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Stratigraphy and palaeoecology of the Upper Marine Molasse (OMM) of the central Swiss Plateau

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Abstract The lithostratigraphic framework of the Upper Marine Molasse (OMM) in Switzerland is represented by two concepts. One was established in the central-northern Molasse Basin largely based on informal lithostratigraphic units without biostratigraphic control. The other concept was developed in the southern basin part and resulted in the distinction of the Lucerne Formation and the St. Gallen Formation based on detailed lithofacies analysis. This study aims at linking both concepts at map scale 1:25,000 for a potentially basin-wide correlation of the existing lithostratigraphic units. Based on lithostratigraphic analyses, mammal biostratigraphy and on the palaeoecological reconstruction of marine selachian faunas throughout the OMM of the central Swiss Plateau, we were able to allocate this part of the OMM into the well-established Lucerne Formation and St. Gallen Formation (Middle–Late Burdigalian, mammal units MN3a to MN4b). We further define two new lithostratigraphic units: The *member* Safenwil-Muschelsandstein (Lucerne Formation), and the *bed* Staffelbach-Grobsandstein (St. Gallen Formation). The Safenwil-Muschelsandstein denominates the well-known marker horizon of shell sandstone deposits, rich in fragments of irregular echinoids (*scutella* sp.), near the top of the Lucerne Formation. The Staffelbach-Grobsandstein represents a coarse-grained, often pebbly sandstone or even a fine-grained conglomerate at the base of the St. Gallen Formation. In the study area, the distinction between the Lucerne Formation and the St. Gallen Formation is best documented in the composition of the remnant marine fauna (especially teeth of selachii). Throughout the Lucerne Formation, the marine fauna is dominated by shallow marine faunal elements. In contrast, the Staffelbach-Grobsandstein reveals for the first time a large number of faunal elements of the open sea, which is interpreted as an indication of the marine transgression of the St. Gallen Formation. Furthermore, we present a unique palaeoecological study on marine faunas (mostly sharks) throughout the entire OMM sequence of the central Swiss Plateau.

Keywords Swiss Molasse Basin · OMM · Miocene · Lithostratigraphy · Biostratigraphy · Palaeoecology

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1 Introduction

Sediments of the Molasse Basin are widely distributed along an elongated stretch neighboring the northern margin of the European Alps roughly between Geneva and Vienna. As part of the North Alpine Foreland Basin they are largely composed of Alpine debris reflecting thus the uplift and denudation history of the late phase of Alpine orogeny during the Oligocene/Miocene (e.g. Diem 1986; Pfiffner 1986; Pfiffner et al. 1997). In Switzerland and southwestern Germany, the Molasse deposits are subdivided classically into two marine-to-terrestrial depositional sequences referred to as Lower and Upper Marine and Freshwater Molasse (UMM, OMM, and USM, OSM[1]; Matter et al. 1980; Lemcke 1988; Doppler et al. 2005). The terrestrial deposits of USM and OSM consist largely of Alpine debris that was shed into the Molasse Basin via numerous large alluvial fans and fluvial systems, and distributed basin-wide by braided and meandering river systems (e.g. Schlunegger et al. 1996, 1997b; Kempf et al. 1997, 1999; Strunck and Matter 2002). Occasionally, lacustrine depositional environments developed (e.g. Berger et al. 2005). The propagation of the Alpine orogenic wedge through time towards the northwest (e.g. Sinclair and Allen 1992) reflects the prograding facies belts in the same direction. Sediments of UMM and OMM formed within an elongated trough under coastal to offshore marine conditions, characterised by wave- and tide-dominated currents (e.g. Homewood and Allen 1981; Allen et al. 1985; Diem 1986; Keller 1989). Along the southern basin margin, large fan deltas continued to shed large amounts of Alpine debris into the basin where strong currents redistributed the sediment throughout the basin (e.g. Allen et al. 1985; Homewood et al. 1986; Schlunegger 1997a).

The OMM, on which we are focusing here, consists of a lithostratigraphic group of Early Miocene (Burdigalian) marine sediments that are widely exposed throughout the Swiss Plateau between Lausanne in the southwest and St. Gallen in the northeast (Fig. 1; e.g. Büchi 1957, 1958; Berger 1985; Keller 1989). Exposures continue east of the Bodensee in Germany and Austria (e.g. Schaad et al. 1992; Frieling et al. 2009). OMM sediments are well exposed along the southern basin margin owing to tilting through Alpine deformation (southern margin of the Plateau Molasse, e.g. Keller 1989). Its central flat-lying part, however, is discontinuously and poorly exposed and frequently covered by Quaternary gravel deposits and till. Further to the north and northwest, in the present-day Jura Mountains, sediments of the Molasse Basin are restricted to relict occurrences.

In the central Swiss Plateau Molasse sediments of the OMM are best exposed in numerous gravel pits and quarries, natural exposures are mostly found along small and deeply incised creeks. The OMM is here generally composed of mostly greenish-grey siltstone, fine- to coarse-grained sandstone, and occasionally of conglomerate and mudstone. There is a significant increase of sediment thickness from north to south (from few metres to hundreds of metres), along with the area of greatest subsidence during time of deposition.

[1] For convenience we here use the German abbreviations UMM, OMM, and USM, OSM for the Lower and Upper Marine, and Lower and Upper Freshwater Molasse, respectively.

In the regions of Switzerland, Vorarlberg (West Austria) and South Germany, the OMM has been classically subdivided into two depositional units: an older "Burdigalien" and a younger "Helvétien" (e.g. Kaufmann 1872; Miller 1877; Büchi 1957, 1958). Büchi (1957, 1958) applied this subdivision to the central Swiss Plateau Molasse and developed a regional lithostratigraphic classification scheme (Fig. 2). Since Büchi (1957) could not rely on biostratigraphic data he pointed out that his classification scheme is purely lithostratigraphic and only tentatively correlated chronostratigraphically (as implied by the misleading terms "Burdigalien" and "Helvétien"). Regardless of its poor definition, this classification provided the basis for stratigraphic correlation of OMM deposits in this area until recently (e.g. Gerber and Kopp 1990; Gerber 1994). Along the tilted southern basin margin, Keller (1989) studied the sedimentology of the OMM deposits between the Napf region and the Bodensee and carried out a detailed lithofacies analysis in these well exposed thick and continuous outcrop sections. Keller (1989) established the terms Lucerne Formation (Luzern-Formation in German) for the "Burdigalien", and St. Gallen Formation (St.-Gallen-Formation in German) for the "Helvétien" (i.e., OMM-I and OMM-II of Berger et al. 2010). He further proposed a lithostratigraphic subdivision of both formations guided by the predominance of either a wave-dominated or tide-dominated sedimentary facies, or a mixture of both. Keller (1989) showed that the Lucerne Formation terminated with a regressive sequence, which even led to subaerial exposure and hence to terrestrial conditions at the southern basin margin, and that the succeeding deposits of the St. Gallen Formation commenced on a transgressive surface. Frieling et al. (2009) observed such a regressive-transgressive depositional sequence also east of the Bodensee. The termination of the Lucerne Formation is there indicated by the occurrence of a palustrine coal horizon (Frieling et al. 2009).

Biostratigraphic data derived from mammal teeth allowed a more precise stratigraphic calibration of the OMM formations: The Lucerne Formation can be correlated to the Mammal Neogene Zones (? MN2b) MN3a–MN3b, whereas the St. Gallen Formation is represented by (? MN3b –) MN4b (Keller 1989). MN3a and MN3b correlate with early to late Burdigalian, MN4b to late Burdigalian (Schlunegger et al. 1996; Kempf et al. 1999; Reichenbacher et al. 2013). Thus, along the southern basin margin, the regression at the end of the Lucerne Formation occurred during the mid-Burdigalian (MN3b, Keller 1989; Kälin 1997).

At the northern basin margin, sediments of the second depositional unit ("Helvétien", St. Gallen Formation) reach much further to the north than those of the first depositional unit ("Burdigalien", Lucerne Formation).

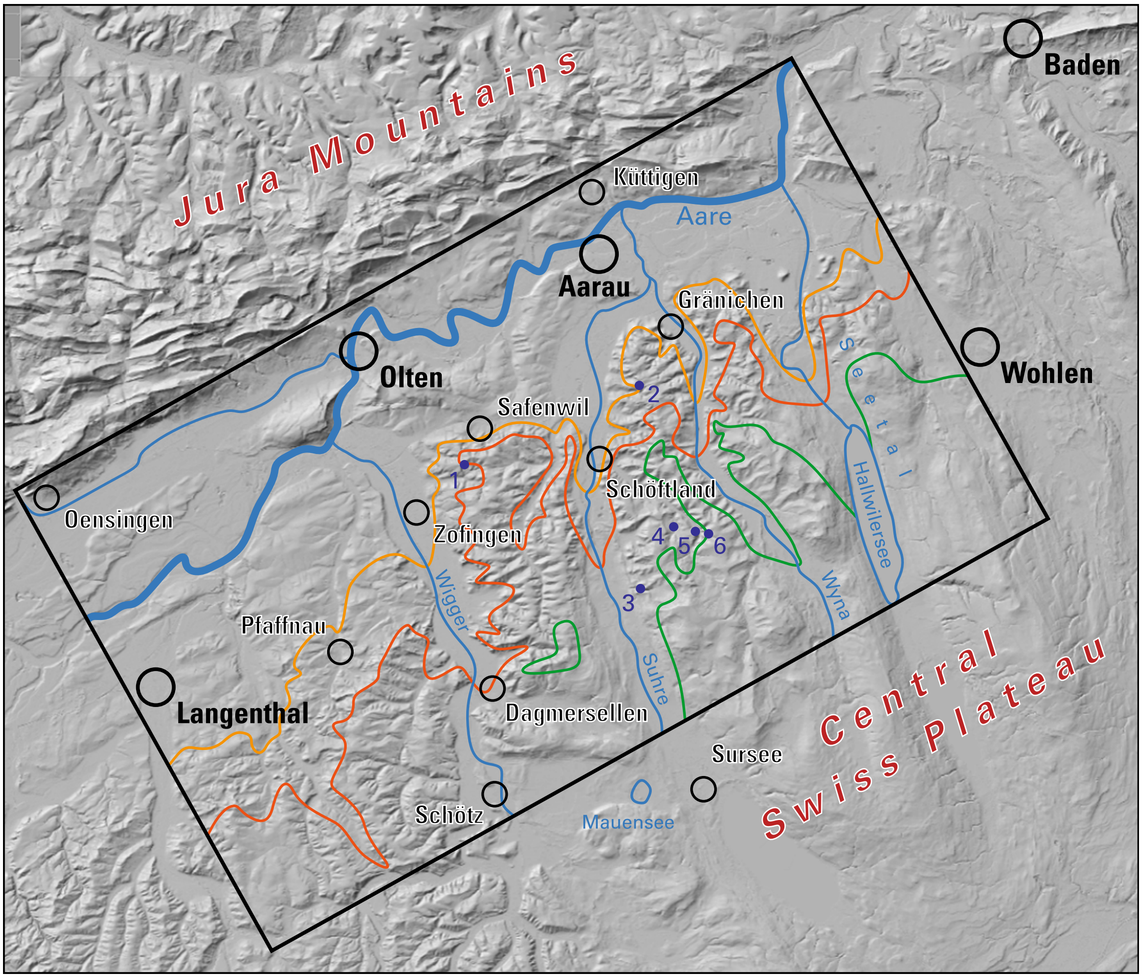


Fig. 1 Overview of the investigated area (*black box*) of the central Swiss Plateau. *Colored lines* represent generalised northern limit of USM/OMM (*orange*), OMM-I/OMM-II (*red*) and OMM/OSM (*green*) boundaries. *Blue dots* show localities of sections 1–6 shown in Figs. 3a and 5

Hence, the second depositional unit documents therefore the farthest and northernmost transgression of the OMM-Sea (Rollier 1903; Heim 1919; Baumberger 1927). A karstic fissure filling in the Jurassic Reuchenette Formation near Glovelier (west of Delémont, Swiss Jura Mountains), which was flooded by this transgression yielded an age of MN4a (Hug et al. 1997). This age is thus in accordance with the proposed age of MN3b for the regression that occurred at the end of the Lucerne Formation at the southern basin margin (Keller 1989).

A proper correlation of OMM deposits from the southern basin margin to its equivalents in the central Plateau Molasse based on this lithostratigraphic scheme, however, is hindered owing to the following aspects: (1) Outcrops between the southern basin margin and the central plateau are discontinuous through extensive cover by Quaternary drift deposits, (2) the thickness of the OMM deposits strongly decreases towards the north, and (3) the sedimentary facies varies from south to north. To overcome this correlation challenge we investigated the OMM deposits of the central Swiss Plateau Molasse for lithostratigraphy, biostratigraphy, and palaeoecology. The aim of our paper is therefore twofold: (1) We complement and discuss the stratigraphic correlation scheme of the OMM deposits of the central Swiss Plateau, and suggest two new formally defined lithostratigraphic units: the Safenwil-Muschelsandstein (member) and the Staffelbach-Grobsandstein (bed). (2) Based thereon, we present new palaeoecological data from the marine selachian fauna and biostratigraphic data from mammal teeth.

2 The central Swiss Plateau Molasse: geographical and geological setting

Initiated by various mapping campaigns of the Swiss Geological Survey, we studied the area roughly between Aarau in the north, Langenthal in the west, Sursee in the south, and the Seetal in the east (Fig. 1). This area covers

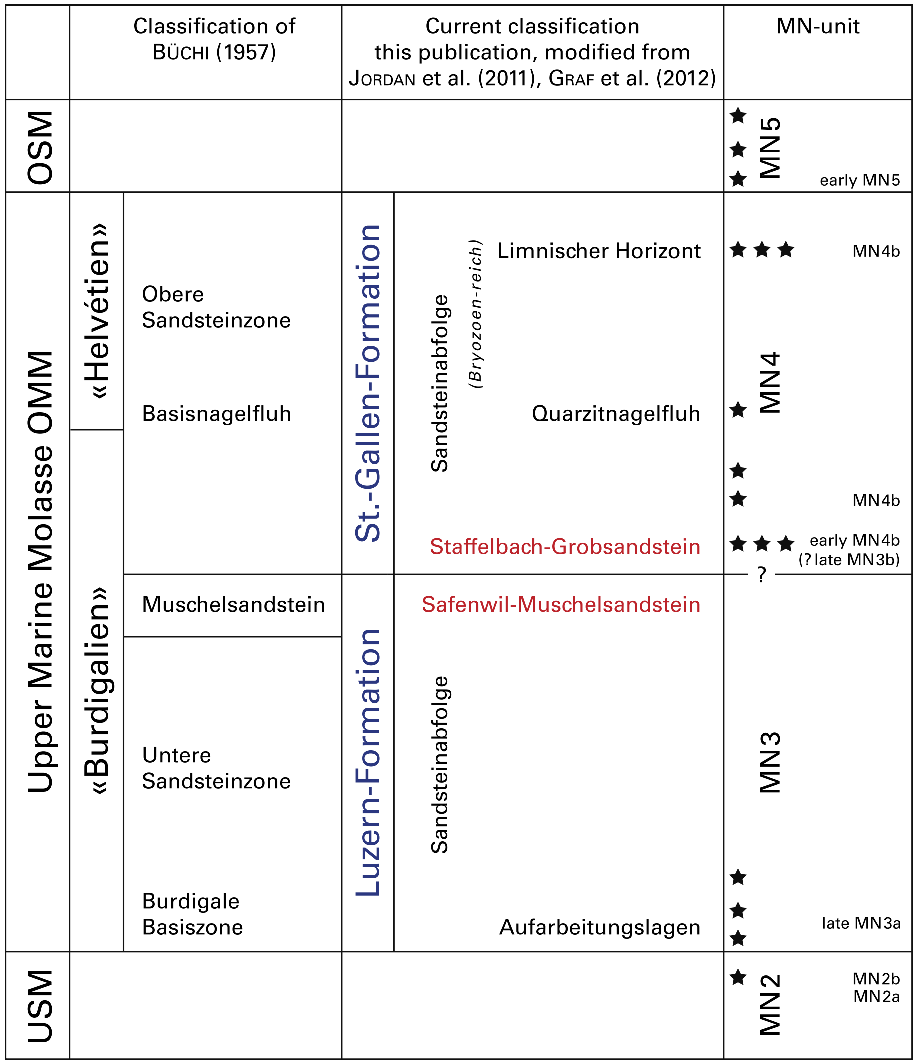


Fig. 2 Comparison of the current and former OMM classification (in German). *Red* Newly defined member and bed of Lucerne Formation and St. Gallen Formation. *Right column* Stratigraphically important fossil sites of small mammal finds and their assignment to MN zonation. See text for discussion. *USM* Lower Freshwater Molasse, *OSM* Upper Freshwater Molasse. *Black asterisk* mammal site

significant parts of map sheets 135 Aarau (Jordan et al. 2011a, b) and 150 Schöftland (Graf et al. 2012a, b) of the Geological Atlas of Switzerland 1:25,000, out of which the following field descriptions are mostly taken. The northern part of our study area connects to the southern limit of the eastern-central Jura Mountains, and the Molasse sediments are therefore weakly tilted due to late Alpine deformation, i.e. by backthrusting of the Born-Engelberg anticline (Bitterli 1979; Jordan et al. 2011b). Further south the sediments underwent very little deformation and are thus basically flat-lying or only slightly south to southeast dipping by less than 5° (Graf et al. 2012a, b). The stratigraphic succession of the central Swiss Molasse Basin comprises from base to top USM, OMM, and OSM sediments, which rest above Jurassic limestone and marlstone (e.g. Büchi 1957, 1958); deposits of the UMM never reached the study area. The USM comprises poorly exposed variegated mottled mudstone, siltstone and sandstone and is of Late Oligocene to Early Miocene (Chattian to Aquitanian) age. These sediments are succeeded by a series of greenish grey sandstone and subordinate conglomerate, grey siltstone and mudstone of the OMM (Burdigalian); shell fragments are common in specific horizons. The Molasse sequence terminates with a series of mottled mudstone, siltstone and sandstone with few cm- to dm-thin lacustrine marlstone or limestone beds of the OSM. The thickness of the OMM deposits ranges from 50 m to 200 m from north to south in the investigated area reflecting thus the wedge-shaped asymmetric geometry of the Molasse Basin (e.g. Kuhlemann and Kempf 2002). The coarse clastic debris originated from the Napf fan delta in the southwest, which drained the central Swiss Alps during the Early Miocene (Schlunegger et al. 1997a), as indicated by the clast and heavy mineral compositions (Büchi and Hofmann 1960; Matter 1964). The transport direction was roughly from southwest to northeast. In the distal part of the central Molasse Basin, fossiliferous horizons with biostratigraphic significance are very sparse and mostly restricted to the

Lower and Upper Freshwater Molasse (USM, OSM; e.g. Kälin 1997).

3 Methods

For geographic reference, all localities mentioned in the text and figures are provided in Swiss coordinates (CH1903+/LV95).

3.1 Lithostratigraphy

During fieldwork we performed a detailed lithostratigraphic logging of more or less continuous composite sections throughout the OMM in the perimeter of the map sheets Aarau and Schöftland (Jordan et al. 2011b; Graf et al. 2012a, plate II). These sections can be considered as representative of both lithofacies and thickness. We noted lithology, sedimentary structures and grain-size distribution, as well as the lateral continuity of beds where observable. Since the dip of bedding is generally less than 5°, correlations across several hundreds of metres are fairly feasible, especially when additionally guided by lithostratigraphic markers. The lithostratigraphic units discussed here are considered to be mappable at 1:25,000 scale.

3.2 Palaeontology

We investigated several hundred samples for palaeoecology and biostratigraphy, especially of marine macrofauna and mammal teeth. Most of the material is stored in the private collection of J. Jost, for other collections the reader is referred to Fig. 6.

The sediment samples—OMM sandstone of various sites—were washed and sieved down to 500 µm, occasionally even to 400 µm, to avoid extremely large quantities of residue. The fine-grained sediments of the limnic horizon, however, were sieved to 300 µm. While the sandy sediment is generally washed with water, and only occasionally additionally treated with H_2O_2 if necessary, the fine-grained sediments of the limnic horizon is always treated with H_2O_2 and in some cases even with gasoline.

The sieved residue is then picked under the microscope; the finds are carefully prepared, i.e. cleaned and prepared for classification. The amount of washed, sieved and picked sediment totals approximately 12 t for the entire Lucerne Formation, 5 t for the Staffelbach-Grobsandstein, 4 t for the limnic horizon, and 10 t for the rest of the St. Gallen Formation.

4 Results

Büchi (1957, 1958) classified the OMM-deposits on lithostratigraphic criteria: He used clearly recognisable marker beds of frequent occurrence and established a system of sandstone zones separated by these marker beds. He tentatively separated the “Burdigalien” from the “Helvétien” (Fig. 2) at the base of a well-visible and widespread basal conglomerate (Basisnagelfluh, burdigale Basiszone). A direct correlation of the “Burdigalien” and the “Helvétien” with the Lucerne Formation and St. Gallen Formation (Keller 1989), respectively, is problematic, largely due to laterally varying facies within the OMM and to the lack of biostratigraphic age control (Büchi 1957, 1958; Büchi and Hofmann 1960; Homewood and Allen 1981). To connect these lithostratigraphic concepts, we investigated the lithostratigraphy, biostratigraphy and palaeoecology in well exposed outcrops.

4.1 Lithostratigraphy

OMM sediments are here mainly composed of greenish grey medium-grained massive sandstone. Mudstone and siltstone, fine-grained sandstone and conglomerate occur secondarily. The sandstone beds show a variety of distinct sedimentary structures, such as wave-ripple lamination, cross bedding, and scours, which can frequently be interpreted to have formed in a tide-influenced shallow marine environment. Open marine deposits are, where present, characterised by faint horizontal lamination and predominantly fine-grained lithologies such as fine-grained sandstone, siltstone and mudstone.

A subdivision of the OMM, applicable at a map scale 1:25,000, was performed on the basis of infrequently occurring lithostratigraphic markers such as shell sandstone beds (Muschelsandstein; e.g. Büchi 1957). These are medium- to large-scale cross-stratified, pebbly sandstone units of a few metres thickness on average with abundant shell and echinoid fragments. It is assumed that individual shell sandstone beds have been deposited during a relatively short period of time, thus forming a more or less coeval horizon (see also below). Other markers are poorly stratified massive conglomerate horizons, which occur at regional scale. However, since they appear to be highly variable in thickness (when present, they reach thicknesses of <1 m to locally >25 m), these conglomerate horizons are potentially heterochronous.

Based on the field observations and mapping in the investigated area, Jordan et al. (2011a, b) and Graf et al. (2012a, b) lithostratigraphically correlated the sedimentary succession of the OMM (Fig. 2). In the following, we discuss this connection of these lithostratigraphic units to the Lucerne Formation and St. Gallen Formation.

4.1.1 Sandstone succession ("untere Sandsteinzone"; Büchi 1957)

The lowermost OMM unit is in the study area represented by a succession of olive-green grey to brown, (fine- to) medium-grained sandstone (i.e. the typical appearance of OMM-sandstone, as seen in many buildings throughout the Swiss Plateau). Frequently, the glauconite-bearing sandstone appears massive and is largely devoid of macrofossils or pebbles (see also, e.g., Büchi 1957; Frieling et al. 2009). Sedimentary facies can best be studied in larger outcrops (Figs. 3a, 5), typical sedimentary structures include low-angle trough-cross bedding, sometimes showing cm- (dm-) scale bed sets increasing or decreasing in thickness and steepness, and with mm-thin silty laminae in-between. Bed surfaces show occasionally symmetric ripples. For example, at Brittnau-Chüeweid, a trough-cross bedded sandstone with bed sets thinning and flattening towards the bed set toes is separated by mm-thin siltstone laminae. The individual bed set surfaces are not planar but wavy and may have resulted from indistinct ripple surfaces. The entire bedform, 0.5–1 m thick, can be interpreted as tidal sand wave (Fig. 4). Individual sandstone beds can be solid and therefore less prone to weathering, while the majority of sandstone beds appears to be weakly cemented. The total thickness is ca. 80 m in the Safenwil area in the north, 100–130 m in the central part and over 250 m in the south of the investigated area.

This lowermost OMM unit typically lacks continuous outcrops of more than a few metres vertically but can be found in many places. An almost continuous section is exposed at Muhen-Rütisgraben (base: 2648.200/1242.725, top: 2648.225/1243.050; Jordan et al. 2011b, Fig. 12). At the base of this section, below an outcrop gap of 15–20 m, the top USM is exposed.

Basal reworked (pebbly) sandstone Within the lowermost 20 m of the sandstone succession, local beds, which are in part rich in shell-fragments, occur occasionally (e.g. Niggli 1912, 1913; "burdigale Basiszone" of Büchi 1957, 1958). The dm-thick, medium-grained, yellowish-brown to grey sandstone beds can be up to approximately 2 m thick, have sharp erosive (channelised) bases, and contain mm-thin yellowish-brown silty to fine sandy bands. They show a lateral extent of a few metres up to probably a few tens of metres. They further include discrete string lines or bands of Alpine and, more importantly, mudstone pebbles (up to 8–10 cm in diameter), and also reworked caliche nodules of the underlying USM. Occasionally, these beds contain numerous shell fragments appearing thus as proper (pebbly) shell sandstone. Individual beds occur only locally, they do not form a single horizon. Trough-cross bedding and wave-ripple lamination is frequently seen indicating shallow marine, high-energy deposition under tidal influence. Well exposed outcrops of these reworked sandstone beds can be found at Brittnau (2638.300/1234.200) and Oberentfelden (2647.570/1243.980), local shell sandstone beds are present at Zofingen (2640.275/1238.925) and Safenwil (2640.150/1240.400).

4.1.2 Safenwil-Muschelsandstein

The OMM deposits can be divided by a shelly sandstone (Muschelsandstein), which forms a mappable, regionally occurring marker horizon (e.g. Büchi and Hofmann 1960; Allen et al. 1985) (Fig. 3a). Based on the regional occurrence of the Muschelsandstein between western Switzerland (Seeland) and the Bodensee region, and although variable in outcrop appearance (e.g. types 1 and 2 of Allen et al. 1985), it is justified to formally define the *Safenwil-Muschelsandstein* as a lithostratigraphic member of the lower OMM. The type locality of the ca. 10-m-thick Safenwil-Muschelsandstein is at Safenwil-Blatten (2641.100/1240.250/555 m; Fig. 3a, Safenwil section). Further well exposed outcrops nearby are at Safenwil-Berg (2640.550/1239.950; ca. 5 m thick) and at Safenwil-Chünigrain (2642.125/1240.725/560 m). Along the hiking path near Muhen-Rütisgraben (2648.300/1243.075), nearly the entire sediment succession of the lower part of the OMM can be observed (Fig. 3a); there, the Safenwil-Muschelsandstein reaches a thickness of 5–6 m.

The Safenwil-Muschelsandstein is typically rich in and easily recognisable by fragments of irregular echinoids of *Scutella* sp., and can be observed at many localities throughout the study area. Those echinoids cannot tolerate brackish conditions but favor shallow marine sandy environments, where they also may accept falling dry (e.g. on tidal flats); fragmentation was probably caused in situ by wave activity (R. Trümpy in Büchi 1957). It is composed of solid to very solid, medium- to coarse-grained, yellowish-grey, often cross-bedded platy sandstone with abundant Alpine pebbles as well as intra-formational mudstone pebbles. Small-scale cross-bedding, wave-ripple lamination and a channelised base are also frequently seen. Occasionally, the Safenwil-Muschelsandstein is lacking or may be present as echinoid-bearing sandstone. The investigated outcrops resemble the second Muschelsandstein-type of Allen et al. (1985), which they described as thin (metre scale), small-scale cross-bedded shelly sandstone of tidal origin. According to these authors, this type concentrates on localities close to the former Napf fan delta (Allen et al. 1985). Below the Safenwil-Muschelsandstein, intensely reworked dm- to m-thick sandstone, rich in yellowish-brown mudstone pebbles occurs frequently, and indicates

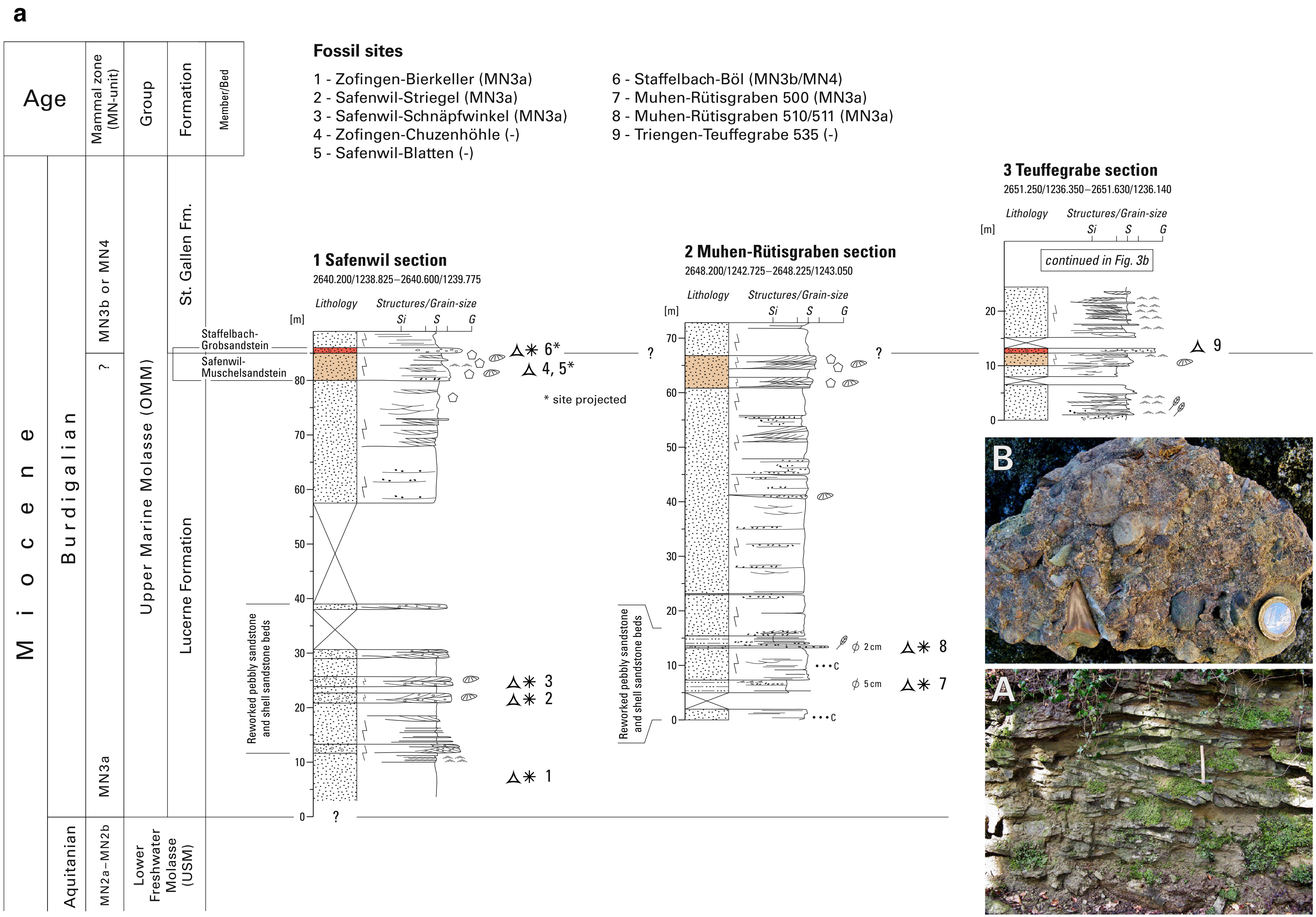
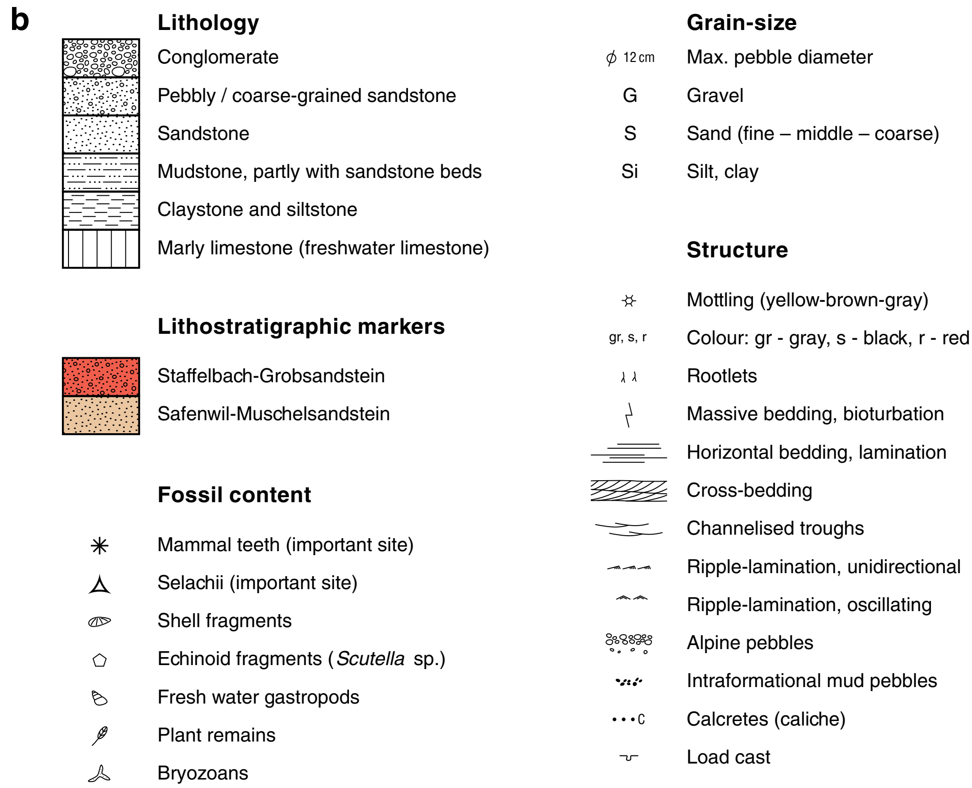


Fig. 3 **a** Composite lithostratigraphic key sections (from Graf et al. 2012b, plate II) of the lower part of the OMM (Lucerne Formation). Photographs depict the Safenwil-Muschelsandstein of the Muhen-Rütisgraben section (*A*) and a hand specimen of the Staffelbach-Grobsandstein from the type locality at Staffelbach-Böl (*B*). Photos J. Jost 2008/2009. **b** Legend of **a** and Fig. 5

Fig. 3 continued



intense reworking, pointing towards a high-energy depositional environment.

While the Safenwil-Muschelsandstein represents a discrete, several m-thick, and clearly visible sandstone unit in the north of the investigated area, it becomes thicker (up to more than 15 m) but less well defined in the south. However, based on appearance and its typical fossil content (echinoid fragments), no difference is evident between both types.

The Bisig-Muschelsandstein (Gerber and Kopp 1990; Gerber 1994) further to the south and west appear to be a lateral equivalent of the Safenwil-Muschelsandstein. The shell sandstone beds can easily be traced and correlated from the Safenwil region towards Brittnau, Roggliswil and Melchnau. A possible correlation further to the west (Wynigen, Burgdorf) is not yet clear but is part of our current work. To the northeast, the shell sandstone beds can be followed to Lenzburg, potentially even to Mägenwil/Othmarsingen, however without biostratigraphic proof at the moment. There, the Muschelsandstein corresponds to type 1 of Allen et al. (1985) characterised by large-scale cross bedding and a strong bedform asymmetry.

4.1.3 *Staffelbach-Grobsandstein*

The Staffelbach-Grobsandstein is a coarse-grained, often pebbly sandstone, occasionally even a fine-pebbly (often matrix supported) conglomerate, which forms sometimes

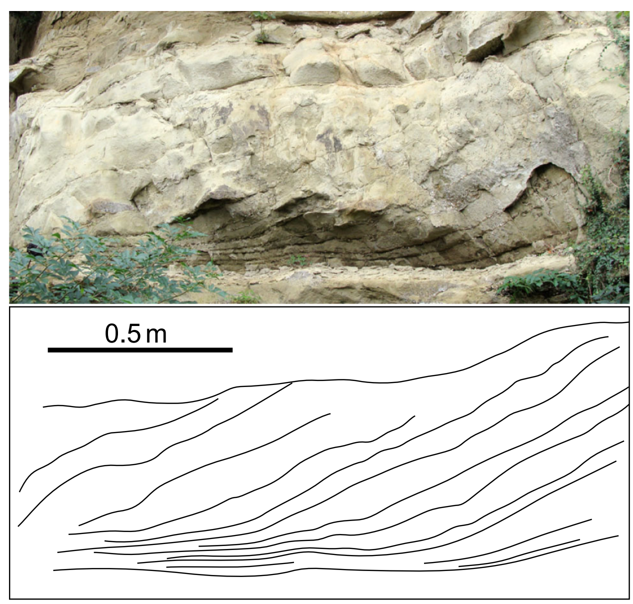


Fig. 4 Field photograph of a tidal sand wave of the Lucerne Formation at Brittnau and, below, line drawing of the bed sets. Photo O. Kempf (2009)

solid, sometimes weakly consolidated beds (Fig. 3a). Owing to its distinct aspect we here formally define the *Staffelbach-Grobsandstein* as lithostratigraphic bed. At the type locality Staffelbach-Böl (2645.450/1236.950; Graf et al. 2012a, b), a former sandstone quarry east of Staffelbach, the Staffelbach-Grobsandstein is represented by a pebbly sandstone of roughly 1 m thickness following approximately 20 m above the Safenwil-Muschelsandstein. In other places, it can also be situated directly on top of the Safenwil-Muschelsandstein.

The conglomerate and pebbly sandstone is often matrix-supported, the composition of the Alpine pebbles is dominated by greenish quartzite typical of the Schüpferegg-Nagelfluh (Matter 1964). Therefore, the sediment is considered to be derived from the Napf alluvial fan in the southwest and probably deposited by mass flow processes. The thickness of the Staffelbach-Grobsandstein varies from few centimetres to about 3 m at most; locally, it may be lacking. The rather coarse-grained facies is restricted to localities in the western and southern areas. Further to the north and east it is fine-grained and contains fewer and only fine pebbles; it is there difficult to clearly recognise the bed in the field. A continuous succession from the Safenwil-Muschelsandstein to the Staffelbach-Grobsandstein is visible in the northern study area at Safenwil-Berg (Fig. 3a, Safenwil section), among other localities.

The Staffelbach-Grobsandstein can be found between Suhr/Gränichen in the north and Schötz/Ohmstal in the south; farther south it is hidden below the surface, if present at all. A comparable pebbly sandstone exposed occasionally in the Burgdorf-Langenthal-Sumiswald region may serve as an equivalent of the Staffelbach-Grobsandstein.

4.1.4 Sandstone succession ("obere Sandsteinzone"; Büchi 1957, lower part)

A thick unit of predominantly medium-grained, grey-brownish sandstone with few discrete Alpine pebble layers or thin pebble sheets higher-up follows above the Staffelbach-Grobsandstein. The frequently parallel-laminated or low-angle cross-bedded sandstone may be weakly cemented or shows solid beds. A well exposed section can be seen in the Teuffegrabe (Sect. 3, Fig. 5). The base of the section is characterised by trough-cross bedded sandstone, with bed sets abundantly draped with clay- to siltstone laminae. A heterolithic, wavy bedded unit of a few metres thickness occurs above. Large-scale cross-bedding is occasionally visible in outcrop, the cm- to dm-thick bed sets (mostly medium sand with occasionally mudstone pebbles) are draped with mm-thin mostly siltstone that show ripple lamination directed towards the opposite direction of the large-scale sandstone cross-bedding. This indicates again tidal conditions during time of deposition. Sandstone layers full of grey platy mudstone pebbles or an intercalation with yellow-brownish cm-thin mudstone layers occur frequently within the lower part of the sandstone succession. Very locally (e.g. at Teuffegrabe), a dark-grey, laminated siltstone to very fine-grained sandstone unit, a few metres thick, occurs near the base of the succession. Higher-up, the sandstone succession is increasingly constituted of thin bands of Alpine and mudstone pebbles, before it is interrupted by a sequence of quartzite-rich conglomerate of variable thickness. This sandstone unit is best exposed in the southern parts of the investigated area, where some important fossil sites are also located (see also Jordan et al. 2011a, b; Graf et al. 2012a, b).

This sandstone succession can be traced continuously from Gränichen (east) to at least Melchnau (west). In the region Wynigen/Burgdorf the sandstone succession continues, though largely without Alpine pebble layers.

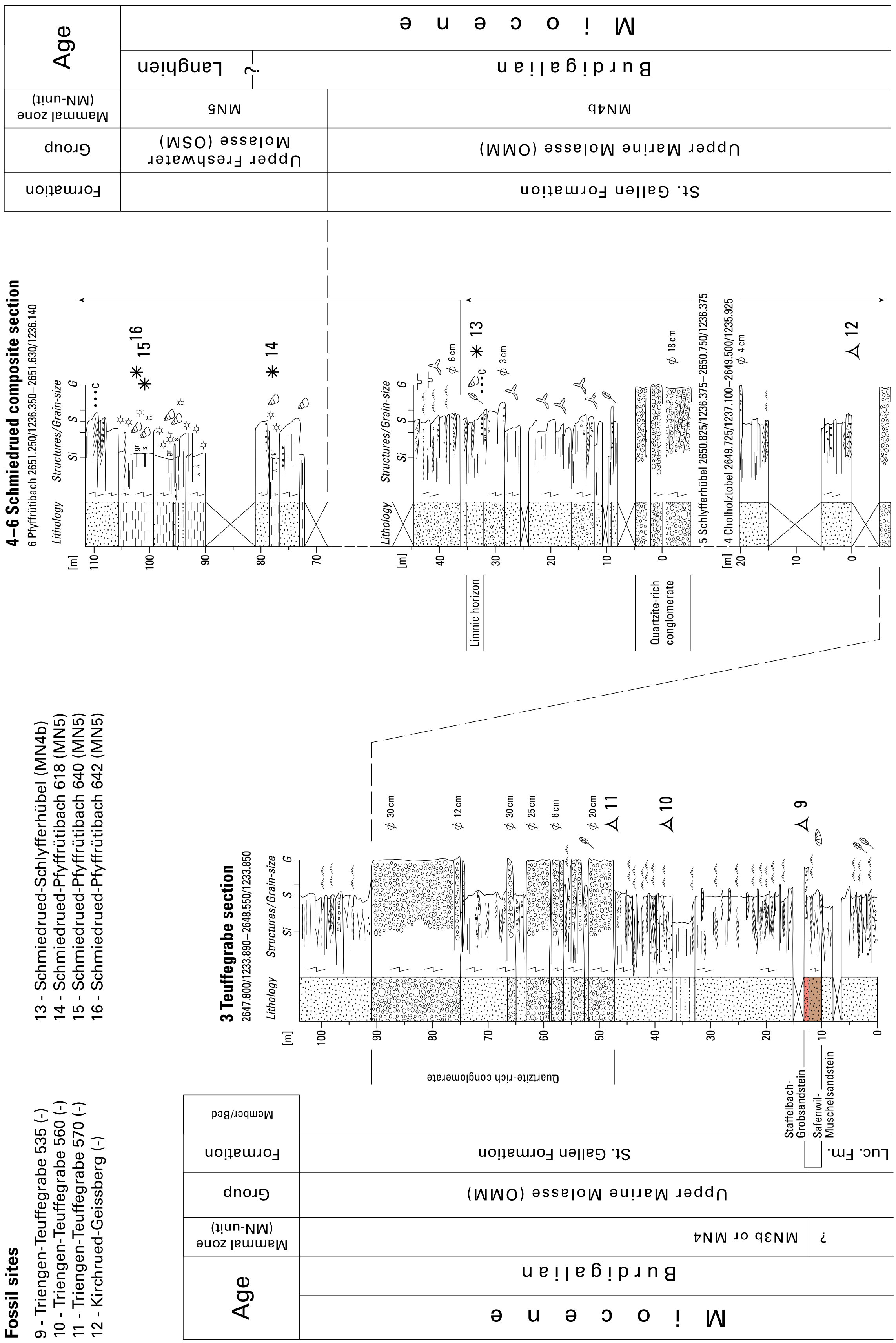
4.1.5 Quartzite-rich conglomerate (Quarzitnagelfluh)

The quartzite-rich conglomerate is generally poorly sorted, mostly coarse-grained and has a sandy matrix; sharp erosive bases are common. Occasionally, yellowish sandstone interlayers, which may consist of few Alpine pebbles, occur. The sandstone is frequently cemented in a patchy manner. Rarely, the conglomerate may even contain oyster shells. The size of the Alpine clasts varies from few cm to > 30 cm. The thickness of the conglomerate can vary strongly throughout the study area. Typically, it is between 1 and 5 m thick and horizontally bedded but may occasionally show cross-bedding at metre scale; greatest thickness exceeds 35 m at Teuffegrabe (Fig. 5). Locally, the quartzite-rich conglomerate may be lacking.

Like in the Staffelbach-Grobsandstein, the composition of the Alpine pebbles is dominated by greenish quartzite. Therefore, the sediment is also considered to have been derived from the Napf alluvial fan (Matter 1964) in the southwest.

4.1.6 Bryozoan-rich sandstone succession (obere Sandsteinzone; Büchi 1957, upper part)

A roughly 30-m-thick, yellowish-brown, medium- to coarse-grained sandstone unit, occasionally with Alpine and mudstone pebble layers, follows above the quartzite-rich conglomerate. Since the sandstone is full of calcareous bryozoan fragments it may be referred to as a bryozoan sandstone. Patchy cementation resulting in spheroid-shaped solid sandstone blocks within weakly cemented sandstone forms a characteristic feature within this succession ("Knauersandstein"). The massive sandstone is made up of planar cross bedding with set heights of cm to dm, occasionally with an erosive channelised base. Horizontally or planar-cross bedded fine-grained sandstone shows mudstone-draped symmetric ripple surfaces pointing towards a tidally influenced depositional regime. Towards the top, particularly above the limnic horizon (see below), these planar-cross stratified (rarely trough-cross stratified)


Fossil sites
9 - Triengen-Teuffegrabe 535 (-)
10 - Triengen-Teuffegrabe 560 (-)
11 - Triengen-Teuffegrabe 570 (-)
12 - Kirchrued-Geissberg (-)
13 - Schmiedrued-Schlyfferhübel (MN4b)
14 - Schmiedrued-Pfyffrütibach 618 (MN5)
15 - Schmiedrued-Pfyffrütibach 640 (MN5)
16 - Schmiedrued-Pfyffrütibach 642 (MN5)
3 Teuffegrabe section
2647.800/1233.890–2648.550/1233.850
4–6 Schmiedrued composite section
6 Pfyffrütibach 2651.250/1236.350–2651.630/1236.140
5 Schlyfferhübel 2650.825/1236.375–2650.750/1236.375
4 Cholholztobel 2649.725/1237.100–2649.500/1235.925
Lithology
Structures/Grain-size
Si
S
G
[m]
Quartzite-rich conglomerate
Limnic horizon
Staffelbach-Grobsandstein
Safenwil-Muschelsandstein
Age
Miocene
Burdigalian
Langhien
Mammal zone (MN-unit)
MN3b or MN4
MN4b
MN5
Group
Upper Marine Molasse (OMM)
Upper Freshwater Molasse (OSM)
Formation
St. Gallen Formation
Luc. Fm.
Member/Bed

◀**Fig. 5** Composite lithostratigraphic key sections (from Graf et al. 2012b, plate II) of the upper part of the OMM (St. Gallen Formation) and the transition into the Upper Freshwater Molasse (OSM). See Fig. 3b for legend

beds occasionally include pebble layers or pebbly pockets at the bed-base (e.g. at Schmiedrued). The contact to the succeeding Upper Freshwater Molasse is nowhere directly exposed in the study area.

Limnic horizon A few metres thick and lithologically highly variable unit of limnic sediments can be found occasionally within the uppermost part of the bryozoan sandstone succession (Fig. 5). Rich otolith faunas are indicative of the limnic environment (e.g. Jost et al. 2006), though most localities also show a weak marine influence, e.g. by the presence of oysters and very rare shark teeth. There is a great variety in the lithological and facies appearance of the limnic horizon: At the reference locality Mauensee (Map sheet Sursee, see Fig. 1; Reichenbacher et al. 2005; Jost et al. 2006), the sediments are predominantly formed by an intercalation of 3.7 m mudstone and freshwater limestone beds. In the region of Schöftland, the purely limnic beds are represented by a marly, fine-detritic mudstone at Schmiedrued (2650.720/1235.410) and

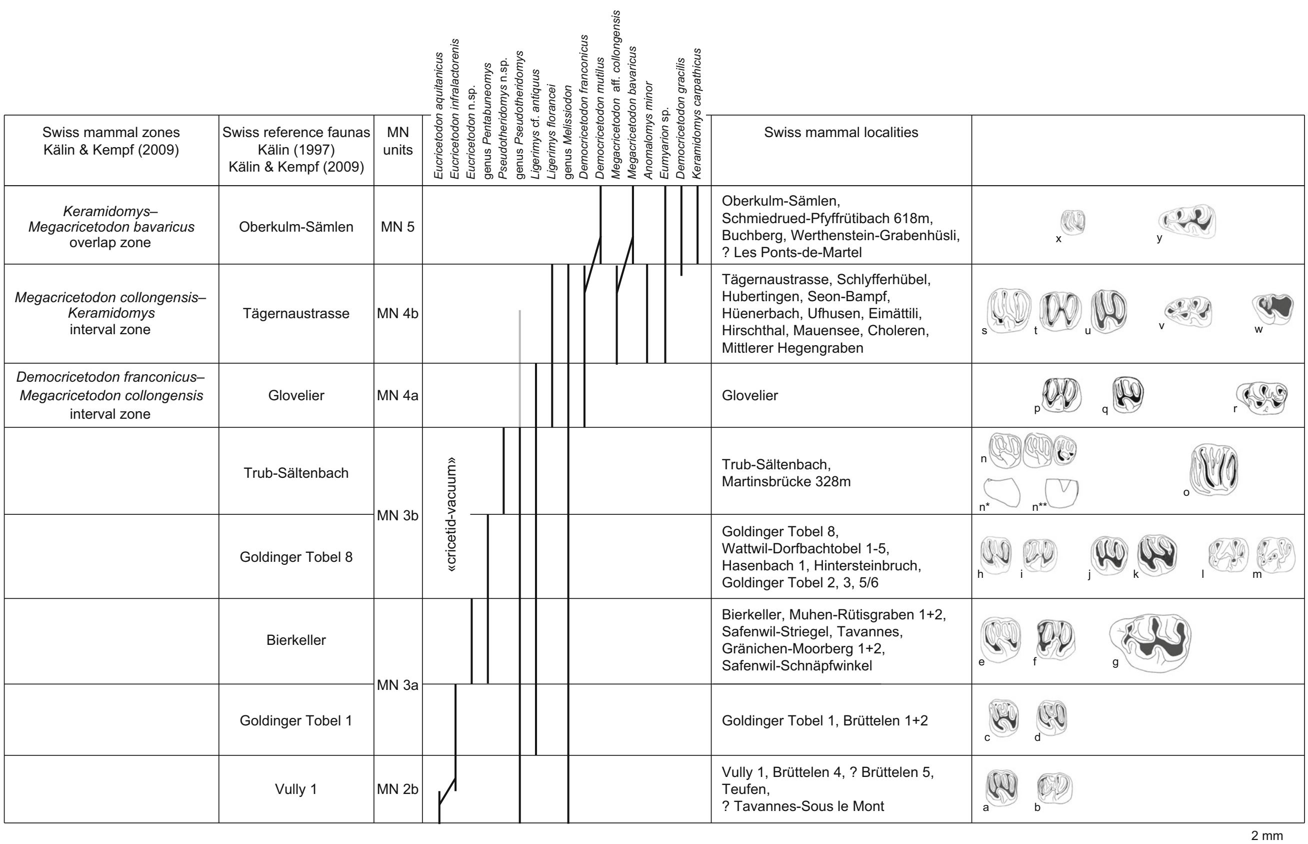


Fig. 6 Significant rodent taxa of the mammal units MN 2b–MN 5 (base). **a**, **b** *Pseudotheridomys* aff. *lacombai* Alvarez Sierra, 1987 from Brüttelen 2, M^1 dext. (inverse) J.J. 1, m_2 sin. J.J. 3. **c**, **d** *Ligerimys antiquus* Fahlbusch, 1970 from Goldinger Tobel 1, M^1 dext. (inverse) J.J. 23, M^2 sin. Gt. 8. **e**, **f** *Ligerimys lophidens* Dehm, 1950 from Bierkeller, M^1 dext. (inverse) J.J. 14, m_2 dext. (inverse) J.J. 16. **g** *Eucricetodon* n. sp. from Bierkeller, M^1 sin. J.J. 32. **h**, **i** *"Ligerimys" oberlii* Engesser, 1990 from Goldinger Tobel 8, M1/2 dext. (inverse) KGt. 1, $m_{1/2}$ dext. (inverse). KGt. 2. **j**, **k**) *Ligerimys lophidens* Dehm, 1950 from Hintersteinbruch, P^4 sin. Hsb. 1, M^1 dext. (inverse) Hsb. 5. **l**, **m**) *Pentabuneomys rhodanicus* Hugueney & Mein, 1968 from Hasenbach, m_1 sin. Hab. 3, m_2 sin. Hab. 4. **n** *Pseudotheridomys* n. sp. from Trub-Sältenbach, $M^{1/2}$ dext. (inverse) KTrs. 2, $M^{1/2}$ dext. (inverse) KTrs. 3, M3 sin. KTrs. 4. **n***, **n**** *Pseudotheridomys* n. sp., $M^{1/2}$ (inverse) KTrs. 2 from Trub-Sältenbach in frontal and lingual view. **o** *Nievella* sp. from Trub-Sältenbach, $M^{1/2}$ sin. KTrs. 5. **p** *Ligerimys florancei* Stehlin & Schaub, 1951 from Glovelier, $m_{1/2}$ dext. (inverse). Gvl.2. **q** *Ligerimys* cf. *antiquus* Fahlbusch, 1970 from Glovelier, $M^{1/2}$ dext. (inverse). Gvl.3. **r** *Democricetodon franconicus* Fahlbusch, 1966 from Glovelier, M^1 dext. (inverse). Gvl.1. **s** *Ligerimys* cf. *florancei* Stehlin & Schaub, 1951 from Hirschthal, M^1 dext. (inverse) M.M. 2419. **t** *Ligerimys* cf. *florancei* Stehlin & Schaub, 1951 from Schlyfferhübel, $M^{1/2}$ dext. (inverse), J.J. 33. **u** *Ligerimys* cf. *florancei* Stehlin & Schaub, 1951 from Choleren, $M^{1/2}$ sin. Kcho 1. **v** *Megacricetodon collongensis* (Mein, 1958) from Schlyfferhübel, m_1 sin. J.J. 34. **w** *Anomalomys minor* Feifar,1972 from Hirschthal, M^1 sin. **x** *Keramidomys carpathicus* Schaub & Zapfe, 1953 from Oberkulm-Sämlen, $M^{1/2}$ sin. J.J. 35. **y** *Megacricetodon bavaricus* Fahlbusch, 1964 from Oberkulm-Sämlen, m_1 sin. JOKS 1. Figures **a**–**f**, **j**–**m**, and **s** redrawn from Engesser (1990). Specimen without prefix = Natural History Museum Basle, prefix J = private collection Jürg Jost, prefix K = private collection Daniel Kälin

Table 1 Occurrences of the most important selachian families and genera of the OMM of the central Swiss Plateau

Family	Genus	BS	SM	SG	SF	QB
Carcharhinidae	*Carcharhinus*	++	++++	++++	+++	++
	Physogaleus	+++				
	Galeocerdo	++	+++	+++	++	
	Isogomphodon			++	++	++
	Rhizoprionodon		++++	++++	+++	++
Hemigaleidae	*Chaenogaleus*		+++	+++	+++	
	Paragaleus			++	++	
	Hemipristis	++	++	++	++	
Triakidae	*Iago*			+	+	
Sphyrnidae	*Sphyrna*		++	+++	+++	++
Scyliorhinidae	*Premontreia*	+++++	+++++	+++	+++	+++++
	Scyliorhinus (cf. fossilis)		+	+++++	+++++	
Lamnidae	*Megaselachus (Carcharocles)*		++	++		
	Cosmopolitodus		+++	+++	+++	
Odontaspididae	*Carcharoides*	++	+++	+++	+++	
	Carcharias	+++++	+++++	++++	+++	+++++
	Araloselachus	++	+++	+++	++	+
	Odontaspis			++	++	
Pseudocarchariidae	*Pseudocarcharias*			+++	+++	
Mitsukurinidae	*Mitsukurina*		+	+++++	+++++	
Alopiidae	*Alopias*		+++	+++	+++	
Cetorhinidae	*Keasius*	++	+++	+++	++	
Rhincodontidae	*Rhincodon*				+	
Hexanchidae	*Notorhynchus*		+++	+++	+++	
Heptranchidae	*Paraheptranchias*			++	++	
Squatinidae	*Squatina*		+++	+++	+++	
Squalidae	*Squalus*		+	+++	+++	
Centrophoridae	*Centrophorus*		++	+++++	+++++	
	Deania			++	++	
Dalatiidae	*Isistius*		++	++++	+++	
	Squaliolus			+	+	
Pristiophoridae	*Pristiophorus*		++	+++	+++	
Dasyatidae	*Dasyatis*	+++++	++++	+++	++	++++
	Taeniura	+++	+++	+++	+++	+++
Rhinopteridae	*Rhinoptera*	+++	++++	+++	++	++
Myliobatidae	*Aetobatus*	+++	++++	+++	++	
	Mobula			++	++	
	Plinthicus				+	
Rhynchobatidae	*Rhynchobatus*		+++	+++	+++	
Rhinobatidae	*Rhinobatos*			++	++	++++
Gymnuridae	*Gymnura*		+	+	+	
Rajidae	*Raja*	++	++	+++++	+++++	++
Torpedinidae	*Torpedo*			+	+	

BS Basal reworked (pebbly) sandstone, local shell sandstone beds (Lucerne Fm.), *SM* Lower sandstone sequence and Safenwil-Muschelsandstein (Lucerne Fm.), *SG* Staffelbach-Grobsandstein (St. Gallen Fm.), *SF* Upper sandstone succession (St. Gallen Fm.), *QB* Quartzite-rich conglomerate and bryozoan-rich sandstone (St. Gallen Fm.)

Occurrences: +++++ very frequently; ++++ frequently; +++ regularly; ++ rare; + very rare

Gontenschwil (2653.025/1235.800). At most other localities, however, reworking and the presence of Alpine and intra-formational mudstone clasts characterise this limnic intercalation; occasionally occurring caliche nodules point, at least sporadically, to subaerial exposure (Jordan et al. 2011b; Graf et al 2012a).

The thickness of the upper part of the OMM totals less than 70 m in the north, 100–120 m in the central part and over 200 m in the south of the investigated area.

4.2 Mammal biostratigraphy

The biostratigraphic classification of OMM sediments is mainly based on teeth of fossil rodents, despite their predominantly marine facies. Indeed, remains of fossil mammals do not only occasionally occur within intercalated brackish or terrestrial sediments but also in clearly marine sediments. Terrestrial animals and plants have been sporadically transported by rivers into the nearby sea, distributed by coastal currents, and deposited in the marine environment. This is indicated by pebble-rich sediments containing remains of both terrestrial and marine origin (mammals, plants, rays, sharks, etc.). Unfortunately, there are only few sites offering a rich and biostratigraphically significant mammal fauna in the investigated area. The resulting time frame refers to the Neogene mammal biostratigraphic chart, expressed in MN units, as established by Mein (1975, 1989).

Local biostratigraphy has been established on the basis of several sections within the OMM or in freshwater sediments that were contemporaneous to OMM sediments (Kälin 1997). The lower part of the OMM (Lucerne Formation) is subdivided into four mammal assemblages (Fig. 6). The lowermost assemblage zone of Goldinger Tobel 1 is characterised by the first representatives of the genus *Ligerimys*. The next younger assemblage zone of Bierkeller is characterised by the last and largest representative of the cricetid genus *Eucricetodon*. The following assemblage zones of Goldinger Tobel 8 and Trub-Sältenbach are dominated by eomyids and are lacking cricetid remains (with the exception of the genus *Melissiodon*); both zones represent the characteristic "cricetid vacuum" (Daams and Freudenthal 1989). The next younger zone of Glovelier is represented only by a single fauna from a karstic fissure filling near the northern coast of the OMM-sea. This karstic system has been flooded by the northernmost transgression of the OMM-sea. The fauna is characterised by the first record of modern cricetids (*Democricetodon franconicus*). Finally, the first record of *Megacricetodon, Eumyarion*, and *Anomalomys* defines the next younger zone of Tägernaustrasse.

Top USM/base OMM: The youngest deposits of the USM contain late MN2a to early MN2b faunal assemblages of the latest Aquitanian (cf. Graf et al. 2012a, plate II; Fig. 3a). The most important locality in the study area is the site Oberentfelden-Eistel (2647.150/1244.250/450 m) showing faunal assemblages of MN2a–MN2b. This represents the last period of freshwater deposition in the central Plateau Molasse before the marine transgression. Further west, at Brüttelen, Jolimont or Mt. Vully, the marine transgression is more pronounced and appears to have commenced somewhat earlier than in Central Switzerland (unpubl. mammal data D. Kälin and J. Jost).

Lower OMM MN3a assemblages already characterise the lower sandstone succession of the lower part of the OMM in the study area. Keller (1989, p. 237 f.) suspects that the base of the OMM may be heterochronous in the southern part of the basin (and potentially further to the west), where the OMM-transgression may have started already during the late Aquitanian. Unfortunately, to date, there is no biostratigraphic evidence for or against this hypothesis.

The same faunal assemblages are occasionally found higher up but still below the Safenwil-Muschelsandstein. Important mammal-bearing sites of MN3a age include Zofingen-Bierkeller (2640.225/1238.825/490 m), Safenwil-Schnäpfwinkel (2640.200/1240.550/540 m) and Safenwil-Striegel (2640.175/1240.375/530 m), Gränichen-Moorberg-1 (2649.030/1244.350/450 m), as well as Muhen-Rütisgraben-1 (2648.250/1242.750/500 m). Until now, no unambiguous and stratigraphically distinctive assemblages have been derived directly from the Safenwil-Muschelsandstein horizon. These faunas are in fact correlated to a younger MN 3a faunal assemblage (Bierkeller), while remains of the older MN 3a faunal assemblage (Goldinger Tobel 1) have not been found yet throughout the investigated area (see also Fig. 6).

Base upper OMM The few finds of mammal teeth in the Staffelbach-Grobsandstein point to a maximum age of MN3b. The most important tooth from Staffelbach is an elephant-like species (Proboscidea): No such teeth found in Europe are older than MN3b (pers. comm. U. Göhlich, Vienna, and E. Heizmann, Stuttgart).

Upper OMM The few mammal teeth of the upper sandstone succession indicate an age of MN4b. Of greatest importance are *Eumyarion* sp. of site Wikon-Ried (2641.300/1234.960; Graf et al. 2012a) and *Megacricetodon* sp. of Roggliswil-Hornwald (de Bruijn and Saraç 1992). Less suitable for biostratigraphic purposes are teeth of eomyids and other mammals. A find of *Mirabella* sp. from the locality Reiden-Sertel (de Bruijn and Saraç 1992) is difficult to assign biostratigraphically, because only one other tooth of this form has been found yet (in Rembach, Bavaria, Ziegler and Fahlbusch 1986) outside of Greece/Turkey.

Mammal finds from the quartzite-rich conglomerate succession, a pebbly sandstone at the locality Dürrenäsch-Stalten (2653.750/1241.430/520 m), result in an age of MN 4b. Mammal finds are otherwise rare. MN4b ages were also derived from sediments of the uppermost OMM-II, particularly from the limnic horizon (Reichenbacher et al. 2005). The small mammal faunas comprise especially rodents, e.g. species of hamster, sleeper and squirrel, as well as types of hare and various insectivores. Large mammal teeth of cervids, rhinoceros, hogs, and elephantine types are also proven.

Base OSM Mammal biostratigraphic data of the basal Upper Freshwater Molasse (OSM) from various sites at Schmiedrued-Pfyffrütibach (Jost et al. 2015) indicate already the faunal assemblage zone of early MN5 (cf. Graf et al. 2012a, plate II; Fig. 5).

4.3 Marine fauna and palaeoecology

The marine fauna of the OMM deposits, mostly of the sandstones, turned out to be of great importance in understanding the palaeoecological evolution of the depositional system. In the following we refer to families and genera of selachii[2] as shown in Table 1 and on Fig. 8.

Teeth of stingrays (*Dasyatis*), cat sharks (*Premontreia*) and sand tiger sharks (*Carcharias*) dominate the fauna of the local *reworked sandstone beds* near the base of the Lucerne Formation. *Physogaleus* cf. *latus* Storms, 1894 is a rare but regularly occurring shark species at this level. All selachian species derived from the reworked (pebbly) sandstone beds can be found exclusively in very shallow water, the total amount of ten species of sharks and six species of stingrays is rather low to moderate. Additional marine fossils derived from the shell-bearing sandstone beds comprise mostly molluscan shells (Cardiidae, Veneridae, Pectinidae), but also bony fish teeth of sea breams (Sparidae). Fossil teeth from terrestrial (crocodile, small mammals) or freshwater (Cyprinidae) occur as well.

Faunas derived from the reworked sandstone beds and local shell sandstone beds show generally a poor diversity. All selachian species are characteristic of shallow marine, near coastal conditions. An environment of laterally migrating tidal channels may be distinctive for the faunal assemblages found in the local shell sandstone beds. There, large amounts of fossils may accumulate by concentration. Terrestrial or limnic fossils were occasionally transported into the shallow marine environment by rivers. Since even very fragile teeth are well preserved, the activity of currents was presumably rather weak.

The diversity of selachian species within the lower *sandstone sequence* above the reworked sandstone beds becomes successively much greater up-section. Teeth of shark, ray, and bony fish species are abundant again. In particular, the family of requiem sharks (Carcharhinidae) comes up with a number of new species. But also the genera of basking shark *Keasius (Cetorhinus)*, sevengill shark (*Notorhynchus*), thresher shark (*Alopias*), mako shark (*Cosmopolitodus*), angel shark (*Squatina*), and others occur or become more frequent. Dogfish sharks (*Squalidae*) are now regularly present with *Squalus* sp. cigar shark (*Isistius*), however, is still rare. Among the ray genera, the stingray (*Dasyatis*) is still the dominant form, but cownose ray (*Rhinoptera*) and eagle rays (*Myliobatis, Aetobatus*) increase in number. A new form is guitarfish (*Rhynchobatus*), whereas thornback ray (*Raja*) becomes more important. The total amount of roughly 20 shark species and 10 ray species is significantly higher than in the reworked beds, below. Bony fish species also increase in number. First occurrences of fragments—rarely complete specimens—of irregular echinoids (*Scutella* sp.) can be observed, especially in outcrops close to the basin center. Fragmented balanids occur regularly, as do complete specimens. Interestingly, the shallow marine brachiopod genus *Pliothyrina* occurs. This taxon needs stenohaline conditions to survive (pers. comm. H. Sulser 2015).

The selachian fauna of the lower sandstone succession is almost exclusively composed of shallow water species. Therefore, a shallow marine sea with subaqueous tidal channels, in which fossils may accumulate, still characterises the depositional realm. The preservation of the fossils is less favorable than in the beds below, teeth with signs of reworking occur more frequently; it seems that the energy of waves and currents had increased.

In the *Safenwil-Muschelsandstein* teeth of selachian species are frequently found in a great variety, the number of species and specimens increases again. Owing to the fact that in the past particularly the well-visible large-tooth specimens were collected in the active quarries of the Safenwil-Muschelsandstein, these species seem to be overrepresented in the Swiss collections in which the smaller teeth seem to be missing to a large degree. The most frequent taxa are therefore sand tiger shark (*Carcharias*), tiger shark (*Galeocerdo*), mako shark (*Cosmopolitodus*), fossil shark (*Hemipristis*) or sevengill shark (*Notorhynchus*). Teeth up to 15 cm long of *Megaselachus (*syn. *Carcharocles)*, an extinct mackerel shark species, are rare. Among other species one can regularly find teeth of toothed whales (Odontoceti). As in the underlying levels, a variety of bony fish species frequently occur, which is, however, often difficult to properly classify. Fragments of irregular echinoids (*Scutella* sp.) occur here in uncountable masses. Fragmented balanids occur regularly, as do

[2] For details on determination and nomenclature we refer to http://www.shark-references.com/.

complete specimens. Molluscan shells (cockle, clam, scallop, oyster, etc.) are frequently present, both with preserved shells and as endocasts. Wood relics are abundant.

The depositional environment of the Safenwil-Muschelsandstein is comparable to the basal reworked sandstone beds; however, a further increase in energy is probable. The large number of irregular echinoids, which lived buried in mud and sand, is characteristic. It is noteworthy that those echinoids cannot tolerate brackish conditions but favor shallow marine sandy environments, where they also may accept falling dry (R. Trümpy in Büchi 1957).

In the *Staffelbach-Grobsandstein* a very rich selachian fauna of more than 70 species can be found. Selachian teeth can be very abundant, i.e. hundreds of teeth are found within a few kg of sediment. Newly appearing taxa occur in addition to the known genera of the Safenwil-Muschelsandstein, which themselves also become much more abundant. The new genera prefer deeper water, and important representatives are the goblin shark (*Mitsukurina*), crocodile shark (*Pseudocarcharias*), smalltooth sand tiger shark (*Odontaspis*), cow shark *Paraheptranchias* as well as dogfish sharks (*Centrophorus, Deania, Isistius*) and saw shark (*Pristiophorus*). Teeth of many bony fish and toothed whale species (Odontoceti) also frequently occur. Fragments of irregular echinoids (*Scutella* sp.) are still abundant in some localities, as are balanid and molluscan fragments.

Fossil sites of the lower part of the upper *sandstone succession* document a highly variable selachian fauna including more than 70 species. The dominant forms are those, which had occurred in the Staffelbach-Grobsandstein for the first time. They prefer deeper water environments. Of greater interest are some rare forms that appear for the first time or become more abundant in this unit. These are the giant devil rays (*Mobula* and *Plinthicus*), and there is even evidence of the whale shark (*Rhincodon*) from the lowermost part of this succession. Bony fish are still common, even with some new species, molluscans like oysters can be found occasionally. Teeth of toothed whales (Odontoceti) become very rare, while spines of sea urchins, balanids and crabs are occasionally found in the sediment. Fragments of irregular echinoids are no longer present.

The selachian fauna documents here the most open marine conditions and the greatest water depth during deposition of OMM sediments. The detected whale sharks and devil rays are planktonic feeders of subtropical to tropical regions requiring large amounts of nutrients. Many of the dominant species prefer today a water depth of at least 100 m, which may provide a good estimate for this part of the OMM. Most specimens are well preserved and only rarely rounded. Towards the quartzite-rich conglomerate up-section, the fauna evidences a successive decrease of water depth, and more and more teeth are again rounded and transported. Thus it seems that the influence of waves and currents increases up-section. It is interesting to note that the selachian fauna found here is extremely similar to the fauna found in the southern part of the Rhône valley near Avignon, which is interpreted as a bathyal environment (Ledoux 1972; Vialle et al. 2011).

Rarely, selachian teeth indicating shallow water conditions can be found in more sandy deposits of the *quartzite-rich conglomerate*. Individual localities show accumulations of oyster fragments, remains of freshwater fish and terrestrial mammal teeth, as well as frequently seen remnants of driftwood.

5 Discussion

5.1 Lithostratigraphic correlation

Based on excellent outcrop conditions and long continuous sections at the southern basin margin, Keller (1989) subdivided the OMM by a detailed lithofacies analysis, which resulted in the recognition and definition of the Lucerne Formation and the St. Gallen Formation. He was able to further subdivide the Lucerne Formation informally into a basal wave-dominated lithofacies association, succeeded by a tide-dominated, and, higher up, by a mixed wave- and tide-dominated lithofacies association (Keller 1989). In the study area, however, this succession of facies associations is somewhat different since we have not found wave-dominated deposits to a larger extent. On the other hand, as suggested by the seismic interpretation of Schlunegger et al. (1997), the lowermost, wave-dominated lithofacies association seems to never has reached the study area and disappeared towards the north some 10 km north of Boswil, i.e., only the mixed and tide-dominated lithofacies associations are present. Thus, a wave-dominated lithofacies association is most likely not to be expected in the study area. The marine transgression probably reached the area only later, after deposition of the wave-dominated facies association. This is further supported by mammal biostratigraphy indicating that the faunal assemblage older MN 3a (Goldinger Tobel 1) is missing in the entire study area.

Field observations of the lithofacies recorded in the OMM of the central Swiss Plateau offer a variety of sedimentary structures of various marine depositional environments. Of great significance is the recognition of tidal or tidally influenced deposits (e.g. Homewood 1981), which characterises deposition throughout the OMM (e.g. Allen et al. 1985; Keller 1989, 2012). Among the most obvious tidal deposits of the study area are sand waves that are interpreted to have formed in a coastal environment

(Homewood 1981, Allen & Homewood 1984). According to Allen & Homewood (1984) the sand wave at Brüttelen (lower OMM, western Swiss Plateau) is characterised by a cross-bedded medium-grained sandstone body with cm- to dm-thick foreset beds separated by mm-thin very fine sandy or silty layers, which occasionally show ripple marks. The individual foreset beds tend to upwards increase in thickness. Similarly, the large-scale planar-cross bedded sandstone draped with finer-grained ripple-sandstone at Brittnau (lower OMM) and at Teuffegrabe (upper OMM) is likewise interpreted as tidal sand wave. Allen et al. (1985) describe the ca. 5 m thick Muschelsandstein at Langnau/Reiden as caused by migrating megaripples overlying and covering a bipolar sand wave facies. Owing to their weakly pronounced asymmetry, these Muschelsandstein beds formed under a more symmetrical tidal regime (Allen et al. 1985). Thus, there is clear evidence of tidal influence in the deposits throughout the OMM of the central Swiss Plateau, which, in turn, can be linked to both the Lucerne Formation and the St. Gallen Formation, which are defined by largely tide-influenced or tide-dominated lithofacies (Keller 1989, 2012).

To correlate the lithostratigraphic units described above to either the Lucerne Formation or the St. Gallen Formation it is important to recognise the sequence boundary at the top of the Lucerne Formation, which is, at the southern basin margin, represented by regressive sediments (Keller 1989; Schaad et al. 1992; Frieling et al. 2009). In the study area, no terrestrial sediments are found within the OMM, neither palaeosols (Keller 1989) nor coal seams (Frieling et al. 2009). Schlunegger et al. (1997) observed 10 m palaeosol (top Lucerne Formation) in the drill core Hünenberg-1 southeast of the study area, and two coarsening-upwards sequences in the drill core Boswil-1, which they correlated to the Lucerne Formation and the St. Gallen Formation, respectively. A hiatus between both formations is indicated by southwards onlapping reflectors in the seismic lines (Schlunegger et al. 1997). Moreover, Allen et al. (1985) describe vadose cements from the Safenwil-Muschelsandstein indicating that this unit must have been exposed periodically above sea level. In the study area, this may serve as the most convincing indication of the regressional sequence boundary on top of the Lucerne Formation. Thus, the top of the Lucerne Formation can be placed after deposition of the Safenwil-Muschelsandstein. This is further supported by the palaeoecological data implying the shallowest marine environment of the lower part of the OMM; above, marine sedimentation continued without noticeable break (Allen et al. 1985).

The succeeding Staffelbach-Grobsandstein seems to represent the transgression, and therefore the base of the St. Gallen Formation in the study area. The transgression extended the marine environment farther towards north, e.g., as documented in the karst filling at Glovelier, which is filled by marine sediments of the younger OMM (Hug et al. 1997). Reworked sediments accompany the marine transgression, such that near the base of the St. Gallen Formation numerous horizons of sandstone full of reworked brown to grey mudstone pebbles (chips) occur. The Staffelbach-Grobsandstein was derived from the Napf fan delta as indicated by the petrographic composition (Matter 1964, see above) and seems to represent a mass flow deposit as suggested from the matrix-rich/matrix supported pebbly sandstone and conglomerate. There is also a tendency to sorting from proximal (Napf region) towards distal areas, though coarse-grained facies can be observed as far northeast as Gränichen. From a palaeoecological point of view, the sediments of and above the Staffelbach-Grobsandstein represent a significantly deeper environment compared to the top of the Lucerne Formation, as documented in the marine faunal assemblages described above.

The succession of the St. Gallen Formation above the Staffelbach-Grobsandstein shows in the Teuffegrabe section (Fig. 5) a deepening- and fining-upwards sequence of tidal sandstone beds, cross bedded at low angles, slightly channelised with abundant wave-ripple surfaces followed by a few metres of horizontally laminated siltstone layers. Interbedded, cm-thin sandstone layers may result from storm events. This resembles the situation further to the south at Root, where Keller (2007) interpreted a core through the St. Gallen Formation. There, a basal wave-dominated facies (ca. 10 m) is succeeded by a tide-dominated facies (ca. 75 m) and topped by a 65-m-thick succession of mudstone and siltstone of a deeper deltaic bay (Keller 2007). The conglomerate bed above is interpreted by Keller (2007) as delta front deposit and already classified as Upper Freshwater Molasse (OSM). This contrasts to the situation in the study area, where again tidal deposits showing frequently reworking overlie the mudstone succession, mud-draped bed sets and wave ripple lamination. The following thick conglomerate succession indicates progradation of the Napf delta front, however, without leading into terrestrial freshwater deposits, but again into tidal deposits (heterolithic wave-ripple laminated sandstone beds). Thus, the quartzite-rich conglomerate documents a temporarily active lobe of the large Napf fan delta that delivered sediment towards the north-northwest. This illustrates that sediment transport from the Napf fan into the depositional area is here accentuated. Moreover, conglomerate deposition is visible throughout the Swiss Plateau, which even had led former authors to define a "basal conglomerate of the Helvétien" (e.g. Büchi 1957). Anyhow, the conglomerate deposition marks the end of fully marine conditions in the St. Gallen Formation.

The sandstone succession above the conglomerate in the study area is again tidally influenced, is typically bryozoan-rich and may incorporate temporarily few metre thick limnic sediments of local extent (limnic horizon, e.g. Reichenbacher et al. 2005; Jost et al. 2006).

OSM sediments above are documented by mottled mudstone deposits with rootlets and freshwater marl and limestone beds higher up (Fig. 5 Schmiedrued composite section; Jost et al. 2015).

5.2 Mammal biostratigraphy

Compared with the Swiss mammal succession (e.g. Kälin 1997), the OMM of central Switzerland displays some differences. First of all, the assemblage zone Goldinger Tobel 1 (early MN3a) is not recorded. This missing faunal assemblage could be explained by the palaeogeographic position and a later transgression of the OMM-sea in the study area, as, e.g., can be assumed from the seismic interpretation of Schlunegger et al. (1997). A second faunal assemblage zone is also missing in the study area: the assemblage zone Trub-Sältenbach (late MN3b). A greater distance to the shoreline could explain this, such that mammal remains were deposited preferably in coastal environments rather than farther offshore. In contrast, the Tägernaustrasse assemblage zone (MN4b) is very well documented at several localities, some of them very rich in fossil mammals (e.g. at Schmiedrued-Schlyfferhübel, Seon-Bampf).

Concerning the boundary between the Lucerne Formation and the St. Gallen Formation (boundary at ?MN3b/MN4), three mammal localities situated within the Staffelbach-Grobsandstein yielded scanty mammal remains. The faunas are mainly composed of glirids and eomyids. An important tooth is an upper third molar of a cricetid from the locality Staffelbach-Böl 1. It has not yet been possible to assign this tooth to a specific genus (Fig. 7). Additionally, the peculiar faunal assemblage cannot be placed accurately within a specific assemblage zone. Thus, the possibility of reworking of older sediments has to be taken into account. The locality Roggliswil-Hornwald (2634.950/1229.100/640 m), situated ca. 40 m above the Staffelbach-Grobsandstein, is of special interest since it yielded a small representative of the genus

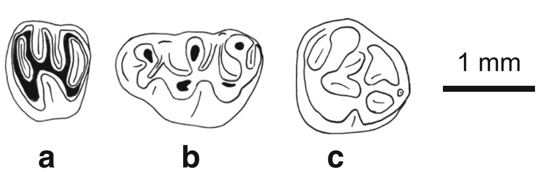


Fig. 7 a *Pseudotheridomys* sp. from Roggliswil-Hornwald, M^1 sin. J.J. 29. **b** *Megacricetodon ?collongensis* (MEIN, 1958) from Roggliswil-Hornwald, M^1 sin. J.J. 31. **c** Cricetide gen. et sp. indet. from Staffelbach-Böl 1, M^3 sin. J.J. 30. All specimens are of the private collection Jürg Jost

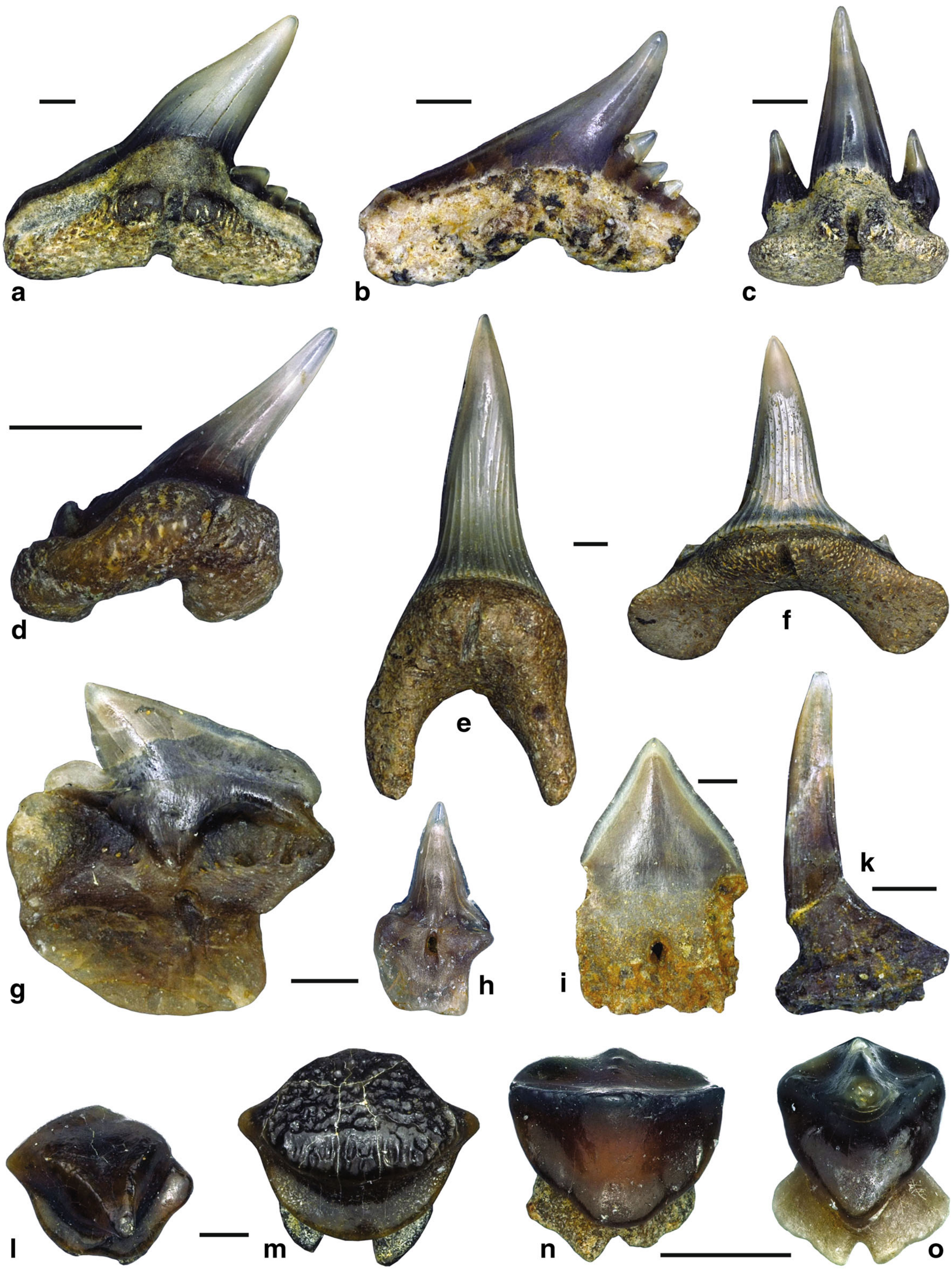
Megacricetodon together with an upper molar of the genus *Pseudotheridomys* (see also de Bruijn and Saraç 1992, p. 37). This faunal composition is not known from any other mammal locality in the Swiss Molasse Basin. Latest MN3b faunas like Trub-Sältenbach (Kälin 1997) are dominated by a hypsodont *Pseudotheridomys* species, but are lacking cricetid remains (with the exception of the aberrant genus *Melissiodon*) and represent the "cricetid vacuum" (Daams and Freudenthal 1989). The next younger Glovelier assemblage zone (MN4a) yielded the first modern cricetid *Democricetodon*, together with two species of *Ligerimys* (*L. antiquus* and *L. florancei*). The genus *Pseudotheridomys* has neither been recorded at this level, nor in the next younger Tägernaustrasse assemblage zone (MN4b), which is documented by many mammal localities comprising several thousand small mammal teeth. However, the presence of *Megacricetodon* indicates that the locality Roggliswil-Hornwald is clearly of MN4b age.

The co-occurrence of the genera *Megacricetodon* and *Pseudotheridomys* is unique for Switzerland, but a comparable assemblage (*Democricetodon* together with *Pseudotheridomys*) has been described from the Czech localities Dolnice 1-3 (Fejfar 1974) and from the SE-German Molasse Basin (Pippèrr et al. 2007).

5.3 Marine fauna and palaeoecology

As of now, a large number of papers dealing with selachian faunas of the OMM of the Molasse Basin have been published; among others are studies from South France (e.g. Cappetta 1970), or from South Germany (e.g. Barthelt et al. 1991). These publications describe and discuss the selachian faunas at individual sites in great detail but restricted to a narrow stratigraphic range. In contrast, our approach is to compare a multitude of selachian sites of a larger region within a stratigraphically well-established sedimentary sequence. This allows investigating the development of the palaeoenvironment through time.

A surprisingly manifold picture results from the palaeoecological analysis of the *Staffelbach-Grobsandstein*: On the one hand, species preferring shallow water habitats, comparable to the fauna of the *Safenwil-Muschelsandstein*, are still present, while many new forms favor a deeper-water environment. This combination of faunal elements from shallow marine and open marine habitats is difficult to interpret. Many teeth of both environments show signs of transport and reworking (e.g. rounded edges), but the teeth can also be well preserved. The size of the teeth largely reflects the grain-size of the sediment and is thus a result of sorting by currents: large teeth are found exclusively within pebbly sandstone beds, while small teeth, especially delicate teeth of squalids, and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◀**Fig. 8** Examples of frequently in the text cited selachian teeth of the OMM. a) *Physogaleus* cf. *latus* Storms, 1894 (Locality: Zofingen-Bierkeller, Lucerne Fm., Basal reworked pebbly sandstone), **b** *Chaenogaleus affinis* Probst, 1878 (Safenwil-Berg, Lucerne Fm., Safenwil-Muschelsandstein), **c** *Premontreia* (Syn. *Pachyscyllium*) *distans* Probst, 1879 (Zofingen-Bierkeller, Lucerne Fm., Basal reworked pebbly sandstone), **d** *Scyliorhinus fossilis* Leriche, 1927 (Roggliswil-Hornwald, St. Gallen Fm.), **e** *Mitsukurina lineata* Probst, 1879, anterior tooth and **f** *Mitsukurina lineata* Probst, 1879, lateral tooth (Roggliswil-Hornwald, St. Gallen Fm.), **g** *Centrophorus* cf. *granulosus* Bloch & Schneider, 1801, lower tooth and **h** *Centrophorus* cf. *granulosus* Bloch & Schneider, 1801, upper tooth (Roggliswil-Hornwald, St. Gallen Fm.), **i** *Isistius triangulus* Probst, 1879 (Roggliswil-Hornwald, St. Gallen Fm.), **k** *Pristiophorus* sp., rostral spine (Roggliswil-Hornwald, St. Gallen Fm.), **l** *Dasyatis rugosa* Probst, 1877, male tooth and **m** *Dasyatis rugosa* Probst, 1877, female tooth (Zofingen-Bierkeller, Lucerne Fm., Basal reworked pebbly sandstone) **n** *Raja* sp., female tooth and **o** *Raja* sp., male tooth (Roggliswil-Hornwald, St. Gallen Fm.)

also more frequently rounded teeth are characteristic of the fine-grained sandstones of the northern and eastern occurrences. Towards the south, a decrease in the dominance of species preferring deep-water can be observed. The strong increase of open-water faunal elements therefore suggests that the Staffelbach-Grobsandstein formed during the major transgression of the St. Gallen Formation. This is further supported by the find of a tooth of proboscidea, which yields a maximum age of MN3b.

The particular faunal composition of the Staffelbach-Grobsandstein may also have been caused by a gradual replacement of the shallow water fauna. Initially, living conditions may have been suboptimal but still acceptable for many species. During transgression and therefore during time of sea level rise, the nutrient supply may also have changed, such that the shallow water specialists had to move southwards into preferably shallow water habitats.

6 Conclusions

We have conducted a lithostratigraphic, biostratigraphic and palaeoecological study on sediments of the Upper Marine Molasse (OMM) in the central Swiss Plateau.

1. Guided by the recognition of lithostratigraphic units mappable at 1:25,000 scale, the investigated sedimentary succession of the central Swiss Plateau Molasse allows a correlation of the revised lithostratigraphic scheme of Büchi (1957) to the Lucerne Formation and the St. Gallen Formation, as defined in the southern part of the Swiss Molasse Basin (Keller 1989).
2. The well recognisable, few metres to over 15 m thick Safenwil-Muschelsandstein forms a new member of the uppermost part of the Lucerne Formation. The well-cemented and intensely cross-bedded pebbly shell sandstone, which has a lateral (west-east) extend of several tens of kilometres, is characterised by abundant echinoid fragments of *Scutella* sp.
3. The base of the St. Gallen Formation is in the study area represented by the up to 3 m thick, coarse-grained pebbly sandstone or fine-grained conglomerate of the Staffelbach-Grobsandstein, which is here introduced and formally defined as a lithostratigraphic bed. The selachian fauna of this particular bed reveals an admixture of shallow marine and, for the first time during OMM-deposition, open marine elements. We interpret this bed as a result of the transgression of the sediments of the St. Gallen Formation.
4. Mammal biostratigraphy, although established for a few horizons only, suggests in the study area an age of late MN3a for the lower part of the Lucerne Formation, an age of ?MN3b/MN4 for the base of the St. Gallen Formation and an age of MN4b for the limnic horizon in the upper part of the St. Gallen Formation. These results perfectly agree with the existing data of mammal-based age determination for the OMM in Switzerland.
5. Selachian faunas provide valuable information on the depositional realm of the OMM in the study area. Comparison of fossil teeth with modern analogues allows to reconstruct a shallow marine and partly high-energy environment for the Lucerne Formation, and a significant deepening (i.e., a transgression) with the onset of the St. Gallen Formation (Staffelbach-Grobsandstein).
6. This study provides a unique description of the selachian faunal assemblages and their development through time for the entire Upper Marine Molasse in the central Swiss Plateau.

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