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Reconstructing an eroded scoria cone: the Miocene Sośnica Hill volcano (Lower Silesia, SW Poland)

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The basaltic rocks of Sośnica Hill near Targowica (Fore-Sudetic Block) belong to the Cenozoic Central European Volcanic Province. The volcanic succession at Sośnica is over 40 m thick and comprises pyroclastic fall deposits (mainly tuff breccias), subvolcanic intrusions (plug, dykes and other intrusive sheets) and aa-type lavas. Field relationships and structural data enable a detailed reconstruction of the vent location, morphology and eruptive history of the original volcano. Initial Hawaiian to Strombolian-type explosive eruptions produced a pyroclastic cone. Subsequently subvolcanic intrusions and lavas were emplaced. The lavas were fed from the central vent of the volcano, breached the cone and flowed southwards. Later eruptions resumed at a new vent on the western slopes of the main cone. The final volcanic edifice — a breached Strombolian scoria cone with a lava flow and a parasitic cone — was 500–1000 m in diameter at the base and 90–180 m high. The preserved SW sector of this volcano, where the pyroclastic deposits were protected from erosion by the surrounding plugs and lavas, corresponds to *ca*. 1/2 of the height and 1/8 of the volume of the original volcano. Compared with many other remnants of Cenozoic volcanic centres in Lower Silesia, this volcano is exceptionally well preserved and exposed.

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INTRODUCTION

Scoria cones represent the most common type of small volcanoes on the Earth's land surface (e.g. Cas and Wright, 1987). Their origin and styles of activity are well constrained by numerous observations of recent eruptions as well as abundant data on extinct and ancient examples. A typical scoria cone is a monogenetic volcano characterized by a regular form of truncated cone with a bowl-shaped crater on top. Such volcanoes originate during single, mildly explosive eruptions of basaltic magma. However, most other scoria cones show a more complex morphology and a greater variation in lithology (e.g. Chain des Puys, France: de Goër, 1994; Eifel Volcanic Field, Germany: Sigurdsson *et al*., 2000, Schmincke, 2004). These features reflect changing styles of eruptive processes and, ultimately, a more advanced development of magma plumbing systems of these volcanoes at depth. Scoria cones and related eruptions are subjects of intense volcanological and petrological studies due to the volcanic hazards they pose in areas of recent activity and their implications for the understanding of the evolution of magmatic systems (e.g. Siebe *et al*., 2004; Shaw, 2004, and references therein). Reconstruction of the original form and vent location of eroded scoria cones may also be of some economic significance, as such studies are helpful to the recognition and exploitation of basalt deposits.

This paper describes the internal structures, volcanic evolution and reconstruction of a strongly eroded, Cenozoic scoria cone located at Sośnica Hill near the village of Targowica in Lower Silesia (south-west Poland; Fig. 1). In Lower Silesia there are over 300 outcrops of Cenozoic basaltic rocks, and the majority of them are veins, dykes and plugs (many of them extensively quarried) which likely represent the roots of former basaltic volcanoes. Relics of lavas and pyroclastic deposits are not common, and only in a few cases is the preservation of eruptive products good enough for the original volcanic landforms to be reconstructed: e.g. at Gracze (Birkenmajer, 1974) and at Góra Świętej Anny (Niedźwiedzki, 1994 and references therein), where a cluster of pyroclastic cones and a strongly eroded caldera, respectively, were recognized.

An excellent opportunity for a detailed volcanological study is provided at Sośnica by pronounced facies variation of volcanic and volcaniclastic rocks, well exposed in a big, recently operating quarry. Detailed field work enabled prepara-

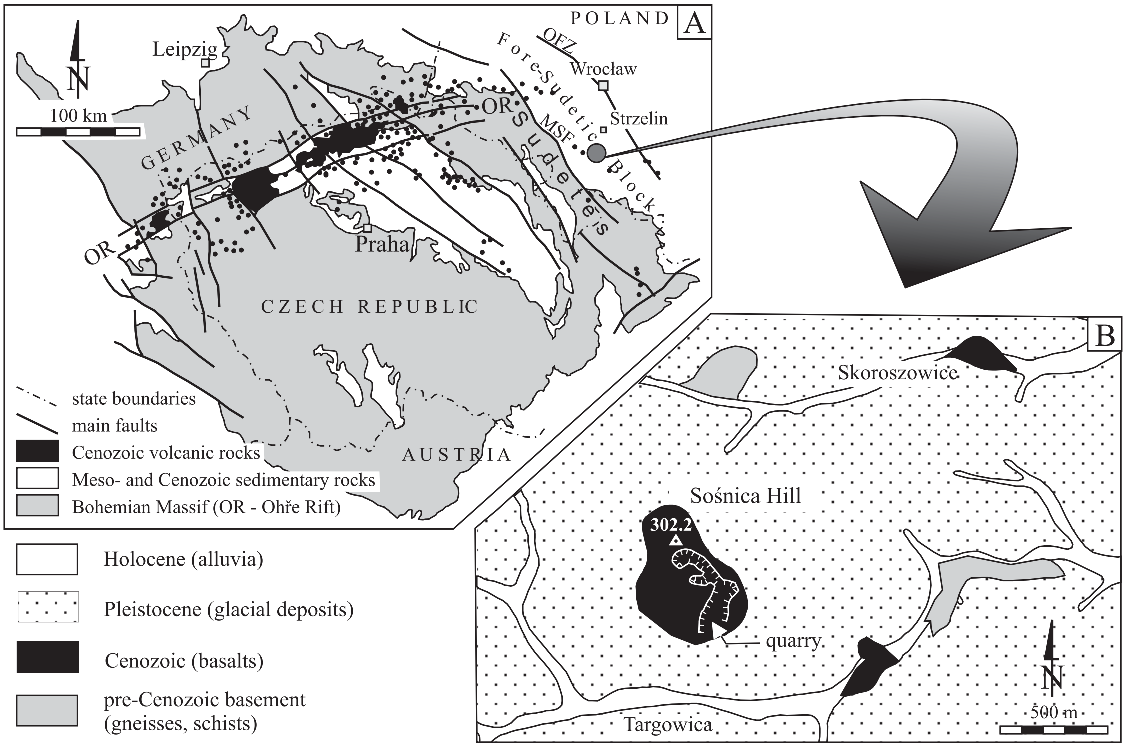

Fig. 1. Geological setting of Cenozoic basalts of the Targowica area

A — location of the study area (grey spot) relative to the Bohemian Massif and the Ohře (Eger) Rift (modified from Ulrych *et al*., 1999); OFZ — Odra Fault Zone, MSF — Marginal Sudetic Fault; B — geological sketch of the study area and location of the quarry at Sośnica Hill (modified from Wójcik, 1973*a*)

tion of a geological map and cross-sections of the quarry, together with structural and lithological characteristics of the deposits exposed there. These data enabled the identification of pyroclastic and autoclastic deposits, subvolcanic intrusions and lavas, and analysis of their emplacement processes and sequence. Finally, the type, location, dimensions and successive stages of evolution of the original volcano — a scoria cone with a complex morphology — were reconstructed.

GEOLOGICAL SETTING

In Cenozoic times intra-continental rifting processes and related volcanic activity affected large areas of Europe (Wilson and Downes, 1990; Ulrych *et al*., 1999, 2002). One of well-defined Cenozoic rift zones of Europe is the Ohře (Eger) Rift, which developed along a terrane boundary within the Bohemian Massif, an uplifted block of pre-Mesozoic, largely crystalline rocks (Fig. 1). Basaltic volcanism in Lower Silesia, at the northern termination and eastern flanks of the Ohře Rift, spanned the Oligocene–Pliocene interval (e.g. Jerzmański and Maciejewski, 1968 and references therein). Recent K-Ar radiometric age determinations from this region range from 30.9 to 3.8 Ma (Birkenmajer and Pécskay, 2002; Birkenmajer *et al*., 2002*a*, *b*, 2004). The volcanic rocks are mostly basanites and tephrites, more rarely nephelinites and alkali basalts as well as trachytes and latites (Kozłowska-Koch, 1987). The magmas originated from heterogeneous mantle sources and locally underwent limited fractionation and crustal assimilation (Alibert *et al*., 1987; Blusztajn and Hart, 1989; Dziedzic, 1990; Ladenberger *et al*., 2004).

The study area is located *ca*. 100 km east of the Ohře Rift, in the eastern part of the Fore-Sudetic Block, south of the town of Strzelin (Fig. 1A). The basalts and related volcanic rocks of this area are grouped into the "Strzelin-Ziębice concentration" (Cwojdziński and Jodłowski, 1982), being likely a relict of a small volcanic field. The volcanic activity in this field spanned the turn of Oligocene and Miocene, as suggested by recent K-Ar dating ranging from *ca*. 27 to 19 Ma. Two samples of basic lavas from a quarry near the village of Targowica (the main site of this study) were dated at *ca*. 23–20 Ma (the Early Miocene; Birkenmajer *et al*., 2004).

The Cenozoic volcanic rocks of the Strzelin-Ziębice region cut through, and rest upon, a crystalline basement composed of gneisses, schist and granitoids of the Strzelin massif. Locally, sands and clays of inferred Miocene age are also found (Meister, 1932; Wójcik, 1973*b*). The crystalline basement as well as the Cenozoic volcanics and sediments are extensively covered by Quaternary deposits up to several tens of metres thick, including Pleistocene sands, boulder-clays and loess, as well as Holocene alluvia. The pre-Quaternary rocks crop out as isolated "islands" surrounded by the younger deposits (Fig. 1B). However, drilling and geophysical prospecting for basalt deposits showed that the sub-Quaternary extent of the volcanic rocks is often wider than the present outcrops, and that some isolated basaltic "islands" may join underneath the Quaternary (Cieśla, 1968; Cwojdziński and Jodłowski, 1982). Significant lateral variations of basalt thicknesses and vertical displacements of basaltic horizons attributed to faults have been found (Majkowska, 1992, 2003). These complex relationships possibly reflect the influence of several factors, including pre-volcanic basement morphology, scattered distribution of the volcanic products, pre-Quaternary erosion, Cenozoic faulting, accumulation of Quaternary deposits, and, in particular, the presence of partly eroded and buried volcanic landforms.

FIELD RELATIONSHIPS AND EMPLACEMENT PROCESSES OF THE VOLCANIC ROCKS

Near the village of Targowica, basaltic volcanic and volcaniclastic rocks form three outcrops (Fig. 1B). Two small outcrops near Skoroszowice and east of Targowica are very poorly exposed, and massive to vesicular basaltic lavas can be observed at small localities in stream valleys. The largest outcrop, *ca*. 700 m long and 400 m wide, is situated on Sośnica Hill (302.2 m a.s.l.) and is well exposed in a large quarry (over 300 m in size). Within the quarry (Fig. 2) the total thickness of volcanic rocks is *ca*. 40 m (Majkowska, 1992), being made up of volcaniclastic rocks, intrusions and lavas (Meister, 1932; Birkenmajer *et al*., 1970; August *et al*., 1995; August and Awdankiewicz, 1999; Budzyńska, 2001; Birkenmajer *et al*., 2004). The chemical composition of scoria clasts in the volcaniclastic deposits and the composition of intrusions and lavas at Sośnica and near Skoroszowice correspond to alkali basalts (Awdankiewicz, 2004).

VOLCANICLASTIC ROCKS

LITHOLOGIES, THEIR SPATIAL DISTRIBUTION AND STRUCTURES

The volcaniclastic rocks are reddish to gray-coloured. A chaotic fabric and an open framework are typical features of these rocks. Their main components are scoriaceous basaltic clasts ranging from several mm to several cm in diameter, with variable amounts of massive basalt blocks and volcanic bombs. The latter include spatter-like, spindle-shaped and broken ribbon bombs up to 0.5 m in diameter. Following the descriptive terminology of volcaniclastic rocks (Fisher, 1961; Cas and Wright, 1987) these deposits are generally classified as basaltic breccias, and further subdivided into: nonbedded breccias (Figs. 2 and 3A) bedded breccias (Fig. 3B, C). The nonbedded breccias are relatively coarse-grained, poorly sorted and vary from volcanic bomb-rich deposits (Fig. 4A) to block-rich deposits (Fig. 4B). The latter lithology is rare. The bedded breccias are characterized by a better sorting and a distinctive predominance of scoria over the other clast types, and grade into relatively fine-grained deposits, strongly dominated by fine, lapilli-sized scoria (Fig. 4C).

The breccias crop out extensively in the northwestern part of the quarry (Fig. 2) where their exposed sequence is *ca*. 20 m-thick. The lower half of this sequence consists of nonbedded, volcanic bomb-rich breccias (Fig. 3A), while the upper part comprises the bedded breccias (Fig. 3B). The fine-grained lapilli-sized scoria deposits are found in loose blocks derived from the upper part of the succession (barely accessible due to their exposure high at quarry walls). The bedding is indistinct and best seen in places where weathering accentuated slight differences in consolidation and/or grain size of successive beds. The beds are from a few centimetres to several tens of centimetres thick and dip to the west and south-west at 15–35°. Despite some local variations, there is a systematic change in dip directions, from more westward dips in the northern part of the breccia outcrop, to more southward dips in the southern part (Fig. 2).

In the central part of the quarry, variable nonbedded to bedded breccias occur as lenses and irregular bodies, several metres in thickness, interlayered with basaltic lavas. Further east and south only the nonbedded breccias are observed. They form a discontinuous outcrop along the deepest quarry levels, below massive basalts. Lateral thickness variations (from a few to over 10 m) and gradations from bomb-rich to block-rich breccias are observed. Locally, an upward gradation from basalts to nonbedded breccias is found. Further descriptions and interpretation of these lava-associated breccias are given in the section on basaltic lavas.

The pores between and within clasts of the basaltic breccias are locally filled with pink smectites. This late- to post-magmatic cementation is most extensively developed in the main breccia outcrop in the north-western part of the quarry and was characterized in more detail by Kościówko *et al*. (1986), August *et al*. (1995) and August and Awdankiewicz (1999).

DEPOSITIONAL AND ERUPTIVE PROCESSES

The basaltic breccias cropping out at Sośnica Hill show structures and lithological characteristics typical of pyroclastic deposits as well as autoclastic deposits (the autoclastic breccias are discussed together with lavas in the following sections). In particular, pyroclastic processes were dominant in the formation of the 20 m thick breccia sequence in the northwestern half of the quarry, which is characterized by the presence of abundant volcanic bombs and a well-developed bedding. Using the granulometric terminology of pyroclastic rocks after Fisher (1966; also Fisher and Schmincke, 1984), the nonbedded breccias would be generally classified as tuff breccias with some gradations towards agglomerates, while the bedded breccias represent tuff breccias gradational to lapillistones. These rocks may be attributed to pyroclastic fall related to mildly explosive, Hawaiian to Strombolian-type eruptions of basaltic magmas. Strombolian eruptions are characterized by several successive discrete explosions of large gas bubbles, while the Hawaiian eruptions represent more continuous lava fountaining. The characteristics of such eruptions and related fall deposits were overviewed by Fisher and Schmincke (1984) and Cas and Wright (1987).

The structural and lithological differences between the nonbedded and bedded breccias described in this paper reflect variable styles of eruption of the volcano and accumulation of tephra. In the nonbedded breccias, the massive structure and poor sorting suggest rapid deposition during, essentially, a single depositional event. By contrast, the presence of bedding and better sorting suggest a slower rate of deposition and several successive depositional episodes for the bedded breccias. The vertical succession from the nonbedded to the bedded deposits thus indicates a decreasing deposition rate and an increasing

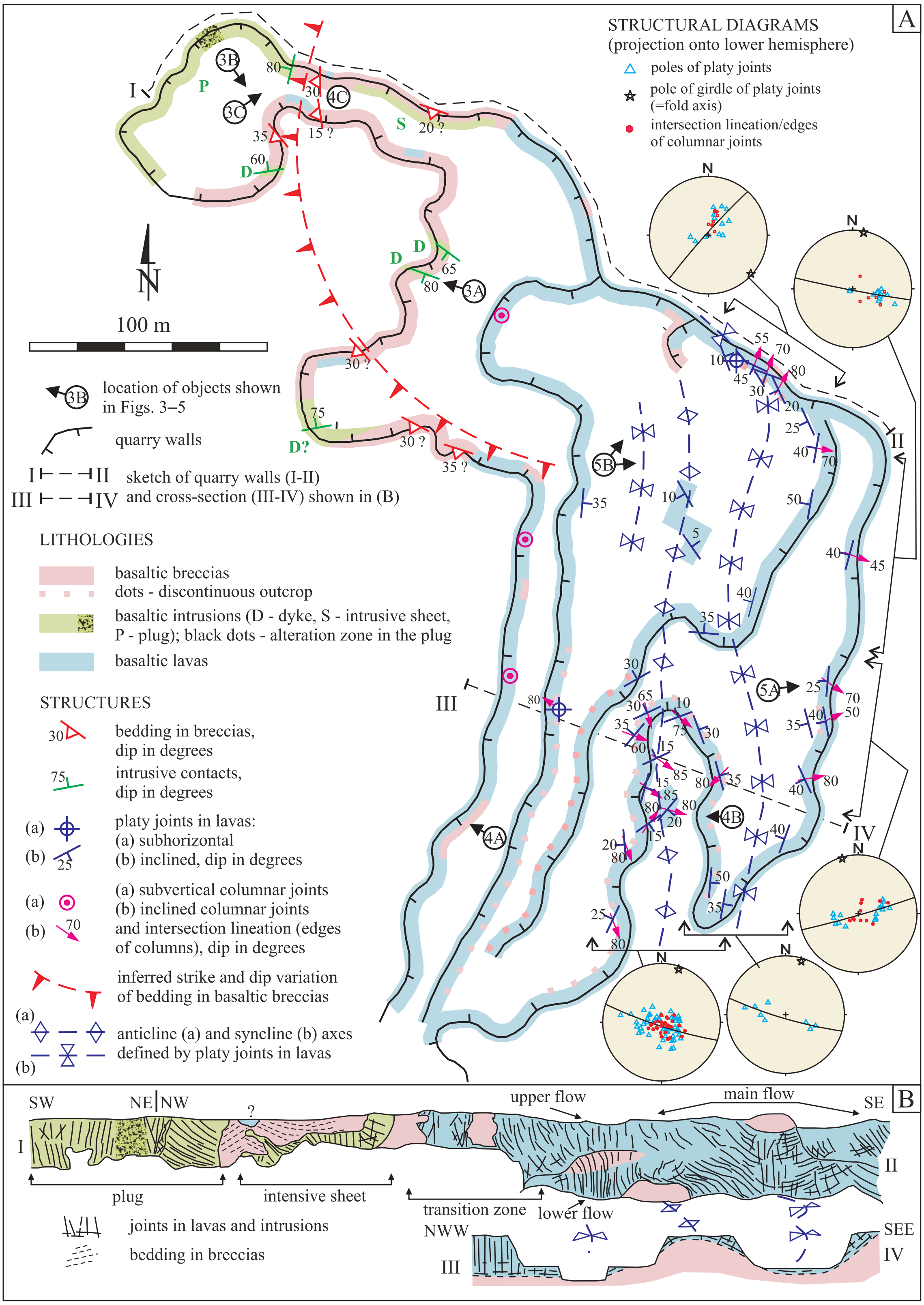

Fig. 2. A — geological map; B — cross-sections of the basalt quarry at Sośnica Hill (scale, colours and other symbols as in the map)

episodicity of depositional processes with time. In addition, the lithological variation of the deposits, with abundant volcanic bombs in the nonbedded deposits, and rare fragments of this type in the overlying bedded deposits, suggests some change in the eruptive mechanism with time. Probably, the activity commenced with almost continuous series of explosions alternating

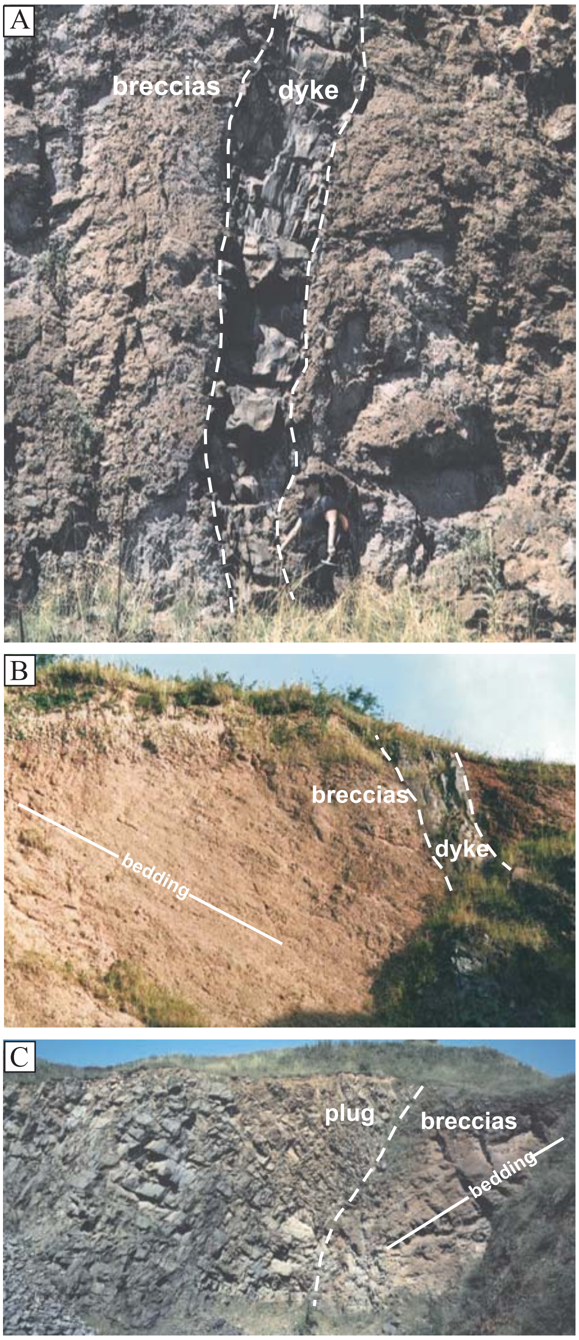

Fig. 3. Structures of basaltic breccias and intrusions

A — nonbedded breccias cut by a dyke 60–100 cm wide; B — bedded breccias cut by a dyke, the quarry wall is *ca*. 10 m high; C — bedded breccias and a margin of the plug, the quarry wall is *ca*. 12 m high; the location of the objects shown is indicated in Figure 2

with lava fountaining, resulting in the accumulation of the nonbedded deposits. This type of activity may be classified as transitional from Hawaiian to Strombolian. The later stages of the eruption consisted of more discrete explosions, typical of Strombolian-type activity, when the bedded deposits accumulated. Other factors, such as the eruption rate and related height of the eruption column, might also have influenced the depositional processes, but the role of these factors is not well constrained at present.

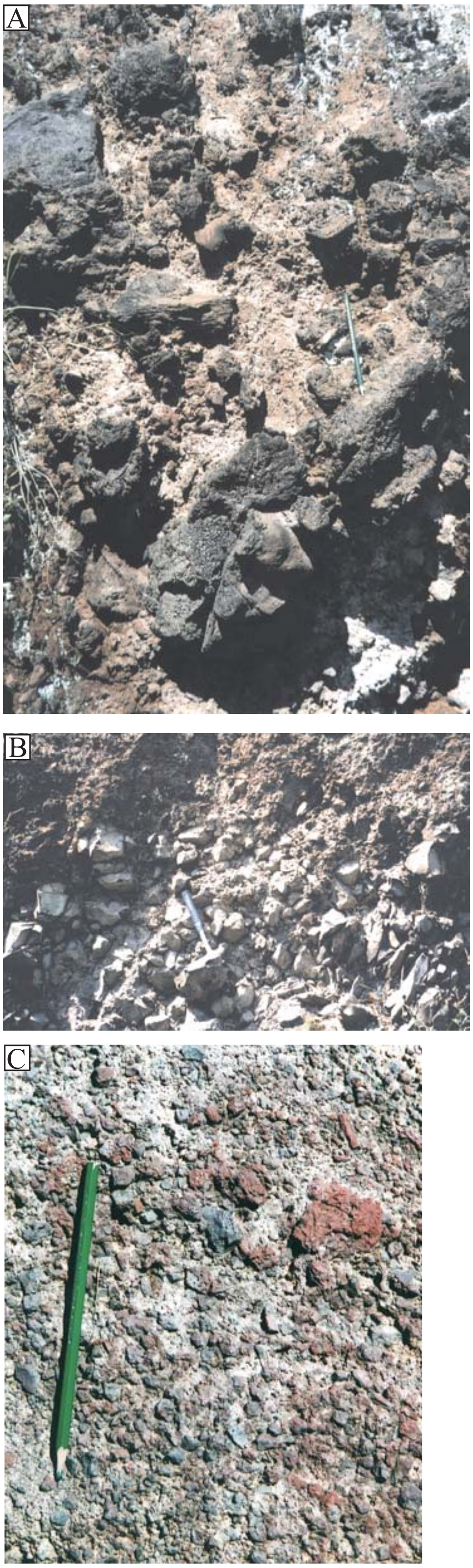

Fig. 4. Lithological variation of the basaltic breccias

A — nonbedded breccia with abundant volcanic bombs, the pencil is 17 cm long; B — nonbedded breccia with abundant angular blocks, the hammer is 30 cm long; C — close-up of fine-grained, scoria-rich breccia, photo from a loose block, the pencil is 17 cm long; the location of the objects shown is indicated in Figure 2

VENT POSITION AND VOLCANO GEOMETRY

The general strike variation of bedding in the pyroclastic deposits suggests that the main breccia outcrop represents the southwestern sector of a cone several hundred metres in diameter (Fig. 2). The centre of the cone, and the eruptive vent of the pyroclastic deposits, was thus located north of the quarry, probably several tens of metres away (and almost certainly not further than 200 m). The diameter of the cone cannot be precisely determined (neither the vent nor the outer cone margin are precisely located), but a likely value is within the range of 500–1000 m. Considering the eruption styles and pyroclastic deposit types discussed above, the volcanic edifice can be classified as a basaltic scoria cone. Such volcanoes often show the regular shape of a truncated cone, with a bowl-shaped central crater, and there are linear relationships between the cone basal diameter (W_{co}), cone height (H_{co}) and crater width (W_{cr}): $H_{co}= 0.18W_{co}$ and $W_{cr}= 0.40W_{co}$ (Wood, 1980). It follows that the Sośnica cone was originally 500–1000 m wide at its base, rose 90–180 m above the pre-eruptive surface, and the central crater was 200–400 m in diameter. Additional information on the details of the morphology of the volcano (parasitic vents, central crater shape) come from the study of subvolcanic intrusions and lavas discussed below. The original volcanic edifice was apparently strongly eroded and the observed deposits represent its remnants. This problem is discussed in the final chapter.

SUBVOLCANIC INTRUSIONS

DISTRIBUTION, GEOMETRY AND STRUCTURES

The pyroclastic deposits discussed above are cut by basaltic intrusions, including a plug, a subhorizontal intrusive sheet and dykes (Fig. 2). The plug is located in the north-westernmost pit of the quarry. At the exposed level it is *ca*. 100 m in diameter. The eastern margin of the plug cuts the bedded breccias and dips steeply, at 80°, to the west (Fig. 3C). The other margins of the plug are not exposed. The plug shows a composite, asymmetrical structure, illustrated in cross-section I–II in Figure 2. In the eastern part there is *ca*. 20 m wide marginal zone characterized by subhorizontal to inclined columnar joints, nearly perpendicular to the contact with breccias. The basalts are slightly vesicular in a narrow (cm to dm) zone along the contact. Further west, towards the plug interior, is a thin zone with less regular, platy to columnar, subvertical joints, followed by a *ca*. 12 m wide zone of strongly altered amygdaloidal basalts with abundant clay minerals, carbonates and zeolites. The central, widest zone of the plug is characterized by subvertical columnar joints.

The subhorizontal intrusive sheet crops out within breccias to the east of the plug (Fig. 2, section I–II). This is a flat-lying, sill-like intrusion 8–9 m thick, which can be traced laterally for *ca*. 70 m. This intrusion is emplaced close to, and slightly oblique to, the boundary of the nonbedded and bedded breccias. The western and eastern terminations of the intrusion show a complex geometry. To the east the subhorizontal sheet bends upwards and grades into an inclined sheet dipping steeply (*ca*. 70°) to the west. At the western termination, within the bedded breccias, the sheet wedges out and splits into a few conformable to discordant and variably inclined intrusive sheets. One of the subvertical offshoots further grades upwards into an oval, saucer-shaped mass of basalt set within bedded basaltic breccias. Bedding of the breccias shows a variable orientation adjacent to the sill offshoots.

The intrusion described is largely composed of massive basalts with columnar to platy, subvertical joints. There is a thin layer of vesicular basalts at the top. The intrusive veins at the northwestern termination of the main sheet are structurally variable. Some of them consist of massive and vesicular basalts with platy joints parallel to the margins of the veins, while others consist of vesicular basalts without distinctive joints.

Four dykes 0.5 to 3 m thick crop out within the basaltic breccias south-east of the plug (Figs. 2 and 3A, B). The dykes show steep dips (over 60°) towards the north-north-west and south-west. The dykes consist of massive basalts showing platy joints parallel to their margins. At the contacts with the host breccias there are thin (cm to dm) zones of vesicular basalts. The south-easternmost dyke is the thickest and shows a more complex internal structure (variably vesicular zones ?), but it is not well exposed. Smaller, poorly exposed dykes are also present in other parts of the quarry.

EMPLACEMENT PROCESSES OF THE INTRUSIONS

All the intrusions reflect relatively late episodes of activity of the volcano, postdating accumulation of their host pyroclastic deposits. Close links between the pyroclastic and intrusive activity are documented by the subhorizontal intrusive sheet. The westward wedging out of this intrusion suggests that the magma was supplied from the east. It is thus likely that the basaltic magma which formed the intrusion was fed from the same conduit as the magma that fed the pyroclastic eruptions. This sheet intruded close to the boundary of the nonbedded and bedded pyroclastic deposits, which represented a structural discontinuity within the pyroclastic succession of the cone and thus might have acted as a preferred horizon for the emplacement of basaltic magma. However, the gradation from the steeply inclined sheet into the subhorizontal sheet described above shows that other, subvertical discontinuities (faults ? fractures ?) also controlled the emplacement of this intrusion. The western termination of the sheet could have almost reached the cone palaeosurface — the relationships illustrated in section I–II in Figure 2 suggest that some of the subvertical offshoots of the sheet broke out to the surface and formed small, local vent(s). In addition, the variable orientation of bedding near the western termination of the sheet may be related to deformation processes induced by forceful intrusive emplacement of the basaltic magma.

It is possible that the time span between the pyroclastic and intrusive activity was very short, and that these activities represented successive phases of the same eruption. This suggestion stems from the well-known activity patterns of scoria cones, which form essentially during a single eruption, and 95% of the observed eruptions terminated within one year (Wood, 1980). On the other hand, the plug — the largest of the intrusions at Sośnica — probably formed after a relatively long repose period between successive eruptive stages of the volcano, long enough for the main, central vent north of the quarry to become inactive, e.g. due to filling with consolidated lava. The plug seems to represent a conduit of another vent formed on the western slopes of the main cone. Any eruptive products related to this hypothetical vent were not recognized so far, as they are either not exposed or were removed by erosion. The complex internal structure of the neck indicates that this intrusion developed due to the emplacement of at least two or three main magma batches, each solidified independently, with the development of a specific joint system. In addition, the alteration zone in the eastern part of the neck shows that it was also a site of subsequent activity of post-volcanic, fumarolic fluids.

The dykes represent smaller intrusions emplaced within the volcanic cone of Sośnica Hill. The four measured dykes are aligned along two trends: WSW–ENE and NW–SE (Fig. 2). These two trends point towards the two inferred vents of the volcano: the main vent north of the quarry, and the parasitic vent on the western slope, respectively. Although only four dykes were measured, it can be speculated that the dykes within the volcanic cone intruded in two main stages, each related to a different conduit.

LAVA FLOWS

DISTRIBUTION, STRUCTURE AND LITHOLOGY

Small outcrops of massive to vesicular basaltic lava are locally found below the basaltic breccias in the northwestern part of the quarry (Fig. 2). However, basaltic lavas crop out extensively in the central and southern parts of the quarry. The lava units are up to *ca*. 30 m thick and largely consist of massive basalts with polygonal to columnar and platy joints of variable orientation (details below). In many places the massive basalts are underlain by the nonbedded basaltic breccias. The breccia/basalt contacts are sharp but uneven due to the presence of dome- to ridge-like accumulations of breccia several metres high. Locally, the massive basalts grade upwards into vesicular basalts and nonbedded breccias. Columnar joints, well developed in the massive basalts, partly extend into the top breccias (the *lower flow* and the *main flow* in Fig. 2, cross-section I–II). Similarly to the basal breccias, the top breccias also show lateral thickness variation. The lithology of breccias associated with the lavas is variable and both volcanic bomb-rich deposits and massive block-rich deposits were found (Fig. 4A, B).

The transition zone between the pyroclastic deposits with intrusions to the north-west, and basaltic lavas to the south-east, is exposed in the middle part of the quarry (Fig. 2). This transition is marked by an irregular interlayering of lavas and breccias and breccia-filled troughs within the lavas. Further east, along the northeastern quarry wall, two flows, each 10–20 m thick, are found one upon the other (the lower and upper flows, section I–II in Fig. 2). The breccia zone that separates these two successive lavas wedges out south-eastwards, and the flows merge into a single unit 35 m thick (the main flows in Fig. 2). The basal breccia/massive basalt interface in the lower part of the main flows is inclined to the north, as documented by scarce breccia exposures in the deepest, northeastern part of the quarry, and abundant breccia exposures below the massive lavas further south at higher quarry level.

The main flows is the dominant unit in the eastern half of the quarry. It characteristically shows two systems of joints: platy and polygonal, nearly perpendicular to each other (Fig. 5A). The platy joints represent a system of subparallel planes that subdivide the lavas into dm-thick slabs. The polygonal joints comprise a few subsets of distinctive orientation, and their intersection defines columnar joints and an intersection lineation (parallel to the edges of columns). In the western part of the lava the platy joints are nearly subhorizontal, and the polygonal joints are subvertical and form well-developed columns. However, in the eastern and southern parts of the quarry the platy joints show a wavy arrangement with variable dips of up to 50° and define a system of southerly aligned folds with subhorizontal axes (Figs. 2 and 5B): two synclines (marked by inwardly dipping platy joints) separated by an anticline (marked by outwardly dipping platy joints). The polygonal joints are also variably inclined and the intersection lineation and the columnar joints (well developed only locally) show a fan-like arrangement, radiating downwards within synclines and upwards in the anticline (see the structural diagrams in Fig. 2).

The western syncline can be traced for a few tens of metres only in the northern part of the flow (Fig. 2). Southwards this syncline disappears and grades into a flat-lying, columnar jointed part of the lava.

Fig. 5. Structures in the lavas

A — relationships between platy, polygonal and columnar joints; the quarry wall is *ca*. 5 m high; B — syncline defined by the platy joints in lavas; the axis of the syncline strikes oblique, at *ca*. 30°, relative to the quarry wall; the quarry wall is *ca*. 35 m high; the location of the objects shown is indicated in Figure 2

The anticline is a pronounced feature in the southern part of the quarry, forming a ridge with the core of breccias mantled by outwardly dipping platy jointed lavas (Fig. 2, section III–IV). The hinge of this anticline is undulose, plunges generally to the north, but emerges near the base of the northeastern quarry wall, where a ridge of breccias mantled by lavas is again exposed (Fig. 2, section I–II).

The eastern syncline can be traced for over 200 m along the eastern part of the quarry. The axis of this structure is nearly horizontal with very shallow dips of a few degrees. The strike of the axis is wavy and varies from NW–SE in the north to NNE–SSW in the south (Fig. 2).

EFFUSIVE PROCESSES AND STRUCTURE OF THE CRATER OF THE VOLCANO

The lavas described above document effusive activity of the Sośnica Hill volcano. The alignment of outcrop and anticlinal/synclinal structures within the main lava show that the lavas were southerly aligned. Considering the interpretations discussed for the pyroclastic deposits, it is likely that the lavas were fed from the north, from the inferred main vent of the volcano. In addition, the presence of locally overlapping lava lobes (the lower and upper flows) suggests that the effusive eruption comprised several episodes of varying intensity.

The fold-like structures described are not common in basaltic lavas and indicate rather specific conditions of formation. It is considered here that these structures were formed due to flow of lava in a confined, narrow channel within the volcanic cone: the thermal joints, which define the structures, mirror the general shape of the confining channel. The synclinal structures probably reflect the main streams of flowing lava (lava rivers ?), while the intervening anticline represents a ridge (lava levée ?; Cas and Wright, 1987) that partly separated the adjacent streams and was later overtopped and buried by the lava as the latter inflated. Moreover, the rather chaotic interlayering of lavas and pyroclastic deposits in the transition zone (Fig. 2) suggests the influence of some destructive process in the volcano's development: e.g. troughs in lava filled with breccias seem to represent extensional or collapse-related features. These observations lead to the interpretation that initially the lavas partly filled the central crater of the volcano, and then breached the cone and drained away through a channel within the southern flank of the cone. Destruction of the cone flank could have been aided by some explosive activity. Such breached scoria cones are relatively common and several examples are known from the Chain des Puys, France (de Goër, 1994; Schmincke, 2004).

The lavas from Sośnica can be classified as aa-type flows, which are characterized by brecciated zones along the base and top. Close genetic links between the breccias and the lavas at Sośnica are demonstrated by the thermal joints, which locally continue from the coherent flow interior into the overlying breccias, implying cooling as a single unit. Other features of the breccias, such as their chaotic structure and dominantly scoriaceous lithology, are also consistent with an autoclastic origin. However, the breccias locally contain abundant massive basalt blocks as well as typical volcanic bombs. While the massive blocks may be of both auto- and pyroclastic origin, the basaltic bombs (together with some scoria ?) likely formed due to an explosive eruption of basaltic magma. This pyroclastic component in the lava-related breccias might essentially have originated due to two processes:

— a fall of fresh tephra onto the flowing lava, or

— reworking of earlier tephra forming the cone of the volcano by the flowing lava.

Simultaneous explosive and effusive eruptions are often observed at scoria cones, but reworking processes, as e.g. rolling of volcanic bombs from the steep slopes of a cone on to the lava, are also likely. A similar effect on the lithology of the flow breccias would be expected in both cases, and a precise genetic interpretation is difficult. In conclusion, the breccias associated with the lavas at Sośnica Hill are in part polygenetic deposits, gradational between autoclastic deposits and pyro- and/or epiclastic deposits.

The position of the basaltic lavas relative to the pyroclastic, cone-forming breccias shows that the emplacement of the lavas considered essentially postdated the formation of the cone (but might have already started during the late stages of the pyroclastic activity). However, the cone deposits are underlain by other, poorly exposed basaltic lavas in the north-western part of the quarry (Fig. 2). These older lavas generally reflect effusive activity predating the cone-forming eruptions of the volcano. However, a genetic link to the volcano at Sośnica Hill is uncertain, as these lavas might have also been erupted from another, older, unrelated volcanic centre. The exposure and available data are insufficient to solve this problem at present.

THE SOŚNICA VOLCANO AND ITS ERUPTIVE HISTORY: A SUMMARY AND FINAL REMARKS

The interpretations discussed above can be integrated into a model of the original structure of the volcano and the main phases of its eruptive history. The earliest stages of the volcano evolution are not well documented due to insufficient exposure (e.g. the crystalline bedrocks and the earliest eruptive products are not exposed). Limited, early effusive activity cannot be excluded. The well-exposed deposits document three main stages of volcano development: initial explosive activity, later lava effusion and finally formation of a parasitic vent and cone (?). Subvolcanic intrusions were emplaced within the volcanic edifice in several episodes. The successive stages might have partly overlapped in time. The suggested, idealized eruptive scenario is illustrated in Figure 6.

At the 1st stage the Strombolian/Hawaiian-type and Strombolian-type explosive eruptions produced thick pyroclastic deposits (tuff breccias with some gradations towards agglomerates and lapillistones) forming a cone. This volcanic edifice can be classified as a Strombolian scoria cone. The cone was 500–1000 m wide at its base, 90–180 m high, with a central crater 200–400 m in diameter. The main, central vent of the cone was located north of the present quarry at Sośnica Hill.

The explosive activity of the 1st stage was shortly followed by the effusive 2nd stage. The lavas were fed from the central vent of the volcano, breached the southern flank of the cone and flowed southwards. The lavas comprised several lobes of aa-type. A specific system of synclines and anticlines defined by joints developed in the lavas due to their flow in a confined

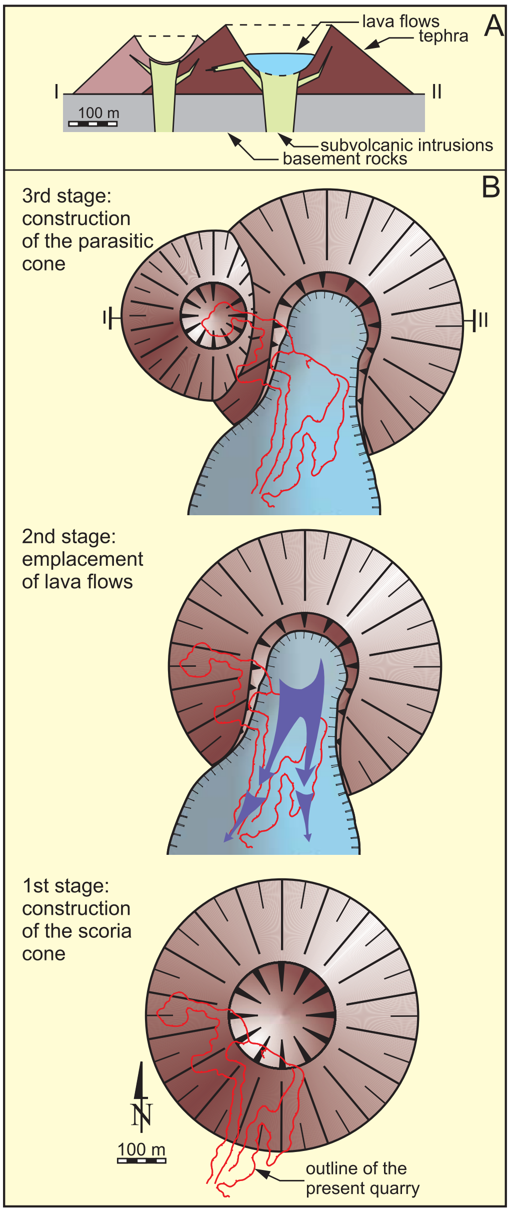

Fig. 6. A — Schematic cross-section of the final volcanic edifice; B — reconstruction of the main stages of the evolution of the Sośnica Hill scoria cone

channel within the volcanic edifice. The origin of associated basaltic breccias, hosting primary and/or reworked pyroclastic components (volcanic bombs) is partly gradational between autoclastic and pyro- and/or epiclastic deposits.

Following the effusive 2nd stage the main, central vent of the volcano became inactive, probably due to partial filling with solidified lavas and/or a longer repose period. During the next, 3rd stage, the activity resumed on the western flank of the main cone, where another, smaller (parasitic) cone probably formed. The remnant of this cone is a 100 m wide neck (former lava conduit) which records the emplacement of two to three discrete magma batches and a post-volcanic phase of fumarolic activity.

Small volumes of magma intruded the volcanic edifice as dykes and other intrusive sheets, possibly starting from the latest stages of the initial explosive activity. The emplacement of these intrusions was controlled by structural discontinuities within the cone, including stratification (the boundary between the more massive inner cone and the better stratified upper and outer parts of the cone) and fractures.

The volcanic evolution of the Sośnica scoria cone reflects the arrival at the surface of several small batches of basaltic magma with a total volume of, probably, a fraction of a cubic kilometre (detailed calculations are problematic due to erosional effects). Considering recent, well-documented analogues, it is likely that this volcano formed in a single, polyphase eruption, or two eruptions, within a time span of weeks to years. In contrast, recent K-Ar dating of two lava samples from the Sośnica volcano gave values of 23.20±0.89 Ma and 20.13±0.86 Ma "consistent with their respective geological ages" (Birkenmajer *et al*., 2004). However, it seems unlikely that these K-Ar numbers reflect really a 3 My period of volcanism at Sośnica, as the time-scales of scoria cone activity are orders of magnitude shorter and, moreover, the two samples analysed most probably come from the same lava unit (the main lava of this study) and not successive lavas as considered by Birkenmajer *et al*. (2004). In this context, the 3 My difference in "age" between the two samples may rather represent uncertainty in the K-Ar age determinations at Sośnica.

After the activity ceased, the volcanic edifice was substantially eroded. The preservation of easily erodable pyroclastic deposits of the southwestern sector of the cone was enhanced by "protection" from the more resistant plugs and lavas surrounding this cone segment from the west, north and east. At present the Sośnica Hill rises 50–70 m above the adjacent stream valleys where, possibly, distal basaltic lavas of the volcano crop out and approximate the pre-volcanic surface elevation. The upper slopes of the hill are inclined at *ca*. 12°. If the original volcanic edifice was 90 to 180 m high, with steep slopes of up to 33°, the present Sośnica Hill represents a relatively small part of the original volcanic edifice. The remnants of the southwestern sector preserved correspond to a half or less of the height, and *ca*. 1/8 of the volume of the original volcano. However, compared with many other remnants of Cenozoic volcanoes in Lower Silesia (usually eroded down to their underlying plugs within the basement rocks), the Sośnica Hill represents one of the most completely preserved and best exposed volcanoes. Considering the present-day abundance of scoria cones in many intra-continental settings, and the general style of Cenozoic volcanism within the Central European Volcanic Province, it is likely that scoria cones similar to that of Sośnica Hill were also very common in the Cenozoic volcanic sub-province of Lower Silesia.

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