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# Quaternary deposits: concept for a stratigraphic classification and nomenclature—an example from northern Switzerland

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**Abstract** A. Penck's and E. Brückner's "classical" subdivision of Quaternary deposits, developed in the Alpine foreland of southern Germany, was used for a long time as a basis for the classification of Quaternary deposits on Swiss geological maps. Due to fundamental differences between southern Germany and northern Switzerland regarding the morphogenetic control of the drainage system—especially regarding the morphostratigraphic position of various lithostratigraphic units—this subdivision should no longer be applied in Switzerland. With this in view, a new concept for a stratigraphic classification and nomenclature is presented here. It is based on the national guidelines for stratigraphic nomenclature compiled by the Swiss Committee on Stratigraphy SCS. In addition, a corresponding system for map legends is proposed. This concept has already been applied in a number of sheets of the Geological Atlas of Switzerland 1:25,000 and will be implemented in future maps.

**Keywords** Quaternary deposits · Stratigraphic classification · Stratigraphic nomenclature · Geological mapping · Guidelines · Northern Switzerland

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## 1 Aims of the project

This paper is based on a research project initiated and funded by the Swiss Geological Survey (swisstopo). The primary aim of this project was to develop a concept for the stratigraphic classification and nomenclature of Swiss Quaternary deposits for the Geological Atlas of Switzerland 1:25,000, complying to the national guidelines for stratigraphic nomenclature.

Basically, the mapping units on the sheets of the Geological Atlas of Switzerland 1:25,000 are lithostratigraphic units, i.e. rock bodies that are defined and delimited on the basis of their lithological content. In this context, Quaternary units have always occupied a particular position, because their description and subdivision based solely on lithological criteria is inadequate. Further criteria, such as the geomorphological position, have to be taken into account. The aim of the research project was to improve the classification by means of a conceptual study. The first step was to determine whether the current classification of Quaternary deposits in the Alpine foreland of southern Germany can be used as a basis for the classification of the corresponding deposits in Switzerland. In case this should turn out to be not feasible, i.e. that the traditionally used "classical" terms can no longer be used for scientific reasons, recommendations for a stratigraphic procedure, classification and nomenclature of Quaternary deposits of the northern Alpine foreland of Switzerland were to be developed.

## 2 Historical background

The nomenclature of the Quaternary units on older maps of the Geological Atlas of Switzerland followed the so-called "classical" northern Alpine Quaternary stratigraphy, which was developed by Penck and Brückner (1901–1909) for the Alpine foreland of southern Germany. This stratigraphic scheme is largely based on two elements: (a) the sedimentological concept of the "glacial series" ("glaziale Serie") and (b) the morphostratigraphy of gravel terraces (see e.g., Fiebig and Preusser 2008). On this basis, A. Penck and E. Brückner defined the four glacials Günz, Mindel, Riss and Würm. In the course of the 20th century, the subdivision of the southern German (Pliocene–)Pleistocene was successively enlarged and refined, resulting in the definition of the following other glacials: Donau (Schaefer 1953), Biber (Eberl 1930), Haslach (Schreiner and Ebel 1981) and Paar (Schaefer 1975; disputed) as well as in the subdivision of the Riss Glacial (e.g., Schreiner 1992).

On the older maps of the Geological Atlas of Switzerland, the Günz, Mindel, Riss and Würm glacials were related to morphostratigraphically distinct levels of glacial gravel deposits, namely the terrace of the Höhere Deckenschotter (Günz Glacial), the terrace of the Tiefere Deckenschotter (Mindel Glacial), the Hochterrasse (Riss Glacial) and the Niederterrasse (Würm Glacial). However, recent studies in northern Switzerland show an interpretation that differs from traditional correlation with the southern German model (e.g. Schlüchter and Kelly 2000; Graf 1993, 2009a, b).

## 3 Chronostratigraphic subdivision in Switzerland

The base of the Quaternary was defined at Monte San Nicola, Sicily, Global Stratotype Section and Point (GSSP) at 2.58 Ma (base of the Gelasian stage; Gibbard et al. 2010), acknowledging the fact that there is evidence for glacials or phases with increased global ice volume since 2.58 Ma. Furthermore, this boundary corresponds to the Gauss–Matuyama palaeomagnetic reversal, thus allowing its recognition in suitable terrestrial sediments as well (e.g., Morrison and Kukla 1998). With this boundary, one can assume that all of the (peri)glacial deposits in Switzerland belong to the Quaternary, including those on a number of maps of the Geological Atlas of Switzerland that were classified as "(Pliocene–)Pleistocene" (e.g., Map Sheet 1070 Baden, Graf et al. 2006).

The boundary between the Early and the Middle Pleistocene is defined in conformity with the Matuyama–Brunhes palaeomagnetic reversal (Richmond 1996), situated at 0.78 Ma (Gibbard et al. 2004; Gibbard and Cohen 2008). Thus, the Early Pleistocene sediments belong to the predominantly reversely polarised Matuyama chron, whereas the Middle and Late Pleistocene sediments belong to the normally polarised Brunhes chron. Regarding the determination of the base of the Middle Pleistocene in the Swiss northern Alpine foreland, information is very scarce. The analysis of a drill core from the Thalgut gravel pit in the Aare valley, southeast of Bern, reveals that the whole profile, which comprises several climatic cycles, is normally polarised (Forster 1991). On the other hand, unpublished data from the Tiefere Deckenschotter in the abandoned gravel pit of Allschwil near Basel hint to a deposition during a reversely polarised time period (comm. C. Schlüchter, T. Forster), possibly the Matuyama chron. Based on this weak evidence and lacking better information so far it is assumed that the boundary between the Early and the Middle Pleistocene coincides with the limit between the two morphostratigraphic units Tiefere Deckenschotter and Hochterrasse. Consequently, it is assumed that the Matuyama–Brunhes reversal took place approximately during this phase of regional lowering of the drainage system of the Swiss northern Alpine foreland, which was directed towards the Upper Rhine (Oberrhein).

The boundary between the Middle and the Late Pleistocene is defined at the base of the Eemian interglacial (Gibbard 2003; Gibbard and Cohen 2008), which approximately coincides with the base of MIS 5e (MIS = marine isotope stage). For Switzerland this can be equated to the base of the Gondiswil Interglacial, which corresponds to the Eemian of the Quaternary stratigraphy of northwestern Europe (Wegmüller 1992).

The boundary between the Pleistocene and the Holocene is set at the end of the Younger Dryas, which corresponds to 10 ka $^{14}C$ (uncalibrated) and 11.5 ka BP (calendar years), respectively. The definition of a stratotype is currently under discussion (Walker et al. 2009). For Switzerland no parastratotypes have been determined so far.

## 4 Quaternary stratigraphy in the northern Alpine foreland

As mentioned in Sect. 1, the first step of this study was to determine (a) whether the current knowledge of the Quaternary deposits of northern Switzerland still justifies a correlation with the corresponding deposits in the Alpine foreland of southern Germany, and, consequently, (b) whether the German classification still can be regarded as a basis for the classification of the Quaternary units used in the Geological Atlas of Switzerland 1:25,000. This issue is discussed below mainly by reference to current compilations of the Quaternary stratigraphy of the northern Alpine foreland of Switzerland (Preusser et al. 2011), Baden-Württemberg (Ellwanger et al. 2011) and Bavaria (Doppler et al. 2011). Our focus is not on a detailed discussion of the situation in each region but rather on the question whether the characteristics of the Quaternary deposits in these regions, as well as their geomorphological interrelationship, allow for a straightforward correlation within the northern Alpine foreland.

### 4.1 Swiss northern Alpine foreland

According to Preusser et al. (2011) the morphostratigraphic units of the older literature (Höhere and Tiefere Deckenschotter, Hochterrasse and Niederterrasse) still have some significance for the subdivision of Quaternary deposits in northern Switzerland, as they provide a framework for the classification. Nevertheless, these morphostratigraphic units can be further subdivided lithostratigraphically (Figs. 1, 2).

The Höhere Deckenschotter of northern Switzerland were deposited in at least four phases, which were separated from each other by warm periods or phases of significant erosion (Graf 1993). The type locality for this subdivision is the Irchel hill in the Canton of Zürich (Figs. 1, 2), where four gravel units were deposited in superposition. For the two older units (including their equivalents throughout northern Switzerland), no correlations with glacigenic sediments have been detected so far, but such deposits are locally intercalated with the two younger deposits (Schöfflisdorfer Platten north of Wehntal, Cantons of Aargau and Zürich; Graf 1993).

After a regional lowering of the regional drainage system the Tiefere Deckenschotter were formed in at least four phases, which are separated from each other by not less than two temperate intervals and a major erosional phase (Graf 1993, 2000; Bitterli et al. 2000). Boreholes drilled on the Iberig hill in the lower Aare valley reveal three units overlying each other in a normal stratigraphic succession, two of which contain glacigenic sediments. In the Rhine valley downstream of the village of Eglisau and in the area of the Lake Constance lobe of the Rhine glacier in general (Graf 2009b) a further unit occurs at slightly lower altitudes; this is attributed to a younger erosion–accumulation cycle.

A second lowering of the regional drainage system preceded the deposition of the sediments attributed to the Hochterrasse and the Niederterrasse and resulted in the erosion of fluvial channels. At least six major phases of glaciation, separated by several warm intervals, can be assumed for the period during which Hochterrasse and Niederterrasse sediments were deposited. Glacigenic and lacustrine sediments at the bottom of palaeochannels prove a glacier advance at least as far as the Möhliner Feld area in the Rhine valley (Möhlin Glacial; see also Dick et al. 1996). Afterwards, from a more internal position of the glaciers (e.g. Habsburg in the Aare valley, Habsburg

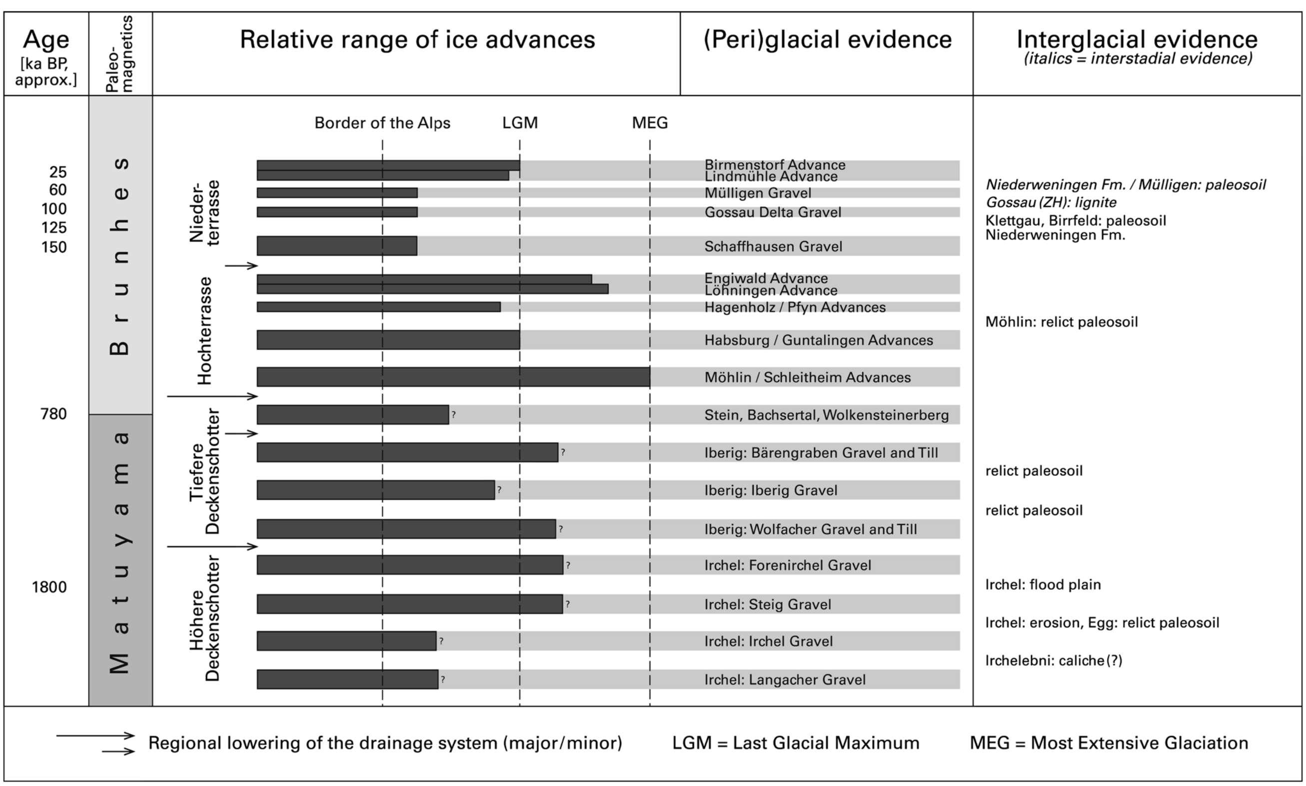



**Fig. 1** Stratigraphic scheme showing the glaciation history of northern Switzerland. After Schlüchter and Kelly (2000), Müller et al. (2002) and Graf (2009a, b), with updated nomenclature of Deckenschotter units

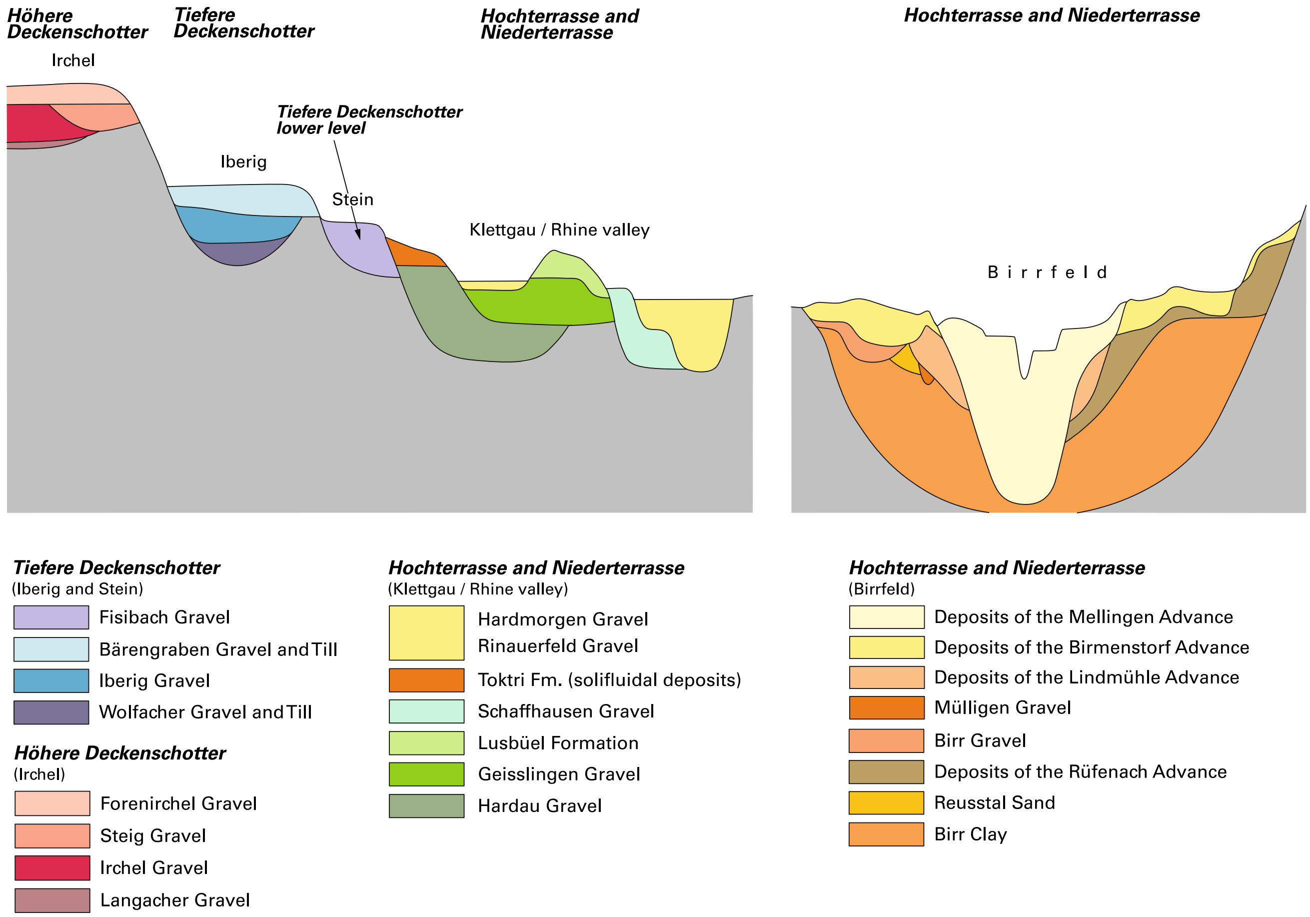



**Fig. 2** Lithostratigraphic scheme of Pleistocene deposits of northern Switzerland. After Müller et al. (2002), updated after Graf (2009a), including nomenclature of Deckenschotter units

Glacial; Preusser et al. 2011), large gravel bodies were deposited while glacial basins were eroded, later being filled with thick basin sequences. During the subsequent retreat of the glaciers, a number of new fluvial channels were formed, with base levels that were located at distinctly higher altitudes than those of the oldest Hochterrasse sediments. After an interglacial (palaeosoil of Möhliner Feld, Dick et al. 1996) the Beringen Glacial followed. This can be subdivided into the early glacial Hagenholz Advance (formerly Hagenholz Glacial, Graf 2009a, see also Preusser et al. 2011), followed by two main advances reaching, among others, the Klettgau area (Löhningen and Engiwald Advances; Graf 2009a), and a late-glacial readvance (Langwiesen Advance). Again, thick basin sequences can be attributed to these advances (Dehnert et al. 2012). In the course of the retreat phase, new fluvial channels were formed with base levels situated at an altitude similar to that of the old Hochterrasse palaeochannels. The last glaciation (Birrfeld Glacial) began with two minor advances. The subsequent main phase consists of two advances as well. In the glacial outwash plains, the Niederterrasse gravels in the proper sense were deposited, whereas basin sequences were formed in more internal positions. Several phases of deposition and erosion during the retreat, i.e. the transition to an ice-free Alpine foreland, can be discerned (see Keller and Krayss 2005 for the Rhine glacier area).

## 4.2 Southern German Alpine foreland

For the Alpine foreland of Bavaria, the results of a thorough re-evaluation of the classical stratigraphic classification (Doppler et al. 2011) largely confirm the terrace stratigraphy based on Penck and Brückner's (1901–1909) work, which was extended and elaborated during the course of the 20th century. Thus, on the one hand, the subdivision of the Quaternary is determined by the succession of fluvial terraces, with the oldest units situated at the highest altitudes and the subsequently formed younger deposits at successively lower levels. This applies largely to both the bases of the respective sediment bodies and their upper limits. Normal stratigraphic superposition of gravel bodies (young over old) only occurs exceptionally. On the other hand, glacigenic sequences formed by moraine amphitheaters and adjacent terraces (Penck and Brückner's 1901–1909 "glacial series") constitute another cornerstone in the subdivision of the Quaternary in Bavaria. The scenario can be schematically described as a drainage system that was successively and seemingly constantly lowering (in step with the glaciations), with a greater amount of lowering near the Alps (Doppler et al. 2011).

A similar picture of a successively and constantly lowering drainage system emerges from the succession of gravel terraces in the distal Alpine foreland of Baden-Württemberg (Ellwanger et al. 2011). It seems, however, that the terraces are much less well preserved compared to those in Bavaria. Apparently, Early Pleistocene deposits, which possibly could be correlated with the oldest Deckenschotter of the Bavarian Alpine foreland (Biber Glaciation), are missing in particular. It can be assumed that this is the result of erosional events during the Middle and Late Pleistocene. During this period, several extensive advances of the Rhine glacier affected the area, leading to the formation of overdeepened basins. These new glacigenic elements indicate a geomorphological change from a "Bavarian-type" ramp with foothills to a topography with intercalated glacial basins that comprise a series of staggered moraine amphitheaters. The current classification of the outwash plain deposits of Baden-Württemberg considers the fact that the gravels deposited by glacial rivers draining towards the Danube differ—in geomorphological terms—from those deposited by rivers draining towards the Rhine. Thus, the Early Pleistocene Oberschwaben Deckenschotter (oriented towards the Danube) are discerned from the assumedly coeval Hochrhein Deckenschotter (oriented towards the Rhine). The Middle to Late Pleistocene terrace deposits are subdivided in a similar way. The classification of the glacigenic and fluvioglacial basin deposits, based on a thorough analysis of the sedimentary sequences, led to the distinction of three units that are separated from each other by prominent bounding discontinuities (from old to young): Dietmanns Formation, Illmensee Formation and Hasenweiler Formation.

### 4.3 Conclusions

As stated above, there are fundamental differences between the gravels transported towards the Danube and those transported towards the Rhine. In particular, the correlation of gravel terraces between these areas causes difficulties (Ellwanger et al. 2011). This raises the question concerning the influence of the morphogenetic development of both areas, i.e. whether the respective gravel terraces can be correlated at all.

In the Alpine foreland of both northern Switzerland and Bavaria, the succession of gravel terraces points to a gradual lowering of the drainage system. This development basically is controlled by headward erosion along the river profile, with steepening of the headwater and flattening of the tailwater, or by adjustments of vertical tectonic movements (uplift in the headwater, lowering in the tailwater). Both parts of the Alpine foreland could be equally affected by an uplift of the Alpine orogen and, consequently, show an analogous pattern of terraces. However, the major part of the Rhine drains towards the tectonically subsiding area of the Upper Rhine graben, whereas no such activity is known in the Alpine foreland belonging to the Danube system.

The gravel terraces of the Bavarian Alpine foreland show a conspicuously regular pattern of erosional incision and gravel deposition, which can be interpreted as a result of a constant uplift of the Alpine hinterland with a periodic adjustment of the base level (in step with the glaciations). In contrast, the circumstances in the Swiss northern Alpine foreland (Fig. 2) lead to the conclusion that three time intervals with no substantial lowering of the drainage systems occurred, during which the sediments of successive glaciations were deposited in a normal stratigraphic manner, i.e. one on top of the other. The three intervals were separated by two phases of major incision, during which the drainage system was considerably lowered. What exactly caused this is still a matter of debate. It is possible that phases of tectonic quiescence alternated with phases of activity. In this case, the Alpine orogen can be excluded as the active zone, since the conditions in the Danube system imply a constant tectonic uplift. Instead, it can be assumed that subsidence in the Upper Rhine graben played a major role. However, it cannot be ruled out that the (relative) base level of the Rhine lowered more or less constantly. This movement would have been buffered for some time (possibly in the hinge zone between the Jura Mountains and the Black Forest) before manifesting itself once a threshold was exceeded.

These considerations show that a major prerequisite for a direct correlation between the morphostratigraphic classifications of the Rhine and Danube systems, respectively—i.e. a similar tectonic and fluvial-dynamic control on morphogenesis—is probably not met (see Ellwanger et al. 2011). This raises doubts regarding a detailed correlation among fluvial terraces throughout the northern Alpine foreland; instead, it can be assumed that there are differences that are fundamental. It is therefore necessary to take another path for the classification and nomenclature of Quaternary stratigraphic units in Switzerland.

## 5 Lithostratigraphic classification of Quaternary deposits in Switzerland

### 5.1 Lithostratigraphic principles

The nomenclature of lithostratigraphic units is regulated by the International Stratigraphic Guide (Salvador 1994). A guideline for its implementation in Switzerland was formulated by a working group of the Swiss Committee on Stratigraphy SCS (Remane et al. 2005). The most important principles of the lithostratigraphic classification of the Quaternary are given below.

The geological mapping of a given area is primarily based on lithostratigraphy. Consequently, the definition, naming and depiction of mapping units have to be carried out according to the principles of lithostratigraphy. Lithostratigraphic units are rock units (both solid and unconsolidated rock) defined by lithological characteristics that distinguish them from stratigraphically underlying and overlying units. Rock units that are bounded everywhere by discontinuities—including the earth's surface—can be defined by the lithological and structural characteristics of the bounding discontinuities. Such units were classified by Salvador (1994) as a separate stratigraphic category (unconformity-bounded units). Since there are no fundamental differences in the criteria for defining the two categories, both are designated as lithostratigraphic units in this paper.

A *formation*, the basic unit in lithostratigraphy, has to be mappable at a scale of 1:25,000; it is defined at a type locality. The name of a formation comprises the toponym of the type locality and the capitalised term Formation, which defines its hierarchical position (e.g. Schmerlet Formation). Alternatively, the term Formation may be replaced by a lithological term that characterises the unit (e.g. Rafzerfeld Gravels). Several adjacent formations may be grouped into a *group*, and several groups may be combined to form a *supergroup*. Formations may be subdivided into *members*. For their definition, the same rules as those for formations apply. Single characteristic strata may be designated as *beds*.

### 5.2 Peculiarities of Quaternary deposits

Ever since the recognition of a dominantly glacigenic origin of Quaternary sediments, these deposits have been understood and discussed in a climatic context. This contradicts the nomenclature based on advanced lithostratigraphy, which is devoid of any palaeoclimatic implications. The effect on single rock units (e.g. Rafzerfeld Gravels) is minimal, but problems arise with hierarchically superior units (e.g. a hypothetical "Siblingen Group"), which contain different deposits formed during a particular glaciation. It is therefore necessary to establish guidelines for stratigraphic classification and nomenclature that take this issue into account. Furthermore, the following aspects have to be considered:

- Glacial deposits are characterised by a marked heterogeneity and small-scale facies changes. Distinguishable units commonly occur only in the vicinity of the type locality. They invariably are in close relation to the relief of their substratum (both solid and unconsolidated rock), which is why their geographic and geomorphological positions (e.g. altitude) constitute significant individual characteristics (Remane et al. 2005).
- The geological processes that are characteristic of a glaciation may have repeatedly taken place in a particular zone, which therefore may have been located in the depositional area of the same sediment type over time. As a consequence, similar deposits (e.g. fluvioglacial gravels, glaciolacustrine deposits) of different age may be superimposed. Such deposits can only be subdivided by means of discontinuities (unconformity-bounded units, Salvador 1994). In many cases, discontinuities can only be discerned locally, sometimes only in boreholes.
- The dynamics of glacial processes lead to the formation of discontinuities (both concordant and discordant) of various magnitudes. These typically document major climatic or morphogenetic events and are therefore a very important means of correlation.
- The present is part of the Quaternary, thus Quaternary deposits may form today. This leads to the question whether active sedimentary bodies should undergo a lithostratigraphic classification. According to Remane et al. (2005), only those deposits with a terminated formation by causal processes should be lithostratigraphically classified. Therefore, active alluvial fans, fluvial deposits, mass movements etc. are not classified and named.
- Because of the limited number and quality of outcrops, the extent and structure of glacial deposits in the northern Alpine foreland can only exceptionally be conceived in their entirety. In particular, the lower and lateral limits of the sedimentary bodies are commonly hidden. Consequently, the requirements for defining formal lithostratigraphic units are not fully met (Remane et al. 2005). Therefore, the definition of Quaternary lithostratigraphic units in strict adherence to the guidelines is rarely possible.

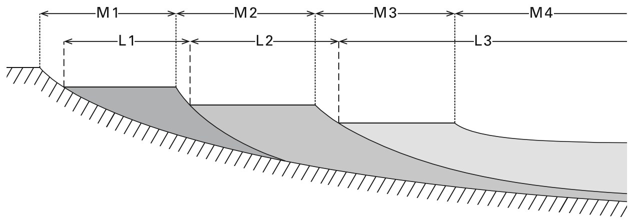



**Fig. 3** Relationship between lithostratigraphic units (L1–L3, grey areas) and morphostratigraphic units (M1–M4), using the example of a hypothetical section through a succession of gravel terraces. The grey areas mark different sediment bodies constituting lithostratigraphic units, and L1–L3 denote their outcrops. Morphostratigraphic units are characterised by their surface and topographic positions. Morphostratigraphic unit M4 was formed solely by erosion and therefore has no lithostratigraphic equivalent

### 5.3 Relationship between lithostratigraphy and morphostratigraphy

The classification of Quaternary deposits on older maps of the Geological Atlas of Switzerland 1:25,000 was largely based on morphostratigraphic units (e.g. gravel terraces). These are landforms composed of a particular lithology, reflecting certain phases of landscape morphogenesis (see Catt 1992), in which the altitude plays an important role ("terrace stratigraphy"). A depositional landform used as a morphostratigraphic unit (surface) comprises at least one lithostratigraphic unit (sedimentary body). This is not the case with morphostratigraphic units that are based on erosional landforms. In particular, the cartographic limits of gravel terraces differ, depending on whether they are mapped as lithostratigraphic or morphostratigraphic units (Fig. 3).

The spatial relationship between different lithostratigraphic units (superposition, intersection) results in a relative chronological succession (usually "old at the base—young at the top"). As a prerequisite for determining their spatial relationship, two subsequent units must be in direct contact with each other in at least one place. Likewise, the spatial relationship between morphostratigraphic units allows the determination of a relative succession; however, a direct contact between the units is not necessary here. In the case of terraces, which formed by an incremental lowering of the base level, "old at the top—young at the base" applies (see Fig. 3).

The morphostratigraphic classification of a certain area may therefore be understood as a succession of discontinuities. In the case of a stepped sequence of gravel terraces, the discontinuity constituting the lower boundary of a given gravel body begins at the break in slope of the terrace higher up and continues along the bedrock surface, underneath the concerned gravel body (Fig. 3). The upper bounding discontinuity is defined either by the earth's surface or by the lower boundary of superimposed, younger sediments.

## 6 Guidelines for the classification and nomenclature of Quaternary units in Switzerland

### 6.1 Principles

As stated above, formations constitute the basic units for classification and mapping of Quaternary units. Formations are defined solely on the basis of observable, objective lithological and geomorphological criteria. However, grouping of formations into groups (and groups into supergroups) is only meaningful if it is based on a genetic analysis of the sediments. Only then is it possible to recognise characteristic discontinuities that are common to several formations. This is indeed an interpretative procedure, which is not consistent with the requirements for the definition of formal lithostratigraphic units. The results of this procedure strongly depend on the state of geological knowledge. Units defined in such a manner (=genetic units) may be regarded as hierarchically superior lithostratigraphic units (groups, supergroups) if they share a common bounding discontinuity at their base and top (see Ellwanger et al. 2011).

### 6.2 Definition and nomenclature of Quaternary formations

Quaternary lithostratigraphic units (sediment bodies) are to be defined on the basis of lithological and geomorphological criteria so as to be clearly distinguishable from adjacent units. They are to be named after their type locality. In order to imply the climatic background of their formation, the second part of their name, indicating their hierarchical position, should be replaced by the dominant lithology, where applicable (e.g. Rafzerfeld Gravels instead of Rafzerfeld Formation). On the other hand, units that comprise several lithologies (e.g. kame deposits) should be termed formations.

### 6.3 Definition and nomenclature of Quaternary genetic units

As a rule, the definition of hierarchically superior genetic units is only meaningful for glacial, fluvioglacial and glaciolacustrine deposits, since they are sufficiently large to be mapped at the scale of 1:25,000. The designations to be used for each hierarchical level should reflect a "climate stratigraphic" background. The following terms are proposed here:

– *Advance* (German: *Vorstoss*; French: *avancée*; Italian: *avanzata*): The presence of a glacier—documented by corresponding sediments—within the area of extension

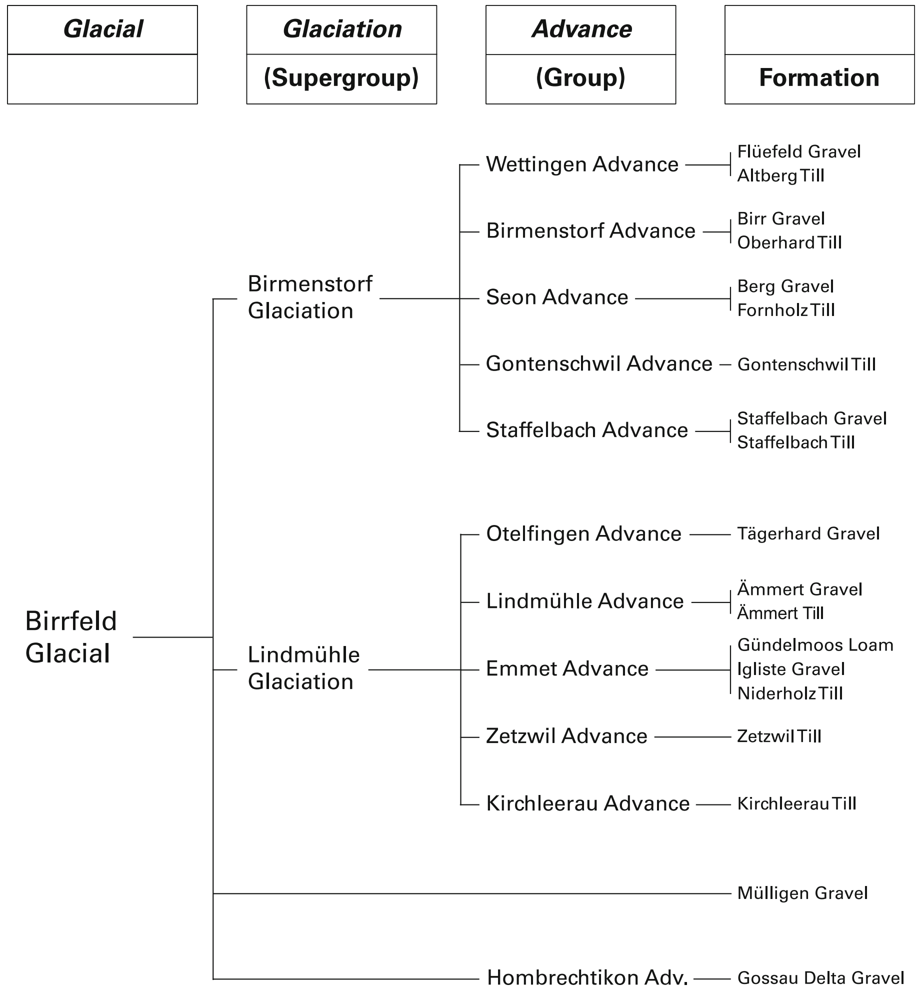



**Fig. 4** Classification of the deposits of the last glacial in northern Switzerland (Birrfeld Glacial). After Graf (2009a), partially hypothetical

of a glacier lobe is termed advance. An advance is defined by all sediment bodies (i.e. lithostratigraphic units) that were formed in the context of the corresponding glacier presence (including glacier advance and retreat).

– *Glaciation* (German: *Vergletscherung*; French: *glaciation*; Italian: *glaciazione*): A glaciation is a major phase of regional ice buildup, expressed by advances of several individual lobes of a glacier (interpreted as being "simultaneous"). A glaciation is defined at a locality with a distinct lithostratigraphic situation.
– *Glacial* (German: *Eiszeit* [*Glazial*]; French: *période glaciaire*; Italian: *periodo glaciale*): A glacial is delimited by two warm periods (interglacials). It may comprise several glaciations. A cold period delimited by two warm periods, during which no substantial ice buildup has taken place, is called a glacial as well. A glacial is defined in an area with a distinct lithostratigraphic situation.

The classical morphostratigraphic units (e.g. Hochterrasse) may also be conceived as supergroups, since they contain similar deposits of several glacials in some cases. However, classical morphostratigraphic units should only be used if a sediment body cannot be attributed to a particular advance.

Taking the last glacial as an example, Fig. 4 displays the classification scheme described above.

## 6.4 Miscellaneous

### *6.4.1 Interglacial and interstadial deposits*

In Switzerland interglacial and interstadial deposits, such as peat and overbank deposits, are relatively scarce and of limited extent. For mappable sediment bodies, the same guidelines as those for sediments deposited during cold periods apply. Temperate lake sediments frequently evolve from glaciolacustrine sediments without a distinct boundary. In such cases, criteria that refer to the lithological transition are to be specified in a type profile (e.g. "the lowermost peat layer in profile *x* represents the basis of the *y* Formation").

#### 6.4.2 Till cover

Many of the maps of the Geological Atlas of Switzerland 1:25,000 covering the Swiss Plateau display a more or less continuous till cover of the last glacial, marking at best only some moraines that denote retreat stadials. A plausible subdivision of the till cover, taking into account both deposits and landforms, would certainly be worthwhile. Such a classification is indeed feasible, as was demonstrated by Keller and Krayss (2005), Graf et al. (2006, 2012) and Jordan et al. (2011).

#### 6.4.3 Ice-marginal deposits

Ice-marginal deposits are commonly characterised by a pronounced lithological heterogeneity. In some instances, monolithological bodies within ice-marginal deposits are large enough to be considered mapping units of their own. In this case, all the ice-marginal deposits pertaining to a certain glacier advance should be classified as a formation, and the corresponding mappable subunits as members.

#### 6.4.4 Periglacial formations

In the area beyond glacial activity, various periglacial sediments are formed, such as loess, fluvial deposits and scree. In Switzerland only few loess occurrences are known; they usually represent a relatively large timespan but cannot be subdivided for more detailed mapping. In most cases, only a maximum age can be stated if the age of their substratum is known. Periglacial fluvial deposits also occur scarcely (e.g. Graf et al. 2006). Complexly bedded and, in some cases, thick scree sequences are nevertheless of some importance, since some of them consist of deposits (e.g. from solifluction, mass movements) of successive cold phases during which there was no stabilizing vegetation cover. In many cases, the scree sequences are affected by recent instabilities and should therefore not be treated as lithostratigraphic units (see Sect. 5.2). However, if scree and similar deposits are part of a stratified succession (e.g. covered mass waste deposits), they should be classified as lithostratigraphic units.

#### 6.4.5 Glacial overprint

In many instances, glacier advances lead to a specific overprint of pre-existing rocks (glacial tectonics, glacial abrasion). Glacial tectonics may form rock bodies large enough to be mappable. However, these should not be classified as lithostratigraphic units but instead be understood as characteristics of a (bounding) discontinuity.

#### 6.4.6 Pedogenesis

The upper boundaries of sedimentary bodies, represented by today's surface of the earth, were formed at a specific moment in time and may therefore differ in age; this is reflected in various degrees of pedogenetic overprint. The characteristics of a weathering horizon (pedogenesis: soil type and thickness) can be taken into account for the definition of lithostratigraphic units.

## 7 Mapping of Quaternary units

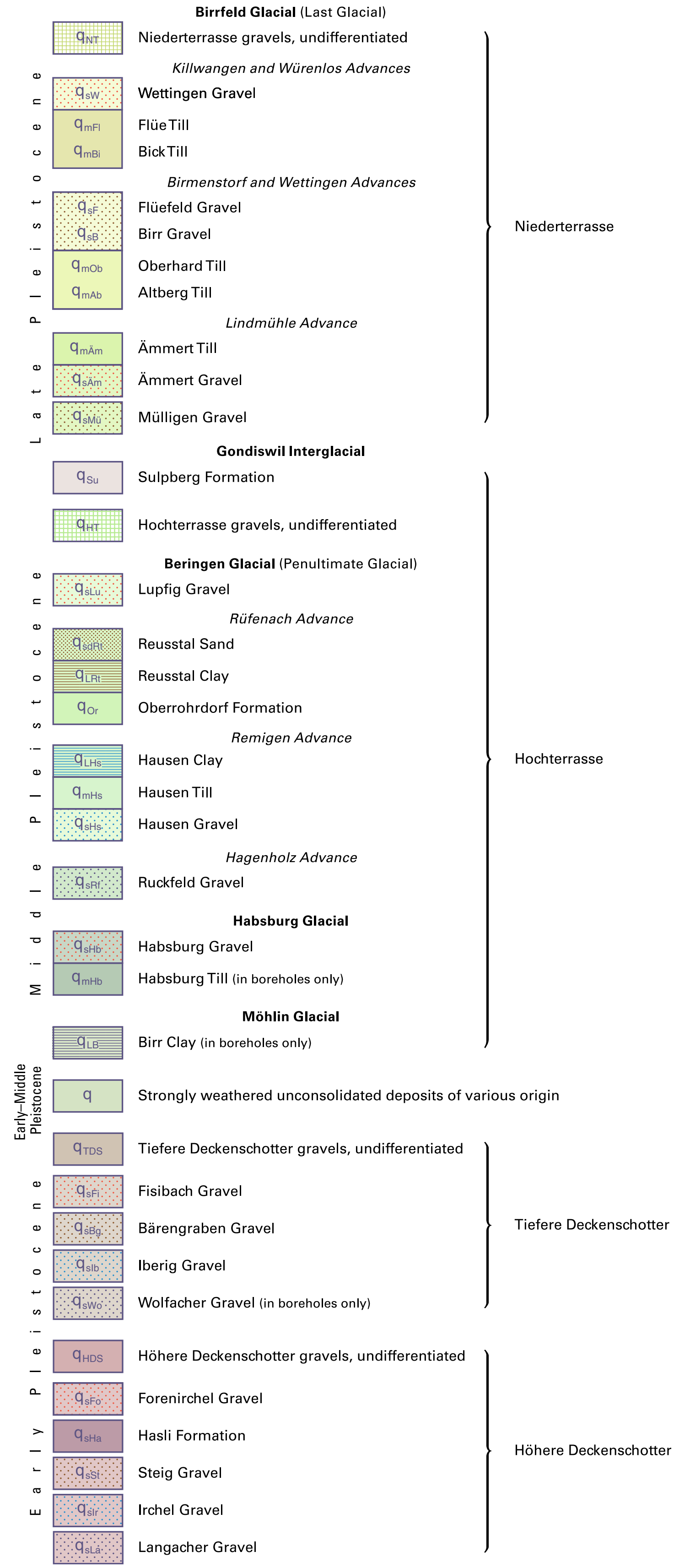
The depiction of all hierarchical levels of Quaternary units solely in a map image, in such a way that their geographic and stratigraphic context (and thus chronological order) can be fully understood, is hindered by the geometrical complexity of Quaternary deposits. Only the combination of map image, legend structure and a system of index codes (abbreviations) permits a comprehensive representation of the geographic and stratigraphic situation.

Following the general principle of geological mapping, only formations, i.e. observable rock units, are depicted on a geological map. The interpreted, genetic units (advances, glaciations, glacials) are described by means of a suitable legend structure with relevant headings (Fig. 5). The time period during which a rock unit was formed is depicted by a specific base color. Accordingly, all units pertaining to a certain glacial are represented by a common base color. The chronostratigraphic attribution of the rock units is indicated in a separate column, and their morphostratigraphic classification can be shown similarly (Fig. 5).

The index codes used on geological maps serve the purpose of an unambiguous identification of the mapped units. In the Geological Atlas of Switzerland 1:25,000 the Quaternary units are marked by the letter "q", followed by abbreviations for dominant lithology and unit name. The lithology is indicated in subscript lower case (see below) and the unit name in subscript upper case (e.g. Wettingen Gravels = $q_{sW}$). The abbreviations for lithology are the following: s = gravel (in German legends), g = gravel (in French legends), sd = sand, si = silt, m = till, r = ice-marginal sediments, L, SL = (glacio)lacustrine sediments, e = fossil scree.

Index codes of sediment units that cannot be named after a type locality, but that can be attributed to a hierarchically higher ranking genetic unit, are abbreviated as above but in subscript upper case to denote the genetic unit (e.g. glacigenic deposits of the Beringen Glacial = $q_{mB}$). For sediment units that can only be attributed to a morphostratigraphic unit, the abbreviation of this unit is used (e.g. Hochterrasse Gravels = $q_{HT}$). Index codes of units for

**Fig. 5** Proposal for a legend structure for Quaternary units; Geological Atlas of Switzerland 1:25,000 (see also Graf et al. 2006)



which no attribution is possible only show the abbreviation of the lithology (e.g. $q_m$).

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