

Provenance of basalt blocks from Roman sites in Vleuten-De Meern (the Netherlands) traced to the Tertiary Siebengebirge (Germany): a geoarchaeological quest using petrological and geochemical methods

K. Linthout^{1*}, H. Paulick² & J.R. Wijbrans³

1 Institute for Geo & Bioarcheology, Faculty of Earth & Life Sciences, VU University Amsterdam, De Boelelaan 1085, 1081HV Amsterdam, the Netherlands.

2 Steinmann Institut für Geologie, Mineralogie und Paläontologie, Poppelsdorfer Schloss, Universität Bonn, D - 53115, Germany.

3 Department of Isotope Geochemistry, Faculty of Earth & Life Sciences, VU University Amsterdam, De Boelelaan 1085, 1081HV Amsterdam, the Netherlands.

* Corresponding author. Email: klinthout@cs.com

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Abstract

Unshaped basalt blocks from archaeological sites along the border of the Roman Empire (*limes*) in the lower Rhine area near Vleuten-De Meern (Utrecht) have been studied petrographically, analysed by XRF for major and trace elements, and dated by the ⁴⁰Ar/³⁹Ar method. The blocks are from a revetment in the bank of a fossil branch of the Rhine and a contiguous ship De Meern 4, both built around 100 AD. All nineteen blocks are alkali olivine basalt (AOB) with xenoliths of peridotite derived from the upper mantle and quartz xenocrysts from the continental crust; eighteen blocks contain resorbed plagioclase xenocrysts as well. Abundances of major and trace elements show that those eighteen samples form a chemically coherent group. The outlier, different in chemistry and without plagioclase xenocrysts, is from the ship. A basalt block from ship De Meern 1 (148 AD) conforms compositionally to the defined group. AOB lumps from a *limes* watchtower (2nd-3rd century) form a chemically distinct group.

Low SiO₂ contents (<46 wt.%) and high abundances of Mg, Ti, Ni, and Sr indicate a within-plate origin, directly from primitive melts; proportions of selected trace elements point at a continental rift setting. In the archaeological context, the most likely source region for the blocks is the Cenozoic European Volcanic Province, upstream along the Rhine and its tributaries.

The petrographic and analytical data of the blocks have been compared with 432 published analyses of German AOB. On petrographic grounds, the Eifel can be ruled out as a source area since typical Eifel basalt minerals, amphibole, biotite, K-feldspar and feldspatoids, are absent in the blocks. Applying seven geochemical criteria, based on abundances of major elements in the Roman blocks, twelve sites with matching AOB were found in the Siebengebirge, seven in the Vogelsberg, and one in the Westerwald.

The ages of the blocks (26.3 - 28.5 Ma) are compatible with ages determined for AOB from the Siebengebirge (27.4 - 29.9 Ma), and preclude their provenance from the Vogelsberg (< 18 Ma). The matching Westerwald sample is from 60 km beyond the *limes*, a prohibitive distance from the perspective of Roman logistics.

AOB quarries of optimal logistic position are located adjacent to the Rhine, between Bonn and Remagen, a zone with significant Roman settlements from the first century AD. Geochemical correlation indicates AOB bodies at Rolandsbogen and Godesburg (S of Bonn) as potential sources of the blocks from the 100 AD revetment and ships. Similarly, the Erpeler Ley (E of Remagen) is indicated as the likely source for the blocks from a 2nd-3rd century AD watchtower.

As the Godesburg basalt is at 1.6 km from the Rhine today, it is not obvious how the blocks were transported from there. However, it may be that the adjacent, now sanded, branch of the old Rhine river system, was navigable for flat-bottomed vessels in Roman times.

Our study demonstrates that substantial detailed information regarding ancient mining and trading activities can be retrieved from seemingly indistinctive basalt blocks.

Keywords: basalt blocks, ⁴⁰Ar/³⁹Ar ages, petrography, geochemistry, archaeometry, Roman times, Vleuten-De Meern

Introduction

Over the last decade, excavations at Roman archaeological sites in the southwestern part of the municipality of Utrecht recovered hundreds of blocks of natural rock, predominantly of basaltic composition. They reveal that the use of basalt in building activities, as preserved at many places along the frontier of the Roman Empire (*limes*) in Germany, also occurred in the lower Rhine areas, over 200 km away from nearest natural basalt occurrences.

In 2003, archaeologists of the Municipality of Utrecht, investigating the military infrastructure along the *limes*, discovered Roman remains from the first centuries AD. At excavation De Balije 2, site-code LR39, the team found a revetment enforced with basalt blocks in the bank of a fossil branch of the Oude Rijn near the towns of Vleuten and De Meern (Fig. 1). Similar blocks were found aboard the Roman ship De Meern 4, which was encountered lying across the revetment (Fig. 2; De Groot & Morel, 2007).

Dendrochronological investigation indicates 100 AD \pm 2 as the felling date of the wood used in the ship (Jansma, 2007). The Utrecht archaeologists infer that the revetment was part of a large-scale Roman program of improvements of roads, watchtowers and 'castella' along the *limes*, which were carried out in the early years of the reign of Trajanus (98-117 AD; M. Langeveld, pers. comm., 2006).

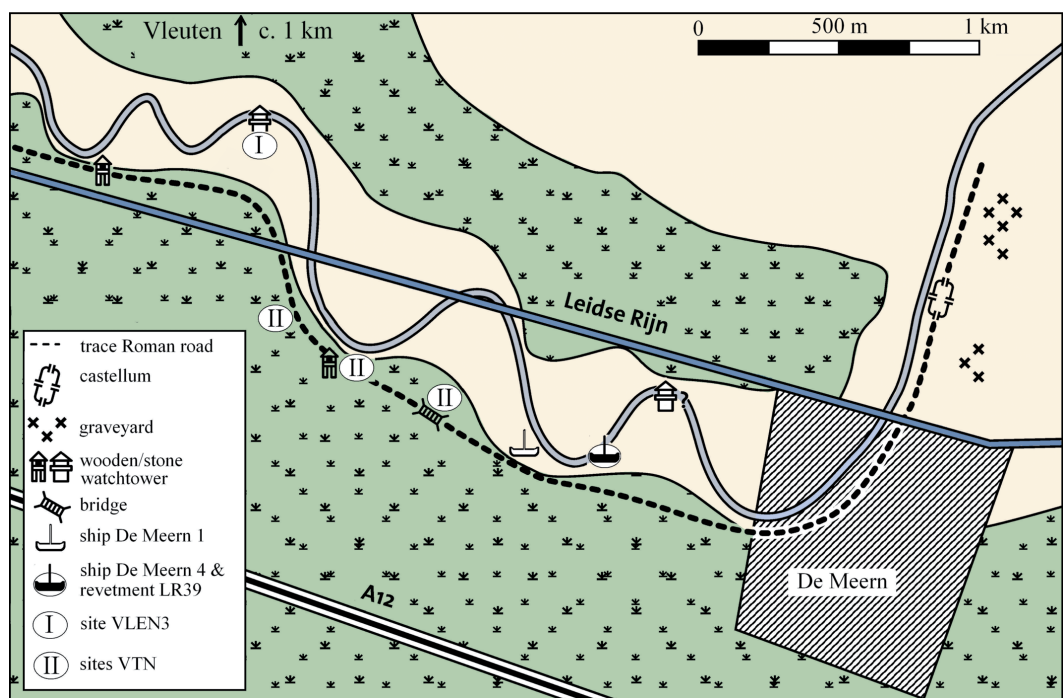
Petrological study of the basalts can be helpful in solving local archaeological questions, like the point of debate concerning the deposition of the oddly placed ship De Meern 4

(Morel, 2007; Van Dinter & Graafstal, 2007). Did it sink by accident, or was it brought to sink on purpose? In that discussion, it is an asset to know whether the blocks from the ship are geologically different from those of the revetment or not. Also, a sound petrological investigation of the basalt blocks may lead to the identification of their geological sources, which may guide the archaeological search for traces of Roman quarrying activities, and help to reconstruct the trade routes of bulk material to the Rhine delta.

In order to provide geological constraints for archaeological follow-up research we investigated the blocks by microscopic petrography of thin sections and by whole rock chemical analysis. Age determinations by the $^{40}\text{Ar}/^{39}\text{Ar}$ method provide a third, independent geological criterion for correlation with possible source lavas.

We studied thirteen samples of basalt from the revetment, six from ship De Meern 4, and one from another ship De Meern 1, which was built around 148 AD and found at 150 m to the west of De Meern 4 (Fig. 1; Jansma & Morel 2007). In order to broaden the scope of this study, we include in our discussion Laanbroek's (2004) geochemical analyses and thin sections from the excavation 'Gemeentewerf' (= municipal shipyard, site-code VLEN3, marked 'T' in Fig. 1). Most rocks from that site, which is still under archaeological study, were used in and around a watchtower dating from the late 2nd or early 3rd century (E. Graafstal, pers. comm., 2007). In total, the considered chemical database from the Vleuten-De Meern archaeological sites comprises the analyses of 30 basalt samples.

Fig. 1. The infrastructure of the *limes* along a now fossilised branch of the Old Rhine during Roman times. The meander belt (blank) is bounded by moors. De Meern village, the canalised waterway Leidse Rijn and motorway A12 are added for topographic reference. Adapted after Van Dinter & Graafstal (2007).





a.

Fig. 2. a. Excavation site De Balije II in Vleuten-De Meern, displaying basalt blocks along the limes in the 100 A.C. Roman revetment (LR39) and on ship De Meern 4. Carved lines, pointing to the upper left, mark the ground trace of the disappeared stern of the ship. After Morel (2007) with permission of RACM; b. Hexagonal prismatic basalt block from the 100 A.C. Roman revetment (LR39) at site De Balije II in Vleuten-De Meern (currently at the Mineralogisches Museum, Poppelsdorfer Schloss, Uni-Bonn).



b.

Petrology of Roman basalt blocks from Vleuten-De Meern

Macroscopic observations

The blocks from the revetment and the ships are several dm in diameter (Fig. 2). The largest block is hexagonal prismatic with a longest diameter of 42 cm and a height of 40 cm. Most of these blocks have a prismatic shape, indicating that they were quarried from columnar jointed rock, as is commonly seen in basalt. The blocks from the watchtower are generally smaller, measuring between $21 \times 17 \times 7.5$ and $8 \times 6.5 \times 6$ cm; three of these lumps can be recognized as fragments of columns by the presence of couples of flat boundary planes under obtuse angles (Laanbroek, 2004). Beneath a veneer of light grey clay, the freshly broken surface shows a dark grey, almost black, very

dense rock with little or no vesicles. The porphyritic-aphanitic rock contains up to some centimetres large phenocrysts of light green, forsteritic olivine and black pyroxene. Phenocrysts of feldspar have not been found. Fragments of peridotite as well as light-coloured, quartz-rich rock are common.

Microscopic petrography

Thin sections of thirteen samples from the revetment, six from ship De Meern 4, one from De Meern 1 and twelve from the watchtower were studied with a petrographic microscope. For

comparison, 85 thin sections of basalts from the Siebengebirge were included in this project.

The microscopy confirms that the rocks are fresh to slightly altered basalts. Olivine crystals in some samples show incipient serpentinization along cracks and iddingsite at rims, and groundmasses may contain minor celadonite and chlorite. These secondary minerals indicate reactions with hydrothermal solutions likely during cooling of the basalt soon after emplacement.

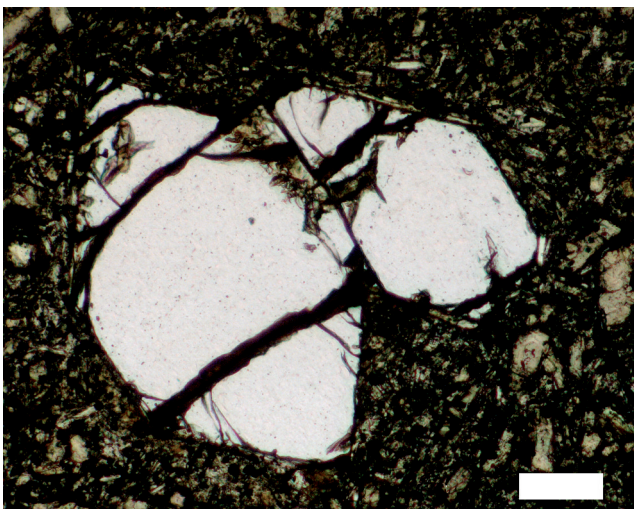
All rocks have a (micro-)porphyritic structure: scattered phenocrysts of euhedral olivine of 0.3 - 6 mm, mostly ca 1mm (Fig. 3a), and pyroxene, in the size range of mm to occasionally cm, stand out against a very fine to fine-grained matrix. The micro-phenocrysts (0.4 - 1.5 mm) of Ti-augite are oscillatory zoned, mostly with hourglass texture; the larger ones have corroded, usually green cores, which are interpreted as relictic clinopyroxene from the mantle (Figs 3b, c, d). Importantly, feldspar phenocrysts are absent. The groundmass consists of a very-fine fabric of intergrown clinopyroxene, plagioclase (0.05 - 0.25 mm) and magnetite, and in many cases olivine as well; there is little or no glass.

Commonly, mm to cm sized polycrystalline xenolithic rock-fragments and xenocrysts are enclosed in the matrix. These include fragments likely derived from the mantle and crustal material incorporated into the basalt magma during ascent. All samples contain olivine- and pyroxene-rich rock fragments, interpreted as mantle-derived peridotites *s.l.* (up to 6 mm; Fig. 3e). Other relicts from the mantle are: green clinopyroxene, contained as irregularly abraded cores inside the Ti-augite phenocrysts (Fig. 3d); rounded grains of brown-black (Cr-bearing) spinel; and some strongly corroded and strained crystals of olivine, which are commonly larger than the olivine phenocrysts.

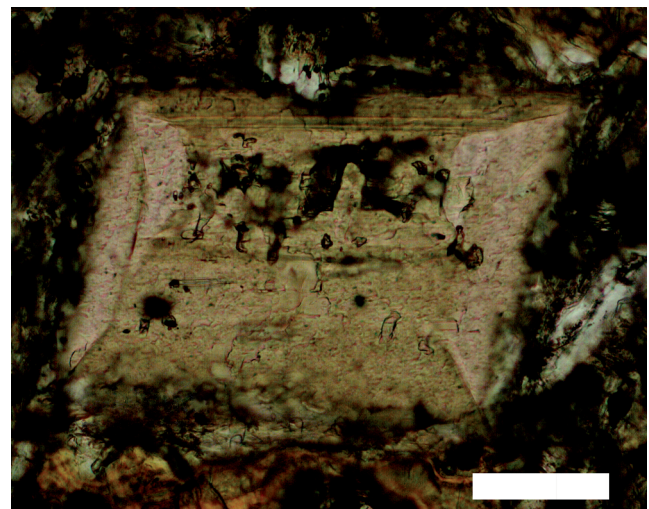
As xenocrysts derived from the continental crust, rounded grains of quartz, featuring characteristic reaction rims with fine-crystalline pyroxene prisms, are always present (Fig. 3f); plagioclase as single corroded crystals, usually ≤ 1 mm and only one to four per thin section, are common. Typically, the plagioclase xenocrysts show signs of resorption and narrow mantles of fresh plagioclase, grown during crystallisation of the matrix plagioclase (Fig. 3f, g). Although plagioclase xenocrysts come in very small numbers, they are found in all samples from the revetment, in all but one (DMN4-01) from the ships, and in nine of twelve samples from the watchtower. Notably, fifteen plagioclase xenocrysts were counted in sample DMN1-184.

Petrographical classification and nomenclature

In accordance with directions of the 'International Union of Geological Sciences' (IUGS), the fresh, glass-free volcanic rocks, in which the mineral mode can be readily determined, are properly qualified in the QAPF diagram (Le Maitre 1989). As cogenetic quartz (Q), alkali feldspar (A) and feldspatoids (F) are all absent, and cogenetic plagioclase (P) is confined to the matrix, these dark rocks are properly named basalt (not andesite). The additional petrographic features are in perfect accord with the extensive list of criteria for the qualification alkali olivine basalt (AOB). This justifies the notion that the rocks are critically undersaturated in silica, which predicts that nepheline (*ne*) will appear in the norm (Hughes, 1982; McBirney, 1985). As shown in Table 1, *ne* does occur in the norms of all but two samples; the exceptions are explained by low sodium contents due to incipient chemical alteration (see next section).



a.



b.

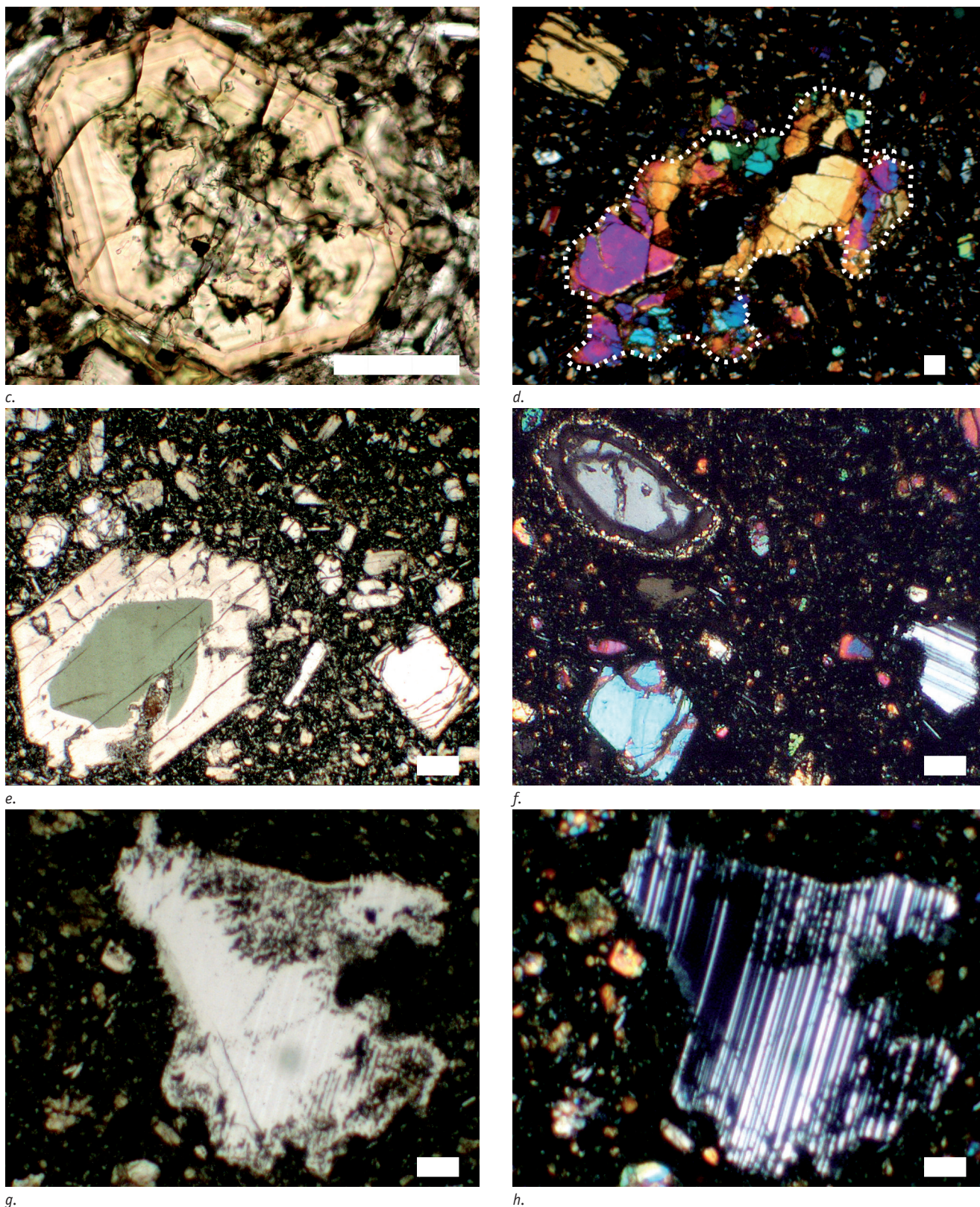


Fig 3. Microphotographs of thin sections of basalts from the revetment (LR39) and the ship De Meern 4 (DMN4); the white bars in the lower right of each picture are 100 μm . a. Two microphenocrysts of forsteritic olivine in synneusis (LR39-442; plane polarized); b. Ti-augite microphenocryst with hourglass texture (LR39-431; plane polarized); c. Ti-augite microphenocryst, oscillatory zoned (LR39-431; plane polarized); d. Peridotite xenolith (LR39-394; crossed nicols); e. Ti-augite phenocryst grown around a corroded fragment of mantle-derived pyroxene (LR39-372; plane polarized); f. Olivine, e.g., as phenocryst in the lower left, in co-occurrence with a quartz xenocryst (upper left), the latter featuring a reaction rim of polycrystalline pyroxene; at the lower right a plagioclase xenocryst (LR39-1540; crossed nicols); g. Embayed plagioclase xenocryst with signs of partial melting (LR39-330; plane polarized); h. Idem (crossed nicols).

Table 1. Chemical compositions of alkali olivine basalt blocks from Roman archaeological sites along the limes in Vleuten-De Meern (Utrecht);

	Revetment														Ships	
	LR39														DMN4	
	#307	#330	#359	#372	#394	#398	#431	#440	#442	#1540	#1560	#1580	#1650	range	#01	#03
Major and minor elements in wt.% of oxides																
SiO ₂	44.78	44.9	44.26	44.41	44.54	44.68	44.17	45.27	45.84	44.83	44.98	44.54	44.54	44.17 - 45.84	43.54	44.92
TiO ₂	2.24	2.22	2.26	2.29	2.18	2.28	2.26	2.21	2.23	2.24	2.18	2.23	2.30	2.18 - 2.30	2.76	2.20
Al ₂ O ₃	13.54	13.62	13.21	13.19	13.2	13.25	13.42	13.37	13.71	13.40	13.31	13.52	13.23	13.19 - 13.71	14.16	13.34
Fe ₂ O ₃	11.32	11.49	11.48	11.62	11.34	11.28	11.49	11.36	11.75	11.38	11.5	11.37	11.61	11.28 - 11.75	12.72	11.71
MnO	0.19	0.19	0.18	0.18	0.18	0.19	0.19	0.18	0.20	0.19	0.19	0.19	0.18	0.18 - 0.20	0.19	0.21
MgO	10.76	11.25	11.5	11.79	11.07	10.99	10.90	11.32	11.49	10.96	11.1	11.17	11.68	10.76 - 11.79	10.09	11.39
CaO	10.79	10.39	10.81	11.04	10.46	11.07	10.43	10.44	10.55	10.61	10.47	10.61	11.01	10.39 - 11.07	10.53	10.44
K ₂ O	1.46	1.47	0.9	1.36	1.41	0.86	1.64	1.3	1.46	1.49	1.47	1.43	1.40	0.86 - 1.64	1.50	0.92
Na ₂ O	3.14	2.99	3.34	3.08	3.15	3.36	2.78	3.08	3.05	3.02	3.06	3.24	2.89	2.78 - 3.36	2.69	3.17
P ₂ O ₅	0.52	0.51	0.51	0.50	0.51	0.54	0.52	0.51	0.50	0.51	0.50	0.52	0.50	0.50 - 0.54	0.53	0.51
SO ₃	0.09	0.12	0.28	0.01	0.07	0.07	0.09	0.07	0.02	0.01	0.11	0.29	0.18	0.01 - 0.29	0.01	0.01
Traces in ppm																
V	254	238	236	245	233	249	238	228	235	240	235	234	261	228 - 261	283	252
Cr	365	377	403	431	358	417	340	366	369	380	351	374	428	340 - 431	251	375
Ni	263	269	264	278	276	239	232	266	280	247	254	257	285	232 - 285	231	352
Cu	61	63	49	45	28	73	50	54	53	41	62	41	52	28 - 73	45	54
Zn	106	98	97	95	103	106	100	95	98	104	104	100	99	95 - 106	88	107
Ga	20	20	24	18	19	15	18	19	18	17	14	21	12	12 - 24	23	23
Rb	48	48	33	41	43	44	48	39	46	43	51	49	39	33 - 51	27	33
Sr	730	771	700	694	694	755	723	799	691	712	698	702	715	691 - 799	697	674
Y	29	28	22	29	19	28	30	27	23	24	18	24	26	18 - 30	27	23
Zr	242	242	228	222	221	243	235	240	228	234	234	236	217	217 - 243	183	215
Nb	83	81	80	80	81	80	84	80	82	82	77	81	76	76 - 84	68	79
Mo	7	8	5	4	11	5	6	11	2	8	4	5	3	2 - 11	2	2
Ba	617	629	574	600	625	619	647	561	648	582	591	605	617	561 - 648	595	628
La	59	95	62	75	57	59	43	28	67	40	73	58	74	28 - 95	34	67
Ce	83	117	107	95	91	112	96	76	109	99	98	74	92	74 - 117	62	57
Nd	33	51	47	43	57	49	44	31	35	40	38	32	44	31 - 57	41	28
Pb	3	14	3	3	17	3	7	18	5	3	16	15	3	3 - 18	3	6
L.O.I.	1.05	1.18	0.97	0.03	0.8	1.51	1.01	1.04	0.59	0.36	1.12	0.93	0.35	0.03 - 1.51	0.67	1.24
Total	100.22	100.68	100.04	99.83	99.21	100.4	99.21	100.48	101.73	99.32	100.31	100.41	100.21		99.65	100.33
CIPW norms² in vol. %																
Anorthite	21.6	23.8	23.7	19.1	21.4	23.9	22.9	24.5	23.5	22.2	22.7	21.3	21.9	19.1 - 24.5	25.5	26.4
Albite	5.3	6.1	3.6	4.3	5.2	3.4	6.5	5.5	5.9	5.6	5.8	5.2	5.0	3.4 - 6.5	6.60	4.21
Orthoclase	22.50	21.31	24.00	21.30	22.73	24.17	20.15	22.02	21.40	21.68	21.89	23.14	20.66	20.2 - 24.2	19.40	22.77
Nepheline	6.13	4.83	3.18	7.51	5.80	3.58	5.96	3.75	4.97	5.92	5.05	5.58	5.69	3.2 - 7.5	5.63	2.43
Leucite	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0 - 0.6	0.00	0.00
Diopside	21.98	19.92	20.88	23.41	21.57	22.13	20.92	20.37	20.41	21.73	21.14	20.88	22.48	19.9 - 23.4	19.21	19.63
Hypersthene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0 - 0.0	0.00	0.00
Olivine	16.29	17.83	18.09	17.69	17.23	16.68	17.24	17.75	17.89	16.82	17.31	17.32	17.78	16.3 - 18.1	16.69	18.51
Ilmenite	2.78	2.74	2.82	2.83	2.72	2.84	2.83	2.73	2.71	2.78	2.71	2.76	2.85	2.7 - 2.9	3.45	2.74
Magnetite	1.96	1.98	2.00	2.01	1.97	1.96	2.01	1.96	1.99	1.97	1.99	1.96	2.01	2.0 - 2.0	2.22	2.03
Apatite	1.17	1.14	1.15	1.13	1.14	1.21	1.19	1.14	1.10	1.14	1.12	1.14	1.13	1.1 - 1.2	1.19	1.15
Zircon	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.0 - 0.0	0.02	0.03
Chromite	0.04	0.05	0.05	0.05	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.05	0.0 - 0.1	0.04	0.04
Na ₂ SO ₄	0.18	0.24	0.59	0.02	0.14	0.14	0.18	0.14	0.04	0.02	0.22	0.60	0.36	0.0 - 0.6	0.02	0.02
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100 - 100	100	100
Mg# ³	70.18	70.80	71.27	71.53	70.74	70.70	70.14	71.16	70.77	70.46	70.50	70.87	71.36	70.14 - 71.53	66.27	70.66
CAI ⁴	34.25	35.23	33.90	33.44	34.23	33.59	34.99	34.77	35.03	34.44	34.47	34.39	33.79	33.44 - 35.23	36.33	34.95

1 Watchtower data after Laanbroek (2004)

2 Assuming Fe²⁺/Fe^{tot} = 0.8 for the whole rock following Middlemost (1989)

3 Mg# = [100·Mg/(Mg + 0.8 Fe^{tot})] (molal)

4 CAI = 100·[Al₂O₃ / (Al₂O₃+CaO*+Na₂O+K₂O)] (molal). CaO* as CaO^{tot} minus CaO^{apatite}

for site locations see Fig. 1.

De Meern 4 & De Meern 1						Watchtower ¹											
#18	#31	#32	#35	range ex. #01	#184	DMN1		VLEN3									range ex. #262
						#153	#154	#261	#262	#298	#310	#328	#353	#433	#552		
45.49	43.84	44.97	44.82	43.84 - 45.49	44.62	45.38	44.29	44.63	43.57	43.76	42.62	44.20	43.67	44.02	43.74	42.62 - 45.38	
2.19	2.15	2.19	2.24	2.15 - 2.24	2.14	2.60	2.63	2.53	2.77	2.72	2.62	2.58	2.70	2.67	2.65	2.53 - 2.72	
13.35	12.8	13.36	13.34	12.80 - 13.36	13.12	14.11	13.86	13.75	14.09	13.90	13.47	13.84	13.91	13.90	13.78	13.47 - 14.11	
11.46	11.42	11.74	11.63	11.42 - 11.74	11.20	11.78	11.92	11.56	12.96	12.26	11.95	11.65	12.21	12.16	12.18	11.56 - 12.26	
0.21	0.19	0.21	0.2	0.19 - 0.21	0.18	0.18	0.18	0.18	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18 - 0.18	
11.16	11.26	11.23	11.43	11.16 - 11.43	10.76	10.04	10.32	9.87	10.26	10.42	10.21	10.16	10.29	10.33	10.40	9.87 - 10.42	
10.44	10.98	10.43	10.75	10.43 - 10.98	10.87	10.13	10.34	9.86	11.14	10.80	10.40	10.04	10.62	10.62	10.54	9.86 - 10.80	
1.50	1.23	1.48	0.92	0.92 - 1.50	0.82	3.49	3.58	3.61	2.45	3.08	2.75	3.11	3.26	3.18	3.29	2.75 - 3.61	
2.38	1.71	2.82	3.13	1.71 - 3.17	2.25	0.90	0.91	0.74	0.85	1.41	1.95	1.41	1.16	1.17	1.12	0.74 - 1.95	
0.47	0.49	0.49	0.51	0.47 - 0.51	0.52	0.56	0.56	0.55	0.70	0.57	0.56	0.55	0.58	0.57	0.57	0.55 - 0.58	
0.01	0.01	0.01	0.01	0.01 - 0.01	0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
240	227	234	279	227 - 279	215	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
380	391	357	420	357 - 420	373	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
280	326	291	284	280 - 352	239	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
49	57	52	51	49 - 57	54	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
95	96	106	102	95 - 107	103	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
19	15	19	19	15 - 23	19	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
50	45	45	33	33 - 50	39	46	44	45	43	48	43	42	36	38	61	36 - 61	
723	938	712	690	674 - 938	890	976	1107	999	981	1209	935	877	862	948	1340	862 - 1340	
23	27	21	31	21 - 31	25	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
222	212	219	222	212 - 222	243	322	339	329	298	374	274	288	266	288	406	266 - 406	
74	76	83	78	74 - 83	82	102	112	105	96	123	89	94	87	93	129	87 - 129	
2	2	5	2	2 - 5	8	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
634	599	644	665	599 - 665	702	645	636	618	672	600	591	636	591	600	591	591 - 645	
86	38	58	72	38 - 86	68	67	71	68	61	76	56	60	55	58	82	55 - 82	
78	96	91	115	57 - 115	105	127	135	130	116	144	107	114	104	112	157	104 - 157	
55	54	32	51	28 - 55	52	56	59	57	52	64	48	50	47	50	70	47 - 70	
6	3	3	3	3 - 6	16	3	3	2	2	2	2	2	2	2	3	2 - 3	
1.56	2.96	0.84	1.19	0.84 - 2.96	2.43	1.24	1.24	1.12	1.42	0.95	0.66	1.16	1.17	1.19	0.86	0.66 - 1.24	
100.52	99.36	100.06	100.46		99.27	100.79	100.20	98.76	100.76	100.41	97.71	99.24	100.10	100.36	99.67		
29.7	34.3	24.2	25.7	24.22 - 34.26	33.4	26.61	23.31	26.39	32.03	21.42	18.75	24.06	22.59	23.57	22.47	18.75 - 26.61	
7.70	6.93	6.22	3.99	3.99 - 7.70	4.6	16.62	14.58	17.45	12.75	11.05	8.97	13.47	12.55	12.76	12.71	8.97 - 17.45	
17.07	12.75	20.25	22.45	12.75 - 22.77	16.60	6.46	6.62	5.40	6.11	10.18	14.33	10.26	8.41	8.47	8.13	5.40 - 14.33	
1.79	0.00	4.74	3.05	0.00 - 4.74	0.00	7.93	10.98	8.20	4.73	11.71	12.33	9.09	11.35	10.34	11.32	7.93 - 12.33	
0.00	0.00	0.00	0.00	0.00 - 0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00 - 0.00	
20.00	21.47	20.73	20.65	19.63 - 21.47	19.85	20.31	22.10	20.51	20.04	23.16	23.12	20.64	22.50	22.28	22.68	20.31 - 23.16	
0.00	0.34	0.00	0.00	0.00 - 0.34	6.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00 - 0.00	
17.88	18.18	17.88	18.14	17.88 - 18.51	13.51	15.53	15.71	15.53	16.94	15.62	15.69	15.89	15.73	15.78	15.89	15.53 - 15.89	
2.73	2.77	2.72	2.78	2.72 - 2.78	2.74	3.21	3.28	3.20	3.48	3.39	3.35	3.25	3.38	3.34	3.33	3.20 - 3.39	
1.99	2.05	2.04	2.01	1.99 - 2.05	2.00	2.03	2.08	2.03	2.28	2.13	2.13	2.04	2.13	2.12	2.13	2.03 - 2.13	
1.06	1.13	1.10	1.15	1.06 - 1.15	1.20	1.25	1.28	1.25	1.61	1.29	1.28	1.26	1.31	1.28	1.29	1.25 - 1.31	
0.03	0.03	0.03	0.03	0.03 - 0.03	0.03	0.04	0.05	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.05	0.04 - 0.05	
0.05	0.05	0.04	0.05	0.04 - 0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00 - 0.00	
0.02	0.02	0.02	0.02	0.02 - 0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00 - 0.00	
100	100	100	100	100 - 100	100	100	100	100	100	100	100	100	100	100	100		
70.69	70.94	70.32	70.88	70.32 - 70.94	70.41	67.85	68.20	67.88	66.21	67.78	67.90	68.34	67.61	67.77	67.89	67.61 - 68.34	
35.57	35.01	34.96	34.50	34.50 - 35.57	35.37	36.32	35.43	36.16	36.33	34.99	34.89	36.10	35.28	35.38	35.18	34.89 - 36.32	

n.a. = not analysed

Chemistry of the Roman basalt blocks from Vleuten-De Meern

Chemical analysis and presentation of data

Samples from the revetment and the ships were analysed by X-ray fluorescence for major and trace elements (V, Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Ba, La, Ce, Nd, and Pb). The existing geochemical data base from the Siebengebirge Volcanic Field (Vieten, 1987) was supplemented by seven additional samples. Measurements were carried out at the geochemical laboratory of the Steinmann Institut für Geologie, Mineralogie und Paläontologie at the University of Bonn (formerly: Mineralogisch-Petrologisches Institut) using a Philips-PW 1480 XRF spectrometer. Measurements of lithium borate glass fusion beads are based on calibrations using 84 international rock standards and application of internal standards for quality control. Relative precision (2σ) was generally better than 2% for the major oxides and better than 10% for trace elements. An existing collection of volcanic samples, thin sections and geochemical data of the Siebengebirge (sampled by Prof. em. K. Vieten) was used for comparison. These samples were analysed by XRF at the Mineralogisch-Petrologisches Institut of Bonn University during the late 1980s and early 1990s using the same equipment (Vieten, 1987). Major and trace elements of the watchtower samples were analysed by XRF and ICP-MS, respectively, at the Department of Petrology (VU University Amsterdam; Laanbroek, 2004).

The set of chemical data, including the CIPW norms, is given in Table 1. Data used in the compositional diagrams have been normalized to 100% on a volatile free basis.

Chemical alteration

Proper use of the TAS classification diagram, in which total alkalis are plotted vs. silica, requires that rocks are not altered and it is advised to apply TAS only to rocks with $H_2O^+ < 2$ and $CO_2 < 0.5$ wt.% (Le Maitre 1989). As shown in Fig. 4a, samples with elevated L.O.I. (>1.5 wt.%) – suggesting high water and/or CO_2 content, which for basalts are indicative of alteration – contain comparatively little Na_2O . Furthermore, this Na depletion is accompanied by enrichment in Sr (Fig. 4b), which is consistent with the results of previous studies which demonstrated that incipient subaerial weathering of AOB is associated with the loss of Na and gains in Sr (Bogaard et al., 2001). Therefore, we consider the high L.O.I. values and low Na_2O contents of samples DMN4-31 and DMN1-184 to be due to incipient alteration. Nevertheless, the low values for the

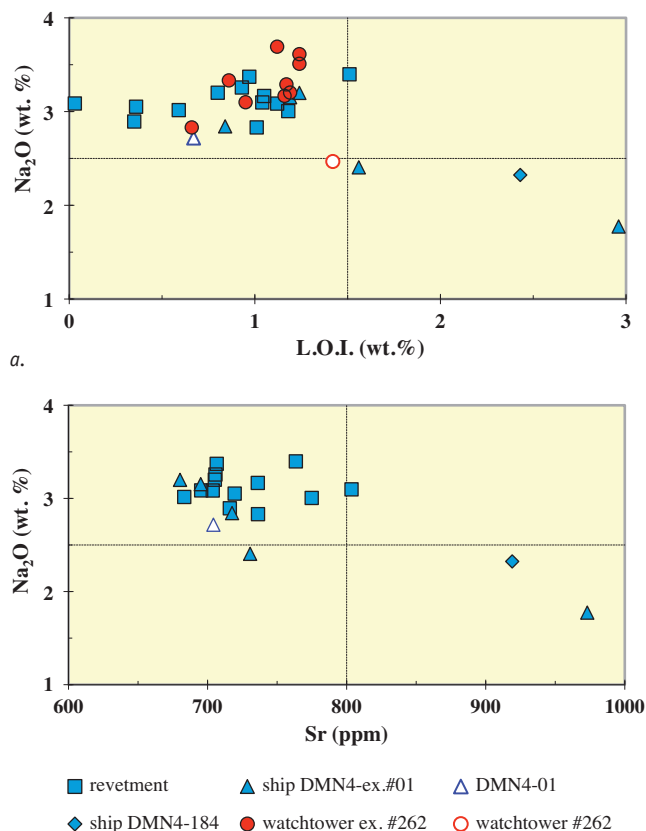


Fig. 4. a. Plots of L.O.I. versus Na_2O of basalt blocks along the limes near Vleuten-De Meern; b. Plots of Na_2O versus Sr; for watchtower blocks Sr not analysed.

chemical alteration index, as defined by Nesbitt & Young (1982), for all analysed samples ($CAI = 33.4 - 36.3$; Table 1) demonstrate that the rocks underwent only minor or no chemical modifications due to weathering (cf., Bogaard et al. 2001). Also, as will be shown in a later section, the incipient alteration in some samples, causing some loss of Na, did not significantly influence the proportions of other elements. Most analyses can therefore be considered to represent pristine compositions controlled by magmatic processes only.

IUGS classification and nomenclature

In the TAS-diagram, the IUGS classification diagram for volcanic rocks (Le Bas et al. 1986; Le Maitre 1989), all data from the revetment, ships and watchtower plot within a small domain straddling the basanite – basalt boundary (Fig. 5). For the samples with $SiO_2 < 45\%$ the name basanite is applicable because they have normative olivine $>10\%$ (Table 1). Thus, within the microscopically defined group of AOB, a basanitic subgroup can be recognized on chemical grounds.

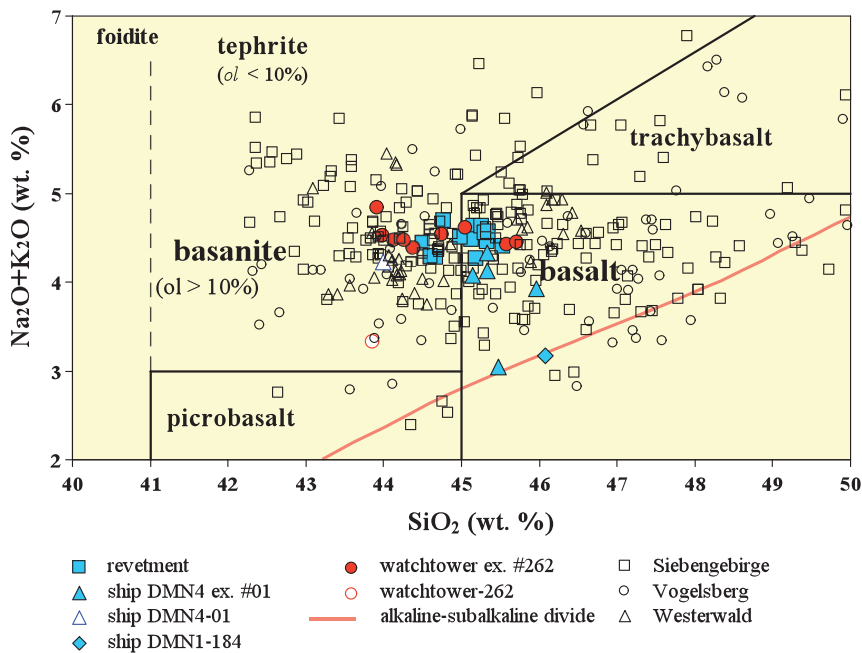


Fig. 5. Roman basalt blocks from Vleuten-De Meern and basalts from German Tertiary fields in the TAS classification diagram for volcanic rocks after Le Bas et al. 1986. Siebengebirge data after Vieten (1987); Westerwald data after Haase et al. (2004); and Volgelsberg data after Bogaard & Wörner (2003). The alkaline-subalkaline divide is after Irvine & Baragar (1971).

Not counting the two samples with relatively low total alkali due to sodium loss, the rocks plot well above the divide between the alkaline and subalkaline geochemical suites (Fig. 5). This corroborates the notion, already made on the basis of microscopic petrography, that the rocks have an alkaline composition. The SiO₂-undersaturated nature of the rocks is confirmed by the mineral norms as calculated from the chemical compositions using the CIPW procedures: *ne* features in all but the Na-leached samples DMN1-184 and DMN4-31 (Table 1).

Origin of the magmas and tectonic-igneous association

The low SiO₂ content (44 to 46 wt.%) coupled with high concentrations of compatible elements, such as Mg (10.8 to 11.8 wt.% MgO), Ti (2.2 to 2.8 wt.% TiO₂), Ni (233 to 355 ppm, not analysed for watchtower samples), and Sr (>680 ppm), indicates that the samples represent primitive mafic melts (Table 1). Such melts form directly by partial melting from the mantle source with minor or insignificant chemical differentiation (Winter, 2001). AOB containing xenoliths from the continental crust are produced in a continental intra-plate tectonic environment (Winter, 2001). This notion is corroborated by the abundances of certain trace elements, normalized to the primitive mantle composition after Sun & McDonough (1989): Apart from a relative depletion of P and a deep trough for K, the spidergram (Fig. 6) shows a regular increase of the normalized concentrations with increasing incompatibility, culminating in strong enrichment of moderately and highly incompatible elements, which is typical for intra-plate alkaline basalts

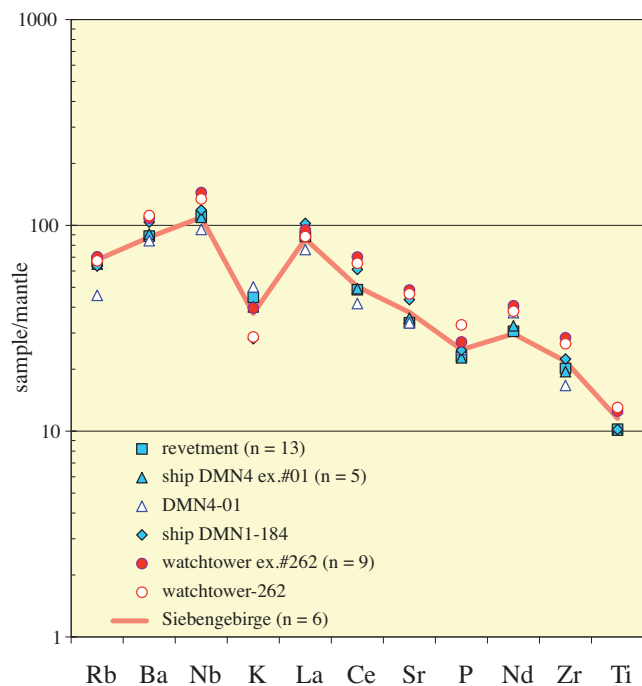


Fig. 6. Spidergram: trace element abundances in Roman basalt blocks from Vleuten-De Meern, normalized against the primitive mantle composition after Sun & McDonough (1989). Watchtower data after Laanbroek (2004). The spidergram for Siebengebirge basalts (analysed with the same equipment) is given for reference.

(Winter 2001; cf. Bogaard & Wörner 2003). Plots in the La/10 - Y/15 - Nb/8 discrimination diagram for basalts indicate a continental (rift) origin (Fig. 7; after Cabanic & Lecolle, 1989). Note the strong correlation, in both diagrams, between the Roman blocks and alkali basalts from the Siebengebirge, a typical example of a volcanic field in a continental rift setting.

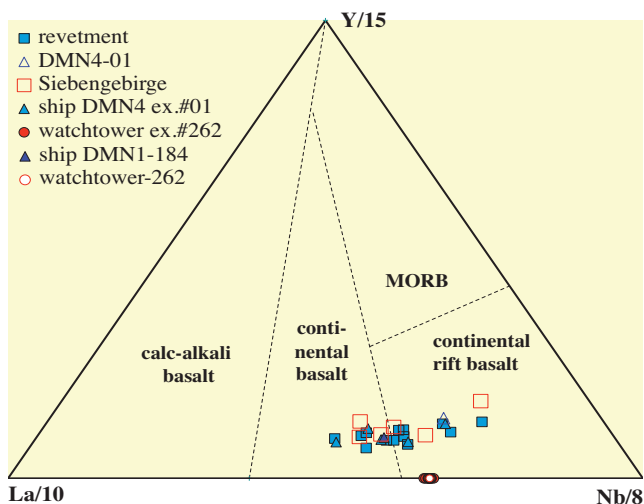


Fig. 7. Roman basalt blocks in the discrimination diagram for basalts after Cabanic & Lecolle 1989. Note that the watchtower samples were not analysed for Y.

⁴⁰Ar/³⁹Ar age determinations

Methods

Two samples from the revetment, one from ship De Meern 4 and two from potential quarry sites in the Siebengebirge Volcanic Field were selected for ⁴⁰Ar/³⁹Ar dating (cf. Summary Table 2; for full data the reader is referred to the electronic supplement). The results were calculated using the decay constant and abundance for 40K recommended by Steiger and Jäger (1977). The flux monitor used in this study is DRA-1 with an age of 25.26 Ma, modified from Wijbrans et al. (1995) to the consistent set of standards recommended by Renne et al. (1998).

⁴⁰Ar/³⁹Ar incremental heating experiments were carried out in the geochronology laboratory at the VU University, Amsterdam. The groundmass samples were crushed and sieved.

Sieve fractions were washed and ultrasonically cleaned to remove surface intergrowths. The 250 - 500 µm fraction was used for dating. For each sample ca 100 mg was packed in 9 mm diameter Al-foil packages and stacked with packages containing DRA-1 mineral standard into a 10 mm OD quartz tube. The quartz vial was packaged in a standard Al-irradiation capsule and irradiated for 24 hours in a Cd-lined rotating facility (RODEO) at the NRG-Petten HFR facility in the Netherlands. Upon return to the laboratory the groundmass samples were spread out evenly in 6 mm diameter depressions in a Cu-sample tray, and placed in a UHV vacuum house. Samples were incrementally heated by increasing laser power every step using a continuous wave CO₂ laser (Synrad 48-5, 25 W+ 25 W dual plasma tube instrument, 10.6 micrometer wave length). The sample house was fitted with a 49 mm diameter ZnS double vacuum UHV window. Positioning of the laser beam was achieved using an analogue Raylease scanhead fitted with a dual mirror system for X-axis and Y-axis adjustment and a ZnS 300 mm focussing lens. The beam delivery system achieved a beam diameter of ca 300 micrometer at the focal point. The laser power was increased for each next heating step between 0.5 and 30% of the full 50W of laser power. Complete and even heating of the grains was achieved by using a computer controlled motor stage that moved the sample in 4 circles with increasing radius. The scan head was used to diffuse the laser beam by applying a 200 Hz triangular current to the Y-mirror causing a rectangular laser beam pattern with a width of 3 mm. For the groundmass we loaded ca. 20 - 30 mg in each position. System blanks and air aliquots were measured before during and after each run. System blanks were found to be stable and predictable during the runs. Sample to blank ratios for the ⁴⁰Ar ion-beam were systematically well in excess of 100 for the larger and older age steps.

Table 2. Summary of results of Ar-Ar investigations on alkali olivine basalts: three blocks from Roman archaeological sites along the limes in Vleuten-De Meern (LR39-372; LR39-1650; DMN4-35) and two samples from the Siebengebirge (194A; 104HP).

Sample identification	Age ± 2σ (Ma)	MSWD	³⁹ Ar(k) (%),n	K/Ca ± 2σ	⁴⁰ Ar(a)/ ³⁶ Ar(a) ± 2σ	Age ± 2σ (Ma)	MSWD
VU65-C10	± 0.61	1.80			± 4.0457	± 0.80	
basalt 194/A	29.89 ± 2.02%	14	84.56	0.087 ± 0.036	301.8173 ± 1.34%	28.88 ± 2.77%	1.06
VU65-C11	± 0.52	1.71			± 4.6264	± 0.86	
basalt DMN4 35	28.47 ± 1.83%	14	85.95	0.098 ± 0.049	298.5240 ± 1.55%	28.02 ± 3.07%	1.61
VU65-C12	± 0.56	1.95			± 7.3564	± 1.11	
basalt 104HP	27.39 ± 2.04%	14	94.43	0.022 ± 0.013	307.1463 ± 2.40%	25.77 ± 4.30%	1.11
VU65-C13	± 0.41	1.81			± 6.6057	± 0.92	
basalt LR39/372	28.03 ± 1.45%	15	86.48	0.100 ± 0.044	297.2773 ± 2.22%	27.82 ± 3.29%	1.91
VU65-C14	± 0.23	1.50			± 4.4613	± 0.40	
basalt LR39/1650	26.25 ± 0.88%	16	78.87	0.266 ± 0.084	299.4111 ± 1.49%	25.96 ± 1.54%	1.31

Results

All five $^{40}\text{Ar}/^{39}\text{Ar}$ experiments show common features: excellent plateaux in the age spectrum diagrams, and steadily decreasing K/Ca ratios when proceeding from the low temperature to the high temperature steps in the experiments. Such decreasing K/Ca ratios are commonly observed in basalt groundmass experiments and indicate that in the polycrystalline fragments the K-bearing components degas more readily than the Ca-bearing components. The summed K/Ca ratios range from 0.2 to 0.02, probably reflecting a range in K-contents in these basalts. The groundmass experiments with the highest K/Ca ratio yielded the lowest analytical uncertainties and that with the lowest K/Ca ratio (#194A) yielded the highest analytical uncertainty, reflecting the effect of K-content on the analytical uncertainties. When analysing polycrystalline groundmass samples, compositional effects may cause slight recoil artifacts that can be observed in lowered ages in the final fusion steps and slightly elevated ages in the initial low temperature steps (cf. Koppers et al., 2000, for a detailed discussion of this effect). The plateaux, however, are defined using the mean square weighted average (MSWD) over the plateau as diagnostic for argon derived from a single homogeneous source (MSWD <2.0). Preservation of plateaux in basalt groundmass dating experiments depends on the degree of alteration and the glass content. In these samples, the alteration is minor and volcanic glass is absent. The plateaux range from 78.9% to 94.4% of the total gas release and are based on 14 to 16 individual steps. This satisfies all criteria commonly used for data quality control.

When regressed in terms of isotopic composition (only using the steps representing the plateau), three samples (LR39-372, LR39-1650, and DMN4-35) showed non-radiogenic intercepts in the $^{39}\text{Ar}/^{40}\text{Ar} - ^{36}\text{Ar}/^{40}\text{Ar}$ space that are very near to the $^{36}\text{Ar}/^{40}\text{Ar}$ of atmospheric argon. Hence, the isochron ages for these three samples are indistinguishable from the plateau ages. Two experiments, #194A (Erpeler Ley) and #104HP (Godesburg), showed slightly elevated non-radiogenic intercepts that may point to a small proportion of inherited (magma chamber) ^{40}Ar in the magma at the time of eruption. The isochron ages therefore are slightly lower than, but at 2-sigma level still overlapping with the plateau ages. Under these conditions we prefer to quote the plateau ages as representing the age of eruption of the lavas.

Discussion

Geochemical subdivision of the Roman AOB blocks

Notwithstanding strong resemblances in texture and mineralogy of the AOB blocks, clear distinctions can be made on the basis of their chemistry. The geochemical data of the revetment, ships De Meern 4 and De Meern 1, and watchtower are presented in Table 1. Ranges in composition for the individual sites are given as well; from these, however, samples DMN4-01 and VLEN3-262 are excluded because of their exceptional compositions, as discussed below. Not counting these outliers, the contents of most major elements and traces in each of the three groups of samples (revetment, ship De Meern 4 and watchtower) vary within narrow limits.

A selection of bivariate diagrams (Fig. 8) show particular features in the abundances of major and trace elements:

- Limited spreads for the groups of samples from revetment, ship De Meern 4 and watchtower, respectively.
- Substantial overlaps of spreads for samples from revetment and ship De Meern 4.
- Sample DMN1-184, despite of sodium loss apparent in the TAS diagram, does conform to the behaviour of the other elements in the revetment-De Meern 4 group.
- Marked gaps between ranges for the watchtower group and those of the combined revetment-De Meern 4-De Meern 1 group.
- Exceptional chemical compositions of samples DMN4-01 and VLEN3-262, each in its own way. Since the respective analyses show good to acceptable totals (99.65; 100.76 wt.%), and low L.O.I. values (0.67; 1.42 wt.%), these deviating compositions are neither due to poor analytical quality nor to chemical alteration. Note that the petrography of DMN4-01 is also exceptional since plagioclase xenocrysts are lacking.

From these observations we infer that:

1. Samples from revetment and the ships, De Meern 4 (excl. DMN4-01) and De Meern 1, form one coherent group of 19 chemically very similar AOB, which hence will be designated as the revetment-ships group.
2. The watchtower group is chemically different from the revetment-ships group.
3. Samples DMN4-01 and VLEN3-262 are genuinely distinct solitaries, outlying from the two defined multi-sample groups.

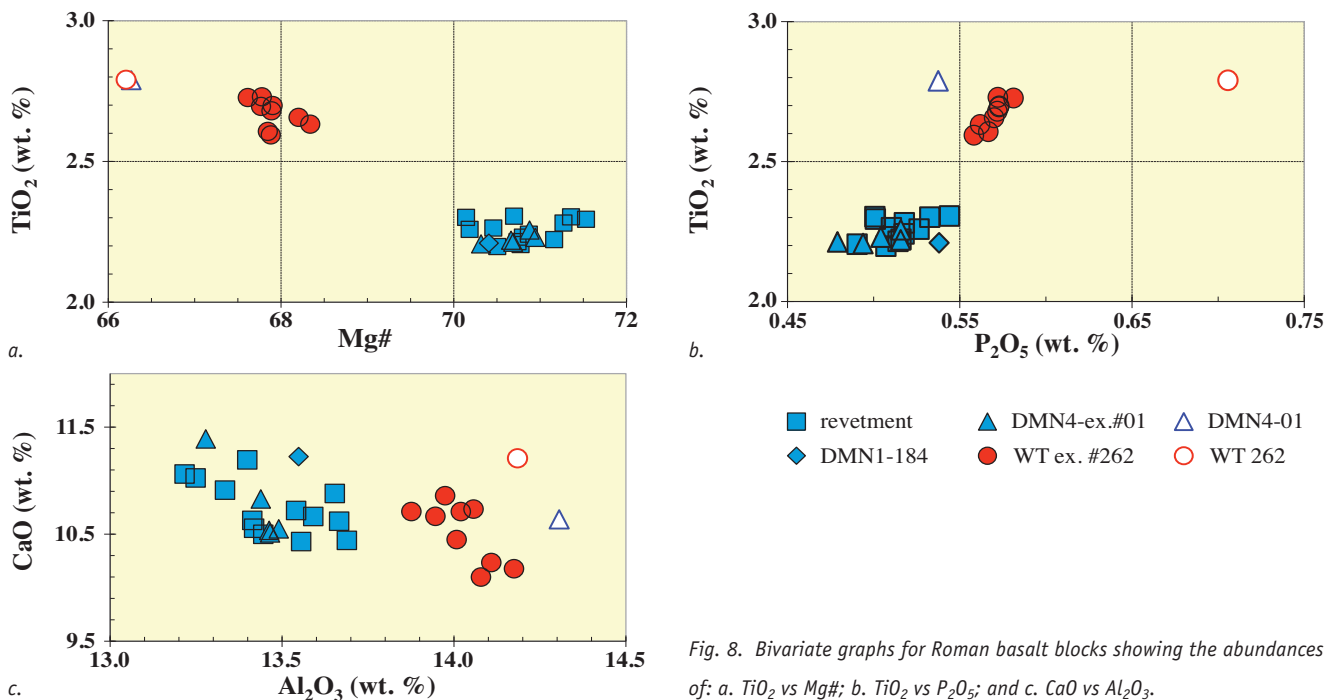


Fig. 8. Bivariate graphs for Roman basalt blocks showing the abundances of: a. TiO_2 vs $Mg\#$; b. TiO_2 vs P_2O_5 ; and c. CaO vs Al_2O_3 .

Quest for the sources of the Roman blocks

Regional scale considerations

Continental intra-plate volcanism, which produces predominantly alkali basalts, ranging from olivine nephelinite to alkali olivine basalt, is common in the Cenozoic Central European volcanic province (CEVP; Wedepohl & Baumann, 1999). The volcanic areas form a broad semi-circle around the Alpine chain, from East France over Germany, Hungary and the Czech Republic to Poland. Most appropriate as a source area for the Roman basalts in the Netherlands is the German part of the CEVP, since this is traversed by the *limes* as it existed in the Trajanian era, 98 - 117 AD, when the revetment and ship De Meern 4 were built (Fig. 9). The 50 km wide belt, extending about 350 km from west to east, comprises several areas with abundant alkali basaltic rocks: West and East Eifel; Hocheifel; Siebengebirge; Westerwald; Vogelsberg; Hessian Depression; and Rhön (Lippolt 1983; inset Fig. 9). Volcanic activity in these fields took place in overlapping periods during the Tertiary, from about 45 to 5 Ma, with a late phase in the East and West Eifel during the Quaternary. The areas are closely related genetically, with basanites and AOB as dominant rock types in most of them (Wedepohl et al., 1994). As shown in the TAS diagram (Fig. 5), data from German volcanic fields are substantially overlapping those from the Roman blocks. Therefore, if we want to narrow in on the source areas for the Roman basalts, and possibly locate their quarry sites, a multi-element discrimination approach must be applied.

Petrographic considerations

Microscopic petrography is of limited use for discrimination of source areas since the mineral content of the alkali basalts of most Tertiary German areas is similar to those described for the blocks. However, the petrographies of basaltic rocks from the Quaternary and Tertiary Eifel fields are characterized by the presence of one or more of the minerals amphibole, biotite, K-feldspar, nepheline, leucite and members of the sodalite group (Schmincke et al., 1983; Mertes & Schmincke, 1985; Huckenholz, 1983; Huckenholz & Büchel, 1988). Considering that none of those minerals have been found in the Roman blocks, the Eifel is a very unlikely source area. Kars et al. (2001) came to the same conclusion on the basis of a microscopic petrography of basalt lumps from other sites along the *limes*. These sites, marked 'II' in Fig. 1, expose a road, a bridge (100 AD) and a settlement (120 - 180 AD; E. Graafstal, pers. comm., 2007).

Geochemical considerations

The variability in chemical compositions of the CEVP is well documented (Bogaard & Wörner, 2003; Ehrenberg & Hicketier, 1994; Haase et al., 2004; Huckenholz & Büchel, 1988; Mertes & Schmincke, 1985; Schmincke et al., 1983; Vieten et al., 1988; Wedepohl, 1983). Hence, a search for the potential source of the Roman blocks can be based on chemical characteristics. For that purpose, we used an iteration of criteria that are based on the spreads in abundances of SiO_2 , $Na_2O + K_2O$, TiO_2 , Al_2O_3 , CaO , P_2O_5 , and the Mg number [$Mg\# = 100 \cdot Mg / (Mg + 0.8Fe^{tot})$ molar],

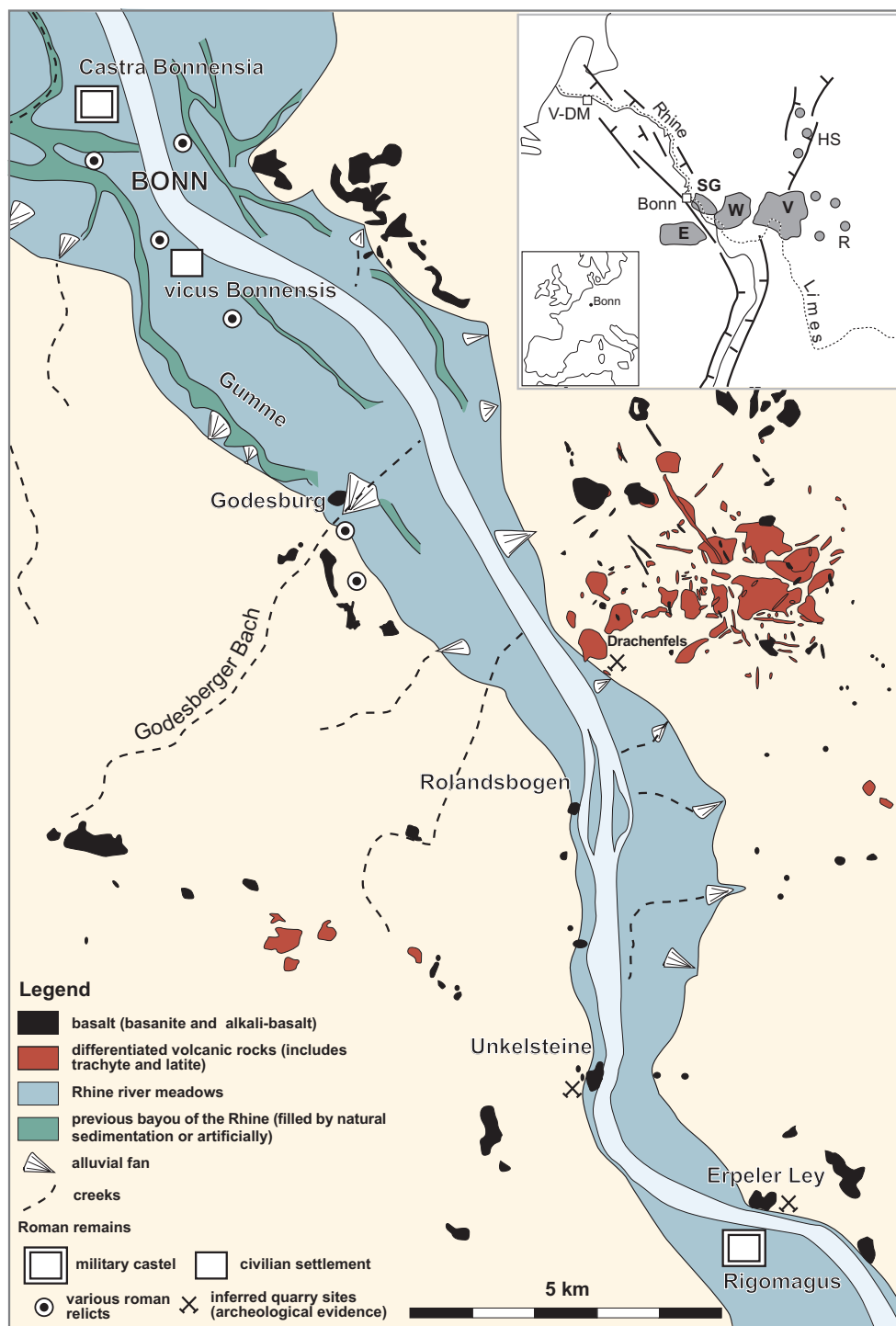


Fig. 9. Geological situation of the area south of Bonn (Germany). The river Rhine has eroded into the Devonian basement (off-white areas) generating a steeply terraced topography and extensive river meadows. Within the limits of the City of Bonn (stretching from north of 'Castra Bonnensia' to south of the Godesburg) there are abundant remnants of old river branches, now filled and integrated in the city's infrastructure. One of these old waterways is referred to as 'Gumme' and may have played a role in recovering basalt potentially quarried at the Godesburg site. The Siebengebirge Volcanic Field (SG on the inset) consists of a central part to the east of the Drachenfels where abundant differentiated (SiO_2 -rich) volcanic rocks are present and an outer zone with basaltic volcanic rocks. Note that the SVF extends further to the NW, W, and SW than shown in this figure. Distribution of Tertiary volcanic rocks from geological map sheets (1 : 25,000); geomorphology and location of 'Gumme' and other old waterways after Grunert (1988). Evidence for Roman quarrying at the Drachenfels trachyte includes written evidence (engravings) and actual traces of rock breaking activity still preserved today (Röder, 1974). Volcanic fields of the Cenozoic European Volcanic Province shown in the inset: the Eifel (E); the Siebengebirge (SG); the Westerwald (W); the Vogelsberg (V); Rhön (R); and the northern Hessian Depression (HS).

as analysed for the respective groups and outliers. Since the basalts represent primitive melts, and it has been shown that Mg-Fe ratios of such liquids change markedly in the early stages of crystallization (Oskarsson et al., 1982; Wilkinson, 1982), we let the proportions of Mg and Fe be presented by their ratio, the Mg#. The selected criteria are extended by 4% relative, to allow for analytical error, i.e., 2% for the analyses of the blocks plus 2% for those of the volcanic field samples. For our study we used 433 modern analyses of basaltic rocks with SiO₂ <50 wt.% (data normalized to 100% volatile free) from eight German CEVP fields. The results summarized in Table 3 show that the three Eifel sub-areas, Rhön and Hessen do not yield any matches. Chemical matches for the revetment-ships group are found in samples from the Siebengebirge (7×) and the Vogelsberg (7×); for the watchtower group in samples from the Siebengebirge (4×) and the Westerwald (1×); for outlier DMN4-01 in the Siebengebirge (2×); and for outlier VLEN3-262 no match at all. A graphical approach of a three-step check towards matching archaeological samples to potential source areas is presented in Figure 10.

Age constraints applied to the compositionally selected areas

For basanites and alkali basalts from the Siebengebirge Volcanic Field (SVF) nine K-Ar ages between 20 ± 1 and 26 ± 2 Ma and one of 27.5 ± 5.5 Ma were published thus far (Todt & Lippolt, 1980).

Our ⁴⁰Ar/³⁹Ar ages of 27.39 ± 0.56 and 29.89 ± 0.61 Ma for two AOB from the Siebengebirge (Table 2), indicate that a substantial portion of SVF volcanism may have erupted earlier than previously thought. The ⁴⁰Ar/³⁹Ar ages for the three AOB samples from Vleuten-De Meern, between 26.25 ± 0.23 Ma and 28.47 ± 0.52 (Table 2), are in excellent agreement with these new, relatively high SVF ages.

The established ages fall in a period of less intensive subsidence along the Rhine Graben rift system, from 31 to 25 Ma, which followed a phase of maximum subsidence, from 42 - 31 Ma (Ziegler 1992). This correlation in time suggests a strong regional tectonic control of the AOB production in the Siebengebirge.

The main phase of volcanism in the Vogelsberg area started about 18 Ma ago and peaked between 16 and 17 Ma (Bogaard & Wörner 2003, and references therein). Clearly, although the Vogelsberg has produced AOB of matching chemistry, the roughly 10 Ma younger age of its volcanism disqualifies that field as a source area for the Roman blocks in Vleuten-De Meern.

A major phase of AOB production in the Westerwald was from 30 to 17 Ma (Lippolt 1983), which period comprises the time span found for the Roman blocks. However, the one

Table 3. Basalts from German areas within the CEVP checked against criteria¹ set by basalt blocks used by the Romans along the limes near Vleuten-De Meern

	Revetment & ships (excl. DMN4-01)				Watchtower ² (excl. VLEN3-262)				DMN4-01				VLEN3-262 ²													
	Si	Na+K	Ti	Al	Mg# ³	Ca	P	Si	Na+K	Ti	Al	Mg# ³	Ca	P	Si	Na+K	Ti	Al	Mg# ³	Ca	P	Si	Na+K	Ti	Al	
	42.72	2.93	2.11	12.69	67.34	10.01	0.46	42.16	4.20	2.49	13.32	64.91	9.69	0.53	42.23	4.06	2.68	13.73	63.61	10.21	0.52	42.11	3.19	2.68	13.62	
n ⁴	47.92	4.88	2.40	14.24	74.39	11.85	0.57	47.55	5.03	2.84	14.74	71.07	11.30	0.61	45.75	4.40	2.90	14.88	68.92	11.06	0.56	45.62	3.45	2.90	14.75	
Total	432 Iterative accounts of matches⁵																									
East Eifel ^a	2	2	0					2	0						2	0										
Rhön ^b	28	10	6	0				9	1	0					9	2	0									
West Eifel ^c	11	1	1	0				2	2	0					4	0										
Hocheifel ^d	13	8	6	1	0			8	3	2	0				5	1	0									
Hessen ^e	50	27	10	9	4	2		23	8	2	0				7	1	0									
Westerwald ^f	35	30	25	7	0			29	9	9	5	3	1	1	23	7	2	0								
Vogelsberg ^g	99	68	45	22	21	13		70	20	7	1	0			41	6	0									
Siebengebirge ^h	194	167	121	69	44	17		168	86	23	20	15	10	4	120	29	3	3	3	2	2	2	2	113	3	0

1 Between 96 and 104% of ranges in wt. % of oxides of listed elements, normalized to 100% dry
 2 Laanbroek, 2004
 3 Mg# = 100MgO/(MgO + 0.8FeO^{tot}) molal
 4 Number of analyses with SiO₂ <50 wt. %
 5 Number of matches found for the samples of preceding column
 a Schmincke et al., 1983 (Table 1)
 b Ehrenberg & Hückethier, 1994 (Tables 6, 7, 8, 10)
 c Mertes & Schmincke, 1985 (Table 2)
 d Hückenholz & Büchel, 1988 (Table 5)
 e Wedepohl, 1983 (Tables 6, 7, 8)
 f Haase et al., 2005 (supplementary data, J. Petrol. on line)
 g Bogaard & Wörner, 2003 (supplementary data, J. Petrol. on line)
 h Vieten et al., 1987, available at Mineralogisch-Petrologisches Institut, Uni-Bonn

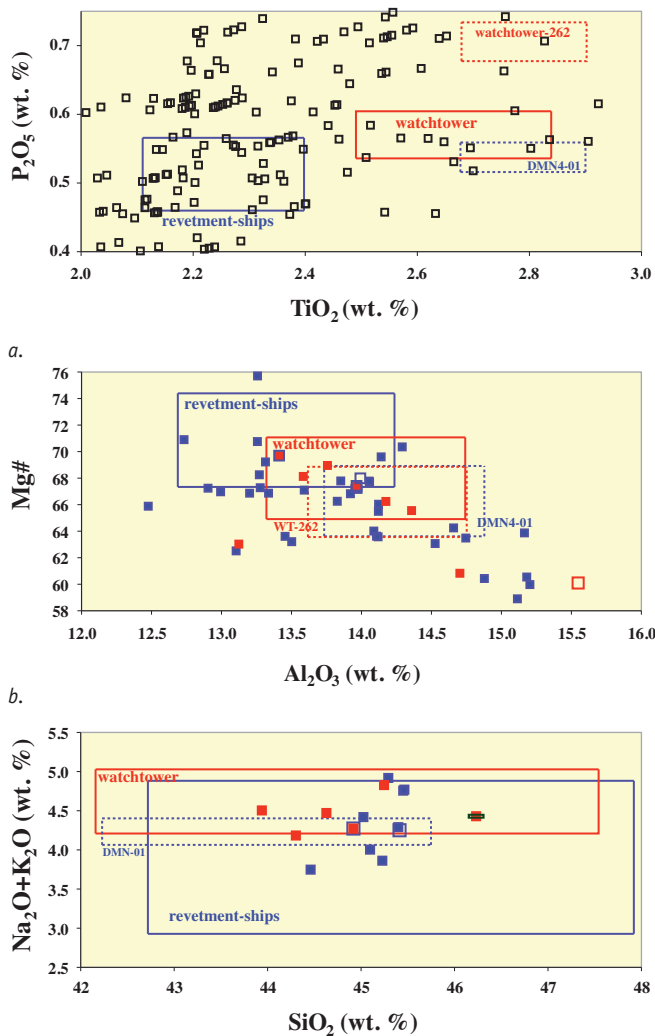


Fig. 10. Three-step graphical search for matches between chemical compositions of basalt samples from the Siebengebirge volcanic field (SG in Fig. 9; Vieten, 1987). The acceptance windows are based on the compositional ranges found in basalts used by the Romans in the Netherlands, taking analytical error into account (see text): for the revetment-ships group windows are in drawn blue lines; for outlier DMN4-01 in stippled blue lines; for the watchtower group in drawn red lines; and for outlier VLEN3-262 in stippled red lines. a. The first step takes place in the P_2O_5 - TiO_2 space, which is highly discriminative; only two windows show some overlap with only two Siebegebirge samples in it; b. Samples selected by the respective windows in (a) are plotted in the $Mg\#$ - Al_2O_3 space, using filled symbols for matches with the two groups and open symbols for the two outliers, each in the appropriate colour; c. Most of the samples that were accepted in (b) are accepted here as well. Only one filled blue and one filled red symbol are just outside their windows for having slightly high and low total alkali contents, respectively. Note that the red symbol with the bar is disqualified for having a low CaO content. As also indicated in Table 4, there are seven full matches for the revetment-ships group; four for the watchtower group; two for outlier DMN4-01; and none for outlier VLEN3-262.

chemical match in the Westerwald (# 041-1(W); Haase et al. 2004, Suppl. data) hails from 60 km E of the *limes*, far inside Alemania Libera. This far outlying position disqualifies the site as a source for Roman blocks for reasons of safety and logistics (see further).

Consequently, only the SVF remains as a likely source area for the provenance of the Roman basalts used in Vleuten-De Meern.

The local source problem – how to select likely quarry sites in the Siebengebirge Volcanic Field

From the geological point of view

Geochemistry

As shown in Table 3 and Fig. 10, seven SVF basalts satisfy the criteria for the revetment-ships group; four specimens match the watchtower group; and two samples match outlier DMN4-01. With the exception of one remote place, the sampling sites of the chemical matches are concentrated in an elongated zone of about 6 km \times 20 km, marking the NW-SE strike of the Lower Rhine embayment, parallel to the local graben structure (Fig. 11).

Petrography

Microscopy of 87 thin sections from 43 localities, largely inside the elongated zone, reveals that the AOB feature the same porphyritic texture and phenocrystic minerals as recognized in the Roman blocks. However, plagioclase xenocrysts, that are found in all thin sections of the revetment blocks, in all but one of those from the ships and in nine of twelve from the watchtower, are rare and of local occurrence in the SVF. Plagioclase xenocrysts were found in only six sites of AOB (and three sites of trachybasalt); together, these occurrences confine a limited field in the middle of the elongated zone (Fig. 11).

Is finding sources using compositional criteria biased by sampling density?

Just two samples, #104HP and #207HP, fully match the chemical criteria set by the revetment-ships group and contain plagioclase xenocrysts as well (Table 4). From a strictly geological point of view, this would make the Godesburg and the Rolandsbogen prime candidates as sites of provenance for the blocks from the revetment and the ships, and the Erpeler Ley for the outlying ship's sample DMN4-01. This would leave the source of the watchtower blocks still elusive. Indeed, if the presence of plagioclase xenocrysts should be taken as a *sine qua non*, further refinement of the selection of likely sources for the watchtower blocks on geological grounds alone would

not be possible. On the other hand, recognizing the very subordinate quantity of the plagioclase xenocrysts, it may well be that the criterion is missed in the thin section. If therefore the sine qua non aspect is waved, the Erpeler Ley can be considered the likely source of the chemically matching watchtower group, even if not all thin sections of watchtower blocks contain this xenocryst.

Although Vieten's (1987) data set of analyses covers the SVF extensively, it is also very disperse, with often just one sample per volcanic body. As shown by three samples from the Erpeler Ley, with several tens to a few hundreds of meters between them (for coordinates, see Table 4), one volcanic body may show significant chemical variation. Each of the three analyses matches a different group of Roman blocks. Similarly, of the two Godesburg samples, taken 60 m apart, one matches the revetment-ships group and the other one matches none at all (Table 4). Note that five chemical matches had been missed if

our own samples – #194A, #194B, #104HP and #114.1A.KL – had not been added to the SVF reference set (Table 4). Clearly, a higher density of sampling in the Siebengebirge will improve the overall results. Also, a denser sampling may give a better insight in the distribution of the crucial plagioclase xenocrysts.

From the perspective of Roman logistics

Position with respect to the *limes* and distance from the Rhine

It seems quite reasonable to contend that the Romans preferred to quarry their basalt blocks inside the *limes* and possibly closest to a navigable waterway, *casu quo* the Rhine.

In this region, three large basalt bodies are exposed at the immediate borders of the Rhine: *viz.*, Rolandsbogen, Unkelsteine and Erpeler Ley (Fig. 9). Interestingly, Roman quarrying activities at the Unkelsteine and Erpeler Ley have been inferred by interpretation of archaeological documents (Horn,

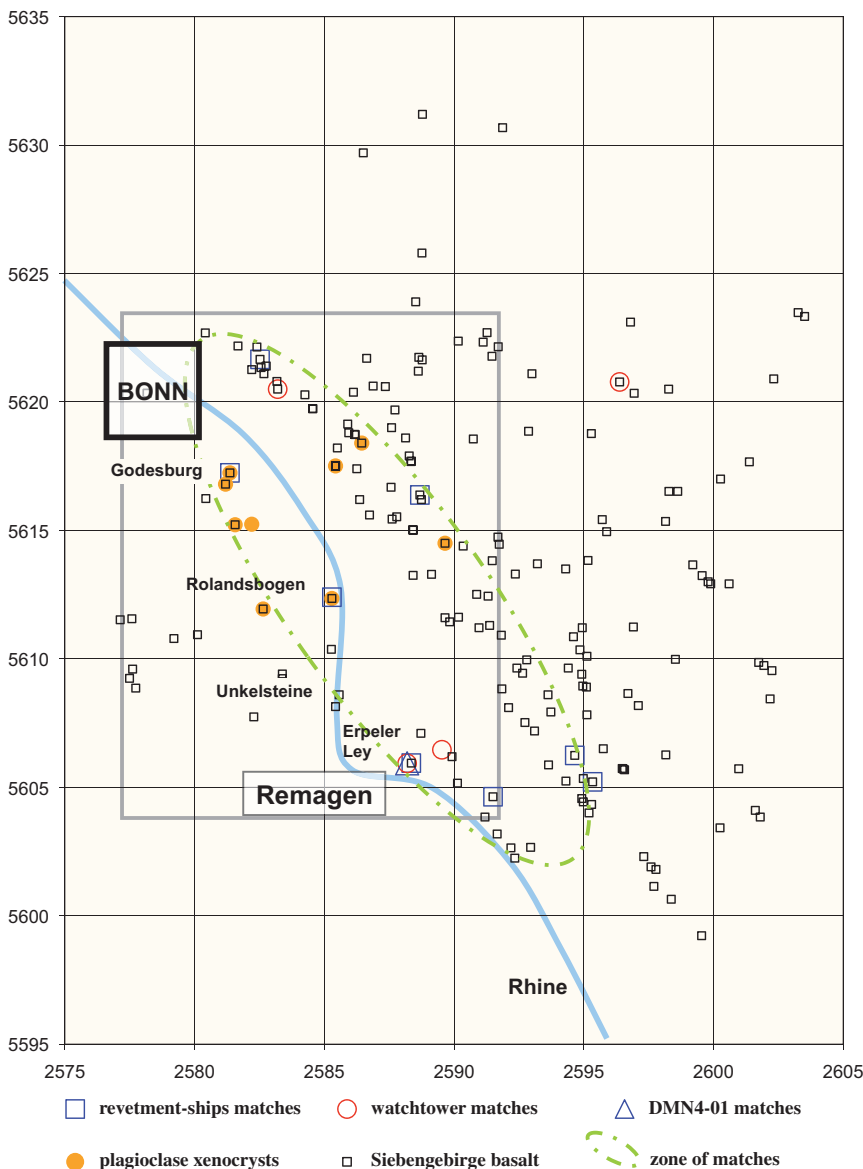


Fig. 11. Map with sites of analysed Siebengebirge basalts (Vieten, 1987; this paper). Geographical coordinates are based on the German coordinate system in order to facilitate correlation with the original German data files; units are in km, squares are thus 5 × 5 km. The centre of the city of Bonn is located at 7°05' E and 50°44' N. The river Rhine, which marks the region's *limes*, is shown in blue. The green oval comprises the sites of basalts that match chemically with basalt blocks used by the Romans in Vleuten-De Meern. The rectangular inset is the outline of the map of Fig. 9.

1987). Apparently, the situation of the Erpeler Ley, strictly at the foreign side of the Rhine *limes*, was no objection for the Romans to quarry there. In this respect it is noteworthy that the Erpeler Ley lies directly opposite the Roman auxiliary fortress 'Rigomagus' (Remagen), dating from the 1st century, and thus was under close military vigilance.

With plentiful basalt available at a number of safe and logistically favourable places, directly at the borders of the Rhine, it is highly improbable that the Romans would have opened quarries at higher river terraces (logistically unprofitable) and beyond the *limes* (insecure, difficult to defend). Hence, such sites, even if feasible on grounds of chemistry, will not be considered as likely sites of provenance (Table 4).

The Godesburg, although not lying directly at the Rhine, merits a separate discussion from the logistic point of view because thus far it is one of only two sites that produced a sample fully matching both the chemical and the petrographic criteria of Roman blocks.

The Godesburg and Bonn in the 1st century AD

At first sight, lying at about 1.6 km from the current river bed of the Rhine, the Godesburg does not seem to be logistically attractive for opening a quarry in the Roman era. However, the local topography may not have been quite the same in the first century AD. The volcanic body is exposed at the lower river terrace, next to the Godesburger Bach affluent to the Rhine, and

Table 4. Topographic, chemical and petrographic data of basalts from the Siebengebirge which are discussed in the text as possible sources of basalt blocks used by the Romans at the *limes* near Vleuten-De Meern (the Netherlands).

				Chemical criteria set by Roman basalts (see text)								Matches	Plagioclase xenocryst?
				SiO ₂	Alkali ^{tot}	TiO ₂	Al ₂ O ₃	Mg#	CaO	P ₂ O ₅	wt. % normalized to 100% volatile free		
Basalt occurrences according to logistic position 100 A.C. (see text)	Distance to E/W bank Rhine (km)	Sample	Coordinates* Right Up	42.72	2.93	2.11	12.69	67.34	10.01	0.46	Revetment & ships		
				47.81	4.88	2.40	14.24	74.39	11.85	0.57			
				42.16	4.21	2.49	13.32	64.91	9.70	0.54	Watchtower		
				47.54	5.03	2.84	14.74	71.07	11.29	0.60			
Advantageous													
Erpeler Ley	at E bank	194	2588.35 5605.94	45.46	4.77	2.13	14.06	67.78	10.25	0.51	revetment & ships	–	
		194A	2588.19 5605.92	44.92	4.27	2.69	13.97	67.42	10.52	0.55	watchtower	–	
		194B	2588.38 5505.79	45.41	4.25	2.70	13.99	67.99	10.29	<u>0.52</u>	watchtower	–	
Birgelerkopf, W of Unkelstein	at W bank	33.1	2585.43 5608.14	45.79	3.57	<u>2.04</u>	<u>11.93</u>	73.26	<u>9.69</u>	<u>0.46</u>	–	–	
Unkelstein, S side	id.	33	2585.57 5608.60	44.20	3.99	2.35	12.99	<u>66.97</u>	10.84	0.56	revetment & ships	–	
Rolandsbogen	id.	207HP	2585.29 5612.35	45.03	4.42	2.28	13.26	70.76	10.85	0.55	revetment & ships	yes	
Attainability uncertain													
Godesburg, S of Bonn	1.6 W	104HP	2581.36 5617.18	45.10	4.00	2.31	13.85	67.79	11.16	0.51	revetment & ships	yes	
		104	2581.36 5617.24	45.07	4.05	2.18	14.12	<u>66.03</u>	11.11	0.52	revetment & ships	yes	
Unfavourable													
Dornheckensee, Ramersdorf	1.45 E	81	2582.52 5621.66	45.45	4.76	2.11	14.06	67.71	10.25	0.48	revetment & ships	–	
Nubenak, Oberkasbach	1 E	114.1A.KL	2589.53 5606.46	44.63	4.47	2.51	13.76	68.96	10.70	0.54	watchtower	–	
Kuckstein, Oberkassel	1.3 E	74	2583.20 5620.50	45.25	4.83	2.62	14.17	66.24	11.14	0.56	watchtower	–	
Ginsterhahn-S	4.75 E	181	2595.34 5605.21	45.40	4.29	2.15	13.27	68.25	10.88	0.55	revetment & ships	–	
Hargarten-Kaimig	4.75 E	182	2594.65 5606.24	45.23	3.86	2.13	13.31	69.22	11.13	0.55	revetment & ships	–	
E of Margaretenhöhe	4.25 E	36	2588.68 5616.38	44.46	3.75	2.26	12.73	70.90	11.50	0.56	revetment & ships	–	
Eulenberg	13 E	98	2696.38 5620.78	43.94	4.50	2.80	13.41	69.70	10.96	0.55	watchtower	–	

* Based on German coordinate system, units in km; values in bold typical for revetment-ships group; values in bold italic typical for watchtower group; underlined values are mismatches for the marked group

Note that #194A and #194B also match the criteria for DMN4-01 (cf. Table 2).

a 'Gumme', a now sanded watercourse running northward past Bonn (Fig. 9). 'Gumme' is derived from 'Gummia', a local term from the 9th century to denote an old Rhine branch (Gerlach, 2001). In Roman times, the 'Gumme' was water-filled, running past the west side of the 'Viculus Bonnensis' to 'Bonna' (Gerlach, 2001; Horn, 1987). Moreover, as seen in recent excavations in the lower Rhine terrace NE of the Godesburg, Roman settlements underlie meters thick Rhine gravel deposits. These observations lead us to suggest that the Rhine has shifted its main bed eastward over the last millennia, implying that the local topography was quite different in Roman times. If indeed conclusive evidence can be found that in those days the Rhine was closer to the Godesburg, or that water levels in the Godesburger Bach and the 'Gumme' were high enough to allow navigation by flat bottomed vessels, the Godesburg volcanic body deserves a place on the short list of basalt occurrences that were logistically attractive for quarrying in Roman times.

The Godesburg – at the Roman side of the *limes* and close to 'Bonna', a major centre of Roman activities (Horn 1987) – has an excellent location from economic as well as military perspectives. The importance of 'Bonna' is well documented archaeologically. Relicts of Roman settlements are common in the Bonn area and include the military installations of 'Castrum Bonnensis', with a capacity for 7000 soldiers, and civilian buildings (including a public bath) recently discovered during construction activities ('Viculus Bonnensis'). More isolated Roman remnants include graveyards, engraved building and tombstones, pottery, and road constructions (Rey, 2001). The volcanic building materials in 'Bonna' exhibit a certain chronology: in the 1st century sawed blocks of pumice tuff (from the Brohltal, E Eifel) were applied; from the 2nd century trachyte from the Drachenfels is used as well; and only in the 3rd century hard basalt (from Unkelsteine?) was used (Gerlach, 2001). Realizing Bonn's proximity to the quarries, this relatively late introduction of basalt is quite remarkable; the more so, knowing that basalt blocks from the Rhine were already used 100 AD in Vleuten-De Meern.

Considering that the immense scale of basalt quarrying during the last centuries has probably removed all remains of older quarries in the Siebengebirge (C. Keller, Landschaftsverband Rheinland-Rheinisches Amt für Bodendenkmalpflege, Bonn; pers. comm., 2006), it will be difficult, if not impossible, to find original Roman quarries in situ. If so, there is of course little chance of finding the exact equivalents of the blocks that were quarried by the Romans. In this context, it might be that on the Godesburg in particular, in situ evidence of a Roman quarry has been preserved until to-day, just because quarrying there was discontinued altogether when the transporting facilities were severely hampered by shallowing of previously available waterways.

Possible sources and open questions

After all deliberation and based on the available petrographic and geochemical data, the Rolandsbogen, the Godesburg and the Erpeler Ley can be indicated as the most likely sources of the blocks that were used by the Romans in Vleuten-De Meern. Some relevant uncertainties still exist, though.

In the first place it is not yet clearly identified that the Godesburg was attainable by vessels during the Roman times; and secondly, in logistically prospective areas matches with Roman blocks may have been missed because of low sampling density, e.g., the Unkelsteine.

In order to elucidate the remaining uncertainties regarding the Roman basalt quarry sites in the Bonn-Remagen area, we suggest two further studies:

1. A historical topographical study aiming at the 'Gumme' in the Godesburg-Bonn area to ascertain the logistic feasibility of a basalt quarry at the Godesburg.
2. A denser sampling of the basaltic bodies that are situated at the immediate borders of the Rhine, followed by geochemical research and a microscopic search for plagioclase xenocrysts.

Interestingly, if in situ evidence of Roman quarries is still available, a denser sampling pattern may also help identifying the original sites of provenance for the multi-sample groups of Roman blocks, as these are, by definition, chemically homogeneous within narrow limits, and therefore probably come from rather small quarries or from separate corners in a large one.

Summary and conclusions

Basalt blocks from archaeological excavations of Roman sites along the *limes* near Vleuten-De Meern are AOB with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of about 26.3 - 28.5 Ma.

Petrography, geochemistry and volcanic ages of the blocks indicate the Siebengebirge Volcanic Field as their only possible source domain.

Details in abundances of major elements show that five of the six studied samples from the Roman ship Vleuten-De Meern 4 form one coherent group together with all thirteen samples from the contiguous Roman revetment (both 100 AD) and a block from ship Vleuten-De Meern 4 (148 AD). AOB lumps from a nearby Roman watchtower (2nd - 3rd century AD), petrographically similar with the revetment-ships group, form a chemically different group. One sample from ship De Meern 4 and one from the watchtower are genuinely distinct solitaires, outlying from the two chemically defined multi-sample groups.

From the logistical viewpoint, the Erpeler Ley, Unkelsteine, and Rolandsbogen are feasible sites of provenance as their basaltic bodies are exposed directly at the borders of the Rhine. However, there are some discrepancies in the chemical and petrographic fitting of these sites. The samples from the Erpeler Ley, which are chemically compatible with blocks from the revetment-ships group and the watchtower group, do not contain plagioclase xenoliths, which are so characteristic in the archaeological samples. Two samples from the Unkelsteine do not comply with either of the criteria. A sample from the Rolandsbogen does contain plagioclase xenocrysts and also matches the chemical criteria of revetment-ships group.

Full geochemical and petrographical compatibility with the revetments-ships group of samples including the unique presence of tiny amounts (%) of plagioclase xenocrysts, is also demonstrated by a sample from the Godesburg (South of Bonn). However, it should be cautioned that its logistic position during Roman times needs to be evaluated in terms of accessibility since its current position, at 1.6 km from the Rhine, seems to be unfavourable from a Roman logistic perspective. Chemical matches with watchtower blocks are found only in the Erpeler Ley.

On the basis of these observations we suggest that for 1st century constructions in Vleuten-De Meern the Romans imported basalt from either the Godesburg or Rolandsbogen, or both, and for the 2nd-3rd century watchtower, from the Erpeler Ley.

Denser sampling of individual volcanic bodies bordering the Rhine, microscopic petrography and chemical analysis, in addition to historical topographical investigation between the Godesburg and the Rhine, are required to further elucidate the details of Roman basalt mining along the Rhine in the Bonn-Remagen area.

Supplementary data

Supplementary data for this paper are available on: www.njgonline.nl

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