8 Land of Extinct Volcanoes—Rock-Controlled Landforms, Postglacial Gorges, and Faulted Margin of the Sudetes

Piotr Migoń

Abstract

The “Land of Extinct Volcanoes” is an informal name of a part of south-western Poland that includes the Kaczawskie Mountains and the Kaczawskie Foothills in the West Sudetes as well as the adjacent fore-mountain area. The legacy of several periods of volcanic activity in the Paleozoic and Cenozoic is the most distinctive component of regional geoheritage and finds its geomorphic expression in the occurrence of hills and ridges built of more resistant volcanic rocks. Among them, basaltic cones and domes are particularly clear and serve as regional landmarks. Further valuable elements of geomorphological diversity include tors and crags, periglacial blockfields and stepped hillslopes, sandstone cuestas with associated rock towers, boulder fields and non-karstic rock shelters, karstic features, gorges cut by glacial meltwaters during the decay of the Scandinavian ice sheet, and the fault-generated marginal escarpment of the Sudetes. The pending application for the status of a UNESCO Global Geopark reflects both the international dimension of regional geoheritage and the considerable involvement of local communities to promote tourism based on geoscience-related values.

Keywords

Volcanism · Structural geomorphology · Periglacial · Karst · Glaciation · Geopark · Sudetes

P. Migoń (✉)
Institute of Geography and Regional Development, University of Wrocław, pl. Uniwersytecki 1, 50-137 Wrocław, Poland
e-mail: piotr.migon@uwr.edu.pl

8.1 Introduction

The “Land of Extinct Volcanoes” is an informal name of an area in south-western Poland that straddles the low-mountain and upland terrain in the south-west and hilly to lowland terrain in the north-east. Geographically, it includes the regions of the Kaczawskie Mountains, Kaczawskie Foothills (both being parts of the Sudetes mountain range), Silesian Lowland, and in small part the Sudetic Foreland (Solon et al. 2018) (Fig. 8.1). The name “Land of Extinct Volcanoes” is primarily used as a brand name in regional marketing aimed at the promotion of geotourism in the region (Pijet-Migoń and Migoń 2019). It highlights the most distinctive aspect of regional geological history, which is the occurrence of rocks of volcanic origin, widespread across this part of the country. These rocks are of different ages and testify to three different periods of volcanic activity, separated from one another by vast expanses of geological time. The most distant was submarine volcanism in the early Palaeozoic, followed by terrestrial volcanism in the Early Permian and, finally, by volcanic eruptions and extrusions in the late Cenozoic. Each of these phases produced specific rock varieties, which together represent the highest diversity of volcanic materials on the territory of Poland. This eventful volcanic history provided much of the foundation for geomorphic landscape development in the region. As a consequence, distinctive landforms built of volcanic rocks occur widely, with many easily recognizable from afar by their characteristic silhouettes. This is particularly true for the Cenozoic volcanism, the testament of which are numerous basaltic cones, domes, and crags, including Mt. Ostrzyca—the landmark of the “Land of Extinct Volcanoes” (Fig. 8.2).

However, the geodiversity of the region includes much more than remnants of ancient volcanism (Migoń 2021). The rock record not only spans the interval from the Cambrian to the Quaternary, with only the Jurassic being absent, but is represented by an enormous variety of rock

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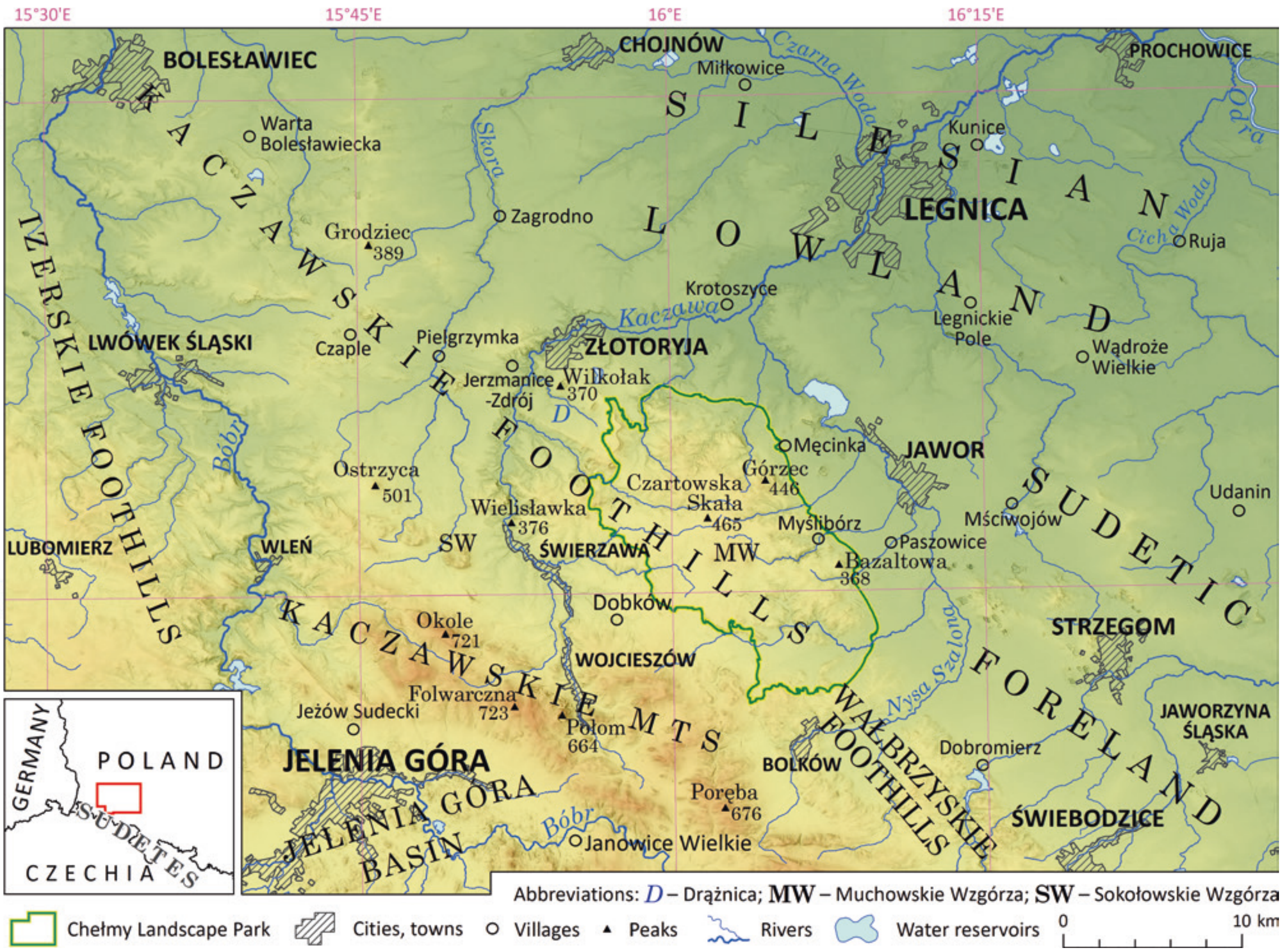

Fig. 8.1 Location map of the "Land of Extinct Volcanoes" at the boundary between the West Sudetes and the Silesian Lowland (map courtesy of Kacper Jancewicz)

Fig. 8.2 Basaltic cone of Mt. Ostrzyca is the landmark of the "Land of Extinct Volcanoes" (photograph by P. Migoń)

types originated in contrasting sedimentary settings, from deep ocean to shallow marine and terrestrial, and includes also plutonic and metamorphic rocks (Baranowski et al. 1990). Consequently, regional topography is also diverse, showing various relationships between rock properties and landform patterns, even though the landforms themselves are rather subdued and the altitude differences within the region do not exceed 500 m. This rock-controlled morphology was partially re-shaped in the Pleistocene, when the Scandinavian ice sheet invaded the area, leaving glacial sediments, outwash landforms, and striking erosional gorges. In the past millennium, rich and varied reserves of mineral resources have been prospected and mined, resulting in evident anthropogenic impact on geomorphology, but also contributing to the regional cultural heritage.

The growing awareness of these different values of the natural and cultural environment prompted local stakeholders to identify geodiversity and geoheritage as the key regional assets and viable foundation of sustainable nature-based tourism, particularly geotourism (Pijet-Migoń and Migoń 2019). After many years of organic growth and steady development of infrastructure and regional identity, an application for the status of UNESCO Global Geopark for the “Land of Extinct Volcanoes” was submitted in 2019 and is currently under evaluation. Consequently, this chapter reviews both geomorphic landscapes and selected landforms of the region, as well as the history of making regional geoheritage more accessible to the general public.

8.2 Geological Background

8.2.1 Pre-Quaternary Rock Record

At the most general level, the geological structure of the “Land of Extinct Volcanoes” can be resolved into two tiers, consistent with the most general division applicable for the entire Sudetes (Żelaźniewicz 2015). The older one includes rocks which originated prior to the final stages of the Variscan orogeny in the Carboniferous and cover the interval from the Late Proterozoic to the Lower Carboniferous (Baranowski et al. 1990; Kryza and Muszyński 1992). Within this tier, most of the region belongs to the so-called Kaczawa Fold Belt, except the eastern extremity of the region. The outcome of the Variscan orogeny was the consolidation of the basement through amalgamation of different terranes, each with a complicated pre-Variscan history, that docked against one another to form a solid foundation for subsequent geological evolution (Aleksandrowski and Mazur 2002). The younger tier includes rocks originated in the post-Variscan period, from the Late Carboniferous to the Quaternary (Fig. 8.3). They are mainly sedimentary formations, deposited in both terrestrial and marine settings, the latter including both very shallow (shelf) and moderately deep environments (Śliwiński et al. 2003; Chrząstek and Wojewoda 2011). In addition, volcanism occurred in the Permian and Cenozoic.

In the rock record, the lower structural tier is represented by various plutonic, volcanic, and sedimentary rocks, which were all subject to metamorphism, often multiple and mostly low-grade (Baranowski et al. 1990; Kryza and Muszyński 1992; Kryza et al. 2007). The dominant rock series are greenschists and phyllites, which are products of metamorphism of primary ocean-floor basaltic lavas and fine-grained clastic sediments, respectively. The greenschists, which are important geomorphologically, occur in several variants, from massive through platy to ones typified by the survival of original pillow-lava textures. Their ages vary from Cambrian to Silurian. In the Cambrian, calcareous deposits of a substantial thicknesses originated in the vicinity of some volcanic fissures, later transformed into crystalline limestones (Lorenc 1983). Other meta-sedimentary rocks include schists, meta-sandstones, and black cherts (lydites). Apart from basaltic extrusions, siliceous volcanism occurred too, testified by isolated outcrops of trachytes and rhyolites in the south-eastern part of the Kaczawskie Mountains (Kryza and Muszyński 1992). In the easternmost part of the region, Late Proterozoic/early Palaeozoic gneisses and mica schists are present, as are granites emplaced much later, by the end of the Carboniferous.

The stratigraphic record of the upper structural tier begins with Upper Carboniferous clastic rocks (mainly sandstones and conglomerates), which are correlative deposits to the erosion of the Variscan mountain range. These are followed by Lower Permian sedimentary series, which are lithologically similar and also include conglomerates, sandstones, mudstones, and shales, but were deposited under different environmental conditions, much drier and with only seasonal or episodic rainfall. They originated as deposits of braided rivers, alluvial fans, debris flows, and ephemeral lakes. Both siliceous and alkaline volcanism occurred at that time, producing rhyolites, trachyandesites, and trachybasalts (Awdankiewicz et al. 2014). Terrestrial sedimentation in the Early Permian was replaced by marine sedimentation in the Late Permian, with limestones, dolomites, sandstones, and shales (Biernacka et al. 2005). Some of these sediments were found to be copper-bearing and gave rise to copper mining industry. The alternation between marine and terrestrial conditions continued in the Early and Middle Triassic, resulting in fluvial sandstones and marine limestones. The period from the Middle Triassic to the beginning of the Late Cretaceous is not represented in the rock record, and regional evidence suggests that

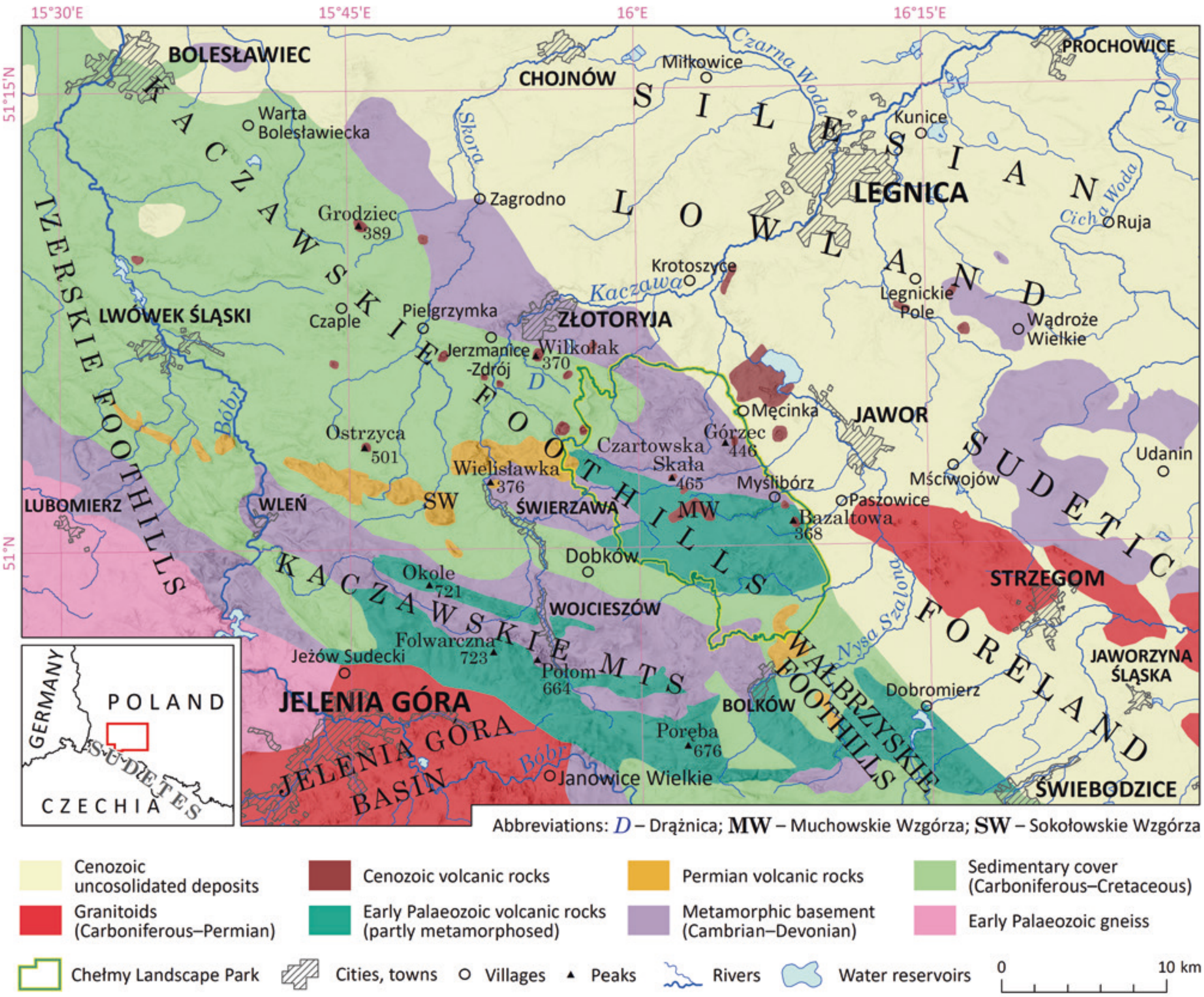

Fig. 8.3 Geology of the "Land of Extinct Volcanoes" (map courtesy of Kacper Jancewicz)

terrestrial conditions prevailed, with efficient deep weathering and the origin of kaolinitic saprolites in the neighbouring areas. Sedimentation resumed with the onset of a marine transgression in the Cenomanian (c. 99 Ma) and continued into the Santonian (c. 85 Ma), resulting in the succession of alternating quartz-rich sandstones, calcareous sandstones, mudstones, and marls (Milewicz 1997; Leszczyński and Nemec 2019). Relating to geological subdivision of the Sudetes, all these sedimentary formations were deposited within the North-Sudetic Synclinorium.

The Cenozoic was the period of dominant denudation and Pliocene/early Quaternary sands and gravels are the only deposits from this protracted period in the Sudetic part of the "Land of Extinct Volcanoes" that preceded Quaternary glaciations (Grodzicki 1972). However, the sedimentary record is much more extensive in the foremountain part, especially in the deep, fault-bounded graben parallel to the margin of the Sudetes. The thickness of the Cenozoic sedimentary series, consisting of unconsolidated gravels, sands, and clays from the latest Oligocene to the early Quaternary, reaches 200 m (Kowalski 1977). It is less thick beyond the graben, a few tens of metres, but this was enough to seal an earlier mid-Cenozoic topography and bury the Palaeogene saprolitic mantles on granites and gneisses (Badura et al. 2004).

The younger part of the Cenozoic was also a period of volcanism, the youngest among the three in the region. According to various radiometric datings, the oldest Cenozoic volcanic rocks originated in the latest Eocene (c. 42 Ma), whereas the youngest ones are from the Middle Miocene (c. 15 Ma), with the majority of dates pointing to the latest Oligocene and the Early Miocene (Badura et al. 2005; Birkenmajer et al. 2007). For simplicity, volcanic products from this broad period are usually called basalts, even though in fact they represent a wider spectrum of mineralogical and chemical compositions, so various specific names apply. Considerable denudation since the period of activity has led to the degradation of primary volcanic landforms, and the contemporary outcrops are mostly exposed volcanic conduits and plugs, veins (probably many are subvolcanic), and only rarely remnants of lava flows and sheets (Birkenmajer 1967).

8.2.2 Cenozoic Faulting, Uplift and Subsidence

Rock formations in the "Land of Extinct Volcanoes" record multi-phase tectonic deformations of different ages and large-scale displacements, especially within the lower structural tier. However, for the contemporary landscapes and landforms, it is the Cenozoic tectonics which is the most important. Within it, two main phases can be distinguished.

At the turn of the Cenozoic, Central Europe was subject to widespread inversion tectonics, with the formation of reverse faults, locally evolving into low-angle thrusts. In the "Land of Extinct Volcanoes", faults of this kind affected the former Permian and Mesozoic sedimentary basins, causing thrusting of metamorphic basement onto the Permian and Cretaceous rocks, deforming the latter in the vicinity of faults, e.g. in the vicinity of the village of Jerzmanice-Zdrój, where Cretaceous sandstones are turned to near-vertical next to the Jerzmanice Fault (Solecki 2008, 2011). They also brought rock series of different strength and resistance into high-angle contact with one another, setting the stage for the subsequent origin of fault-related escarpments. Further consequences included minor regional tilting of sedimentary successions, which later allowed for the development of cuesta landscapes, and—at the site scale—the origin of siliceous bands within sandstones, marking shearing and recrystallization.

In the Neogene and the Quaternary, tectonics was mainly extensional, leading to the development of normal faults and associated fault-generated escarpments (Zuchiewicz et al. 2007). The magnitude of relief differentiation in the "Land of Extinct Volcanoes" was much smaller than in the inner, more elevated parts of the Sudetes (e.g., Kasprzak 2023), but nevertheless it amounted to ~ 300–400 m, as can be inferred from altitude variability. Among the tectonic structures from this period, the most distinctive is the Sudetic Marginal Fault, responsible for the dividing line between the Kaczawskie Foothills in the west and the foreland of the Sudetes in the east (Fig. 8.1). The present-day elevation of the main ridge of the Kaczawskie Mountains is also likely a product of up-faulting, although subsequent erosion and denudation have considerably re-shaped the tectonic relief.

8.3 Regional Landscapes

8.3.1 Kaczawskie Mountains

The Kaczawskie Mountains are a good example of low-altitude mountains that typify the less elevated and peripheral parts of the Central European Variscan belt. The highest peaks only slightly exceed 700 m asl (Mt. Folwarczna—723 m, Mt. Okole—721 m), the height difference between the water divides and the valley floors is 200–300 m, and typical slope inclinations are in the 10–15° range. They are entirely included within the forest belt, although centuries of human impact have resulted in considerable deforestation and replacement of forest communities by arable lands, pastures, and meadows.

Valleys and passes divide the Kaczawskie Mountains into several minor geomorphic units, with the north-trending Kaczawa River valley as the main line separating the WNW–ESE striking ridges of the western part from the less regular pattern of ridges in the eastern part. The western ridges follow the dominant strike of the inherited Variscan structures of the Kaczawa Fold Belt, with more resistant greenschists and meta-sandstones supporting elevations, whereas valley tracts tend to be excavated in phyllites and schists. How these two common rock types, greenschists and phyllites, control relief at a smaller scale, can be observed in the eastern part of the mountain, around Mt. Poręba (676 m), where an alternating sequence of low ridges on the former and shallow trough valleys on the latter occurs (Fig. 8.4). Both the northern and southern margin of the Kaczawskie Mountains are fairly distinct and are most probably degraded fault-generated escarpments. The one facing south, towards the Jelenia Góra Basin, is particularly clear and associated with the Main Intra-Sudetic Fault, which is one of the most important Variscan structures in the Sudetes, very likely to have been reactivated during the Cenozoic. In the central and eastern part of the range, outcrops of crystalline limestones occur in a W–E belt and these support distinctive elevations, with Mt. Połom (664 m) rising nearly 300 m above the adjacent valley floor of the Kaczawa River. These limestones are hosts to karst phenomena, presented in more detail below (see Sect. 8.4.4).

Among minor landforms, natural mid-slope and summit bedrock outcrops add to the geodiversity of the area and are worth particular attention. Some may be called tors, and these rise above the regolith-mantled surfaces in the form of walls, towers, and more complex castellated ruins. Heights above 15 m are recorded. More common are asymmetric outcrops—cliffs, pulpits, and ridge-top crags passing smoothly into debris-covered slopes. Various lithologies support bedrock outcrops, but greenschists, limestones, and trachytes are most represented.

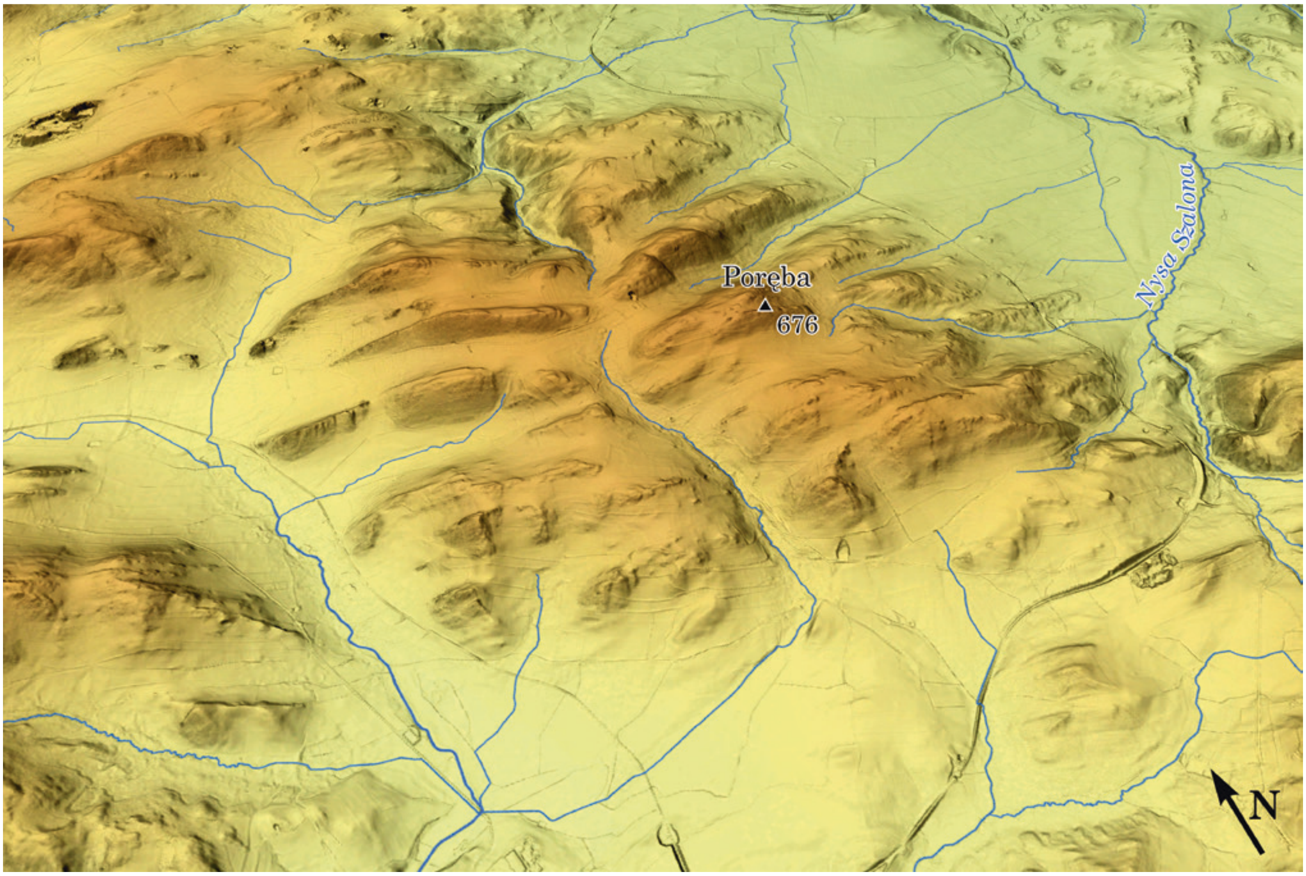

Fig. 8.4 Parallel ridges and troughs around Mt. Poręba (676 m) in the eastern part of the Kaczawskie Mountains illustrate direct rock control on topography. The ridges are built of greenschists, whereas depressions are eroded in phyllites. Beyond the massif of Poręba, along the Nysa Szalona River, a small intramontane basin occurs excavated in weak clastic sedimentary rocks of Permian age. Note also numerous agrarian terraces on slopes, especially in front of the image (visualization courtesy of K. Jancewicz)

8.3.2 Kaczawskie Foothills

To the north of the Kaczawskie Mountains extends a hilly relief of the Kaczawskie Foothills, sharply limited in the east by the faulted margin of the Sudetes, but lacking an evident northern boundary. Altitudes reach 501 m asl (Mt. Ostrzyca), whereas they are typically around 400 m asl, with the eastern part of the sub-region located at higher elevation than the western one. Relative relief does not exceed 200 m, and slopes are generally less than 10°, except numerous but otherwise scattered elevations built of more resistant volcanic rocks from the Permian and Cenozoic volcanic periods.

The Kaczawa valley continues to be a major line separating areas of different topography, related to differences in bedrock. The eastern part is mostly within the metamorphic complex and is dominated by greenschists and phyllites, but the corresponding change in relief is very subtle and the overall relief is rather planar. It becomes more complex in the vicinity of the margin of the Sudetes, where valleys are deeper and locally gorges occur (see Sect. 8.4.5). However, in the north-west, close to the town of Złotoryja, sedimentary rocks occur widely and these have given rise to a distinctive cuesta (see Sect. 8.4.3). The western part is almost exclusively underlain by sedimentary and, subordinately, volcanic rocks and shows low subdued relief, with bedrock extensively concealed by Quaternary deposits of glacial and fluvioglacial origin. However, two prominent basaltic hills (Mt. Ostrzyca, Mt. Grodziec) overlook this rather monotonous landscape.

8.3.3 Mountain Foreland

The fore-mountain part is geomorphologically complex, even though this is not at all evident at the first sight. Immediately before the mountain front of the Sudetes a tectonic graben is located, with the bedrock floor at the depth of more than 200 m. However, the transition to the plains located further to the north is smooth due to the ubiquitous cover of glacial deposits from several inland glaciations. Ice sheets reached the region some 450 ka ago (MIS 12, Elsterian (Sanian) glaciation) and 200–150 ka ago (MIS 6, Saalian (Odranian) glaciation). Rock outcrops built of gneiss, quartzite, and mica schists are few and not very distinctive, although they were more prominent in the Neogene. Topographic lows between the hills are filled with Neogene and Quaternary deposits, which indicates a higher relative relief in the past. In the south-east, elevations are associated with granite of Carboniferous age and these reach 100 m high. However, in contrast to the granite areas inside the Sudetes (e.g., the Karkonosze—see Kasprzak 2023), they almost lack tors and their slopes are very smooth. This may be an effect of repeated glacial erosion in the Pleistocene, probably capable of erasing upstanding, but otherwise rather delicate, bedrock superstructures.

Remnants of the Cenozoic volcanism are not as frequent in the foreland as they are in the mountains. Among them, two lava plateaus are worth mentioning. One is located to the west of the town of Jawor and forms a low plateau, incised by the valley of the Nysa Szalona River. The other one lies further to the north-west and is largely buried under younger sediments. It crops out along the valley side of the Nysa Szalona River and is distinctive by its high degree of in situ saprolitic weathering, as much as 20 m thick. This saprolite owes its survival to the protective sedimentary cover and informs us that any more extensive lava flows in the mountainous part of the region may have been quickly degraded following efficient deep weathering in the warm and humid climate of the Miocene.

8.4 Characteristic Landforms

8.4.1 Geomorphic Expression of Ancient Volcanism

Each of the three periods of past volcanism is associated with specific landforms, but the most evident are those built by volcanic rocks produced during the most recent, Cenozoic phase (Wocke 1927; Birkenmajer 1967). They almost invariably build hills, whose height above the base reaches from 20–25 m to more than 150 m, depending on the area of basaltic outcrop and the difference in strength between the basalt and the host rock (Fig. 8.5a, b). If the latter is weak, as in the case of most sedimentary rocks, the basaltic elevations are more pronounced (Placek 2007). Columnar jointing exposed in numerous natural outcrops and quarries, along with the general absence of pyroclastic materials, shows that most volcanic hills are exposed deeper parts of volcanic conduits and, hence, are best described as necks. Mt. Ostrzyca is the most characteristic among them, reaching 160 m high in an almost perfect cone shape (Fig. 8.2). It has never been quarried, offering a rare opportunity to see the natural slope topography of a volcanic elevation, with extensive scree covers (blockfields) (Fig. 8.5c). It also nicely shows the transition from low-angle footslopes cut in the surrounding Permian sedimentary rocks through moderately inclined mid-slope segments to steep upper slopes dotted by numerous crags, which supply debris to build the voluminous scree below. Other eye-catching elevations are Mt. Grodziec, with its flattened top used to build a castle in the medieval times, Mt. Wilkołak, and Mt. Czartowska Skała, although the latter two have been considerably reshaped by quarrying activity and their sharp silhouettes are deceptive.

Other basaltic elevations are less conspicuous, but no less interesting. The large massif of Muchowskie Wzgórza (Muchów Hills) is of uncertain origin, and both a large composite neck and a fragment of a lava flow have been hypothesized. This massif has been very little quarried too and has retained a fine suite of periglacial landforms and deposits on their slopes (see Sect. 8.4.2). The flat top of Mt. Bazaltowa has developed upon a colonnade of thick basaltic columns, and it is possible that it represents a former lava lake within a crater.

Similar to basalts, the volcanic rocks of Permian age are mechanically strong and resistant to weathering and erosion, rising above the surrounding flat and rolling lands in sedimentary formations. The highest elevations exceed 100 m high (Sokołowskie Wzgórza). By contrast to basalts, in turn, conical forms are absent and typical landforms are dome-shaped hills with steep slopes (locally as much as 40°) and levelled summit surfaces. This shape is represented by Mt. Wielisławka that overlooks the Kaczawa River. It is interpreted as a dome, possibly a laccolith, and has been made famous because of a large outcrop of jointed rhyolite in a former quarry (Fig. 8.5d).

The geomorphic legacy of the Early Palaeozoic submarine volcanism is unlike the other two because of a considerable alteration after lava emplacement, including subsequent erosion and regional metamorphism, and different form of emplacement itself. Therefore, it is practically impossible to link the contemporary occurrence of greenschists and the form of ridges with the primary morphology of lava flows. However, at a small scale, morphological details of various greenschist crags reflect the presence of stacked pillows of lava (Michniewicz 2016) that have apparently survived subsequent deformations or have been only slightly reshaped.

8.4.2 Periglacial Legacy

During the cold periods of the Pleistocene (glacial stages), as the rest of Central Europe, the “Land of Extinct Volcanoes” was repeatedly located in the periglacial zone, where permafrost and frost-related processes decisively

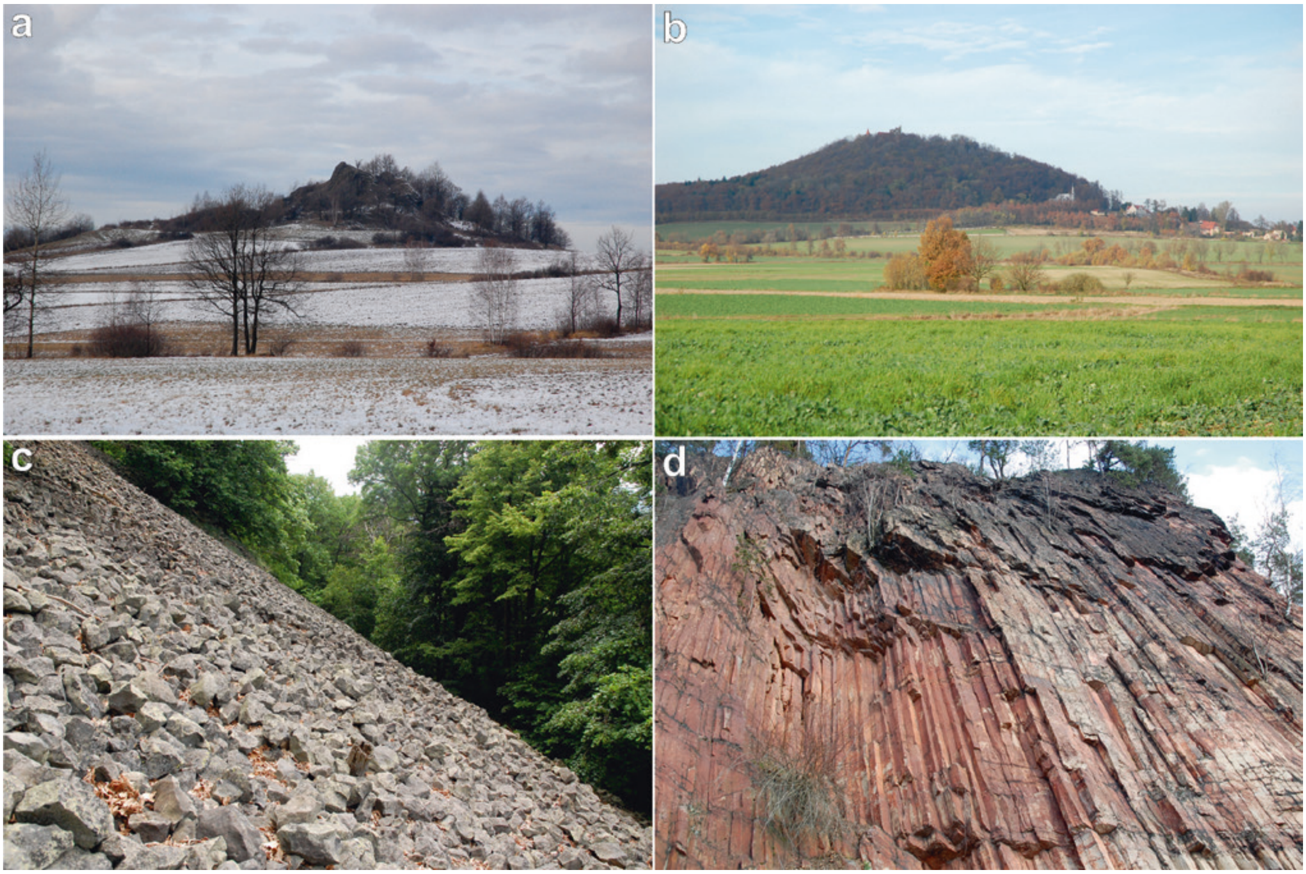

Fig. 8.5 Geomorphic diversity of hills built of volcanic rocks. **a** Low cone of Mt. Czartowska Skała (ca. 30 m high), partly reshaped by quarrying, rises above a denudational surface cut across Palaeozoic metamorphic rocks. **b** Dome-like elevation of Mt. Grodziec is more than 100 m high and the rocks around the hill are sedimentary. **c** Angular blockfield on Mt. Ostrzyca. **d** Columnar jointing in Permian rhyolites at Mt. Wielisławka, exposed in a former quarry (photographs by P. Migoń)

contributed to landform evolution. The geomorphic legacy of periglacial environments is diverse, but most evident are bedrock crags and associated blockfields fields, solifluction landforms and deposits, as well as loess covers (Fig. 8.6).

Causal relationships between crag morphology and periglacial conditions were first explored by Martini (1969), who pointed out that the setting and shapes of greenschist crags in the eastern part of the Kaczawskie Mountains, as well as the characteristics of regolith in their immediate vicinity, are not compatible with the two-stage model of tor evolution through deep weathering and stripping, argued for granite tors in the nearby Karkonosze Mountains (Jahn 1962). Rather, they indicate the dominant role of mechanical weathering, frost wedging, and disintegration into angular fragments, which then accumulated around. Likewise, Michniewicz (2016) explained the origin of greenschist crags on the Okole ridge in terms of periglacial hillslope development, although she also provided evidence of strong structural control on the distribution of crags. They are preferentially associated with south-facing slopes because of the dip of foliation and schistosity planes into the slope. Since mass wasting processes in periglacial environments are more efficient on south-facing slopes (on the northern hemisphere), structural and climatic factors converged to provide an optimal setting for the origin of crags. The height of greenschist tors attains 12 m and the most common shapes are cliffs and mid-slope spurs (Michniewicz et al. 2020) (Fig. 8.6a). Piles and sheets of angular, typically platy debris are ubiquitous on the downslope side of crags, but in contemporary conditions, they are largely overgrown.

Mid-slope crags occur also on those basaltic hillslopes, which have not been altered by quarrying, such as on Mt. Ostrzyca (Migoń et al. 2002; Migoń and Pijet-Migoń 2016). They have shapes and dimensions similar to those formed in greenschists, typically a few metres high and up to 20 m across the slope. Their morphological details clearly reflect the pattern of columnar jointing, and the places, where joints dip into the slope, are preferential locations for basaltic spurs. The crags on Mt. Ostrzyca have supplied debris for blockfields below, which rest at an angle of 15–30° and are only conditionally stable. On the south-facing slopes, they are bare and subject to slow talus creep, as attested

Fig. 8.6 Periglacial inheritance. **a** Greeenschist mid-slope tors on Mt. Okole in the Kaczawskie Mountains. **b** Blockfield in rhyolite in the water gap of the Kaczawa River. **c** Rock cliffs, talus, and possible cryoplanation benches at the Muchowskie Hills. **d** 4-m-thick cover of loess in the marginal zone of the Kaczawskie Foothills, near the town of Złotoryja (photographs by P. Migoń)

by partly buried trees and tree-ring reactions (Remisz and Bijak 2011). However, the blockfields on the north-facing slopes are almost completely covered by trees and rich undergrowth. Blockfields may also occur independently of crags, as in the water gap of the Kaczawa River to the north of Świerzawa, where they exist on rhyolites (Fig. 8.6b).

A different suite of cold-climate hillslope landforms has recently been documented on the low-angle slopes of the Muchowskie Wzgórza massif, in the eastern part of the Kaczawskie Foothills (Migoń et al. 2020). Flattened summit parts terminate against rock cliffs, which are 2–10 m high and supported by thick (up to 2 m in diameter) vertically arranged basalt columns. The lower parts of the cliffs are buried under talus, and there are lateral passages from cliffs to blocky accumulations and vice versa (Fig. 8.6c). Immediately below occur mid-slope benches, with a decreasing density of boulders down the slope. Altogether, this association of forms and deposits is consistent with model examples of frost-riven cliffs and cryoplanation terraces described from various periglacial environments. Further down the slope extend thick solifluction mantles, perhaps up to a few metres thick as inferred from geophysical surveys, with a variable density of basalt blocks at the surface. In some slope sectors, their surfaces are smooth, but in others, high-resolution DTMs derived from LiDAR data revealed steps and risers perpendicular to the general slope. These risers are interpreted as the toe parts of overlapping solifluction sheets.

Loess is present in the northern part of the region, especially around the town of Złotoryja. It is up to 6 m thick and covers the uplands and valley sides (Fig. 8.6d). Being a deposit prone to water erosion, it is associated with gullies, which locally form complex dendritic patterns and may be up to 30 m deep.

8.4.3 Sandstone Cuestas

Cuesta landscape has developed in the northern part of the "Land of Extinct Volcanoes", within the North-Sudetic Synclinorium (Adam 2004). Tilting of strata due to regional tectonics was the necessary prerequisite, whereas differences in rock strength and resistance against weathering and erosion allowed for the emergence of cuestas. These are defined as elongated, asymmetric terrain elevations, adjusted to the strike and dip of strata in such a way that the steep frontal slope is opposite to the dip, the low-angle backslope is generally following the dip, and the lateral extension of the ridge reflects the strike of the strata. Most cuesta landforms in the region have a rather subdued topography, possibly attenuated by ice-sheet erosion during the Pleistocene, but two are very clear. Both are supported by Cretaceous quartz sandstones.

To the south of the town of Złotoryja, one can follow a 15 km long cuesta ridge, cut into two sectors by the meridional Kaczawa valley (Fig. 8.7). The western sector is much lower, up to 35 m high, whereas the eastern one reaches a height of 120 m. Over most of its length, the cuesta follows the WNW–ESE direction, but turns to N–S in the eastern part. The cuesta face in its upper part is built by sandstones of Cenomanian age. They are not exposed as natural outcrops (rock cliffs), but in some sections, sandstone boulders are common, mantling the upper and middle slopes. Some of these boulders are more than 5 m long and occur as a dense pack or are even piled up (Duszyński et al. 2017). The converging backslopes of the cuesta are dissected in the central part by a valley of the Drążnica Stream. Close to the confluence with the Kaczawa River, the stream has significantly undercut its right-side slope, exposing younger sandstones of the Turonian age. Non-karstic caverns a few metres deep have evolved within the valley side, becoming a local geomorphological curiosity.

The other cuesta occurs in the westernmost part of the region, between the valleys of the Skora and the Bóbr rivers. Sandstone of Coniacian age is the main cuesta builder, and the height of the cuesta frontal slope is locally up to 80 m. The backslope is poorly expressed and largely covered by Quaternary sediments. Notable geomorphic features of interest are free-standing rock towers emerging from the cuesta face, with the highest one being 14 m tall, minor rock cliffs, and crevice caves next to the Bóbr Valley (Migoń and Pijet-Migoń 2020) (Fig. 8.8).

Fig. 8.7 Cuesta supported by Upper Cretaceous (Cenomanian) sandstones, with the course of the rim highlighted by dashed red line, is the most distinctive denudational landform in the northern part of the Kaczawskie Foothills. The most important volcanic necks, largely destroyed by quarries, are labelled by their names. 1—section of cuesta front slope with widespread blockfields, 2—location of non-karstic caverns and other rock forms in the Drążnica valley (visualization courtesy of K. Jancewicz)

Fig. 8.8 Sandstone landforms. **a** Isolated rock tower in front of a cuesta. **b** Rock cliffs and non-karstic caves (entrance to one of these shown by arrow) in the Bóbr River valley, north of the town of Lwówek Śląski (photographs by P. Migoń)

8.4.4 Karst

Karst landforms have developed in crystalline limestones of Cambrian age in the Kaczawskie Mountains, but since the limestones occur as separate bodies, apparently without any connection at depth, a large integrated karstic system could not have evolved (Pulina 1977). Instead, each limestone massif hosts its own assemblage of karstic features. In general, local karst is not spectacular, and this is because surface landforms are very poorly expressed. Typical karst mesoforms such as dolines, dry valleys, blind valleys, or karren fields are essentially absent. On the other hand, efficient karstic springs occur in several places, indicating the existence of well-developed subterranean karst. Indeed, caves have long been reported from the area, particularly from Mt. Połom above the town of Wojcieszów, which is the highest limestone hill, once interpreted in terms of tropical karst inheritance and likened to a tropical mogote of the Palaeogene. This hypothesis, however, lacks solid evidence, and the limestone hills are rather rock-controlled forms, which owe their emergence to high rock-mass strength. A few tens of caves have been documented in Mt. Połom, including several deeper than 100 m (Szczelina Wojcieszowska, Jasna Cave) and the longest Gwiaździsta Cave (> 500 m long) (Rogala 2003). Sadly, none of these caves exists, having fallen victims to the ongoing operation in large limestone quarries, although a few others have survived, but are not accessible being located within the mining area. Abandoned quarries within other outcrops, including those at the adjacent Mt. Miłek, host several caves, but these are much shorter, not exceeding 30 m, and quite tight.

8.4.5 Gorges—How Ice Sheets Have Contributed to the Present-Day Relief

Peculiar geomorphic features in the eastern part of the Kaczawskie Foothills are gorge sections of river valleys, otherwise wide open and lacking very steep valley sides. They are characterized by narrow valley floors, locally less than 20 m, very steep and mostly rocky slopes, with bedrock outcrops as high as 20 m, and occasional bedrock steps in the channels (Fig. 8.9). As such, they belong to the most picturesque traits of local landscape and are also localities with considerable biodiversity values, with four being protected as nature reserves. The depth of incision varies from 20–25 m to 70 m. In each case, incision occurred within greenschists, but there is no difference in bedrock between the gorges themselves and more upstream and downstream reaches. Gorges vary in length, from less than 0.5 km to more than 2.5 km in the Jawornik Valley.

The origin of the gorges was proposed to be causally related to the decay of the last ice sheet that covered the Kaczawskie Foothills (Migoń 1999, 2021). The scenario holds that the spatial pattern of preglacial valleys was different from the contemporary one, and the valleys themselves were fairly wide open. During deglaciation, they were for longer filled by ice, including blocks of dead ice, whereas the divides were already ice-free. Under these conditions, meltwaters were incising elevations and margins of the upland in new places, leading to local reorganization of drainage. After all remnant ice melted away, a new drainage network was established, integrating "old" and "new" elements, the latter being deeply incised, rocky gorges (Fig. 8.10). At the same time, abandoned sections of preglacial valleys remained filled by glacigenic sediments and disconnected from the present-day network.

Unfortunately, it is not known with certainty when this could have occurred, whether during the MIS 12 or the MIS 6 glaciation. In the past, it was assumed that these two ice sheets had almost identical extent in the Sudetes, and the currently observed landforms and deposits are the legacy of the younger, MIS 6 glaciation. However, a shift of opinions occurred in the last 25 years or so, and it is now argued that the younger ice sheet reached the marginal parts of the Sudetes, at some 200 m asl, but was unable to transgress into the mountainous terrain. Thus, all glacial elements inside the Sudetes would be associated with the MIS 12 glaciation. Kowalski et al. (2018) have recently documented glacitectonic deformations affecting fluvial and glacial deposits in a gravel pit in the north-western part of the Kaczawskie Foothills (Czaple locality) and assumed that the sedimentary package and the deformation took place during the MIS 6. This locality is at 250–270 m asl, and one can only speculate if this ice sheet could have advanced further to the south, to cover the upland that rises to more than 400 m asl. The clarity of the gorges is not inconsistent with the proposal that it could have indeed been a MIS 6 ice-sheet advance.

8.4.6 Fault-Generated Mountain Front

The eastern morphological boundary of the Kaczawskie Foothills is constituted by a distinctive escarpment (Fig. 8.11), even though it is rather low in terms of relative height (less than 150 m, mostly around 100 m). This escarpment is part of a much larger landform of regional extent, which is the fault-generated mountain front of the Sudetes, related to the Sudetic Marginal Fault. The activity of this fault zone in the Cenozoic is responsible for the separation

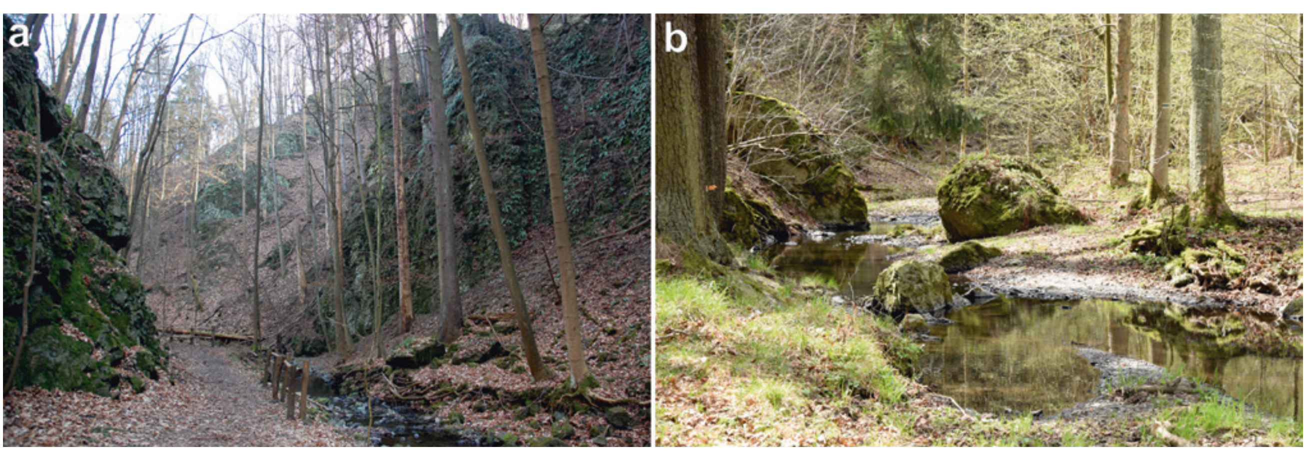

Fig. 8.9 Meltwater gorges in the eastern part of the Kaczawskie Foothills. **a** Greenschist cliffs in the longest Myślibórz Gorge. **b** Rockfall-derived greenschist boulders in the bottom of the Siedmica Gorge (photographs by P. Migoń)

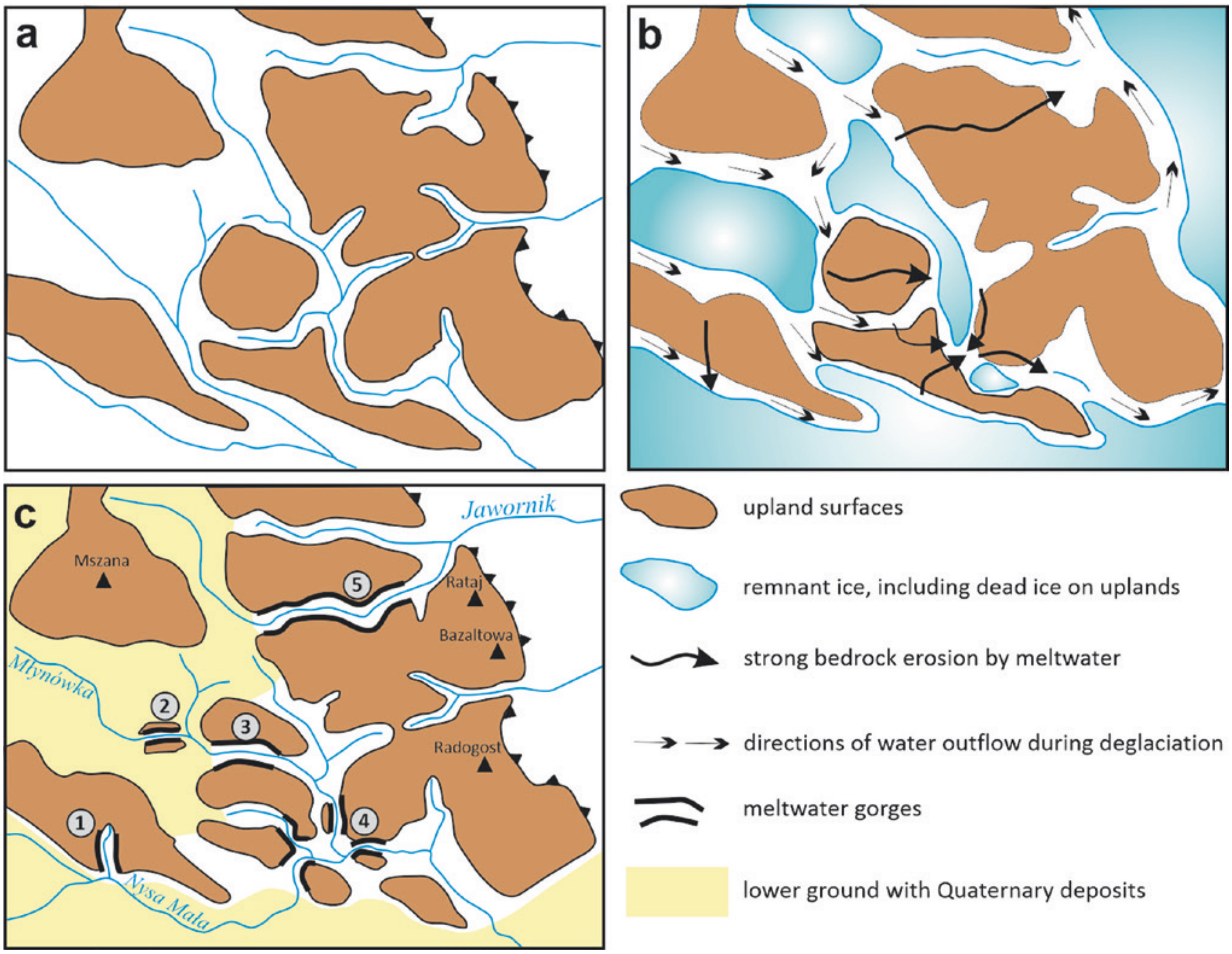

Fig. 8.10 Origin of fluvial gorges in the eastern part of the Kaczawskie Foothills. **a** Probable valley and river network prior to the glaciation. **b** Deglaciation phase: the presence of dead-ice masses in terrain depressions forced meltwater to flow around them and, locally, to cut through bedrock elevations. **c** Contemporary valley and river network. Gorges and water gaps: 1—Lipa, 2—Nowowiejski, 3—Siedmica, 4—gorges near the village of Grobla, 5—Myślibórz

Fig. 8.11 Fault-generated marginal escarpment of the Sudetes is rather subdued along the Kaczawskie Foothills, but is nevertheless a distinctive landform of regional significance (photograph by P. Migoń)

of the Sudetes from its foreland and its rise as a mountainous terrain. The entire length of the mountain front is more than 150 km and its cumulative height in the most uplifted sectors exceeds 500 m (Badura et al. 2007; Różycka et al. 2021). In the north-western part, that is within the area covered by this chapter, the escarpment is much lower and gradually loses height, until it vanishes approaching the town of Złotoryja. The footwall block is built of the metamorphic basement of the Kaczawa Fold Belt, punctuated in places by basaltic outcrops. Wherever the latter occur, the escarpment is steeper, apparently reflecting the resistance of basalt against weathering and erosion. At Mt. Górzec (446 m), the escarpment is partially covered by a vegetated blockfield built of basalt. In contrast to the more southerly sectors of the mountain front, no clear evidence of middle and late Quaternary displacements along the fault in the form of truncated fluvial terrace levels has been recognized (Migoń and Łach 1998), which seems consistent with the subdued nature of the escarpment.

8.5 Towards a UNESCO Global Geopark

Despite the considerable geodiversity and the presence of numerous sites of a very high geoheritage value, the area encompassed by the "Land of Extinct Volcanoes" used to be generally neglected by tourists and rarely visited. Clearly, a mutual negative feedback existed between the poorly developed tourist infrastructure and a limited interest in the region, which was additionally overshadowed by the nearby Karkonosze Mountains—the highest and arguably the most scenic mountain terrain within the Sudetes (see Kasprzak 2023). However, this neglect from the general public contrasted with the popularity of the area among professionals and students of geology and geography, regarding both research (although much more intense in the field of geology than geomorphology) and academic education. Thus, scientific and educational values of the region were realized but poorly communicated outside academia.

The first attempts to increase the visibility of regional geoheritage date back to the 1980s and were focused on the legacy of volcanism (Pijet-Migoń and Migoń 2019). Several basaltic hills and outcrops were connected by a 85-km-long hiking trail named as "The Trail of Extinct Volcanoes". In 1992, the eastern part of the Kaczawskie Foothills became formally protected as a Landscape Park, and an educational centre was opened in the village of Myślibórz. Several publications introducing geology to the general public were launched, and the network of waymarked trails expanded. Parallel to that, various aspects of local mining heritage began to generate interest, including the traditions of gold panning, iron smelting, and lime burning, recreated during annual events. Retrospectively, a milestone development was the establishment of the Local Action Group (LAG) "Kaczawa Partnership" in 2005, which connected more than a dozen municipalities located in the region, both in the Sudetic and fore-Sudetic part. Promotion of sustainable tourism was among the major goals of the LAG, and it was quickly realized that the diverse volcanic heritage, unique within Poland, is among the key assets of the region. In the following 15 years, many new projects aimed at increasing awareness of regional geoheritage were implemented, in the form of publications addressed to different users, trails, interpretation panels, and media promotional campaigns. Last but not least, in August 2015, a geoheritage-oriented educational and information centre was opened in the village of Dobków, in an old Franconian farmstead, specially purchased and adapted to serve these purposes. In 2017, after several years of presenting the idea to various stakeholders, local leaders (municipality mayors) signed a letter of intent confirming the willingness to work towards a UNESCO Global Geopark. In 2018, a complex inventory and valorization of geosites, 130 in total, was prepared, and it confirmed, in a systematic way, that the regional geoheritage is indeed of outstanding international significance, as expected from a UNESCO Global Geopark. This was followed in 2019 by formal submission of an application for membership to the Global Geopark Network of UNESCO. If successful, the "Land of Extinct Volcanoes" would become the third UNESCO Global Geopark in Poland, after the transboundary Muskau Arch (see Koźma and Migoń 2023) and the Holy Cross Mountains Geopark in central Poland. In the meantime, new geosites are being developed for the general public. In 2023, an impressive former basalt quarry at Mt. Wilkołak (Fig. 8.12; see Fig. 8.7 for location) was open to visitors, a few years after basalt excavation came to an end. Its nearly 100-m-high wall and deep pit provide a unique insight into the structure of a volcanic plug, including mega-blocks of thermally-altered Cretaceous sandstone detached and incorporated into the lava.

8.6 Conclusions

The "Land of Extinct Volcanoes" in south-western Poland is both a representative example of less elevated parts of the Central European Variscan ranges (low-altitude mountains and uplands) and an area of outstanding geoheritage in respect mainly to past volcanism that occurred in the Early Palaeozoic, Permian, and Cenozoic. Although the contemporary landscape cannot be considered as volcanic in the strict sense, outcrops of rocks of volcanic and sub-volcanic origin are evident in relief due to their resistance against weathering and erosion. Therefore, they build characteristic landmarks of the region, including conical basaltic hills and rhyolite domes. Numerous quarries, including many long

Fig. 8.12 Basalt quarry at Mt. Wilkołak, itself a volcanic neck, is now developed as a geosite, offering a unique insight into the structure of a lava plug (photograph by P. Migoń)

disused and now open to the public without restrictions, provide insights into the internal structures of volcanic conduits and plugs and reveal spectacular patterns of columnar jointing, which can be linked with the morphological evolution of the hills. However, the regional geoheritage is not limited to the remnants of ancient volcanism. Further localities of geomorphological interest include numerous tors and crags, especially in the more mountainous part of the region, limestone hills, periglacial blockfields on basalt and rhyolite, gullies in loess, and fluvial gorges cut by glacial meltwaters. Thus, even though the subdued landscape of the "Land of Extinct Volcanoes" may look inconspicuous at the first sight, it actually belongs to one of the most diverse in south-western Poland, with its geoheritage being complemented by high-class botanical values and rich cultural heritage that includes, among others, a UNESCO World Heritage listed, seventeenth century Church of Peace in the town of Jawor. The area is therefore a good example of how geodiversity and geoheritage underpin other values and fulfils the ABC approach (abiotic–biotic–cultural) envisaged as optimal for UNESCO Global Geoparks, which is the recognition the "Land of Extinct Volcanoes" is currently seeking.

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Piotr Migoń is Professor of Geography at the University of Wrocław and former Director of the Institute of Geography and Regional Development. His main research interests are rock control in geomorphology, especially in sandstone and granite areas, mass movements in mountain terrain, geoheritage, and geotourism. The Sudetes Mountains in Central Europe is his main research area, but he was also involved in projects in various other European countries (Czechia, Germany, Great Britain, Sweden, Portugal, and Spain), in the United States, Mexico, Brazil, China, Jordan, and Namibia. He used to be the Secretary of the International Association of Geomorphologists (1997–2001), its Vice-President (2009–2013), and member of Executive Committee (2013–2022); he was also the President of the Association of Polish Geomorphologists (2005–2008). He is the series editor of "World Geomorphological Landscapes" series and member of editorial board of *Geomorphology* journal.