Reconstruction of the Landeskrone Scoria Cone in the Lusatian Volcanic Field, Eastern Germany — Long-term degradation of volcanic edifices and implications for landscape evolution

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ABSTRACT

Remnants of numerous monogenetic volcanoes are preserved in the Central European Volcanic Province (CEVP). The Landeskrone Hill, a monogenetic scoria cone in the Lusatian Volcanic Field, is reconstructed here. This was done using measurements of the dip of columnar jointing of lava lake basalts and the detailed mapping of the volcaniclastic rocks. The reconstruction implies a large scoria cone and a lava lake; filling the crater with a thickness of more than 110 m. Volcanic activity was characterized by Strombolian eruptions possibly after an opening phreatomagmatic phase. A scoria cone was developed in an initial maar-diatreme volcano. A late phreatomagmatic phase could explain the unusual modified crater of the scoria cone. The conduit was emptied and so the crater was widened in this late eruption stage. An increased magma flux probably induced a change in the eruptive style and, finally, the crater was filled in a single event by a lava lake. This effusive phase completed the multi-stage volcano development.

The 34 Ma-old volcano is an excellent example for the persistence of relics of monogenetic volcanoes over a long period of time. There are some other remnants of monogenetic scoria cones that survived degradation processes in the area. With respect to the present surface, the reconstruction of the paleosurface implies low uplift and erosion rates of about 3 mm/ka since the Oligocene. These denudation values support and expand on the previously published fission track data (prior to the Upper Cretaceous) and glacio-sedimentological data on neotectonic movements since the Middle Pleistocene. The erosion rate estimated by physical volcanological data implies stagnation of tectonic uplift from the Upper Paleogene to the Middle Neogene and a reactivation of tectonic movement for the Lusatian Massif in the Middle Pleistocene. Thus, the reconstructed edifice provides a powerful tool for the study of landscape evolution by clearly defining the characteristics of the paleosurfaces at certain times.

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1. Introduction

Monogenetic basaltic volcanoes are the most common type of volcanoes in continental areas and occur as scoria cones, tuff rings or maars (e.g. Wood, 1980a; Cas and Wright, 1987; Schmincke, 2004; Lorenz and Kurszlaukis, 2007). The constructs of scoria cones are produced mostly by Strombolian and violent Strombolian eruptions (e.g. McGeehin et al., 1974; Vespermann and Schmincke, 2000; Valentine and Gregg, 2008) that are driven mainly by magmatic volatiles. Maars and tuff rings are the phreatomagmatic equivalent of scoria cones and the magma fragmentation is caused by magma/water interactions (Lorenz, 1986; Wohletz; 1986; Lorenz and Kurszlaukis, 2007). Tuff cones are created by eruptions due to magma contact with abundant surface water (Wohletz and Sheridan, 1983).

In many cases, scoria cone volcanic activity begins with magma/water interaction creating an initial tephra ring as known from the Eifel Volcanic Field in Germany (e.g. Eppelsberg Volcano (Schmincke, 2004)). Such phreatomagmatic deposits are unsorted and mainly consist of country rock fragments with small amounts of juvenile pyroclasts (Lorenz and Kurszlaukis, 2007). The initial phreatomagmatic phase is usually followed by Strombolian or Hawaiian activity because of declining water supply (Lorenz and Büchel, 1980; Lorenz, 1986; Vespermann and Schmincke, 2000; Schmincke, 2004). Subsequent magmatic activity, driven by the continued rise of magma and associated degassing, produces a scoria cone. A typical scoria cone consists of three pyroclastic facies (Head and Wilson, 1989; Keating et al., 2008). The volcanic edifice is constructed of outwardly inclined, mostly non-welded scoria beds of the wall facies and the inwardly dipping partly welded beds of the crater facies (Head and Wilson, 1989; Valentine and Gregg, 2008). In the lower part, the crater facies grades into the vent breccias, which are observed in the sub-surface conduit. Sometimes, simultaneous phreatomagmatic and Strombolian activities take place and alternated (Ukinrek East Maar, Alaska, Kienle et al., 1980, Rothenberg in the Eifel.

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region, Houghton and Schmincke, 1986) or mixed deposits appear (Baruth in eastern Germany, Tietz et al., 2011a). Later ascending magma is characterized by lower gas content. It is extruded out of the vent and in some cases fills the superficial crater or produces lava flows by breaking through or overflowing the cone (Keating et al., 2008; Valentine and Gregg, 2008).

Morphometric characteristics of scoria cones are generally expressed in the so called PW-ratio according to Porter (1972) and Wood (1980a): $W_{cr} = 0.40 \times W_{co}$ and $H_{co} = 0.18 \times W_{co}$, where $W_{co}$ is the basal diameter of the cone, $W_{cr}$ is the diameter of the summit crater and $H_{co}$ is the distance from the baseline to the top of the cone (Fig. 1a). These equations were determined and constantly recalculated on numerous recent and young scoria cones (e.g. Wood, 1980b; Vespermann and Schmincke, 2000; Rodríguez et al., 2010). They are useful only for cones with a simple geometry without early spatter mounds, pit craters or initial maar formation (Fig. 1b,c). The latter three processes shift the modeled baseline of the cone in cross section and so the $W_{cr}$ vs. $W_{co}$—ratios show lower values for a spatter mound and for the two other cases higher values (Riedel et al., 2003).

Over long timescales, scoria cones can be strongly modified and eroded, thus in ancient volcanic successions they are scarcely preserved as intact, recognizable landforms. Therefore, research on older and eroded scoria cones and their remnants is limited. Deeper exposed volcanic assemblages can carry information essential to understanding the magma generation, evolution, rise of magma and its fragmentation through explosive eruption at a well-deﬁned point in a landscape strongly modiﬁed since the time of volcanism (e.g. Németh and Martin, 1999; Shaw, 2004). Moreover, there are wide implications for the landscape evolution itself (Németh and Martin, 1999; Schröder and Peterek, 2002; Martin and Németh, 2004). In addition, the recognition of the existence of scoria cones in the geological past as well as their distinction from their phreatomagmatic equivalents can give valuable information for estimating paleoclimatic and paleohydrologic characteristics of a broader region (Keresztesi et al., 2011).

There is only a small number of papers dealing with the reconstruction of ancient scoria cones older than Pliocene age (e.g. Awdankiewicz, 2005; Rapprich and Caja, 2007; Rapprich et al., 2007; Tietz et al., 2011a,b). However, these data give some information on scoria cone degradation, that modified former quantiﬁcations by e.g. Wood (1980a) or Hooper and Sheridan (1998). The degradation of scoria cones has been modeled for edifices without appreciable lava ﬁlling. Accordingly, the superﬁcial successions of a scoria cone are completely eroded after about 5 Ma and only the subsurface parts of the volcano remain (Wood, 1980b).

In this paper, we present the ﬁeld relationships of remnants of a monogenetic scoria cone of Oligocene age and the reconstruction of the volcanic ediﬁce. We calculate the morphometric values of the ancient monogenetic scoria cone. Additionally, we estimate the implications for landscape evolution in uplifted areas over the long term using volcanological data from adjacent volcanoes. The results of this study provide contexts for understanding scoria cone eruptions, their growth and their long-lasting destruction. The Landeskrone Volcano was chosen to test these applications for landscape evolution by older volcanic structures supplementary or alternative to the other methods such as fission track dating. The Lusatian area is particularly suitable for such investigations because it has been uplifted over the last 100 Ma jointly with many other nearby monogenetic volcano remnants with ages between 34 and 22 Ma.

2. Regional geological setting

The Landeskrone Volcano (14.93260 E, 51.12955 N) is a solitary volcano, situated in the northern part of the Lusatian (Lausitz) Volcanic Field (Fig. 2 inset map). The Lusatian Volcanic Field (Tietz et al., 2011a) is part of the Central European Volcanic Province (CEVP), a volcanic belt in Central Europe distributed over a distance of about 300 km north of the Alps (Wedepohl and Baumann, 1999; Lustrino and Wilson, 2007). The volcanic rocks occurring in this belt are mainly SiO$_2$-undersaturated maﬁc volcanic rocks such as nephelinites, basanites and alkaline basalts as well as their phonolitic and trachytic differentiates. The volcanism was active from the Upper Cretaceous to the latest Tertiary and again in the late Quaternary (e.g. Lustrino and Wilson, 2007) in the Eifel region as well as in the Ohiře Rift (Eger Graben).

The Lusatian Volcanic Field is characterized by a bimodal volcanism from nephelinites to phonolites (Tietz et al., 2011a). Ages of the Cenozoic volcanic rocks ranges from about 41 to 20 Ma (K/Ar-method), with a climax between 30 and 27 Ma (Pfeiffer et al., 1984; Panasiuk, 1986; Suhr and Goth, 2002; Lorenz et al., 2003).

The basaltic rocks appear mostly in small bodies (diatremes, plugs) or in more widely distributed lava ﬂows (e.g. Tietz et al., 2011b). In some cases, there are complex volcanoes created due to simultaneous strombolian to Hawaiian and phreatomagmatic eruptions (Tietz and Büncher, 2007; Tietz et al., 2011a). Normally the volcanic constructs are weathered and removed. However, pyroclastic rocks are commonly preserved in sheltered positions such as in sedimentary basins or under thick lava ﬂows. Primary bedding and structure have survived strong chemical weathering (Büncher et al., 2006). Therefore, also strongly weathered volcanic rocks like saprolite can be used for volcanological reconstructions (Büncher et al., 2006).

Only an unpublished isotopic age (34 $\pm$ 2 Ma K/Ar-method) is available for the Landeskrone Volcano (Pushkarev, 2000), which would make this volcano one of the oldest in the Lusatian Volcanic
Field. Only Panasiuk (1986) reported one older K/Ar age (41.4 Ma) from the Polish part of the Zittau Basin.

The Landeskrone Volcano is situated in the central part of the Lusatian (Lausitz) Massif — an area of continuous uplift since the Upper Cretaceous (Voigt, 2009). The Lusatian Massif (Fig. 3) consists of the Cadomian Lusatian Anticline Zone in the south and the Variscan Görlitz Syncline Zone in the north (Katzung and Ehmke, 1993). Both basement units are separated by the Intra-Lusatian Fault (Innerlausitzer...
The uplift age of the Lusatian Massif is specified by 28 apatite fission track ages by Lange et al. (2008). These ages show a pronounced cooling and uplift event for the interval between 85 and 50 Ma, with an uplift value of 3–3500 m and a denudation rate of 100 m·Ma⁻¹ (100 mm/ka). The samples have been cooled down to surface temperatures since the early Cenozoic. Therefore, Cenozoic denudation is negligible in comparison with complete Post-Variscan denudation according to Lange et al. (2008). Mean values of the denudation rate for the Central European low mountain ranges vary from 20 to 80 mm/ka for Upper Cretaceous time (Wagner and van den Haute, 1992). Upper Cretaceous thermotectonic age dates are congruent with the uplift age for the Lusatian Overthrust according to Krentz (1992). Upper Cretaceous age dates are congruent with the uplift age for the Lusatian Overthrust according to Krentz (2008), who deduces the main uplift time for this fault by synchroneous magmatic dykes with an age between 79 and 48 Ma (mainly by 63 to 53 Ma). The dykes run from NE to SW perpendicular to the Lusatian Overthrust and were opened in connection with the activity of the fault. Krentz (2008) correlated the end of the uplift movements on the Lusatian Overthrust with Upper Eocene sediments in the Zittau Basin to ca. 45–34 Ma (Sühr, 2003). Präger (1964) envisaged younger local tectonic movements for the Middle Pleistocene (app. 400 ka) in the neighboring Berzdorf Basin (Fig. 3). The author estimated a subsidence value up to 100 m in the basin and an uplift value up to 50 m in the surrounding Lusatian Highlands (Lausitzer Bergland). Reports of younger neotectonic movements are rare; Präger (1964) supposed a 10–15 m subsidence for the post-Saalian time and Tietz (2000) assumed a 3 m subsidence since the Late Glacial (Weichselian) time, both in the Berzdorf Basin (see also Tietz and Büchner, 2011).

3. Methods

The distribution of the volcanic products was mapped using GPS data, interpretations of records from a digital elevation model (DEM) and data from boreholes. The DEM had a primary resolution of 20 m and was modified by additional GPS data.

In this work we systematically measured orientations of the columnar jointing of massive basalt at 30 locations around the Landeskron Hill as reported by Koch et al. (1983). In this paper, the crater slope angle of the Landeskron Volcano was extrapolated by determination of the inclination of columnar jointing as well as the measurement of the orientation and distribution of the recent contact of pyroclastic (cone) and effusive (lava lake) rocks similar to that shown in Fig. 4. We considered the lowest values of inclination of columnar jointing in basaltic cliffs for the estimation of crater wall slope angle (Table 1, Fig. 5).

The reconstruction of the volcanic edifice is calculated trigonometrically and geometrically by scale drawing of W–E and S–N cross-sections at a scale of 1:5000. The construction was made in considering all the field observations of estimated sizes and orientations of the volcanic remnants.

Reconstruction of volcano edifices is a useful tool for the estimation of denudation and uplift rates for the post-volcanic time. Therefore, it is necessary to check the volcanic structures and classify them into relevant physical-volcanologic types, such as scoria cone volcanoes, lava flows and dykes (analogous to Rapprich et al., 2007). These classes allow the determination of the syn-volcanic elevation of the landscape. The integration of adjacent volcanoes in a broader area increases the significance of results. Thereby, it is possible to estimate the vertical excavation between the volcano remnants. In this study, nine additional volcano-remnants were incorporated into the determination of the denudation values. The ancient volcanic structures are situated within distances of 4.5 to 13 km of the Landeskron Volcano. A slightly younger example for Late Miocene to Pliocene intra-plate volcanoes is given in Németh et al. (2003) and Martin and Németh (2004).

4. Field relations

The shape of the Landeskron Hill in cross-section view reflects the boundary between country rock and volcanic rocks by the change in the slope angle (Fig. 6). The distribution of the dense basaltic rocks is elliptical in map view (Fig. 2). They are underlain by pyroclastic rocks of a thickness of up to 10 m. The pyroclastic rocks were directly deposited on the Lusatian Granodiorite which is the country rock, and the base of the pyroclastic rocks is nearly horizontal (Figs. 2, 11).

Columnar jointing is developed in dense basaltic rocks in several diameters and shapes. Columns are smaller (20 to 40 cm) and more irregular in contact with the pyroclastic rocks than those a few meters
are the phenocrysts; they are partly altered. There are some
10% respectively) and no plagioclase. Olivine (35%) and clinopyroxene
(together 40%), sometimes ore minerals as well as analcim (up to
microcrystalline groundmass contains clinopyroxene, nepheline
at the summit of the hill. The full range of the inclina-
tic columnar joints transitions to vertical with increasing distance
away from the contact. The dip direction of the columns corresponds
with the slope of the present hill (Fig. 7). The inclination of the basaltic
columnar joints transitions to vertical with increasing distance
from the pyroclastic rock contact, and the columns widen up to 1 m
diameter (Fig. 8). The lowest dip values are at the contact with
the pyroclastic rocks at about 40° and the highest values rise to 90°
at the summit of the Landeskrone Hill. The full range of the inclina-
tions is given in Table 1. Altogether the columnar jointing shows a
3D periclinal structure around the present hill (Fig. 2, Table 1). The
dip direction of the columns corresponds in relation to the recon-
structed crater surface.

There is a general agreement that columnar joints develop per-
pendicularly to the plane of cooling (e.g. DeGraff and Aydin, 1987).
The plane of cooling is, in this case, the surface of the scoria cone
crater. Fig. 4 shows a similar situation of a scoria cone remnant in the
vesicles up to 4 mm in diameter and a few mantle xenoliths are ob-
served. The rock could be interpreted as an olivine nepheline. In
the upper part of the lava body the vesicle content increases (Fig. 9).
We found weakly weathered scoriae in situ in an abandoned quar-
ry on the northern slope of the Landeskrone Hill (Fig. 5). The particle
size of scoriae could not be determined exactly because of alteration.
However, the pyroclastic rocks seem to be composed mainly of
bombs and scoria lapilli; the latter can be observed in thin section
(Fig. 10B). In thin sections the scoria shows a microcrystalline to glassy matrix and is rich in olivine and clinopyroxene phenocrysts up to 1 mm in length (Fig. 10B). The rocks could be interpreted as scoria agglomerates of the scoria cone (wall facies).

5. The volcano edifice
The distribution of volcanic rocks, the occurrence of scoria beds and
the orientation of columnar jointing imply that the Landeskrone Hill
represents a remnant of a lava lake which is nearly completely
preserved in its original thickness. The increase in vesicularity at the
summit of the hill coincides with the uppermost part of the lava
body where the magmatic gases collected below the quenched lava
surf ther and the orientation of columnar jointing imply that the Landeskrone Hill represents a remnant of a lava lake which is nearly completely preserved in its original thickness. The increase in vesicularity at the summit of the hill coincides with the uppermost part of the lava body where the magmatic gases collected below the quenched lava surface, thus following the internal anatomy of a lava flow (e.g. Schmincke, 2004; Bondre and Hart, 2008) or of the Kilauea Iki Lava Lake, Hawaii (Stovall et al., 2009). Therefore, we assume that the recent height of the basaltic hilltop nearly fits the thickness of the original lava lake.

There is a general agreement that columnar joints develop perpendicularly to the plane of cooling (e.g. DeGraff and Aydin, 1987).

Table 1
Measured dip of columnar jointing of basaltic lava lake remnants in the center of the Landeskrone Volcano and complementary (perpendicular cooling) planes.

<table>
<thead>
<tr>
<th>Outcrop no.</th>
<th>Locality</th>
<th>ci</th>
<th>sap</th>
<th>sd</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Old quarry center</td>
<td>357/50</td>
<td>40°</td>
<td>± 7.6°</td>
<td>7</td>
</tr>
<tr>
<td>1b</td>
<td>Old quarry SW-c06Friner</td>
<td>340/57</td>
<td>33°</td>
<td>± 8.0°</td>
<td>7</td>
</tr>
<tr>
<td>1c</td>
<td>Old quarry NE-corner</td>
<td>350/38</td>
<td>52°</td>
<td>± 0.0°</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Cliff over cirkelay, northwestern slope</td>
<td>259/42</td>
<td>48°</td>
<td>± 4.0°</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Cliff over cirkelay, western slope</td>
<td>286/42</td>
<td>48°</td>
<td>± 8.7°</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Cliff over cirkelay, western slope</td>
<td>298/37</td>
<td>53°</td>
<td>± 8.6°</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Cliff over cirkelay, western slope</td>
<td>283/42</td>
<td>48°</td>
<td>± 5.7°</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Western cliff, northern base</td>
<td>259/59</td>
<td>31°</td>
<td>± 5.9°</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Western cliff, southern base</td>
<td>255/58</td>
<td>32°</td>
<td>± 2.2°</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Little cliff</td>
<td>242/65</td>
<td>25°</td>
<td>± 5.7°</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Little cliff on southern way</td>
<td>181/65</td>
<td>25°</td>
<td>± 7.4°</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>Little cliff between southern way and road</td>
<td>189/81</td>
<td>00°</td>
<td>± 4.6°</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>Road upper outcrop</td>
<td>165/75</td>
<td>15°</td>
<td>± 5.0°</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>Road middle outcrop</td>
<td>151/80</td>
<td>10°</td>
<td>± 5.6°</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>Road lower outcrop</td>
<td>146/83</td>
<td>07°</td>
<td>± 3.2°</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>Cliff above Northway</td>
<td>072/62</td>
<td>28°</td>
<td>± 5.7°</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>Slope above Northway</td>
<td>029/62</td>
<td>28°</td>
<td>± 10.3°</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>Slope above Northway</td>
<td>017/68</td>
<td>22°</td>
<td>± 7.0°</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>Northern Slope</td>
<td>020/68</td>
<td>22°</td>
<td>± 5.6°</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>70 m east from observation tower</td>
<td>120/85</td>
<td>5°</td>
<td>± 4.2°</td>
<td>6</td>
</tr>
<tr>
<td>19</td>
<td>50 m east from observation tower</td>
<td>150/86</td>
<td>4°</td>
<td>± 0.8°</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>40 m east from observation tower</td>
<td>165/86</td>
<td>4°</td>
<td>± 0.8°</td>
<td>4</td>
</tr>
<tr>
<td>21</td>
<td>40 m northeast from observation tower</td>
<td>045/82</td>
<td>8°</td>
<td>± 5.6°</td>
<td>4</td>
</tr>
<tr>
<td>22</td>
<td>40 m northeast from observation tower</td>
<td>066/87</td>
<td>3°</td>
<td>± 2.7°</td>
<td>4</td>
</tr>
<tr>
<td>23</td>
<td>40 m north from observation tower</td>
<td>300/85</td>
<td>5°</td>
<td>± 0°</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>55 m northwest from hotel tower</td>
<td>317/88</td>
<td>2°</td>
<td>± 1.4°</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>Northway, junction of road</td>
<td>200/77</td>
<td>13°</td>
<td>± 2.1°</td>
<td>2</td>
</tr>
<tr>
<td>26</td>
<td>Road, 50 m southwest from hotel tower</td>
<td>245/86</td>
<td>4°</td>
<td>± 0°</td>
<td>2</td>
</tr>
<tr>
<td>27</td>
<td>20 m south from Körner monument</td>
<td>036/83</td>
<td>7°</td>
<td>± 2.6°</td>
<td>3</td>
</tr>
<tr>
<td>28</td>
<td>25 m southeast from observation tower</td>
<td>251/81</td>
<td>9°</td>
<td>± 1.7°</td>
<td>3</td>
</tr>
<tr>
<td>29</td>
<td>20 m southwest from Bismark tower</td>
<td>165/83</td>
<td>7°</td>
<td>± 4.2°</td>
<td>2</td>
</tr>
<tr>
<td>30</td>
<td>20 m southeast from Bismark tower</td>
<td>178/84</td>
<td>6°</td>
<td>± 1.5°</td>
<td>3</td>
</tr>
</tbody>
</table>

ci: column inclination, sap: slope angle of perpendicular plane.
sd: standard deviation, n: number of measurements.
German Rhön area (Schwarzenberg Hill (Hofbauer, 2004)). The contact zone between a scoria wall and the remnants of a basaltic lava lake is clearly exposed in the outcrop.

The dip values of the contact between the basalts and the pyroclastic rocks reflect the slope angle of the crater wall, similar to the outcrop seen in Fig. 4. Average values of inclination of the columnar joints near the contact with the pyroclastic rocks imply a steep slope angle for the crater wall as found by Martin and Németh (2006) for their ’type 4’ scoria cones. On average we have quantified values of about 40 to 50° for the slope angle of the crater wall (Fig. 5, Table 1). These values are calculated by using the mean value of the flattest columnar joint cluster (Table 1); all steeper dip values of basaltic columns represent occurrences further inside the lava lake (Figs. 8, 11, Table 1). In reference to our field observations and geometric construction, the Landeskrone Volcano had a basal cone diameter (Wco) of at least 1180 m and a crater width (Wcr) of at least 750 m and a cone height (Hco) of about 160 m. These sizes were determined under the assumption that the cone, according to the Hawaiian Pu’u ‘O’o Crater (Witham and Llewellin, 2006), should be at least one third higher than the level of the lava lake. In our case, the lava filled the crater up to the height of about 110 m above the pre-volcanic paleosurface (Fig. 11). A lower cone would lead to the breaking out of the lava and to the creation of a lava flow. However, our field observations exclude a lava flow from the Landeskrone Volcano. The estimated morphological values of the primordial volcano yield a Wcr vs. Wco ratio of 0.63 and an Hco vs. Wco ratio of 0.14, which are comparable with the modified scoria cone shown in Fig. 2c.

Sizes of primordial scoria cones determined in this way allow the estimation of the erupted volume of the original volcano including the lava lake. This amounts to about 0.1 km$^3$. The lava lake volume accounts for at least 30% (0.03 km$^3$) of the whole volcano. The recent remnant of the scoria cone has a volume of approximately 0.01 km$^3$. The base of the volcanic rocks is quite horizontal, which implies a nearly flat pre-volcanic paleosurface.

According to the deduced values above, the geometric construction of a section through the volcanic edifice suggests the existence of a wide vent (Fig. 11). So the Wcr vs. Wco ratio exceeds the value of 0.40 common for scoria cones (Wood, 1980a). This value and the distribution of the country rock could be explained in our case and in relation to Fig. 2c by an intensive maar phase and a resulting pit crater (cf. Riedel et al., 2003 and Fig. 11). The underlying diatreme would be 400 to 500 m in diameter corresponding approximately with the present outcrop of the massive nephelinite (Fig. 11). The distribution of scoriaceous pyroclastic rocks related with the steep slope angle of the crater wall and a wide crater imply a ’type 4’ scoria cone according to Martin and Németh (2006, and see below).
remnants over a distance of 28 km in the vicinity of the Landeskrone Volcano to reconstruct the landscape evolution (Figs. 13, 14 and Table 2).

The cross-section cuts different volcanic types. We could distinguish scoria cone volcanoes (with and without an initial diatreme phase), lava flows and dykes as the chimney of eroded volcanoes (Fig. 14, Table 2).

The rocks at Knorrberg and Steinberg Hill (No. 1 and 2 in Figs. 13, 14 and Table 2) represent remnants of basaltic lava flows (Graham and Ebert, 1939) and show a recent inversion of relief. The sources of these lava flows are unknown. However, in the case of the Steinberg (Fig. 14), the volcano which erupted these lavas was probably situated at the eastern part of the basaltic rock distribution.

We identified also a remnant of a lava lake smaller than that at Landeskrone Volcano at Quärgelberg Hill (No. 3 in Fig. 14 and Table 2). It is situated about 10 km south of the Landeskrone Hill.

The outcrop shows a similar pericliminal structure of basaltic columnar joints and the distribution of volcanic rocks is again elliptical in map view. Only the size of the remnant of the volcano is smaller with about 190 m in diameter.

Hutberg Hill near the village Schönau-Berzdorf (No. 4 in Fig. 14 and Table 2) is interpreted as a lava flow (Graham and Ebert, 1939). The outcropping basaltic columns at Hutberg Hill are quite homogeneous in size and their inclination is almost vertical. This and the elongated distribution of the volcanic rocks (Fig. 13) are typical for basaltic lava flows. Basaltic rocks on the slope into the Pließnitz River Valley (No. 5 in Fig. 13 and Table 2) represent the continuation of the lava flow at Hutberg Hill. The associated volcano, which erupted the lava flows is not known and lies possibly to the south of the Hutberg Hill.

A basaltic dyke crops out at the summit of Schwarzer Berg Hill (No. 7 in Fig. 14 and Table 2). This dyke represents the feeder vent of a deeply eroded volcano (Büchner et al., 2006). A remnant of a lava flow, which originated from Schwarzer Berg Hill, can be observed in a small abandoned quarry at the southern slope of this hill (No. 6 in Fig. 13 and Table 2). The basaltic rocks of the two localities show similar geochemical signatures and originate from the same volcano (Büchner et al., 2006). The different erosion levels suggest tectonic movement on a fault between the two outcrops (Figs. 13 and 14).

A further scoria cone-remnant is found in the town of Görlitz at the Hospital Hill (No. 9 in Fig. 14 and Table 2), 4.5 km northeast from the Landeskrone Volcano. In this locality the paleosurface was reconstructed according to boreholes (Berg, 1943 and recent unpublished data), more than 50 m below the modern surface. Preliminary studies suggest a large scoria cone which probably erupted in a paleo-valley, comparable in size with the Landeskrone Volcano. The actual Hospital Hill represents a remnant of a lava lake, which filled the crater of this volcano. Post-volcanic tectonic movements cut the volcanic structure in two parts and the central and northern part of the volcano was recently uplifted and eroded. The young tectonic subsidence conserved the whole south flank of the scoria wall, which is covered by Pleistocene sediments 15 m thick. Therefore, we assume a fault is located at the southern slope of the Hospital Hill (Figs. 13, 14).

In addition, a crater-filling structure is observed at Siebenhufen (No. 10 in Fig. 12 and Table 2) about 8 km north of the Landeskrone Hill (Pieitzsch, 1909).

The estimation of the syngenetic paleosurface of reconstructed volcanoes implies a denudation value of up to 90 m, as shown in Table 2 and Fig. 14. This value could be estimated from the assumption that the landscape was flat in volcanic times. Today we find up to 90 m depressions between two adjacent volcano remnants (Schwarzer Berg Hill, No. 6 and 7 in Figs. 13, 14). However, in the case of the Görlitz Hospital Hill, the scoria cone remnant is covered by up to 15 m of late Pleistocene sediments, due to local subsidence.

The highest values of denudation we estimate at the so-called and now defined Görlitz Horst (Figs. 13, 14). This uplifted block is

6. Adjacent volcanoes and implications for landscape evolution

Numerous other Cenozoic volcanoes occur in the vicinity of the monogenetic Landeskrone Volcano. The geological ages of these volcanoes are mostly unknown. However, many age determinations in the Lusatian Volcanic Field mainly spread between 30 and 27 Ma (Pfeiffer et al., 1984; Panasiuk, 1986; Suhr and Goth, 2002). Thus, the Lusatian Volcanic Field mainly spread between 30 and 27 Ma

![Fig. 9. Polished sample section from vesicular basalt indicates a position close to the original lava lake surface. Sample from the southern summit of the Landeskrone Hill about 405 m above the sea level.](image)

![Fig. 10. Volcanic scoriae from the northern foot of the basaltic hill top at 315 m above the sea level. a): Macro-photograph from a scoria from a historic sample (image section = 6 cm) showing flattened and partly filled vesicles. b): Photomicrograph of a thin section from a recent in-situ sample. The microphenocrysts are olivine and clinopyroxene. Note the different shaped vesicles and the impregnation due to secondary ore minerals (plane polarized light).](image)
bounded by the already described faults at Schwarzer Berg Hill in the south and Hospital Hill in the north (Figs. 13, 14).

7. Discussion

7.1. The Landeskrone Volcano — edifice and degradation

The reconstructed measures of the Landeskrone Volcano produce a higher $W_{cr}$ vs. $W_{co}$ ratio and a lower $H_{co}$ vs. $W_{co}$ ratio compared to those of commonly measured ratios (Wood, 1980a; Rodríguez et al., 2010). This result is caused by the steep slope angle of the scoria cone crater wall recalculated from the inclination of the columnar jointing of the lava lake basalts at the contact with the crater wall. Moreover the geometrically constructed virtual shape of the lava body seems to be extraordinary; according to this shape the lowest tip of the crater should reach deeply into the ground as shown in Fig. 11 (see also Fig. 1c). This can only be explained by a pit crater created due to additional phreatomagmatic phases resulting in a maar diatreme of about 400 to 500 m in width. The sizes of the resulting maar volcano are quite speculative and only shown schematically in Figs. 11 and 12. Additionally, there is no direct evidence for this eruption style and hydromagmatic tephra is missing. However, such volcanic activity leads to a distortion of the morphometric properties (Riedel et al., 2003) for example widening and deepening the crater (Figs. 11, 12). The resulting morphometric parameters imply the development of a ‘type 4’ scoria cone after Martin and Németh (2006). Such a volcano has a late phreatomagmatic activity which empties the vent and creates a pit crater and a volcano edifice as shown in Fig. 12-2. The steep slope angle would be developed by downward movement of scoria cone material into the vent, producing a flat crater floor (Fig. 12-2). In our case, the crater, modified in this way, was then filled by massive lava. Thus the observed remnant of Landeskron Volcano is an ancient example of this kind of scoria cone.

The appearance and distribution of the observed scoria beds are common successions for scoria cones and exclude other possible interpretations of the volcanic structure as intrusive magma bodies or remnant lava flows. Furthermore, the internal structures of the lava body exclude an interpretation as a subsurface plug as referred by Keating et al. (2008) for the Grants Ridge (USA). The authors describe horizontal oriented columnar joints as evidence for the sub-volcanic deposition of the lava. At Landeskron Volcano we observed a 3D periclinal structure of columnar jointing. The deposited volcanic rocks represent superficial remnants of the volcano and the determined paleosurface can be found at the contact between pyroclastics and the granodioritic basement (Figs. 2, 5, 11). Additionally a pit crater creation due to phreatomagmatic activity could more plausibly explain the extraordinary shape of the crater itself (Houghton et al., 1999; Martin and Németh, 2006).

### Table 2

Data collection for the N–S cross-section reconstruction of the Landeskron volcano and other surrounding volcano remnants with the subsequently calculated post-volcanic denudation values.

<table>
<thead>
<tr>
<th>No</th>
<th>Locality</th>
<th>Community</th>
<th>Volcanology</th>
<th>Reference</th>
<th>Altitude</th>
<th>Postvolcanic denudation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Highest elevation Paleo land surface</td>
</tr>
<tr>
<td>1</td>
<td>Knorrberg</td>
<td>Bernstadt</td>
<td>Lava flow</td>
<td>Grahmann and Ebert, 1939</td>
<td>378.9 m</td>
<td>325-343 m</td>
</tr>
<tr>
<td>2</td>
<td>Steinberg</td>
<td>Ostritz</td>
<td>Lava flow</td>
<td>Grahmann and Ebert, 1939</td>
<td>320.5 m</td>
<td>300-320 m</td>
</tr>
<tr>
<td>3</td>
<td>Quärgelberg</td>
<td>Schönau-Berzdorf</td>
<td>Crater filling in ?scoria cone</td>
<td>this study</td>
<td>302.4 m</td>
<td>287 m</td>
</tr>
<tr>
<td>4</td>
<td>Hutberg</td>
<td>Schönau-Berzdorf</td>
<td>Lava flow</td>
<td>Grahmann and Ebert, 1939, this study</td>
<td>309.7 m</td>
<td>275 m</td>
</tr>
<tr>
<td>5</td>
<td>Pliesniitz valley slope</td>
<td>Schönau-Berzdorf</td>
<td>Lava flow</td>
<td>Grahmann and Ebert, 1939</td>
<td>225 m</td>
<td>220 m</td>
</tr>
<tr>
<td>6</td>
<td>Schwarzer Berg, southern slope</td>
<td>Markersdorf</td>
<td>Lava flow</td>
<td>Büchner et al, 2006</td>
<td>315 m</td>
<td>&gt;315 m</td>
</tr>
<tr>
<td>7</td>
<td>Schwarzer Berg, summit</td>
<td>Markersdorf</td>
<td>Dyke/initial crater filling</td>
<td>Büchner et al, 2006</td>
<td>393.6 m</td>
<td>ca 395 m</td>
</tr>
<tr>
<td>8</td>
<td>Landeskron</td>
<td>Görliitz</td>
<td>Crater filling in scoria cone</td>
<td>this study</td>
<td>419.4 m</td>
<td>315 m</td>
</tr>
<tr>
<td>9</td>
<td>Hospital</td>
<td>Görliitz</td>
<td>Scoria cone, lava flow</td>
<td>Berg, 1943, this study</td>
<td>222 m</td>
<td>150 m/217 m</td>
</tr>
<tr>
<td>10</td>
<td>Siebenhufen</td>
<td>Schöpfel</td>
<td>Crater filling in ?scoria cone</td>
<td>Pietsch, 1999, this study</td>
<td>255 m</td>
<td>245 m</td>
</tr>
</tbody>
</table>
In case of the Landeskrone Scoria Cone, the volcano edifice should be higher (at least 160 m) than ‘type 4’ scoria cones reported by Martin and Németh (2006). Our estimated sizes correspond with the measures of the Crater Elegante in the Pinacate Volcanic Field in Sonora (Mexico), which has been described in Gutmann (2002) and by Martin and Németh (2006). This volcano had a similar eruption history as that proposed here for the Landeskrone scoria cone. However, we assume initial and late (after scoria cone development) phreatomagmatic phases at the Landeskrone Volcano. The erupted volume of the primordial volcano calculated from a reconstructed idealized cone, as shown in Fig. 11, also implies a large sized monogenetic scoria cone with a very wide crater filled by lava with a thickness more than 100 m. Scoria cones commonly inject $10^4$ to $10^9$ m$^3$ of juvenile material (Vespermann and Schmincke, 2000). Our reconstructed eruption volume amounts about $8.9 \times 10^7$ m$^3$ for the Landeskrone Volcano (see above). To our knowledge, there is no published locality requiring such a huge lava lake fill (at least $3 \times 10^7$ m$^3$) in a monogenetic scoria cone.

The large size and the amount of lava lake nephelinite could be the reason for the preservation of the volcano remnants over such a long period of time (34 Ma) even in an area of uplift and denudation. The original height of the crater rim of the scoria cone is an enigma, because a major part of the scoria cone has been eroded already and, in addition, there are to our knowledge no references for such huge lava lakes in monogenetic scoria cones. The morphological characteristics for only partly welded pyroclastic cones that maintain such a large lava lake without breaching are unknown. Our assumption of the cone altitude is defined empirically and is one third higher than the lava level, conforming to the highest lava lake level at Hawaiian Pu‘u O’o crater (Witham and Llewellin, 2006). Furthermore, due to intense phreatic eruptions the crater rim should have been elevated and stabilized by deposition of hydrovolcanic tephra (Fig. 12).

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The large size and the amount of lava lake nephelinite could be the reason for the preservation of the volcano remnants over such a long period of time (34 Ma) even in an area of uplift and denudation (Fig. 14). A similar situation occurs at Quargelberg (Figs. 13, 14, Table 2) about 10 km south of the Landeskrone Hill. In contrast, scoria cones are often completely degraded and eroded down to the vent after about five million years (e.g. Wood, 1980b; Hooper and Sheridan, 1998). In our case, the remnants of a monogenetic volcano have survived much longer. Further we assume that superficial remnants of scoria cones with a lava lake resist complete degradation over 30 Ma.

### 7.2. Eruption history of the volcano

The eruption style of the monogenetic Landeskrone Volcano can only be supposed to be due to the reconstructed size and shape of the volcanic edifice and the scarcely outcropping pyroclastic rocks. The story perhaps started with an initial phreatomagmatic phase, which probably developed in a weak morphological depression because the ascending magma came into contact with groundwater. Again, there is no direct evidence for this eruption style but in the Eifel Volcanic Field an initial phreatomagmatic phase has been interpreted for nearly all scoria cones (Schmincke, 2004). Afterwards the water supply was cut off and strombolian activity produced a scoria cone over the diatreme (Fig. 12–1). Following Martin and Németh (2006), additional phreatomagmatic phases took place and modified the volcano edifice. The scoria cone was cut by hydrovolcanic explosions and the central part of the volcano slid into the diatreme that widened the crater in a final phase (Fig. 12–2). The combination of scoria cone and maar diatreme volcano causes an unusual shape as well as morphometric ratios not common for single volcano types. A phreatomagmatic eruption style takes commonly place while the magma column is subsiding in the conduit, due to a decreased magma flux (Gutmann, 2002). This should have happened at Landeskrone Volcano followed by a rapidly increased magma ascent rate. The wide and flat crater was filled by a lava lake in a single event (Fig. 12–3). The homogeneous 3D periclinal structure of columnar jointing without any irregularities suggests a lack of later fluctuations in the lava lake. Due to a flat pre-volcanic surface the cone did not breach while massive degassed lava filled the cone and produced a lava lake in the final stage. Otherwise a scoria cone, situated on an inclined surface, would have been broken by the ponded-back lava (Valentine et al., 2006). The original height of the crater rim of the scoria cone is an enigma, because a major part of the scoria cone has been eroded already and, in addition, there are to our knowledge no references for such huge lava lakes in monogenetic scoria cones. The morphological characteristics for only partly welded pyroclastic cones that maintain such a large lava lake without breaching are unknown. Our assumption of the cone altitude is defined empirically and is one third higher than the lava level (Fig. 11), conforming to the highest lava lake level at Hawaiian Pu‘u O‘o crater (Witham and Llewellin, 2006). Furthermore, due to intense phreatic eruptions the crater rim should have been elevated and stabilized by deposition of hydrovolcanic tephra (Fig. 12).

### 7.3. Landscape evolution

Neo-volcanoes can add important information on uplift and denudation rates for old cratons that complement fission track results (85–50 Ma for Lusatia area) and the fluvial/glacial sediment leveling data (1.5–0.4 Ma). These two methods cannot completely close the data gap for the uplift and denudation history for large parts of the low mountain ranges in Central Europe because the main uplift took

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Fig. 12. Schematic view of the development of the Landeskrone Volcano (not to scale), deduced according to the morphometric reconstruction (Fig. 11). 1 — Strombolian eruptions created a scoria cone after a hypothetical initial hydrovolcanic phase. 2 — A second intensive phreatomagmatic phase produced a maar diatreme below the scoria cone. The scoria cone has been modified due to excavating the central part of the cone and sliding of the cone material into the enlarged crater. The crater slope became steeper and the scoria cone covered by a tuff cone. 3 — Final effusive phase produced a lava lake.
place in the Mesozoic and there are no or only rare sediments from that time (Lange et al., 2008).

The amount of morphological denudation in this area can be quantified with up to 90 m being removed since the volcanic activity. This value reflects the amount of tectonic uplift during the last 30–27 Ma. Assuming a broad simultaneity between long-term uplift and denudation rates in tectonically active areas (Hack, 1976; Willet and Brandon, 2002; Ahnert, 2003), the estimated erosion rate would be about 3 mm/ka for the investigation area. In contrast, fission track calculations provide a value of 100 mm/ka for the whole Lusatian Massif in the time period between 85 and 50 Ma (Lange et al., 2008). No rates for modern uplift and erosion, based on in situ $^{10}$Be concentrations in fluvial sediments, are available, but data determined with that method have been published for the Central European block-faulted area with values between 15 and 101 mm/ka or between 47 and 65 mm/ka for the Rhenish Massif (Meyer et al., 2010). These high erosion rates indicate intensive neotectonic movement for the Holocene and disequilibrium between erosion and uplift for the uplifted areas in Central Europe. In comparison, very low erosion rates for the investigated part of the Lusatian Massif would imply a steady state since the Oligocene, during which the rock uplift is balanced by erosion (Hack, 1976; Willet and Brandon, 2002). At that time, some local tectonic subsidence in the Lusatian Massif occurred with the formation of lignite basins (Brause, 1989a, b; Tietz and Czaja, 2004). No tectonic movements have been recorded by sedimentation during Middle and Upper Miocene on the northern margin of the Lusatian Massif (Brause et al., 1964). Tectonic uplift is described for the Pliocene (Bergner, 1987; Brause, 1989a) and for the syn- and post-Elsterian glacial time in the Middle Pleistocene (Präger, 1964; Wolf and Hirschmann, 1964).

Furthermore, the N–S cross-section shows a fracturing within the Lusatian Massif. In addition to the well-established Altbirndorf Graben, we identify a fault 5 km south of the Landeskrone Hill with a fault vertical displacement of at least 90 m. This fault generated the main uplift of the Landeskrone Volcano since the eruption 34 Ma ago. Additionally, we assume reverse tectonic movement along a fault on the southern margin of Hospital Hill (Figs. 13, 14). Tectonic displacement is also observed on the north-western slope of the Hutberg Hill (No. 4 and 5 in Fig. 13). Here, a lava flow is cut and displaced vertically by about 53 m by the marginal fault of the Altbirndorf Rift (Fig. 14). These movements indicate morphologic variation due to tectonic processes and that the syn-volcanic landscape was nearly level. Such a planar landscape was created due to the climatic conditions in Tertiary times (e.g. Liedtke and Marcinek, 2002; Suhr, 2003; Rapprich et al., 2007). For example, Suhr (2003) noted several fluvial connections between North Bohemia and East Germany over the recent Erzgebirge Mountains for eight time intervals between the Eocene and Miocene. Further, the absence of coarser sediments in the study area suggests a low relief for Upper Lusatia in Tertiary times (Suhr et al., 1992; Tietz and Czaja, 2004). Rapprich et al. (2007) got the same result for the pre-volcanic landscape of the Jičín Volcanic Field (NE Bohemia), 75 km south of the study area. The shapes of the Kozákov lava flow bodies imply a pre-volcanic landscape with “relatively flat relief with wide shallow valleys” (Rapprich et al., 2007, p. 177) for Pliocene times (prior to 5 Ma).

The now defined “Görlitz horst”, reconstructed according to the post-volcanic uplift, is a further indication of local tectonic differentiation and movement inside the Lusatian Massif during and since the Cenozoic (for comparable indications see Steding and Brause, 1969; Krentz, 2008).

A peak of post-volcanic degradation rate would have occurred during the Pleistocene. Basaltic scoria pebbles in glacioluvial sediments near the 33–27 Ma-old Baruth Scoria Cone Volcano Complex support such neotectonic movements (Tietz et al., 2011). Today the scoria deposits are nearly completely eroded, but a higher amount of non-weathered scoria pebbles was found in 200 ka-old Saalian-1-glacial meltwater sediments. These discoveries provide a very long lifetime for the scoria cone and imply a young uplift and denudation of the northern and central part of the Lusatian Massif. This young age for uplift has possibly prevented an early and complete destruction of the Landeskrone Volcano. Pleistocene tectonic movements are also known from the Berzdorf Basin. The early Pleistocene river terrace shows here a tectonic subsidence from 25 m compared with the basin surroundings. Additionally, a diagenetic compaction of 8 m for the same time during the last 1.2 Ma can be assumed (Tietz and Bünchler, 2011).

Fig. 13. Shaded relief map of eastern Lusatia with the cross-section line of Fig. 14. The locations of main faults which separate the tectonic units are taken from Krentz et al. (2008) and this study. Remnants of volcanic structures selected in Fig. 14 are mentioned with their number (compare Table 2). Coordinate system: see Fig. 2.
Therefore, the long-lasting degradation of monogenetic scoria cones is not only controlled by the size and composition of primary volcanic edifices but also by the morphological elevation. Landeskron Hill was twice affected by glaciers in the Elsterian Glacial (Tietz and Büchner, 2010). The main part of the movement took place probably immediately after these glaciations in upper Middle Pleistocene. Otherwise, the Landeskron Volcano would have been destroyed completely by today. The final destruction of the volcanic edifices was caused by periglacial erosion in the Saalian and Weichselian glaciations.

Furthermore, we assume no or minor uplift and degradation in the Upper Paleogene and Early Neogene. The tectonic regime in the investigation area is characterized by extensional strain during the Oligocene and Miocene, creating sedimentary basins (Bergerat, 1987; Tietz and Czaja, 2004).

8. Conclusions and outlook

This paper shows that reconstruction of the Cenozoic volcano remnants provides a powerful tool for elucidating the uplift and denudation history. Reconstructed volcanic edifices provide a well defined landscape situation at given times. Further we show the possibility of reconstructing ancient volcanic edifices such as the nephelinitic Landeskron Volcano. The explosive phase of the Landeskron Volcano started and ended with phreatomagmatic eruptions while the main activity in between was characterized by strombolian eruptions. The combination of the two eruption styles in this manner created a large combined scoria cone-maar volcano with a wide and deep crater. This combination of eruption styles led to an extraordinary volcanic development and glaciation history or the cosmogenic 10Be concentration in stream sediments (e.g. Meyer et al., 2010). A 3D modeling for more clearly defined monogenetic volcanic remnants may lead to further knowledge for interpreting landscape evolution in space and time.

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References


Fig. 14. N–S cross-section through the area surrounding the Landeskron Volcano remnant with the reconstructed paleosurface at the time of volcanism, approximately 30–27 Ma ago. Location of the cross-section is shown in Fig. 13.


