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# A marine pebbly mudstone from the Swiss Alps: palaeotectonic implications and some consequences for the interpretation of Precambrian diamictites

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**Abstract** Pebbly mudstones are a conspicuous element of sedimentary sequences deposited in different tectonic settings and sedimentary environments. Whereas for many diamictites a glacial origin seems plausible, the problem to distinguish glacial from non-glacial diamictites is often difficult for Precambrian examples where palaeoclimatic constraints are generally lacking. This article documents an Eocene pebbly mudstone of the Southhelvetic nappes of eastern Central Switzerland (*Blockmergel*) for which a glacial origin can be firmly rejected and which may thus serve as an example for non-glacial marine diamictites and their sedimentary and palaeotectonic environment. The Blockmergel are interpreted as the product of gravitational deposition of single blocks across steep palaeo-slopes (subaqueous rockfall) into a basin otherwise dominated by suspension settling sedimentation. The Blockmergel occur within the basal part of the early fill of the North Alpine Foreland Basin, which constitutes a deepening upward sequence above basal shallow marine limestones. The Blockmergel demonstrate substantial Middle to Late Eocene sub-aerial erosion and fluvial transport (producing the rounded pebbles) and local extensional fault movements in the proximal part of the incipient North Alpine Foreland Basin. They are capped sharply by forced-regressive shoreface sandstones and the whole sequence thus demonstrates locally very shallow to subaerial conditions within an otherwise rather deep hemipelagic marine basin. This, and the extensional fault movements, are linked to a long-standing feature of Helvetic palaeogeography—the Southhelvetic swell zone. That this swell still operated during the Priabonian i.e. shortly before finally being overthrust by the orogenic wedge of the evolving Alpine orogen is a new element in Alpine palaeotectonics and seems to highlight the importance of the reactivation of inherited palaeotectonic faults. Finally, the example of the Blockmergel is suggested as a useful analogue to help distinguishing glacial-sourced from slope-derived diamictites in the Neoproterozoic sedimentary record and may thus help resolving the "diamictite dichotomy".

**Keywords** Subaqueous rockfall · Pseudoglaciation · Extensional foreland faults · Alpine orogeny · Diamictite dichotomy

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## 1 Introduction

Clastic sedimentary deposits composed of sand- and larger sized particles dispersed in a muddy matrix (*diamictites* sensu Flint et al. 1960a, b) have been reported repeatedly from marine sequences in both compressional and extensional tectonic settings (e.g. Ackermann 1951; Crowell 1957; Dott 1963; Schermerhorn 1974; Stauffer 1983; Altermann 1986; Eyles and Januszczak 2004; Menzies and Whiteman 2009). Whereas some of these peculiar deposits, variously referred to as pebbly mudstones, *Geröllton*, tilloids, tillites, diamictites or *Blockmergel*, can be convincingly tied to ancient glaciations, for many other representatives this explanation can be firmly rejected on palaeoclimatic grounds. For most Phanerozoic marine diamictites, tight biostratigraphic and palaeoclimatic constraints allow an unambiguous distinction between glacigenic and non-glacigenic diamictites. This is often not the case for Precambrian deposits and hence the origin of Proterozoic and older diamictites is often controversial and a kind of sedimentologic differential diagnosis (Menzies and Whiteman 2009) has to be applied. Obviously, such diagnoses become the more trustworthy, the more is known about the sedimentology of clear Phanerozoic examples of both glacigenic and non-glacigenic marine diamictites. The aim of the present article is thus threefold. It first describes in detail an Eocene marine diamictite from the Helvetic nappes of Central Switzerland (Fig. 1) thereby providing a case study of a marine diamictite (pebbly mudstone), for which any direct glacial influence can be excluded. Secondly, this pebbly mudstone unit, whose aerial distribution is rather restricted, is connected to Eocene tectonic movements whose existence and nature has hitherto not received full credit. We will thus document, discuss, and interpret this palaeotectonic activity and try to integrate it into existing palaeotectonic accounts of Alpine orogeny and foreland basin development. Thirdly, the potential implications of our study for the resolution of what has been called recently "the diamictite dichotomy" (the co-occurrence of glacially-sourced and slope-derived diamictites, Le Heron et al. 2017) shall be addressed.

## 2 Geological overview

The Penninic and Austroalpine tectonic outliers Klippen of the Iberg (Yberg) area in the Helvetic Alps of Canton Schwyz east of Lake Lucerne (Fig. 2) have attracted geologist's attention ever since the days of Arnold Escher von der Linth around 1845 (Kaufmann 1877; Quereau 1893; Jeannet 1941; Trümpy 2006; Letsch 2017). Of almost equal interest has been the occurrence of big exotic blocks connected to partly heavily deformed flysch units (supposed equivalents of the Schlierenflysch and the Iberg Wildflysch or Mélange) in the footwall of the Mesozoic klippen (Quereau 1893; Heim 1907; Frei 1963; Bayer 1982). The klippen and their flysch cushion rest tectonically on Upper Cretaceous to Eocene rocks of the Helvetic Drusberg nappe (Figs. 1, 2, 3). The front of the latter descends in a series of folds staircase-like towards the North where it abuts against a several km broad stack of Upper Cretaceous to Eocene flysch (Wägitalflysch),

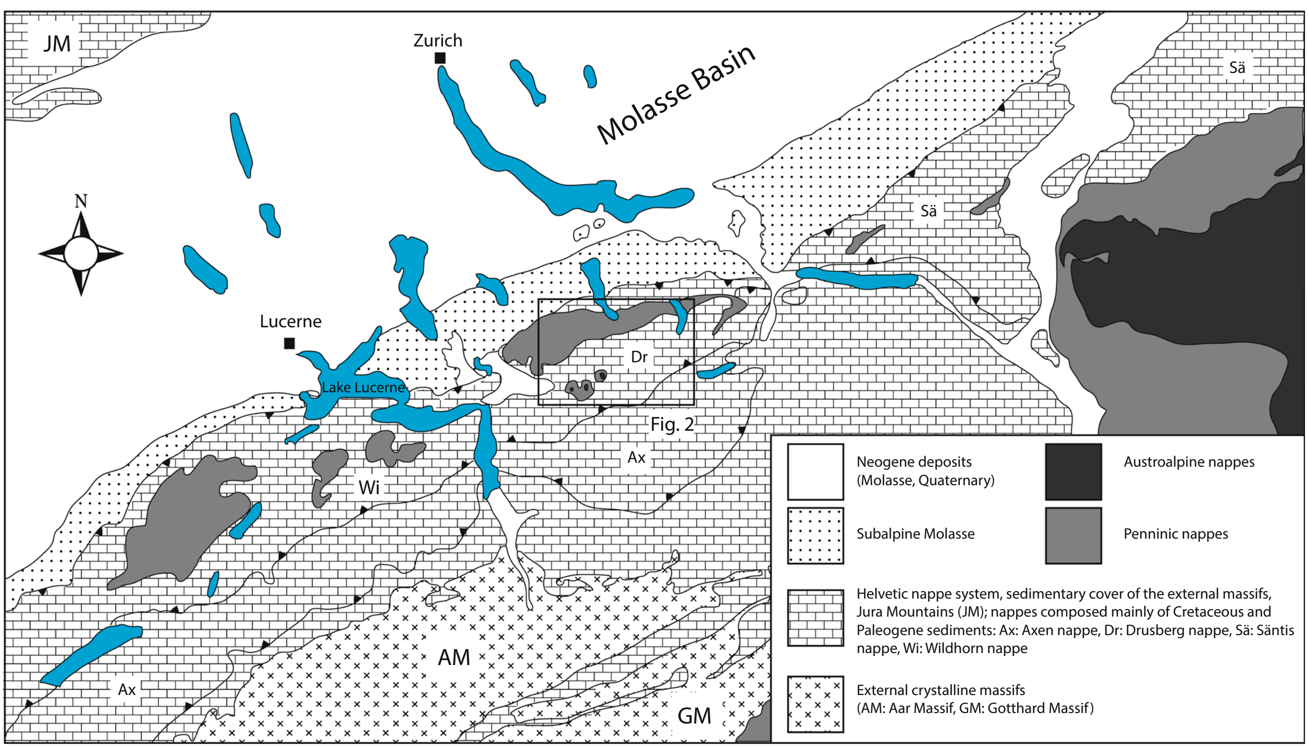


**Fig. 1** Tectonic overview map showing the Helvetic nappes of central and eastern Switzerland and surrounding areas. The field area described in the present article is located within the rectangle defining the region displayed in Fig. 2. Redrawn after "Tectonic map of Switzerland, 2nd edition" (2005)

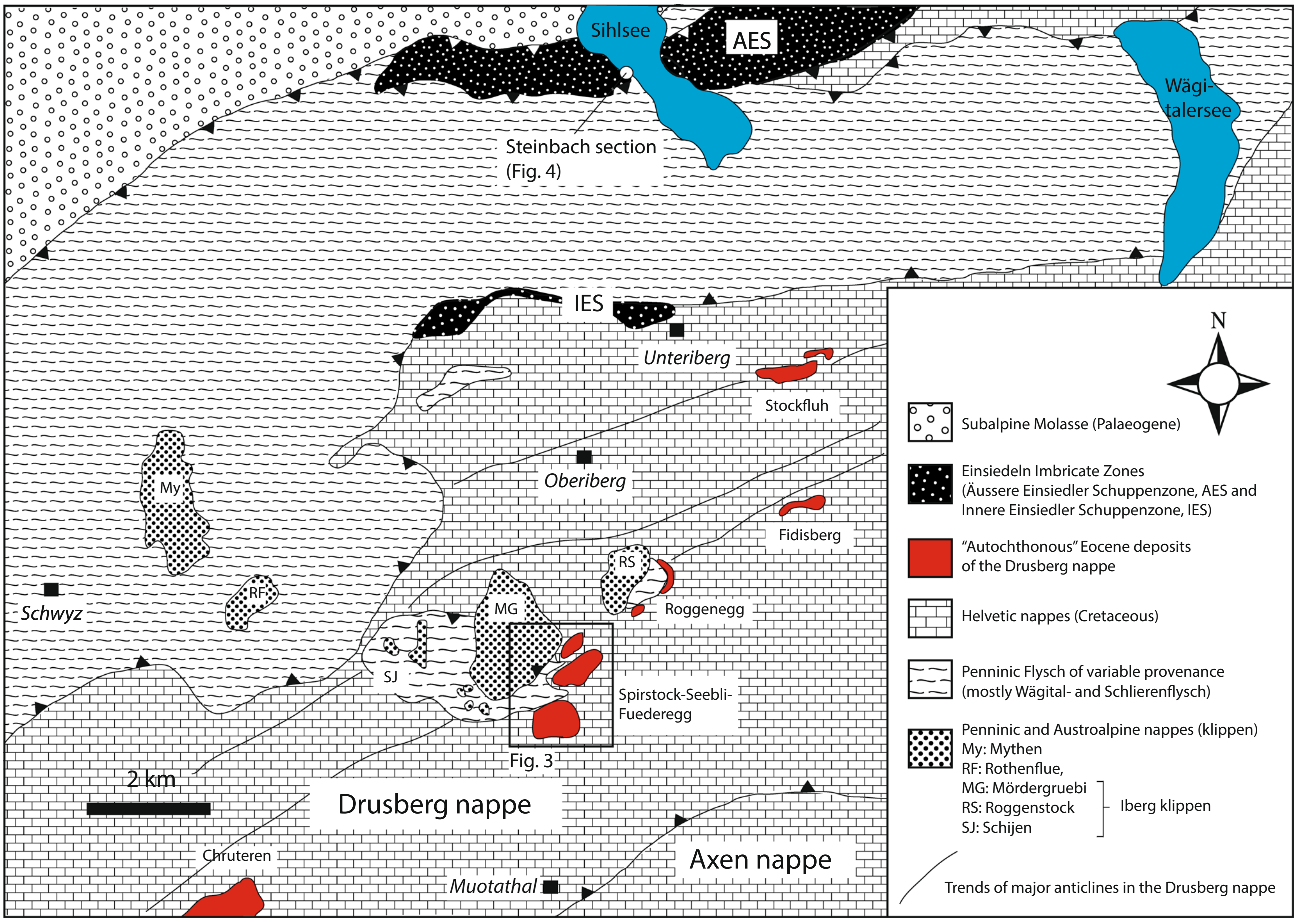


**Fig. 2** Geological map of the wider field area treated in this paper (redrawn and modified after Hantke 1967). The location of Fig. 3 is indicated

which can be correlated with the much thinner flysch units beneath the Iberg klippen (Fig. 2). This flysch zone is accompanied both in the north and in the south in a somewhat patchy manner by tectonically imbricated stacks of uppermost Cretaceous to Eocene rocks referred to as the Äussere and Innere Einsiedler Schuppenzone (Einsiedeln Imbricate Zones), respectively (Frei 1963). These rocks had been sheared off their Cretaceous substratum of the later Drusberg nappe during an early phase of deformation along mechanically weak shales of the Amden Formation. The famous roadcut outcrops of Steinbach along the shore of the Sihlsee (e.g. Heim 1908; Boussac 1912; Jeannet et al. 1935; Leupold 1937, 1942; Kuhn 1972; Letsch 2012) serve as a regional reference section for the Palaeogene of the Drusberg nappe (Fig. 4) and the Steinbach locality represents the type section of the Euthal Formation of Menkveld-Gfeller et al. (2016). From a tectonostratigraphic point of view, the Steinbach section records the earliest phase of the North Alpine Foreland Basin. Whereas the final deposits of the southern European passive continental margin are represented by the hemipelagic Amden Formation, the overlying shallow marine sequence of the Chruteren and Einsiedeln members imply substantial uplift (the "Palaeocene restoration" of Trümpy 1973), which is explained by forebulge uplift near the inflexion point of the European plate with the latter being bent down by the approaching orogenic wedge of the developing Alps (Sinclair 1997). The hiatus and potential angular discordance at the base of the Chruteren Member thus forms the "forebulge unconformity" (Crampton and Allen 1995). The Euthal Formation records shallow marine deposition on a carbonate ramp with two shallowing upward cycles (Lihou 1995), which can be accounted for by a combination of flexural tectonic subsidence and high-frequency eustatic sea level changes (Allen et al. 2001). Eventually, the former factor became predominant and carbonate production ceased thus creating a drowning unconformity (the glauconite and phosphate rich Steinbach Member). The overlying deeper marine hemipelagic marls of the Stad Formation already represent the second unit of Sinclair's (1997) "underfilled trinity of foreland basins".

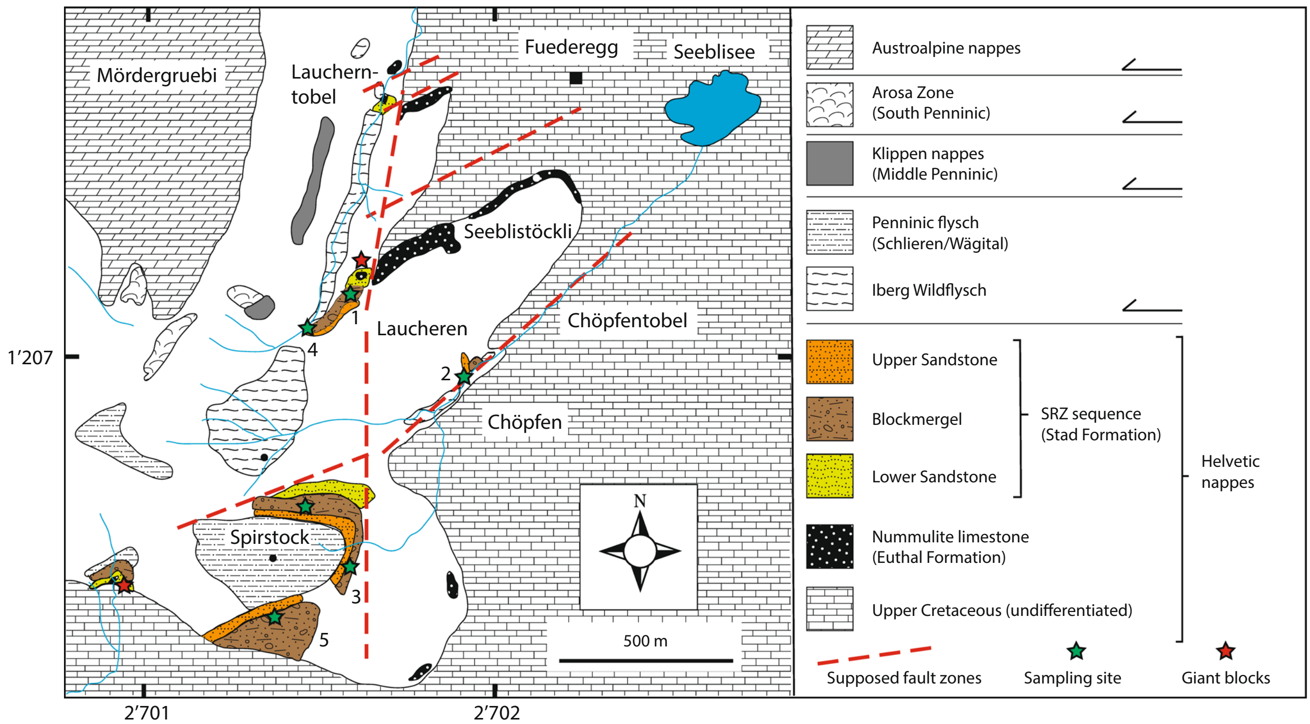


**Fig. 3** Geological map of the Spirstock-Seebli-Fuederegg area. Mostly after own observations, complemented with data from Jeannet (1941), Frei (1963), and Trümpy (2006)

In the southernmost part of the Drusberg nappe, the Amden Formation is gradually replaced by the more resistant Wang Formation and hence the Palaeogene cover stayed in contact with its Cretaceous substratum during the Alpine orogeny ("autochthonous" Eocene deposits on Fig. 2). Interestingly, these southernmost relics of Helvetic Palaeogene rocks exhibit strikingly different facies (including the Blockmergel-diamictite) as their northern counterparts in the Einsiedeln Imbricate Zones. Furthermore, this southern facies records substantial Eocene tectonic activity and erosion which has been partly reported in the older literature (Jeannet 1941; Leupold 1942; Frei 1963; Bayer 1982) but seems to have escaped the attention of more recent accounts on Eocene palaeogeography and palaeotectonics of the Helvetic nappes (Herb 1988; Sinclair 1997; Kempf and Pfiffner 2004; Menkveld-Gfeller et al. 2016). Furthermore, as we shall demonstrate below, these palaeotectonic movements, probably augmented by eustatic sea level changes, led to a dramatic shallowing of a restricted area in the southernmost part of the evolving Northern Alpine Foreland Basin during the Priabonian just before being overthrust by higher flysch nappes. This shallowing constitutes a striking anomaly in the otherwise well-established "underfilled trinity" of peripheral foreland basin fills (Sinclair 1997; Allen et al. 2001).

## 3 Eocene deposits of the southernmost Drusberg nappe

Compared with the well-developed carbonate/glauconite grainstone sequence of uppermost Palaeocene to Middle Eocene age in the Einsiedeln Imbricate Zones (Fig. 4), the "autochthonous" outcrops of Eocene rocks in the southernmost part of the Drusberg nappe display a reduced limestone sequence which is capped by clastic sedimentary rocks that are lacking in the former area. Leupold (1942 and in Decrouez and Menkveld-Gfeller 2003) coined the term "Southern Reduction Zone" (SRZ) for this aberrant facies realm. The SRZ is mainly represented by three isolated outcrop groups which are, from east to west, the Fidisberg, the Roggenegg, and the Spirstock-Seebli-Fuederegg zones (Fig. 2). The most complete stratigraphic section can be reconstructed in the latter-mentioned area which is situated between the overthrust masses (klippen) of the Roggenstock and the Mördergruebi and which has been studied in detail by Jeannet (1941) and Frei (1963). The spatial distribution of and rapid lateral facies changes within the Eocene rocks necessitates the assumption of several NE–SW and N–S trending inverse and normal faults, respectively, which, however, could never be directly observed in the field (Fig. 5). Jeannet (1941), Frei (1963), and Trümpy (2006) assume an Eocene age for most or all of these faults which seems convincing albeit we shall argue later on

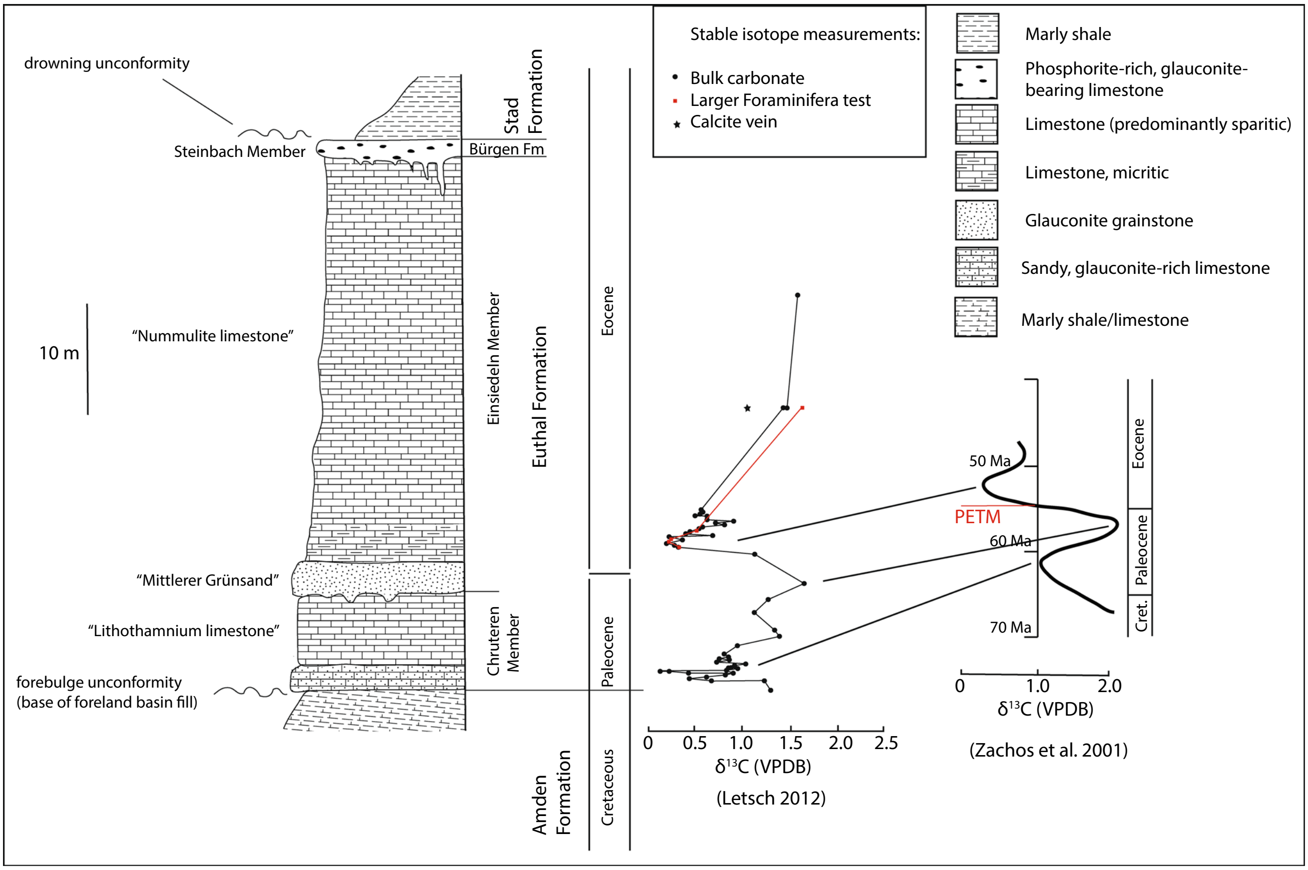


**Fig. 4** Simplified stratigraphic log of the Steinbach section (for location see Fig. 2) representing the "normal" (i.e. not erosionally reduced) facies of the Southhelvetic Palaeogene in Eastern Switzerland (after Leupold in Decrouez and Menkveld-Gfeller 2003). Chemostratigraphic data ($\delta^{13}C$ on carbonates) are taken from Letsch (2012) and a global $\delta^{13}C$ stack (from Zachos et al. 2001) is shown for chronostratigraphic comparison (*PETM* Palaeocene/Eocene Thermal Maximum)

that they originally were N dipping normal faults. However, overthrust flysch relics both on top of the Spirstock and in the upper Chöpfentobel suggest that at least the last movements along the NE–SW fault system took place after the emplacement of the higher nappes. However, for the N–S trending fault zone just to the east of the Laucherentobel and the Spirstock a purely Eocene age seems justified. To the east of the latter fault, the basal part of the Einsiedeln Member has mostly been preserved and ranges in thickness between 25 and 30 m. However, it is altogether lacking to the south of the Laucheren-Seeblistöckli ridge and almost completely to the west of the N-S fault zone. There, only tiny relics of the Einsiedeln Member have been preserved. They and their Cretaceous substratum (Wang Formation) are covered by Eocene rocks of the SRZ which we include here, based on their stratigraphic position, in the Stad Formation sensu Menkveld-Gfeller et al. (2016). From the base to the top three lithostratigraphic members can be distinguished (following Jeannet 1941, see our Fig. 6): "Lower Sandstone", "Blockmergel" (pebbly mudstones), and "Upper Sandstone" ("Plattige Sandsteine" in Jeannet 1941). Relics of the same sequence can partially be observed farther east on the Roggenegg and the Fidisberg (Fig. 2, see Jeannet et al. 1935). Biostratigraphic dating of the three members is based on reworked Larger Foraminifera (providing a robust earliest Lutetian maximum age for the Lower Sandstone) and calcareous nanoplankton dates from Bayer (1982). Thus, the Lower Sandstone contains nannoplankton assemblages typical for NP19 (Younger Priabonian) and the Upper Sandstone assemblages of NP19 or even 20 (youngest Priabonian). We shall next describe these three members separately and try to put them into a sedimentological framework.

## 4 Sedimentology of the Blockmergel and their stratigraphic environment

### 4.1 Observations

#### *4.1.1 Lower Sandstone*

Rather mediocre outcrop conditions do not allow the observation of a complete sequence of the Lower Sandstone but isolated occurrences suggest the following general

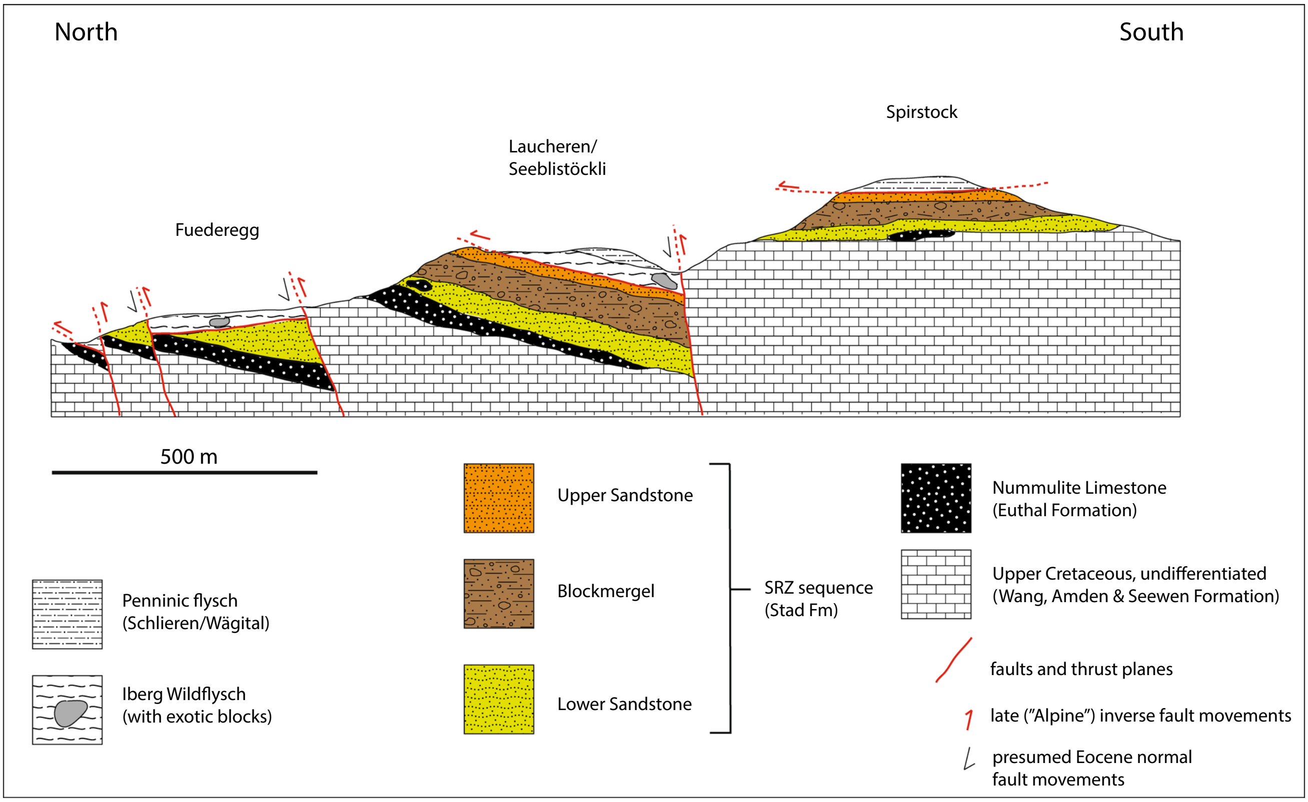


**Fig. 5** Composite geological cross section across the Spirstock-Seebli-Fuederegg area. After own observations with some additional information from Jeannet (1941) and Frei (1963)

stratigraphy. The basal part is constituted by two different facies types, mixed quartz/carbonate or pure quartz sandstones. The first type is composed of coarse to medium grained, quartz-rich sandstones and fine breccias which often contain reworked isolated nummulites (and other Larger foraminifera) and limestone fragments form the underlying Einsiedeln Member. The sandstones often display hummocky cross stratification (HCS) but are generally horizontally bedded with some discrete coarser layers (Fig. 7a, b). The microfacies is dominated by poorly to very well rounded quartz grains (with the bigger ones being generally better rounded) embedded in a fine, probably partly recrystallized, carbonate matrix/cement. Apart from quartz grains, biodetritus is very abundant (Larger and benthic foraminifera, and red algae) and glauconite and mica are also common whereas feldspar is lacking altogether. Lithoclasts are common and are either polycrystalline quartz or micrites with abundant calcispheres. The second facies type is represented by massive, thick-bedded, fine- to coarse grained pure quartz sandstones. At the Roggenegg locality (Fig. 2), it contains pale purple quartz pebbles (Jeannet and Leupold 1935). Their microfacies is rather unspectacular: they are exclusively composed of well-rounded quartz grains (exhibiting sutured contacts due to diagenetic and/or tectonic pressure solution) with some subordinate accessory minerals (zircon, opaque phases). The feldspar-rich (arkose) sandstones mentioned by Jeannet (1941) could not be observed in the field. These two quartz-rich sandstone facies types dominate the base of the Lower Sandstone and the first one also occurs somewhat higher up where it is interbedded with dark sandy shales. Further upwards, coarse sandstones disappear completely and get replaced by fine grained, mica-rich sandstone layers. Of special interest are several isolated megablocks which are embedded in grey shales and fine grained sandstones in the upper part of the Lower Sandstone (see Fig. 3 for locations). The most conspicuous example is an irregularly shaped Nummulite limestone (Einsiedeln Member) block just north of Laucheren with visible dimensions of some 10 × 8 m (Fig. 8). The limestone is thoroughly fractured and a substantial part of it is occupied by calcite veins. Several fault planes with calcite slickensides could furthermore be observed. The contrast to the surrounding, only moderately deformed shales and sandstones is very striking.

### *4.1.2 Blockmergel*

Even though it cannot be observed in continuous sections, the transition from the Lower Sandstones to the Blockmergel seems to be rather gradual with the thin sandstone layers becoming less frequent and being gradually replaced

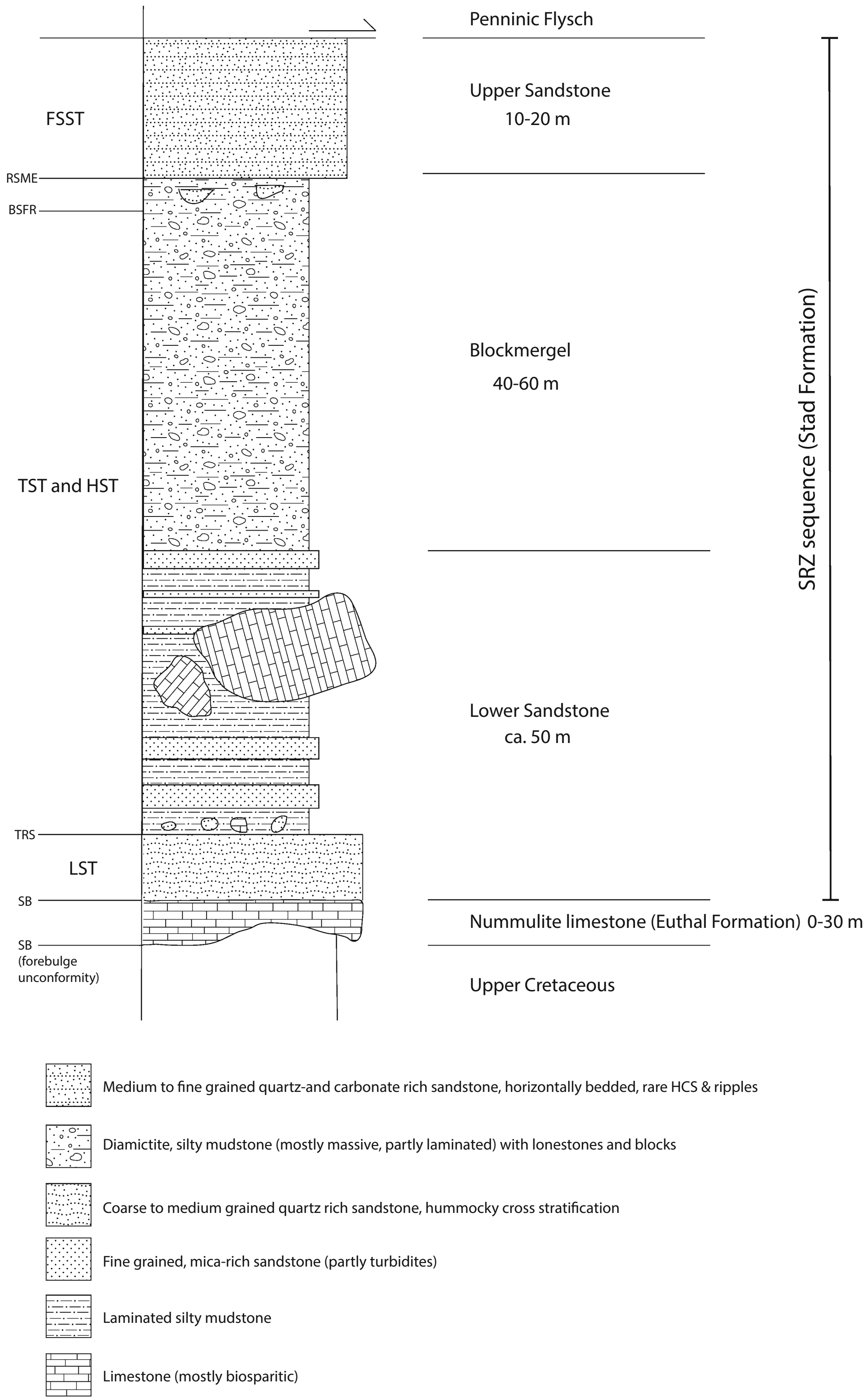


**Fig. 6** Synoptic stratigraphic log of the reduced Eocene facies of the Spirstock-Seebli-Fuederegg area (the Southern Reduction Zone sequence). Mostly after own observations and complemented with data from Jeannet (1941), Frei (1963), and Bayer (1982). Sequence stratigraphic interpretations are according to the present paper and following mostly the sequence nomenclature of Catuneanu (2006). *SRZ* Southern Reduction Zone, *FSST* falling stage systems tract, *RSME* regressive surface of marine erosion, *BSFR* basal surface of forced regression, *TST* transgressive systems tract, *HST* highstand systems tract, *TRS* transgressive ravinement surface, *LST* lowstand systems tract, *SB* sequence boundary

by marls and mudstones. The latter appear mostly massive and structureless in the field but a closer look on favorably weathered surfaces do rarely reveal fine bedding and lamination (Fig. 9f) with some rare signs of slumping. Based on limited observations due to poor outcrop conditions, it seems possible that these laminated marls form discrete, pebble-free intervals within otherwise massive pebbly mudstones (Fig. 9f). In the upper part of the

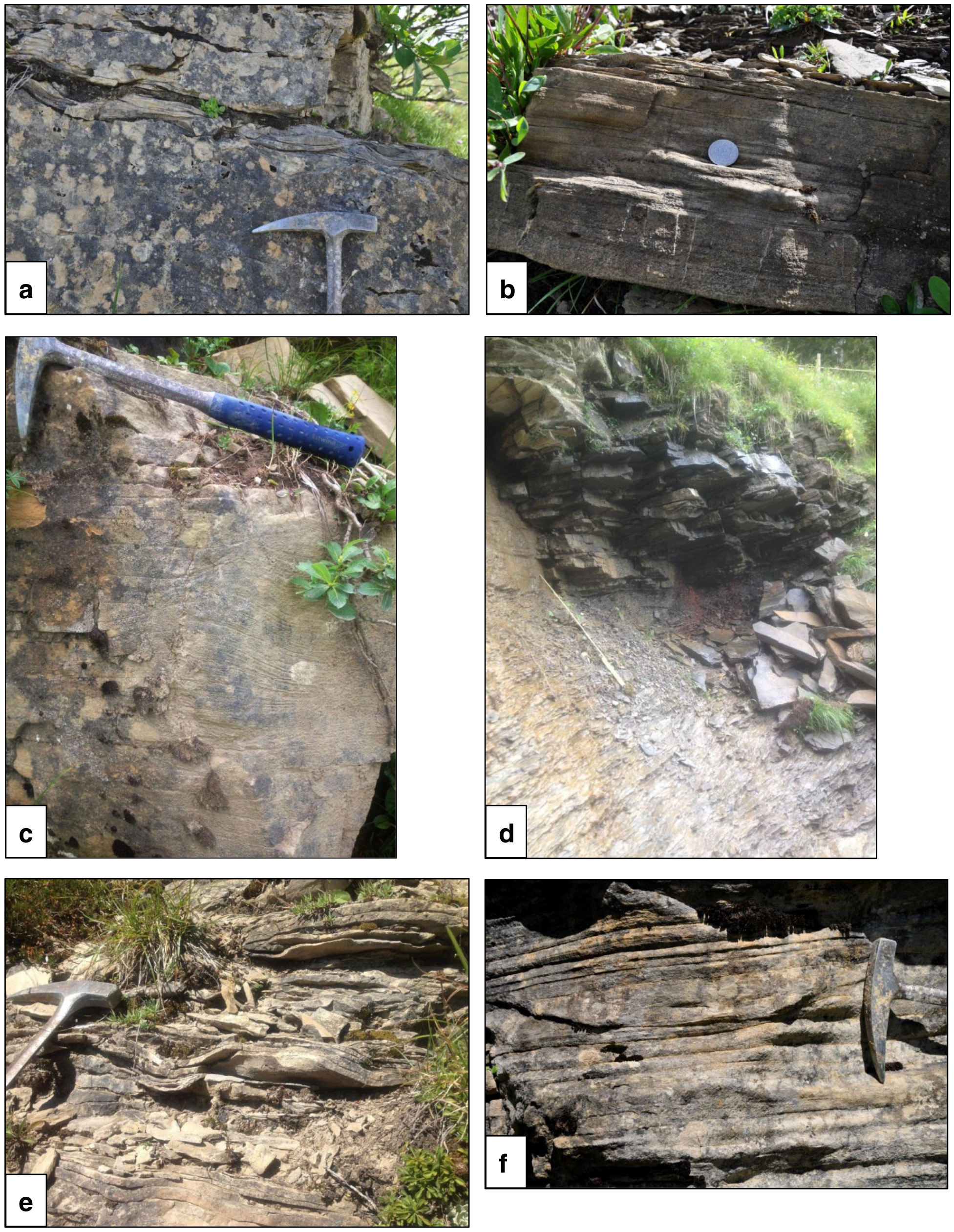


**Fig. 7** Field aspects of the Lower and Upper Sandstone. **a** Upper half of a massive and graded sandstone unit with hummocky cross beds on its upper surface (Lower Sandstone, NE slope of Spirstock). **b** Graded bed of coarse sandstone/breccia (base, below coin) overlain by a horizontally laminated sandstone unit (Lower Sandstone, NE slope of Spirstock). **c** Hummocky cross-stratification (below handle of hammer) at the base of the Upper Sandstone (NE slope of Spirstock) displaying the typical thickening of laminae into the crest. **d** Sharp contact between Upper Sandstone and Blockmergel (locality 4). **e** Upper Sandstone (southern slope of Spirstock, locality 5) displaying horizontal bedding and some low-angle (hummocky to swaley) cross stratification. **f** Upper Sandstone (locality 3) with an isolated channel structure within horizontally bedded sandstone

Blockmergel (last 10 m below the base of the Upper Sandstone), some rare isolated sandstone lenses occur north of Laucheren (locality 1).

Blocks and pebbles of Helvetic origin (mostly carbonates and sandstones, see Sect. 5) are randomly dispersed through the whole Blockmergel and no layers or horizons with a higher concentration of pebbles or pebble clusters occur (Figs. 9, 10). Isolated blocks frequently bend down underlying strata (impact structures, Figs. 9a–d, 10b) and are often covered by higher strata through a combination of onlap and strata bending patterns (using the terminology of Thomas and Connell 1985). The interpretation of these pebbles and blocks as dropstones, i.e. outsized clasts introduced obliquely or vertically into the sediment (Bennett et al. 1996) thus seems feasible, even though it cannot be excluded that some of the strata bending is due to post-depositional compaction (Altermann 1986). An additional indication for the latter process might be provided by generally better lithification in triangular zones laterally attached to bigger pebbles which we suggest to be due to a kind of pressure shadow effect. Alternatively, a slight tectonic overprint cannot be excluded, as very similar, impact-like structures have been frequently reported from tectonically deformed flysch sequences ("lozenge-shaped boudins", Bayer 1982). Developing this explanation somewhat further, one might even argue that the supposed bedding around some of these lonestones is in fact cleavage and the surrounding impact structures simply a cleavage refraction phenomenon. Shape and rounding of some 52 pebbles and blocks (see the pebble inventory in the Online Resource) have been studied quantitatively and qualitatively, respectively. Shapes of 40 pebbles (those which could be completely excavated) have been analyzed in terms of the Zingg parameters (i.e. the relative axial ratios, Zingg 1935). Even though it is generally acknowledged that differences in clast petrography and inherited characters strongly influence pebble shapes of a given sediment, pebble bearing sediments from different settings may yield different pebble shape distribution patterns which can thus be used to infer palaeoenvironmental conditions (Howard 1992). Plotted on a Zingg diagram (Fig. 11a), spherical pebbles are the most abundant (48%), followed by disc-shaped (33%) pebbles. Bladed and rod-like pebbles are much less common (7 and 12% respectively). Quite remarkably, pebbles of Palaeogene and Cretaceous origin (see below) do not show any preferential distribution on the Zingg plot. The a/c diagram (i.e. longest/shortest pebble axis) also reflects the fact that many pebbles can be classified as spheres i.e. plotting rather close to the "perfect sphere" line (Fig. 11b). However, contrary to the Zingg plot, Cretaceous and Palaeogene pebbles show a somewhat different distribution with the latter ones being generally larger. Rounding has not been studied quantitatively for the present study, but based on a qualitative grading in the field (see Online Resource), the vast majority of the clasts has been qualified as partially to well rounded (see also Fig. 10), with the Palaeogene clasts being more angular and less rounded than the Cretaceous ones. Nevertheless, several micrite pebbles have rough surfaces with pits and grooves (Fig. 10c) resembling karst features. Whereas a recent origin of these karst-like features cannot be ruled out, we suggest that they are indeed palaeo-karst phenomena because they can also be observed on freshly excavated pebbles. Pebble orientation has been analyzed in

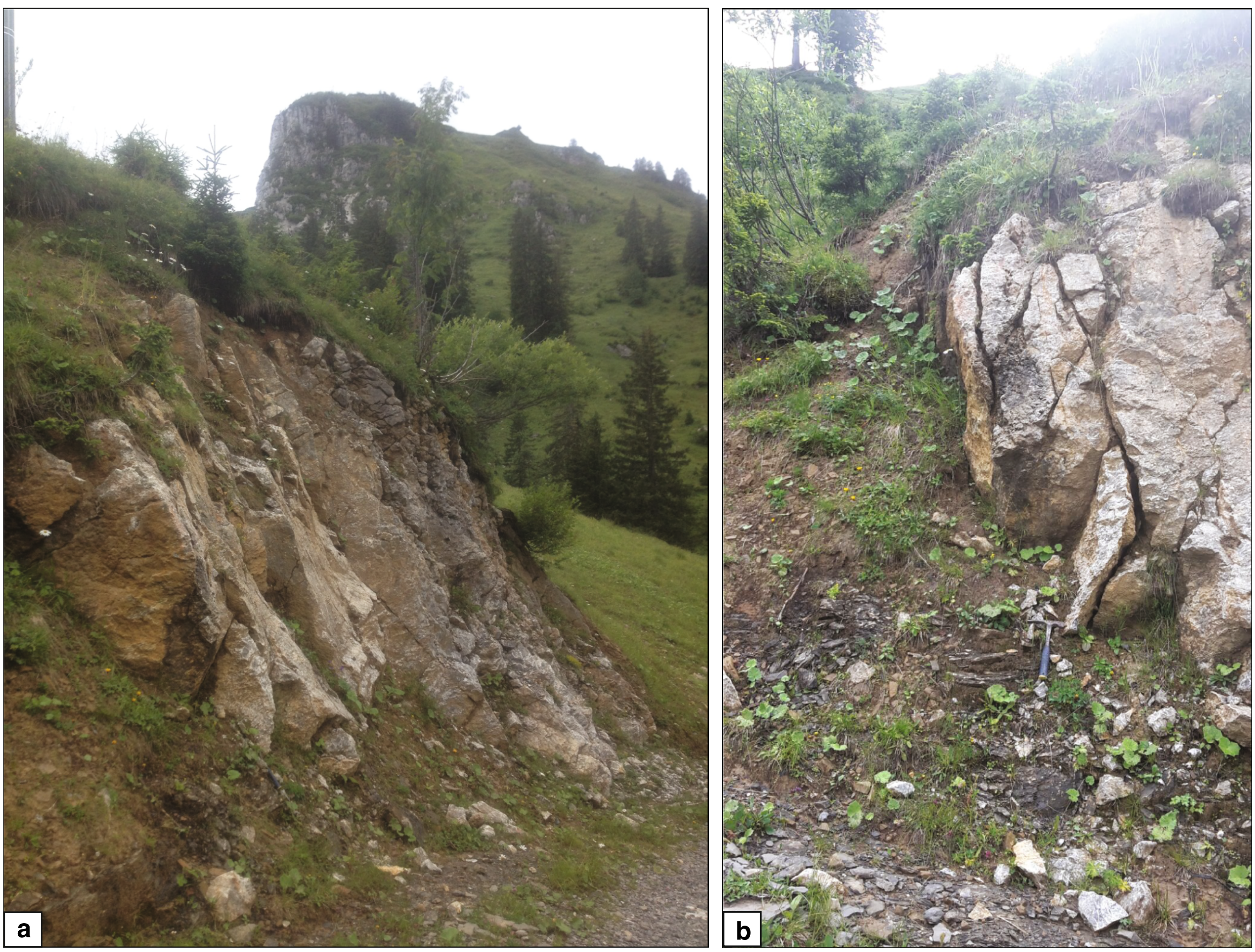


**Fig. 8** Giant Nummulite limestone block in the Lower Sandstone Member. For location see Fig. 3. **a** General view towards the WSW (note the small cliff in the background which is composed of Jurassic limestone of the Penninic Klippen nappe). **b** Detailed view of the contact between the heavily fractured limestone to the right and the horizontally bedded shale with thin sandstone layers to the *left*

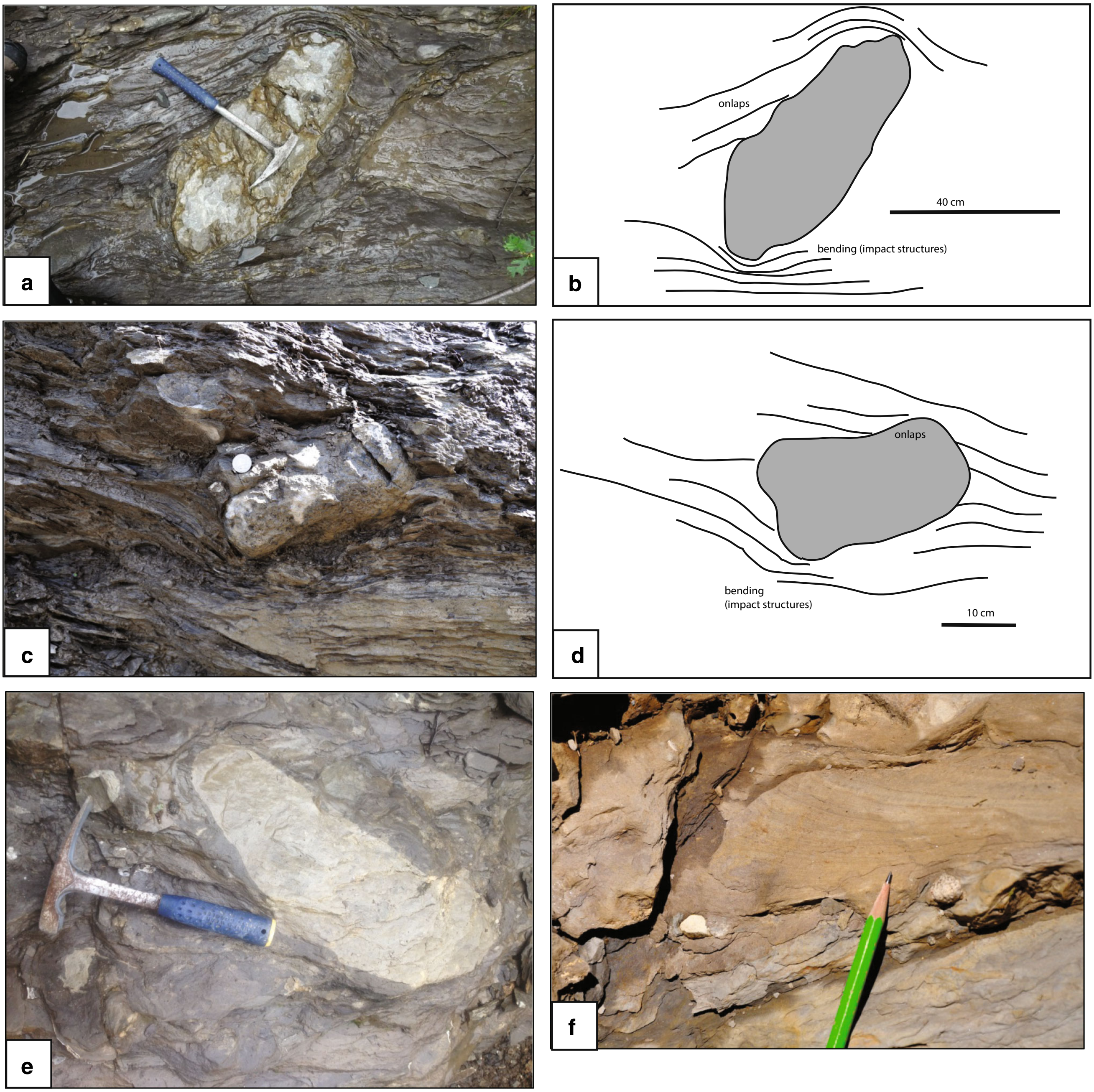


**Fig. 9** Field photographs of blocks I. **a**, **b** Photograph and line drawing of block 3 (locality 2). **c**, **d** Photograph and line drawing of a micrite block from the northern slope of the Spirstock (not numbered but indicated on Fig. 3). **e** Subangular, intraformational, mud pebble from the Blockmergel Member (locality 4). **f** Sharp contact between massive and pebbly mudstone (*below*) and laminated, pebble-free, mudstone above (Blockmergel, locality 5)

terms of the angle between the observed (or inferred) bedding of the matrix and the visible long axes of the pebbles (alpha angle in the Online Resource). A bipolar distribution is apparent. 68% (from a total of 47 pebbles which allowed the determination of this angle) had their long axis within 10° of the bedding plane, 28% were within 10° around the rectangular to the bedding plane, and only 4% formed angles of 10°–80° with the bedding plane (see e.g. Fig. 9a, b). In addition to the pebbles and blocks which clearly have been transported in a completely lithified state, mud pebbles and clasts, often with surprisingly sharp outlines (Fig. 9e), do occur rather frequently but never in clusters (such as mud breccias, Camerlenghi and Pini 2009). These clasts seem to be composed of basically the same material as their matrix except for their slightly different (paler or darker) color.

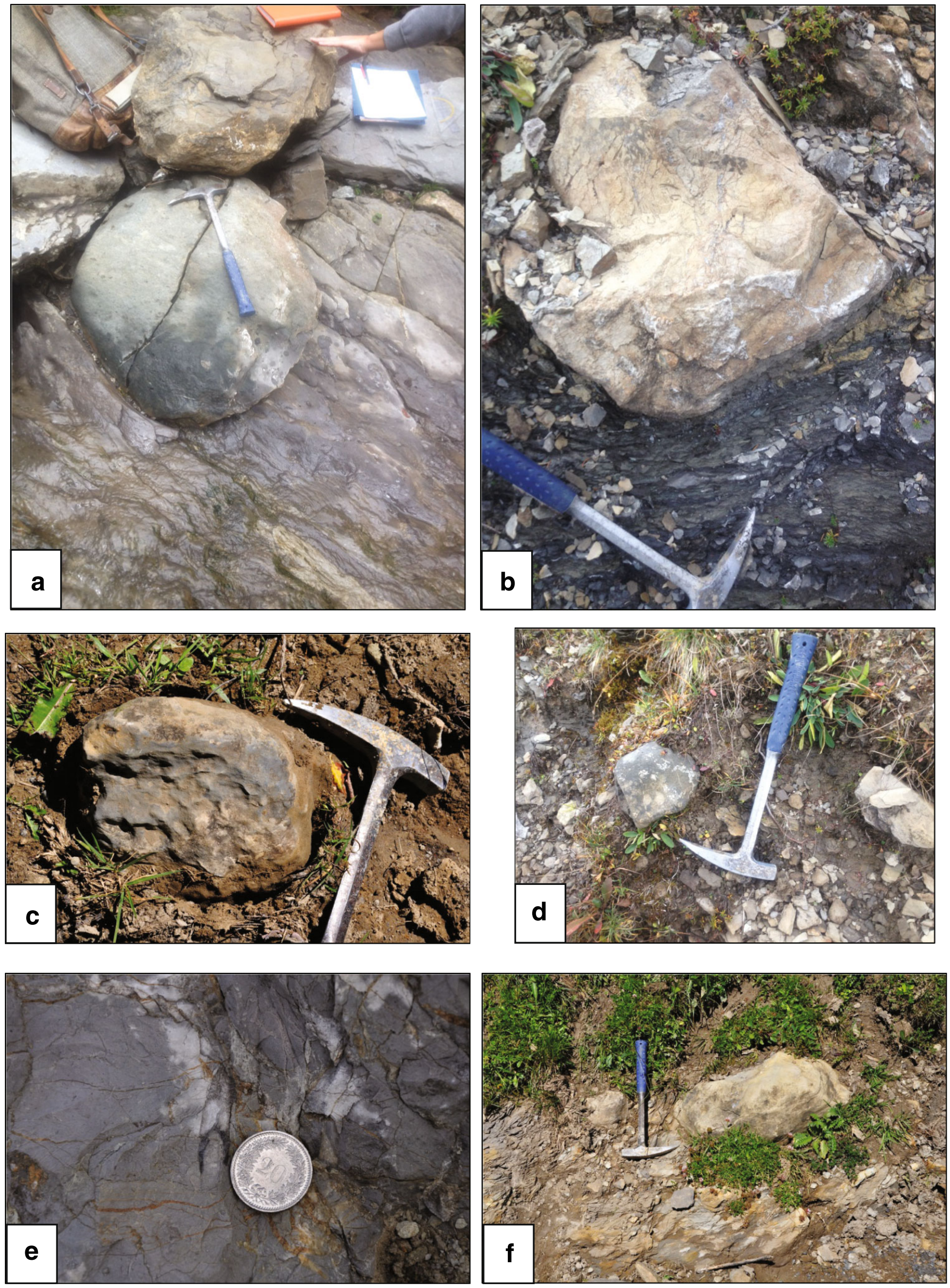


**Fig. 10** Field photographs of blocks II. **a** Block 6 (Eocene glauconite limestone) at locality 2. View is approximately parallel to (the very steep) bedding. **b** Subangular micrite block (Cretaceous?) at locality 1 with clearly visible impact structures below. **c** Carbonate block (Helvetic Kieselkalk, block number 33) with karst features (pits) on its surface (locality 3). **d** Typical, sub- to moderately rounded micrite pebble (locality 1). **e** Detail of micrite block (number 1) with belemnite fragment just left of the coin. **f** Micrite block with long axis parallel to bedding (locality 3)

The microfacies of the Blockmergel has not been systematically studied for the present paper but one thin section from the southern slope of the Spirstock has been inspected. Dominating is a silt and clay rich matrix which hosts abundant small quartz grains with some isolated, well rounded larger grains (1.5 mm at the most). The rounding of the smaller grains is mediocre to very well. White mica flakes, glauconite grains and biodetritus (Larger Foraminifera but also a lot of planktonic forms) are common as well. A very faint, somewhat questionable layering or lamination can at some places be discerned.

### *4.1.3 Upper Sandstone*

The Blockmergel are capped with a very sharp and basically planar to slightly undulating boundary by the Upper Sandstone Member (Fig. 7d). Their conspicuous regular horizontal bedding in the cm to dm range (Fig. 7f) has led Jeannet (1941) to refer to them as "Plattige Sandsteine" but we prefer the more neutral description Upper Sandstone. At most outcrops, pronounced horizontal bedding and lamination is the only visible sedimentary structure which can be observed. Sometimes, the basal few meters

Fig. 11 Pebble dimensions as shown in a Zingg (a) and an a/c (b) plot

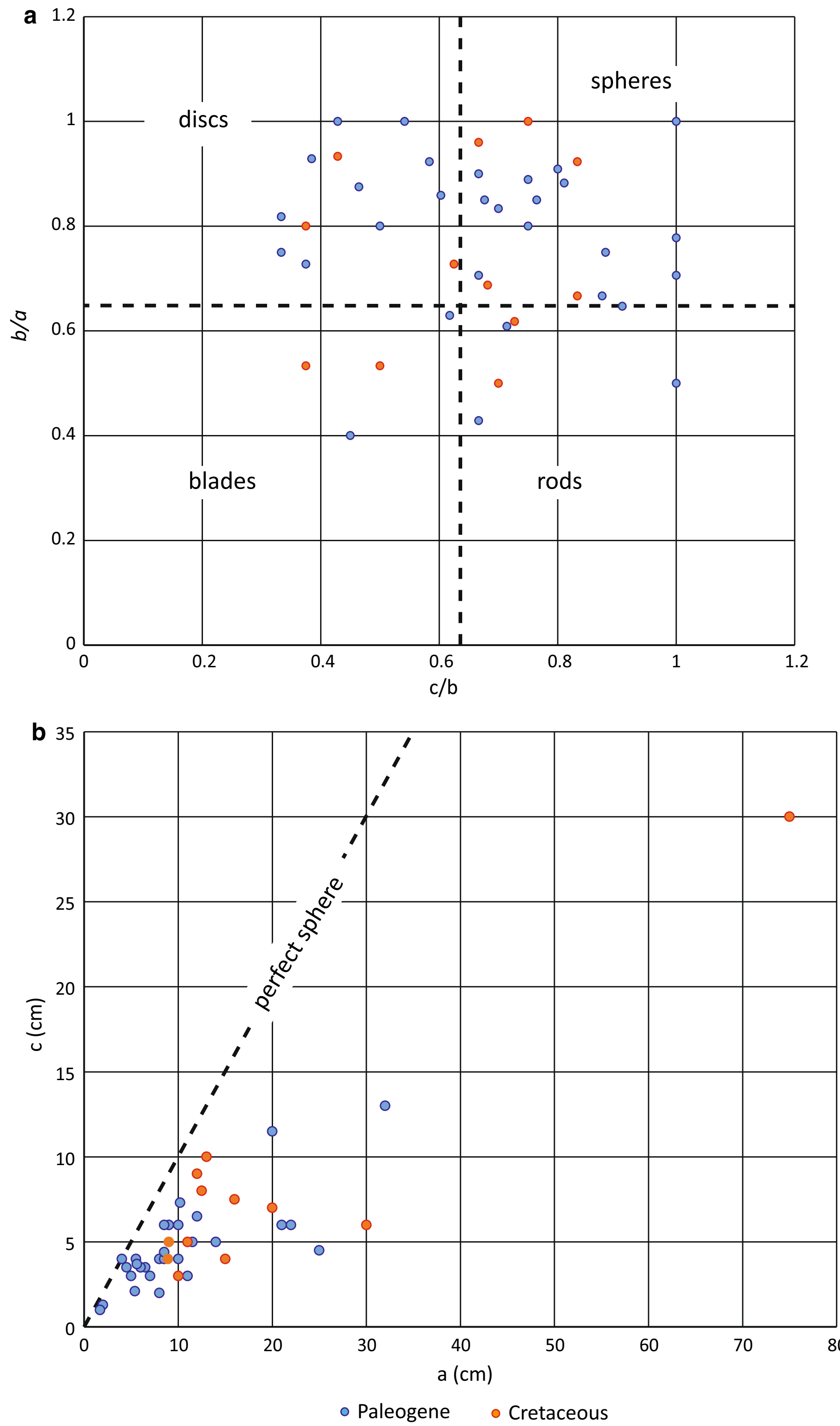


exhibit low-angle cross stratification (HCS and also rare swaley cross stratification, SCS), symmetric ripples, and minor channels (Fig. 7c, e, f). Fine breccias do occur in the lowermost 20 cm at some localities. The Upper Sandstone is of a uniform thickness of 10–15 m. Whilst it's upper boundary is typically concealed, slope topography is suggestive of a recessive strata (i.e. the overthrust flysch unit in the hanging wall). Microfacies generally differ from the

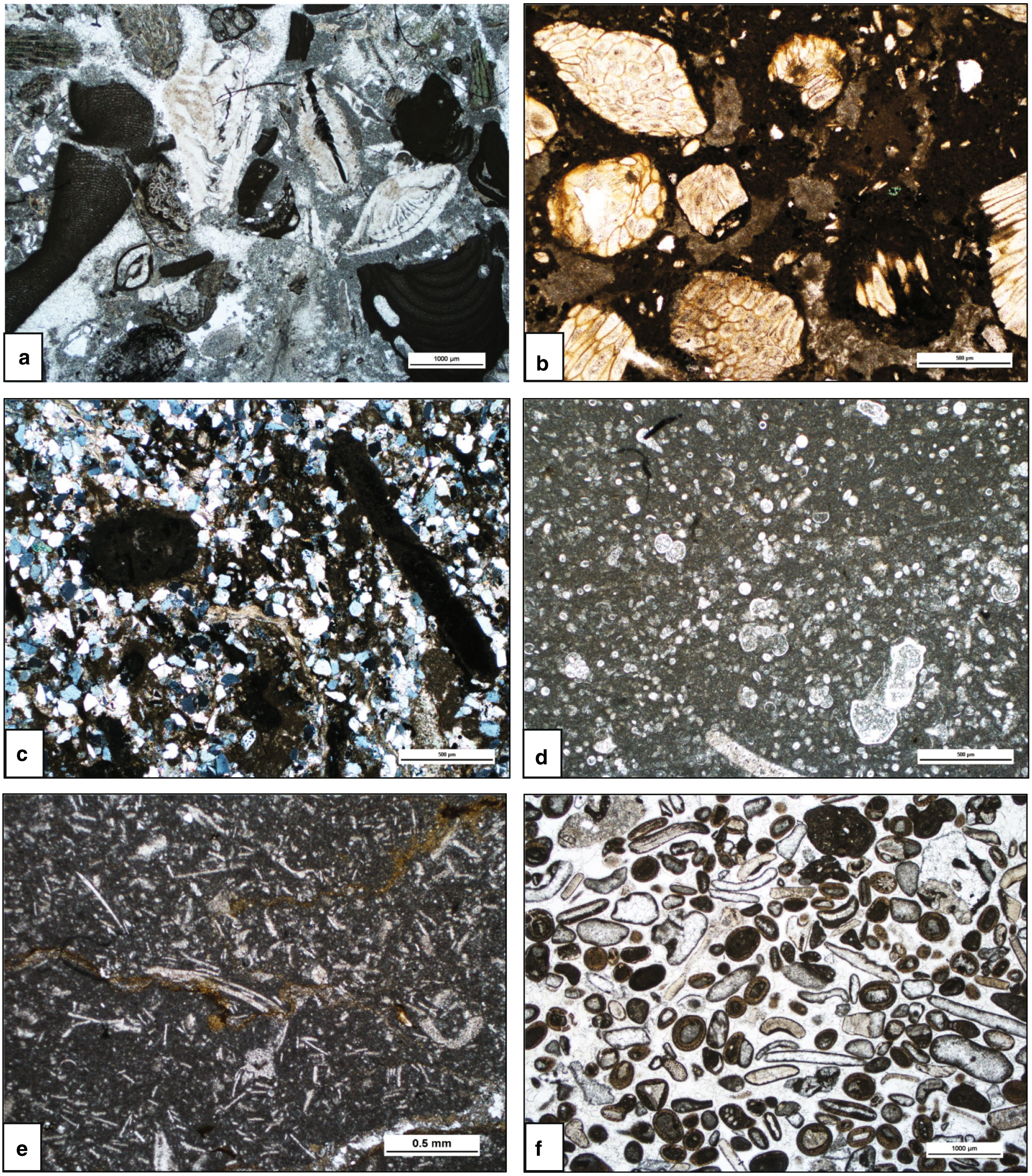


**Fig. 12** Thin section pictures from blocks 11 (**a**), 49 (**b**), 5 (**c**), 8 (**d**), 1 (**e**), and 52 (**f**). Figure 13c with crossed nicols all others with plane light

quartz/carbonate sandstone facies of the Lower Sandstone being finer grained and with less biodetritus. Quartz grains are a mixture of very angular (sharp-edged crystal fragments) and well-rounded grains and feldspar is missing altogether. Sutured quartz grains can be frequently observed and it could be argued that some of the more angular grains are in fact simply diagenetic or tectonic artifacts.

## 4.2 Sedimentologic interpretation

### *4.2.1 Lower Sandstone*

The Lower Sandstone Member contains sedimentary deposits from different depositional environments and they likely reflect a gradual fining- and deepening upward trend. The stratigraphic position just on top of partly eroded Eocene limestones or even directly on Upper Cretaceous rocks, indicates substantial, even sub-aerial (see below) erosion before deposition of the basal quartz-rich sandstones of the Lower Sandstone Member. The abundant biodetritus, the lack of any mud, the mixture of both angular and very well rounded quartz grains, and HCS structures all suggest deposition in a highly energetic shallow marine environment (shoreface to inner shelf realm). The pure quartz sandstones might be derived from the mixed quartz/carbonate sandstones through prolonged sorting processes in the foreshore or shoreface zone of a wave-dominated coast. Further up-section, quartz/carbonate sandstones with HCS interbedded with sandy mudstones are diagnostic features for clastic sedimentation in an inner shelf area with a water depth between the fair weather and storm wave base, where storm waves can produce the HCS sandstones (Dott and Bourgeois 1982; Dumas and Arnott 2006). Thus far, the Lower Sandstone can be interpreted, in sequence stratigraphic terms, to reflect a lowstand systems tract (mature and coarse sandstones at the base, overlying a sequence boundary), with limited creation of new accommodation space and hence intense sedimentary reworking and recycling, followed by a transgressive systems tract with increasingly deeper water conditions of the inner shelf.

At the base of the latter tract one would expect to find evidence for wave scouring and erosion which might in fact be represented in the form of isolated blocks and pebbles of coarse grained quartz sandstones with abundant Larger foraminifera. Above the inner shelf deposits (mudstone/sandstone alternation), standard sequence stratigraphic schemes would suggest the presence of outer shelf mudstones with occasional sediment/fluid gravity flow deposits such as turbidites. In a way, this is exactly what can be observed in the upper part of the Lower Sandstone Member. However, the assumption of a laterally extended and smooth shelf (that underlies standard sequence stratigraphic models) does not seem to apply to the present case. The isolated limestone blocks which are intercalated in sandy shales with thin sandstone layers (Fig. 8) must have been brought there by gravitational sliding movements. Furthermore, their lithology (cataclastic Eocene limestones from the Euthal Formation) suggests a very nearby source (most probably from synsedimentary fault zones with abundant brittle deformation). Similar, locally derived and angular giant blocks or megaclasts have been described by Le Heron et al. (2017) from slope-derived diamictites in Neoproterozoic rift environments. Such megaclasts thus require a steep palaeotopography unless one assumes drifting icebergs as a depositional agent as suggested by Heim (1907) to account for big blocks in the Iberg Wildflysch and related zones. The latter possibility can be firmly rejected on palaeoclimatic grounds (e.g. Grimes et al. 2005, Miller et al. 2008) and hence one has to assume a reasonably steep transition from shallow to deeper water without an extended shelf in between (see below for further discussions). Generally speaking, however, the Lower Sandstone Member records part of a sedimentary sequence with a basal (subaerial?) erosional unconformity, a lowstand systems tract, and a transgressive systems tract in an area with considerable submarine palaeotopography.

### *4.2.2 Blockmergel*

The pebbly mudstones of the Blockmergel Member are the most enigmatic of the three members of the SRZ sequence. Framed by two shallow marine, petrographically mature sandstones without any sedimentary particles finer than fine sand and coarser than small pebbles (except for the limestone blocks in the Lower Sandstone), the Blockmergel are composed to an overwhelming degree by particles finer than sand and coarser than small pebbles. Whereas marine pebbly mudstones provided an enigma for pre-1950 geologists and called for rather exotic depositional mechanisms (e.g. Ackermann 1951), the recognition of submarine massflows as an important agent of sedimentary dispersal and deposition in the aftermath of the Kuenen and Migliorini 1950 paper, has opened a completely new area of sedimentological research (e.g. Crowell 1957; Dott 1963; Carter 1975; Lowe 1982; Postma et al. 1988; Mulder and Alexander 2001; Camerlenghi and Pini 2009; Mutti et al. 2009; Pini et al. 2012).

The majority of the coarse grained detritus of the Blockmergel, the lonestones, are probably of originally fluvial or beach origin. This is suggested by both their shapes (see below) and the often good degree of rounding. The most fundamental question regarding an explanation of the Blockmergel facies is whether or not the lonestones had been deposited together with the fine grained matrix. If one assumes it had, cohesive debris flows (perhaps triggered by fluvial flashfloods), would provide a feasible depositional mechanism. In such laminar sediment gravity flows, pebbles and blocks are kept within the moving mass through the stiffness of the sediment (the so-called matrix strength). However, many features which are characteristic for debris flows are lacking in the Blockmergel. On the outcrop scale, no signs of any substantial event stratification (such as e.g. concentration of pebbles in certain horizons, textural changes etc., cf. e.g. Mulder and Alexander 2001) can be observed. On the other hand, the rare occurrence of laminated and seemingly clast-free intervals could represent a kind of background sedimentation to the mass flows. However, the sparseness of indications for soft-sediment deformation (so clearly documented for coarse submarine mass flow deposits and mass-transport complexes, see e.g. Crowell 1957, Dott 1963, Pini et al. 2012) is a further argument against a major contribution of mass-transport sedimentary processes. This inference would fit perfectly with the frequent observation of impact structures and onlap patterns on lonestones. Hence, we suggest that most of the coarser pebbles and blocks had been deposited independently of their finer grained matrix. On the other hand, some mass-flow contribution to the deposition of the matrix of the Blockmergel is clearly indicated by intraformational mud clasts and rare slumping features.

Somewhat intriguingly, pebbles from the Blockmergel display shapes which might at first be taken as evidence for mass flow transport. Their distribution on a Zingg diagram deviates from published ones for beach and river gravel (Howard 1992) with the former containing much more discs and the latter exhibiting a generally better distribution than the Blockmergel population. However, strong similarity exists to distributions from submarine fan conglomerates (likely mass flow deposits) with a high proportion of spherical pebbles and a scarcity of blades and rods. However, whereas this patterns can be taken as an argument against the assumption of pebble transport by means of biological rafting (i.e. in the roots of drift wood, Bennett et al. 1996; Bernoulli and Ulmer 2016), which would likely yield a random sample of all pebble shapes available at the place of growth of the tree (near a river or a beach), it does not exclude a transport of the pebbles not as one mass (such as in a mass flow) but rather as isolated bodies. The greater abundance of spherical pebbles in submarine fan conglomerates has been attributed by Howard (1992) to selective tractional transport of more spherical pebbles in shallow marine water through storm- or tide-generated currents which thus preferentially reached the heads of submarine canyons. Assuming a very steep submarine slope (as suggested by the limestone blocks in the Lower Sandstone) that directly connected a narrow shore and shoreface realm (with incoming gravelly rivers) with a deeper hemipelagic basin, the pebbly mudstones could be explained by a combination of suspension settling (giving rise to laminated Blockmergel), rare turbidity currents, and jumping and rolling down of (preferentially spherical) single pebbles and blocks. The latter process has been referred to as "subaqueous rockfall" by Dott (1963). Bayer (1982) previously invoked this depositional mechanism for the Blockmergel. The gravitational movement of individual clasts is also a feasible process to explain the introduction of dropstones without assuming biological or ice rafting. Additionally, fluvial flashfloods may have caused minor mass flows in the deeper basin (as part of a "fluvio-turbidite system", Mutti et al. 2009) which might account for the more massive portions of the Blockmergel with small pebbles. Summing up, it seems most plausible to ascribe the Blockmergel not to highly concentrated mass flow deposits but rather to a combination of ordinary suspension settling, some minor mass flows, and the gravitational influx of coarse sediment calibers by subaqueous rockfall across a very steep submarine slope that connected a shore environment and a moderately deep marine basin.

#### *4.2.3 Upper Sandstone*

High textural maturity (excellent sorting and often well rounding of grains, perhaps partly obliterated by diagenetic processes such as pressure solution), tabular stratification, SCS, rare HCS at the base, and minor small channels are all sedimentary features consistent with deposition in a clastic, wave/storm-dominated shoreface to foreshore (i.e. very high-energy) environment (e.g. Plint 1988; Catuneanu 2006). Horizontal, low angle and especially swaley cross stratification (SCS) do commonly develop under such circumstances in the uppermost shoreface (i.e. just below the low tide level) and foreshore (i.e. that part of a beach in front of the beach berm) realms. HCS, on the other hand, are more typical for somewhat deeper water below the normal fair-weather wave base on the inner shelf (Dott and Bourgeois 1982; Dumas and Arnott 2006). The rarity of the latter, the sharp, essentially planar base of the Upper Sandstone, its constant and small thickness (10–15 m), and the lack of any precursory sandstone layers (except for some isolated sandstone channels, see below) in the topmost part of the underlying Blockmergel are further characteristics which require explanation.

The Blockmergel-Upper Sandstone transition suggests a regressive trend leading from deeper water to shoreface-beach conditions. The sharp but horizontal (at least at outcrop scale) base of the shoreface sandstones is best explained by assuming foregoing wave-induced erosion (wave scouring) in the lower shoreface zone which subsequently became covered by upper shoreface sand deposits. This situation is typical for forced regressions in wave-dominated coastal settings i.e. seaward shifts of the shoreline which are not driven by sediment supply but solely by a relative fall of sea level (Plint 1988, Posamentier et al. 1992). The sharp base of the Upper

Sandstone would then represent the "regressive surface of marine erosion" in sequence stratigraphic terms (Catuneanu 2006). The conjecture of a forced regressive trend is further substantiated by the constant and thin thickness of the Upper Sandstones of some 10–15 m which corresponds well with the thicknesses reported for regressive shoreface sand bodies (6–18 m, Plint 1988) with the thickness being determined by the depth of the fairweather wave base (mostly between 5 and 15 m). Earlier workers have generally considered the Upper Sandstone as an early expression of flysch-like sedimentation (Trümpy 1967; Kuhn 1972; Bayer 1982). However, whereas such an interpretation would fit nicely into the overall tectonostratigraphic setting and general models of foreland basin development (see below), we failed to detect any sedimentary structures typical for turbidites.

### 4.3 Sedimentological synthesis and conclusions

Combining the sedimentological interpretations of the three members of the SRZ sequence we will next propose a synthetic sedimentological/sequence stratigraphic model for the whole sequence and draw some conclusions with regard to a later palaeotectonic interpretation (Fig. 13). In doing so, we assume that the SRZ sequence, encompassing the triad Lower Sandstone-Blockmergel-Upper Sandstone but excluding the basal relics of the Einsiedeln Member, represents a genetically linked sedimentary sequence without any substantial unconformities or hiatuses in it. This assumption has been contested by Jeannet (1941) and Leupold (1942) who maintained that an angular discordance exists between the Blockmergel and the Upper Sandstone. However, difficulty to define the bedding in the Blockmergel, and the rather tight biostratigraphic constraints render it difficult to assume a tectonically induced angular discordance. Perhaps, marine erosion preceding deposition of the Upper Sandstone might cause a minor angular discordance which is, however, no indicator for tectonic movements. Starting from the base, the irregular contact between the Lower Sandstone and the Cretaceous substratum with some isolated relics of the Lower Eocene Einsiedeln Member most probably reflects a state of low base level (sea level) with substantial erosion taking place above sea level (fluvial erosion) and/or in a shore setting through wave scouring. *Microcodium*-bearing carbonate pebbles (see below) in the Blockmergel might be taken as evidence for subaerial weathering and erosion before deposition of the SRZ sequence (stage 1 on Fig. 13). We thus place a sequence boundary and putative subaerial unconformity at the base of the Lower Sandstone. The basal part of the latter reflects a somewhat higher sea level with substantial sedimentary reworking but no newly created accommodation space (i.e. sedimentation outpacing sea level rise, a normal regression, see e.g. Catuneanu 2006).

A significant rise in relative sea level is then indicated by the middle and upper part of the Lower Sandstone and the Blockmergel with a transgressive ravinement surface, represented by reworked blocks from the basal quartz/carbonate sandstones (implying early cementation of the Lower Sandstone in a beach-setting), and an overlying transgressive systems tract with increasingly deeper marine mudstones with intercalated turbidites (stage 2). Abrupt lateral thickness variations of both the relict Einsiedeln Member limestones and the overlying SRZ sequence suggest that both relative sea level fall and rise might be related partly due to movements along tectonic faults (Frei 1963), which compartmentalized the sedimentary basin of the SRZ into different subbasins with, at least temporarily, steep slopes (fault scarps) in between. Brittle deformation along these faults provided fresh debris for the deeper basins in form of huge glide blocks (giant Nummulite limestone blocks), and supplied turbidity currents. Rising relative sea-level led to predominantly hemipelagic particle settling sedimentation, which was complemented by fluvially rounded pebbles from a likely southern source (highstand systems tract). The pebbles were brought into the basin across a steep slope which directly connected a gravelly shore/beach area to the south with the deeper Blockmergel-basin further north. A relative fall of base level (a forced regression) can be convincingly demonstrated for the sharp-based shoreface sandstone body of the Upper Sandstone (stage 3). However, it cannot be excluded that the regressive or falling-stage systems tract did start earlier and that the upper part of the Blockmergel Member record forced-regressive shelf mudstones (with the basal surface of forced regression being somewhat below the base of the Upper Sandstone (as suggested on Fig. 6). The isolated sandstone channels observable in the upper Blockmergel could then be interpreted as "gutter-casts" i.e. sandstone filled seafloor scours which typically precede the regressive surfaces of marine erosion (Catuneanu 2006). The regional extension and uniform thickness of the Upper Sandstone Member might be taken as evidence for an at least regional control of this latter relative sea-level fall.

## 5 Provenance of the coarse detritus

Before proceeding to a palaeotectonic model which can explain the sedimentological/sequence stratigraphic explanation given in the preceding section, we shall complement the sedimentological observations with a closer look at the petrography and provenance of the pebbles in the Blockmergel Member. Based on the block and pebble inventory mentioned previously (Online Resource) and the qualitative impression in the field, we estimated semi-quantitatively the proportions of pebbles from Cretaceous and Palaeogene sedimentary rocks and potential other sources. Provenance in this respect does not so much refer to a palaeogeographic realm (sedimentological and palaeotectonic/palaeogeographic considerations suggest a nearby source) but rather to the position within the stratigraphic column. Apart from obvious difficulties such as sampling bias in the field (preference for bigger or more easily recognizable clasts), the main problem is a safe identification of the blocks in the field. Even though a total of 11 blocks have been studied microscopically (Fig. 12), for many clasts, especially fine grained ones without typical fossils, an unambiguous identification is not possible.

Descending in the stratigraphic column, the following lithologies could be identified. Very common are Eocene (possibly Palaeocene) rocks which are easily identified both macro- and microscopically by their abundance of Larger foraminifera (i.e. mainly *Nummulites*, *Assilina*, and *Discocyclina*). Apart from lithologies which can be easily matched with certain members or horizons of the Euthal Formation, such as glauconite rich sand/grainstones (e.g. block number 6, see Fig. 10a), Nummulite limestones, or red algae ("Lithothamnium") bearing micrites (block 11, Fig. 12a), there are many bioclastic sandstones which are most probably reworked from the underlying Lower Sandstone Member. Somewhat enigmatic is block 49, a dark micrite, whose microfacies is dominated by up to mm sized aggregates composed of elongated calcite prisms, which are embedded in a micrite matrix with few glauconite grains (Fig. 12b). These aggregates resemble biosedimentary textures known as *Microcodium* (D. Bernoulli and V. Picotti, personal communications 2016) or might alternatively represent bryozoans (H. Weissert, personal communication 2016). Microcodium formed especially during the Cretaceous and Early Palaeogene in calcrete/caliche-bearing palaeosols (Košir 2004). Thus, this rock type does most likely document subaerial weathering even though its age cannot be determined due to the complete lack of any fossils. Generally, at least two potential age assignments seem possible. Either the rock has been derived from the base of the Lower Sandstone Member lower down in the SRZ sequence itself, where circumstantial evidence suggests very shallow marine erosion and potentially even temporary subaerial conditions. Alternatively, this lithology was derived from farther south of the SRZ from a hypothetical Southhelvetic swell zone and might then also be of Cretaceous age (see below).

Somewhat surprisingly, lithologies from the Upper Cretaceous Wang and Amden formations are very rare or even absent (Jeannet 1941 mentions glauconite bearing pale marly limestones from the Wang Formation) but this might partly be explained by the mechanical weakness of the shales of the Amden Formation. According to Jeannet (1941) and Trümpy (1967), grey micrites from the Seewen Formation are the most common rocks among the pebbles of the Blockmergel. This might be true as grey micrites are indeed very common, however, as pointed out below, some of these micrites reveal a microfacies which is markedly different from those of the Seewen limestones and their abundance might thus be overemphasised. Nevertheless, we propose that the Seewen Formation has yielded the majority of all Cretaceous lithologies in the Blockmergel and their identification is easy in thin section due to abundant planktonic foraminifera (Fig. 12d). Rocks from the Garschella Formation have not been found during the present study even though Jeannet (1941) mentions glauconite bearing limestones which presumably were derived from this formation. The Schrattenkalk Formation, on the other hand, could be identified in several thin sections (bioclastic grain/boundstones with milliolids, orbitolinids, dasyclad algae) whereas ooid-bearing varieties (Fig. 12f) are rather rare. Some sandy limestones with agglutinating foraminifera (orbitolinids, Fig. 12c) might be derived from the middle part of the Schrattenkalk Formation—the "Orbitolinenschichten" (personal communication H.-P. Funk 2016). Lithologies from below the Schrattenkalk are very rare. A sandy limestone with sponge spicules and some glauconite might be derived from the Helvetic Kieselkalk (H.-P. Funk, personal communication 2016).

Finally, a grey micrite block (block 1) with a belemnite (Fig. 11e), which macroscopically resembles rocks from the Seewen Formation, deserves some further discussion. Its microfacies (13e), however, is markedly different from the Seewen micrites and a Cretaceous origin for block 1 can safely be excluded because of the lack of typical planktonic foraminifera (D. Bernoulli, H.-P. Funk, H. Weissert, personal communications 2016). This mud- to wackestone contains some bivalve fragments, sponge spicules, questionable aptychus and belemnite fragments and some echinoderms (e.g. the planktonic *Saccocoma*). Furthermore, un-specific, circular bodies might be calcispheres. Quartz and other extrabasinal detritus is almost absent and the rock thus seems to have been formed in an open-marine quiet environment. An Upper Jurassic origin seems plausible for this rock type (either Quinten or Schilt Formation). Even though no pebbles older than Upper Jurassic have been found, a Southhelvetic origin is the most plausible one for all of the lithologies encountered. We have not studied the provenance of finer grained detritus for the present paper and therefore cannot deliver a sound discussion on that. Nevertheless, the frequent occurrence of fine grained mica flakes in sandstone intercalations of the Lower Sandstone and the Blockmergel (already noted by Jeannet 1941) is noteworthy. Perhaps, they might indicate fine grained contributions from a basement source.

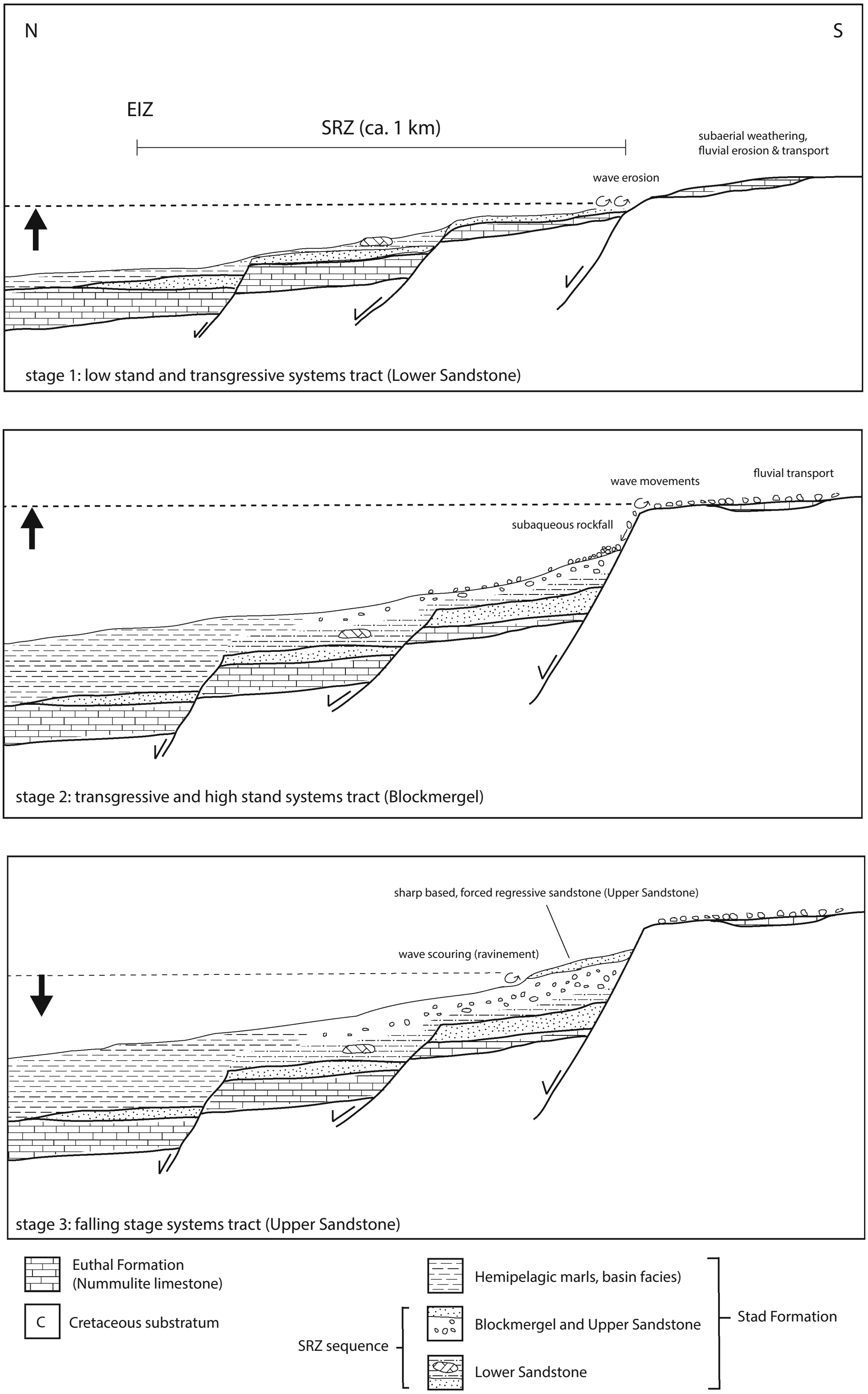


**Fig. 13** Three steps in the supposed palaeotectonic and sedimentologic development of the SRZ during Late Eocene times. Schematic and vertically exaggerated. Bold arrows indicate relative sea-level changes. EIZ: realm of future Einsiedeln Imbrcate Zone. See text for explanation. Note that the we assume the three normal faults to have been active with decreasing slip rates during all three stages. They supposedly rotated during later compressive (Neogene) deformation and inverted to form the steeply south-dipping inverse faults displayed on Fig. 5

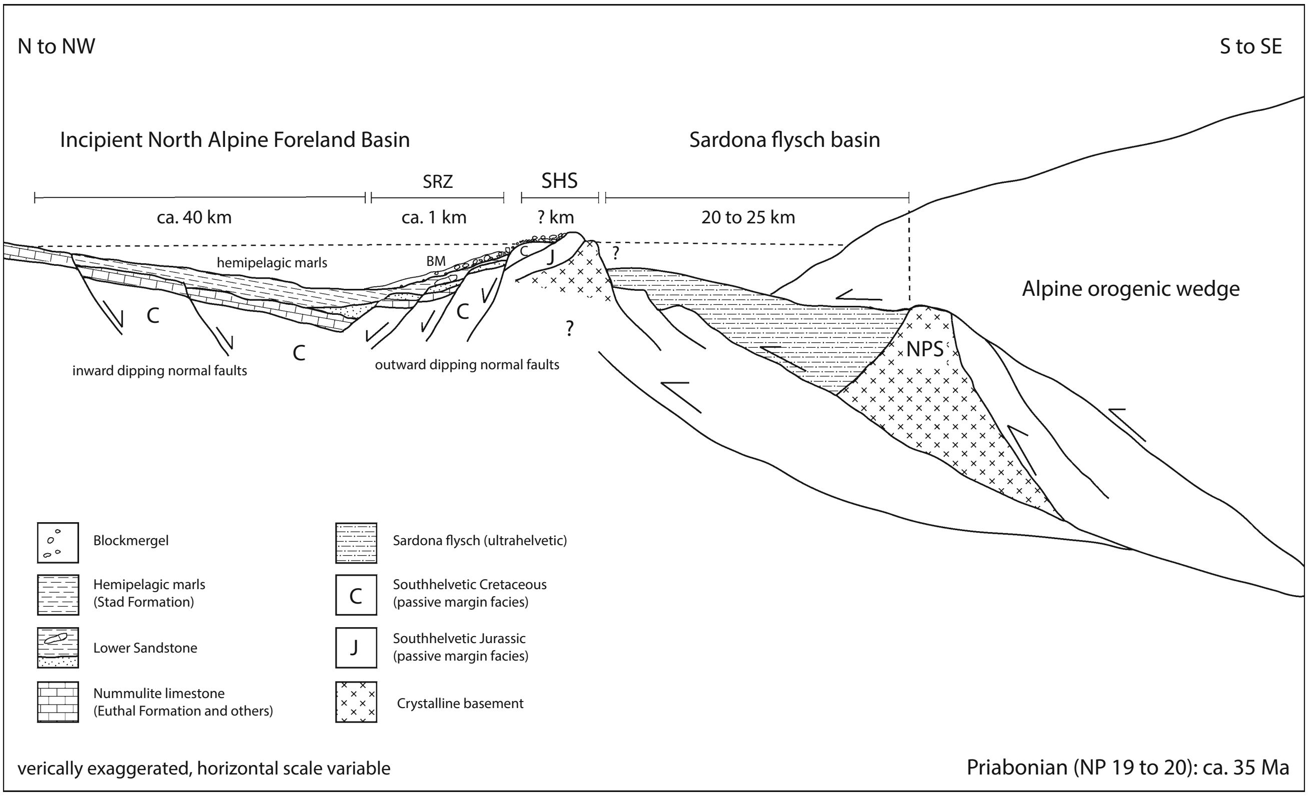


**Fig. 14** Highly hypothetical palaeotectonic sketch cross section of the North Alpine Foreland Basin along the meridian of Iberg during Late Eocene times. Partly inspired by Lihou and Allen (1996). *BM* Blockmergel, *SRZ* Southern Reduction Zone, *SHS* Southhelvetic Swell, *NPS* North Prättigau Swell. See text for further explanations

## 6 Discussion

### 6.1 A palaeotectonic model for the Helvetic Blockmergel

Putting the results of the local sedimentological and sequence stratigraphic analysis of the SRZ sequence within the broader frame of the early tectonosedimentary evolution of the North Alpine Foreland Basin, some interesting new consequences emerge. To get to this stage, a palaeotectonic model is needed which is able to explain the salient features of the SRZ sequence. A starting point is the recognition that at least two different Eocene tectonic movements of different magnitude can be distinguished (as pointed out first by Frei in 1963). First, movements along several SW–NE and N–S trending faults after deposition of the Einsiedeln Member led to differential erosion and reworking of the latter member and to a compartmentalization of the sedimentary basin into different subbasins (Middle Lutetian to Bartonian) which have been partially delivered with fault scarp debris in form of giant cataclastic limestone blocks (Fig. 13). Whereas in the north (i.e. in the area of the present-day Einsiedeln Imbricate Zones) the Nummulite limestone carbonate platform finally drowned and hemipelagic marls of the Stad Formation were deposited (Fig. 4), the SRZ recorded shallow marine sandstone deposition and marine erosion. Even though the faults cannot be directly observed in the field and they likely have been reactivated as inverse faults during later deformations, erosional patterns of the Nummulite limestone and distribution of the SRZ sequence render it probable to infer originally north- or northwest dipping normal faults (Fig. 13). Second, intense uplift (relative to the SRZ), erosion and hence tectonic movements must have taken place south of the SRZ basin. This is indicated by the steep slope necessary to explain the Blockmergel and the Cretaceous to Upper Jurassic pebbles in the latter which point towards fluvial and/or beach transport. To provide pebbles of Upper Jurassic lithologies, erosion must have removed at least the whole Southhelvetic Cretaceous sedimentary sequence (some 1000 m according to Trümpy 1980). Of course, it cannot be excluded that this substantial erosion did partially already take place in pre-Eocene times and that denudation of Upper Jurassic and potentially even older rocks had been facilitated by extensional fault movements. On a larger scale, the presence of north, or more generally speaking, outward (with respect to the axis of the North Alpine Foreland Basin) dipping synsedimentary normal faults is somewhat anomalous.

Whereas inward (south) dipping synsedimentary normal faults are a common feature of foreland basins (due to flexural extension of the downbending continental crust, Bradley and Kidd 1991) and have been reported from the Alpine Eocene in the Central and Western Swiss Alps (Herb 1988; Menkveld-Gfeller 1995; Kempf and Pfiffner 2004), outward dipping faults with a pronounced structural and topographic high or swell on the proximal side of it, are less straight-forward to explain. In fact, the shallowing upward trend recorded by the upper half of the SRZ sequence and the presence of a proximal swell (intrabasinal high) in the North Alpine Foreland Basin active shortly before being overthrust by the orogenic wedge (represented by Penninic flysch and the Klippen, Arosa and Austroalpine nappe), stands in contrast to Sinclair's (1997) tectonostratigraphic model of underfilled foreland basins. According to the latter, the early phase of underfilled foreland basin development is represented by a triad of shallow marine carbonates (Euthal Formation), followed by hemipelagic marls (Stad Formation), and eventually deepwater clastics derived from the orogenic wedge (flysch). The SRZ sequence records an exactly opposite trend leading to a short re-establishment of shallow marine conditions before final overthrusting (a kind of a Late Eocene "restoration" in analogy with Trümpy's 1973 "Palaeocene restoration").

Remarkably, the SRZ sequence has not been delivered with coarse detritus from the orogenic wedge but rather from local sources within the proximal foreland itself (as already pointed out by Bayer 1982). In this respect it resembles the Late Cretaceous to Middle Eocene Ultrahelvetic Sardona flysch (Lihou 1996) which has been deposited between two basement highs and was thus sheltered from wedge-derived detritus during most of its lifespan (Lihou and Allen 1996). Similar "marginal basement highs" have also been proposed for the Western Alps but again for an earlier time span (Homewood 1977). Building upon Lihou's work, we propose a highly schematic and essentially scale-less palaeotectonic sketch cross section for the Middle Priabonien in present-day Eastern Switzerland (Fig. 14). We tentatively assume that the source area of the detritus delivered to the SRZ was located on the same swell zone which had also delivered abundant quartz to the Sardona flysch basin during the Early Eocene (building the "Sardona quartzite", Lihou 1996). The width and exact nature of this "Southhelvetic swell" remains poorly known. However, field evidence from the Blockmergel could be explained by assuming an asymmetric structure with deeper erosion in the south (possibly even reaching the basement and providing a source for detrital mica) and subaerially eroded (fluvial transport of pebbles) and weathered (karst features on pebbles, *Microcodium*-bearing limestones) Mesozoic and Eocene carbonates exhibiting a Southhelvetic facies in the north. Following Lihou and Allen (1996), one could ascribe the late uplift of the Southhelvetic swell to a compressive inversion of inherited normal faults of the former passive margin. An alternative solution would be the assumption of a front-runner thrust (i.e. an early thrust in front of the actual orogenic wedge, see e.g. Allen et al. 1991) which ended as blind thrust and gave rise to an asymmetric ramp fold above (see also Kempf and Pfiffner 2004 for a similar Southhelvetic swell during the Lutetian).

Be that as it may, a long-lasting shallow marine Southhelvetic swell active just until final overthrusting through the orogenic wedge remains a somewhat alien element in Alpine palaeogeography and palaeotectonics. Especially the relations between the shallow marine upper SRZ sequence and the diverse deep marine Southhelvetic flysches of similar age (e.g. the Lavtina Sandstone in the Blattengrat zone of the Glarus Alps, Lihou 1995; Menkveld-Gfeller et al. 2016) remains enigmatic. Perhaps, the Middle to Late Eocene Southhelvetic swell south of the SRZ was just a laterally restricted remnant of the older and more extended Southhelvetic swell in the Sardona area. The prominent N–S trending faults of the Fuederegg area might represent relics of the lateral boundary faults of this late swell zone (perhaps already influenced by extensional tectonic activity in the Rhine Graben area as hinted by Trümpy 2006).

### 6.2 Pebbly mudstones in underfilled peripheral foreland basins

Marine diamictites (including pebbly mudstones highly reminiscent of the Blockmergel) are a common and well-documented element of sedimentary basins formed in extensional settings as e.g. rifted margins (e.g. Eyles and Januszczak 2004; Menzies and Whiteman 2009), or in compressive settings such as fore-arc basins (Camerlenghi and Pini 2009). However, their occurrence is only poorly documented for the early phases of underfilled peripheral foreland basins. In a thorough review of such basin fills, Sinclair (1997) mentions only one example from the Jurassic Brooks Range in Alaska which exhibits pebbly mudstones. However, the Eocene Stad Formation of the Northern Alpine Foreland Basin hosts several, geographically very restricted, occurrences of marine diamictites (Anderegg 1940, Brückner 1945, Herb 1988, Menkveld-Gfeller et al. 2016). Contrary to the Blockmergel of the SRZ, all these other diamictites are mostly clast-supported, often accompanied by coarse sand, and exhibit clasts with only poor rounding. Whereas diamictic breccias such as the

Eocene examples just described, are mostly mass flow deposits and hence distinguishable from glacimarine sediments (except the ones reworked through mass flows), the Blockmergel share many characteristics with such deposits (dropstones, high matrix content, no clear bedding etc.). Without further palaeoclimatic constraints it might indeed become very difficult to distinguish a sequence such as the one of the SRZ and a glacial marine succession. Even the stratigraphic context of the Blockmergel might easily be fitted into glacio-isostatic schemes with the Upper Sandstone representing post-glacial regression due to isostatic rebound caused by deglaciation. We suggest that the Blockmergel of the SRZ provides an intriguing example of a non glacigenic diamictite which nevertheless shares many characteristics with isostatic glacimarine sequences as e.g. described from the Pleistocene of the North American westcoast (Domack 1983).

### 6.3 The Southhelvetic Blockmergel and the "diamictite dichotomy"

The increasing awareness of mass flows as a sedimentary process during the 1950s and 1960s has led to a sometimes almost idiosyncratic skepticism with regard to glacial interpretations of Precambrian diamictites (see especially Schermerhorn1974, cf. Hoffman 2011 for a historical exposé). Whereas this extreme form of sedimentological skepticism seems unwarranted, the problem remains that glacial and non-glacial depositional processes may lead to very similar products (see the preceding paragraph). More recently, detailed sedimentological analyses of Neoproterozoic rift-hosted sedimentary successions have led to the proposal of a highly complex interplay between glacially related sedimentation and processes linked to synsedimentary tectonics and slope failure (Le Heron et al. 2014, 2017). Both processes may and often do result in the deposition of diamictites, lonestones, and giant blocks or megaclasts. Thus, the resolution of this "diamictite dichotomy" (Le Heron et al. 2017) is an exciting new field of geological research and will possibly help to better understand the severe climatic changes during the Neoproterozoic ice-house world ("Snowball Earth"). Even though it is beyond the scope of the present paper to further discuss these issues in detail, we want to stress the remarkable similarity between the megablocks in the Lower Sandstone Member of the SRZ sequence and the megaclasts reported by Le Heron et al. (2014, 2017). However, whereas the latter are embedded in diamictite and were hence interpreted as passive passengers in a high-density olistostrome, the former are embedded in undeformed shale and sandstones and hence points towards deposition independent of their surrounding matrix. Excluding ice-rafting, a possible process to achieve this is gravitational rolling, jumping or sliding across a steep palaeoslope (subaqueous rockfall, Dott 1963). Using the advantage that the SRZ sequence is a pure end-member (i.e. without any glacial influence), the importance of this depositional process for the emplacement of megaclasts can be demonstrated. Hence, the study of Phanerozoic marine diamictites without any glacial contribution can help to distinguish glacial from non-glacial sedimentary processes in mixed Proterozoic successions and add further inspiration to recognize and isolated specific depositional mechanisms.

## 7 Conclusions

- Pebbly mudstones (diamictites), sharing many characteristics with glacimarine diamictites, do also occur in early underfilled foreland basins. Their presence alone cannot be taken as a sufficient indicator for glacial activity in the geological record unless other independent palaeoclimatic or geochronologic constraints are available. The Southhelvetic Blockmergel thus represent an intriguing example of a "pseudo-glaciation" and the SRZ sequence shares many similarities with isostatic glacimarine sequences.
- The detailed sedimentological study of Phanerozoic marine diamictites (such as the one presented in this paper) will likely provide a useful tool for future workers in their struggle to distinguish between glacially-sourced and slope-derived mass flow deposits, especially in the Precambrian record. We furthermore suggest that subaqueous rockfall (sensu Dott 1963) might be a hitherto underestimated depositional process in the production of pebbly mudstones and megaclast bearing diamictites.
- A southern facies realm in the incipient Late Eocene North Alpine Foreland Basin ("the Southern Reduction Zone", SRZ) records a whole depositional sequence with two substantial regressive and one transgressive phases. The latter one is reflected by a peculiar pebbly mudstone facies (diamictites) which bear testimony to substantial subaerial erosion of at least a restricted part of the proximal part of the North Alpine Foreland Basin shortly before being overthrust by the orogenic wedge of the Alps.
- Inherited tectonic features (such as the long-standing extensional basement high of the South Helvetic swell) can considerably distort the relatively easy patterns which are suggested by flexural subsidence models of early foreland basin development. Instead of monotonously deeper marine hemipelagic and finally deep-water clastic (flysch) sedimentation, proximal, generally underfilled, foreland basins may exhibit local

shallowing upward cycles which finally end up in very shallow marine to even terrestrial sedimentation.

- Tectonic activity in early proximal foreland basins can start before final arrival of the overthrusting wedge. The SRZ documents substantial normal faulting which partly controlled sedimentation and led to deposition of marine diamictites. The tectonic significance of these normal faults is not clear. Either they are due to the reactivation of older basement structures (perhaps triggered by the approaching orogenic wedge?) or they might partly reflect a far-distance reaction to the initiation of the European Cenozoic Rift System (Rhine graben).

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