J. Geophys. 48, 18–27, 1980

Journal of Geophysics

K–Ar Age Determinations on Tertiary Volcanic Rocks*: V. Siebengebirge, Siebengebirge-Graben

W. Todt** and H.J. Lippolt

Laboratorium für Geochronologie der Universität, D-6900 Heidelberg, Im Neuenheimer Feld 234,
Federal Republic of Germany

Abstract. Sanidines from 16 tuffs of the first volcanic phase in the Siebengebirge and the Siebengebirge-Graben were dated by the K/Ar-method. Ages range from 24.1 (Nachtigallental) to 22.9 M.y. (core Rott).

Three mineral ages from surface outcrops in the Central Siebengebirge (23.9 ± 0.5 M.y.) are statistically indistinguishable from those of the sub-surface samples Stieldorf-1, Stieldorf-2 and Rott (23.0 ± 0.5 M.y.). These ages confirm the Uppermost Oligocene biostratigraphic age of the 'Blätterkohle Rott' which is interlayered with the trachyte tuff.

Sanidine and biotite mineral ages from five trachyte samples give similar apparent ages from 26.4 to 24.6 M.y. These results show the trachytes to be older than the tuffs, in disagreement with the geologically established sequence. The sequence of eruptions in the Siebengebirge area however (trachyte-tuff, trachyte, latite and alkaline-basalt) was confirmed wherever outcrops allow observations. This discrepancy is discussed.

The apparent ages of three dated latites are in the same range (26.2 to 25.1 M.y.), in agreement with the geological sequence. The latite ages show that the time span between the eruptions of the trachytes and the latites must have been very small. Isolated basalts belonging to a fourth phase yield K/Ar ages from 25 to 19 M.y. Pliocene volcanism could not be verified in the Siebengebirge.

In addition, stratigraphically well-dated glauconites from the Tertiary of the Niederrhein area were used to correlate our isotopic age date with the Cenozoic time scale.

Key words: Potassium-Argon dating – Tertiary – Miocene – Oligocene – Sanidine – volcanic rocks – paleomagnetism – Siebengebirge – Germany.

1. Introduction

The area of interest for our study is the well known mountainous region of the Siebengebirge in western Germany and adjacent areas (Fig. 2). The age of the volcanism in the Siebengebirge is not well defined by stratigraphical methods. The Siebengebirge volcanics are considered to be approximately of the same age as the analogous rocks in the Westerwald. Ahrens (1957) placed the trachyte tuffs of the Westerwald into the Upper Oligocene (Middle Chattian). The basaltic eruptions in the Westerwald continued through the Lower Miocene and perhaps through the Pliocene. Lippolt and Todt (1978) demonstrated that the volcanic action in the Westerwald had several phases and was still active in the Quaternary. The most intensive phase was between Upper Oligocene and Lower Miocene (22–25 M.y.). One object of this study was to check the alleged synchronism of volcanic activity in the Siebengebirge and the Westerwald and to define the chronological sequence in the Siebengebirge.

The stratigraphic classification of the volcanic products in the Siebengebirge-Graben, the most southerly point of the Niederrheinische Bucht, has also been unsatisfactory. The volcanic action there was placed in the Oligocene, since the trachyte tuff is older than the 'Blätterkohle' of Rott, which Stehlin (1932) dated as Upper Oligocene. The second object of this study was to date several trachyte tuffs, which are intercalated with Tertiary sediments. In addition, samples of glauconite from well dated sediments in the Niederrhein area offered another opportunity for correlations.

The third object of this study was to date all the volcanic rocks for which paleomagnetic data have been published, in order to obtain more information about the chronologic evolution of the magnetic field at this time.

2. Geological Setting

The area of the Niederrheinische Bucht formed a sedimentary basin in the Tertiary. Marine transgressions are noticeable in the Oligocene and Miocene sections near the Ruhr-river. Deposition of fine clastic sediments occurred contemporaneously. These sediments now appear as large seams of brown coal. A movement of the crust took place in the course of the so-called Savian tectonic phase at the boundary of the Oligocene and Miocene. Volcanic eruptions in the Siebengebirge (Hesemann 1970, 1975) may have been triggered by a rapid subsidence of the graben-system in the Niederrheinische Bucht. This volcanic activity in the Siebengebirge belongs to the large arc of volcanic centers from the Eifel in the West to the Oberpfalz in the East (Fig. 1).

A period with several phases of eruptions in the area of the Siebengebirge produced, in succession, trachyte tuffs, trachytes, latites and finally alkaline basalts. The trachyte tuffs are interlayered with the sediments of the Niederrheinische Bucht in the Siebengebirge-Graben, so that it is possible to correlate isotopic ages with stratigraphic ages.

The only available K/Ar age published is the age of sanidine separated from the Drachenfels trachyte (22.8 M.y. Lippolt 1961,

---

* Former project title 'K–Ar age determinations on volcanics with known paleomagnetic field parameters'

** Now at Max Planck Institut für Chemie, Mainz

0340-062X/80/0048/0018/$02.00

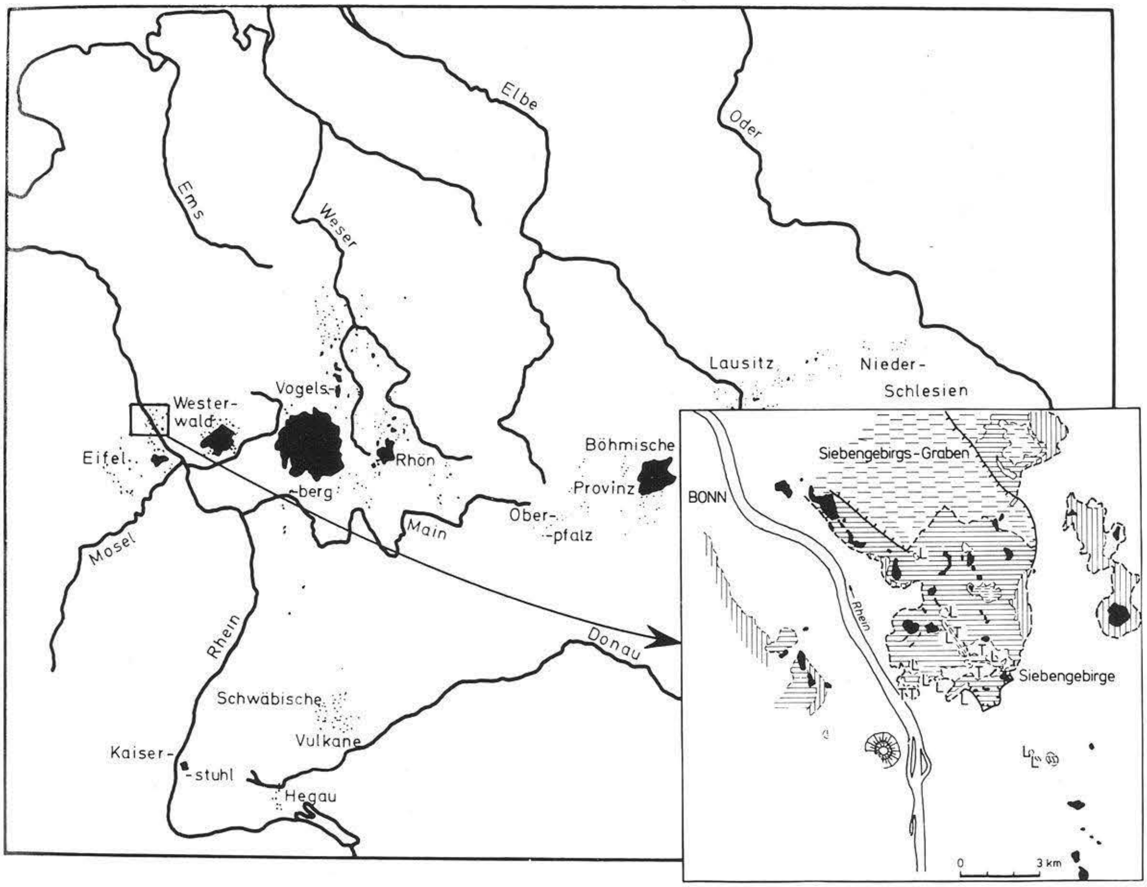

Fig. 1. Map of volcanic centers in Central Europe with area under investigation. Inset: Geological Map of Siebengebirge area

Frechen and Lippolt 1965, 23.1 M.y. calculated with the constants recommended by Steiger and Jäger 1977). The trachyte tuff from the Drachenfels area into which this trachyte intruded should be older than this intrusive rock.

The volcanism in the Siebengebirge has been studied extensively. Detailed studies of the geology and petrography and in regard of the deposition sequence were published by Laspeyres (1900). The chemistry of the rocks was published by Berg (1933). Further mineralogical and chemical analyses were carried out and interpreted by Frechen (1961, 1976), Vieten (1961, 1972) and Frechen and Vieten (1970).

According to the present geological concept, the volcanism in the Siebengebirge occurred in several stages, whereby the pressure of the Mesozoic sedimentary cover (> 1,000 m) was relieved during the first phase of explosive volcanism. In this phase trachyte tuffs were deposited over a large area (> 10 km^2) with an average thickness of about 100 m. Succesive trachyte-, latite-, and alkaline-basaltic magma intruded into these tuffs, forming domes, funnels, pipes, and dikes. The sequence of eruptions is the same throughout the area. It is particularly well established where the intrusive relationships are seen. Differences in the petrography of samples of different localities, however, suggest that it was not a contemporary eruption with a uniform sequence. It is more likely that the volcanism in different areas occurred with a time delay depending on the tectonic situation. This appears to have resulted in a similar, but often incomplete sequence. Volcanism in the Siebengebirge followed different pathways of eruptions as well as complex chemical compositions. The nearby volcanic areas of Eifel and Westerwald (compare Fig. 1) are separated from it by a zone of few eruptions. Figure 2 shows a simplified map of the Siebengebirge area and the majority of the sample localities which are described in the following section and in the appendix.

Further north in the Siebengebirge-Graben the 'Blätterkohle' of Rott is imbedded in trachyte tuff. This 'Blätterkohle' is considered to be a typical example of the brown coal of the Upper Oligocene and contains numerous fossils. In this 'Rott' locality, a *Microbunodon minimum Cuvier* (=Anthracotherium breviceps Troschel) has been dated as Upper Oligocene by Stehlin (1932). According to the Phanerozoic Time Scale (PTS), compiled at the 'Holmes Symposium' 1964 (Funnel 1964) and supplemented by Rast (1971), the boundary between Oligocene and Miocene lies at 25 ± 2 M.y. Since this time new K/Ar data have placed this boundary at 22.5 M.y. (Berggren 1972, Van Eysinga 1975) or even lower at 21–22 M.y. (Odin et al. 1975).

The well defined stratigraphical classification of the 'Blätterkohle' of Rott and the intercalation of the trachyte tuffs in the sediments of the Siebengebirge-Graben made it possible to date this coal seam absolutely and to assign hereby a further isotopic age to the Oligocene/Miocene boundary. Further calibration points for the PTS come from three glauconite bearing horizons in the Niederrheinische Bucht, where fauna relicts have been very well dated stratigraphically. They are:

(a) Marlstones of the Upper Paleocene in the borehole Hamsfeld near Issum. This horizon is dated as Thanetian (Anderson 1958; Indans 1958). Samples HAM Al and HAM Bl.

(b) Marlstones of the uppermost part of Oligocene in the Rossenray 1 and Hoerstgen mines. The fauna with *Chlamys bitica acuticostata* classified this layer as Lower Eochattian (Anderson

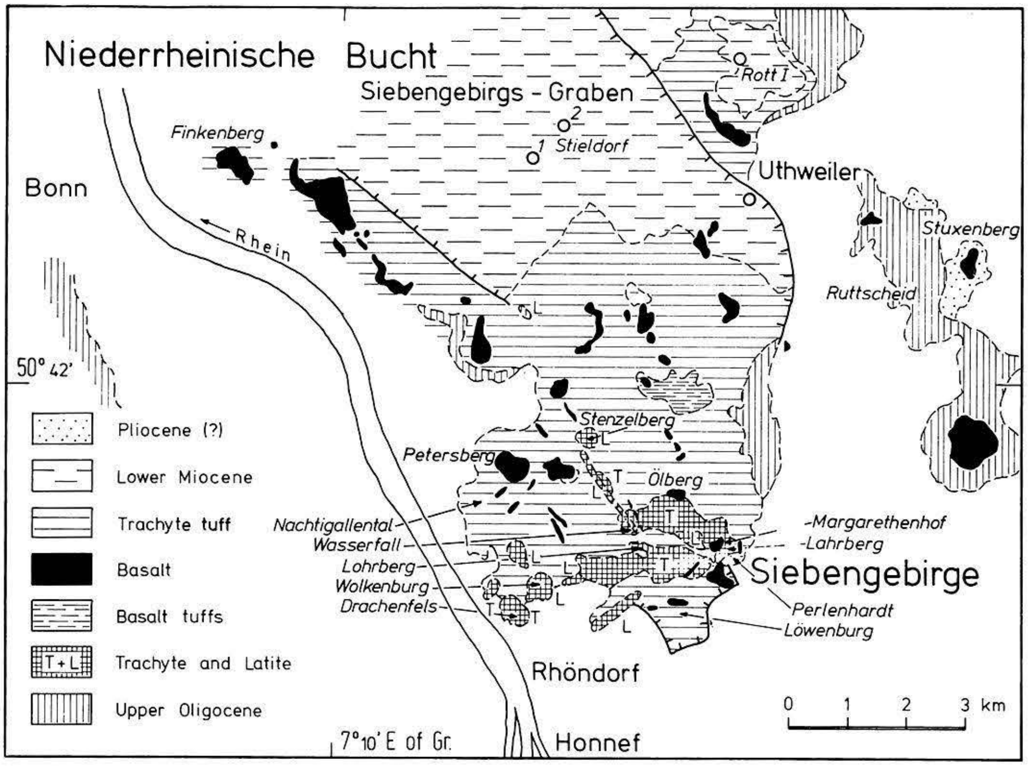

Fig. 2. Geological sketch map of Siebengebirge and Siebengebirge-Graben and sample localities (Samples E 33, E 34, E 35, E 39 in the South and E 36 in the Northeast are not included). Map after Teichmüller (1974) in Burghardt (1979)

1958; Indans 1958; Ellermann 1958). Samples ROS and HOER.

(c) Very fine pelitic sand from the Miocene of the Hoerstgen mine. This sand is also rich in fauna, with large numbers of tropical forms. Therefore it very likely belongs to the Hemmoor formation (Anderson 1958; Indans 1958). Sample 261A.

Glauconite separates from these layers prepared by the Geological Survey of Nordrhein-Westfalen served to correlate our data on the volcanism with the Geological Time Scale.

3. Analysed Samples

Cores from boreholes drilled by the Geologisches Landesamt Nordrhein-Westfalen (Krefeld) in the Siebengebirge-Graben, supplied samples of the graben area. Minerals from the tuff horizon in boreholes Stieldorf-1 and Stieldorf-2 were used to date this trachyte tuff. The cores of the two drill holes allowed Grünhagen (1970) to describe, layer by layer, the petrographic composition of the 100-m-thick graben section composed of trachyte tuff. Separation of sanidine allows us to determine their K/Ar ages. Grünhagen (1970) was able to recognize similar layers in the core of the drillhole Rott-1 but not to correlate them with the cores of Stieldorf. Sanidine has also been separated for K/Ar analyses from these layers. Tuff layers with sanidine had been found close to the 'Blätterkohle' near Uthweiler (Schmidt 1951). This sanidine was also dated by K/Ar analyses.

Sanidines from three layers in the central Siebengebirge (Nachtigallental, Heisterberg and Ruttscheid) were separated in order to evaluate the correlation between the Siebengebirge-Graben and the Siebengebirge trachyte tuff. Representative suites were chosen from the igneous rocks in the Siebengebirge covering the different phases of volcanism. Wherever mineral separations were possible we analysed sanidine- and biotite-samples, in the other cases we resorted to total rock analyses (TR). All samples were as fresh as possible, and classified by the criteria of Horn et al. (1972) as fresh volcanic rocks with the exception of Finkenberg basalt (No. 40) which was altered. Descriptions of the samples are given in the appendix.

4. Analytical Methods

Potassium was analysed by flame photometry with a 1σ-error of $\sim$0.5%. The argon was determined by isotope dilution in a 180°-5 cm-mass-spectrometer (Varian MAT GD150). The samples ($\sim$0.5 g) were wrapped in nickel foil and carefully predegassed in vacuum prior to the analyses to minimize the atmospheric argon contribution. The argon blank was about $1 \cdot 10^{-8}$ cm^3 STP argon. A detailed description of the analytical technique is published in Horn et al. (1972). The following decay constants were used (Steiger and Jäger 1977): $\lambda(^{40}K_{\beta^-}) = 4.962 \cdot 10^{-10}$/yr; $\lambda(^{40}K_e) + \lambda'(^{40}K_e) = 0.581 \cdot 10^{-10}$/yr; $^{40}K = 0.01167$ atom%. These constants yield ages about 1% higher than those calculated with the former set of constants. The error of the argon determination was calculated after Todt (1971) basing on the statistical error of the measurements and the atmospheric argon correction. The error of the age is the sum of the K- and Ar-errors. On the standard sample LP6-Bio of the US Geological Survey we determined $4.335 \cdot 10^{-5}$ cm^3 STP $^{40}Ar_{rad}$ per gram.

5. Results and Discussion

The results of the analyses are presented in Table 1. The discussion of the results begins with our glauconite data (Table 1A) since glauconites are the basis for the correlation of the stratigraphy in the Niederrheinische Bucht (Kreuzer et al. 1973).

4. *Ages of Stratigraphically Controlled Samples*

The apparent age of the iron-rich glauconite fraction from the Thanetian sand in the Hamsfeld core is 57.8 ± 1.3 M.y. According to the PTS, the time base of the Upper Paleocene is 58–60 M.y. (Table 2). The age of the less-magnetic fraction of this sample is too high (67.2 ± 1.5 M.y.). X-ray analyses and mineralogical tests by Grünhagen (unpublished) suggest that impurities (detrital illite) might be the reason. These illites were not completely converted into glauconites.

Glauconites of the Asterigerina-horizon (Ellermann 1958) at the base of the Chattian in the Hoerstgen mine yield an age of 28.3 ± 1.0 M.y. in agreement with the PTS. The age of the glauconites (26.4 ± 0.9 M.y.) in a comparable layer (Lower Eochattian) from the Rossenray-1 mine is 2 M.y. lower and corresponds with the Uppermost Oligocene.

The results for the glauconite samples of Hemmoor in the Hoerstgen mine yield an age of 18.2 ± 0.9 M.y. and are somewhat younger than glauconites separated from the drillchips from Oldenburg Hemmoor (19.2 and 20.4 M.y.). Kreuzer et al. (1973) have measured ages of glauconites from Lattorfian sediments (Nannoplankton zone NP 21) close to Helmstedt (37.3 to 39.3 M.y.) and from corresponding glauconites close to Lehrte (38.4 and 38.9 M.y.). Four glauconite samples from the Neochat-

Table 1. Analytical results of the K/Ar measurements. For sample notations see chap. Appendix

Sample		Potassium (%)	Ar run No.	$^{40}\mathrm{Ar}_{\mathrm{rad}}$ (10^{-6})	^{40}Ar (atm) (%)	K-Ar age M.y. ± 1σ	Mean value M.y. ± 1σ
(A) Glauconite samples							
1. 261 A	Miocene (Hemmoor)	5.85	1260	4.146	51	18.2 ± 0.8	
2. ROS	Oligocene (Chatt)	6.40	595 790	6.609	6	26.4 ± 0.9	
3. HOER	Oligocene (Chatt)	5.83	599 601	6.333	28	28.3 ± 1.0	
4. HAM B1 (more magnetic)	Paleocene (Thanet)	5.42	596 598	12.305	23	57.8 ± 1.3	
5. HAM A1 (less magnetic)		5.12	597	13.870	20	67.2 ± 1.5	
(B) Tuff Samples from drill core Stieldorf-1							
6. G2S	Sanidine	8.16	715/1410	7.169	10	23.5 ± 0.7	
7. G3S	Sanidine	6.95	694/731/1824	6.186	14	22.5 ± 0.5	
8. G7S	Sanidine	7.85	718/819	5.986	11	(19.6 ± 0.6)	23.1 ± 0.5
9. G7H	Hornblende	1.46	602/787	1.334	43	23.3 ± 0.8	
10. Basalt	Totalrock	1.04	932/957	1.024	76	25.7 ± 2.3	
Tuff Samples from drill core Stieldorf-2							
11. G5S	Sanidine	7.53	588/688 817/1413	6.715	19	22.5 ± 1.5	
12. G1S	Sanidine	7.85	585/695/734 815/1828	7.371	13	24.0 ± 0.4	
13. G6S	Sanidine	8.57	589/693/1832	7.485	8	23.2 ± 0.5	
14. G4S	Sanidine	5.72	586/689/722	4.909	12	22.0 ± 0.4	23.0 ± 0.8
15. G8S	Sanidine	6.61	691/729	6.079	17	23.4 ± 0.8	
Tuff Samples from drill core Rott 1							
16. (A) 13m	Sanidine	8.09	1563/1585	7.292	20	23.0 ± 0.5	
17. (B) 25m	Sanidine	7.04	1043/1117	6.300	5	22.8 ± 0.5	23.0 ± 0.3
18. (C) 43m	Sanidine	8.16	1044/1120	7.306	6	23.1 ± 0.5	
Tuff from artificial outcrop							
19. Uthweiler	Sanidine	6.87	1408/1530	6.420	9	23.9 ± 0.7	

Table 1 (Continued)

	Bonn No.	Sample		Potassium (%)	Ar run No.	$^{40}Ar_{rad}$ (10^{-6})	^{40}Ar (atm) (%)	K-Ar-age M.y. ± 1σ	Mean value M.y. ± 1σ
(C) Hard rock samples from the Siebengebirge									
20.	BN (2)	Drachenfels	Sanidine	8.03	1588/1650	8.15	13	26.1 ± 1.5	
		Quartz trachyte	Biotite	7.23	1083/1049	7.14	22.5	25.4 ± 0.6	
21.	BN (4)	Perlenhardt	Sanidine	8.58	1235	8.60	6	25.8 ± 0.8	
		Quartz trachyte	Biotite	7.39	1076/1047	7.35	20	25.6 ± 0.6	
22.	BN (7)	Lohrberg	Sanidine	8.80	1236	8.79	5	25.7 ± 0.8	
		Trachyte	Biotite	7.02	1045/1081	6.93	23	25.4 ± 0.6	
23.	BN (8)	Wolkenburg Quartz latite	Totalrock	3.71	558/623	3.71	14	25.7 ± 0.6	
24.	BN (11)	Stenzelberg Quartz latite	Totalrock	3.33	557/556	3.25	17	25.1 ± 0.6	
25.	BN (21)	Löwenburg Foidic trachyte	Totalrock	3.02	561/605/619	3.04	43	25.9 ± 1.3	
26a.	BN (37)	Ölberg-Südfuß	Sanidine	8.76	1247/1353	8.58	5	25.2 ± 0.6	
		Trachyte	Biotite	7.33	1048/1079	7.21	15	25.3 ± 0.5	
26b.	BN (54)	Alcaline basalt	Totalrock	1.14	555/615	1.02	35	23.0 ± 0.7	
27a.	BN (38)	Wasserfall	Sanidine	8.83	1250	9.06	6	26.4 ± 0.8	
		Trachyte	Biotite	7.46	1050/1085	7.13	15	24.6 ± 0.6	
27b.	BN (42)	Latite	Biotite	6.08	1893	6.19	53	26.2 ± 1.3	
28.	BN (39)	Lahrberg Trachyte	Sanidine	8.67	1261/1309	8.49	7	25.2 ± 0.6	
29.	BN (36)	Am Margarethenhof Alc. Basalt	Totalrock	1.12	559/612	1.07	52	24.6 ± 1.1	
(D) Trachytic tuffs from the Siebengebirge									
30.	BN (61)	Nachtigallental	Sanidine	5.60	1565/1590/1674	5.25	13	24.1 ± 1.5	
31.	BN (62)	Heisterbg/ Petersbg	Sanidine	5.39	1567/1596	4.99	14	23.8 ± 0.6	23.9 ± 0.5
32.	BN (63)	Ruttscheid	Sanidine	7.34	1568/1598	6.79	8	23.8 ± 0.6	
(E) Isolated basalt occurrences neighbouring the Siebengebirge; Totalrock measurements									
33.	BN (51)	Dächelsberg/ Niederbachem		1.22	566/614	1.19	60	25.1 ± 1.3	
34.	BN (57)	Kahlenberg/ Burgbrohl		0.968	565/613	0.918	56	24.4 ± 1.2	
35.	BN (58)	Asberg/ Kalenborn		1.15	564/611	1.073	56	24.0 ± 1.1	
36.	BN (60)	Stein/Eitorf		1.07	450/627	0.786	61	18.9 ± 1.1	
37.		Stieldorf	compare sample B-10						
38.		Stuxenberg/ Oberpleis		1.32	1594	1.277	29	24.9 ± 0.9	
39.	BN (59)	Steinsbergkopf/ Niederlützingen		1.31	452/626	1.135	43	22.3 ± 1.0	
40.		Finkenberg Bonn-Beuel		1.35	451/608/625	1.443	92	27.5 ± 5.4	

Table 2. Stratigraphic division of the Tertiary in the Niederrhein basin and pertinent K/Ar-data by Kreuzer et al. (1973) and from this work

Pliocene		Data for Time scale boundaries		Data from Kreuzer et al. (1973)		Data from this work	
		Rast (1971)	Berggren (1972)	K-Ar Age M.y.	Stratigraphic Age	K-Ar-Age M.y. ± 1σ	Stratigraphic Age
		10±3	5				
Miocene	Upper Miocene						
	Reinbek						
	Hemmoor			19.2–20.4	Hemmoor	18.2±0.9	Hemmoor
	Vierland						
		25±2	22.5	23.3–23.6	Olig/Miocene	23.0±0.3	Upper Oligocene
Oligocene	Chattian			23.8–24.8	Neo-Chattian		
	Rupelian					26.4±0.9	Lower Eo-Chattian
	Lattorfian					28.3±1.0	
		37±2	37.5	37.3–39.3	Lattorfian		Asterigerina Horizon
Eocene							
		58±4	53.5				
Paleocene	Thanetian					57.8±1.3	
	Danian-Montian					(67.2±1.5)[a]	Thanetian
		67±3	65				
Cretaceous							

[a] Discussion in section 5A

tian sediments below the Oligocene/Miocene transition zone are dated at 23.3 and 23.6 M.y. We conclude from these dates that K/Ar determinations on glauconites in the Niederrhein-Tertiary largely confirm the PTS (Table 2), with the only exception that the Oligocene/Miocene time boundary might be too high.

Core Rott-1: From the trachyte tuffs of the Rott-1 core three sanidine samples from the depths of 13, 25 and 43 m were analysed. All results agree perfectly (23.0±0.3 M.y.). Because of the intercalation of the 'Blätterkohle'-seam with these trachyte tuffs, the result also dates this seam. The PTS puts the Oligocene/Miocene transition at 25±2 M.y. This implies that the 'Blätterkohle' would belong to the Lower Miocene, in disagreement with the presumed stratigraphic age; conversely if we believe the stratigraphic age to be right, the Oligocene/Miocene transition must be younger than 23.0±0.3 M.y.

These data on the sanidines and the data on the glauconites do support the suggestions by Berggren (1972) and Odin et al. (1975) that the Miocene-Oligocene boundary is younger than that given in the PTS.

B. Results From Sanidines From Stieldorf-1 and Stieldorf-2

Stieldorf-1. Three sanidines, one hornblende and the whole rock basalt were analysed from this drill sample. The sanidines from the two upper samples give K/Ar ages of 23.5±0.7 and 22.5±0.5 M.y. Sanidine and hornblende analyses of sample G7 yield 19.6±0.6 and 23.3±0.8 M.y. ages respectively. This sanidine was the only sample with isotropic grains – perhaps glass. Glass is known for its low argon retentivity (compare references in Dalrymple and Lanphere 1969, p. 176). An additional possibility to explain the argon loss is the concordant age of the hornblende with the two other samples of this core. The age of the TR-sample of the basalt (25.7±2.3 M.y.) was unexpected, because it was assumed to be a sill (Teichmüller, personal communication). This result means that the basalt was already present when the trachyte-tuff erupted, and that the basalt was filled in by the tuff.

Stieldorf-2. Five sanidine samples from this core resulted in ages between 22.0 and 24.0 M.y. (similar to Stieldorf-1). The youngest sample G4 shows patches with microcline cross-hatching, which could be a reason for argon loss (compare references in Dalrymple and Lanphere 1969, p. 168). The results show that these tuffs were formed before or shortly after the Oligocene-Miocene transition.

C. Results on the Samples From the Siebengebirge

Three sanidine samples from the trachyte tuff of the central Siebengebirge were analysed in order to evaluate the isotopic age position of the trachyte cores of the area and to confirm the results on the trachyte tuff in the Siebengebirge-Graben. These three samples (30, 31, and 32) yield ages of 23.9±0.5 M.y. thereby supporting our previous result that the trachyte tuffs have younger apparent ages than the trachytic igneous rocks. As will be discussed in the next sub-section, all igneous rocks (except some basalts) were older than 24 M.y.

The analytical results of the minerals and total rock samples for the volcanics from the Siebengebirge are presented in Table 1 C. We measured sanidines and biotites from all trachytes which have been collected. All sanidine- and biotite-ages agree within error-limits. The Wasserfall trachyte (27) is an exception since the biotite appears to be younger (24.6±0.6 M.y.) than the sanidine (26.4±0.8 M.y.). The reason for this is not yet understood. The average ages of all sanidines are 25.7±0.5 M.y. The corresponding average age of all biotites is 25.3±0.4 M.y. Hence the ages of both minerals agree.

The average age of the three analysed latities is 25.7±0.6 M.y. which suggests the eruptions of the trachytes and latites occurred within a very short time span at about 25 M.y.

The alkaline-basalts, which are considered to be products of the last eruptive phase in the Siebengebirge area, yield K/Ar ages ranging from 25 to 19 M.y., indicating they were produced from the beginning of the volcanic activity and continual eruptions over a time span of several million years.

D. Paleomagnetism

Paleomagnetic data from eight analysed samples in the Siebengebirge showed reversed magnetization for five alkaline-basalts (26, 29, 33, 34, and 35) while two quartz-latites (23 and 24) and the feldspathoidal-trachyte (25) are normally magnetised. The age range for the normally magnetised samples is 25.9–25.1 M.y. and for the other samples 25.8–23.0 M.y. These results therefore show an older group with normal magnetization (latites and trachytes) and a younger group with reverse magnetization (alkaline-basalts). The event for the reversal from normal to reverse polarity occurred ~25 M.y. ago. This corresponds to the 25±2 M.y. reversal, dated in the basaltic province of the Oberpfalz by Todt and Lippolt (1975).

6. General Discussion

Geologic studies of the area suggest the Siebengebirge volcanism took place in five phases (compare Hesemann 1970). It appears from local geologic observations that the first phase produced the trachytic tuffs as a thick layer over the whole area which was then intruded by trachytic magmas during a second volcanic phase. This relationship can be seen at the Drachenfels and in the Lohrberg quarry. Unfortunately these locations have not been sampled for the present study.

Our K/Ar results conflict with this chronology. Here the tuffs appear to be younger than the lavas. All our analysed ages for the tuff layers are in the range 24.1 to 22.0 M.y. while the youngest trachyte has an age of about 25 M.y. as do the latities. From this, one would conclude that all dated tuffs must have been deposited within a relative short time span (2 M.y.) and that they erupted after nearly all other magmas had been erupted. On the other hand our results for the suite of hard rocks show the expected sequence of eruption.

Since the same mineral (sanidine) was analysed in the tuff and in the hard rocks our K/Ar results should be comparable. Each set of data (hard rock/tuff) seems to be consistent. The hard rock sanidine ages are supported by coexistent biotite ages. The tuff sanidines give consistent values for all the boreholes of the graben and for the outcrops in the mountain range. They have all the same age within the errorlimits.

On the other hand there is no reason to expect an inferior retentivity behaviour of sanidines from tuffaceous origin. Baadsgaard et al. (1961) reported that fresh sanidine obtained from various volcanic bentonite horizons retained the radiogenic argon sufficiently well to yield reliable ^{40}Ar/^{40}K ages. Their short-term (days) tests of argon leakage from pure sanidines showed that the radiogenic argon is quantitatively retained at temperatures below 400° C. Moreover Baadsgaard et al. (1961) reported one case (Crowsnest volcanics, Alberta, Canada) were sanidine from a trachyte flow yielded significantly lower ages than the sanidine from a correlated bentonite. One could however argue that the tuffs and the flows of the Siebengebirge and the Siebengebirge-Graben might have experienced different geochemical histories. The tuffs are diagenetically altered and might have had more hydrothermal alteration.

In our suite of samples there is unfortunately no pair of neighboring tuff and trachyte where the age relationship is clearly discernible in the field. We are therefore faced with two alternatives:

1. Production of tuff is not confined to a short phase of activity but lasted a rather long time. Sanidines from the tuff production of the starting phase were not observed in the field and therefore could not be analysed. This would imply that we have to look for samples where the field relationships are clear (Lippolt and Vieten in preparation).

2. There is a hitherto unknown process observed which influenced the results on the sanidines from the tuffs. Earlier studies have demonstrated the reliability of sanidine in K/Ar dating. There is however a grain size and a chemical difference between the sanidines from the two rock types which may affect Ar retentivity. The sanidines of the tuffs are smaller (mm) than those from the trachytes (cm) and the potassium contents of the tuff-sanidines are lower than the contents of the others and they have a much wider spread (5.4–8.6% compared to 8.0–8.8%).

At the moment we cannot distinguish between these two alternatives. To solve the question we intend to begin a more detailed study of two pairs of sanidines from tuff and trachyte in neighboring position. By determining the K/Ar ages using conventional and neutron activation techniques, and studying the chemical compositions of the minerals by XRF technique we hope to resolve this problem (Lippolt and Vieten in preparation).

7. Conclusion

Our results are illustrated in a simplified crossection through the Niederrheinische Bucht in Fig. 3. The right side of the figure shows the results on the igneous rocks of the Siebengebirge. We consider these to be the most reliable ages because of the concordance of sanidine and biotite ages. These analyses fix the main phase of the Siebengebirge igneous rock production at about 26–24 M.y. The left side of the figure shows the age determinations of glauconites, implying that the age levels of the Tertiary part of the PTS (after Funnel 1964 and Rast 1971) are also valid in the Niederrheinische Bucht.

At their face value, the results on the minerals from the tuffs (right central part of the figure) may be interpreted as follows:

The ages of the sanidines in the Siebengebirge-Graben, particularly in the Rott core, add new evidence to the age of the Oligocene/Miocene transition. If we take the correct stratigraphical age of these layers as Upper Oligocene, this boundary must be younger than 23.0±0.3 M.y. Hence the results on the tuffs favor the 22.5 M.y. transition age as published by Van Eysinga (1975). This would also be the correct age for the Oligocene/Miocene transition in the Siebengebirge-Graben. But the discrepancy between results from tuffs and igneous rocks does not allow us to resolve this question at present.

In Fig. 4 our new results are compared to K/Ar age distributions of other areas in the Rhenish Shield. Approximately 24 M.y. ago all volcanic areas were active, which conflicts with the idea of a hotspot moving from E to W or a plate moving from W to E over the hotspot (Duncan et al. 1972; Burke et al. 1973). Two periods of volcanism prevail in the Eifel area: the Tertiary phase from 44 to about 24 M.y. and the well known Quaternary phase. The Tertiary Eifel volcanism mostly precedes the Wester-

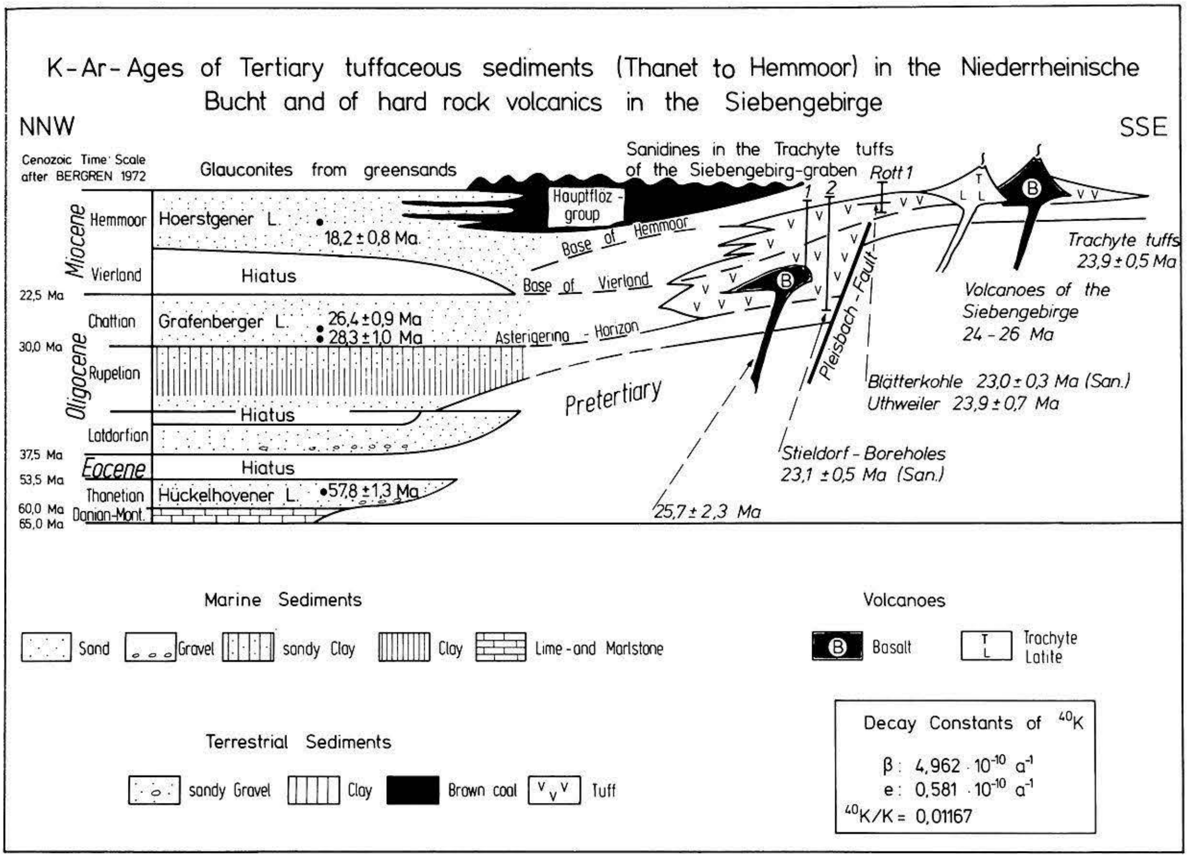

Fig. 3. Synopsis of the results as a simplified cross section (NNW-SSE) through the Niederrhein basin and the Siebengebirge. (After Teichmüller 1974)

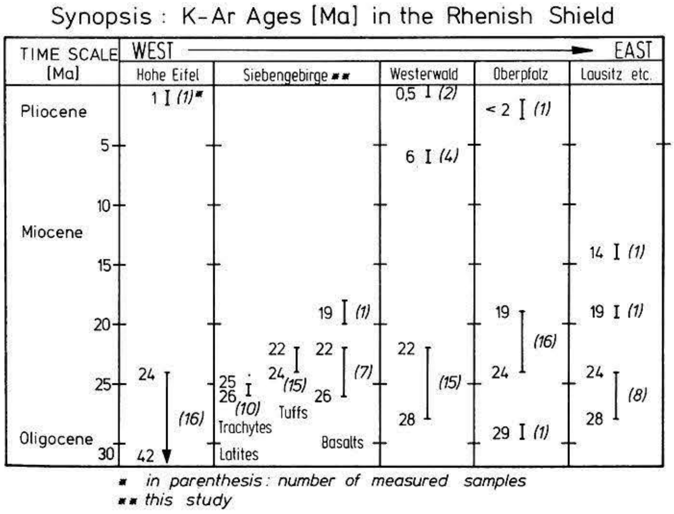

Fig. 4. Age distribution of volcanic activity in the Rhenish Shield from Hocheifel (*W*) to Saxony (*E*) after the results of papers published earlier and of this study (Siebengebirge area)

wald-Siebengebirge volcanism. However the contemporaneity of the volcanic activity in these two latter areas is still correct based on our data. After a longer time span volcanism began again during the Pliocene/Quaternary in the Eifel, Westerwald and Oberpfalz. In the Siebengebirge area proper, however, it has not been possible to find any Pliocene volcanism.

Acknowledgements. We are indebted to Drs. H. Grünhagen and R. Teichmüller (Geologisches Landesamt Nordrhein-Westfalen in Krefeld) for the preparation of the samples 1 to 19 and 37 to 38 and helpful discussions about the Tertiary in the Niederrheinische Bucht. We are also indebted to Prof. Drs. J. Frechen and K. Vieten (Universität Bonn) for separating minerals from crystalline rocks in the Siebengebirge (samples 20 to 29), and preparation of the sanidine samples 30 to 32. Professor J. Frechen also guided us when we collected samples 33 to 36 and 39. With Professor K. Vieten we had fruitful discussions concerning the tuff-igneous rock sequence.

We are grateful to H.-J. Funke and A. Lutz for their careful technical assistance.

We further wish to thank R. Hurst for taking the trouble to improve the English text.

This work was partly supported by the Deutsche Forschungsgemeinschaft (Bonn) under the priority research program 'Geologische Korrelationsforschung'.

8. Appendix: Sample Description

A. Glauconite-Samples

These samples are prepared in the Geologisches Landesamt Nordrhein-Westfalen in Krefeld: After wet sieving, the 200–500 µm-fraction was separated on a Frantz-magnetic separator. Handpicking under a stereo-microscope produced about 100% clean separates (Grünhagen 1970).

1. *Sample 261 A:* shaft IV of the Friedrich-Heinrich AG at Hoerstgen. TK 25, sheet 4404 Issum, $r=32\ 826$, $h=09\ 320$; depth 35.8 m, stratigraphic classification: Hemmoor.
2. *Sample ROS:* shaft I Rossenray TK 25, sheet 4405 Rheinberg, $r=38818$, $h=09395$, depth 91.1 m, stratigraphical classification: Lower Eochattian.
3. *Sample HOER:* Shaft IV of the Friedrich-Heinrich AG at Hoerstgen. cp sample 261 A, depth 128.2 m, stratigraphic classification: Lower Eochattian.
4. *Sample HAM B 1:* Borehole Hamsfeld. TK 25, sheet 4404 Issum. $r=29437$, $h=10069$, depth 309.65–309.75 m, stratigraphic classification: Upper Paleocene, strong manetic fraction.
5. *Sample HAM A 1:* The same sample as HAM B 1, but a less magnetic fraction with impurities of illite.

B. Tuff-Samples From the Siebengebirge-Graben

These samples are also prepared in the Geologisches Landesamt Nordrhein-Westfalen in Krefeld. The slightly solidified tuffs are ground wet in a porcelain-mortar, then elutriated. The feldspars are separated from the 200–400 µm and 400–600 µm sieve-fractions with a Frantz-magentic separator and heavy liquids. The sanidine-concentrates were handpicked under a stereo-microscope and checked for purity with refracting liquids. With one exception (G7S: 85% sanidine) the concentrations are higher than 98% (Grünhagen 1970; Todt 1971).

Borehole Stieldorf-1: TK 25, sheet 5209 Siegburg, $r=25\ 85575$, $h=56\ 2273$

6. *G 2 S:* Sanidine from a fine greenish trachyte tuff, depth: 45.5 m.
7. *G 3 S:* Sanidine from a lightgreen trachyte tuff, fine grained, depth: 58.5 m.
8. *G 7 S:* Sanidine from a grey, solid trachyte tuff, depth 67.5 m.
9. *G 7 H:* Hornblende from a grey, solid trachyte tuff, depth 67.5 m.
10. *Basalt:* depth 81.2 m, cp. E-37.

Borehole Stieldorf-2: TK 25 sheet 5209 Siegburg, $r=25\ 68100$, $h=56\ 23320$.

11. *G 5 S:* Sanidine from a green to grey trachyte tuff, depth 82.6–83.7 m.
12. *G 1 S:* Sanidine from a green to grey trachyte tuff, depth: 92–94 m.
13. *G 6 S:* Sanidine from a grey, finegrained trachyte tuff, depth 124.0–125.4 m.
14. *G 4 S:* Sanidine from a green, mediumgrained solid trachyte tuff, depth 134.1–137.0 m.
15. *G 8 S:* Sanidine from a brown clay, downwards more and more carbonaceous, depth 148.0–148.7 m.

Borehole Rott-1: $r=25\ 89200$, $h=56\ 25100$.

16. (A) Sanidine from a trachyte tuff, depth 12.70–12.95 m.
17. (B) Sanidine from a trachytic lapilli tuff, argillaceous with rock fragments, depth 25.0–25.5 m.
18. (C) Sanidine from a trachytic tuff and tuffite, the tuff is partly rich on sanidine, partly with feldspar and biotite, depth 43.25–43.4 m.
19. Uthweiler: Streamscarp at Frechwinkel. Sanidine from the lower tuff-bank in the 'Blätterkohle', about 2 m below the hanging boundary of the 'Blätterkohle'. TK 25, sheet 5209 Siegburg, $r=88\ 890$, $h=22\ 600$.

20.–32. *C, D. Igneous-Rock- and Tuff-Samples From the Siebengebirge*

These samples are prepared in the Mineralogisch-Petrologisches Institut der Universität Bonn. The purity of all mineral-separates was higher than 98%. In Table 1 we also list the lab-numbers of the University of Bonn in addition to our lab-numbers. Detailed description of all these samples may be found in the following publications: Vieten (1961), Vieten (1972), Frechen (1976), Frechen and Vieten (1970).

E. Isolated Basalts

33. Dächelsberg/Niederbachem. Alkaline-Ol-Basalt, unfresh.
    Phenocrysts: mostly Px, some with reabsorptions, Ol only marginal transformed into Iddingsite.
    Matrix: fine-crystalline, Plg more than Px, in some parts strong calcitization and zeolitization.
34. Kahlenberg/Burgbrohl. Alkaline-Ol-Basalt, unfresh.
    Phenocrysts: mostly Ol, with transitions to completely transformed bowlingite, minor Px.
    Matrix: coarse-crystalline, carbonates mostly concentrated in spots, partly strong zeolitization.
35. Asberg/Kalenborn. Alkaline-Ol-Basalt, fresh.
    Phenocrysts: Ol with no or little transformation to bowlingite, dominating over Px.
    Matrix: very fine-crystalline, Plg dominating over Px, minor amount of calcite.
36. Stein/Eitorf. Alkaline-Ol-Basalt, fresh.
    Phenocrysts: Ol dominating with beginning bowlingitization, minor Px with resorption-features.
    Matrix: coarse-crystalline, rich of ore-minerals, minor calcite and zeolites, Plg dominating.
37. Stieldorf (B-10). Alkaline-Ol-Basalt, unfresh.
    Phenocrysts: rare, mostly Ol (strongly to completely bowlingitized), minor Px.
    Matrix: mostly Plg, strong calcitization and zeolitization.
38. Stuxenberg. Nepheline-Basanite, fresh.
    Phenocrysts: abundant, mostly Px, also Ol (– 1 mm), marginal transformed to bowlingite.
    Matrix: poor in Plg, partly Neph, fine-crystalline, mostly prismatic Px, ore-minerals, minor amount of glass, beginning calcitization.
39. Steinsbergkopf/Niederlützingen. Alkaline-Ol-Basalt, fresh.
    Phenocrysts: mostly Px, also fresh Ol, minor amount of Px, xenocrysts with strong reaction-rims.
    Matrix: localy: calcite and zeolites, otherwise fresh, fine-crystalline, rich in ore-minerals, Plg dominating over Px and Ol.
40. Finkenberg/Bonn-Beuel. Alkaline-Ol-Basalt, unfresh.
    Phenocrysts: abundant, mostly Px locally concentrated, minor amount of Ol heavy to completely bowlingitized, also very fresh.
    Matrix: rich in calcite and zeolites (in spots and along cracks) Plg dominating over Px.

References

Ahrens, W.: Überblick über den Aufbau des Westerwälder Tertiärs, mit besonderer Berücksichtigung der stratigraphischen Stellung der vulkanischen Gesteine. – Fortschr. Mineral. **35**, 109–116, 1957

Anderson, H.J.: Zur Stratigraphie and Paläogeographie des marinen Oberoligozäns und Miozäns am Niederrhein aufgrund der Mollusken-Faunen. – Fortschr. Geol. Rheinl. Westfalen **1**, 277–295, 1958

Baadsgaard, H., Lipson, J., Folinsbee, R.E.: The leakage of radiogenic argon from sanidine. Geochim. Cosmochim. Acta **25**, 147–157, 1961

Berg, G.: Geologische Beobachtungen im Siebengebirge. – Verh. nat-hist. Ver. Rheinl. Westfalen **91**, 99–134, 1933

Berggren, W.A.: A Cenozoic time-scale – some implications for regional geology and paleobiography. – Lethaia **5**, 195–215, 1972

Burghardt, O.: Siebengebirge – Landschaft im Wandel – Geologisches Landesamt Nordrhein-Westfalen 64 p, 1979

Burke, K., Kidd, W.S.F., Wilson, J.T.: Plumes and concentric plume traces of the Eurasian Plate. – Nature 241 Phys. Sci. pp. 128–129, 1973

Collinson, D.W., Creer, K.M., Irving, E., Runcorn, S.K.: Palaeomagnetic investigations in Great Britain I–IV. – Proc. R. Soc. London, Ser. A: **250**, 71–156, 1957

Dalrymple G.B., Lanphere, M.A.: Potassium-Argon Dating. pp. 166–184, San Francisco: W.H., Freeman and Co. 1969

Duncan, R.A., Peterson, N., Hargraves, R.B.: Mantle plumes, Movement of the European Plate, and Polar Wandering. – Nature **239**, 82–86, 1972

Ellermann, C.: Die mikrofaunistische Gliederung des Oligozäns im Schacht Kapellen bei Moers. – Fortschr. Geol. Rheinl. Westfalen **1**, 205–214, 1958

Eysinga, F.W.B. Van (Compiler): Geological Time Table 3rd edn. – Amsterdam: Elsevier 1975

Frechen, J.: Einführung zu den Exkursionen der Deutschen Mineralogischen Gesellschaft. – Deutsche Mineral. Ges. 38. Jahrestagung in Bonn/Rl. Fortschr. Mineral. **39**, 161–185, 1961

Frechen, J.: Siebengebirge am Rhein – Laacher Vulkangebiet – Maargebiet der Westeifel. – Slg. Geol. Führer **56**, 4–27, – Borntraeger, Berlin-Stuttgart, 1976

Frechen, J., Lippolt, H.J.: Kalium-Argon-Daten zum Alter des Laacher Vulkanismus, der Rheinterrassen und der Eiszeiten. – Eiszeitalter Ggw. **16**, 5–30, 1965

Frechen, J., Vieten, K.: Petrographie der Vulkanite des Siebengebirges. I. Die subalkalische Gesteinsreihe Quarztrachyt-Latitbasalt. II. Die peralkalische Gesteinsreihe Alkalitrachyt-Sanidinbasanit. Decheniana **122**, 337–377, 1970

Funnel, B.M.: The Tertiary period. The Phanerozoic time-scale. A Symposium dedicated to Arthur Holmes. – Q. J. Geol. Soc. London **120**, [Suppl.], 179–191, 1964

Grünhagen, H.: Petrographie der Bohrungen Stieldorf-1 und -2. – Geol. Landesamt Nordrhein Westfalen, Krefeld 1970

Hesemann, J.: Zum Vulkanismus des Siebengebirges. – Decheniana **122**, 199–206, 1970

Hesemann, J.: Geologie Nordrhein-Westfalens. pp. 268–278, – Paderborn: F. Schöningh, 1975

Horn, P., Lippolt, H.J., Todt, W.: Kalium-Argon-Altersbestimmungen an tertiären Vulkaniten des Oberrheingrabens. I. Gesamtgesteinsalter. – Eclogae Geol. Helv. **65**, 131–156, 1972

Indans, J.: Mikrofaunistische Korrelationen im marinen Teritär der Niederrheinischen Bucht. – Fortschr. Geol. Rheinl. Westfalen **1**, 223–238, 1958

Kreuzer, H., Daniels, C.H., v., Gramann, F., Harre, W., Mattiat, B.: K/Ar-Dates of some Glauconites of the North West Germany Tertiary Basin. – Fortschr. Mineral. **50**, (Beih. 3), 94f., 1973

Laspeyres, H.: Das Siebengebirge am Rhein. – Verh. nat.-hist. Ver. Rheinl. Westfalen **57**, 119–591, 1900

Lippolt, H.J.: Alterbestimmungen nach der K-Ar-Methode bei kleinen Argon- und Kaliumkonzentrationen. – Heidelberg, Nat.-Math. Fak. Dissertation, 82p, 1961

Lippolt, H.J., Todt, W.: Isotopische Altersbestimmungen an Vulkaniten des Westerwaldes. – Neues Jahrb. Geol. Palaeontol. Monatsh. **6**, 332–352, 1978

Nairn, A.E.M., Kürsten, M.: Mitteilungen über paläomagnetische Untersuchungen an Basalten des Siebengebirges und seiner Umgebung. – Neues Jahrb. Geol. Palaeontol. pp. 348–352, 1959

Odin, G.S., Hunziker, J.C., Lorenz, C.R.: L'âge radiométrique du Miocène inférieur en Europe Occidentale et Centrale. – Geol. Rundsch. **64**, 570–592, 1975

Rast, N.: Isotope dating in the USSR – an essay review. – In: The Phanerozoic Time scale, W.B. Harland, E.H. Francis eds.: pp. 39–50. Geol. Soc. London Spec. Publ. No. 5, 1971

Schmidt, W.: Ein aufgeschürftes Tertiärprofil bei Uthweiler im Siebengebirge. – Geol. Jahrb. **65**, 603–610, 1951

Stehlin, H.G.: Über die Säugetierfauna der Westerwälder Braunkohlen. – Eclogae Geol. Helv. **25**, 314–319, 1932

Steiger, R.H., Jäger, E.: Subcommission on Geochronology: Convention on the Use of decay constants in Geo- and Cosmochronology. – Earth Planet. Sci. L. **36**, 359–362, 1977

Teichmüller, R.: Die tektonische Entwicklung der Niederrheinischen Bucht. Approaches to Taphrogenesis, Int. Union Comm. Geophys. Sci. Rep. **8**, 269–285, 1974

Todt, W.: Kalium-Argon-Altersbestimmungen an mitteleuropäischen miozänen Vulkaniten bekannter paläomagnetischer Feldrichtung. – Heidelberg, Naturwiss. Gesamtfakultät Dissertation, 74–106, 1971

Todt, W., Lippolt, H.J.: K-Ar-Alterbestimmungen an Vulkaniten bekannter paläomagnetischer Feldrichtung. I. Oberpfalz und Oberfranken. – J. Geophys. **41**, 43–61, 1975

Vieten, K.: Die Trachyt-Latit-Alkalibasalt-Assozation des Siebengebirge am Rhein. – Bonn, Nat.- Math. Fak. Dissertation 112 p. 1961

Vieten, K.: Über die Heteromorphie-Beziehungen in der Vulkanit-Assoziation des Siebengebirges und ihre petrogenetische Bedeutung. – Neues Jahrb. Mineral. Abh. **117**, 282–323, 1972

Received April 30, 1979; Revised Version October 25, 1979