

# Geometry of laccolith margins: 2D and 3D models of the Late Paleozoic Halle Volcanic Complex (Germany)

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**Abstract** Well data and core samples from the Late Paleozoic Halle Volcanic Complex (HVC) have been used to describe the geometry of the rhyolitic porphyritic laccoliths and their margins. The HVC formed between 301 and 292 Ma in the intramontane Saale basin, and it comprises mainly rhyolitic subvolcanic bodies (~300 km<sup>3</sup>) as well as minor lava flows and volcanoclastic deposits. The major HVC laccolith units display aspect ratios ranging between 0.04 and 0.07, and they are separated by tilted and deformed Carboniferous–Permian host sediments. For the margin of the Landsberg laccolith, a major coarsely porphyritic unit of the HVC, an exceptional data set of 63 wells concentrated in an area of 10 km<sup>2</sup> reaching to depth of 710 m exists. It was used to explore the 3D geometry and textures, and to deduce an intrusion model. For a 3D visualization of the Landsberg laccolith margin, Geological Object Computer Aided Design; Paradigm<sup>®</sup> software (GOCAD) was used. *Curve objects* have been derived from the intrusion–host contacts. Automated GOCAD<sup>®</sup> methods for 3D modelling failed. As a result, manual refinement

was essential. A major finding of the 3D modelling is the presence of prolate sediment rafts, up to 1,400 m in length and up to 500 m in thickness, surrounded by Landsberg rhyolite. The sedimentary rafts dip away from the laccolith centre. The engulfing laccolith sheets reach thickness of 100–300 m. For other HVC laccolith units (Löbejün, Petersberg, Brachstedt), well data reveal vertical rhyolite/sediment contacts or magma lobes fingering into the host sediments. HVC laccolith contact textures include small-scale shearing of the intruding magma and of the host sediment. In addition, internal shear zones have been detected inside the rhyolite bodies. The present study suggests that the emplacement of successive magma sheets was an important process during laccolith growth in the HVC.

**Keywords** GOCAD<sup>®</sup> · Well data · Magma sheet emplacement · Porphyritic rhyolite

## Introduction

Traditionally, subvolcanic complexes have been in the focus of geological interest either as important factor in geological basin development or for their genetic link with economic resources/deposits. For the understanding of both, the geometry and dimensions of these complexes are the key elements. Three-dimensional modelling of basaltic sill complexes has been carried out based on seismic data of hydrocarbon plays, e.g. in the North Atlantic (Thomson and Schofield 2008). The geometry of sills and laccoliths, among others their aspect ratio (height by length), is strongly controlled by composition and thus by viscosity, and by magma volume (Bunger and Cruden 2011).

The emplacement of laccoliths and the mode of vertical inflation are still a matter of debate. As one end member,

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piston-shape uplift by ballooning developing onion-skin geometry of the flow foliation was the favoured model for a long time (Gilbert 1877; Schwab 1959; Corry 1988). The other end member is the Christmas tree laccolith complex featuring a number of rather flat laccolith units intruding the host sediments in different levels (Cross 1894; Rocchi et al. 2010). More recently, batch-wise or successive lid emplacement has been assumed facilitating a vertical growth of subvolcanic bodies and plutons. Cruden and McCaffrey (2001) discussed batch-wise underplating of plutons by floor subsidence. For the Trachyte Mesa and Black Mesa intrusions in the Henry Mountains, a growth by overplating is viewed where successive magma sheets intruded between the sedimentary cover and the previously emplaced batch (de Saint Blanquat et al. 2006; Morgan et al. 2008; Horsman et al. 2009). The contact zones between emplaced sheets are visible at the outer margins of the subvolcanic bodies in the form of a few centimetre wide shear zones with minor (millimetre wide) offsets (Morgan et al. 2008).

During the evolution of subvolcanic complexes, domains of the host rock can get engulfed by magma. When lobes (“fingers”) of mafic magma that intruded into different levels of the sedimentary host inflate, sediment domains (“bridges”) form (Awdankiewicz et al. 2004; Hutton 2009). Small-scale sediment pockets (a couple of metres across) engulfed by dacitic magma sheets have been described from the north-western margin of the Trachyte Mesa intrusion in the Henry Mountains (Morgan et al. 2008). Apparently, analysis of texture and geometry of the lateral margins reveal important information on the evolution of laccoliths, whereas in the interior many textures are being destroyed by annealing and recrystallization (Morgan et al. 2008).

The Halle Volcanic Complex (HVC) is the type locality for a “Halle-Type” laccolith complex (Breitkreuz and Mock 2004; Breitkreuz et al. 2009), where the laccolith units initially emplaced in different levels of the sedimentary fill of the Saale basin (Ehling and Gebhardt 2012). The laccolith units are separated by tilted and deformed host sediments (Fig. 1). Although this overall geometry is well documented by 1,000 s of wells along with scarce outcrops, little has been published about the contact zones of the rhyolitic bodies and the intervening host sediments. Here, we present an updated schematic profile through the HVC and a new profile of the contact zone between two neighbouring laccolith units. The main part of the contribution features a drill data-based 3D-geometric model of a laccolith margin in the south-eastern part of the HVC.

## Geological setting

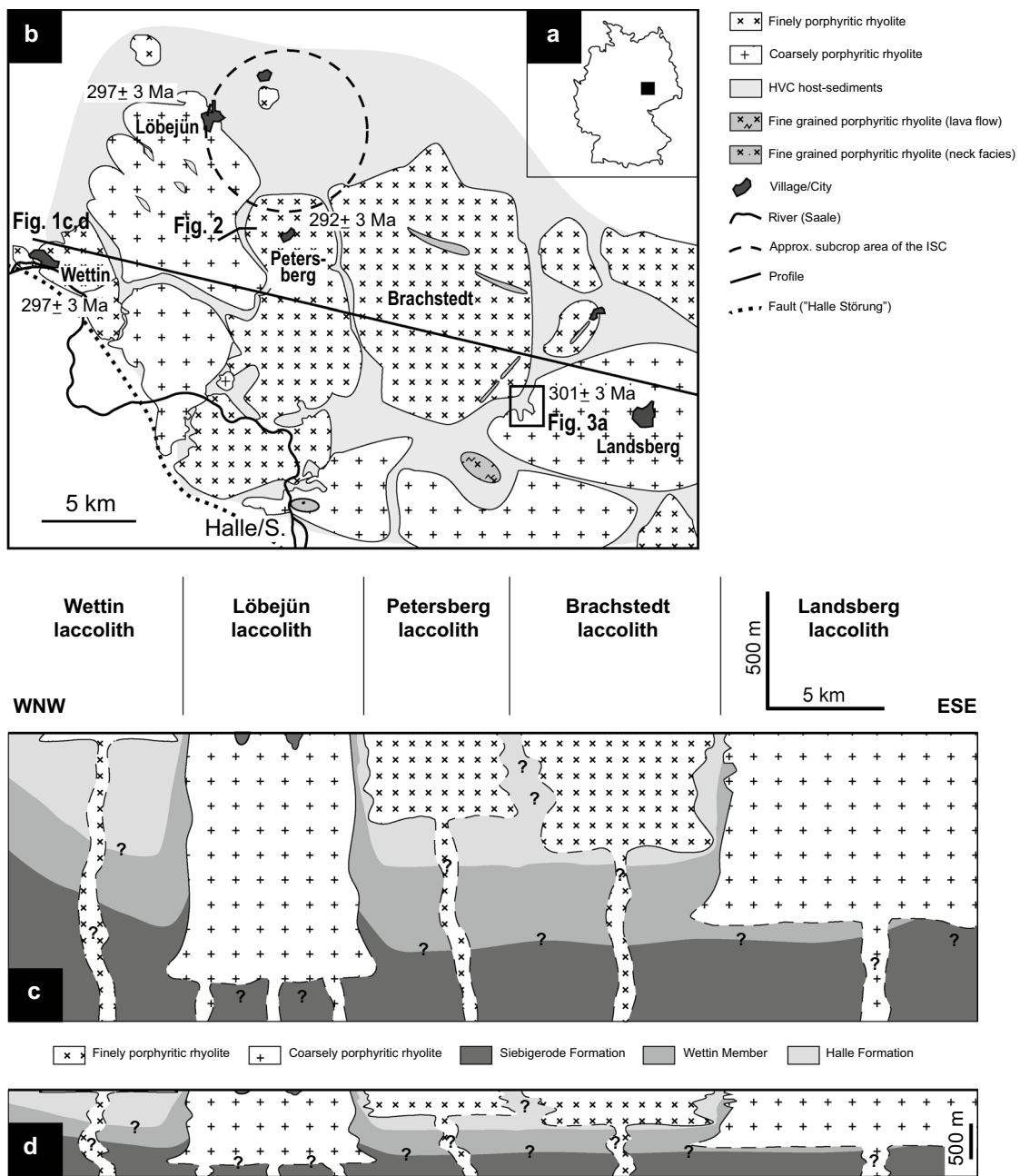
The HVC mainly comprises a 300 km<sup>3</sup> silica-rich subvolcanic complex, which formed over a period of about 9 Ma

(Gzhelian–Asselian) in the north-eastern part of the intramontane Late Paleozoic Saale Basin (Fig. 1b; Mock et al. 2005; Breitkreuz et al. 2009). The average SiO<sub>2</sub> content is 72 wt% (Romer et al. 2001), and the amount of felsic phenocrysts varies between 20 and 30 % (Mock et al. 2005). K-feldspar phenocryst size between 12 and 40 mm is the most noticeable difference between coarsely and finely porphyritic HVC units (Mock et al. 2005). In the northern part of the HVC, a small intermediate sill complex (ISC), precursory to the HVC rhyolites, has been discovered by exploration drilling (Fig. 1b; Siegert 1967; Schulz 2010; Breitkreuz et al., accepted).

The HVC magmatism was a relatively late stage in the evolution of the Saale basin, and it was associated with activity of a major NW–SE trending fault (“Halle–Störung”) confining the HVC at its south-west border (Hoth et al. 1993; Knoth et al. 1998; Gebhardt and Lützner 2012). The different HVC units intruded into the clastic sediments of the Siebigerode Formation (lower Gzhelian), into its coal seam-bearing basin centre equivalent, the Wettin Member, and into the overlying (volcani)clastic sediments of the Halle Formation (Gzhelian–Asselian; Breitkreuz et al. 2009; Ehling and Gebhardt 2012).

Only 20 % of the HVC is exposed in outcrops at the surface, because of extended cover by Cenozoic sediments. However, about 6,000 wells, several reaching down to 700 m depth and more, allow for an assured picture of the distribution of rhyolitic laccoliths and intervening host sediments (Figs. 1, 2). The highly and coarsely porphyritic Löbejün and Landsberg units initially emplaced relatively deep in the Siebigerode Formation and Wettin Member, respectively. The base of the Löbejün and Landsberg laccoliths has never been perforated by wells. During growth, these two units pierced the sedimentary cover forming intrusive–extrusive complexes (Fig. 1c, d; Breitkreuz et al. 2009; Breitkreuz et al., accepted, see also Lorenz and Haneke 2004). The finely porphyritic Wettin, Petersberg and Brachstedt units emplaced as relatively thin laccoliths in the Halle Formation (Fig. 1c, d; Breitkreuz et al. 2009). For the coarsely porphyritic Löbejün and Landsberg units, aspect ratios are in the order of 0.07, whereas for the finely porphyritic Petersberg and Brachstedt units, aspect ratios of about 0.04 have been calculated (the Wettin unit is not suitable to aspect ratio calculation due to its advanced status of erosion; Fig. 1). Only the finely porphyritic HVC units like Petersberg and Wettin feature prominent flow foliation and flow-oriented phenocrysts (Mock et al. 2005).

Based on data from numerous coal exploration wells, Kampe et al. (1965) published three profiles (also shown in Mock et al. 2005) of the NE margin of the Löbejün laccolith. The profiles display a vertical contact between the laccolith and the partly overturned host sediments. Five



**Fig. 1** The Halle Volcanic Complex in eastern Germany. **a** HVC location, **b** Outcrop and subcrop map of the HVC laccoliths with intrusions ages (Breitkreuz et al. 2009), **c** schematic profile (ten times vertical exaggeration), **d** same as c with three times vertical exaggeration

kilometres to the south, the Löbejün and Petersberg laccoliths are closely positioned separated by only 500 m of tilted host sediments (Fig. 2). The western margin of the Petersberg unit is characterized by lobes emplaced into the Halle Formation. In contrast, the eastern margin of the Löbejün laccolith appears to be vertical. Steep dip angles documented for the Halle Formation in the wells (Fig. 2)

are presumed to reflect the deformation during the vertical growth of the intrusive–extrusive complex.

The Landsberg coarse-grained porphyritic laccolith represents an early ( $301 \pm 3$  Ma; Breitkreuz et al. 2009) emplacement unit of the HVC (Fig. 1b, c). Horizontal extent is ca. 14 by 8 km; wells drilled down to 710 m did not reach the base. Thus, a minimum volume of ca.  $63 \text{ km}^3$  can be inferred.

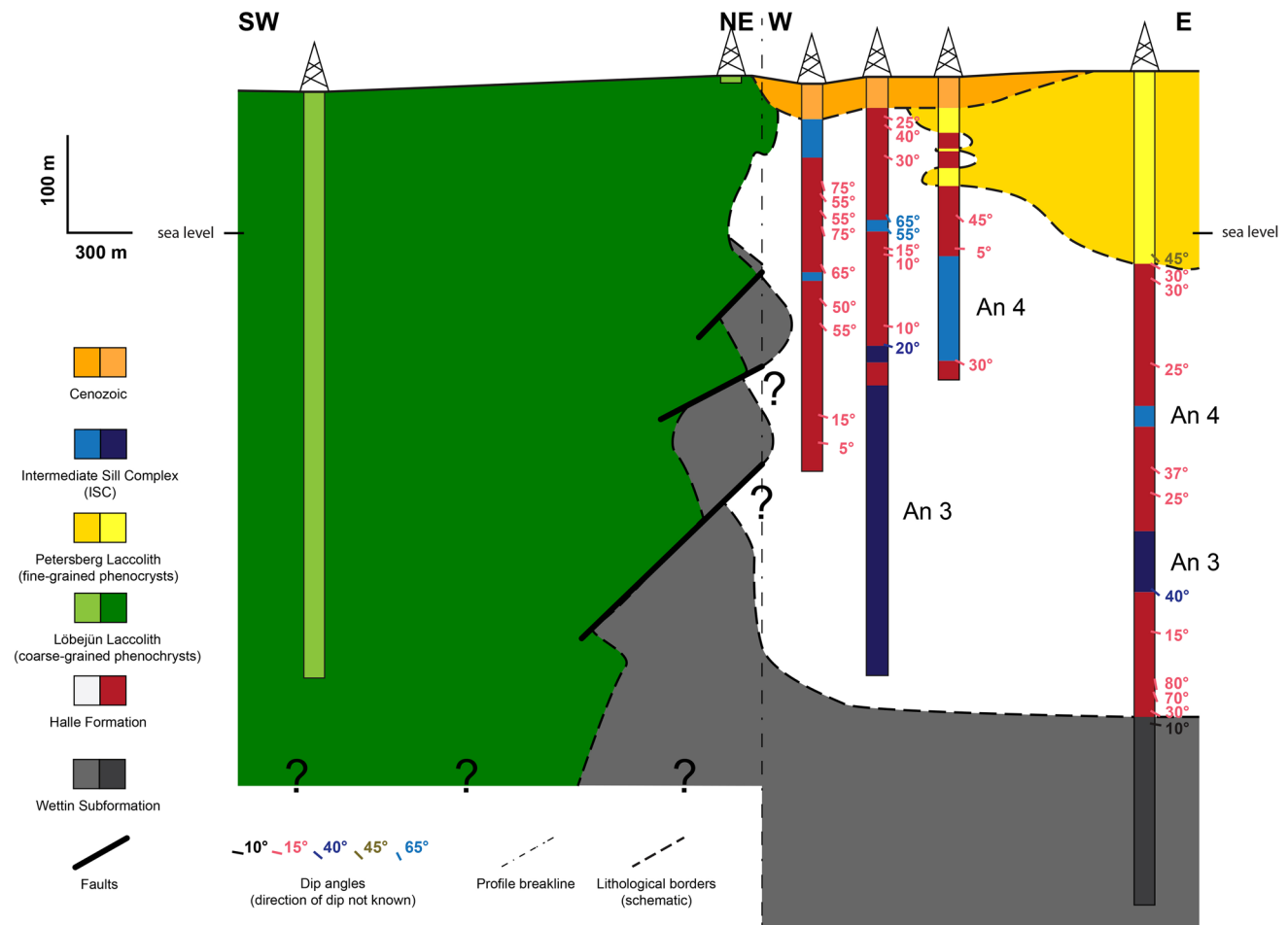
## The Landsberg laccolith margin

### The 3D model: methods

At the western margin of the Landsberg laccolith unit, 63 wells, concentrated in an area of 10 km<sup>2</sup>, have been drilled (Figs. 1b, 3a). The majority of the drillings were performed by the Wismut GmbH for uranium and coal exploration in the second half of the twentieth century. Additional information came from shallow wells of hydrogeological investigations in the area. The investigated area is located between UL N 5713376, E 4505103 and LR N 5710010, E 4508105 (German Grid) on the ordnance map “4438 Landsberg” (Fig. 3a). Well documentation and drill cores are filed and kept by the State Survey of Geology and Mining of Saxony-Anhalt in Halle. We collected data of well location, azimuth and dip (most of the wells have been drilled obliquely), depth of contacts and dip of sedimentary bedding.

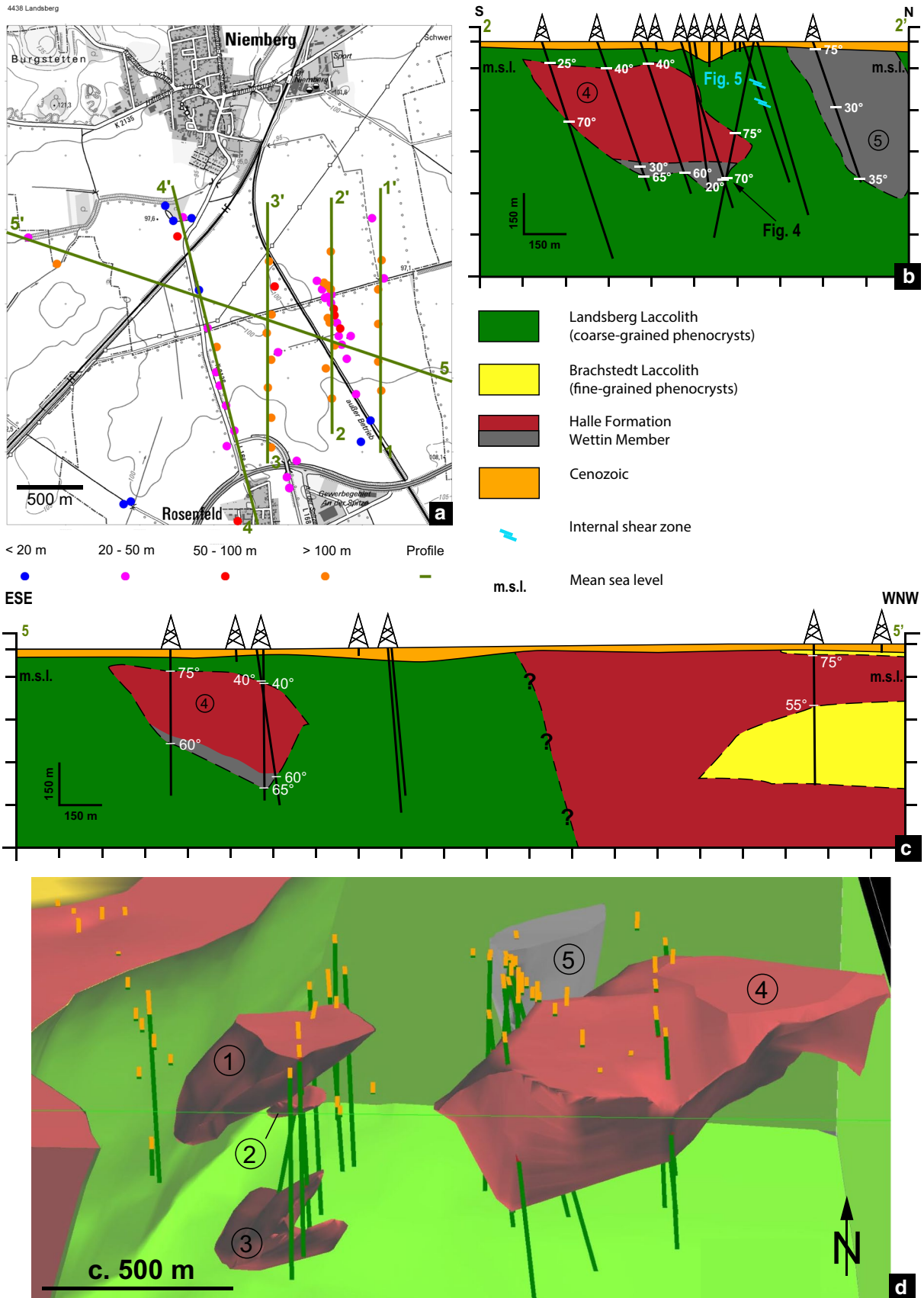
**Fig. 3** Geometric 3D model of the Landsberg laccolith margin south of Niemberg. **a** Topographical map with well starting points and profile locations (see Fig. 3b, c, and ESM Appendix). **b** Profile 2–2' features rafts 4 and 5; dip angles (*white*) of the contacts and of internal bedding are given relative to well axis. **c** Profile 5–5' shows the Landsberg laccolith in the ESE, and two lobes of the Brachstedt unit in the WNW; the location of the Landsberg margin is poorly constrained; dip angles (*white*) of the contacts of raft 4 and the Brachstedt lobes are given relative to well axis, dip direction unknown. **d** View onto the 3D model from the south (viewed obliquely from above) depicting the well paths and sedimentary rafts 1–5; the basal part of raft 4 comprise Wettin Member sediments (see Fig. 3b, c); however, for technical reasons, it is not shown here; part of the Brachstedt laccolith unit (*yellow*) is shown in the NW corner of the model; Cenozoic cover is represented only by the colour code of the well paths

The 3D geometry modelling of the HVC was performed with the software package GOCAD<sup>®</sup> (Geological Object Computer Aided Design) from Paradigm<sup>®</sup>. This software is well adapted to the peculiarities of geological data and



**Fig. 2** Profile through the contact zone of the neighbouring Löbejün and Petersberg laccoliths and the intervening host sediments (Wettin Member and Halle Formation with ISC units An3 and An4, Siegert 1967; Schulz 2010), based on well data (for location see Fig. 1b); the

assumed geometry was inspired by profiles through the NE margin of the Löbejün laccoliths published by Kampe et al. (1965), see also Mock et al. (2005) and emplacement models published by Horsman et al. (2009) for the Henry Mountains





bodies. The modelling technique used in GOCAD<sup>®</sup> was developed by Mallet (1989) and works with discrete objects. Initial geological data are often represented by points indicating, e.g. the position of a stratigraphic interface in a borehole, or by lines (segments connecting points) representing a stratigraphic interface on a seismic section. Geological discontinuities like horizons or faults are modelled by *triangulated surfaces*.<sup>1</sup> Since the geological structure to be modelled is not known a priori, the GOCAD<sup>®</sup> methodology creates an initial plane *surface* and defines the data *points* as constraints that the *surface* should respect. The *surface* is then fitted to the data by the *Discrete Smooth Interpolation* algorithm which minimizes the global roughness of the *surface* while taking into account constraints like *control points* (constraints which are respected in a least-square manner) or *control nodes* (constraints that have to be triangle nodes of the surface with a fixed position). Geological bodies can be modelled from the *triangulated surfaces* as boundary representations, which display the spatial extent of a geo-object only by its boundaries. A coherent boundary representation is achieved, when the volume of the body is completely confined by *surfaces* without holes and overlaps. If *surfaces* overlap, they can be *cut* with a GOCAD<sup>®</sup> tool, and overhanging *surface* parts can be deleted.

The input data have been listed in a text file for incorporation into GOCAD<sup>®</sup>. The import took place in two phases—the import of the well path and the import of the particular *well markers*. The import mask used was X-Y-TVDSS-MD (easting-northing-true vertical depth subsea-measured depth). When available from the well logs, azimuth and horizontal deviations of the wells were also listed as additional information.

A *Voxel box* with the defined geometric borders of the model was created. Its top surface resulted from a geo-referenced image of the topographical map (1:7,500), which textured the *directly triangulated ground surface*. The creation of the *surface* at the base of the Cenozoic cover was straightforward. However, constructing the laccolith-sediment contacts by automated usage of GOCAD<sup>®</sup> was not successful. As will be shown below, we identified two types of rhyolite-sediment contacts, namely the contact of the laccolith outer margin (i.e. the Landsberg and the Brachstedt laccoliths) and the border of sediment rafts. For classification of a contact in a given well, we used, in an iterative process, geometric information of neighbouring wells and the overall concept the entire 3D model.

*Well markers* have been manually connected by *curve objects*. Additional *curve objects* have been manually implemented with the aim to produce a realistic geological shape of the modelled lithological body. Band-shaped

assistance *surfaces* have been combined from neighbouring *curve objects*. In a next step, the assistance *surfaces* have been successively *merged* to obtain the final contact *surface*. For the sedimentary rafts, an upper and a lower *surface* have been created, overlapping parts of which have been *cut*, and *merged* to form 3D bodies. Finally, for all *surfaces*, the *beautify* tool was applied to automatically form *triangle equality*. Five profiles have been generated from the final 3D model (see Fig. 3b, c; and ESM Appendix), to visualize the geometric setting of the Landsberg laccolith margin and the detected sedimentary rafts.

#### The 3D model: results

The height of the *Voxel box* was fixed considering the maximum depth of the wells and the altitude above sea level of the well starting points and the land surface (digital elevation model, DEM). A total of 150 m has been added above mean sea level in order to accommodate the DEM with the drill starting points into the *Voxel box*. Likewise, we added 150 m at the base of the box to facilitate modelling of basal surfaces. The model displays the well paths and the lithological boundary surfaces (Fig. 3d). A movie which shows the model from different view angles is archived as electronic supplementary material in the appendix.

The top of the model comprises Cenozoic sedimentary cover with an average thickness of 30 m (Fig. 3b, c). For the finely porphyritic Brachstedt unit, a maximum thickness of up to 500 m has been documented (Fig. 1b; Breitreuz et al. 2009). In the north-western part of our model, the Brachstedt laccolith is represented by two intrusive lobes, the upper lobe being strongly eroded and covered by Cenozoic sediments (Fig. 3c, d). The lower unit has a thickness of 240 m as defined by one well. The eastward termination of the Brachstedt lobes is not well constrained by the model.

Two shallow wells document the presence of a north-south trending domain of host sediments separating the Brachstedt laccolith in the north-west from the Landsberg laccolith in the east (Fig. 3b–d). In the well documentation, this domain is identified as Halle Formation. A possible presence of the Wettin Member in greater depth, as depicted in Fig. 1c, d, cannot be ruled out.

The Landsberg laccolith occupies the eastern part of the geometric model, constrained by 47 wells (Fig. 3b–d). Our model reveals five sedimentary rafts in the Landsberg laccolith (labelled 1–5) comprising sediments of the Halle Formation and of the Wettin Member (Fig. 3b–d). The rafts show internal deformation or tilting (see varying dip values in Fig. 3b). A set of three rafts has been modelled located at least 200 m away from the Landsberg outer margin (Fig. 3d). Raft 1 is a prolate west-dipping body with a maximum diameter of 450 m (as measured in the 3D model).

<sup>1</sup> GOCAD<sup>®</sup> technical terms given in italics.

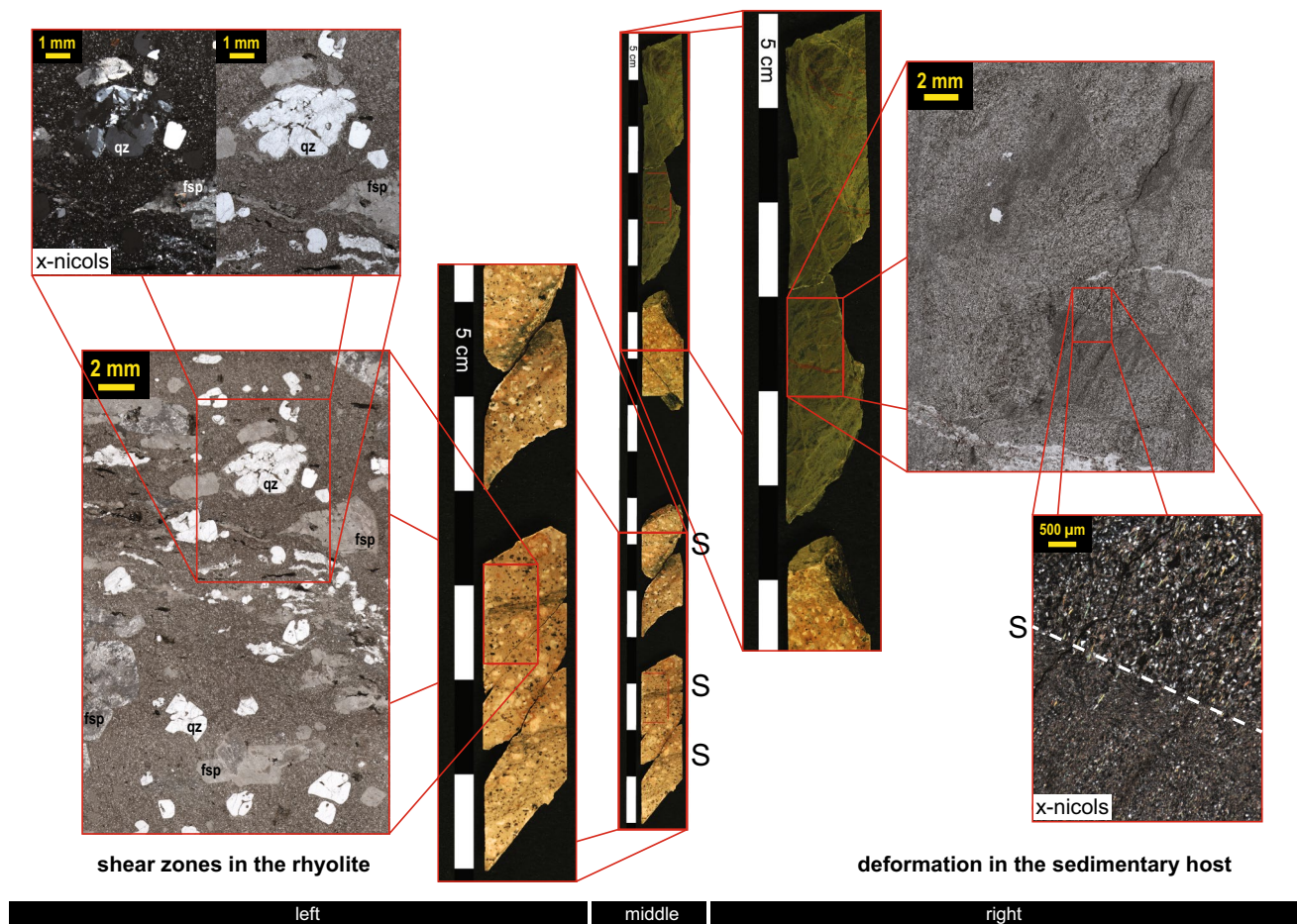
It has an erosive upper contact with the Cenozoic cover. It consists of sediments of the Halle Formation. Below raft 1, a smaller sedimentary body has been separated (raft 2, Halle Formation); however, a connection with raft 1 cannot be excluded. Some 200 m below, raft 3 (Halle Formation) displays a complex reconstructed cramp-like shape. The base of raft 3 is not known since the wells did not perforate it completely. The model does not preclude a possible connection of raft 3 with the domain of Halle Formation west of the Landsberg laccolith margin. Further to the east, some 250–300 m away from rafts 1 to 3, a large complex raft occurs surrounded by Landsberg rhyolite (Fig. 3b–d). Raft 4 is well defined by a number of wells, and it measures 1,400 m in north–south extent (Profile 1 in ESM Appendix) and is approximately up to 500 m thick (Fig. 3d). Dip angles of the contact with the hosting rhyolite support the modelled shape (Fig. 3b, c). The upper part of raft 4 comprises Halle Formation, while the basal part consists of Wettin Member. As shown in Fig. 3c, the transition between

the two sedimentary units dips towards the west. The shape of raft 5 is constrained by only one well that exposed the basal contact with the hosting rhyolite (Fig. 3b, d). The raft consists of strongly tilted sediments of the Wettin Member.

#### Contact textures

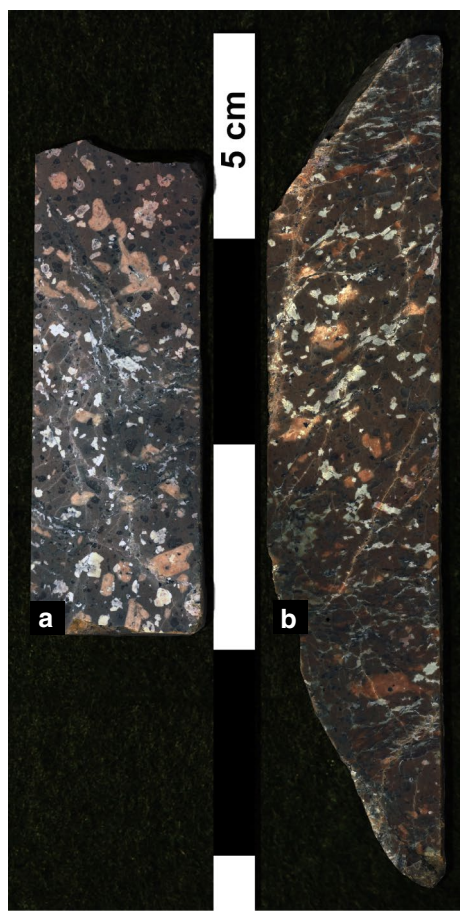
The textures observed in the intruded rhyolite and in the host sediments bear information on melt viscosity, strength of host sediments and strain accommodation. A limited number of cores drilled in the HVC are still available in the depository of the Survey for Geology and Mining in Halle. Mock et al. (2005) documented some contacts of Löbejün and Landsberg laccolith margins, and listed brecciation and peperitic textures, and ductile shear zones. In addition, zones of brecciation in the interior of the Landsberg laccolith have been depicted (Fig. 7 in Mock et al. 2005).

Textures of the rhyolite-sediment contact at the base of raft 4 are illustrated in Fig. 4. The silt to fine sandstones of



**Fig. 4** Textures at the basal contact of sedimentary raft 4 with the Landsberg rhyolite (for location see Fig. 3b; *middle*). The sediment–rhyolite contact is sharp; the sediments (Wettin Member) are strongly faulted, and within the upper 50 cm of the rhyolite margin, discrete

shear zones (S) developed; *right*. Details of the deformed host sediments (core halves and thin sections; *left*). Sheared and fragmented phenocrysts in the rhyolite (core halves and thin sections; *qz* quartz, *fsp* feldspar)



**Fig. 5** Zones of internal deformation in the Landsberg laccolith: alternating domains of strongly sheared and of unaffected feldspar phenocrysts; the deformation zones are interpreted to represent contacts between successively emplaced magma sheets. **a** 152 m depth, **b** 247 m depth; for location see Fig. 3b

the Wettin Member show intense shearing and overprinted by brittle faulting close to the contact. Fluidization textures indicative of an unconsolidated status of sediments (Kokelaar 1982) during the rhyolite emplacement are not evident. The contact to the rhyolite is sharp. Contact-parallel thin shear zones are visible in the rhyolite within 50 cm away from the contact (Fig. 4; middle). Thin sections show shattered quartz and sheared feldspar phenocrysts (Fig. 4; left).

In a completely cored well (labelled “Fig. 5” in Fig. 3b) exposing 500 m of Landsberg rhyolite, we detected two internal, dm-wide shear zones, 95 m apart from each other. They comprise alternating domains of strongly sheared and unaffected feldspar phenocrysts (Fig. 5).

## Discussion

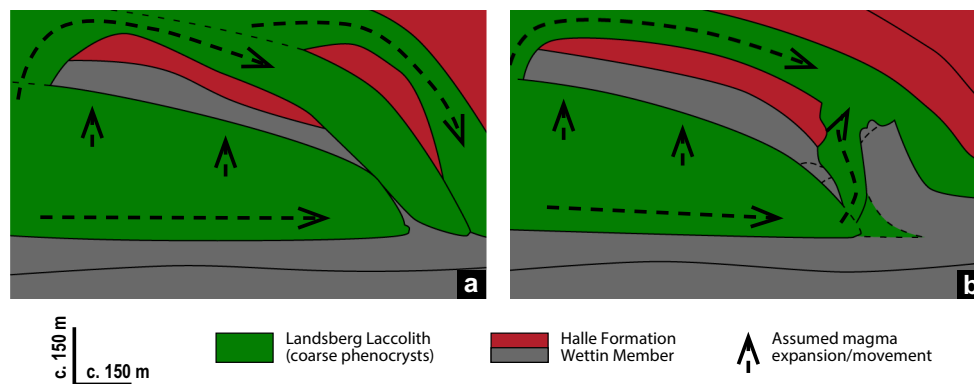
For the HVC laccoliths, three margin geometries can be distinguished: (1) vertical margin of an intrusive–extrusive

complex (Löbejün, Fig. 2; Kampe et al. 1965; Breitzkreuz et al., accepted; Lorenz and Haneke 2004), (2) stacked lobes/fingers (Petersberg, Brachstedt, Figs. 2, 3c; Pollard et al. 1975; Hutton 2009) and (3) sediment rafts engulfed by rhyolite sheets (Landsberg, Fig. 3b–d; Morgan et al. 2008). The three types presumably do not represent completely different emplacement mechanisms, rather there might exist a transition from one type to another. Parameters such as magma density, viscosity and volume may be important here.

Mock et al. (2005) calculated a difference in density of about 1 % based on the different amount of phenocrysts present in the highly porphyritic Löbejün and Landsberg and the lower crystalline Petersberg-, Wettin- and Brachstedt-intruding magmas. Applying the concept of neutrally buoyant elevation (Corry 1988), the calculated density contrast is probably not sufficient to account for the observed difference in the level of initial emplacement of up to 500 m (Fig. 1c, d; Mock et al. 2005). Mock and Breitzkreuz (2006) also assumed a higher viscosity for the highly porphyritic melts due to larger supercooling and phenocryst content. The HVC laccolith units are of a remarkably homogenous rhyolitic composition (Romer et al. 2001). Nevertheless, they display systematically different aspect ratios (0.07 for the coarsely porphyritic Löbejün and Landsberg units; 0.04 for the finely porphyritic Petersberg and Brachstedt units). However, the aspect ratio of laccolith bodies is not solely controlled by magma viscosity. For example, the satellite subvolcanic intrusions on the eastern slope of the Mt. Hillers (Henry Mountains, UT) are of dacitic to quartz–monzodioritic composition (de Saint Blanquat et al. 2006; Morgan et al. 2008), at the same time they have a wide range of aspect ratios (Black Mesa: 0.13, Trachyte Mesa: 0.03, Horsman et al. 2009).

Only the finely porphyritic HVC units like Petersberg and Wettin feature prominent flow foliation and flow orientation of phenocrysts (Mock et al. 2005). Apparently, in these low-viscosity rhyolitic melts, shear stress was accommodated by distributed strain affecting the entire emplacing unit. In contrast, we assume that the more viscous Landsberg and Löbejün melts emplaced as plug flow with shearing restricted to the margins of the emplacing unit. This is evidenced by discrete shear zones detected in the Landsberg unit within 50 cm away from the contact to a sediment raft (Fig. 4; middle) and by internal shear zones (Fig. 5). From the Trachyte Mesa laccolith, Morgan et al. (2008) described similar shear zones restricted to the igneous rock/host sediment contact. Horsman et al. (2009) observed that internal contact zones between successively emplacing magma sheets are only preserved at the laccolith margins, and these authors inferred annealing in the inner part of the laccolith. This deduction is questioned by the presence of internal shear zones detected in the Landsberg rhyolite





**Fig. 6** Two possible processes for emplacement of rhyolite sheets at the NW margin of the Landsberg laccolith. **a** Downward directed propagation of protruding magma sheets, **b** upward directed magma intrusion along fractures and faults

(Figs. 3b, 5). In a quickly cooling subvolcanic system, the recrystallization of strongly sheared feldspar back to idiomorphic phenocrysts is unlikely.

Chronostratigraphic evidence (Fig. 1b) and field relations support the idea that the emplacement of the HVC rhyolites took place into still unconsolidated sediments (Mock et al. 2005; Breitkreuz et al. 2009; Gebhardt and Lützner 2012). Rhyolite/sediment contacts documented for the Landsberg laccolith (for Löbejün see Mock et al. 2005) show intense shearing and successive brittle faulting (Fig. 4). The observed deformation textures allow for the assumption that more than one melt sheet used this contact. The first pulse provoked deformation, and shearing of then-unconsolidated host sediments and heat flow caused a contact metamorphic lithification. The subsequent melt sheet used the same contact plane; however, due to the acquired enhanced shear strength, the sediments now react with brittle failure, and a part of the strain is accommodated within the marginal zone of the emplacing rhyolitic melt (Fig. 4; left).

A spectacular feature of the presented 3D model of the Landsberg laccolith margin is the presence of sedimentary rafts (Fig. 3). The five rafts form an array of westwardly dipping bodies of up to 1,400 m length. We assume that they formed by engulfing magma sheets that protruded laterally from the central part of the growing Landsberg laccolith as has been described for the Trachyte Mesa laccolith in the Henry Mountains (Morgan et al. 2008; Horsman et al. 2009). We envision two possible intrusive mechanisms leading to the geometry observed in the 3D model, i.e. downward and upward intrusion of magma sheets. It is assumed that during an initial phase, the central part of the Landsberg laccolith grew vertically and thus tilting and bending adjacent host sediments, as documented for the Löbejün laccolith margin in Fig. 2. During a later phase of the Landsberg laccolith evolution, overplating melt sheets followed down-dipping bedding planes and fractures.

Eventually, these downward intrusions merged with rhyolite bodies emplaced earlier (Fig. 6a).

Vertical growth of HVC laccoliths also caused failure and breaking of the adjacent host sediments as documented already by Kampe et al. (1965) for the Löbejün margin (see also Pollard and Johnson 1973; de Saint Blanquat et al. 2006). It is conceivable that the intruding magma used these fault planes as pathways for upward migration (Fig. 6b). It seems to be a viable process to lift raft 5 (Fig. 3b, d) into the observed position.

The thickness of emplacing magma sheets of the Landsberg laccolith can be estimated from the distance between the sedimentary rafts in the 3D model (200–300 m, Fig. 3d) and from the spacing of internal shear zones in the rhyolite (95 m, Figs. 3b, 5). Mock et al. (2003) used crystal size distribution analysis to infer sheets of 100–200 m thickness building up the Petersberg unit. In summary, the 3D model of the Landsberg unit revealed the presence of sedimentary rafts up to 1,400 m in length, up to 500 m thick and engulfing rhyolite sheets with thickness in the order of 100–300 m. The overall geometry resembles that of the Trachyte Mesa laccolith margin (Morgan et al. 2008); however, in the HVC, the magma sheet thickness and the size of sedimentary rafts are larger by an order of magnitude, presumably controlled by a higher viscosity of the HVC melts (Mock and Breitkreuz 2006).

Mock et al. (2005) measured the spatial orientation of flow foliation in HVC laccolith units and interpreted the observed cupola-shaped (Petersberg unit) and bowl-shaped (Wettin unit) geometries as the result of laccolith growth by ballooning. From the results presented here, i.e. fingering margins of the Petersberg and Brachstedt units (Figs. 2, 3c) and the downward and/or upward intrusions of the Landsberg laccolith margin, it is inferred that emplacement of successive sheets was an important intrusive mechanism during HVC evolution.

## Conclusions

Well data and 3D GOCAD<sup>®</sup> modelling were used to investigate the margins of rhyolitic laccoliths in the HVC. Three geometries have been detected: (1) vertical margins of intrusive–extrusive complex (Löbejün), (2) stacked lobes/fingers (Petersberg, Brachstedt) and (3) sediment rafts engulfed by rhyolite sheets (Landsberg).

In a first phase, the highly viscous, highly porphyritic melts led to vertical growth of the Landsberg laccolith and to strong tilting and bending of the host sediments. Later in the laccolith evolution, magma sheets protruded into the host sediments downwards along tilted bedding planes (Fig. 6a) and upwards along faults created in the host sediments (Fig. 6b) during vertical laccolith growth. The protruding magma sheets presumably had a thickness of 100–300 m, and they engulfed sedimentary rafts of up to 500 m thick and 1,400 m long.

In the rhyolite–sediment contact zones, repeated intrusion of magma sheets led to baking of the unconsolidated host sediments. Shear zones are present on both sides of the contact, in the sediment and within 50 cm of the rhyolite (Fig. 4).

In the HVC, differences in viscosity seem to have played a crucial role for the laccolith form. For the highly porphyritic and highly viscous Löbejün and Landsberg units, an aspect ratio of 0.07 has been estimated, whereas the lower viscous Brachstedt and Petersberg units have an aspect ratio of 0.04. Although ballooning cannot be excluded as a mechanism of laccolith growth, the present study suggests that the emplacement of successive magma sheets was the major mechanism during HVC evolution.

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