33 Geomorphological Evidence of Past Volcanic Activity in the Southeast of Austria

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Abstract

Active volcanoes do not exist in Austria today. However, remnants of volcanoes that were active during two main eruption periods between about 23 and 1 million years ago are prominent geomorphic features in the southeast of Austria. In this chapter, we discuss a complex landform evolution, in which sedimentological, tectonic, volcanic, and erosional processes acted together to create the present landscape. The study area is the Styrian basin and its vicinity, where 31 volcanic sites are located. Today, nothing is left of the primary volcanic landscape due to erosional processes lowering the original surface by some hundreds of metres since the end of the eruptions. The two main volcanic landforms present today are (i) maar-diatreme volcanoes, which form prominent and steep mountains consisting of basaltic tuff and maar lake sediments, and (ii) residuals of complex volcanoes consisting of tuff, scoria and massive basalt layers, partly buried by post-eruption sediments. The former are smaller in their spatial extent and monogenetic, whereas the latter are polygenetic, rather large, but partially buried by sediments. Some of the former volcanoes are characterized by well-developed planation surfaces that developed during the last million years. Hypsometric analyses were carried out for six volcano remnants (i) for morphometric characterization and (ii) to compare them with active volcanoes. The results revealed that only well-eroded diatreme volcanoes such as Güssing can be suitably characterized by means of a hypsometric analysis. In all other cases, this approach fails due to the complex formation and erosion history of the volcanoes.

Keywords

Volcano remnant • Maar-diatreme volcano • Stratovolcano • Planation surface • Hypsometric analysis

33.1 Introduction

In this chapter, we discuss volcanic landforms located in the southeast of Austria, i.e., in the federal provinces of Styria and Burgenland (Fig. 33.1). This part of Austria was influenced by volcanic activity over a period of several million years ending around 1.71 ± 0.72 Ma ago (cf. Table 33.1). Since the beginning of volcanic activity in the study area, the region has been influenced by large-scale subsidence followed by a period of uplift, causing formation and destruction of both volcanic and non-volcanic landforms.

Most landforms are the result of both, tectonic processes creating an initial relief and of the sculpturing effects of erosion by wind, water, gravity and ice destroying the previously built-up relief. However, volcanic landforms are special, being the result of enhanced constructive and opposing destructive forces acting on a more local to regional scale compared to tectonic forces (Francis 1993). Constructive processes operate as long as a volcano is active. The active phase might be an extremely short period, forming small landforms such as single lava flows or scoria cones. Volcanic activities might also last intermittently for several thousands of years, forming large volcano edifices (Martí et al. 1994; Rhodes and Lockwood 1995).

Francis (1993) pointed out that erosion of new volcanic material begins on a volcano as soon as the volcano starts growing and even before its new lavas and pyroclastic deposits have cooled (see also Cotton 1944). A large volcano may experience several phases of rapid construction

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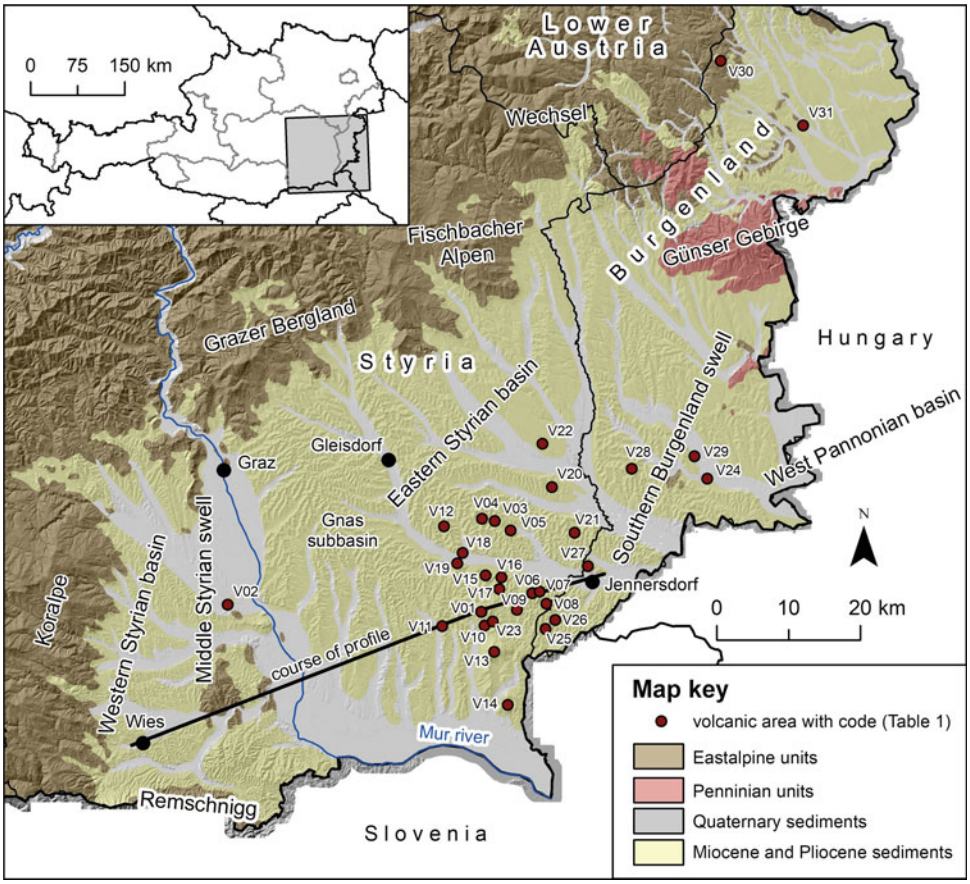

Fig. 33.1 Topographical and geological setting of the south-eastern part of Austria with the main geological basins and swells (see text for details). All volcanic areas listed in Table 33.1 and the course of the geological cross-profile shown in Fig. 33.3 are indicated. Geology based on Weber (1997)

during which the rate of build-up exceeds the rate of erosion. On the Hawaiian Islands, for instance, phases of construction alternated with phases of massive flank collapses, which are traceable in the Pacific Ocean (Moore et al. 1994). On large volcanoes, erosion may be active on one slope, whereas new lava and tephra are being added to another.

Tectonic forces change the relative position and elevation of the sea level. In case of prevailing subsidence and formation of a basin within surrounding mountains, sediments from these mountains might accumulate in the basin, causing complete or partial burial of a volcano.

The aim of this chapter is (i) to give an overview of the tectonic, volcanic and denudational chronology of the Styrian basin since the Miocene and (ii) to describe its geomorphic legacy on the present landscape in qualitative and quantitative analyses.

33.2 Study Region

The study area is located in the western part of the Pannonian basin system (Schönlaub 2000). The Styrian basin is about 100 km long, 60 km wide, up to 4 km deep (Gross et al. 2007) and is surrounded by the Remschnigg mountains to the south-west, the Koralpe and Grazer Bergland to the west and northwest, and the Fischbacher Alpen and Wechsel mountains to the north (Fig. 33.1). The basin is separated by the NNE-SSW striking Southern Burgenland swell from the Western Pannonian basin and internally divided by the Middle Styrian swell into a Western and an Eastern Styrian basin. Because of geological, morphological and volcanological similarities, we also consider the volcano remnants located at the Southern Burgenland swell and those north of the Günser Gebirge in this chapter.

The Southern Burgenland swell was formed due to different subsidence rates of the basins mainly during the Middle Miocene, but continued to form until the Late Miocene (Gross et al. 2007). The swell stretches from the settlement of St. Anna in the southwest to the Günser Gebirge in the northeast and is composed of phyllitic shales, green shales and limestone shales of the Silurian and carbonates of the Devonian (Schönlaub 2000). These Palaeozoic units are widely covered by transgressive Miocene sediments of brackish to freshwater origin (Flügel and Heritsch 1968; Gross et al. 2007).

Table 33.1 List of volcanic areas in the study area with names, location, estimated age ranges and relevant references. For the location of sites see Fig. 33.1

Code	Lat (°N)	Long (°E)	Name	Municipality/-ies	Estimated age (in Ma)	References*
V01	46.8893	15.9092	Gleichenberger Kogeln	Bad Gleichenberg, Feldbach	12.2[4]–17.2[2] 22.97 ± 1.93	1, 2, 4, 6 3
V02	46.8955	15.4456	Weitendorf	Wildon, Dobl-Zwaring	14.0–17.5	1, 2, 4
V03	47.0032	15.9331	Riegersburg	Riegersburg	3.71	7
V04	47.0061	15.9097	Altenmarkt	Riegersburg		
V05	46.9915	15.9621	Stang	Fehring, Riegersburg		
V06	46.9129	16.0023	Fehring (Burgfeld, Heißberg, Waxenegg, Zinsberg)	Fehring	5.15	7
V07	46.9148	16.0161	Beistein	Fehring	5.82	7
V08	46.8997	16.0283	Aschbuch	Fehring, Kapfenstein		
V09	46.8919	15.9743	Kapfensteiner Kogel	Kapfenstein	4.68–4.86	5, 7
V10	46.8720	15.9155	Bad Gleichenberg (Albrechtshöhe, Sulzberg, Wierberg)	Bad Gleichenberg	5.26	7
V11	46.8710	15.8382	Gnas	Gnas	2.88	7
V12	46.9961	15.8402	Edelsbach	Edelsbach bei Feldbach	3.52	7
V13	46.8390	15.9332	Stradner Kogel	Bad Gleichenberg, St. Anna, Straden, Tieschen	1.71 ± 0.72	4
V14	46.7727	15.9587	Königsberg/Klöch	Tieschen, Klöch	2.56 ± 1.2 2.17–2.56	4, 5
V15	46.9350	15.9170	Steinberg (Mühldorf)	Feldbach	2.64–3.05	4
V16	46.9325	15.9457	Pertlstein	Fehring	3.32	7
V17	46.9177	15.9424	Forstkogel	Feldbach	7.51	7
V18	46.9631	15.8744	Auersberg (Gniebing)	Feldbach	2.87	7
V19	46.9499	15.8647	Unterweissenbach/Kalvarienberg (Gniebing)	Feldbach	2.27–2.73	4, 7
V20	47.0461	16.0375	Stadtbergen	Fürstenfeld	6.48	7
V21	46.9888	16.0795	Stein (Großsteinberg/Hiebüchl)	Loipersdorf bei Fürstenfeld		
V22	47.1002	16.0199	Jobst	Bad Blumau		
V23	46.8773	15.9302	Muhrn (Bairisch Kölldorf)	Bad Gleichenberg		
V24	47.0571	16.3227	Güssing	Güssig	5.03–6.3	5, 7
V25	46.8682	16.0271	Neuhaus (several smaller areas around Neuhaus)	Neuhaus am Klausenbach	3.11–3.76	4, 5
V26	46.8794	16.0445	Neuhaus (Wolfsriegel north)	Neuhaus am Klausenbach		
V27	46.9471	16.1041	Grieselstein (two parts)	Jennersdorf		
V28	47.0695	16.1842	Limbach	Kukmirn	5.72	7
V29	47.0853	16.2993	Tobaj	Tobaj	4.98	7
V30	47.5807	16.3472	Pauliberg	Kobersdorf	10.5–12.3	4
V31	47.4996	16.5000	Oberpullendorf	Oberpullendorf	11.1	4

* References: 1—Lippolt et al. (1975), 2—Steininger and Bagdasarjan (1977), 3—Kolmer (1980), 4—Balogh et al (1994), 5—Seghedi et al. (2004), 6—Bojar et al. (2008), 7—Bojar et al (2013)

Today, the Styrian basin and the Southern Burgenland swell form undulating lowlands with elevations between 200 and 600 m asl and comprise Neogene and Pleistocene sediments covering the basement and the volcanic rocks. The highest summit in the area, the Stradner Kogel, is 609 m asl high. The lowest point in the area is located at the border to Slovenia, where the Mur River leaves Austria (200 m asl). In general, the difference in elevation between the two ridges or hills and the valley in between is in the order of 100–200 m. The main valley bottoms are mostly wide and flat (e.g. Mur

Valley in Fig. 33.1), smaller valleys are often V-shaped. Steeper slopes are mostly related to volcanic rocks.

Climatic conditions are moderately continental with snow-poor winters, and the precipitation maximum is in summer. Mean annual precipitation values are between 800 (in the SE) and 1000 (near the mountains) mm. Mean annual air temperatures are influenced by local topographical conditions and are in the order of 8–9 °C (Prettenthaler et al. 2010).

33.3 Geological History

Until the Late Miocene, the palaeogeographical environment of the Styrian basin was marine, belonging to the Paratethys (Gross et al. 2007). The basin formation is connected to continental escape tectonics of alpidic crustal wedges at the final collision stage of the Adriatic plate with the European plate during the Late Oligocene to Miocene (Neubauer and Genser 1990; Ratschbacher et al. 1991). The development of the Carpathian chain and the Pannonian basin system in the Miocene was controlled by retreating subduction in front of the orogen and by back-arc extension associated with the diapiric upraise of the astenosphere (Kovac et al. 2000; Konecny et al. 2002). Lateral escape took place along large, E-W trending strike-slip faults, generating small pull-apart basins. Simultaneously, isostatic uplift of thickened continental crust was associated with gravitational sliding of higher parts of the lithosphere along flat downthrow faults. This led to the exposure of deeper units (Penninic unit). Downthrow faults are regarded as responsible for horizontal block tilting, which caused asymmetric, N-S striking extensional structures like the Styrian basin (Neubauer and Genser 1990; Neubauer et al. 1995). The tectonic evolution of the Pannonian basin system was accompanied by magmatism of variable composition that is documented by two main volcanic phases in the Styrian basin.

33.3.1 Basin Development Since the Miocene

Based on Kollmann (1965), Gross et al. (2007) provided a summary of basin development, which included a stratigraphic chart of the Neogene basin fill of the Styrian basin. The ages published for the different stages of the Miocene vary between the different parts of the Central Paratethys (Kovac et al. 2018). Here we follow mainly the ages presented by Gross et al. (2007). Figure 33.2 gives a summary of the evolution of the Styrian basin and its surrounding basement as judged from Miocene to Quaternary sediments, planation surfaces (here used as a purely descriptive term for a low-relief plain cutting across various rocks and structures) and age constraints. The filling of the basin started in the Early Miocene during the Ottnangian (c.18.3–17.0 Ma) with limnic-fluvial sediments (Figs. 33.2 and 33.3). The alluvial fan and delta sediments of that time are locally coal-bearing (Ebner and Sachsenhofer 1991). Weathered ash-tuff layers (bentonite), intercalated in this sedimentary succession, have also been reported (Gross et al. 2007). Volcanic activity was probably initiated even earlier, around the Oligocene/Miocene transition some 23 Ma ago (Table 33.1), as judged from dates presented by Kolmer (1980). However, later dating results at the same volcano (VO1) revealed younger ages, therefore the onset of volcanism in the study area is not known with certainty (see Table 33.1).

In Karpatian times (c.17.0–16.0 Ma), the increase of tectonic activity caused considerable subsidence, which led to a marine transgression at the basin margin. Besides the formation of the Middle Styrian swell, volcanic activity increased and a compound volcano, consisting of acidic and intermediate material, formed in the Gnas subbasin (Fig. 33.1). The maximum marine extent occurred during the Early Badenian, at 16–15 Ma. Coral reefs and limestone platforms (Leitha Limestone) developed around higher-elevated basement mountains. Some of these former reefs are karstified today (Friebe 1990; Bauer 2015). The westernmost volcanic landform in the Styrian basin was formed 17.5–14.0 Ma ago in Weitendorf (V02 in Fig. 33.1).

The almost complete isolation of the Paratethys from the Mediterranean and the Indopacific (Rögl 2001) during the Sarmatian (c.12.8–11.6 Ma) caused substantial environmental changes. Friebe (1994) inferred a repeatedly oscillating sea level because of mixed siliciclastic-carbonate sedimentation. The Pannonian (c.11.6–7.1 Ma) started with an extensive regression and tectonic fragmentation, causing the origin of horst and graben structures as shown schematically in Fig. 33.2. The coarse sediments of the Pannonian are suitable aquifers and contain large amounts of groundwater. This geological context was of high relevance for the phreatomagmatic eruptions during the Late Miocene to Pleistocene. Ebner and Sachsenhofer (1995) pointed out that during the Middle to Late Miocene a final, rather strong subsidence was followed by the beginning of the uplift of the lowland.

In summary, a massive sedimentary pile developed between ~18 and 11 Ma in the Styrian basin accompanied by a period of active volcanism from 23.0 (or at least 17.5; cf. Table 33.1) to 10.5 Ma ago. According to Ebner and Sachsenhofer (1995), tectonic movement inverted around 5–6 Ma, causing the end of sedimentation and the beginning of the uplift history of the Styrian basin.

33.3.2 Miocene Volcanic Period

The strong crustal extension during the Karpatian was accompanied by volcanic activity, which continued until the

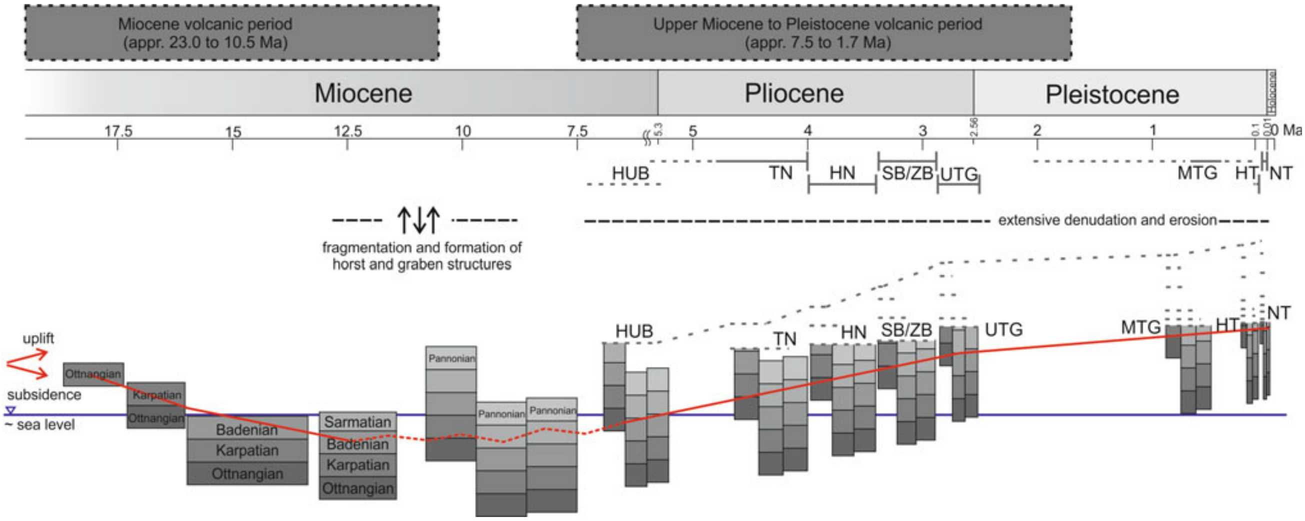

Fig. 33.2 Tectonic and sedimentary evolution of the Styrian basin and its surrounding basement derived from Miocene to Quaternary sediments, planation surfaces and age constraints. The approximate temporal extents of the two main volcanic phases are indicated (based on dates in Table 33.1). Abbreviation of the different planation surfaces and stream terraces (from old/more elevated to young/less elevated): HUB = Hubenhalt niveau, TN = Trahütten niveau, HN = Hochstraden niveau, SB/ZB = Stadelberg/Zahrerberg niveau, UTG = Upper terrace group, MTG = Middle terrace group, HT = high terrace gravels, NT = low terrace gravels (after Wagner et al. 2011; Fig. 33.8, modified)

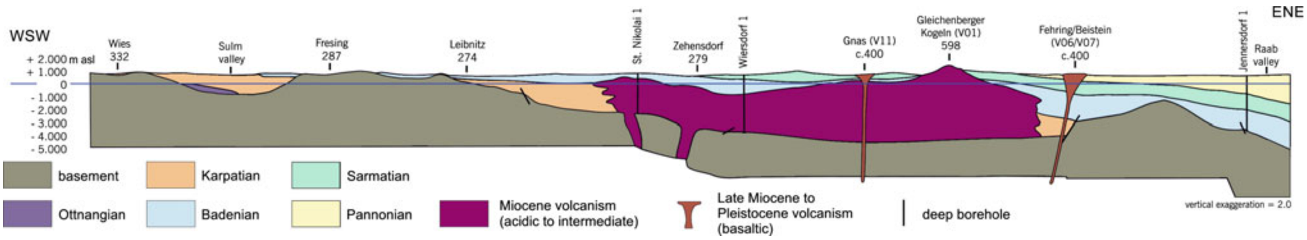

Fig. 33.3 Geological cross-profile of the Styrian basin based on deep boreholes (selected ones are indicated in the profile). For the location of the profile see Fig. 33.1. Profile modified after Ebner and Sachsenhofer (1991, appendix 2)

end of the Early Badenian in the Styrian basin (Handler et al. 2006) and until the Pannonian in Burgenland (Balogh et al 1994). Eruptions of acidic to intermediate composition occurred in the Gnas subbasin. Polygenetic volcanism (i.e., several eruptions form the volcano edifice) prevailed during this first phase of volcanism. Ebner and Sachsenhofer (1991) speculated about a subduction-related origin of the potassium-rich subalkaline-alkaline magma. Huge shield volcanoes developed, which were later nearly completely buried by younger sediments. The knowledge of the sediment-buried volcanic structures stems from drillings (e.g. petroleum exploration; examples on Fig. 33.3) and geophysical surveys (Kröll et al. 1988). Younger alkali-basaltic volcanism forming alkaline effusive rocks of Early Pannonian age (c. 12.3–10.5 Ma) are located north of the Günser Gebirge in the area of Pauliberg and Oberpullendorf (V30 and V31 in Fig. 33.1 and Table 33.1). Figure 33.1 and Table 33.1 give an overview of the 31 relevant volcanic areas. As indicated in this table, only few volcanic areas (V01, V02, V30 and V31) are attributed to this Miocene volcanic phase.

33.3.3 Late Miocene to Pleistocene Volcanic Period

The second phase of volcanic activity, this time primarily of alkali-basaltic composition, occurred between ~7.5 and 1.7 Ma (Table 33.1). In Styria and southern Burgenland, rising magma from the Earth's mantle came into contact with groundwater contained, for instance, in the coarse Pannonian sediments (Pöschl 1991; Fritz 1996; Gross et al. 2007). Hence, phreatomagmatic eruptions occurred, creating funnel-shaped craters in the pre-volcanic surface and producing pyroclastic rocks. These rocks erupted explosively and contain fragmented juvenile and lithic clasts in different compositions. Bomb-sag-structures and low-angle-cross-stratification as well as the existence of accretionary and armoured lapilli indicate phreatomagmatic eruptions and are evident at several volcanic remnants in the Styrian basin.

Presumably, hundreds of rapidly succeeding eruptions produced huge amounts of tephra that were primarily deposited in layers, building up maar-diatreme-volcanoes

(Lorenz 1986). Subsequently, the material solidified and formed volcanic tuff. After the volcanic activity had ceased, craters filled with water, forming maar lakes. Into these maar lakes tephra from the surrounding tuff-rims was re-deposited, forming characteristic fine-clastic maar lake deposits (White and Ross 2011). The once deeper-lying harder volcanic pyroclastic rocks were uncovered through the subsequent erosion of the surrounding loose sedimentary rock. At some localities—Stradner Kogel (V13), Klöch (V14), Steinberg (V15), Altenmarkt (V04), Stein (V21) and Neuhaus (V25 and V26)—basaltic extrusions and/or intrusions are preserved. The volcanoes from this activity period commonly had a short eruptive history and were presumably in most cases monogenetic volcanoes like scoria cones or maar-diatreme volcanoes (Németh and Kereszturi 2015). As shown in Table 33.1, most volcanic areas are attributed to this volcanic phase.

33.4 The Visual Legacy of the Volcanic and Erosional History

33.4.1 The Role of Erosion and Denudation

Starting 5–6 Ma ago, large-scale sedimentation processes diminished and erosion began to prevail. Almost no sediments of the Pliocene age are preserved today (Gross et al. 2007; Wagner et al. 2011). The Styrian basin was never glaciated during the Pleistocene. Relics of landforms that date back to the Late Miocene—such as planation surfaces (cf. Figs. 33.2 and 33.4)—are still preserved today. Geological and geomorphological investigations of the Styrian basin started in the nineteenth century. One of the pioneers working on the reciprocal effects of erosion and build-up (including volcanism) on the Styrian basin was Arthur Winkler-Hermaden. His publication of 1957 reflects the state of knowledge at that date (Winkler-Hermaden 1957).

With the beginning of uplift, several distinct morphological levels were formed in the Styrian basin and the surrounding basement. Wagner et al. (2011) summarized earlier findings for these levels and discussed their ages based on dating and correlations with cave levels, stream terraces and planation surfaces (Fig. 33.3). The two highest planation surfaces (Hubenhalt niveau/HUB and Trahütten niveau/TN) are only found in the mountains surrounding the Styrian basin. Two lower planation surfaces also exist in the Styrian basin itself. These are the Hochstraden niveau (HN) —also termed Kalkleiten-Möstl (Hilber 1912) or Gebirgsrandflur (Untersweg, 1979)—and the Stadelberg/Zahrerberg level (SB/ZB). The elevation above the present-day Mur River (Fig. 33.1) is 325–450 m asl and 180–300 m asl, respectively. The volcanic rocks at the Königsberg near Klöch (V14) and at the Stradner Kogel (V13) are of high relevance in this regard, because planation surfaces developed across them. At about 550 m asl, a well-developed planation surface formed at the Stradner Kogel, giving rise to the name “Hoch(=high)straden” niveau. At a lower level of the Stradner Kogel mountain and in the nearby Klöch area, the SB/ZB level is well-preserved (Fig. 33.4). Both planation surfaces are covered by red loams (Fink 1961), suggesting warmer climatic conditions during formation.

The age of the HN and SB/ZB levels must obviously post-date the volcanic eruptive phase. Balogh et al. (1994) presented K/Ar-ages of the basaltic rocks at Klöch of 2.56 ± 1.2 Ma, and of the ones at Stradner Kogel of 1.71 ± 0.72 Ma. This age range gives a maximum age constraint on the SB/ZB level and suggests that its main formation is younger than the upper limit of the basalt age at both sites, i.e., <2.43 Ma.

As described in Sect. 3.3, the top of the volcanic rock/sediment pile is formed by maar lake sediments. The altitude at which maar sediments are found today (e.g. at Altenmarkt/V04, Burgfeld near Fehring/V06,

Fig. 33.4 Zahrerberg area near Klöch with a well-developed planation surface (Zahrerberg level) consisting of basaltic rocks; **a** the southern part of the planation surface with the view towards west (note the approximate delineation of the slightly inclined and moderately incised planation surface), **b** basalt rock outcrop at the southern margin of the planation level. The Zahrerberg area is intensively used for wine growing due to favourable climate and soil conditions. Photographs by the authors

Gleichenberger Kogeln/V10 and Gnas/V11) can therefore be used to estimate denudation rates since the time of volcanic activity. The result of c. 300 m is consistent with data suggested for comparable settings in the Pannonian basin (Kereszturi et al. 2011).

In summary, erosional processes prevailed during the Pliocene and Pleistocene periods at higher levels of volcanic and non-volcanic landforms. Large-scale sedimentation processes acted only in the main valleys and their tributaries (Wagner et al. 2011). Rates of sedimentation and erosion in the Styrian basin during the Pliocene and the Quaternary are not known.

33.4.2 The Anthropogenic Influence on Volcanic Landforms

Human activities have modified the volcanoes in the region to some extent through surface mining. Figure 33.5 shows two examples of basalt quarries in the Styrian basin. The first example is from a basalt quarry slightly north of the settlement of Klöch. Gross et al. (2007) described well-bedded tuff-layers forming the basis of the volcanic succession and being in discordant contact to the Sarmatian sediments. Intrusive nepheline-basanites and pyroclastic rocks are exposed in the quarry. At the upper part of the open mine, weakly bedded, red tuff breccia with some small lava flows are exposed, forming the top of the volcanic succession. The second example is from the Steinberg area about 2 km SE of Feldbach. The volcanic material at this site covers sediments of Pannonian age (Heritsch 1968). Figure 33.6 depicts one example of the use of volcanic rocks (lapilli tuff) in the study region for construction purposes, in this case to build the church in the municipality of Riegersburg.

On an annual basis, the Austrian Federal Ministry for Sustainability and Tourism (www.bmnt.gv.at) publishes the output of the national mining industry. According to the reports for 2014–2016, basaltic rock was mined at one site in the federal province of Burgenland (V30/Pauliberg) and at five sites in Styria (V14/Klöch, V15/Steinberg/Mühldorf, V13/Stradner Kogel, V02/Weitendorf and V01/Gleichenberger Kogeln) during the reporting periods. As shown in the inset graph in Fig. 33.5, the amount of mined basalt increased from 2012 to 2014, but has decreased slightly since then. On average, 1.57 Mio. t/yr of basalt were mined during the 5-year period 2012–2016.

33.4.3 Visible and Obscured Volcanic Remnants

33.4.3.1 General Conditions

There are many places around and even within the Styrian basin with magnificent views over the morphology of the basin (Fig. 33.7). Prominent features visible from far away are distinct ridges or hills, often with flat summit areas. Such rounded and often forested mountains are called “Kogel”. Because of their greater resistance to weathering as compared to the predominantly non-solid clastic sediments, the volcanic rocks stand out against their surroundings. Examples are the Gleichenberger Kogeln (V01; a double summit culminating at 598 and 563 m asl), Kapfensteiner Kogel (V09; 461 m asl), Stradner Kogel (V13; 609 m asl) or the Königsberg-Zarawald-Seindl area (V14; 462 m asl). The most spectacular volcanic forms in the study area are the steep diatremes of Riegersburg (V03; 484 m asl) and Güssing (V24/318). Both of them were used as locations for fortifications in the past and have impressive castles at their tops (Fig. 33.8).

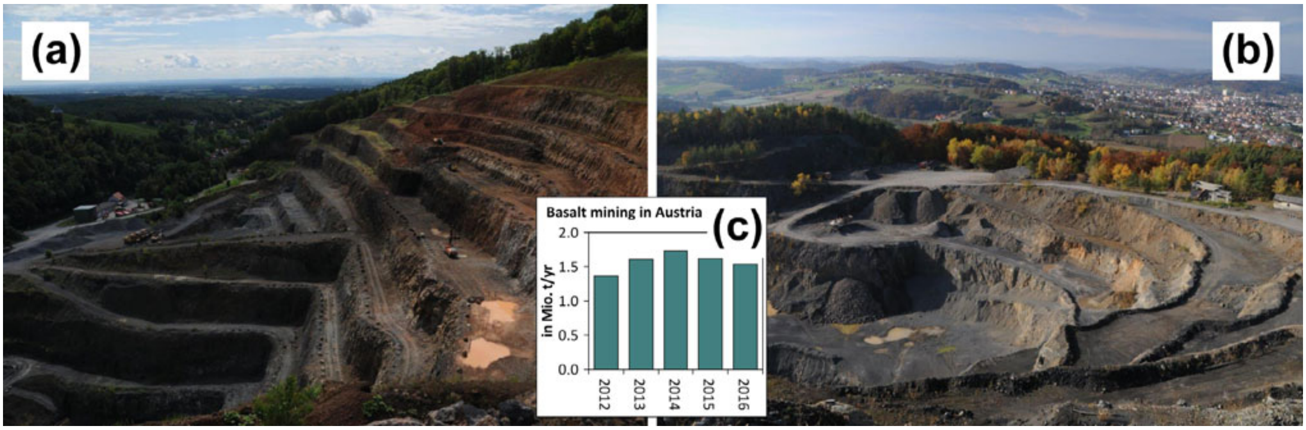

Fig. 33.5 Examples of anthropogenic influence on the volcanoes in the Styrian basin due to surface mining: **a** basalt quarry near Klöch (V14), view towards S; **b** basalt quarry at Steinberg (V15), view towards NW, note the town of Feldbach and the volcano remnants of Unterweissenbach/Kalvarienberg (V19) left (south) of Feldbach; **c** depicts the amount of mined basalt in Austria (all six relevant quarries are located in the study region) during the period 2012–2016 (for data source see text). Photographs by the authors

Fig. 33.6 An example of the use of volcanic rocks in the study region for construction purposes. The church of the settlement of Riegersburg (**a**) is made of basaltic tuff (**b**), which was quarried from the nearby diatreme of Riegersburg (V03). Note the handrail in B for scale. Photographs by the authors

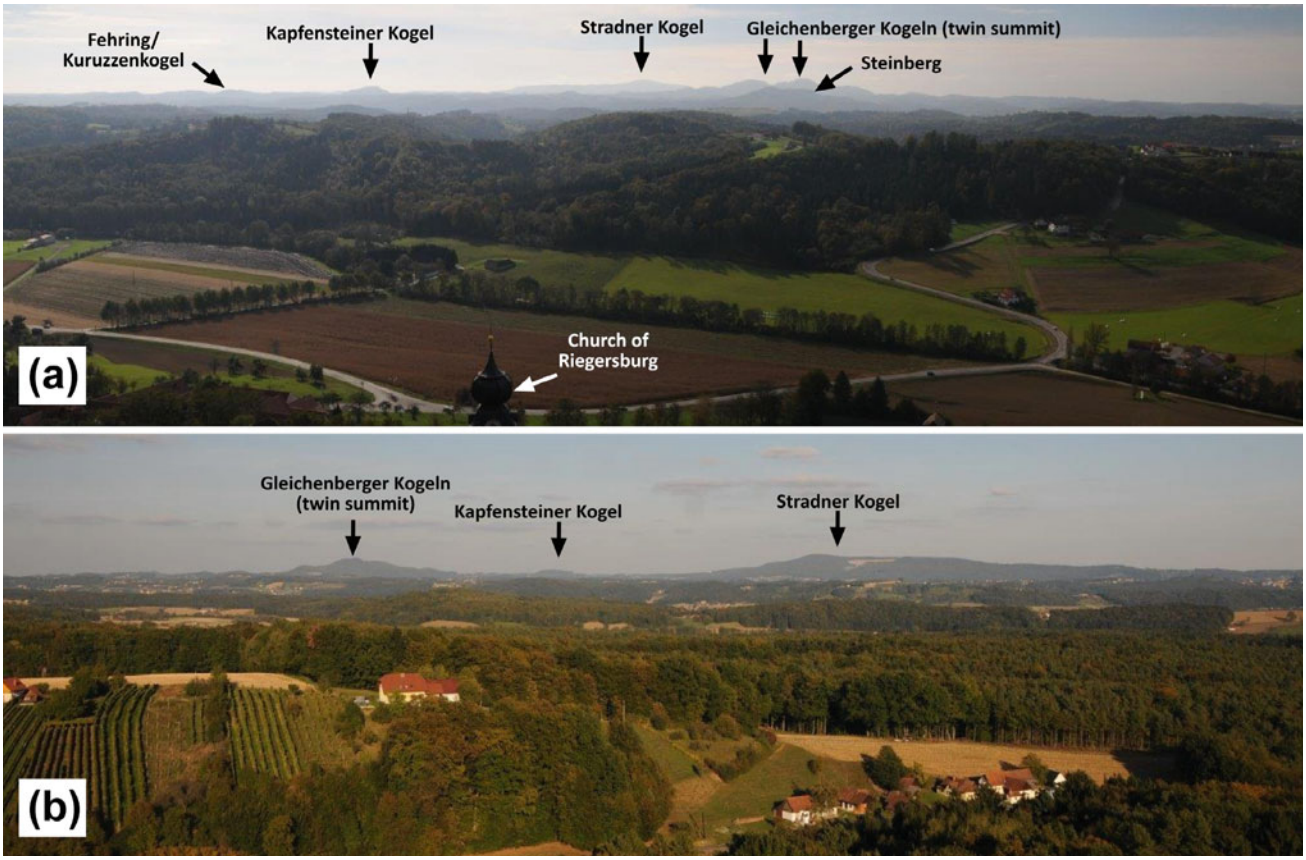

Fig. 33.7 Examples of prominent volcanic landforms in the Styrian basin; **a** view over the basin from the Riegersburg (V03) diatreme towards south over the hilly landscape; **b** view over the basin from a lookout point at St. Peter am Ottersbach towards east. The hills in the foreground of both images consist of Miocene sediments. The pronounced mountains in the background are mainly of volcanic origin. Photographs by the authors

Whereas smaller diatremes, probably derived from smaller and/or older events, clearly rise above the surrounding surface, larger and complex remnants of maar volcanoes are difficult to detect in the landscape using only morphological evidence. The two neighbouring volcanoes of Riegersburg (V03) and Altenmarkt (V04) serve as good

Fig. 33.8 Diatreme of Riegersburg (V03), with the settlement of Riegersburg at its foot (at 320–380 m asl) and a mighty, medieval castle on the top (max. 484 m asl). The church shown in Fig. 33.6 is visible near the right margin of the image. Photograph by the authors. For an aerial view of the Riegersburg from the opposite direction see Fig. 8b in Chap. 1

examples of this difference. V03 is a very well-exposed diatreme (Fig. 33.8), whereas V04 is a complex volcano of a maar-volcano system that is hardly recognizable in the present landscape. Volcanoes, which produced—after an initial phreatomagmatic eruption—scoria cones with partly huge basaltic intrusions and lava lakes (Klöch-Königsberg, Steinberg) or lava flows (Stradner Kogel) are particularly impressive and represent good examples of inverted relief formed during the post-eruption erosional period. Lava flows, which formerly filled the valleys, are now supporting high-elevated hills or ridges.

33.4.3.2 Morphometric Analysis of Selected Volcanic Remnants

Six selected volcanoes are considered in this section in more detail. By means of calculating hypsometric curves for these six volcano remnants, it was aimed to (i) morphometrically characterize them focusing on similarities and differences, and (ii) to compare them with active volcanoes to bring them into a wider geomorphic context. In general, differences in the shape of hypsometric curves between landscapes arise because of different geological conditions and geomorphic processes that shaped the landscape. Table 33.2 gives an overview of the six volcanos, also describing how an area at and around the volcano, subject to morphometric analysis, was delineated. Since the present topography of the volcanic area is often rather similar to that of the surrounding area that consists of non-volcanic rocks and lacks distinct geomorphometric borderlines, the delineation of the six analysed areas is, to some extent, arbitrary. However, in all cases the central part of the studied area (polygon or rectangle) is also the central part of the former volcano. For each of the six volcanoes, a hypsometric analysis was accomplished in ArcGIS and involved the calculation of hypsometric curves using an open-source digital elevation model (www.data.gv.at) with a grid resolution of 10 × 10 m.

Hypsometric curves from one stratovolcano and three shield volcanoes were additionally analysed to bring the six hypsometric curves calculated in our study into a broader volcanological context. Hypsometric data from the shield volcanoes were taken from Bleacher and Greeley (2008). Hypsometric data from the stratovolcano (Mt. Fuji) were calculated using SRTM elevation data (pixel resolution 30 × 30 m). Only the volcano edifice above 1200 m asl (and

Table 33.2 Overview of the six analysed volcanoes within the study area with code, name, and description of the delineation of the morphometrically analysed area

Code	Location	Delineation of morphometrically analysed area (cf. Fig. 33.9)	Area (km^2)	Elevation (m asl)			
				max	min	mean	diff
V03	Riegersburg	Mainly along valleys/gullies	1.57	474	293	341	181
V24	Güssing	Rectangle around the volcano; the surrounding area is flat	1.44	319	211	223	108
V04	Altenmarkt	Rectangle; surrounding topography is similar to the one at the volcano	4.41	446	302	359	144
V14	Klöch-Königsberg	Rectangle; surrounding topography is similar	11.56	462	240	323	222
V13	Stradner Kogel	Mainly along valleys/gullies	48.86	608	232	335	376
V01	Gleichenberger Kogeln	Mainly along valleys/gullies	10.64	598	273	379	325

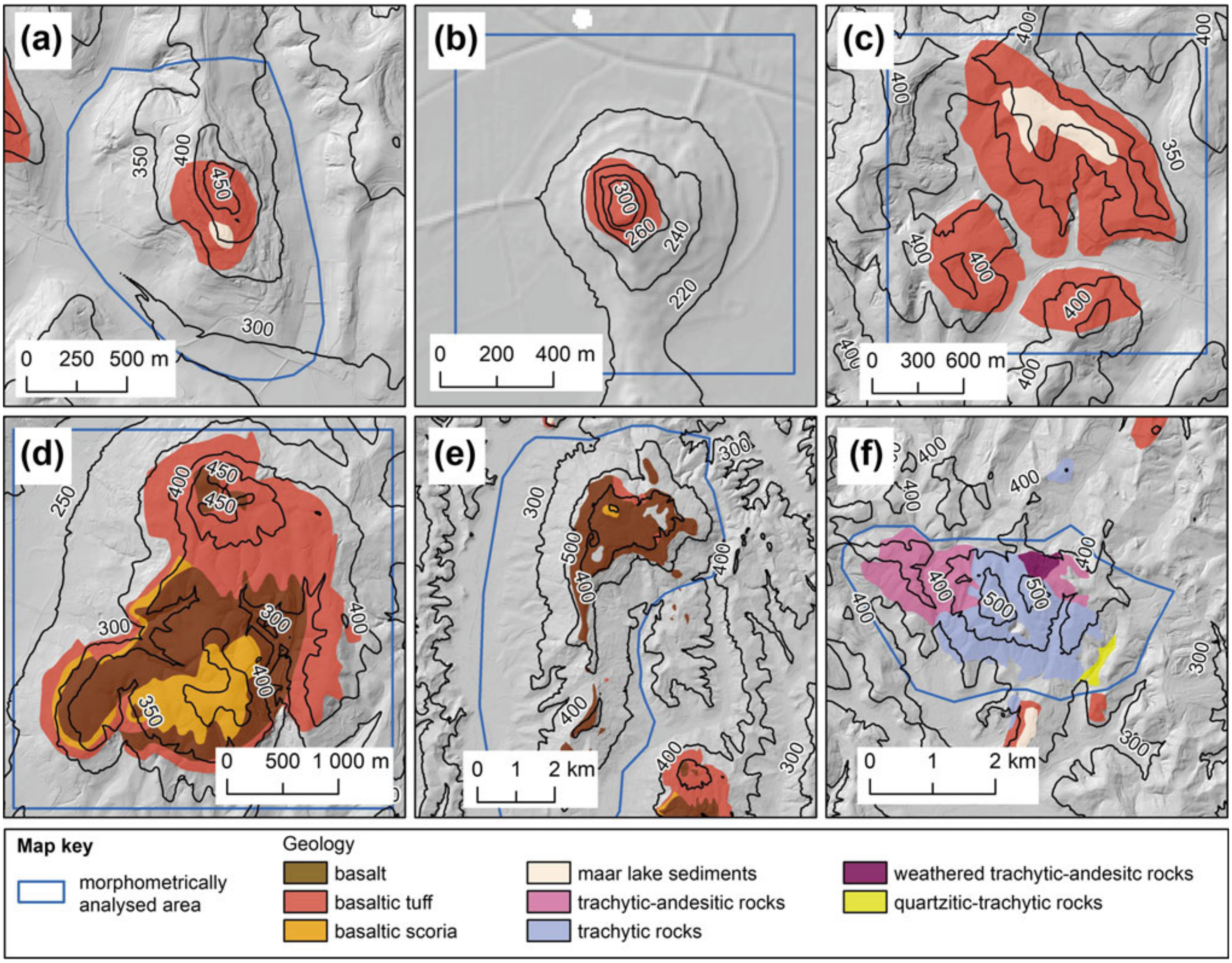

Fig. 33.9 Geological and topographical conditions (depicted as hillshade maps) at six volcanic areas in the southeast of Austria. **a** V03/Riegersburg, **b** V24/Güssing, **c** V04/Altenmarkt, **d** V14/Klöch-Königsberg, **e** V13/Stradner Kogel, **f** V01/Gleichenberger Kogeln. The areas used for calculating the hypsometric curves are indicated. Data sources: geological map of the Geological Survey of Austria, Vienna, provided via GIS-Steiermark, and Fritz (1996). Note that scale differs

up to 3776 m asl) was analysed. Above this elevation, Mt. Fuji is a well-developed stratovolcano. All four volcanoes are “active” following the definition by the Global Volcanism Program; i.e., they erupted at least once during the Holocene.

The first three volcanoes are examples of strongly eroded diatremes. Riegersburg is a very special landmark of Styria and well known as a volcano remnant. The volcano in Güssing is very similar to Riegersburg in its present appearance, whereas Altenmarkt is an example of a diatreme with still preserved lake sediments of the maar. Erosional processes since the end of the volcanic eruptions have resulted in surface lowering in the order of several hundreds of metres at all three sites, causing the complete erosion of the ejecta rings and complete (Riegersburg, Güssing) or at least partial erosion (Altenmarkt) of the maar structures.

The fourth volcano at Klöch-Königsberg is an example of a strongly eroded complex monogenetic volcano, which started with an initial phreatomagmatic phase that was soon followed by scoria ejection phases and the formation of a lava lake. The fifth volcano is the Stradner Kogel, with the highest peak in the study area (608 m asl). This volcano was mainly formed by effusive volcanism, with lava flows covering the Sarmatian sediments and now representing an example of inverted relief.

The Gleichenberger Kogeln is a stratovolcano that was once possibly of similar shape as today’s Etna in Sicily. A huge volcanic massif with a base diameter of some 30 km emerged around 23.0—or 17.2 (see Table 33.1 for different efforts at age dating)—to 12.2 Ma ago at this site. We only know the approximate dimensions and expansion of this volcano, with its SiO_2-rich magma forming trachytic to andesitic rocks, from drilling and geophysical investigations. During its period of activity, environmental conditions also changed (Fig. 33.2). The ocean advanced during that time from the southeast, flooding the entire Styrian basin. The peaks of this mighty stratovolcano became active volcanic islands rising more than 2000 m above the sea level. Later on, this volcanic massif was covered by different sediments (limestones, gravel, sand and clay), possibly even entirely. Subsequent erosion uncovered the remnants of the volcano. Today, we only see small peaks of a former huge volcanic system. Local sources of thermal (for spa usage) and mineral waters are related to this volcanic activity and the fault systems, but will not be discussed here.

Figure 33.9 depicts the geological and topographical conditions at the six selected volcanic areas and also shows the delineations for calculating the hypsometric curves. Riegersburg and Güssing solely consist of basaltic tuff. In

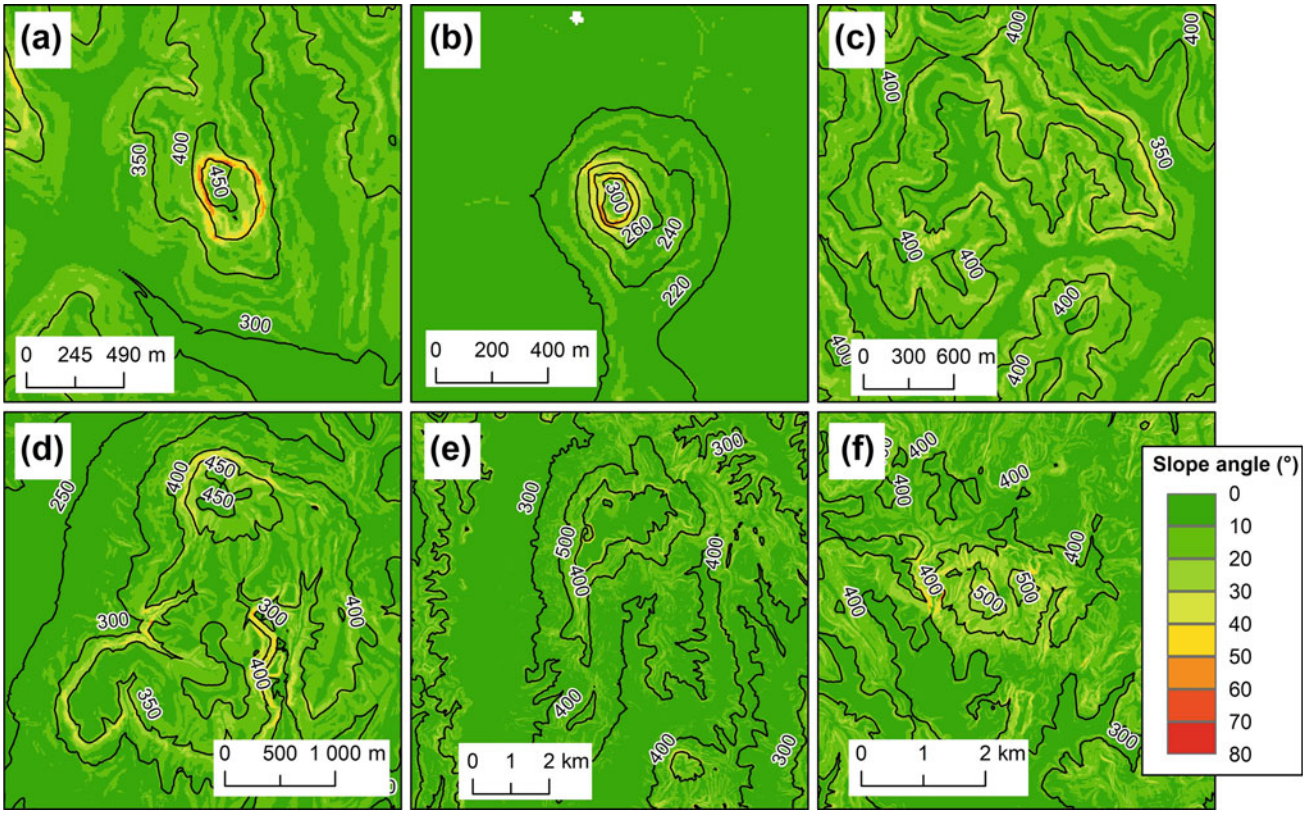

Fig. 33.10 Slope angle maps of the six volcano landforms and their surrounding areas. **a** V03/Riegersburg, **b** V24/Güssing, **c** V04/Altenmarkt, **d** V14/Klöch-Königsberg, **e** V13/Stradner Kogel, **f** V01/Gleichenberger Kogeln. Note that scale differs

contrast, at Altenmarkt, basaltic tuff but also maar sediments occur. The geology at Klöch/Königsberg is more diverse, with tuffs, basalts, tuff in close contact to basalt and scoria basalt. Geological conditions at the Stradner Kogel are comparable to those at Klöch/Königsberg, with basalts, basaltic tuff and scoria basalt. In contrast, geological conditions at the Gleichenberger Kogeln are substantially different, with trachytic to andesitic rocks with breccia, tuff and weathered tuff ("trass") at the Gleichenberger Kogeln site itself and basalts and basaltic tuff of a younger age (i.e., from the second volcanic period) in the vicinity of the volcano. However, the boundaries of the volcanic rocks are not clearly traceable in the topography.

The hypsometric curve of the volcano in Altenmarkt is of particular interest, because major valleys are cut into the volcanic rocks, dividing the former volcano into three

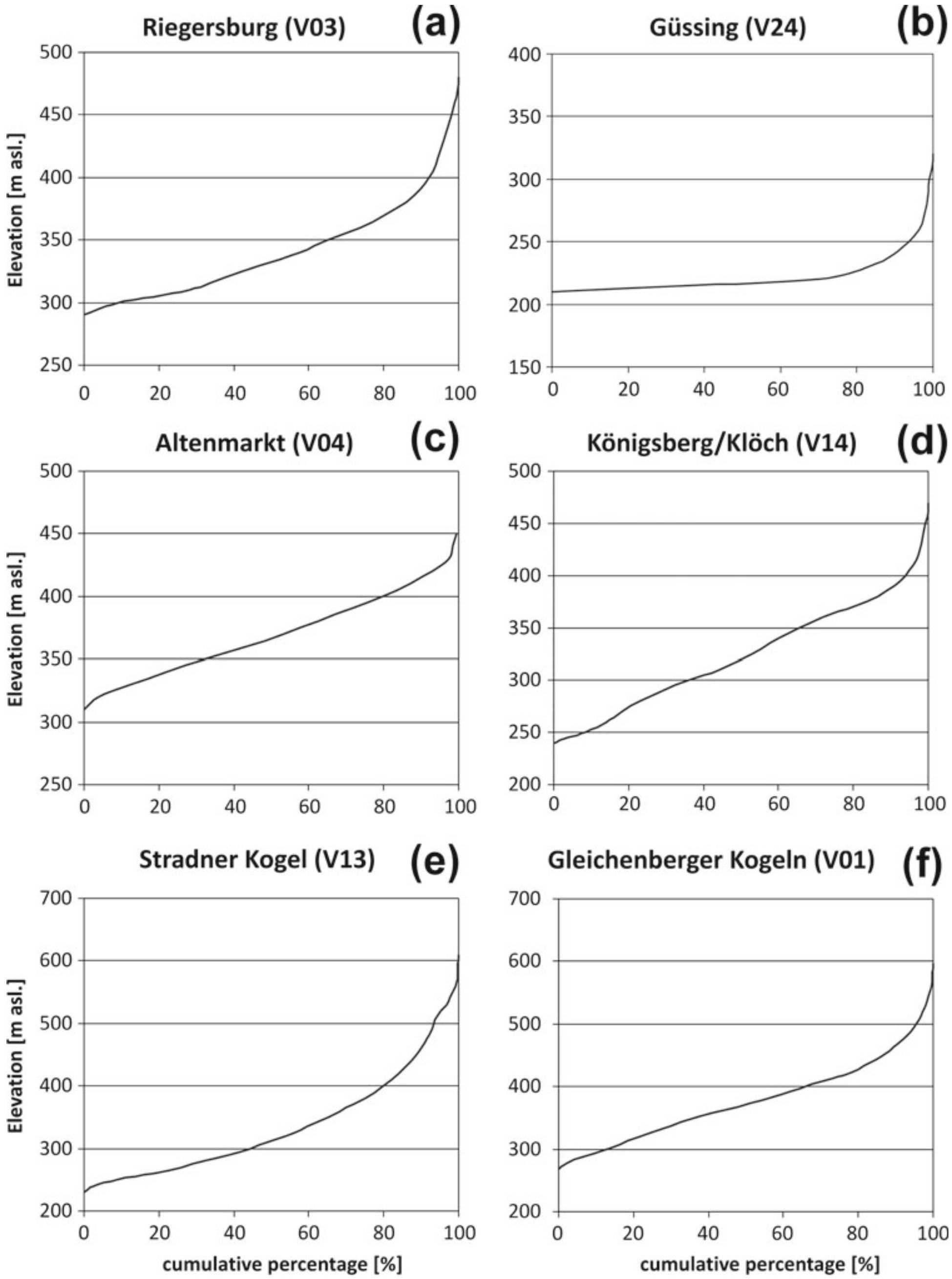

Fig. 33.11 Hypsometric curves of six former volcanoes. **a** V03/Riegersburg, **b** V24/Güssing, **c** V04/Altenmarkt, **d** V14/Klöch-Königsberg, **e** V13/Stradner Kogel, **f** V01/Gleichenberger Kogeln. The areas used for calculating the hypsometric curves are shown in Fig. 33.9

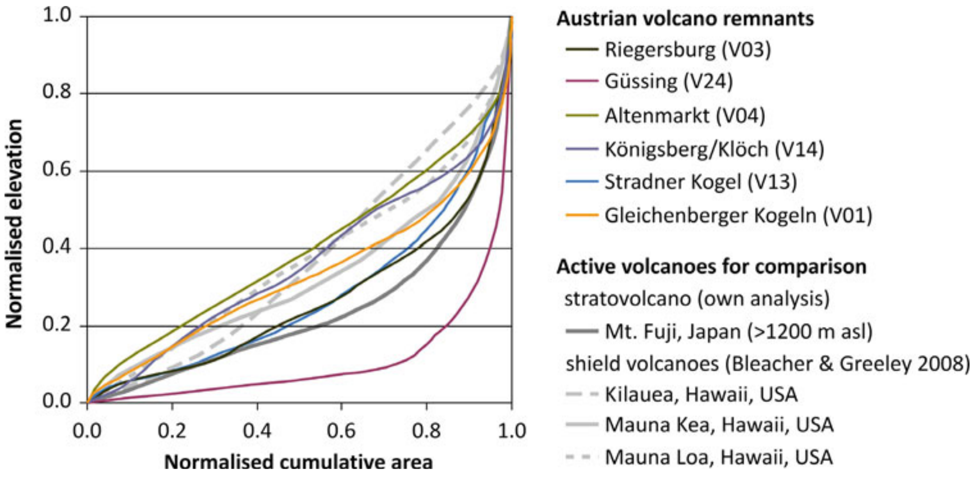

Fig. 33.12 Normalized hypsometric curves of six selected volcanic areas in the study region. For comparison, the normalized hypsometric curves for four active and well-developed volcanoes (one stratovolcano and three shield volcanoes) are additionally plotted

different parts. Figure 33.10 depicts slope angle conditions at the six studied volcanoes. The steepest slopes in five of the six cases (the exception is Altenmarkt) are found at the margins of the volcanic rock terrain, illustrating the generally higher resistance of volcanic rocks against erosion compared to the surrounding clastic sediments. At Altenmarkt, no clear slope-geology-relationship can be determined.

Figure 33.11 depicts the hypsometric curves of the six volcanoes. The largest vertical difference between the lowest and the highest parts of the volcanic areas are at Stradner Kogel and the Gleichenberger Kogeln, exceeding 300 m. In contrast, rather low-relief values have been calculated for the volcanoes in Riegersburg, Altenmarkt and particularly Güssing. The Güssing volcano is special because its surroundings are flat in all directions, apart from the south with some minor hills. Hence, Güssing is a good example of a steep diatreme prominently standing out above its surrounding. The hypsometric curve of the geologically comparable Riegersburg has a very different overall shape. However, the curve at Riegersburg above 400 m asl (6% of the total area) is almost identical to the curve at Güssing above 240 m asl (also 6%), suggesting that the higher parts of the Riegersburg diatreme are morphologically very similar to those at Güssing. The hypsometric curve of Altenmarkt has a rather constant slope. This is also true for the central parts of the hypsometric curves for the Königsberg/Klöch area and the Gleichenberger Kogeln, although in these two cases the final rise of the curve becomes strongly concave, indicating rapidly decreasing areal percentages. Finally, the curve of the Stradner Kogel is concave-shaped along its entire course, although with a lower decrease rate in areal percentages at its upper parts related to the rather high share of planation surfaces ("Hochstraden niveau") at the capping lava flow.

Figure 33.12 shows the same hypsometric data as in Fig. 33.11, but in relative dimension. In addition, the hypsometry of one stratovolcano and three shield volcanos are plotted for comparison purposes. The results clearly show that the normalized hypsometric curves of the six volcanoes differ in shape, partly substantially, from each other. This is, of course, a somehow expected result, because millions of years of sedimentation and erosion have obscured and altered the volcanic landforms in Styria and Burgenland. This also highlights the problem that the delineation of a volcanic area subject to hypsometric analysis is not straightforward in case of a strongly eroded and partly sediment-covered volcano. However, for all studied volcanoes we can conclude that (a) at least 70% of the total area is below 50% of the elevation range or (b) only 10% or less of it is in the upper 25% of the elevation range. The Güssing example is exceptional, because a large, steep and strongly eroded diatreme protrudes from an almost flat area.

A comparison of the volcano remnants studied here with active and potentially active volcanoes around the globe naturally faces substantial problems (e.g. scale differences, delineation differences, forming process differences). Nevertheless, such a comparison is valuable, bringing the own results into a wider volcano-morphological context. Maars formed in the recent past are normally not striking landforms in relationship to their surrounding (e.g. the Ukinrek maars formed in 1977; 57.832 °N, 156.510 °W; White and Ross 2011). Therefore, we decided to compare the six volcanoes analysed in this study with volcanoes with well-known volcanoes on Earth. As shown in Fig. 33.12, the curves of the one stratovolcano and the three shield volcanoes are strongly divergent. Our six curves are placed basically in between (apart from the one of Güssing). Four of our six curves are more similar to those of the three shield volcanoes. One exception is the curve of the very gently sloping Kilauea, with some 35% of its area in the upper half of the volcano edifice. Interestingly, the curve of Riegersburg has strong similarities with the curve of the well-developed stratovolcano Mt. Fuji. In summary, the six studied volcanoes are morphometrically (at least as judged from hypsometric curves) inconspicuous when compared with present active volcanoes. Only strongly eroded diatreme volcanoes such as Güssing can be suitably characterized by this approach.

33.5 Conclusions

Landscape evolution of the Styrian basin was very variable during the last 23 Ma, with a complex tectonic (uplift versus subsidence, fragmentation and formation of horst and graben structures), sedimentological (marine, lacustrine, terrestrial or biogenic sediments), erosional (linear erosion versus denudation) and volcanic (subaerial versus phreatomagmatic eruptions, basaltic versus andesitic rocks, valley fill versus inverted relief) history. These processes acted together, causing on the one hand the burial of large volcano edifices by a pile of sediments several thousand metres thick, and on the other hand, the erosion of diatreme-maar volcanoes, exposing their rock-filled fracture and forming steep, rather small mountains, which were used in historical times as locations for fortifications.

Today, only remnants of the former volcanoes are visible and nothing is left of the original volcanic landscape due to the erosion of several hundreds of metres of rock material of different origin. Two main volcanic landforms prevail in the Styrian basin. These are, on the one hand, maar-diatreme volcanoes, which in some instances form steep mountains. They consist of basaltic tuff, are mostly small in their spatial extent and were presumably produced by a single eruption. On the other hand, residuals of complex and large volcanoes consisting of tuff, scoria and massive basalt, formed during longer, polygenetic eruptions, and visually dominate the landscape due to their greater elevation. The highest mountains in the study area, often characterized by erosional planation surfaces of Miocene to Pleistocene age, are all of volcanic origin and form prominent features in the panoramic views of the area.

Delineation of Austrian volcanoes is not straightforward due to the complex evolution histories in terms of formation, erosion and deposition that make the interpretation of results of hypsometric analyses difficult. Only the curves of strongly eroded diatremes protruding from a flat landscape are substantially different from those typical for volcanoes, which are embedded in non-volcanic sediments.

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