The Subvolcanic Units of the Late Paleozoic Halle Volcanic Complex, Germany: Geometry, Internal Textures and Emplacement Mode

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Abstract

The Late Paleozoic Halle Volcanic Complex (HVC) formed in the Saale basin, a NE-SW-trending intermountain depositional system located in the Variscan orogen in Central Europe. Apart from minor lava flows and pyroclastic deposits, the HVC is dominated by a c. 300 km³ rhyolitic laccolith complex. The individual porphyritic rhyolite units display aspect ratios between 0.04 and 0.07. They initially emplaced at different levels of the Saale basin fill. As a consequence, the units are separated by tilted host sediments. Precursory to the emplacement of the rhyolitic laccoliths, a small-volume intermediate sill complex formed at the northern margin of the HVC. This chapter summarizes knowledge on the geometry, composition, internal textures, age, and host rock deformation of the HVC subvolcanic units.

1 Introduction

In central Europe, the aftermath of the Variscan orogeny during the Late Paleozoic was characterized by, among others, the formation of extended subvolcanic complexes (Fig. 1; Von Seckendorff 2012). Outcrops, intensive quarrying and drilling provide, in places, excellent 3d exposure which has been utilized to improve our understanding for the evolution of large scale dyke, sill and laccolith complexes. Awdankiewicz (2004) reported on silica-rich laccoliths and basic sill complexes that formed in the Intra-Sudetic basin. Lorenz and Haneke (2004) discussed the sill and laccolith systems that developed during the Early Permian in the Saar-Nahe basin in south western Germany. Awdankiewicz et al. (2004) carried out a detailed textural analysis of a 30 km andesitic sill system exposed in the Flechtingen-Roßlau Block (FRB in Fig. 1) emplaced during the Carboniferous-Permian transition above folded Variscan basement and below a thick welded ignimbrite. Extensive dyke swarms developed co-genetically with the Altenberg-Teplice Volcanic Complex during the Late Carboniferous (Winter et al. 2008; Hoffmann et al. 2013, and references therein). A number of sills and dykes

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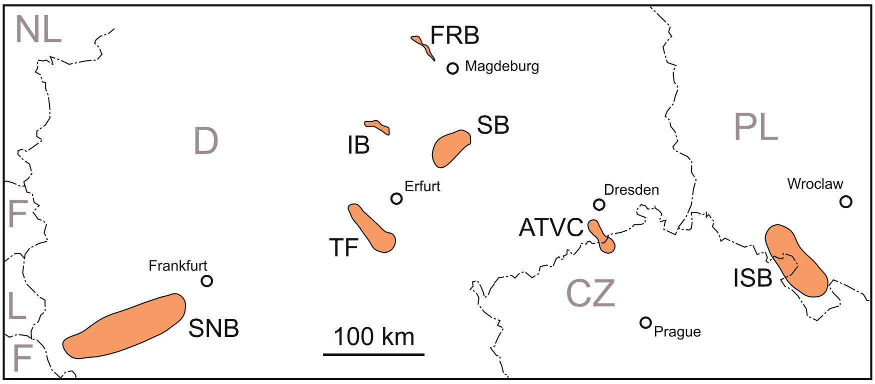

Fig. 1 Sketch map of central Europe depicting the location of Late Paleozoic basins and volcanic complexes which comprise a large portion of subvolcanic units; *ATVC* Altenberg-Teplice Volcanic Complex, *FRB* Flechtingen-Roßlau Block, *IB* Ilfeld Basin, *ISB* Intra-Sudetic Basin, *SB* Saale Basin, including the *HVC* Halle Volcanic Complex, *SNB* Saar-Nahe Basin, *TF* Thuringian Forest

have been reported from the Thuringian Forest (Fig. 1; e.g. Obst et al. 1999).

Breitkreuz and Mock (2004) employing examples from Late Paleozoic complexes in Germany (i.e., Saar-Nahe basin, Ilfeld basin, and the Halle Volcanic Complex, Fig. 1) proposed a genetic relation between laccolith formation and the activity of trans-tensional basin systems. They suggest that in these intra-montane basins the accumulation of thick sedimentary infill and the vertical orientation of the maximum principal stress (i.e., $\sigma_1 = \sigma_v = \rho gz$) favoured low ascent rates and devolatilisation of magma resulting in their emplacement as subvolcanic complexes. Also, sub-horizontal strength anisotropies in the host rock may arrest the ascent of rising magma (Hogan and Gilbert 1995).

This chapter integrates 20 years of joint research of the authors on the Halle Volcanic Complex (HVC). Our work has benefited from 200 years of research in the area and a long-standing debate about the effusive versus subvolcanic nature of the HVC rhyolitic and intermediate magmatic bodies (see references in Ehling and Breitkreuz 2006; Breitkreuz et al. 2009). In the present contribution, a geometric model for the Halle Intermediate Subvolcanic Complex (HISC), precursory to the HVC rhyolitic laccoliths, is presented; however, the HVC rhyolitic laccolith complex comprises the focus of this chapter. The HVC is dominated by a 300 km^3 rhyolitic laccolith complex the units of which were emplaced at different depths within a pile of then unconsolidated sediments[1] (Fig. 2). As such, Breitkreuz and Mock (2004) defined the HVC rhyolites as a type of laccolith complex ("Halle Type"). As will be shown below, the intrusive nature of the main HVC rhyolites is indicated by the geometry of the units, its textural homogeneity and the deformation of the hosting sediments (Mock et al. 2003, 2005; Schmiedel et al. online).

2 The Tectonic and Stratigraphic Framework of the Halle Volcanic Complex (HVC)

The HVC formed in the north eastern part of the Late Paleozoic Saale Basin (Fig. 1). The NE-SW trending basin developed as an intra-montane system under dextral trans-tension in the Saxothuringian Block during the decay of the Variscan orogen (Ehling and Gebhardt 2012). Subsidence and sedimentation started in the Moscovian

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[1] The HVC comprises subvolcanic bodies and a minor amount of lava and pyroclastic deposits. The rhyolitic subvolcanic units have non-plutonic textures. Therefore we maintain the term "rhyolite" for the laccolith bodies and we use the notion "Halle Volcanic Complex", both terms have been established in regional literature over the last 200 years.

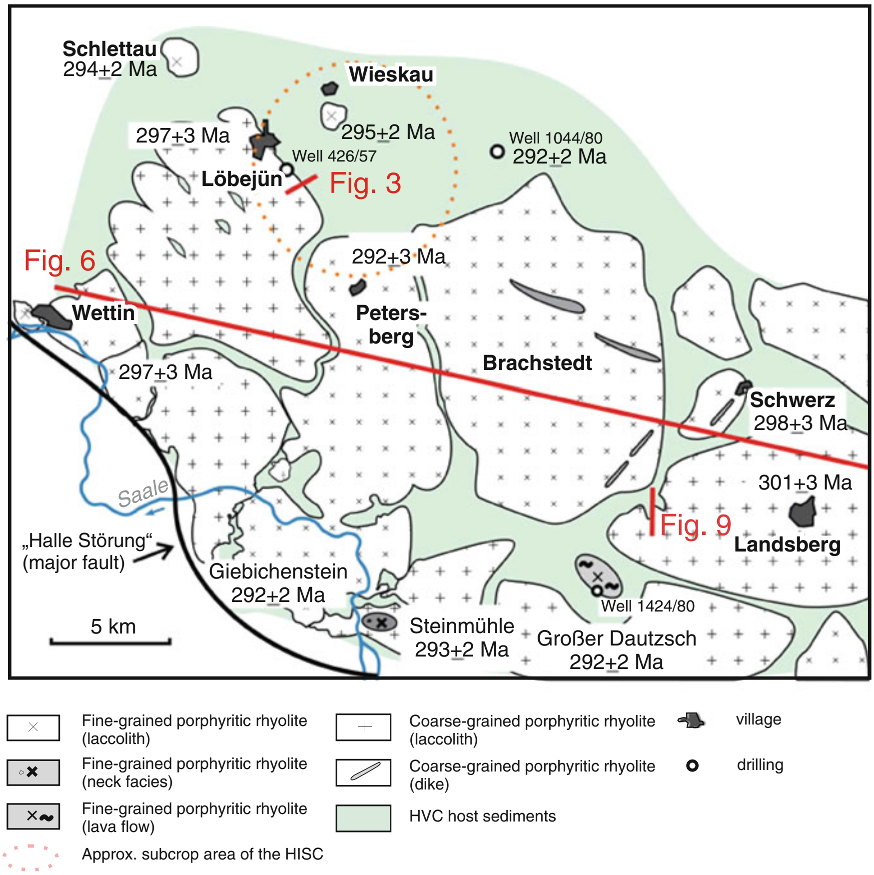

Fig. 2 Outcrop/subcrop map of the Halle Volcanic Complex (HVC) in the north eastern Saale Basin (Fig. 1), post-HVC cover not depicted; the age data have been taken from Breitkreuz et al. (2009)

(Westfalian) and continued into the Permian. Part of the basin fill consists of alluvial to fluvial conglomeratic to sandy red beds, the Siebigerode Formation (lower Gzhelian), which is replaced in the basin centre by grey coal-bearing clastics of the Wettin Member (≤350 m thickness; Ehling and Breitkreuz 2006; Breitkreuz et al. 2009). In some drill cores, the Wettin Member contains silica-rich volcanic fragments and subvolcanic intrusions demonstrating initial volcanic activity. Thus, the Saale Basin was affected relatively late by magmatism in its evolution.

The Halle Formation (Gzhelian-Asselian) overlies, locally unconformably, the Wettin Member. The >700 m thick Halle Fm. comprises reddish to green alluvial, fluvial to lacustrine (volcani-) clastic deposits (Ehling and Gebhardt 2012). It starts with a characteristic fluvial quartzite-chert sandstone-conglomerate complex (“Kieselschiefer-Quarzit-Konglomerat”, KQK, Kampe et al. 1965) which contains up to 20 % of carbonate pebbles (stromatolith fragments, ooids, onkoids, and pedogenic nodules; Ehling and Gebhardt 2012). Field relations and radiometric dating (Breitkreuz et al. 2009) indicate that the subvolcanic intrusions and volcanic eruptions of the HVC took place for some 9 Ma (292–301 Ma; Breitkreuz et al. 2009) contemporaneously to the deposition of the Halle Formation.

Only about 20 % of the HVC is exposed in natural outcrops or quarries (Mock et al. 2005). The area is relatively flat with a total relief less than 140 m. It was levelled by Pleistocene glaciers and the HVC rocks are partly covered by Cenozoic sediments. The 3d geometry of the HVC is constrained by data from more than

6,000 wells; most of which are shallow wells for foundation ground investigation and raw material exploration. Nevertheless, several hundreds of wells (coal and uranium exploration, and scientific investigation) have perforated the HVC to a depth of a couple of hundred metres (one well reached 1,100 m depth; Breitkreuz et al. 2009). A fraction of the recovered drill core is preserved in the core depository of the Sachsen-Anhalt Survey for Geology and Mining in Halle; documentation exists for every well.

3 The Magmatic Units of the HVC

Figure 2 depicts the outcrops and subcrops of the HVC. In the south west, the HVC is truncated along the "Halle Störung" (Knoth et al. 1998), a major fault which apparently confined the HVC already during its activity. This is suggested by drillings located some 10 km south west of the fault, such as well Querfurt 1/64 which does not cross HVC rhyolitic bodies (Hoth et al. 1993; Gebhardt and Lützner 2012). Whether this fault acted as a feeding system for HVC laccoliths, as e.g. Grocott et al. (2009) documented for plutons in northern Chile, is not known.

The HVC is dominated by rhyolitic laccoliths (Mock et al. 2005). Apart from these, the following other volcanic and subvolcanic rock types are known:

- Lava complexes developed late in the evolution of the HVC; e.g., a c. 100 m thick porphyritic lava flow with a basal and top breccia has been documented by Geißler (2001) in drilling 1044/80 (Fig. 2) and it has been dated with SHRIMP U/Pb on zircon at 292 ± 2 Ma (Breitkreuz et al. 2009); another, aphanitic lava is exposed in well 1424/80 (Fig. 2).
- Ignimbrites and other pyroclastic deposits such as fallout and flow deposits, some associated with vulcanian eruptions, are present within the Halle Fm. (Breitkreuz et al. 2009).
- Within the city of Halle, a number of permanent and temporary outcrops exposed products of explosive volcanic centres such as the Steinmühlen Vent Complex with diatreme breccias and pyroclastic dykes (Fig. 2, 293 ± 3 Ma; Ehling and Bachmann 2006; Breitkreuz et al. 2009).
- The Halle Intermediate Sill Complex (HISC), scarcely outcropping, but intensively drilled, has been discovered at the northern margin of the HVC (Fig. 2; Kampe et al. 1965; Schulz 2010). Furthermore, a number of other drillings detected intermediate sills and dykes in the eastern HVC (Breitkreuz et al. 2009).

The HISC rocks are of trachybasaltic to trachydacitic composition, and contain petrographic features that are interpreted to indicate magma mixing (Siegert 1967a; Romer et al. 2001). In contrast, the HVC rhyolites have a very homogenous, calc-alkaline, mildly peraluminous low-SiO_2 composition (71.2–72.2 wt% SiO_2, A/CNK = 1.04 – 1.21; Romer et al. 2001). Major and trace element whole rock composition, and Nd-, Pb-, Sr-isotope ratios in alkali feldspar phenocrysts indicate the source for HVC magma was an enriched mantle mixed with a large crustal component. The trace element and isotope systematics indicate that the HVC rocks were affected by hydrothermal alteration (Romer et al. 2001), presumably during the early Mesozoic (Brecht 1999; Jacobs and Breitkreuz 2003).

4 The Halle Intermediate Subvolcanic Complex (HISC)

The HISC located in the north of the HVC (Fig. 2) has been interpreted as a lava complex by Kampe et al. (1965) and subdivided into four units which allegedly evolved over a long time during the deposition of the Wettin Member and Halle Formation (Siegert 1967a, b). Subcrop relations indicate that the HISC is a precursor of the HVC rhyolitic laccoliths (Fig. 3). Using data from 1,200 wells in a 58 km^2 area at the northern margin of the HVC (Fig. 2), we constrained the 3d geometry of the 3rd and 4th series of HISC (Schulz 2010[2]). The geological objects were

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[2] Unpublished diploma thesis by Nicole Schulz, co-author of the present contribution (N. Pastrik)

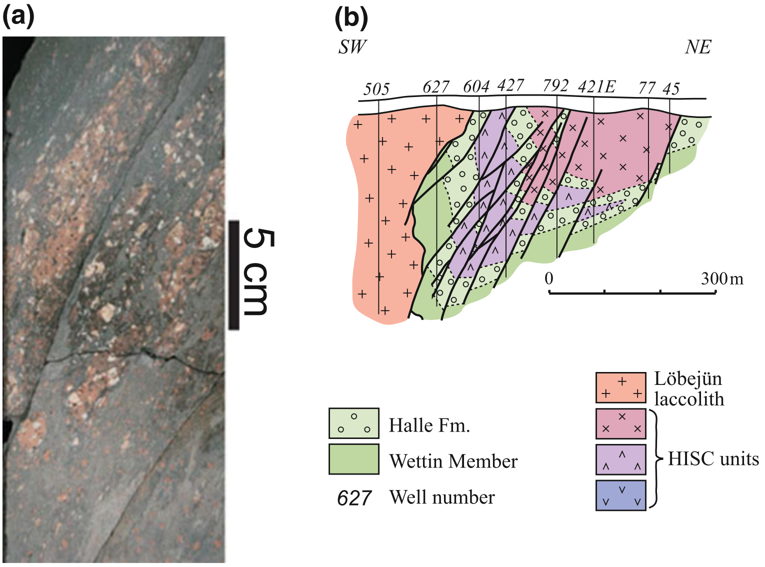

Fig. 3 The NE margin of the Löbejün laccolith unit: **a** In the contact zone of the intrusive-extrusive complex peperitisation and intense shearing took place; the *photo* shows aligned fragments of porphyritic rhyolite in highly deformed host sediments (drill core 426/57, for location see Fig. 2); **b** SW-NE profile through the margin of the rhyolite and its deformed and overturned host sediments and HISC units (after Kampe et al. 1965; for location see Fig. 2)

modeled and interpreted by the 3d-software GOCAD which is based on Discrete Smooth Interpolation (DSI) and uses nodes and control points to define heterogeneous data. GOCAD incorporates other numeric properties, not only the geometry like other 3d-modeling software (Mallet 2002). The Delauney-triangulation (min-max-criterion) is used for minimizing the roughness of the interpolation surface by the optimization of the triangulated mesh.

A number of HISC bodies cross cut the KQK at the base of the Halle Fm.; an observation that resulted in a reinterpretation of the HISC as a subvolcanic system of saucer-shaped sills (Fig. 4). Figures 4b, c illustrate that the HISC units, up to 290 m thick and up to 3.6 km long with aspect ratios between 0.08 and 0.14, were emplaced into the Wettin Member and the Halle Formation on both sides of a NW-SE trending horst structure marked by the KQK (Fig. 4c). Complex interactions between tectonic, volcanic activities and sedimentation affected magma rising, sill emplacement and subsequently displacements. Some units appear to be stacked one upon the other (e.g. HISC units AN 3a and 4a; Fig. 4c), possibly fed by common conduits. The andesites are mainly fed by single-feeder systems (e.g. HISC unit AN 4c, Fig. 4b) but also multi-feeder dykes are identifiable (e.g. HISC unit AN 4a, Fig. 4b). The model reveals geometric relationships of the HISC with the KQK which suggests that the then unconsolidated conglomeratic horizon facilitated initial sill emplacement (Fig. 4a, c). Furthermore, from the modelled cross-sections (e.g. Fig. 4c) we infer that the KQK was displaced into today´s horst structure before the HISC melts took place (Schulz 2010).

5 Geometry of the HVC Rhyolitic Laccoliths

The HVC is dominated by ca. 300 km^3 of rhyolitic laccoliths (Mock et al. 2005). This is a minimum estimation, as it includes known units and does not consider parts of laccoliths removed by erosion. The larger rhyolitic HVC units are (i) the coarsely porphyritic laccoliths, such as Löbejün-, Giebichenstein-, Großer Dautzsch- and Landsberg units, and (ii) the finely porphyritic

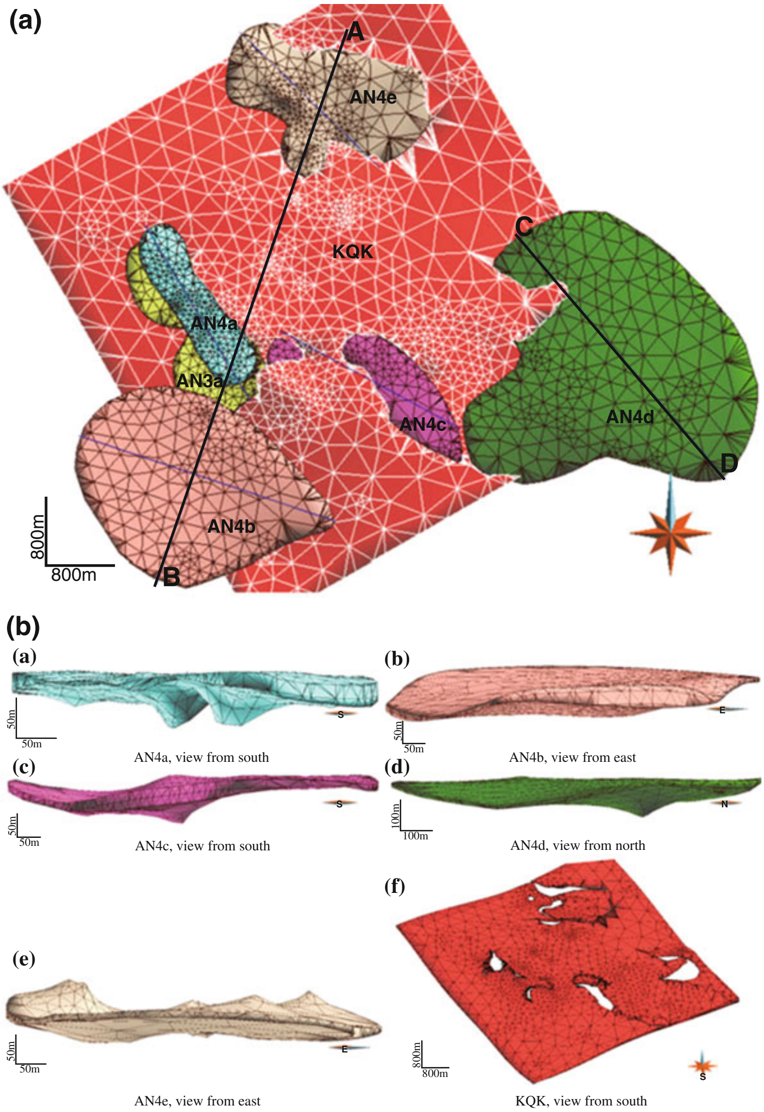

Fig. 4 The Halle Intermediate Sill Complex (HISC) in the northern part of the HVC (see Fig. 2 for location); **a** birds eye's view of the 3d HISC model (GOCAD) showing the top plane of the KQK (*red*; see text) and subvolcanic units AN 3a and 4a–e, AN 3b covered by KQK; **b** lateral geometry of five HISC bodies and the KQK viewed from different directions; the white areas in the KQK plane mark locations where the HISC units pierced the KQK; **c** profiles *A*–*B* and *C*–*D* (see Fig. 4a for location) generated from the 3d model emphasizing the cross cutting relation of the HISC bodies with respect to the horst structured KQK (=base of the Halle Fm.), showing the nested units AN 3a and AN 4a, the conical feeding structure of AN 4d and the implications of the Löbejün fault for the sill emplacement on the western margin of KQK (from Schulz 2010), note the vertical exaggerations

units like Wettin, Petersberg, Brachstedt and Schwerz (Figs. 2 and 5; Breitkreuz et al. 2009). The most intriguing aspect of the HVC are the domains of deformed host sediments (Siebigerode Formation, Wettin Member and Halle Formation) separating the laccolithic units (Figs. 2 and 6). Integration of field observations, drill hole data, and modelling of the magnetic field intensity (Fig. 7; Lange 2000) were used to constrain the distribution of the intervening sediments and the thickness of the HVC laccolith units (see also Schmiedel et al. online).

The Wettin laccolith unit has been eroded down to about 50 m (Mock et al. 1999; Exner and Schwab 2000). The Petersberg unit measures about 380 m (Mock et al. 2003), and the Brachstedt laccolith about 500 m. For the other units such as Löbejün and Landsberg only minimum thickness estimates (>600 m) can be given as the floor of these laccoliths has never been penetrated by drilling (Breitkreuz et al. 2009). Schmiedel et al. (online) calculated aspect ratios between 0.04 and 0.07 for the HVC rhyolitic laccoliths.

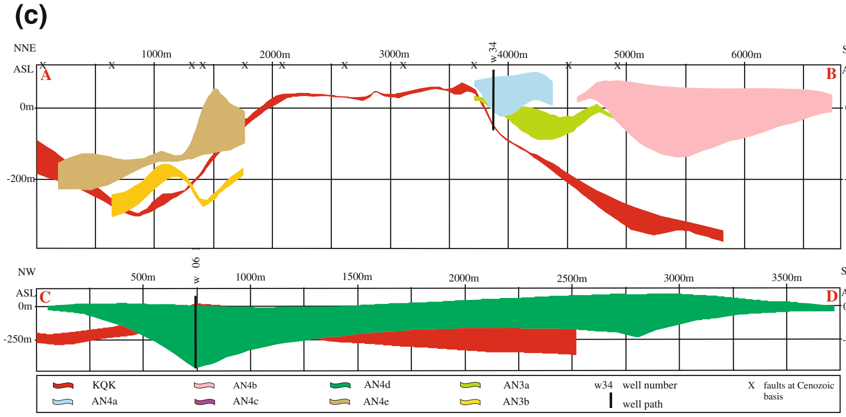

Fig. 4 (continued)

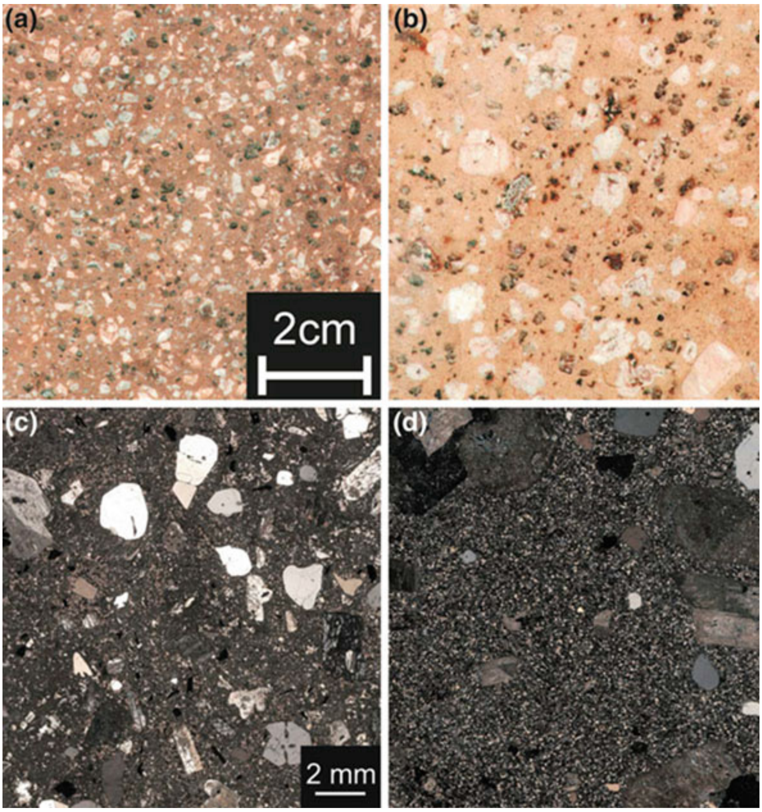

Fig. 5 Photographs of polished rock slabs and thin sections of HVC rhyolites; **a** finely porphyritic Petersberg unit; **b** coarsely porphyritic Löbejün unit; **c** Petersberg unit, x nicols; **d** Löbejün unit, x nicols

The Löbejün and the Landsberg units display features indicative of intrusive-extrusive complexes. Intrusive-extrusive complexes receive high volumes of viscous magma sufficient to lift up the overburden and pierce the sedimentary cover (Stark 1912; Lorenz and Haneke 2004). Coal exploration drilling at the north eastern margin of the Löbejün complex revealed vertical to overturned contact zones of the coarsely porphyritic magmatic body with the host succession (Fig. 3; Kampe et al. 1965; Mock et al. 2005). Piercing is also inferred from the fact that

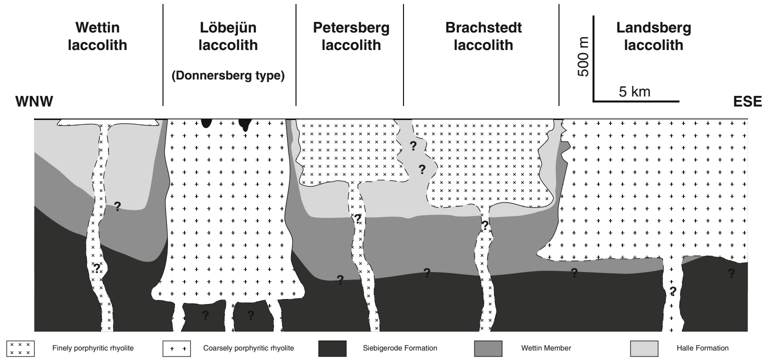

Fig. 6 Schematic WNW-ESE profile through the major HVC laccolith units; topography and post-emplacement tectonic displacement not depicted; for location see Fig. 2; note strong vertical exaggeration (Schmiedel et al. online)

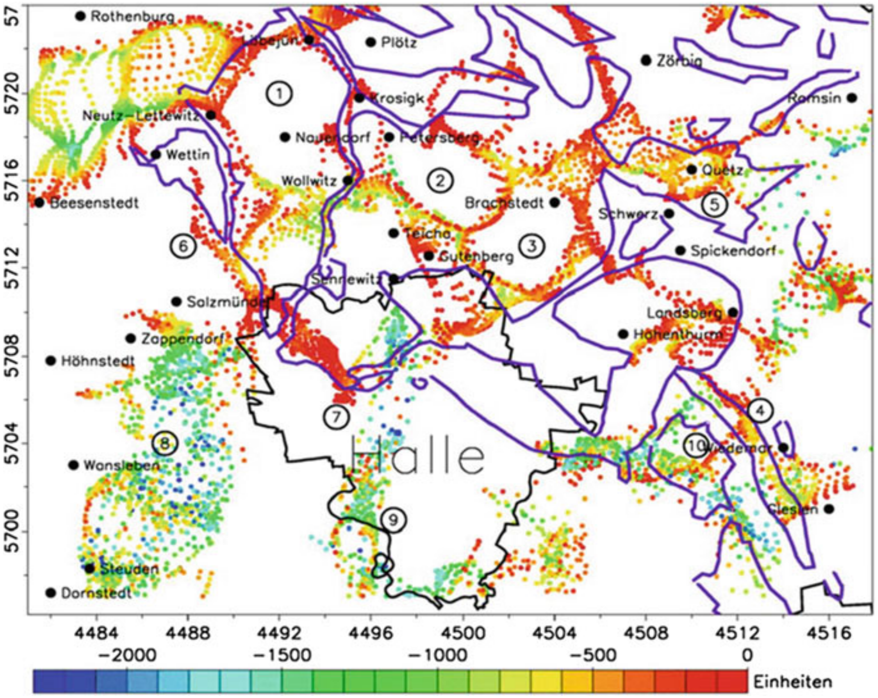

Fig. 7 Euler de-convolution of the pole-reduced magnetic field of the HVC area (from Lange 2000); the coloured dots display only a relative depth trend; the violet lines mark the geological HVC borders according to Knoth et al. (1998); The model indicates the position of the host sediments separating HVC laccolith units (compare to Fig. 2)

different units of the overburden (Siebigerode Formation, Wettin Member, Halle Formation, and intercalated HISC units) are in direct contact with the magmatic body, in places displaying intensive shearing and peperites (Fig. 3). Finally, four isolated pockets of Siebigerode Fm. have been detected by drilling in the top region of the Löbejün subvolcanic body (Figs. 2 and 6). These pockets are interpreted as remnants of the upper host sediments of the initial sill intrusion. Similar pockets of host sediments have been mapped in the summit area of the Late Paleozoic Donnersberg intrusive-extrusive complex in the Saar-Nahe basin in western Germany (Fig. 1; Lorenz and Haneke 2004). Therefore we infer that the Löbejün intrusive-extrusive complex represents a Donnersberg-type laccolith (Breitkreuz and Mock 2004), where several rhyolitic units were initially emplaced at a common level in the Siebigerode Fm.

For the Landsberg unit, evidence of an extrusive late phase comes from the presence of monomict mass flow deposits exposed in the Halle Fm. in the lower part of drilling WISBAW 1424/80 (Fig. 2). These sedimentary breccias comprise exclusively clasts of Landsberg porphyritic rhyolite, and are interpreted as gravitative mass flow deposits originating from the upper extrusive part of the Landsberg laccolith.

6 Internal Textures of the HVC Laccoliths

The HVC rhyolitic laccoliths are highly porphyritic with phenocrysts of alkali feldspar, plagioclase, and quartz (and minor amounts of biotite) in a finely crystalline groundmass (65 to 90 %, Figs. 5 and 8; Mock et al. 2005). Except for some domains of black rhyolites in the Schwerz laccolith unit (Fig. 2) which contains magnetite in the groundmass (Krauß 2003), the rhyolites are typically reddish to pink in color due to fine-grained hematite in the groundmass and in the alkali feldspar phenocrysts. The most noticeable difference between the coarse and fine-grained HVC units is the size of alkali feldspar that ranges from less than 10 to almost 40 mm (Figs. 5 and 8). Crystal size distribution analysis (CSD) suggests that the size of felsic phenocrysts in HVC rhyolites did not change significantly after emplacement (Mock et al. 2003, 2005). Instead, it must have been attained during magma ascent and temporal storage in magma chambers below the Saale basin at mid-crustal level (Breitkreuz and Mock 2004).

A major difference between subvolcanic rhyolites (sills and laccoliths) and subaerial lava is the dominance of carapace facies over core facies, the latter being characterized by brecciation, vesiculation, and the formation of spherulites and lithophysae (Manley and Fink 1987; Paulick and Breitkreuz 2005; Breitkreuz 2013). With the HVC subvolcanic rhyolites, the carapace facies is restricted to dm-wide marginal domains with spherulitic and perlitic groundmass and sheared phenocrysts (Mock et al. 2005; Schmiedel et al. online). Drilling Brachwitz 2/62 revealed larger brecciated domains at the south western margin of the Wettin laccolith unit (Fig. 8 in Mock et al. 2005). The rest of the HVC laccolith units display core facies with a homogenous finely crystalline groundmass (Fig. 5c, d).

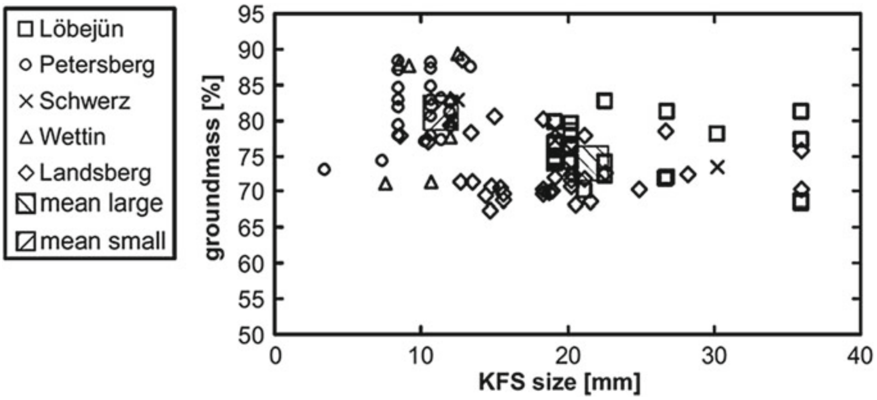

Fig. 8 Maximum particle size (MPS) of alkali feldspar phenocrysts versus area % of groundmass of HVC rhyolites (Mock et al. 2005)

Only the finely porphyritic units show flow foliation and scarce irregular-shaped vesicles (Mock et al. 2005). Mock et al. (1999) reported brecciation planes associated with the flow foliation from the Wettin laccolith unit. Flow foliation is marked by a variation in phenocryst concentration and size, the presence of brecciated lenses, and scarce vesicles aligned along flow planes. Distance between foliation planes is 20–40 cm. In the Wettin laccolith unit, the flow foliation resembles a bowl-shaped architecture, with the planes dipping towards the centre of the laccolith body with dip angles between 8°–80° (Mock et al. 2005). The bowl-shaped flow geometry is consistent with the assumption of advanced erosion removing the upper portions of the Wettin laccolith such that only the lower third remains. In contrast, the flow foliation architecture in the Petersberg laccolith unit resembles a complex cupola shape with dip angles of 18°–83° away from the centre of the magmatic body. This and the occurrence of carapace facies in the summit area of the Petersberg hill suggest that the today's erosional level exposes the upper third of that unit (Mock et al. 1999, 2005).

7 Emplacement of HVC Laccoliths: Textures and Models

Different models have been proposed for the horizontal and vertical growth of silica-rich subvolcanic systems. Inflation by periodic or continuous magma intrusions into the central part of the growing laccolith is the traditional model ("ballooning"; e.g., Schwab 1959; Corry 1988; Lorenz and Haneke 2004). Successive emplacement of magma sheets at the top of the growing subvolcanic body is the other, more current concept (Horsman et al. 2009). As will be discussed below, in the HVC laccolith complex we find indications for both models.

With some local exceptions, such as the Wettin (Mock et al. 1999) and the Schwerz laccolith complex (Krauß 2003), outcrops and drill cores of the HVC typically do not show prominent liquid-solid contacts within a given laccolith unit. From this, a batch-wise or continuous laccolith growth can be inferred, where the following magma batch was emplaced before the previous batch solidified (Horsman et al. 2009).

In R-value versus matrix % plots, the spatial distribution patterns (SDP) can be differentiated for ordered versus clustered distribution of phenocrysts (Jerram et al. 1996). This plot also allows for a distinction between touching and non-touching phenocryst frameworks. Mock et al. (2003) explored the SDP for six samples from a 300 m well through the Petersberg laccolith, revealing a non-touching framework (see also Mock and Jerram 2005) and a clustering to ordered distribution of felsic phenocrysts. R-value versus sample depth (from drill cores) plots have been applied for the Petersberg-, Löbejün- and Landsberg laccolith units to estimate the thickness of emplacing sheets in the growing laccolith (Mock et al. 2005). The data suggest sheet thickness in the order of 100 and up to 200 m.

In some areas of HVC, well spacing density allows for a more detailed geometric modelling of the laccolith margins. "Fingering" of rhyolite melt (Hutton 2009) into the sedimentary host has been documented for the Wettin laccolith unit (Fig. 8 in Mock et al. 2005), and for the western margin of the Petersberg laccolith unit (Schmiedel et al. online). Drill core data, from a dense cluster of uranium exploration wells, allowed the spectacularly complex margin of the Landsberg laccolith unit to be constrained by GOCAD geometric modelling (Schmiedel et al. online). Based on these results, the Landsberg laccolith is interpreted to have formed from melt sheets 100–300 m thickness. At its north western margin, the melt batches tilted, engulfed, and deformed rafts, up to 1,400 m in diameter, of the host Wettin Member and Halle Formation, (Fig. 9). A few xenoliths of sedimentary and crystalline rocks up to several meters in diameter have also been described from other HVC laccoliths (Koch 1981; Mock et al. 2005).

Similar deformed sedimentary domains surrounded by subvolcanic sheets, however on much smaller scale, have been described from the margin of the Trachyte Mesa laccolith in the Henry Mountains, Utah (Morgan et al. 2008;

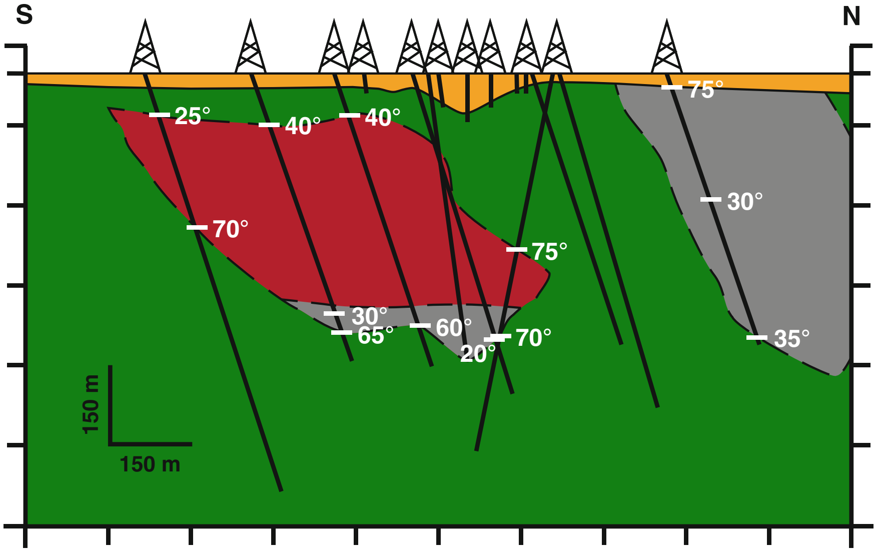

Fig. 9 GOCAD modelled cross section through the Landsberg margin (for location of profile see Fig. 2): *green* Landsberg laccolith, *grey* Wettin Member, *red* Halle Formation, *yellow* Cenozoic cover, *dip angles* bedding relative to drill axis; (Schmiedel et al. under review)

Horsman et al. 2009). Textural and AMS analysis in the Trachyte Mesa, Maiden Creek and Black Mesa intrusions in the Henry Mountains of Utah (USA) revealed that a series of sub-horizontally stacked dacitic magma sheets were emplaced at 3–4 km depth into consolidated sediments resulting in horizontal and vertical growth of the subvolcanic bodies (Horsman et al. 2005, 2009; Morgan et al. 2008). Individual sheets measure between 1 and 20 m thick. We speculate that the greater thickness of HVC sheets is probably related to a higher viscosity of the porphyritic rhyolites and to a shallower depth of intrusion (<1,000 m).

Estimating an original thickness of about 1,000 m for the Löbejün and Landsberg laccolith units may have formed by emplacement of 5–6 successive batches of magma. Assuming a cooling time of about 300 years per batch—inferred from calculations carried out by Mock et al. (2005)—emplacement of the c. 65 km^3 Löbejün and Landsberg units would have lasted less than 2,000 years. This corresponds to magma ascent rates of 0.01–0.1 km^3 a^{-1}, which are typical values for magmatic bodies of this size (de Saint-Blanquat et al. 2011).

In summary, HVC evolution lasted about 9 Ma (Breitkreuz et al. 2009), punctuated by the short-lived formation (<2,000 years each) of coarsely and finely porphyritic laccoliths some of which grew up to 65 km^3 (Löbejün and Landsberg units). Explosive and effusive volcanic eruptions occurred late in the HVC evolution. As emphasized by Romer et al. (2001), throughout the HVC evolution the rhyolitic rocks are of remarkably homogenous composition, implying the longstanding existence of a large mid-crustal magma chamber which had been tapped repeatedly during active phases of HVC construction (Breitkreuz and Mock 2004). In this *Halle-type* laccolith complex, highly porphyritic units emplaced initially at deeper levels of the Saale basin fill, compared to less porphyritic units such as Wettin, Petersberg- and Brachstedt. During ascent and emplacement, the highly porphyritic Löbejün and Landsberg melts presumably were characterized by density 17–20 kg/m^3 higher than the finely and less porphyritic melts (Mock et al. 2005). High density together with high viscosity, the latter inferred from the high phenocryst content and thus higher supercooling, presumably led to a deeper level of initial emplacement, and to a stronger vertical inflation of the Landsberg and Löbejün units (Mock and Breitkreuz 2006).

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