Int J Earth Sci (Geol Rundsch) (2015) 104:123–145
DOI 10.1007/s00531-014-1055-0

ORIGINAL PAPER

The volcano-sedimentary evolution of a post-Variscan intramontane basin in the Swiss Alps (Glarus Verrucano) as revealed by zircon U–Pb age dating and Hf isotope geochemistry

Dominik Letsch · Wilfried Winkler · Albrecht von Quadt · Daniela Gallhofer

Received: 26 March 2014 / Accepted: 28 June 2014 / Published online: 6 July 2014

Abstract The Late Palaeozoic Glarus Verrucano basin (GVB, Glarus Alps, eastern Switzerland) formed as an intramontane graben in the aftermath of the Variscan orogeny. Its fill, the Glarus Verrucano, consists of immature alluvial fan and playa lake deposits with intercalated bimodal volcanics (basalts and rhyolites). Despite its importance for local and regional geology, no modern sedimentologic or stratigraphic studies on the GVB exist. By means of sedimentologic and geochronologic studies, we reconstruct the volcano-sedimentary evolution of the GVB: it developed at the Carboniferous/Permian boundary and experienced a first (bimodal) volcanic phase around 285 Ma. For the same time, indications for temporarily humid climate in the otherwise rather arid Early Permian are demonstrated (e.g. pyrite-bearing sandstones). During the Middle and Early Late Permian, increasing aridity is indicated by playa deposits, fanglomerates and subaerial ignimbrites, which mark a second (silicic) volcanic phase at 268 Ma. The detrital zircon age spectra are dominated by Late Variscan ages and thus demonstrate that older sedimentary and metamorphic rocks once forming the Variscan nappe edifice were already mostly eroded at that time. Finally, some larger-scale speculations are given which could indicate a causal connection between the widespread tectono-magmatic Mid-Permian Episode and the local development of the Glarus Verrucano basin.

Keywords Lower Permian · Swiss Alps · Detrital zircon ages · Variscan orogeny · Bimodal volcanism · Verrucano · Red beds · Basin analysis

Electronic supplementary material The online version of this article (doi:10.1007/s00531-014-1055-0) contains supplementary material, which is available to authorized users.

D. Letsch (✉) · W. Winkler · A. von Quadt
Department of Earth Sciences, Geological Institute, ETH Zentrum, Sonneggstrasse 5, 8092 Zurich, Switzerland
e-mail: dletsch@ethz.ch; dletsch@erdw.ethz.ch

D. Gallhofer
Department of Earth Sciences, Institute of Geochemistry and Petrology, ETH Zentrum, Clausiusstrasse 25, 8092 Zurich, Switzerland

Introduction

In the aftermath of crustal shortening and thickening due to multiple collisions between Gondwana-derived continental fragments and Laurussia during Middle to Late Palaeozoic times (culminating in the Variscan orogeny in the Mid-Carboniferous, e.g. von Raumer et al. 2013), numerous small intracontinental basins opened all over Europe (McCann et al. 2006). They developed due to crustal re-equilibration processes and/or post-collisional strike-slip movements, which resulted in a Basin-and-Range topography (Lorenz and Nicholls 1976). During the last five decades, age and geologic development of many of these basins was worked out in detail (e.g. Roscher and Schneider 2006; McCann et al. 2006; Pochat and van den Driessche 2011), and this work provides information on, e.g. late to post-orogenic volcanism, basin evolution, or regional climate development at the turn from the Carboniferous to the Permian. Several such basins do occur in the Western and Central Alps and their forelands (Fig. 1), and much sedimentologic and geochronological work has been done in some of them during the last three decades (e.g. Matter 1987, Schaltegger and Corfu 1995, Schaltegger 1997, Capuzzo and Bussy 2000, and Capuzzo and Wetzel 2004).

One of the most extensive Swiss examples of such a basin, the Glarus Verrucano Basin (GVB, Figs. 2, 3), played

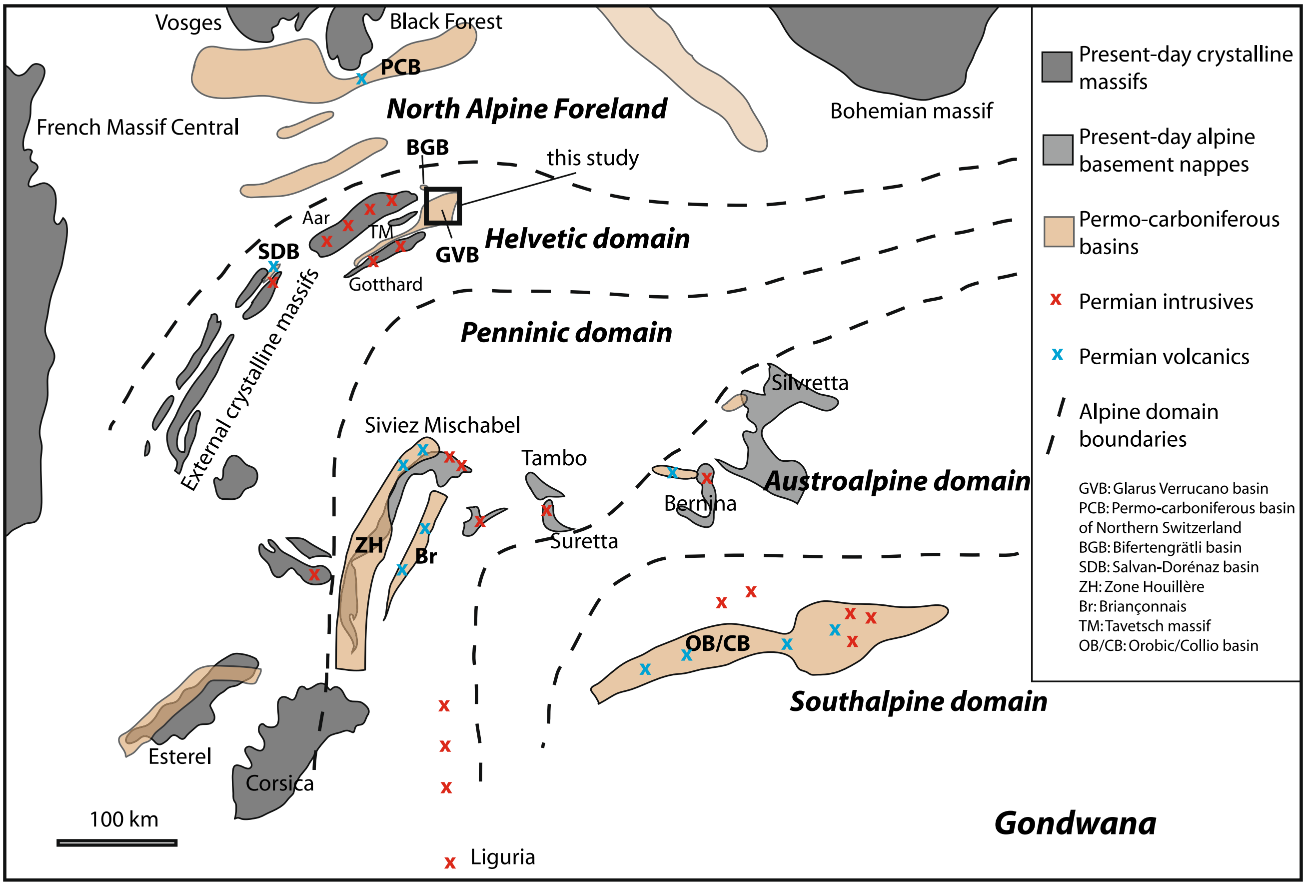

Fig. 1 Palaeogeographic sketch map of the area of the future central and western Alps at the end of the Palaeozoic. Redrawn and modified from Pfiffner (2009). The outlines of certain present-day massifs and nappes are drawn for the purpose of orientation

a paramount role in the historic development of tectonic research in the Swiss Alps during the nineteenth century (e.g. Letsch 2014). The fill of this basin, the so-called Glarus Verrucano, forms the hanging wall of the famous Glarus overthrust (Fig. 4). Even though it can neither be compared to the classic Verrucano of Tuscany (Monte Pisano) nor to the South Alpine Verrucano Lomabardo, this study follows Trümpy's (1966) suggestion and uses *Glarus Verrucano* as a general term encompassing all presumably Upper Palaeozoic detrital and volcanic rocks of the Glarus Alps, which occur above the crystalline basement but below the transgression of the Triassic (Ladinian) Mels Formation (Gisler et al. 2007). The once very common term *Sernifite* is retained in the present study to denominate the typical coarse fanglomeratic facies of the Glarus Verrucano.

The GVB is a palaeogeographic link between the Permo-Carboniferous basins of Germany/northern Switzerland and the southern Alpine Permo-Triassic basins of northern Italy (Cassinis et al. 2012). Furthermore, the GVB is an excellent area to study Permian bimodal volcanism (rhyolithic and basaltic). Despite these peculiarities, no modern stratigraphic, sedimentologic, petrologic, or geochronological studies exist. The lithostratigraphy and tectonics had been worked out by several unpublished PhD theses some decades ago (Wyssling 1950; Fisch 1961; Huber 1964; Ryf 1965; Markus 1967; Richter 1968; Nio 1972; see Trümpy and Dössegger 1972 for a summary). The volcanic rocks had been investigated by Beder (1909), Amstutz (1954), and Amstutz and Patwardhan (1974). Regional tectonic studies have touched on the Glarus Verrucano (e.g. Siddans 1979; Pfiffner et al. 2010; Pfiffner 2011), and Hirt et al. (1986) carried out a palaeomagnetic survey.

This paper is intended to summarize the existing data, to present new sedimentologic, stratigraphic, and volcanic and detrital zircon U–Pb and Hf isotope data which help to constrain the tectono-sedimentary and volcanic development of the GVB.

Tectonic setting and palaeotectonic position

The Glarus Verrucano forms the backbone of the Helvetic nappes of eastern Switzerland between the Rivers Linth and Rhine (Figs. 2, 3, 4). It has been sheared off together

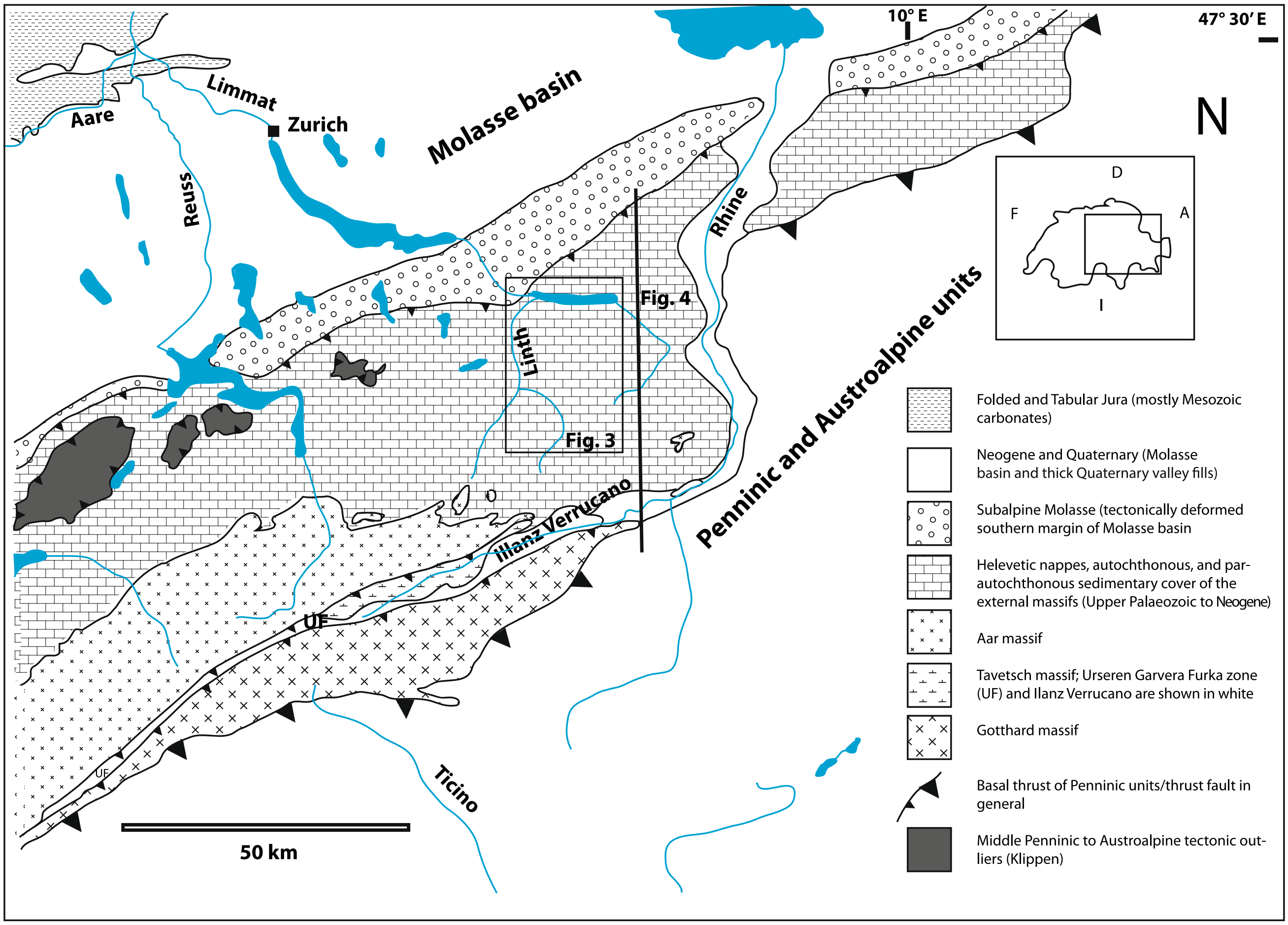

Fig. 2 Tectonic overview map (redrawn and simplified after "Tektonische Karte der Schweiz" 1980). The study area is outlined by a *rectangle,* and the trace of the cross section (Fig. 4) is also shown

with its Mesozoic and Paleogene cover from its crystalline substratum during the late stages of Alpine orogeny in the Miocene (Trümpy 1969, Pfiffner 2009). With the exception of a tiny crystalline slice at the base on the western side of the Linth valley (Trümpy 1947), the Glarus Verrucano rests with a pronounced tectonic contact (the Glarus Thrust) on parautochthonous and tectonically displaced South- to Ultrahelvetic tectonic units of mostly Palaeogene age. With respect to the Mesozoic strata, several different Helvetic nappes can be distinguished (Figs. 3, 4). However, the boundaries between them get diffuse and eventually disappear when the thrust planes continue into the Verrucano. Thus, e.g. the Mürtschen thrust is mappable in the Murgtal and Gufelstock area where Verrucano of the Mürtschen nappe is juxtaposed onto Triassic rocks of the underlying Glarus nappe (Fig. 3). However, further towards the SE, this thrust plane pinches out and can no longer be mapped in the Fuggstock area (Fisch 1961). The displacement along it must have been compensated by internal movements in the Verrucano mass (Trümpy 1969). Attempts to distinguish individual nappes inside the Verrucano (Oberholzer 1933a, b; Trümpy in Brückner et al. 1957; Schielly 1964) have only been partially successful; in most areas, the Verrucano seems to represent one continuous stratigraphic column (Nio 1972), whereas to the west of the Sernf river, the Verrucano mass is increasingly cut into individual thrust masses (Schielly 1964; Trümpy and Dössegger 1972, Fig. 3).

Little direct evidence is available of the original palaeotectonic setting of the Glarus Verrucano. Its pronounced geographic restriction, the pronounced increase in thickness from 0 to some 1,600 m, and the knowledge about analogous deposits in Extra-Alpine Europe, make it plausible to assume that it had been deposited in a NNE–SSW- to NE–SW-oriented graben structure (Fisch and Ryf 1966). Pfiffner (2011) suggests that the GVB was a more or less N–S trending symmetric graben structure whose bounding faults have been reactivated during Alpine orogeny and led to the development of N–S trending, flat-lying folds. One of these folds can be mapped in the western Freiberg area

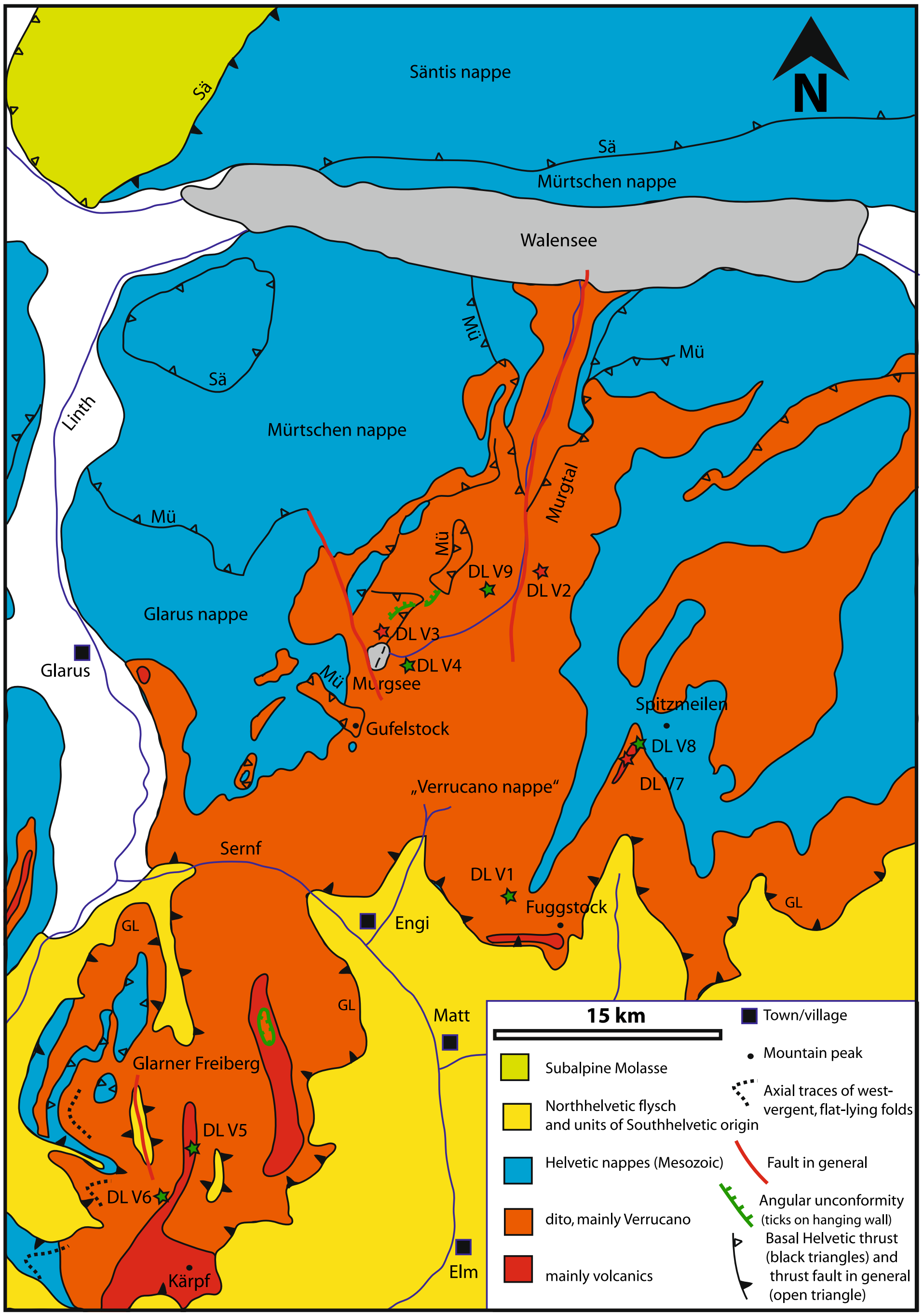

Fig. 3 Tectonic map of the study area (redrawn and modified from Pfiffner et al. 2010). Sample localities for U–Pb zircon dating are indicated with asterisks (*green*/*red* samples yielding enough/not enough zircons for analysis). The distribution of volcanic rocks is drawn after Beder (1909), Oberholzer (1933a, b), Schindler (1959), Huber (1964), and Ryf (1965)

(Fig. 3). The original substratum of the Verrucano is the palaeogeographic realm of the Helvetic nappes and was most prNorth and the Gotthard massif to the South (obably situated between the southern flank of the Aar massif to the Figs. 1, 2, see also Trümpy 1999, Pfiffner et al. 2010; Pfiffner 2011).

Facies of the Verrucano sediments

Despite the remarkable variability of the Verrucano sediments, two characteristic lithofacies types can be distinguished of which the major part of the Glarus Verrucano is composed (Trümpy and Dössegger 1972).

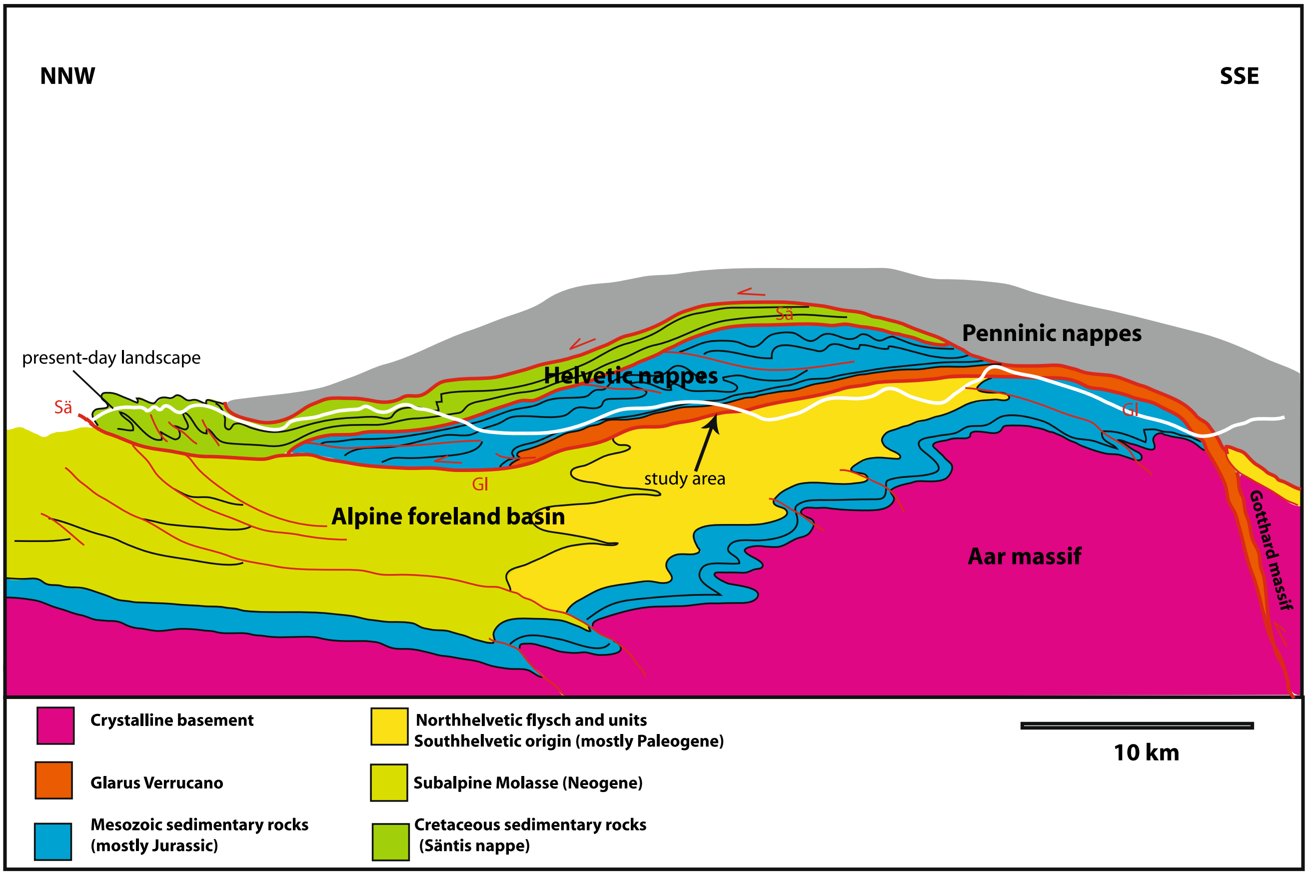

Fig. 4 Tectonic cross section through the Glarus nappe system (redrawn after Pfiffner et al. 2010). The trace of this section is shown in Fig. 2

The *Sernifite facies* (or *psephitic marginal facies* of Trümpy and Dössegger 1972) encompasses fine- to coarse-grained, texturally and petrographically immature, purple to reddish-brown (more rarely pale grey to greenish) breccias, which may alternate with silty and sandy shales of an often intense red colour. The largest components of the breccias are blocks of volcanic rock (spilite, see below), which can reach volumes of several m^3 (Huber 1964). The breccias occur in massive, often matrix-supported, chaotically structured, or sometimes faintly layered units (Fig. 5) ranging in thickness from some 10 cm to the order of several m. Sedimentary structures are relatively rare; normal and inverse grading (Fig. 5), local cross-bedding, and very rare imbrication of cobbles and blocks can be observed (Ryf 1965). The bases of the breccia units are sharp and only rarely exhibit scours and small channels (Fig. 5a). If the underlying unit is composed of sandy shale, load casts can frequently be observed. Remarkable is the common occurrence of rather thin breccia layers which lack almost any fine material (Ryf 1965) and which often exhibit a less intense red colour (Huber 1964). In rare occasions, a thin-bedded (some 0.1 m) alternation of matrix-rich and matrix-poor breccia layers can be observed (Schielly 1964).

Clasts are mainly composed of crystalline rocks, while sedimentary clasts are rare and metamorphic ones almost absent (with the exception of some greenschist and amphibolite pebbles from the uppermost Sernifite which crops out only towards the east of the present study area, cf. Richter 1968). The crystalline rocks are dominated by reddish rhyolites and granites, dark purple or green metabasalts (identical to the volcanic intercalations in the Verrucano), quartzites, and single quartz pebbles. The rare sedimentary clasts are reworked intrabasinal mud chips, Sernifites, sandstones, or red and dark grey cherts (Fisch 1961; Ryf 1965) which contain questionable microfossils (Ryf 1965). In thin sections (Fig. 5d), the Sernifites are dominated by angular and broken, sometimes polycrystalline quartz grains which often exhibit corroded margins (volcanic resorption features). Feldspar is also very abundant with the majority being plagioclase (albite and oligoclase) with polysynthetic twinning. K-feldspar is rare and occurs mostly as microcline or as grains with perthitic exsolution patterns. Rock fragments can be observed as well (mostly metabasalts and quartzites). Mica and sericite are common and occur either in individual bands or constitute the majority of the matrix (together with quartz and chlorite). Calcite does mainly

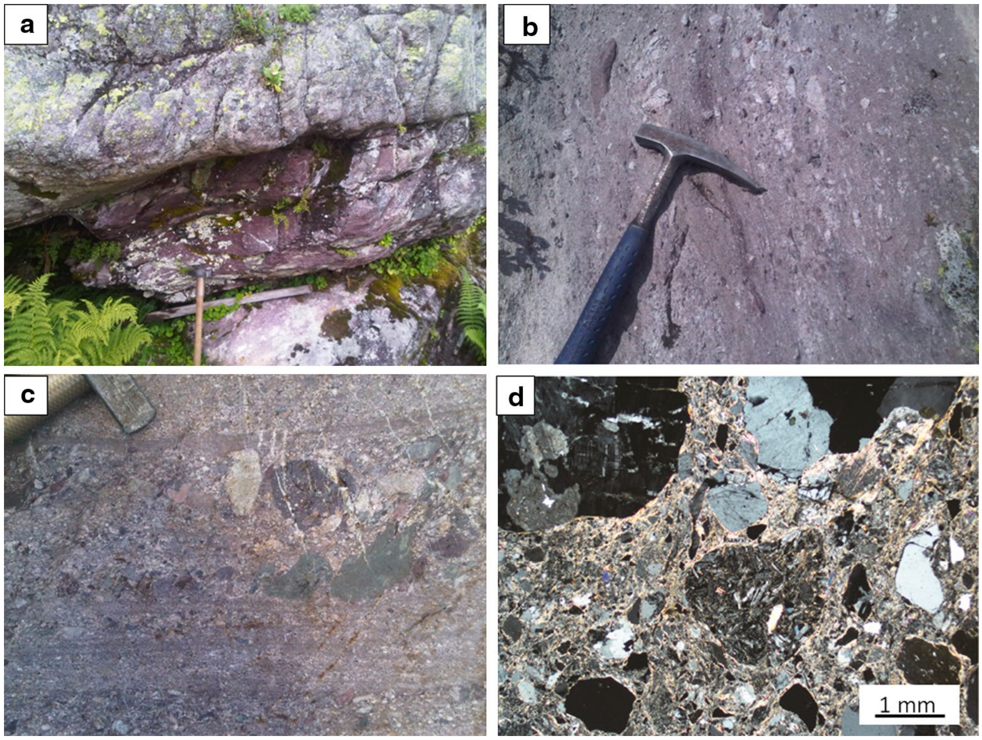

Fig. 5 Sernifite facies. **a** Sharp base of a breccia unit above red silty shales (Fuggstock Formation, upper Murgtal); **b** matrix-supported medium-grained Sernifite (bedding is vertical, Fuggstock Formation, near Fuggstock); **c** a single debris flow depositional unit with a winnowed lag layer surface at its top with volcanic clasts projecting upward into fine sandstone which later draped the winnowed surface (Üblital Formation, Üblital area NW of Gulderstock); **d** thin section (crossed nicols) of Sernifite from the Üblital Formation (middle Murgtal; DL V2): angular quartz and feldspar grains, spilite clast in the centre, sericite–mica–quartz matrix

occur as secondary crystallizations filling pore spaces and tectonic veins. The pigment giving rise to the peculiar red colour of the Sernifite occurs either as single haematite grains or as thin grain coatings which in turn may be overgrown by secondary quartz (Nio 1972).

The *silty and sandy shale and slate facies* (or *pelitic basin facies* of Trümpy and Dössegger 1972) consists of variably coloured pelites with substantial amounts of coarser-grained detritus. The colours range from silky shining purple, pale greenish, or reddish to intense red (Fig. 6). Specifically the finer-grained, silty parts of this facies exhibit intensive cleavage which totally obliterates the original bedding. The latter can then only be deduced from former sandy layers (now occurring as quartzite layers or lenses, so called "quartz knauers"), intercalations of volcanic tuffs, or horizons which are rich in calcite. The latter seem to be of a pedogenic (caliche) or shallow aquatic origin. The same explanations also apply to the abundant spherical carbonate nodules of millimetre to centimetre size (Fig. 6a) which are arbitrarily dispersed in the red pelites. Specifically in the finer-grained and more reddish shales and slates, pale green reduction spots can often be observed, which were later tectonically deformed to ellipsoids recording the local strain (Huber 1964; Siddans 1979; Hirt et al. 1986).

The subordinate occurrence of sediments, lacking the typical red colour and the poor sorting of the two main Verrucano facies, deserves attention. They occur either as lense-shaped or laterally continuous thin packages of some 10 m thickness (so-called *Sonnenberg horizons*, Nio 1972). Even though they do not all belong to one and the same stratigraphic horizon, they only occur in a certain stratigraphic interval. They are composed of dark grey, pyrite- and mica-bearing arcosic sandstones (Fig. 7c), dark freshwater limestones with questionable fossils (probably gastropods, Schielly 1964), dark pelites (Fig. 7d), and distinctive conglomerate layers (Trümpy in Brückner et al. 1957). The latter may exhibit planar cross-bedding (Amstutz 1957) and are composed of remarkably well-rounded crystalline pebbles. One of these conglomerate layers (the *Chammseeli conglomerate*) has been sampled for detrital zircons in the present study.

Volcanic rocks

Volcanic intercalations (Fig. 8) occur throughout the whole section of the Glarus Verrucano; however, they are most common and volumetrically most important in its

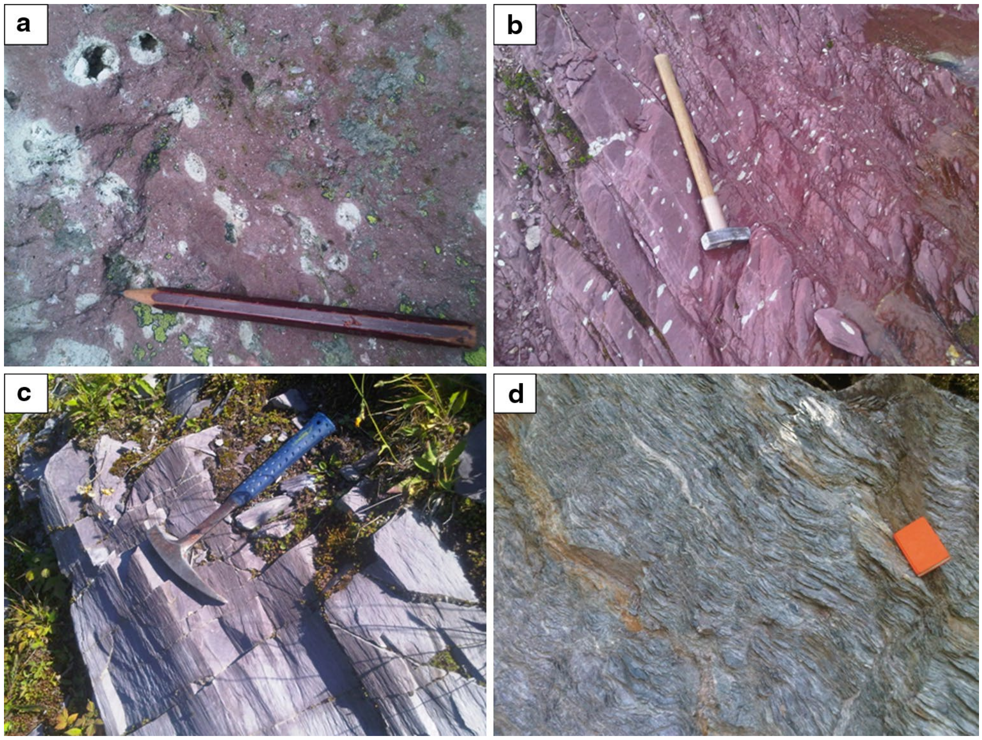

Fig. 6 Sandy/silty shale (playa) facies. **a** Nodular carbonate concretions in sandy shale (Mären Formation, Alp Bütz, middle Murgtal); **b** typical red shales/slates of the Schönbüel Formation with deformed green reduction spots (view onto cleavage plain; Schönbüel area in the upper Chrauchtal); **c** "silky" shining slate with intense cleavage (Foostock layers, Fuggstock area); **d** so-called Plagioklasgneiss (see text, upper Chrauchtal)

middle part (Fig. 9). Two suites of rocks can be distinguished: a mafic and a silicic to intermediate one (Fig. 8). The latter is composed of greenish-white, grey, and sometimes slightly pink rhyolites and rhyodacites which occur most often as ignimbrites (with broken quartz grains and recrystallized glass shards) and reworked tuffs and tuffitic shales and sandstones. The mafic suite is composed of either dark pink or green, Na-rich metabasalts (spilites). The two characteristic colours derive either from haematite or chlorite, respectively. The feldspar they contain is exclusively albite and oligoclase (Amstutz 1954). Olivine and augite pseudomorphs can frequently be observed in thin sections (Beder 1909; Amstutz 1954; Bächtiger 1960). The spilites show characteristic vesicles and amygdules i.e. subspherical cavities, which are either open or filled with calcite, chlorite, epidote, and several Cu-bearing ore minerals (Amstutz 1954; Bächtiger 1960). Both types of metabasalt occur either as lava flows, which sometimes show brecciation in their top parts, or as more or less unstructured tuff masses. For detailed petrographic descriptions see Beder (1909), Amstutz (1954), Bächtiger (1958, 1960), and Amstutz and Patwardhan (1974). Field evidence suggests that the basaltic lava flows developed subaerially without the contribution of any substantial amount of water (e.g. no pillow structures, Fisch 1961). Amstutz (1954), and Amstutz and Patwardhan (1974) still maintained the hypothesis that the spilites are primary magmatic products. However, the assumption of a primary spilitic "hydromagma" is not in accordance with modern petrologic models, and spilites are generally considered as basalts which later experienced ocean–floor metamorphism and metasomatism. Thus, it remains somewhat enigmatic, when and how the Glarus basalts changed their mineralogy since they extruded in a dry continental setting. As also the basaltic clasts in the Sernifites are spilitic (Fig. 5c, d), the spilitization must have occurred rather shortly after the emplacement of the basaltic flows and clearly before their reworking into the Sernifites. Similarly altered intracontinetal basalts do occur in other Late Variscan basins as well, as e.g. the German Saar-Nahe basin (von Seckendorff et al. 2004). For these latter occurrences, Lorenz and Nicholls (1976) proposed slight synsedimentary thermal metamorphism and metasomatism due to the generally increased geothermal gradient in western Europe during the Late Carboniferous and Early Permian (e.g. Burg et al. 1994). The local occurrence of Cu- and U-bearing ore deposits both in Sernifites (Bächtiger 1958) and metabasalts (Bächtiger 1960) of the GVB

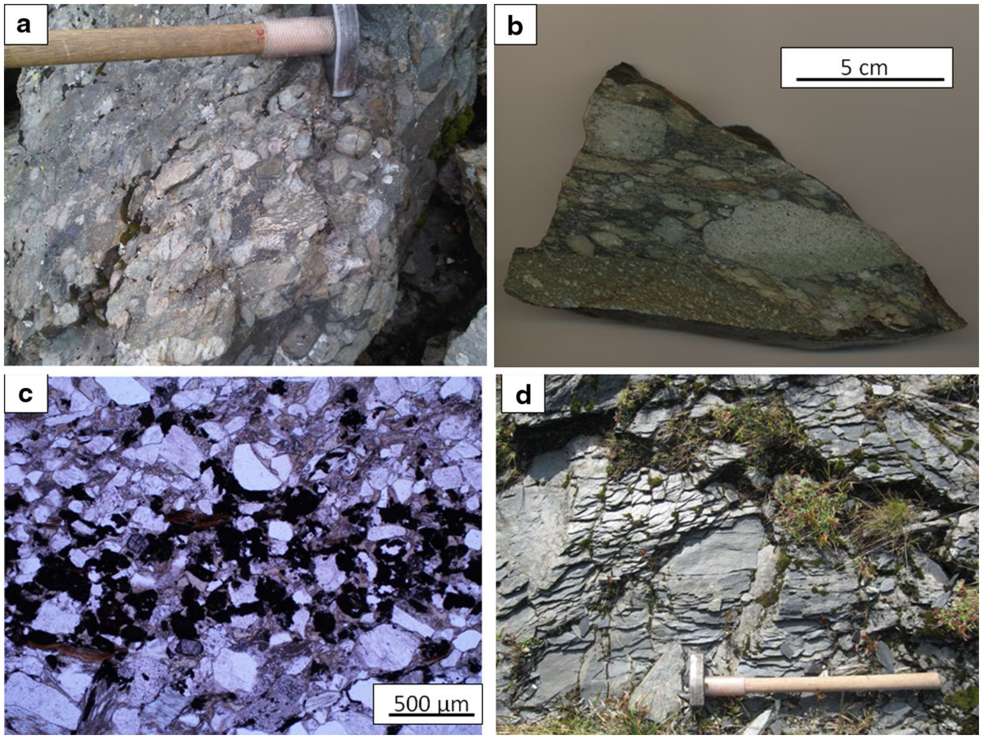

Fig. 7 Sonnenberg horizons: **a** block of Chammseeli conglomerate (from its type locality where also sample DL V6 was taken); **b** cut and polished slab of the block shown in **a**; **c** thin section (plane light) from arkosic sandstone from the Chammseeli locality; note the pyrite-rich layer; **d** dark and C_{org}-rich shale (locality see Fig. 11)

might also be attributed to synsedimentary geothermal activity.

Interpretation of the Verrucano sediments

The Sernifite facies lacks almost totally sedimentary structures which are typical for the fluvial environment. The chaotic structure, and the textural and petrographic immaturity suggest a very dynamic depositional environment. The poor rounding of the clasts, the high amount of matrix, the occasionally inversely graded breccia beds, and the palaetectonic boundary conditions suggest deposition in an alluvial fan environment under rather arid climatic conditions (Blair and McPherson 1994). The characteristic thick breccia beds are interpreted as deposits of high-density sediment gravity flows (debris flows, Blair and McPherson 1994), which developed due to precipitation-induced destabilization of loose colluvium on steep mountain slopes. Matrix-free layers are also diagnostic for such deposits. They form during the time between two debris flow events on the fan surface. Wind, non-catastrophic runoff, and groundwater flows slightly erode and winnow the fan surface and thus produce these characteristic lag deposits (Blair and McPherson 1994, see our Fig. 5c) together with the local deposition of cross-bedded sandy and silty material by minor rivulets. The rare occurrence of thin-bedded matrix-poor/matrix-rich breccia couplets can readily be interpreted as deposits stemming from repeated sheetfloods, i.e. catastrophic and unconfined water flows that expand on the fan surface and thereby lose their transporting capacity and hence deposit their sedimentary load as coarse/fine couplets (Blair and McPherson 1994).

The pelitic basin facies does also fit into an arid to semi-arid alluvial fan environment. It may have been laid down as basin-floor deposit in a playa-like environment. The wide aerial and quite uniform distribution of (partly reworked) tuff layers (Richter 1968), fine-grained and laminated layers exhibiting slump structures (Ryf 1965), carbonate nodules, and the very rare (probably because of tectonic obliteration) occurrence of desiccation cracks (Huber 1964) suggest a flat and temporarily aquatic depositional environment in the central parts of the GVB. Marginally, these playa deposits interfinger with the coarser Sernifite facies (Fig. 5a). Coarser-grained parts of the pelitic basin facies may represent distal equivalents of mass flow deposits. The total lack of any halite or gypsum is remarkable as one would expect them in a playa environment, and as anhydrite nodules have been found in analogous deposits (Matter 1987)

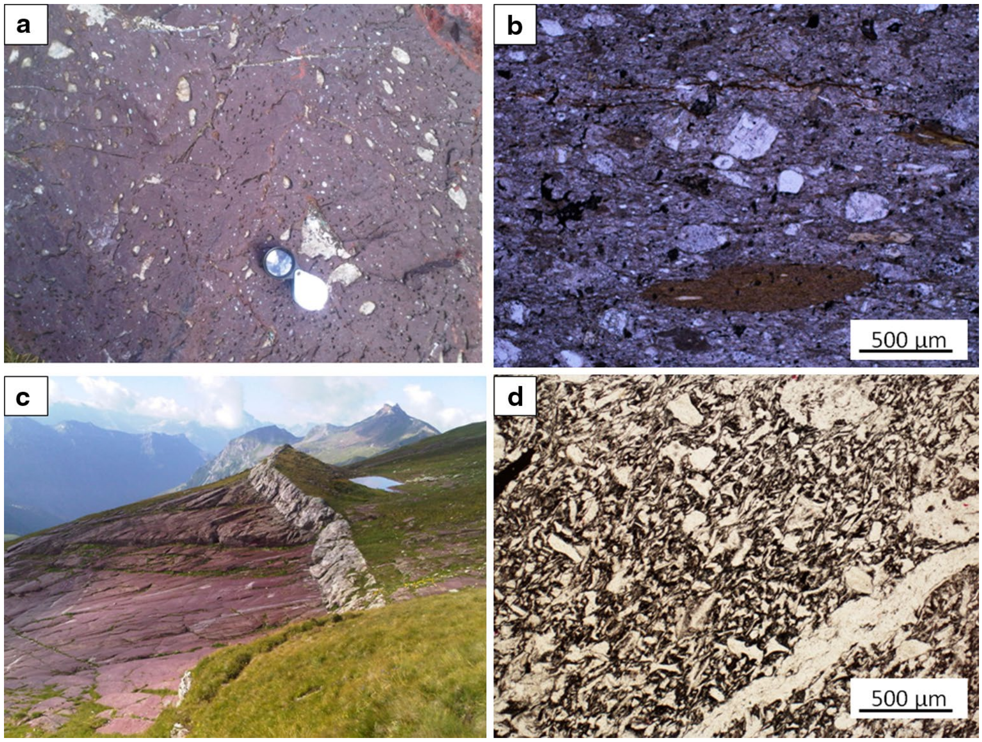

Fig. 8 Volcanics: **a** vesicle-rich spilite with most of the vesicles filled with mainly calcite (Auerental, western Freiberg); **b** thin section (plane light) of sample DL V5 (see Fig. 11): possibly reworked, rhyolitic tuff with lense-shaped cryptocrystalline and flattened pyroclasts and angular quartz and feldspar fragments; **c** rhyolitic ignimbrite layer (Schönbüel area, uppermost Chrauchtal) in red shales/slates (Schönbüel Formation); the latter exhibit a pronounced cleavage which intersects the original bedding (indicated by the ignimbrite) at a high angle of some 60°; **d** thin section (plane light) from the ignimbrite layer shown in e (taken from sample locality DL V7): note the recrystallized glass shards and the abundant dark phases (haematite)

in the Permo-Carboniferous basin of northern Switzerland (Fig. 1). The abundant carbonate nodules are presumably of pedogenic or early diagenetic origin. Groundwater motion beneath playas in the central parts of intramontane basins under dry climatic conditions is often upwards (Walker 1976). This can promote the widespread precipitation of calcite either at the groundwater table, in the soil as caliche, or in spring-fed ponds due to CO_2 degassing.

Compared to the previously described two facies, the Sonnenberg horizons are of a distinct character. The abundance of pyrite, C_{org}-rich shales and sandstones, well-bedded conglomerates with large-scale cross-bedding, and the rare occurrence of freshwater limestone (Trümpy in Brückner et al. 1957; Schielly 1964; Nio 1972) implies—at least temporarily—rather wet conditions. The observed deposits were most probably laid down in a fluvial and lacustrine environment. Clear evidence for any marine influence (as originally speculated by Trümpy in Brückner et al. 1957) is lacking (Schielly 1964; Nio 1972). Due to the rather poor outcrop conditions, it is difficult to evaluate the character of these rivers (e.g. braided versus meandering). The significance of the Sonnenberg horizons will be discussed below.

Stratigraphy

Lithostratigraphy

With the exception of Schielly (1964), all authors arrived at more or less coherent stratigraphic schemes, even though the exact correlations between different subareas are somewhat ambiguous, if one recalls the lack of good marker horizons and the rapid vertical and horizontal facies changes. The Glarus Verrucano can be divided into several informal units (Fig. 9). The boundaries between them are often gradational and difficult to define in the field. Due to this, the fast facies changes, and the often only poorly known local tectonics (local thrusts, folds, and deformation due to simple and pure shear), the thicknesses indicated on Fig. 9 have to be taken with considerable care.

The Glarus Verrucano starts in all studied sections with Sernifite, the *Üblital Formation* (Fisch 1961). The base is tectonic (except for the tiny crystalline slice described by Trümpy 1947) and defined by the Glarus thrust, the base of the Helvetic nappes. Due to Alpine tectonic deformation, the basal parts of this Formation can acquire an intensely green, foliated, and gneiss-like appearance (Fig. 6d) which

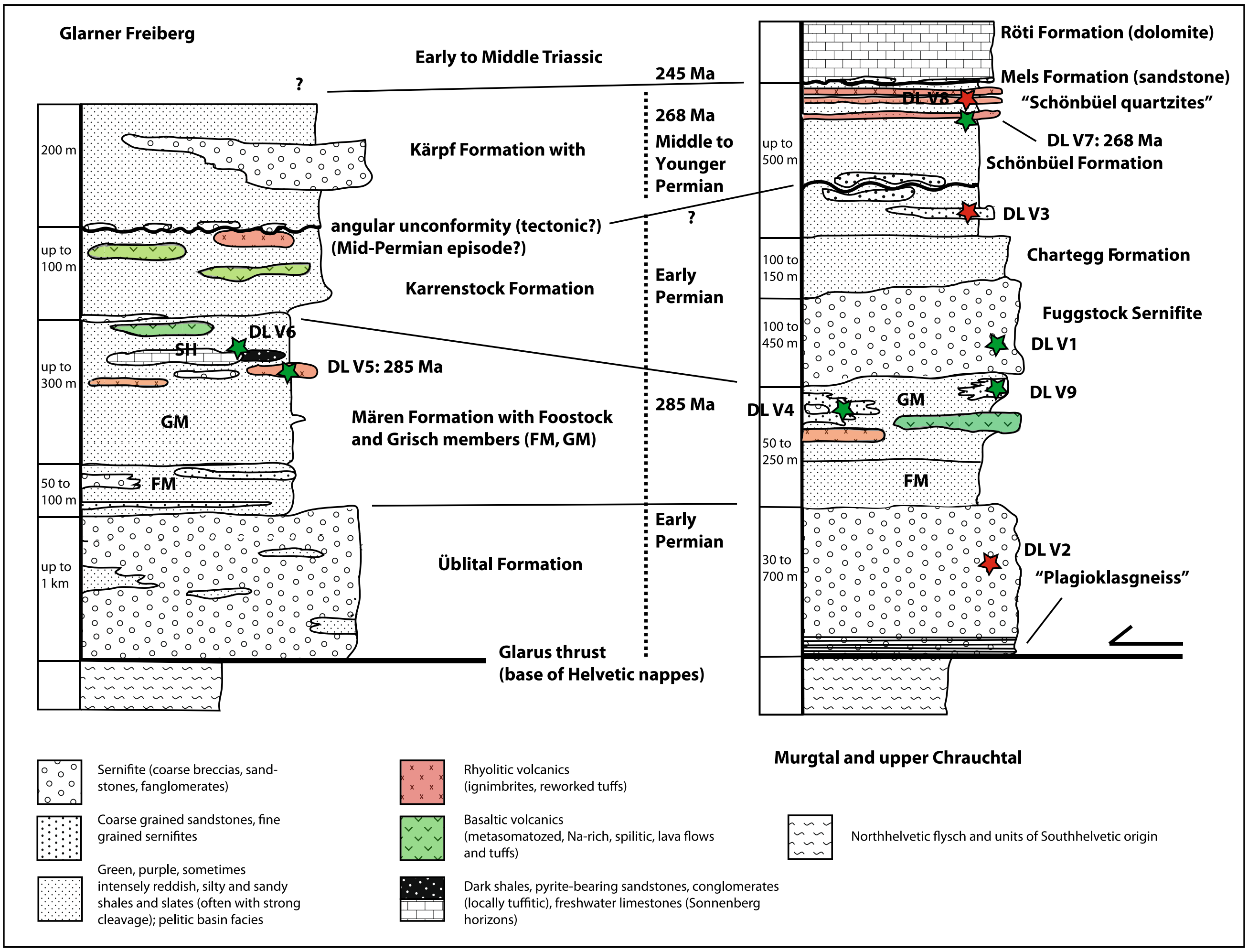

Fig. 9 Composite stratigraphic sections through the Verrucano in the Freiberg (*left*) and Murgtal/upper Chrauchtal area (*right*). Summarized from Fisch (1961), Ryf (1965), and Nio (1972). Sampling sites for U–Pb zircon dating are indicated with asterisks (red/green: samples yielding not enough/enough zircons for analysis. Absolute ages are from the present study

has led Blumenthal (1911) to introduce the petrologically misleading term *"Plagioklasgneiss"*. The Üblital Formation is mainly built by a coarse- to fine-grained, purple-brown to green Sernifite with some shaly intercalations. The thickness decreases towards the SE, and the mean particle sizes decrease upwards and towards the SE. From these observations and from rare imbrications, a transport direction towards the SSE can be deduced (Ryf 1965). In the NW part of the study area—around the Gufelstock and the upper parts of the Murgtal—the Üblital Sernifite merges with higher Sernifite bodies to one continuous sernifite mass (Ryf's Murgtal Sernifite). In the same area, Huber (1964) described a single occurrence of a metabasaltic lava flow with volcanic breccias in the basal part of the Üblital Formation. Metabasaltic components are the quantitatively most important constituent of the Sernifite (up to 40 % of all clasts, Ryf 1965, cf. Fig. 5c), followed by red rhyolites, granites, and quartz pebbles.

The Üblital Formation grades upward into the *Mären Formation* (Fisch 1961) which is dominated by fine grain sizes and the abundant occurrence of volcanic rocks and the peculiar *Sonnenberg horizons*. This Formation can be divided into a lower part without any volcanics (the *Foostock Member*, Fisch 1961) and an upper part with abundant volcanics (the *Grisch Member*, Wyssling 1950). The Mären Formation is characterized by sandy and silty pelitic rocks of reddish, purple, or green colour. Intense red colours as in the Schönbüel Formation (see below) lack. In the Grisch member, volcanic rocks and darker sediments of the Sonnenberg type may dominate the section, especially in the Freiberg area (Amstutz 1954). In the Murgtal area, the Mären Formation passes laterally into a sandy marginal facies dominated by sandstones and fine-grained breccias (Ryf 1965).

The Mären Formation develops upwards into coarser-grained deposits which, however, differ in the Freiberg area and in the area NE of the Sernftal. In the former place, they are overlain by the *Karrenstock Formation* (Nio 1972) which is composed of sandy and silty shales with some volcanic (mainly metabasaltic) intercalations and Sernifite bodies at the base. In the latter area, the Mären Formation passes gradually into a finer-grained, brownish-red or locally purple Sernifite, the *Fuggstock Sernifite*. Contrary to the Üblital Formation, this Sernifite body thins towards the NE and was thus most probably shed from the SW, i.e. the area of the present-day Freiberg (Fisch 1961; Ryf 1965). It contains only little spilitic detritus (Ryf 1965) but very much, often well-rounded, quartz grains (up to 50 % of all components). The rest is composed of feldspar and mica with the former often exhibiting in thin sections irregular patches and spots where the feldspar has been replaced by calcite and sericite. This is reminiscent of partly weathered feldspar grains described from Neogene fanglomerates of the SW USA (Walker 1976) and weathered granite boulders from the Salvan-Dorénaz basin (Capuzzo et al. 2003) where the silicate became partly displaced by calcite and clay minerals. The Fuggstock Sernifite is very rich in heavy minerals, particularly zircon, especially in comparison with the zircon-poor Üblital Formation (see below). The Fuggstock Sernifite is tentatively correlated with the Karrenstock Formation in Fig. 9. However, this correlation is not straightforward and is just one of several possibilities.

In the area NE of the Sernftal (Chrauchtal and Murgtal), the Fuggstock Sernifite gradually fines upward and develops into silty shales of purple and green colour, often with characteristic quartz layers (*Chartegg Formation*, Ryf 1965). In the Freiberg area, on the other hand, the top of the Karrenstock Formation, which is often composed of spilite or rhyolite, is truncated by an angular unconformity across which the angle between bedding planes can reach up to 10° (Schielly 1964, Nio 1972). The significance of this unconformity will be discussed below. Above this surface, the youngest Formation of the Glarus Verrucano in the Freiberg area, the *Kärpf Formation* (Schielly 1964, Nio 1972), follows. It is dominated by a coarse clastic body, the Kärpf Sernifite, which builds the prominent summit of the Kärpf mountain.

In the upper Chrauchtal and Murgtal, the Verrucano ends with an intensely red, silty shale succession (playa deposits) with abundant green reduction spots and some intercalated coarser-grained layers (sandstones and Sernifites), the *Schönbüel Formation* (Fisch 1961). In the basal parts of the Schönbüel Formation north of the Murgsee, Ryf (1965) could observe a marked angular unconformity in fine-grained Sernifites. The layers below the unconformity dip some 25° steeper than the layers above and the latter fill channels which are incised into the former (see the pictures provided by Ryf 1965). Possibly, this unconformity could be correlated with the one in the Freiberg area (as suggested in Fig. 9). On Fig. 3, the approximate areas where this unconformity crops out are drawn after the descriptions of Ryf (1965). This author could follow the unconformity across the Mürtschen thrust, and he could demonstrate that the former is offset only by some tens of metre by the latter which indicates only a moderate amount of displacement across the Mürtschen thrust in this area. At the type locality of the Schönbüel Formation (the Schönbüel plateau between the Spitzmeilen and the Rotgandwand) the uppermost part of this Formation, a few 10 m below the erosional base of the Triassic Mels Formation (Gisler et al. 2007), is interrupted by three very prominent, reddish-white, feldspar- and quartz-rich layers, each between 0.5 m and 4 m thick (see Fig. 8c, the so-called *"Schönbüel quartzites"* of the older literature) which were identified by Ryf (1965) as partly reworked rhyolitic tuff layers. Markus (1967) and Richter (1968) could follow these three tuff layers in the areas to the E and NE of the present study area (Flumserberge, Schilstal, and Guscha group) over an area of at least 150 km^2.

Biostratigraphy

Poorly preserved plant debris from the Mären Formation (Jongmans 1950, Amstutz 1957) may stem from arborescent horsetails (*Calamites*) which, however, do not allow of a closer stratigraphic designation than Carboniferous *or* Permian. Quite well-preserved fossil wood from the Freiberg could be identified as *Cordaites* (Fisch 1961, Nio 1972), a gymnosperm which occurred from Late Carboniferous to Early Permian. Thus, from a palaeontological point of view, the Mären Formation was probably deposited in the Latest Carboniferous or Early Permian. Hence, the thick successions from the Fuggstock Sernifite up to the Schönbüel Formation must have been laid down during the long span of time between the Early Permian and the Early Triassic, as the overlying Mels Formation is dated palynologically as Early Anisian (Gisler et al. 2007).

U–Pb dating and Hf isotope geochemistry of zircons: samples

To get more precise constraints on the age of the Glarus Verrucano, the stratigraphically lowest and highest occurrence of silicic volcanic rocks have been sampled for high-precision CA-TIMS U–Pb dating of single zircons (for sample localities see online resource 1). On the same zircons, additionally the Hf isotope geochemistry was evaluated.

Additionally to the high-precision age dating, we dated detrital zircons with the less precise but less time-consuming LA-ICP-MS method. U–Pb ages of detrital zircons

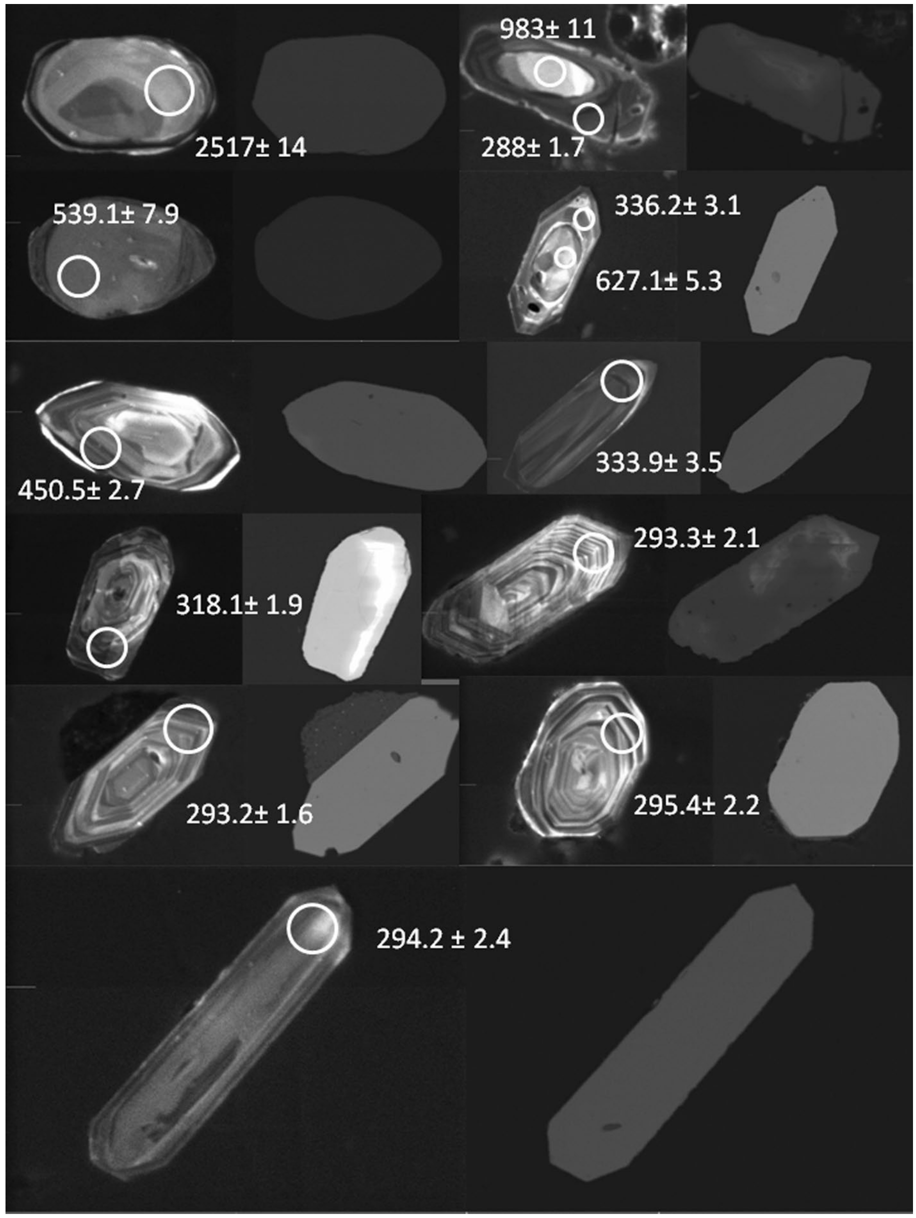

Fig. 10 Cathodoluminescence (CL) and backscattered electron (BSE) pictures of some representative zircons from different age domains present in the age spectra. The spots measured with LA-ICP-MS are indicated on the CL pictures by *circles* (30 μm diameter). Some inclusions and fractures are visible on the BSE pictures. These areas of the zircons have been avoided for age measurements

have been used in sedimentary provenance analysis for about the last three decades (e.g. Girty et al. 1985; Smith et al. 1995). However, it was only with the increasing application of the relatively quick and cost-effective U–Pb dating of zircons by means of laser ablation inductively coupled mass spectrometry (LA-ICP-MS) that detrital zircon ages have become a standard tool in provenance analysis (Košler et al. 2002).

In the case of the GVB, the dominant mass flow deposits on alluvial fans exclude the possibility of far-distance transport of detrital grains. Fan sediments, on the contrary, are prone to yield high-quality provenance information about the immediate mountainous hinterland supplying the fans (Blair and McPherson 1994). The source areas of the Glarus Verrucano are thus well known: either the easternmost present-day Aar or Gotthard massif (Fig. 1). Detrital zircon ages could thus be an additional source of geochronologic information on volcano-magmatic activity in these areas, and Hf isotope ratios can provide further information on the origin of the magmas in which the zircons crystallized Fig. 10.

Samples for high-precision age dating (CA-TIMS)

Sample DL V5 (Figs. 8, 11) has been mapped by Amstutz (1954) as a tuffitic sandstone. Macroscopically, it appears as a greenish-grey, fine-grained rock with millimetre-sized white feldspar and clear quartz grains. The rock exhibits signs of cleavage, is crudely bedded, and has an approximate thickness of some 3 m. In thin sections, the rock is

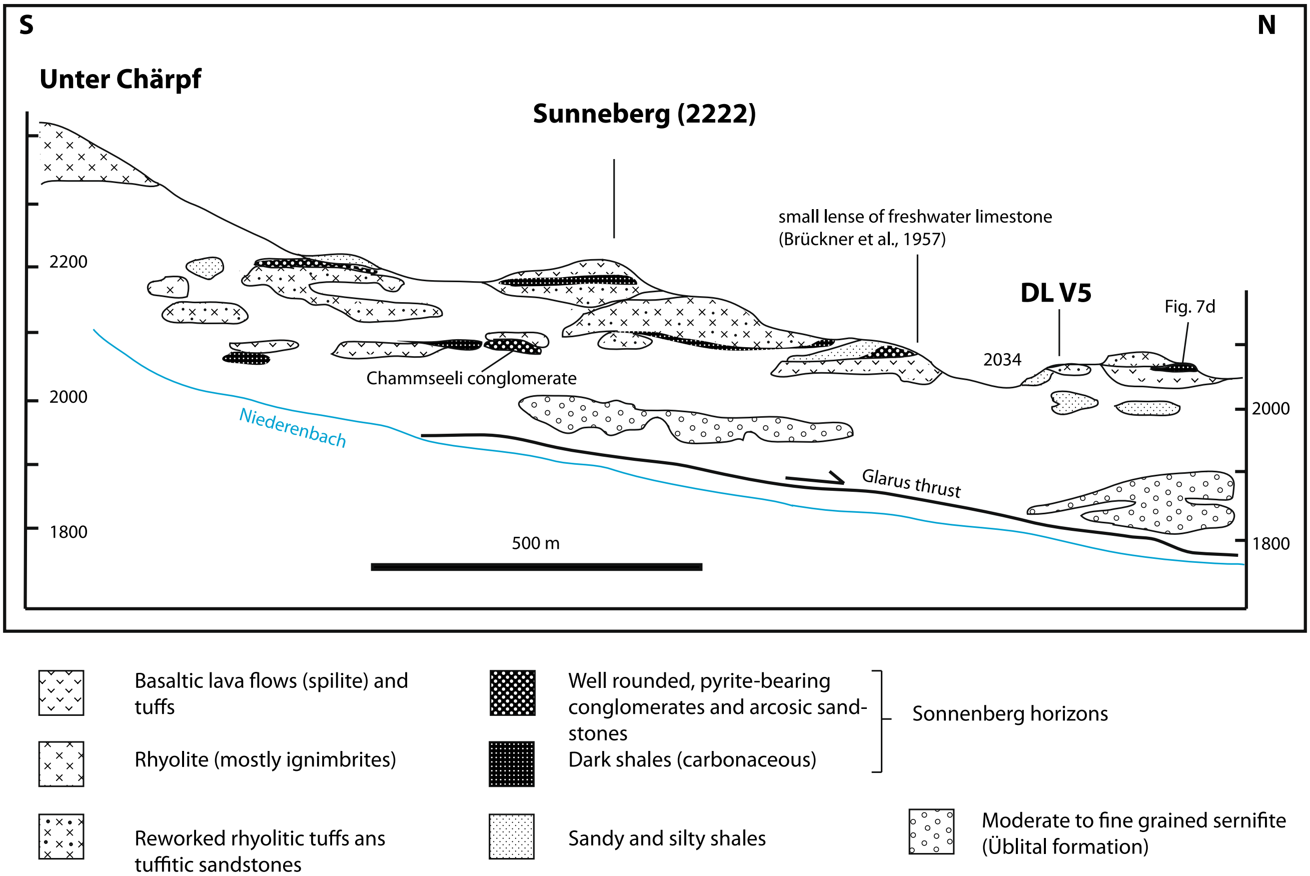

Fig. 11 Panoramic view of the Sunneberg in the western Freiberg with the sample localities DL V5 and V6 (the latter was taken from the other side of the Sunneberg). Redrawn and modified after Amstutz (1954)

composed of a brownish, microcrystalline matrix with embedded angular to poorly rounded quartz and feldspar grains, spindle- to tear-shaped microcrystalline grains, and some opaque minerals (mainly magnetite and haematite, possibly also pyrite). It is difficult to identify this rock either as a primary pyroclastic deposit (ignimbrite) or as a reworked pyroclastic deposit (possibly a lahar).

Samples DL V7 and DL V8 were taken from the lowest and from the middle layer of the Schönbüel quartzites, respectively. Only DL V7 yielded enough zircons for U–Pb dating. Macroscopically, the lower layer (DL V7) is a pale red, sometimes purple, but generally whitish rock with peculiar dark purple domains of irregular shapes. Its thickness is about 2 m. In thin sections (Fig. 8d), the latter turn out to be rich in opaque minerals (mainly haematite) which contrast markedly with the felsic phases which can be identified as recrystallized glass shards, and broken feldspar and quartz grains. The haematite is even more abundant in millimetre-sized schlieren-like domains. The boundaries to the pale and almost haematite-free domains are irregular but very sharp. This rock can clearly be identified as a subaerial pyroclastic deposit—an ignimbrite.

Samples for detrital zircon dating (LA–ICP–MS)

Six sampling sites have been chosen for detrital zircons (Fig. 3). Only four sites yielded enough zircons for analysis. The locations of the sampling sites are given in online resource 1.

DL V1 was taken from the base of the Fuggstock Sernifite, near its type locality, the Fuggstock Peak. The rock is a pale purple to reddish-grey, fine-grained (maximum clast diameter 2 cm), matrix-supported Sernifite with clear signs of tectonic deformation. The clasts are mainly vein quartz and rhyolite, spilites seem to lack. The sample yielded abundant heavy minerals and many often euhedral zircons.

Sample DL V4 was taken from a dark red to brown, fine-grained (most clasts <1 cm) Sernifite just south of the Unter Murgsee in the Murgtal (Fig. 3). Among the larger clasts, rhyolite and vein quartz dominate. In thin sections, broken and angular quartz and feldspar grains (mostly albite, some euhedral, millimetre-sized perthitic K-feldspar grains) dominate. The quartz may exhibit well-developed, toungue-shaped resorption features. The sample yielded only few heavy minerals and zircon, in particular.

DL V6 was taken from the Chammseeli conglomerate mentioned previously (Amstutz 1957; Schielly 1964) at its type locality, the Chammseeli in the western Freiberg. It is a fine- to medium-grained (well-rounded pebbles up to 10 cm), well-rounded conglomerate (Fig. 7a). Its matrix is dark arkosic sandstone with abundant pyrite. The grains are broken and angular, and some of them are cryptocrystalline and have a tuff-like appearance with recrystallized glass shards. The pebbles are mostly elongated and (tectonically?) stretched (Fig. 7b). They often are composed of very fine-grained crystalline rocks of a pale green colour. In thin sections, they are dominated by quartz and feldspar phenocrysts (often Ca-bearing as shown by feldspar staining) embedded in a cryptocrystalline matrix with mica and some opaque phases. Schielly (1964) identified 60–90 % of the pebbles as rhyolites. The abundant occurrence of Ca-bearing feldspars, however, indicates the presence of more basic rocks (rhyodacites, dacites, and possibly andesites). Notable is the very contrasting degree of rounding between the pebbles (well rounded) and the grains in the matrix (broken and barely rounded). Some of these grains plastically impinge into adjacent pebbles. This has led Schielly (1964) to assume that these pebbles were volcanic bombs and lapilli which had been deformed and amalgamated in still a soft state. Similar "tuffitic conglomerates" have also been described from the base of the Ilanz Verrucano (Wyssling 1950; Wyss and Isler 2011). A further discussion of Schielly's suspicion is given below. The sample yielded abundant heavy minerals (zircon, pyrite, magnetite).

DL V9 was taken from a coarse-grained, greenish-purple sandstone with transitions into a fine-grained, matrix-supported Sernifite. It crops out near Alp Bütz in the middle Murgtal and belongs stratigraphically to the sandy marginal facies of the Mären Formation (Ryf 1965). Most peculiar components are pinkish granites and rhyolites. The sample yielded relatively much heavy minerals; however, zircons were rather rare.

U–Pb dating and Hf isotope geochemistry of zircons: methods

From each sampling site, approximately 4 kg of rock have been collected and crushed by applying a high-voltage pulse power fragmentation procedure in a Selfrag device at the Department of Earth Sciences at ETH Zurich. The 0.063-mm to 0.4-mm fraction has been separated by sieving. It was subjected to an HCl treatment to remove any carbonates. The heavy mineral fraction was separated by methylene iodide heavy liquid separation and afterwards split into different fractions in a Frantz magnetic separator.

For CA-TIMS dating, zircons were picked under a binocular microscope. Individual grains (if possible without any inclusions) were chosen and subjected to a combined thermal annealing and chemical abrasion treatment (Mattinson 2005) to remove grain domains which might have experienced lead loss. The grains were then dissolved in HF–HNO_3 in miniaturised dissolution vessels. Chemical separation of U, Pb, Lu, and Hf was achieved on anion exchange resin in chemical separation columns (Krogh 1973) by using minimal amounts of ultrapure acids in the clean lab of the Institute for Petrology and Geochemistry at ETH Zurich. U–Pb isotopic analyses were performed on a TRITON (Thermo Finnigan) thermal ionisation mass spectrometer (TIMS).

For the LA–ICP–MS dating, the hand-picked zircons were embedded in epoxy pills and polished until the majority of the grains showed a sufficiently large cross section. These pills were then coated with graphite, and cathodoluminescence (CL) and backscattered electron (BSE) images were obtained using a TESCAN scanning electron microscope at the Department of Materials at ETH Zurich (see online resource 3 and Fig. 10). These pictures allowed the recognition of the internal zoning of the zircons, possible inherited cores, fractures, or inclusions which all influence the results of the U–Pb dating. The LA-ICP-MS analyses and data procession have been carried out at the Institute for Petrology and Geochemistry at ETH Zurich. The diameter of the laser beam was fixed at 30 μm. If inherited cores were visible on the CL images, both, core and rim, have been dated.

Lu–Hf isotopic ratios from both volcanic and detrital zircons were measured on a Nu instruments multiple collector inductively coupled plasma mass spectrometer (MC–ICP–MS, Nu-500) attached to an excimer laser ablation unit from Lambda Physics with a wavelength of 193 nm at ETH Zurich. Age-corrected epsilon Hf values ($\varepsilon Hf_{(t)}$) have been calculated assuming a present-day bulk silicate Earth (chondritic uniform reservoir, CHUR) with $^{176}Hf/^{177}Hf = 0.282785$ and $^{176}Lu/^{177}Hf = 0.0336$ (Bouvier et al. 2008).

The processed data have been plotted with the excel toolkit Isoplot (Ludwig 2003). Age distribution plots have been constructed using the ^{238}U–^{206}Pb ages and their errors. Core and rim ages do often exhibit an appreciable age difference in an individual grain; however, taken as a whole, rim and core ages do not fall into fundamentally different age groups and were thus generally plotted without any differentiation in the figures.

U–Pb dating and Hf isotope geochemistry of zircons: results and interpretation

Single grain analysis of volcanic zircons (CA-TIMS)

Single grain dating revealed the presence of quite different ages in sample DL V5 (Fig. 12, see online resource 2 for the numeric data). Three discordant ages between 650 and 700 Ma are probably due to inherited cores with younger overgrowth rims, whereas two ages around 460 Ma are concordant. A morphologically coherent, short prismatic, mostly clear, but partly milky zircon population yielded concordant ages clustering around 300 Ma. One single grain (short prismatic and turbid) yielded an appreciable younger concordant age (around 285 Ma). The interpretation of zircon ages from acidic volcanic deposits is often difficult (Miller et al. 2007). Capuzzo and Bussy (2000) reported U–Pb zircon ages from an Late Carboniferous tuff layer similar to DL V5 from the Salvan-Dorénaz basin (Fig. 1), which gave exclusively old inherited ages. Capuzzo and Bussy (2000) suspected that the magmas giving rise to acidic volcanic deposits were often quenched and did not have time to crystallize significant amounts of young zircons, whereas they contained abundant inherited zircons which were not resorbed during magma genesis. Bearing these difficulties in mind, we would tentatively interpret our results as follows. All pre-Variscan zircons (460 Ma and older) represent either inherited components in otherwise younger grains, or they are zircons taken up by the magma from the host rock during ascent (xenocrysts sensu Miller et al. 2007). Furthermore, detrital input cannot be excluded as the same ages have also been found in detrital zircon samples. The prominent population around 300–305 Ma corresponds to widespread volcano-magmatic activity in Central Europe (Alps: e.g. Schaltegger and Corfu 1992; Bussy et al. 2000: northern Switzerland: Schaltegger 1997; NE German basin: Breitkreuz and Kennedy 1999). However, the single younger concordant age (285 Ma) renders it difficult to ascribe the DL V5 tuff to this volcano-magmatic episode. Unless one assumes very prominent inheritance of 15-Myr-older zircons in 285-Ma magma, the 300-Ma population must be considered as detrital input. Irrespective of these two possibilities, we would tentatively date DL V5 285 Ma (Middle Artinskian, Early Permian), however, this age has to be considered as a maximum age.

DL V7 (Fig. 13) confronts us with the same difficulties as DL V5: many grains exhibit either inherited age components or they were later incorporated into the magma (during ascent through the upper crust: xenocrysts), or into the hot ash cloud which finally deposited the ignimbrite layer. Two grains (both euhedral, prismatic, and clear) yielded concordant ages, which are close together (mean age: 268.36 ± 0.54 Ma). One slightly older grain (V7-1) could either be a xenocryst or a zircon which crystallized in an earlier magma pulse in the magma chamber and which later mixed with the magma pulse which finally caused the ignimbrite (antecryst sensu Miller et al. 2007). Thus, we propose a maximum age of 268 Ma for the lower Schönbüel-quartzite (DL V7; Early Wordian, Late Permian).

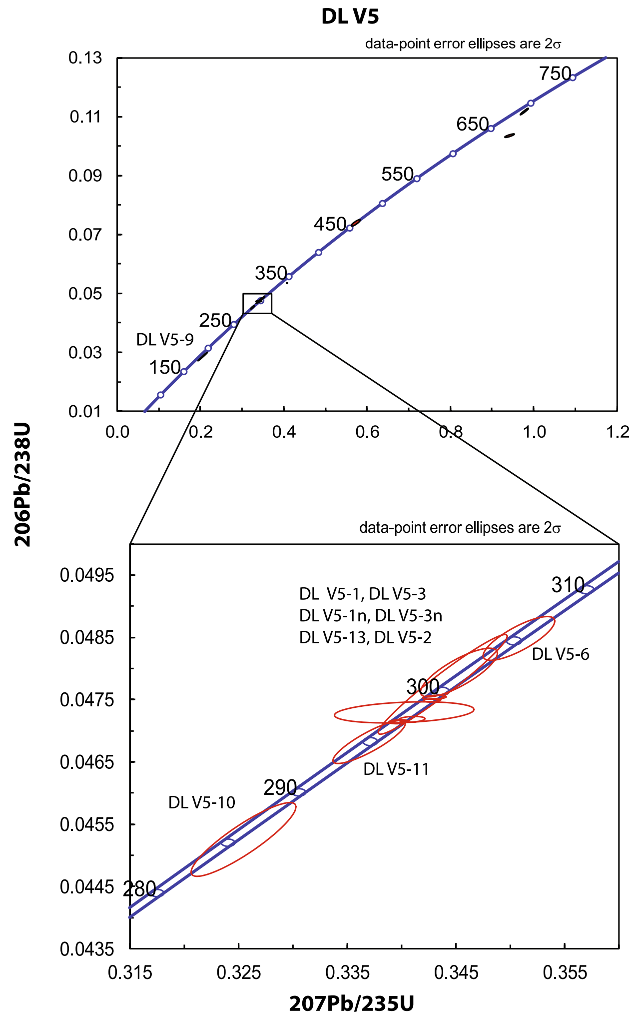

Fig. 12 Concordia (CA-TIMS) plots from sample DL V5 (reworked pyroclastic flow, Mären Formation). Note that even though most ages cluster around 300 Ma, a single concordant age of 285 Ma suggests that the older ages stem from detrital contamination or from xenocrysts taken up by the magma during ascent to the surface

The high-precision age dating implies that the Mären Formation (with the peculiar Sonnenberg horizons) was deposited during the Early Permian and the upper part of the Schönbüel Formation during the Late Permian. This is not in contradiction to the few hints from biostratigraphy, but it decreases the possible age brackets given by the sparse fossils to a narrower time frame of some 17 Myr for deposition of the major part of the Glarus Verrucano.

Detrital zircons age dating (LA-ICP-MS)

The results of the detrital zircon age datings are displayed graphically in Figs. 14 and 15 (for the numeric data see online resource 4). The results of the Hf isotope measurements are given in online resource 2 and Fig. 16.

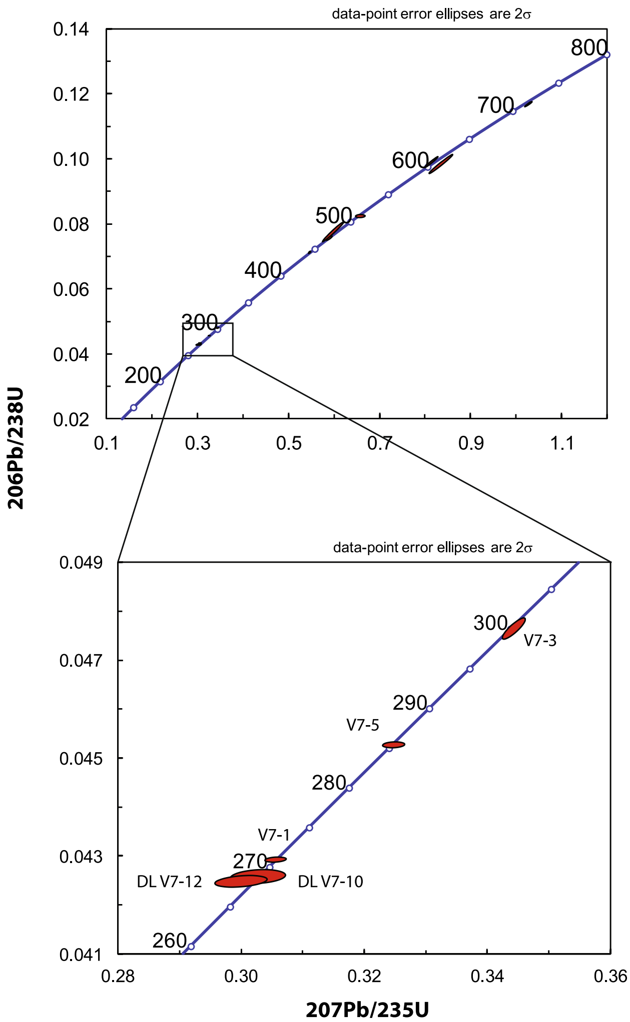

Fig. 13 Concordia (CA-TIMS) plots from sample DL V7 (rhyolitic ignimbrite of the Upper Schönbüel Formation, "Schönbüel quartzite"). The youngest ages cluster around 268 Ma which is interpreted as the depositional age of the ignimbrite

DL V1 (Fuggstock Sernifite) yielded a total of 102 concordant ages. Seventy-seven grains yielded concordant rim ages. Twenty-five of these grains (33 %) yielded concordant ages from inherited cores. The age distribution of both cores and rims is bimodal. The major peak occurs at 298 Ma and a minor one at 458 Ma. A few ages, mostly from inherited cores, are between ca. 730 and 930 Ma. The oldest date stems from a well-rounded, oval-shaped zircon grain without any core and is around 2.5 Ga (Fig. 10). Surprisingly, only three zircons from the main mode (298 Ma) exhibit an inherited core of substantially older age. Otherwise, these zircons have often a well-developed acicular shape and exhibit either no core at all, or a core of similar age as the rim. The age maximum around 298 Ma fits well into the regional picture: Schaltegger and Corfu (1992, 1995) reported zircon U–Pb age data from a granitic suite of intrusions and subordinate volcanics of calc-alkaline to subalkaline character from the Aar and Gotthard massif which fall into the time span of 296–303 Ma. Prominent and important representatives do mostly occur in the Aar massif (e.g. the Central Aar Granite and the Grimsel granodiorite, or the Windgällen porphyry, Schaltegger and Corfu 1995) but also in the Gotthard massif (Fig. 10). The minor mode at 458 Ma might correspond to the poorly known orogenic activity between 480 and 450 Ma which was reported by Schaltegger et al. (2003) from the Aar massif. Voluminous intrusions of slightly younger age (e.g. the Streifengneis, 435–440 Ma, Schaltegger 1994) are also recorded from the Gotthard massif, and they correspond in age to syntectonic volcanism in areas affected by the Caledonian orogeny (e.g. Scotland, A. Pfiffner personal communication). The only Archean grain falls into the provenance age of 2.49–2.55 Ga proposed by Schaltegger (1993) for old detrital zircons in metasediments of the Aar massif. Its oval and well-rounded morphology also corresponds to the shapes reported by Schaltegger (1993). Similar Precambrian ages have been reported by Scheiber et al. (2013) from inherited zircon cores in Late Palaeozoic granitoids of the Suretta nappe (cf. Fig. 1 for the palaeogeographic location of this nappe). Remarkable are four euhedral and short prismatic grains which yielded $^{238}U–^{206}Pb$ ages between 285 and 290 Ma (mean at 288). These are the youngest reliable and stratigraphically meaningful ages and could be considered as approximate maximum depositional ages of the Fuggstock Formation. However, they are slightly older than the high-precision U–Pb age of the tuff layer in the underlying Mären Formation (DL V5: 285 Ma).

DL V4 (Grisch Member) contained only few zircons. Thirty-two concordant ages could be obtained; 21 grains yielded concordant rim ages, and 11 of these grains (53 %) yielded concordant core ages. The age distribution of all concordant ages is bimodal with two age modes at 325 and 293 Ma. Older ages are rare. Only one single zircon from the two major modes possesses a core of substantially older age. All the other cores do occur either in older zircons, or they are of a similar age as their rims. The zircons of the main mode are often short prismatic to acicular, or they are fragments of zircons of these shapes. Few of them exhibit rounded shapes. The older grains are, on the contrary, often well-rounded fragments. The older ages of the main mode (around 330 Ma) might well correspond to Schaltegger and Corfu's (1992) group A intrusive in the Aar massif. These shoshonitic-ultrapotassic rocks (diorites and granites) are the oldest known Varsican intrusives in the eastern Aar massif, and encompass some well-known intrusions, such as the Punteglias granite (334 ± 2.5 Ma, Schaltegger and Corfu 1992) or the Tödi granite (333 ± 2 Ma, Schaltegger and Corfu 1995). These intrusive bodies constitute the immediate palaeogeographic hinterland of the Glarus

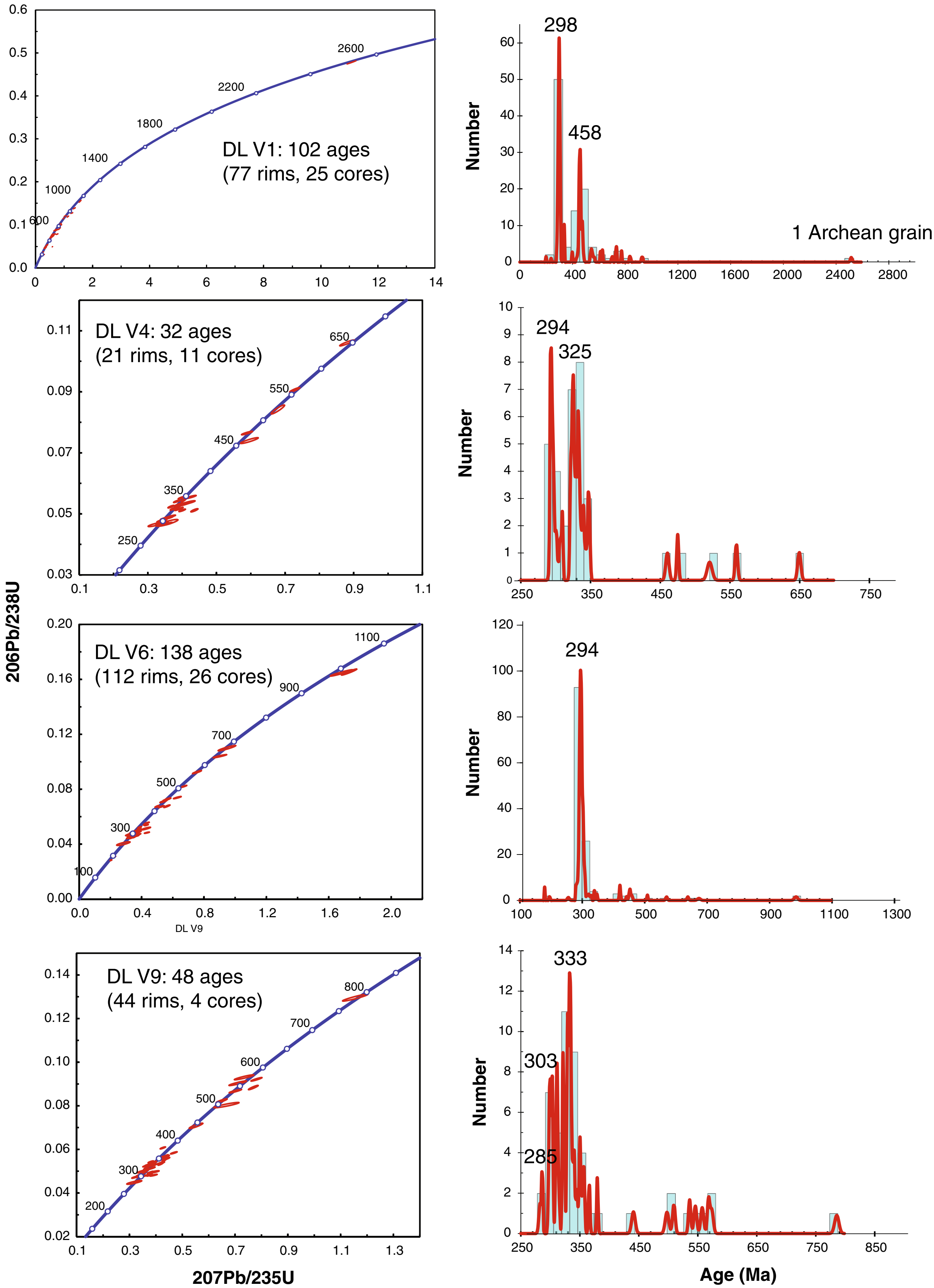

Fig. 14 Concordia (LA-ICP-MS) and probability density plots of samples DL V1, DL V4, DL V6, and DL V9. Note the predominance of Late to post-Variscan ages (333–285 Ma) and the rarity of Early Palaeozoic and Precambrian ages

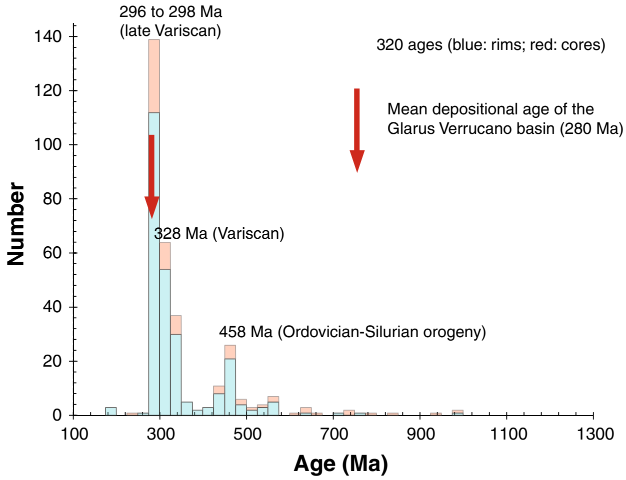

Fig. 15 Compilation of all LA-ICP-MS detrital zircon ages. Core and rim ages are distinguished. Note the young age of most zircons compared to the depositional age of the GVB. Furthermore, the close congruency between core and rim ages can be clearly seen

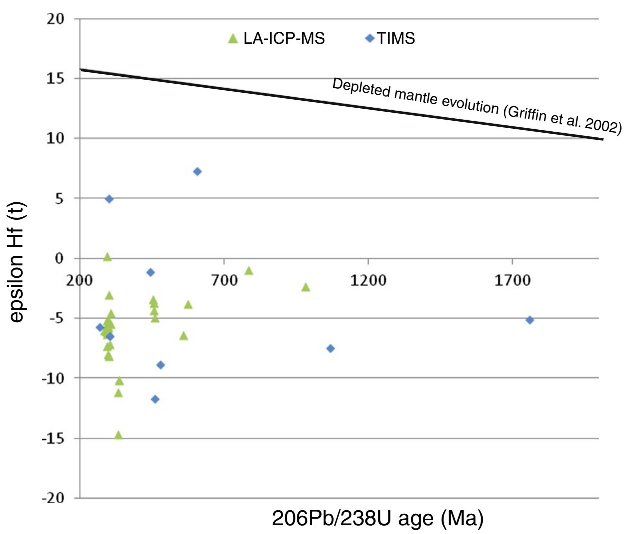

Fig. 16 Hf isotope data. Time-corrected epsilon Hf values were calculated by means of the measured ^{238}U–^{206}Pb ages and by assuming a present-day bulk silicate Earth (chondritic uniform reservoir, CHUR) with $^{176}Hf/^{177}Hf = 0.282785$ and $^{176}Lu/^{177}Hf = 0.0336$ (Bouvier et al. 2008). Negative values point towards crustal magma sources, whereas positive values rather indicate mantle magmatic reservoirs

Verrucano and a sediment transport direction towards the SE seems therefore very plausible. The younger ages of the major mode, clustering around 294 Ma, could correspond to Schaltegger and Corfu's group C; however, most of our ages seem to be some Myr younger and could therefore also be derived from group D intrusions (Schaltegger 1994: 290 to 295 Ma), which are, however, only known from the Gotthard massif. The few older grains were probably derived from old metasediments as they show no younger rims and are often broken and/or mechanically rounded.

DL V6 (Sonnenberg horizons) yielded abundant zircons; 112 grains gave concordant rim ages and 26 of these grains (23 %) additional concordant core ages. The age distribution is extremely unimodal with a centre at 294 Ma. The grains of this major population are mostly euhedral, medium to long prismatic, with abundant apatite (?) inclusions, and generally lack old cores (only four grains had a pre-Variscan core). The older grains of the main mode (around 298–300) would fit to Schaltegger and Corfu's (1992) group C intrusions which are known from both the Aar and Gotthard massifs. The few grains which are much older (between 400 and 990 Ma) show rounded morphologies and were probably reworked from older sediments. Recalling the facies of DL V6, the extreme unimodality of the age distribution might be taken as evidence in favour of Schielly's (1964) suspicion that the pebbles of the Chammseeli conglomerate are indeed volcanic bombs from a synsedimentary acidic to possibly intermediate volcanic eruption. Then, the age of both the Chammseeli conglomerate and the contemporaneous volcanism would be around 294 Ma. However, DL V6 was taken at about the same stratigraphic level as DL V5 (Fig. 11) with the latter yielding a probable maximum depositional age of 285 Ma i.e. substantially younger than the majority of the zircons from the DL V6 main mode. On the other hand, the pebbles could indeed be bombs which originated at around 294 Ma and were later reworked into a younger mixed volcano-sedimentary deposit at around 282 Ma, which is the youngest reliable zircon age from DL V6.

DL V9 (Grisch member) contained rather few zircons. We could obtain a total of 48 concordant ages, 44 from rims and 4 from cores (9 %). Despite the small sample size, a bimodal age distribution can be assumed with a broad major mode between 300 and 333 Ma, and not a very well represented minor population between 500 and 570 Ma. The older ages from the major mode (around 330 Ma) correspond very well to the ages reported by Schaltegger and Corfu (1992) for their magmatic suite A. The few older zircons seem all to be reworked detrital zircons from possibly Pan-African provenance. The Ordovician–Silurian tectonomagmatic activity is almost absent from this sample.

The $\varepsilon Hf_{(t)}$ values (Fig. 16) are predominantly negative and therefore point towards crustal magma sources (e.g. Hawkesworth et al. 2010). The few Precambrian $\varepsilon Hf_{(t)}$ values are negative with the exception of a single Pan-African one (607 Ma) which seems to stem from a mantle melt-derived zircon. The Ordovician zircons exclusively yielded negative values. Our Variscan $\varepsilon Hf_{(t)}$ values also suggest crustal magma sources, and they are in good agreement with the data published by Schaltegger and Corfu (1992) from Variscan plutons in the Aar massif. Our data even reproduce the marked $\varepsilon Hf_{(t)}$ increase from the Variscan plutons (ca.330 Ma, –10 to –15) to the Late Variscan plutons (ca. 300 Ma, −8 to +5, as shown by Schaltegger and Corfu 1992, 1995).

General discussion

Detrital zircon spectra of the Glarus Verrucano

The compilation of all detrital zircon ages from the Glarus Verrucano (Fig. 15) reveals a unimodal to slightly bimodal spectrum. Synsedimentary volcanism is recorded in each of the four samples, and the youngest reliable and stratigraphically meaningful zircon ages approximate the depositional age of their sedimentary host rock and could thus be used as stratigraphic tools in similar deposits which lack biostratigtaphic control but might exhibit tectonic complications.

The main mode is slightly younger than 300 Ma and is linked to widespread late to post-Variscan magmatism and volcanism, which is also well known from other pre-Mesozoic areas in the Alps and in extra-Alpine Europe (e.g. von Raumer et al. 2013; Beltrán-Triviño et al. 2013). Older, pre-Variscan ages are subordinate: a minor population around 458 Ma (Upper Ordovician) is of some importance: these ages might correspond to subduction tectonic activities, partially accompanied by anatectic crustal melting and pluton emplacements (as also supported by the Hf isotope data), at the eastern part of the northern Gondwana margin where the external zones of the Swiss Alps supposedly were located at that time (Schaltegger et al. 2003; von Raumer et al. 2013; Beltrán-Triviño et al. 2013). Early Palaeozoic and Neoproterozoic ages do occur but are very rare. We ascribe them to detrtial zircons which may be of Pan-African origin (around 600 Ma).

In summary, the detrital zircon age spectrum is dominated by zircons derived from Late and post-Variscan plutons and their related volcanoes. The majority of these ages is only some 10 to 15 Myr older than sedimentation in the GVB. From this, we conclude that the major part of the higher units of the Variscan tectonic edifice (especially all the sedimentary nappes with their supposedly more variable detrital zircon spectra) had already been removed (either through erosion or due to extensional tectonics) before the GVB originated at the transition from the Carboniferous to the Permian. Similar conclusions (high exhumation rates, heat flows, and abundant late orogenic magmatism) have been drawn by Capuzzo et al. (2003) from studies of detrital white mica ages in the Salvan-Dorénaz basin (Fig. 1).

Volcano-sedimentary evolution of the GVB

In this section, we will integrate all sedimentologic, stratigraphic, geochronological, and petrological data into an evolutionary scheme of the GVB which then can be compared to analogous basins in Europe. Two basic assumptions are made: 1. The Glarus Verrucano is a coherent stratigraphic section, i.e. it is not affected by doubled stratigraphies due to thrusting or folding as assumed by some earlier authors (Trümpy until around 1964, and Schielly 1964, respectively). 2. The Üblital Formation forms the base of this section i.e. it is the first sedimentary unit which once directly covered the crystalline basement. The first assumption is justified by the investigations of Fisch (1961) and Nio (1972) who could demonstrate by detailed mapping that the Mären Formation with its peculiar Sonnenberg horizons resembling Carboniferous sections in the eastern Aar massif (e.g. the filling of the Bifertengrätli basin, Fig. 1, see Franks 1968; Schaltegger and Corfu 1995) forms *not* the base of a higher tectonic unit in the Verrucano mass, but is instead connected to the underlying Üblital Formation by a stratigraphic transition. Further evidence is provided by our U–Pb zircon ages which prove that the Mären Formation with its bimodal volcanism is at least 15 Myr younger than the Bifertengrätli Formation. The second assumption is justified in a more indirect way. There is no locality known where the Üblital Formation is underlain by another Verrucano-like Formation. The only known occurrence of the original basement of the Glarus Verrucano (a tectonic sliver at the base of the Glärnisch Group, see Trümpy 1947) also starts with a finegrained Sernifite covering deeply weathered gneiss. However, it should be noted in this context that Pfiffner (1972) described dark coloured shales and sandstones, reminiscent to the Carboniferous Bifertengrätli Formation (Franks 1968), which occurred beneath the Verrucano of the parautochthonous Helvetic nappes in the Calanda area (eastern prolongation of the Aar massif). Since age dating is lacking for this occurrence, these Carboniferous-like sediments could also be correlated with the Sonnenberg horizons in the Mären Formation as well and hence need not be of Carboniferous age. The Permian age of the Sonnenberg horizons demonstrates that sediments resembling typical Carboniferous series were also deposited during Early Permian times (see also Roscher and Schneider 2006 for some other European examples of such "Carboniferous" facies recurrences during the Early Permian).

Hence, we propose the following model for the evolution of the GVB. It started to develop during the Early Permian either as a Basin-and-Range type half-graben due to gravity collapse of the overthickened Variscan crust, or as a strike-slip-induced pull-apart basin. It firstly received abundant coarse detritus mainly from the NW (today Aar massif) mostly by alluvial fan transport and sedimentation (Üblital Formation). Some subordinate basic subaerial volcanism also took place. Due to a temporarily wetter climate (possibly one of the five Lower Permian wet phases proposed by Roscher and Schneider 2006) the central part of the GVB became occupied by partly anoxic lakes and perennial streams and abundant vegetation developed (Mären Formation with Sonnenberg horizons). At the same time, widespread bimodal volcanism (basaltic lava flows and rhyolitic to rhyodacitic explosive eruptions with ignimbritic flows, at around 285 Ma) developed. Alluvial fans persisted during this wetter interlude along the basin margins (sandy marginal facies of the Mären Formation and the Murgtal Sernifite). They spread again into the more central parts of the basin when the climate became more arid again (Fuggstock and Karrenstock Formations). Volcanism slowly decreased. Then, during the Mid-Permian, the GVB experienced intrabasinal erosion (possibly triggered by tectonic movements) resulting in an angular unconformity, well developed in the Freiberg area and possibly also in the upper Murgtal. Subsequently, the basin fill became progressively finer grained and the red staining increased. This may either indicate an increasingly arid climate (Roscher and Schneider 2006) or a tectonically induced basin widening which led to increasingly shallower (and temporarily dry) lakes in the basin centre (according to the model proposed by Pochat and van den Driessche 2011). In the Late Permian (268 Ma), at least three rhyolitic eruptions with widespread ignimbrite deposition took place.

For the next 20 Myr, data are sparse. Sernifite sedimentation locally persisted in the East, possibly even into Early Triassic times (Kapfen Sernifite near Mels, Richter 1968). The contacts between the base of the undisputed Triassic (Mels Formation, Early Anisian, 245 Ma) and the uppermost Verrucano either indicate substantial erosion (locally the Schönbüel quartzites have been totally eroded) and/or long-lasting and deeply penetrating (up to 50 m, Fisch and Ryf 1966) weathering processes. Angular unconformities between the Verrucano and the Triassic (e.g. in the Gufelstock group, Huber 1964) furthermore indicate tectonic activity during this major hiatus. The GVB seems to have been hydrologically isolated throughout its history, which is typical for many post-Variscan basins (Pochat and van den Driessche 2011). This is confirmed by the unimodal detrital zircon age spectra which were derived from local sources. The palaeogeographic situation changed with the transgression of the Middle Triassic sandstones of the Mels Formation (Gisler et al. 2007). The marked relief which must still have existed during the development of the GVB was worn down to a peneplain by Early Triassic times with some regional relief remaining in the area of the later Aar massif (Windgällen area, see Milnes in Funk et al. 1983). The zircon age spectrum from the transgressing Mels sandstones (Beltrán-Triviño et al. 2013) is more varied than the ones from the Glarus Verrucano and contains abundant Early Palaeozoic ages but lacks any Permian ages. This change to more heterogeneous zircon age spectra could be taken as an indication for an enlarged sediment source area. Interestingly, the spectrum from the Mels Formation resembles the ones published by Krippner and Bahlburg (2013) from Pleistocene Rhine River sands from southern Germany. Obviously, both the Middle Triassic river system feeding the shallow marine depositional system of the Mels Formation and the Pleistocene middle part of the Rhine River drained areas with similar outcropping Palaeozoic basements. An alternative explanation for the increase of Early Palaeozoic ages in the Triassic zircon age spectra could be the erosional uncovering of pre-Permian basement rocks in the area of the future Helvetic shelf.

The GVB in a regional context

The bimodal volcanism around 285 Ma has no equivalents in the other Late Palaeozoic Basins of the later Helvetic and Penninic palaeogeographic domains (Fig. 1). Widespread bimodal volcanism in the large German Late Variscan basins is generally older (e.g. in the Saar-Nahe basin: bimodal volcanism between 296 and 293 Ma, von Seckendorff et al. 2004). However, it is contemporaneous to widespread, mostly acidic, volcanism in the Southern and the Ligurian Alps (Schaltegger and Brack 2007; Dallagiovanna et al. 2009; Cassinis et al. 2012; Gretter et al. 2013). The angular unconformity which forms the upper boundary of this volcanic phase (Fig. 9) could be correlated to widespread tectono-magmatic activity in the Middle Permian (275 Ma, the "Mid-Permian Episode" of Deroin and Bonin 2003). However, unconformities in rapidly subsiding intramontane basins have to be correlated with care, as they may also form due to variable subsidence and sedimentation rates related to extensional or strike-slip tectonics and need not reflect regional compressive tectonic activities (e.g. Lorenz and Nicholls 1976). The 268 Ma acidic volcanic activity in the GVB could nevertheless mark the last stages of the Mid-Permian episode, which has been brought into causal connection to very large-scale fast strike-slip movements by Schaltegger and Brack (2007; the Pangea B to Pangea A transition of Muttoni et al. 2003). Alternatively, these large-scale strike-slip movements and the contemporaneous magmatism have been attributed to the onset of subduction of the Palaeotethys active oceanic ridge beneath Eurasia and the Variscan orogen resulting in a stable but moving transform-trench-ridge triple junction (Cassinis et al. 2012). On a regional scale, the youngest volcanic rocks in the GVB (ignimbrites, 268.36 ± 3.6 Ma) are quite contemporaneous to local granitic and rhyolitic intrusions in the Tambo (268.0 ± 0.4 Ma, Marquer et al. 1998) and Suretta (268.3 ± 0.6 Ma, Marquer et al. 1998, and 268 ± 4 Ma, Scheiber et al. 2013) nappes. Similar Permian ages were obtained by Scheiber et al. (2014) from the Siviez-Mischabel nappe complex (see Fig. 1 for location). During the same time span, gabbros intruded into the lower crust presently exposed in Val Malenco (269 ± 22 Ma, Hermann et al. 1997), and partial melting under granulite metamorphic facies conditions took place in the (North penninic?) Gruf Complex (282–260 Ma, Galli et al. 2012). Thus, our new age datings from the GVB complete the available evidence for Middle to Late Permian metamorphism and magmatism affecting the whole continental crust beneath the future northern Alpine Tethys margin.

Conclusions

The following conclusions can be drawn from the present study of the GVB

- The detrital zircon spectra from the GVB document long-lasting magmatic and volcanic activity from 333 to 285 Ma in the area of the future northern margin of the Tethys ocean (Helvetic shelf). Hence, the youngest reliable ages from a given sample can be used to determine its approximate depositional age in this biostratigraphically poorly constrained basin fill.
- Volcanic activity within the GVB itself was episodic and restricted to two volcanic phases. A first bimodal phase occurred around 285 Ma and a second silicic phase around 268 Ma.
- The GVB was a hydrologically closed basin which received sedimentary detritus from its immediate hinterland. The latter was part of the remnants of the Variscan orogen which in Early Permian times must have been considerably worn down and dominated by post-Variscan volcanoes. It did not expose any widespread Variscan sedimentary or crystalline/metamorphic nappes of pre-Variscan origin which could have served as quantitatively important sedimentary sources.
- An important reorganization of regional palaeogeography of the future Helvetic shelf must have taken place during the time span from the Late Permian to the Earliest Triassic as the detrital zircon age spectra from Early Triassic rocks are considerably different from the spectra from the Permian Glarus Verrucano.

Acknowledgments We thank A. Beltrán-Triviño for his constant advice in the lab and for numerous discussions. I. Peytcheva, M. Wälle, and S. Koch were of great help while acquiring the U–Pb and the Hf data. The critical but nevertheless benevolent reviews by A. Pfiffner and A. Wetzel helped greatly to improve an early version of this article. Finally, we want to thank P. Brack for some useful advice and T. Blattmann for his enthusiastic help in the field.

References

Amstutz GC (1954) Geologie und Petrographie der Ergussgesteine im Verrucano des Glarner Freiberges. Dissertation, ETH Zurich

Amstutz GC (1957) Kleintektonische und stratigraphische Beobachtungen im Verrucano des Glarner Freiberges. Eclogae Geol Helv 50:141–159

Amstutz GC, Patwardhan AM (1974) A reappraisal of the textures and composition of the spilites in the Permo-Carboniferous Verrucano of Glarus, Switzerland. In: Amstutz GC (ed) Spilites and spilitic rocks. Springer, Berlin, pp 71–81

Bächtiger K (1958) Die Uranmineralisation an der Mürtschenalp (Kt. Glarus, Schweiz). Schweiz Mineral Petrogr Mitt 38: 387–391

Bächtiger K (1960) Ein neues intramagmatisches Kupfervorkommen in den Keratophyrlaven des Gufelstockes (Kt. Glarus, Schweiz). Schweiz Mineral Petrogr Mitt 40:279–288

Beder R (1909) Über basische Eruptivgesteine im ostschweizerischen Verrucano. Dissertation, University of Zurich

Beltrán-Triviño A, Winkler W, von Quadt A (2013) Tracing Alpine sediment sources through laser ablation U–Pb dating and Hf-isotopes of detrital zircons. Sedimentology 60:197–224

Blair TC, McPherson JG (1994) Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. J Sedim Res A64:450–489

Blumenthal M (1911) Geologie der Ringel-Segnesgruppe. Beitr Geol Karte Schweiz NF 33, IV + 71 p

Bouvier A, Vervoort JD, Patchett PJ (2008) The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. Earth Planet Sci Lett 273:48–57

Breitkreuz C, Kennedy A (1999) Magmatic flare-up at the Carboniferous/Permian boundary in the NE German Basin revealed by SHRIMP zircon ages. Tectonophysics 302:307–326

Brückner WD, Heim A, Ritter E, Staub R, Trümpy R (1957) Bericht über die Jubiläumsexkursion der Schweizerischen Geologischen Gesellschaft durch die Glarneralpen. Eclogae Geol Helv 50:509–522

Burg JP, van den Driessche J, Brun JP (1994) Syn- to post-thickening extension in the Variscan belt of Western Europe: modes and structural consequences. Géol Fr 3:33–51

Bussy F, Hernandez J, von Raumer J (2000) Bimodal magmatism as a consequence of the post-collisional readjustment of the thickened Variscan continental lithosphere (Aiguilles Rouges-Mont Blanc Massifs, Western Alps). Trans Roy Soc Edinburgh Earth Sci 91:221–233

Capuzzo N, Bussy F (2000) High-precision dating and origin of synsedimentary volcanism in the Late Carboniferous Salvan-Dorénaz basin (Aiguilles rouges Massif, Western Alps). Schweiz Mineral Petrogr Mitt 80:147–167

Capuzzo N, Wetzel A (2004) Facies and basin architecture of the Late Carboniferous Salvan-Dorénaz continental basin (Western Alps, Switzerland/France). Sedimentology 51:675–697

Capuzzo N, Handler R, Neubauer F, Wetzel A (2003) Post-collisional rapid exhumation and erosion during continental sedimentation: the example of the late Variscan Salvan-Dorénaz basin (Western Alps). Int J Earth Sci 92:364–379

Cassinis G, Perotti CR, Ronchi A (2012) Permian continental basins in the Southern Alps (Italy) and peri-mediterranean correlations. Int J Earth Sci 101:129–157

Dallagiovanna G, Gaggero L, Maino M, Seno S, Tiepolo M (2009) U–Pb zircon ages for post-Variscan volcanism in the Ligurian Alps (Northern Italy). J Geol Soc Lond 166:101–114

Deroin JP, Bonin B (2003) Post-Variscan tectonomagmatic activity in Western Europe and surrounding areas: the mid-Permian episode. Boll Soc Geol It 2:169–184

Fisch W (1961) Der Verrucano auf der Nordost-Seite des Sernftales. Dissertation, University of Zurich

Fisch W, Ryf W (1966) Der Verrucano in den Glarner Alpen. In: Falke H (ed) Atti Del Symposium sul Verrucano Pisa Settembre 1965. Pacini Mariotti, Pisa, pp 233–244

Franks GD (1968) A study of Upper Paleozoic sediments and volcanics in the Northern Part of the Eastern Aar massif. Eclogae Geol Helv 61:49–140

Funk H, Labhart T, Milnes AG, Pfiffner OA, Schaltegger U, Schindler C, Schmid SM, Trümpy R (1983) Bericht über die Jubiläumsexkursion "Mechanismus der Gebirgsbildung" der Schweizerischen Geologischen Gesellschaft in das ost- und zentralschweizerische Helvetikum und in das nördliche Aarmassiv vom 12. bis 17. September 1982. Eclogae Geol Helv 76:91–123

Galli A, Le Bayon B, Schmidt MW, Burg JP, Reusser E, Sergeev SA, Larionov A (2012) U–Pb zircon dating of the Gruf Complex: disclosing the late Variscan granulitic lower crust of Europe stranded in the Central Alps. Contrib Mineral Petrol 163:353–378

Girty GH, Reiland DN, Wardlaw MS (1985) Provenance of the Silurian Elder Sandstone, north-central Nevada. Bull Geol Soc Am 96:925–930

Gisler C, Hochuli PA, Ramseyer K, Bläsi H, Schlunegger F (2007) Sedimentological and palynological constraints on the basal Triassic sequence in Central Switzerland. Swiss J Geosci 100:263–272

Gretter N, Ronchi A, Langone A, Perotti CR (2013) The transition between the two major Permian tectonostratigraphic cycles in the central Southern Alps: results from facies analysis and U/Pb geochronology. Int J Earth Sci 102:1181–1202

Hawkesworth CJ, Dhuime B, Pietranik AB, Cawood PA, Kemp AIS, Storey CD (2010) The generation and evolution of the continental crust. J Geol Soc Lond 167:229–248

Hermann J, Müntener O, Trommsdorff V, Hansmann W (1997) Fossil crust-to-mantle transition, Val Malenco (Italian Alps). J Geophys Res 102(B9):20123–20132

Hirt AM, Lowrie W, Pfiffner OA (1986) A paleomagnetic study of tectonically deformed red beds of the lower Glarus nappe complex, Eastern Switzerland. Tectonics 5:723–731

Huber R (1964) Etude géologique du massif du Gufelstock avec stratigraphie du Verrucano. Dissertation, ETH Zurich

Jongmans WJ (1950) Mitteilungen zur Karbonflora der Schweiz, I. Eclogae Geol Helv 43:95–104

Košler J, Fonneland H, Sylvester P, Tubrett M, Pedersen RB (2002) U–Pb dating of detrital zircons for sediment provenance studies—a comparison of laser ablation ICPMS and SIMS techniques. Chem Geol 182:605–618

Krippner A, Bahlburg H (2013) Provenance of Pleistocene Rhine River Middle Terrace sands between the Swiss–German border and Cologne based on U–Pb detrital zircon ages. Int J Earth Sci 102:917–932

Krogh TE (1973) A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochim Cosmochim Acta 37:485–494

Letsch D (2014) The Glarus Double Fold: a serious scientific advance in mid nineteenth century Alpine Geology. Swiss J Geosci. doi:10.1007/s00015-014-0158-8

Lorenz V, Nicholls IA (1976) The permocarboniferous Basin and Range province of Europe. An application of plate tectonics. In: Falke H (ed) The Continental Permian in Central, West, and South Europe. Reidel, Dordrecht, pp 313–342

Ludwig KR (2003) User's manuel for Isoplot 3.0, a geochronological toolkit for Microsoft excel. Berkeley Geochronology Center Special Publication 4:1–70

Markus JH (1967) Geologische Untersuchungen in den Flumserbergen. Dissertation, University of Zurich

Marquer D, Challandes N, Schaltegger U (1998) Early Permian magmatism in Briançonnais terranes: Truzzo granite and Roffna rhyolite (eastern Penninic nappes, Swiss and Italian Alps). Schweiz Miner Petrogr Mitt 78:397–414

Matter A (1987) Faciesanalyse und Ablagerungsmilieus des Permokarbons im Nordschweizer Trog. Eclogae Geol Helv 80:345–367

Mattinson JM (2005) Zircon U–Pb chemical abrasion ("CA-TIMS") method: combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chem Geol 220:47–66

McCann T, Pascal C, Timmerman MJ, Krzywiec P, López-Gómez J, Wetzel A, Krawcyk CM, Rieke H, Lamarche J (2006) Post-Variscan (end Carboniferous-Early Permian) basin evolution in Western and Central Europe. In: Gee DG, Stephenson RA (eds) European lithosphere dynamics, vol 32. Geol Soc (London), Memoirs, pp 355–388

Miller JS, Matzel JEP, Miller CF, Burgess SD, Miller RB (2007) Zircon growth and recycling during the assembly of large, composite arc plutons. J Volcanol Geoth Res 167:282–299

Muttoni G, Kent DV, Garzanti E, Brack P, Abrahamsen N, Gaetani M (2003) Early Permian Pangaea B to Late Permian Pangaea A. Earth Planet Sci Lett 215:379–394

Nio SD (1972) Geologische Untersuchungen im Verrucano des östlichen Glarner Freiberges. Dissertation, University of Zurich

Oberholzer J (1933a) Geologie der Glarneralpen I. Textband. Beitr Geol Karte Schweiz NF 28, xxxiv + 626 p

Oberholzer J (1933b) Geologie der Glarneralpen II. Atlas. Beitr Geol Karte Schweiz NF 29, 29 plates

Pfiffner OA (1972) Neue Kenntnisse zur Geologie östlich und westlich des Kunkelspasses (GR). Eclogae Geol Helv 65(3):555–562

Pfiffner OA (2009) Geologie der Alpen. Haupt Verlag, Bern

Pfiffner OA (2011) Structural map of the Helvetic Zone of the Swiss Alps. Geological special map 1:100,000 Nr. 128—explanatory notes

Pfiffner OA, Ramsay JG, Schmid SM (2010). Structural map of the Helvetic Zone of the Swiss Alps. Geological special map 1:100,000 Nr. 128, sheet 33 Toggenburg with parts of 38 Panixerpass

Pochat S, van den Driessche J (2011) Filling sequence in Late Paleozoic continental basins: a chimera of climate change? A new light shed given by the Graissessac-Lodève basin (SE France). Palaeogeogr Palaeoclimatol Palaeoecol 302:170–186

Richter H (1968) Die Geologie der Guschagruppe im St. Galler Oberland. Dissertation, ETH Zurich

Roscher M, Schneider JW (2006) Permo-carboniferous climate: early Pennsylvanian to Late Permian climate development of central Europe in a regional and global context. In: Lucas SG, Cassinis G, Schneider JW (eds) Non-Marine Permian biostratigraphy and biochronology, vol 265. Geological Society, London (special publication), pp 95–136

Ryf W (1965) Geologische Untersuchungen im Murgtal. Dissertation, University of Zurich

Schaltegger U (1993) The evolution of the polymetamorphic basement in the Central Alps unraveled by precise U–Pb zircon dating. Contrib Mineral Petrol 113:466–478

Schaltegger U (1994) Unravelling the pre-Mesozoic history of Aar and Gotthard massifs (Central Alps) by isotopic dating—a review. Schweiz Mineral Petrogr Mitt 74:41–51

Schaltegger U (1997) The age of an Upper Carboniferous/Lower Permian sedimentary basin and its hinterland as constrained by

U–Pb dating of volcanic and detrital zircons. Schweiz Mineral Petrogr Mitt 77:101–111

Schaltegger U, Brack P (2007) Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. Int J Earth Sci (Geol Rundsch) 96:1131–1151

Schaltegger U, Corfu F (1992) The age and source of Late Hercynian magmatism in the Central Alps: evidence from precise U–Pb ages and initial Hf isotopes. Contrib Mineral Petrol 111:329–344

Schaltegger U, Corfu F (1995) Late Variscan "basin and range" magmatism and tectonics in the Central Alps: evidence from U–Pb geochronology. Geodinam Acta 8:82–98

Schaltegger U, Abrecht J, Corfu F (2003) The Ordovician orogeny in the Alpine basement: constraints from geochronology and geochemistry in the Aar Massif (Central Alps). Schweiz Mineral Petrogr Mitt 83:183–195

Scheiber T, Berndt J, Heredia BD, Mezger K, Pfiffner OA (2013) Episodic and long-lasting Paleozoic felsic magmatism in the pre-Alpine basement of the Suretta nappe (eastern Swiss Alps). Int J Earth Sci. doi:10.1007/s00531-013-0926-0

Scheiber T, Berndt J, Mezger K, Pfiffner OA (2014) Precambrian to Paleozoic zircon record in the Siviez-Mischabel basement (western Swiss Alps). Swiss J Geosci. doi:10.1007/s00015-013-0156-2

Schielly H (1964) Geologische Untersuchungen im Deckengebiet des westlichen Freiberges. Dissertation, ETH Zurich

Schindler C (1959) Zur Geologie des Glärnischs. Beitr Geol Karte Schweiz NF 107, xiv + 135 p

Siddans AWB (1979) Deformation, metamorphism and texture development in Permian mudstones of the Glarus Alps (Eastern Switzerland). Eclogae Geol Helv 72:601–621

Smith GE, Dickinson WR, Ross GM, Stewart JH, Howell DG (1995) Detrital zircon reference for Cambrian to Triassic miogeoclinal strata of western North America. Geology 23:831–834

Trümpy R (1947) Ein Kristallinvorkommen an der Basis der Mürtschen-Decke oberhalb Luchsingen (Kt. Glarus). Eclogae Geol Helv 40:237–242

Trümpy R (1966) Considérations generals sur le « Verrucano » des Alpes suisses. Atti Smp Verrucano, Soc Tosc Sci Nat Pisa: 212–232

Trümpy R (1969) Die helvetischen Decken der Ostschweiz: Versuch einer palinspastischen Korrelation und Ansätze zu einer kinematischen Analyse. Eclogae Geol Helv 62:105–142

Trümpy R (1999) Die tektonischen Grosseinheiten im Bereich Alp Transit. In: Löw S, Wyss R (eds) Vorerkundung und Prognose des Basistunels. Balkema, Rotterdam, pp 21–29

Trümpy R, Dössegger R (1972) Permian of Switzerland. In: Falke H (ed) Rotliegend—essays on European Lower Permian. Int Sed Petr Ser 15:189–215

von Raumer JF, Bussy F, Schaltegger U, Schulz B, Stampfli GM (2013) Pre-Mesozoic Alpine basements—their place in the European Paleozoic framework. Bull Geol Soc Am 125:89–108

von Seckendorff V, Arz C, Lorenz V (2004) Magmatism oft he late Variscan intramontane Saar-Nahe Basin (Germany): a review. In: Wilson M, Neumann ER, Davies GR, Timmerman MJ, Heeremans M, Larsen BT (eds) Permo-Carboniferous magmatism and rifting in Europe, vol 223. Geological Society (London) special publication, pp 361–391

Walker TR (1976) Diagenetic origin of continental red beds. In: Falke H (ed) The Continental Permian in Central, West, and South Europe. Reidel, Dordrecht, pp 240–281

Wyss R, Isler A (2011) Blatt 1214 Ilanz. Geol Atlas d Schweiz 1:25‘000, Erläuterungen, Bundesamt für Landestopografie

Wyssling L (1950) Zur Geologie der Vorabgruppe. Dissertation, ETH Zurich