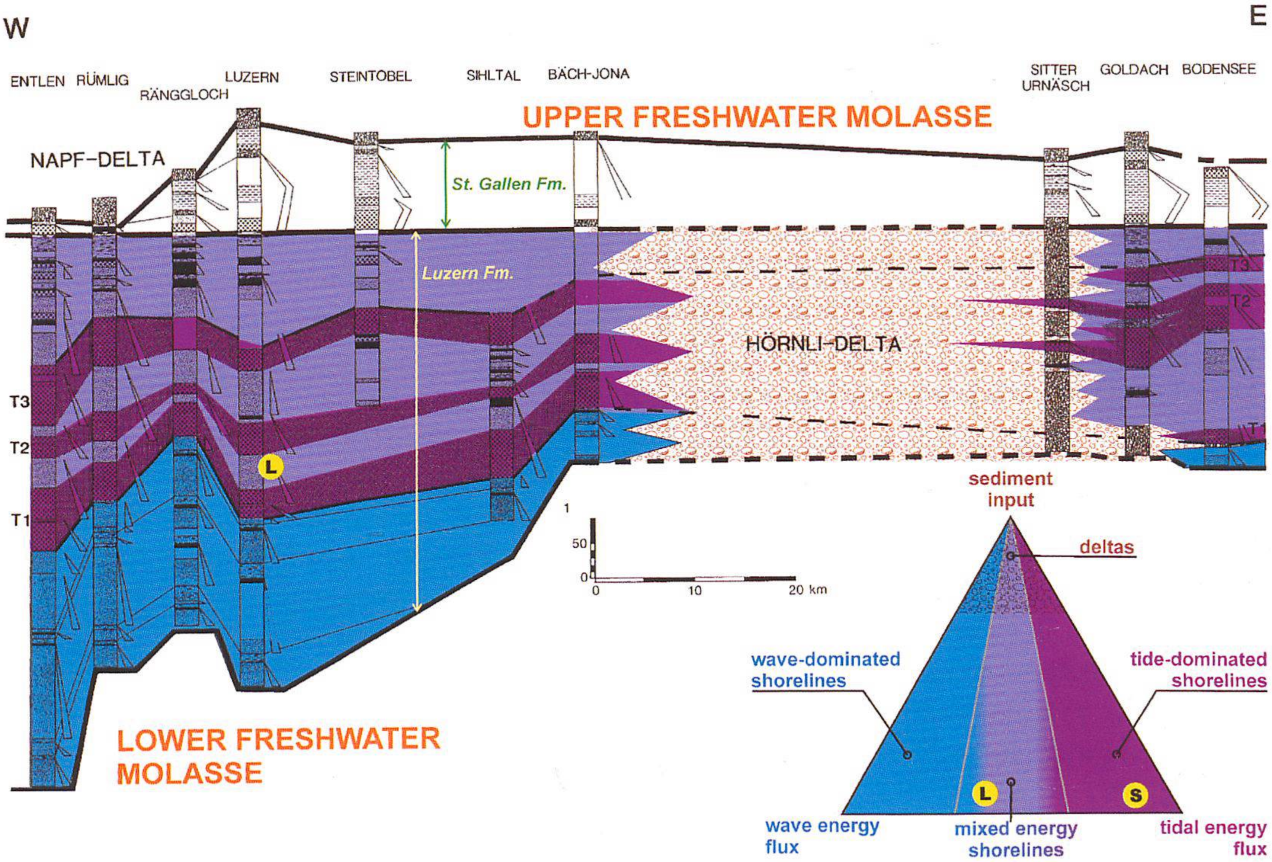


Fig. 11: Overview of the lithofacial buildup of the Upper Marine Molasse between Lake Bodan and the Napf area shows the repeated change in the palaeohydrographic regime of the Burdigalian seaway. At the base of the Lucerne Fm. we find regressive sequences of the wave-dominated facies association. Above it a tripple change between tide-dominated and mixed energy facies associations, separated by the sediment-input-dominated Hörnli delta. At the lower right the ternary diagram, explaining the generation of the different facies associations in dependence of the dominance of the facies factors: sediment input, wave and tidal energy flux (from Keller 1989). Stops: L Löwendenkmal, S Schötz.

the SSE. These megaripples are probably deposits of floodfacing ramps or channels of the sub- to lower intertidal environment. As an entity this sequence can be interpreted as a shallowing-upward sequence, ranging from typically ebb-dominated deeper deposits to flood-dominated shallower deposits within the open marine strait.

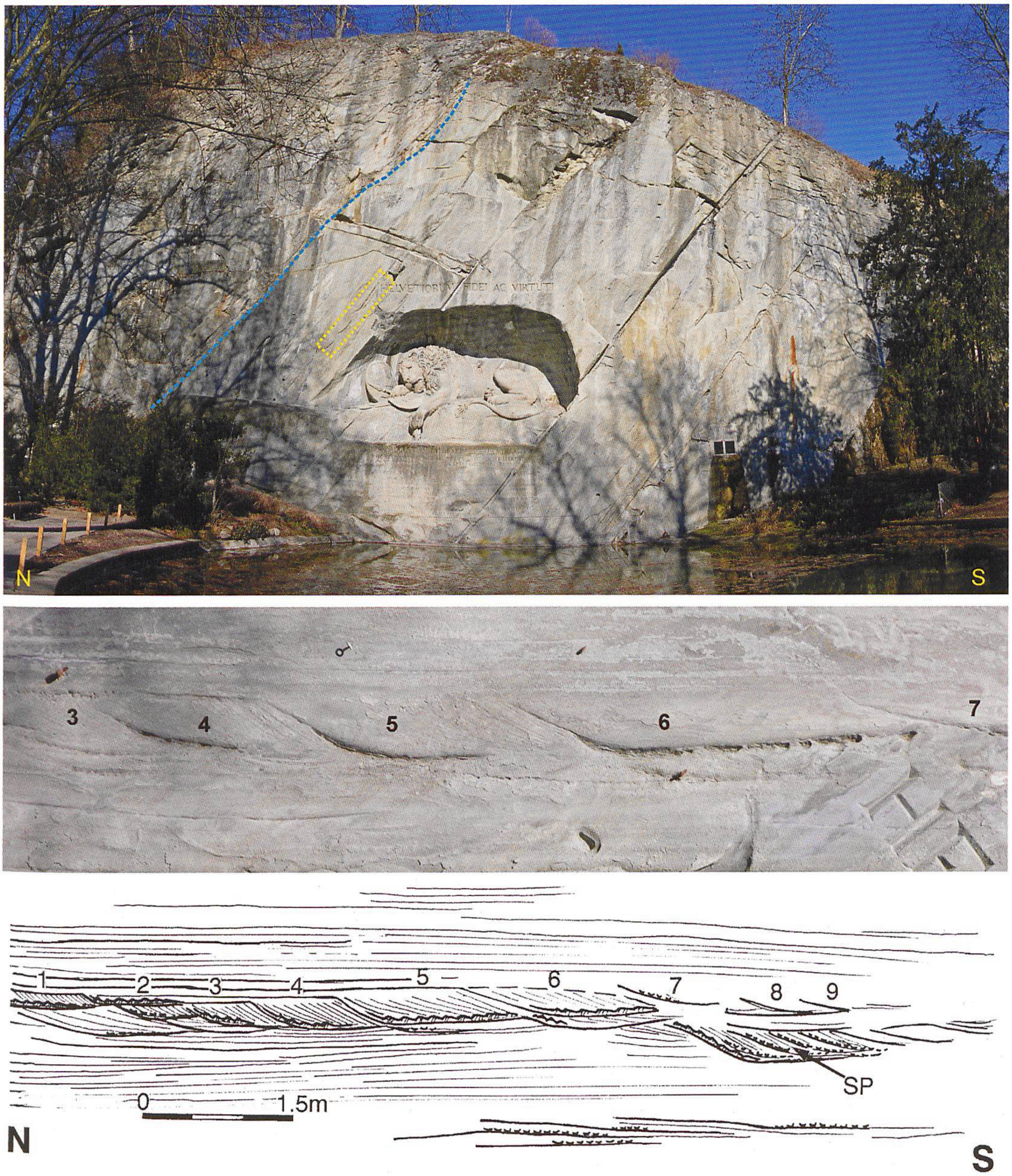


Fig. 12: The Lion Monument is also geologically a highly interesting outcrop: To the right of the blue line lies wave-dominated, mixed energy shoreface and foreshore facies, erosively overlain to the left by tide-dominated facies. In the yellow marked area the deposits of a beach ridge that moved landwards within the tidal rhythm (see also middle picture and lower drawing from Keller 1990). Each depositional bundle corresponds to a flood phase, separated by double drapes and current ripples of the subordinate ebb current. The reconstruction of the beach after a severe storm lasted according to Fig. 13 a mere five days.

5. Upper Freshwater Molasse

The facies of the Upper Freshwater Molasse is in principle comparable with that of the Lower Freshwater Molasse but is distinguished by a larger content of lacustrine deposits. The facies sequence from proximal to distal was essentially described already by Bürgisser (1984). The proximal depositional realm is dominated by the two alluvial fans of the Hörnli in the E and the Napf in the W. It should be noted, however, that the Napf Fan started to develop only with the deposition of the St. Gallen Fm., thus considerably later than the Hörnli Fan (Keller 1989). The reason for this is a fundamental change in the Alpine run-off system. New sedimentological and lithostratigraphic analyses of the base of the proximal Upper Freshwater Molasse between the two fans prove the existence of an extended, poorly drained floodplain, dominated by backswamps and shallow lakes of ephemeral character (Keller 2000). These pelite-rich deposits developed from the facies of inter-deltaic bays of the St. Gallen Fm. They indicate in the proximal foreland basin of the basal Upper Freshwater Molasse clearly under-filled conditions (Keller 2000). This situation reaches its peak during the Langhian, accompanied by grey, often structureless siltstones («Basismergel zone»). Time wise this coincides with the onset of the «new thrusting event» at about 15 million years, postulated by Kempf & Matter (1999). It is also identi-

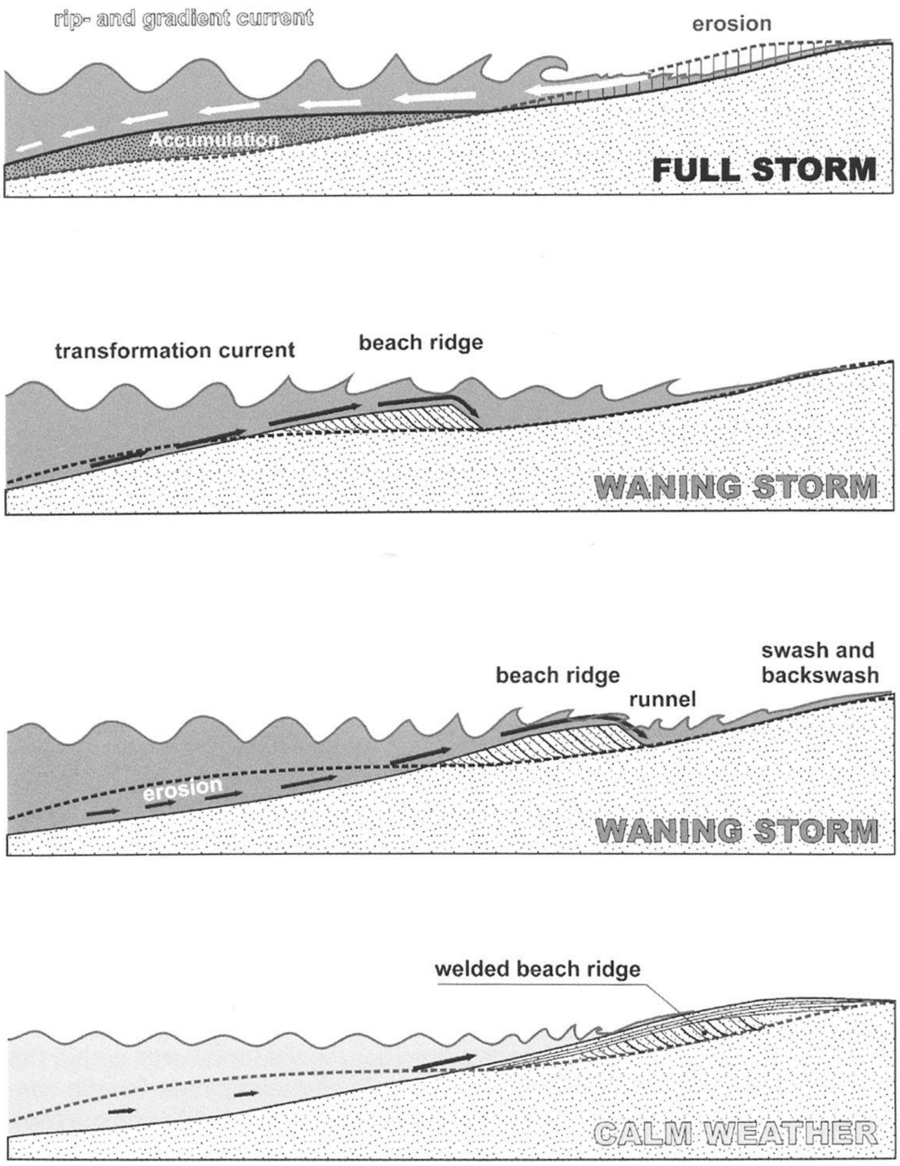


Fig. 13: Explanation of the formation of the beach ridge at the Lion Monument (after Keller 1989) as the result of an exceptionally severe storm. During the waning phase the beach ridge migrated with the tidal action landwards and was eventually welded to the beach.

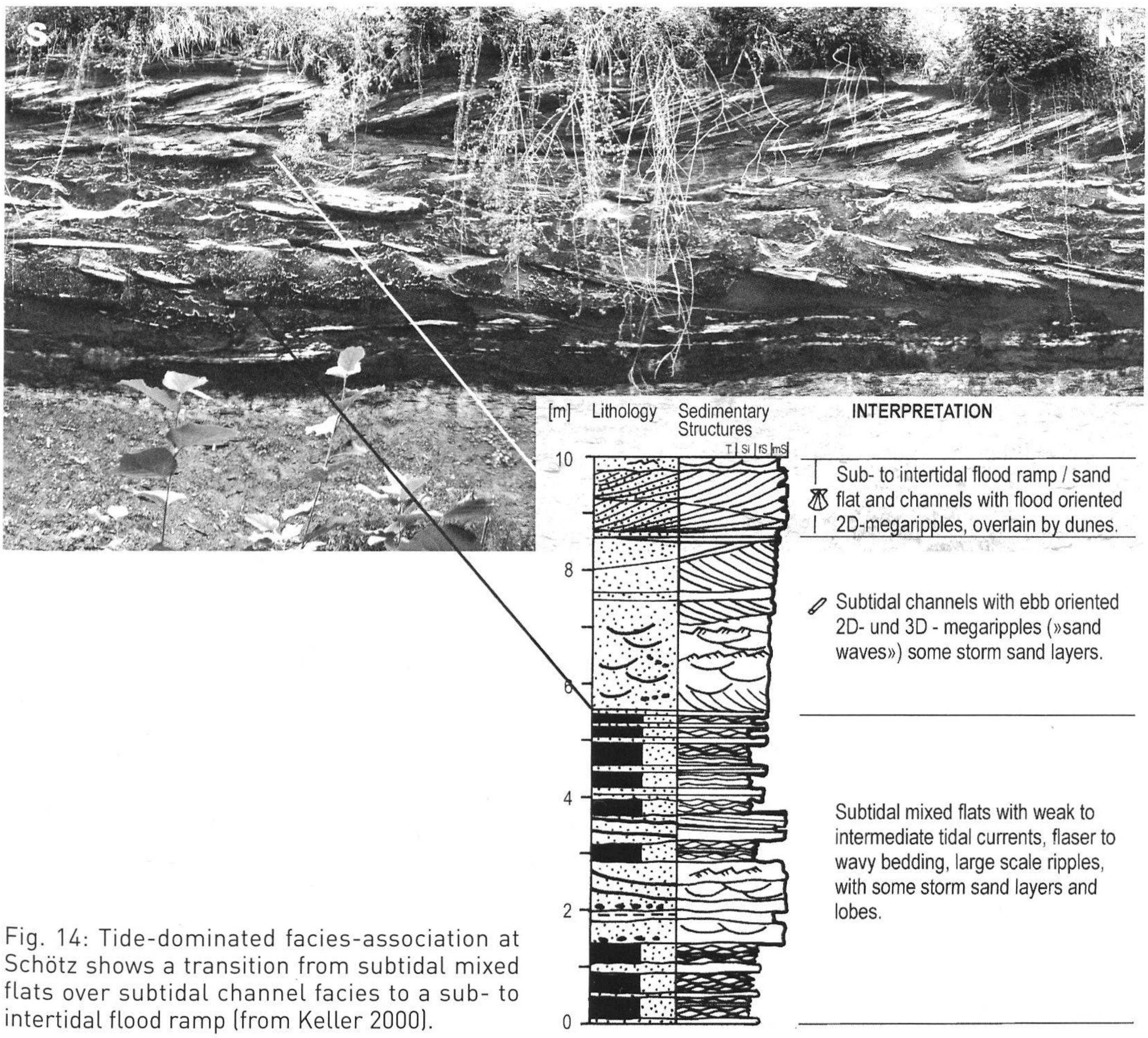


Fig. 14: Tide-dominated facies-association at Schötz shows a transition from subtidal mixed flats over subtidal channel facies to a sub- to intertidal flood ramp (from Keller 2000).

cal with the Ruchi tectonic phase in the sense of Trümpy (1980), who attributed a lower to middle Miocene (upper Burdigalian / Langhian) age to this transition. New sedimentological studies in outcrops of subsurface construction activities in the Lucerne area show during the time of the deposition of the St. Gallen Fm. and well into the basal Upper Freshwater Molasse partly spectacular evidence of a high palaeoseismic activity, probably in connection with the Ruchi tectonic phase. This is expressed in numerous soft-sediment-deformation sedimentary structures, like large-scale ball-and-pillows (Fig. 16), pseudo-nodules of conglomerate, drop and sag structures. All these features indicate strong liquefaction of the sediment, requiring earthquakes of at least a magnitude X after ESI (Environmental Seismic Intensity Scale 2007). In this context also the marker bed (e. g. Degersheim conglomerate, Meilen Limestone) of Bürgisser (1984) can be attributed to the same palaeoseismic triggering mechanism.

In the 130 m high cliff of Badflue at the Kleine Emme (Bergli SSE Wolhusen LU, coord. 647'600/211'100) the Upper Freshwater Molasse is perfectly exposed in a marginal facies of the developing Napf alluvial fan (Fig. 13). The bottom part of the outcrop at the shore of the Kleine Emme is formed by grey, heterolithic deposits of a shallow lake with splays of over-bank sands. They are followed by stacked fluvial sequences (Fig. 7) often with deeply scoured surfaces and with complex internal structures of longitudinal, side and chute bars, overlain by overbank sands and palaeosoils, often with nice root tubules. The outcropping sequence is in the model of Bürgisser (1984) comparable with the conglomerate-siltstone-facies (H2) that has to be seen as the distal part of a humid debris fan. Representative for the distal, palustrine-lacustrine floodplain is the outcrop of the marlpit Chörbligen (Pfaffwil, N Root, coord. 641'470/220'310, Fig. 13). Here we observe above mature reddish palaeosoils with caliche concretions a sedimentary sequence of dark grey lacustrine deposits (mudstones, siltstones), typically with *Limnea* sp., as well as immature, dark palaeosoils, indicating water saturated conditions with a high groundwater table. Very interesting are the numerous crevasse splays and sands, which form within the lacustrine sediments occasionally genuine crevasse deltas with thick climbing ripple cosets.

Acknowledgements

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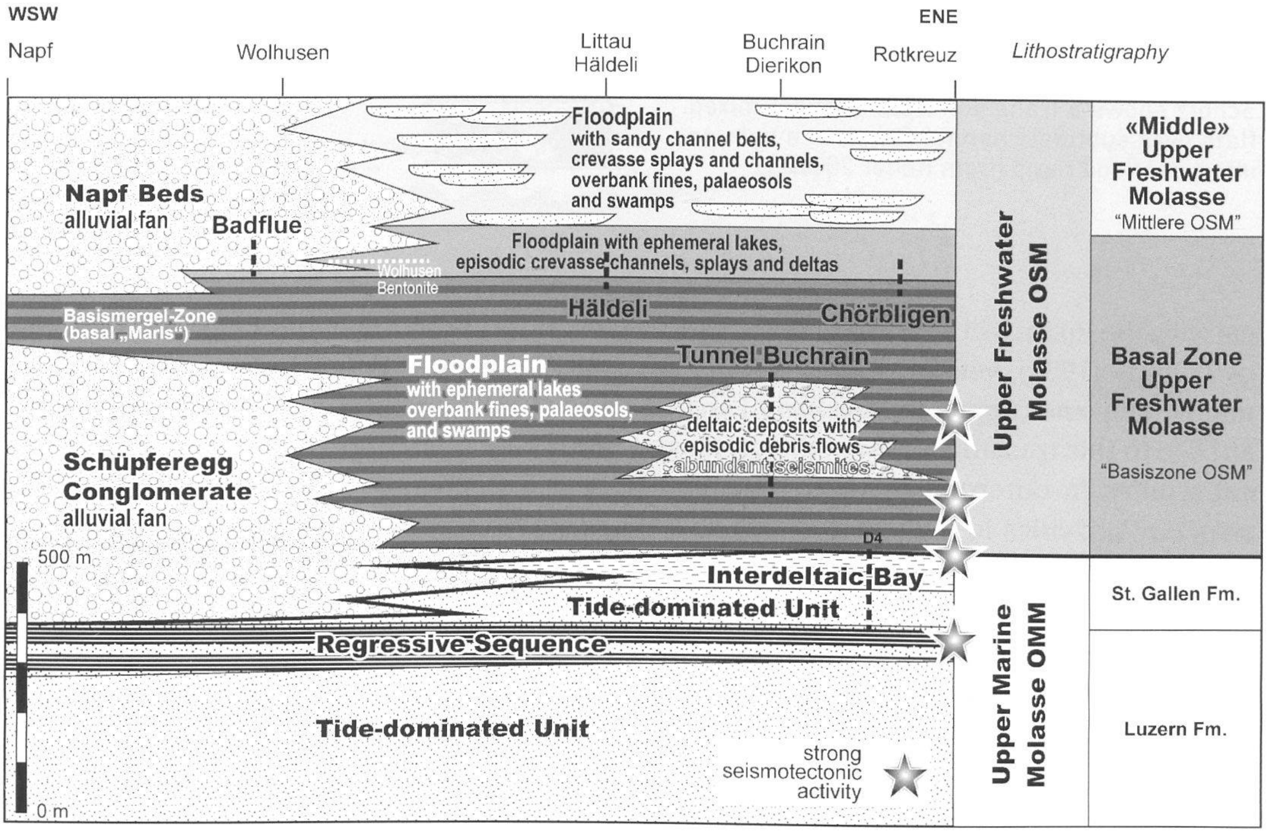

Fig. 15: Synthetic and schematic lithostratigraphic framework and facies distribution between Napf alluvial (W) and distal floodplain (E) for the younger Upper Marine Molasse and the Upper Freshwater Molasse (after Keller 2000).

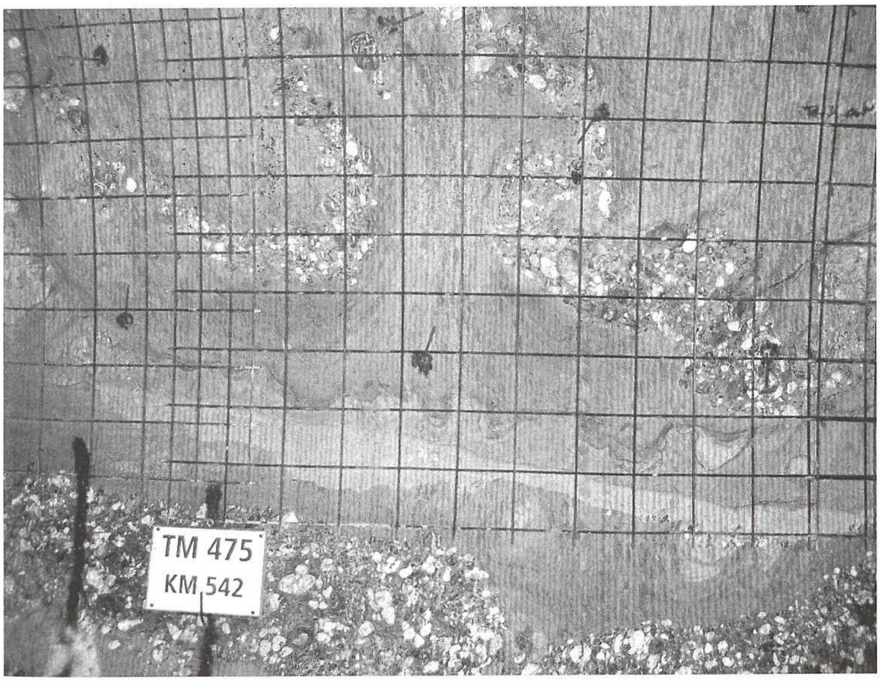

Fig. 16: Large scale dewatering and ball-and-pillow structures in heterolithic sediments of the basal Upper Freshwater Molasse, Tunnel Buchrain (position see Fig. 15), mesh diameter 15 cm.

Fig. 17: View of the 130 m high cliff of Badflue (Fig. 15) W of Wolhusen with stacked fluvial cycles, consisting of gravelly channel belts (CB) and transition into overbank deposits and palaeosoils (P). Behind the fallen blocks in the river bed, grey, heterolithic deposits (H) of a shallow lake are visible. View towards the West.

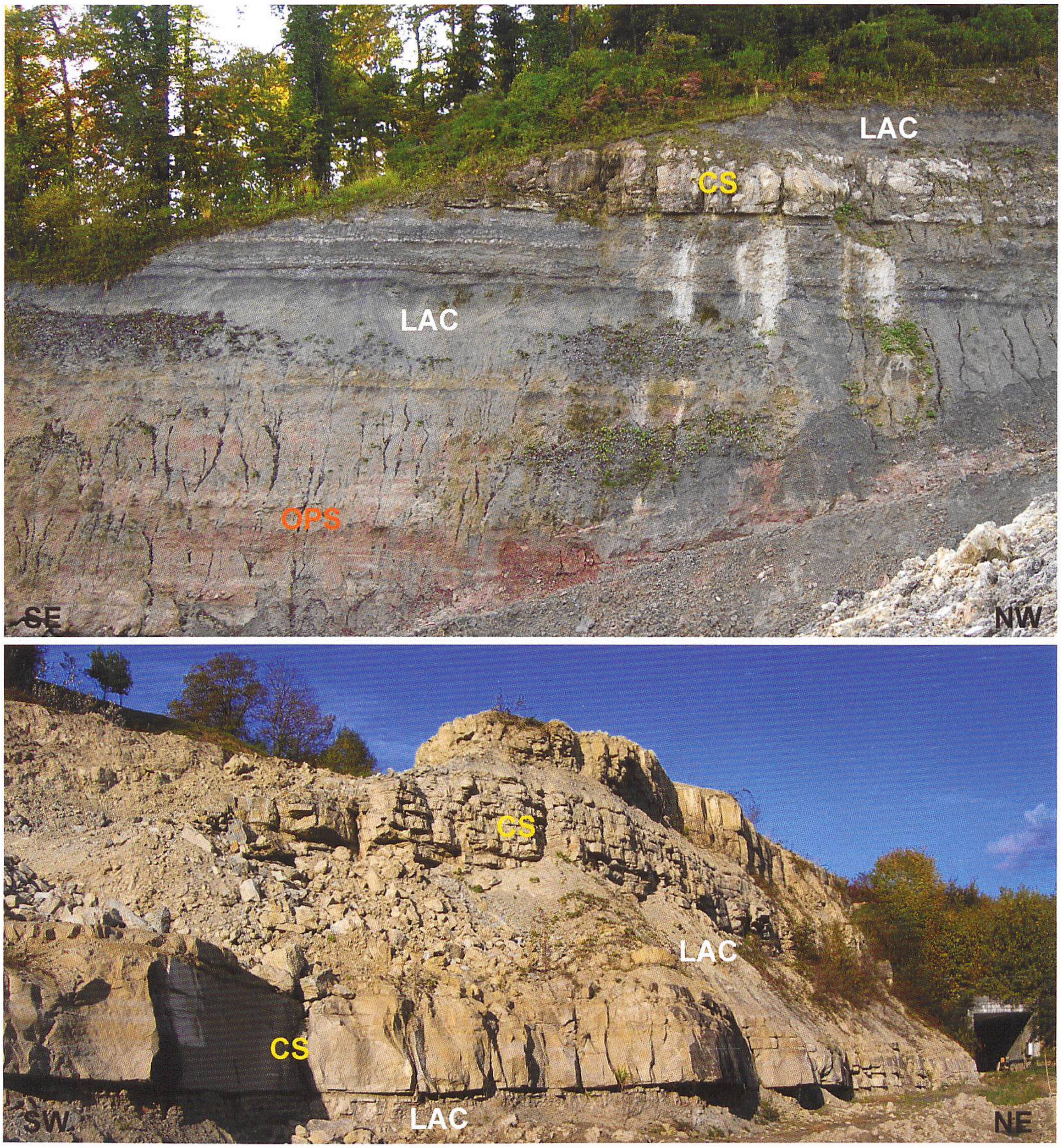

Fig. 18: Interpreted views of the marlpit Chörblige (Pfaffwil). Above: At the base with overbank fines and red palaeosols (OPS), grey lacustrine mudstones (LAC), blackish palaeosols and crevasse sands. Below: Lacustrine deposits (LAC) with low angle stratified crevasse splays and deltas (CS).

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