

## K-Ar AND Rb-Sr DATING IN THE CRETACEOUS ISLAND-ARC SUCCESSION OF BONAIRE, NETHERLANDS ANTILLES<sup>1</sup>

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### ABSTRACT

Priem, H. N. A., P. A. M. Andriessen, D. J. Beets, N. A. I. M. Boelrijk, E. H. Hebeda, E. A. Th. Verdurmen & R. H. Verschure 1979 K-Ar and Rb-Sr dating in the Cretaceous island-arc succession of Bonaire, Netherlands Antilles – *Geol. Mijnbouw* 58: 367-373.

K-Ar and Rb-Sr analyses were made of suites of samples from different units in the island-arc succession of the Washikemba Formation (from late Albian through Turonian/Coniacian) on western Bonaire. Whole-rock K-Ar determinations yield ages of  $78 \pm 2$  Ma (Campanian) and  $61 \pm 4$  Ma (Palaeocene). Both ages are younger than the time span of the magmatism and they are interpreted as reflecting two separate events of low-grade metamorphism. No conclusive ages can be calculated from the Rb-Sr data, but they seem to agree with the corresponding K-Ar ages. The initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of two volcanic units are about 0.7039 and 0.7050, respectively, within the common range of the andesitic-dacitic associations of oceanic island arcs. Hornblendes from a tuffaceous layer indicate an age of  $88 \pm 2$  Ma, in accordance with the biostratigraphic position (Turonian/Coniacian).

### INTRODUCTION

The volcanic core of the island of Bonaire (Fig. 1) consists of a predominantly submarine island-arc succession with a total thickness of over 5000 m (Fig. 2), the Washikemba Formation (PIJPERS, 1933; BEETS ET AL., 1977-a, 1977-b). It consists mainly of flows and shallow intrusions of basalt, basaltic andesite, dacite and rhyodacite, pyroclastic equivalents of the three latter rock types, cherts and (cherty) limestones, and volcanoclastic boulder beds, conglomerates and sandstones. The three latter rock types occur predominantly in the upper part of the formation, furnishing record of the emergence of volcanic island(s). Cherty sediments in the lower half of the formation contain sparse ammonites indicating a late Albian age. In its upper part the formation contains fossiliferous limestones with a fauna of globotruncanids and inoceramids pointing to a Turonian/Coniacian age (BEETS ET AL., 1977-b;

SMT, 1977). All rocks show low-grade metamorphism under the conditions of the zeolite and prehnite-pumpellyite facies. The igneous rocks of the Washikemba Formation have strong affinities with the early island arc tholeiite series, as follows from the major element chemistry, REE and Th contents, and Ti/Cr ratios (BEUNK & KLAVER, 1977).

The regional strike of the Washikemba Formation is roughly N120E with a NE dip of 30-60°. Tilting gave rise to some small-scale folding and faulting, but large structures are absent. After the tilting and some erosion of the sequence, the Washikemba Formation was unconformably overlain by fossiliferous limestones and sandy marls of middle and late Maastrichtian age, the Rincon Formation, but only a few small, up to 30 m thick remnants have been preserved of these deposits (BEETS ET AL., 1977-b; MAC GILLAVRY & BEETS, 1977). Then came successively the deposition of the Palaeocene or Eocene Soebi Blanco Formation, an up to 400 m thick sequence of fluvial sandstones and conglomerates (containing a large proportion of exotic pebbles), and of Eocene conglomerates, limestones and marls (BEETS ET AL., 1977-b). From the Early Miocene onward the island shows a slow, discontinuous emersion, leading to the development of elevated terraces of coral reefs and emerged reef talus (DE BUISONJÉ, 1974; HERWEIJER ET AL., 1977).

<sup>1</sup> Manuscript received: 1979-03-21.

Revised manuscript received and accepted: 1979-04-09.

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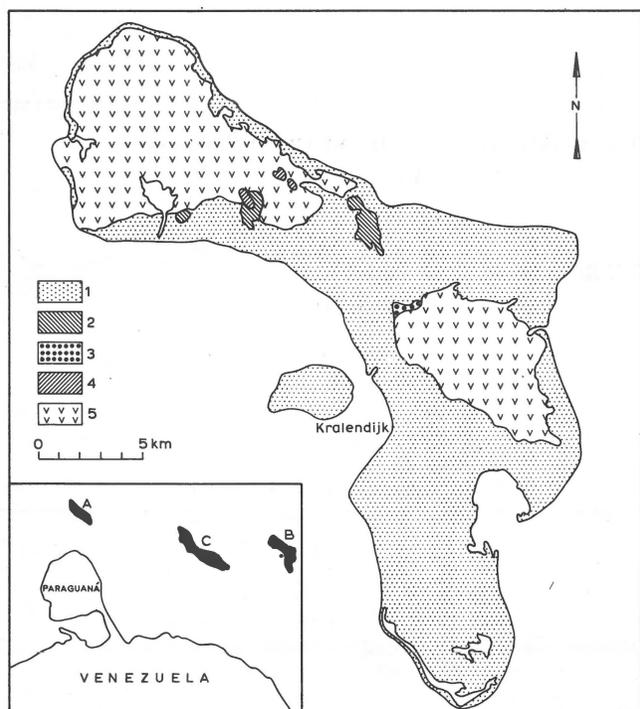


Fig. 1  
Simplified geological sketch map of Bonaire, showing the extension of the Washikemba Formation (after Beets et al., 1977-b). Legend: 1, Quaternary and Neogene limestones; 2, Eocene limestones and conglomerates; 3, Eocene or Palaeocene sandstones and conglomerates (Soebi Blanco Formation); 4, middle and late Maastrichtian limestones and marls (Rincon Formation); 5, Washikemba Formation. The inset shows the position of the Leeward islands of the Netherlands Antilles: A, Aruba; B, Bonaire; C, Curaçao.

### Rb-Sr AND K-Ar INVESTIGATIONS

A total of 17 K-Ar and 13 Rb-Sr analyses was made on 24 samples from different horizons in the Washikemba Formation (Fig. 2). The sampling sites are shown on the map of figure 3. Investigations were made on the following rocks:

(1) Dacitic lavas from Mt. Wecúwa, informally named here the Wecúwa porphyries (6 samples, 3 K-Ar and 6 Rb-Sr analyses). The lavas form part of the deepest exposed level of the Washikemba Formation. Mudstones and siliceous limestones containing the late Albian ammonite fauna occur slightly higher in the section and point to a minimum age of about 96 Ma for the volcanism (see next paragraph).

(2) Dacitic rocks from a sill north of Goto Lake, informally named here the Washikemba porphyries (K-Ar analyses of 3 samples). The sill forms part of an up to 2300 m thick succession of lapilli-tuffs, flows and shallow intrusions of dacitic to rhyodacitic composition in the central part of the Washikemba section, about 1300 m above the level with the late Albian ammonite fauna.

(3) Porphyritic agglomerates from the Ceru di Sumpiña, in-

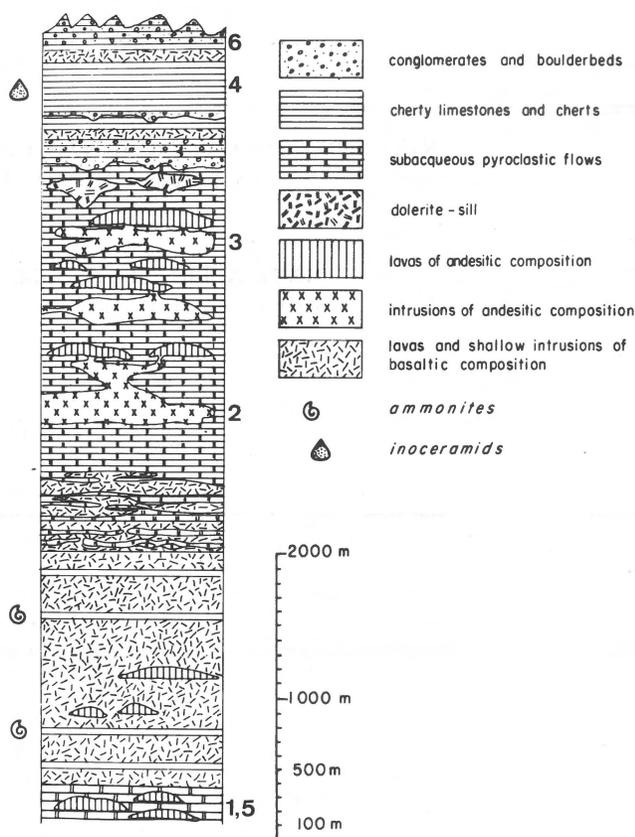


Fig. 2  
Simplified stratigraphic column of the Washikemba Formation in N. W. Bonaire between Mt. Wecúwa and Saliña Matijs (Beets et al., 1977-a), showing the stratigraphic levels from where the investigated samples were taken. The numbers refer to the sample locations of figure 3.

formally named here the Sumpiña porphyries (7 samples, 3 K-Ar and 7 Rb-Sr analyses). They occur in the upper part of the same succession at an approximately 1200 m higher level than the sill of the Washikemba porphyries. Both the lapilli-tuffs and the intrusive sill were derived from the same magma. Siliceous limestones containing the Turonian/Coniacian fauna of globotruncids and inoceramids are found a few hundred metres above the Sumpiña porphyries, setting a minimum age of about 88 Ma to the porphyries (see next paragraph).

(4) A thin bed (about 10 cm thick) of hornblende tuff at Saliña Grandi (K-Ar analyses of 4 separated hornblendes). The bed is intercalated between the siliceous limestones containing the Turonian/Coniacian fauna, but it is poorly exposed and shows the effects of weathering.

(5) A poeneitic layer (potassium-rich spilite) 300 m NE of Saliña Tam (K-Ar analyses of 3 samples). The layer is poorly exposed, but the nature, appearance and texture of the rock make it probable that we are dealing with a submarine lava flow. It occurs at approximately the same stratigraphic level as the Wecúwa porphyries.

(6) A diabase (dolerite) near Rincon (K-Ar analysis of one sample). This is a shallow intrusion in the upper part of the Washikemba Formation.

The composition of the porphyritic rocks is predominantly dacitic to rhyodacitic, minor andesitic. Phenocrysts of albitized plagioclase and chloritic aggregates probably replacing pyroxene are embedded in a quartz-albite-chlorite groundmass. The tuffaceous bed is composed of phenocrysts of hornblende and largely albitized andesine in a calcitic groundmass rich in fine-grained magnetite. The poeneitic rock consists of a reddish mass of albite and chlorite, usually showing an intersertal texture, with phenocrysts of albitized plagioclase partially replaced by K-felspar. The diabase is a rock made of albitized plagioclase, augite largely replaced by chlorite and some magnetite; it has a subophitic texture. All rocks show the (incipient) formation of low-grade meta-

morphic mineral assemblages (albite, epidote, chlorite, prehnite, pumpellyite). The sedimentary rocks of the middle and late Maastrichtian Rincon Formation appear also to have been affected by the low-grade metamorphism, but the Palaeocene or Eocene Soebi Blanco Formation is unmetamorphic.

The primary purpose of this study was to investigate the relation of the K-Ar and Rb-Sr ages to the biostratigraphic ages at different levels in the Washikemba Formation. It was also thought that the isotopic age data could provide useful information about the timing of specific stages in the thermal history of the rocks after their deposition, which is of utmost importance for the reconstruction of the geologic evolution of this part of the Caribbean crust. A number of the results was already published in an earlier progress-report (PRIEM ET AL., 1977).

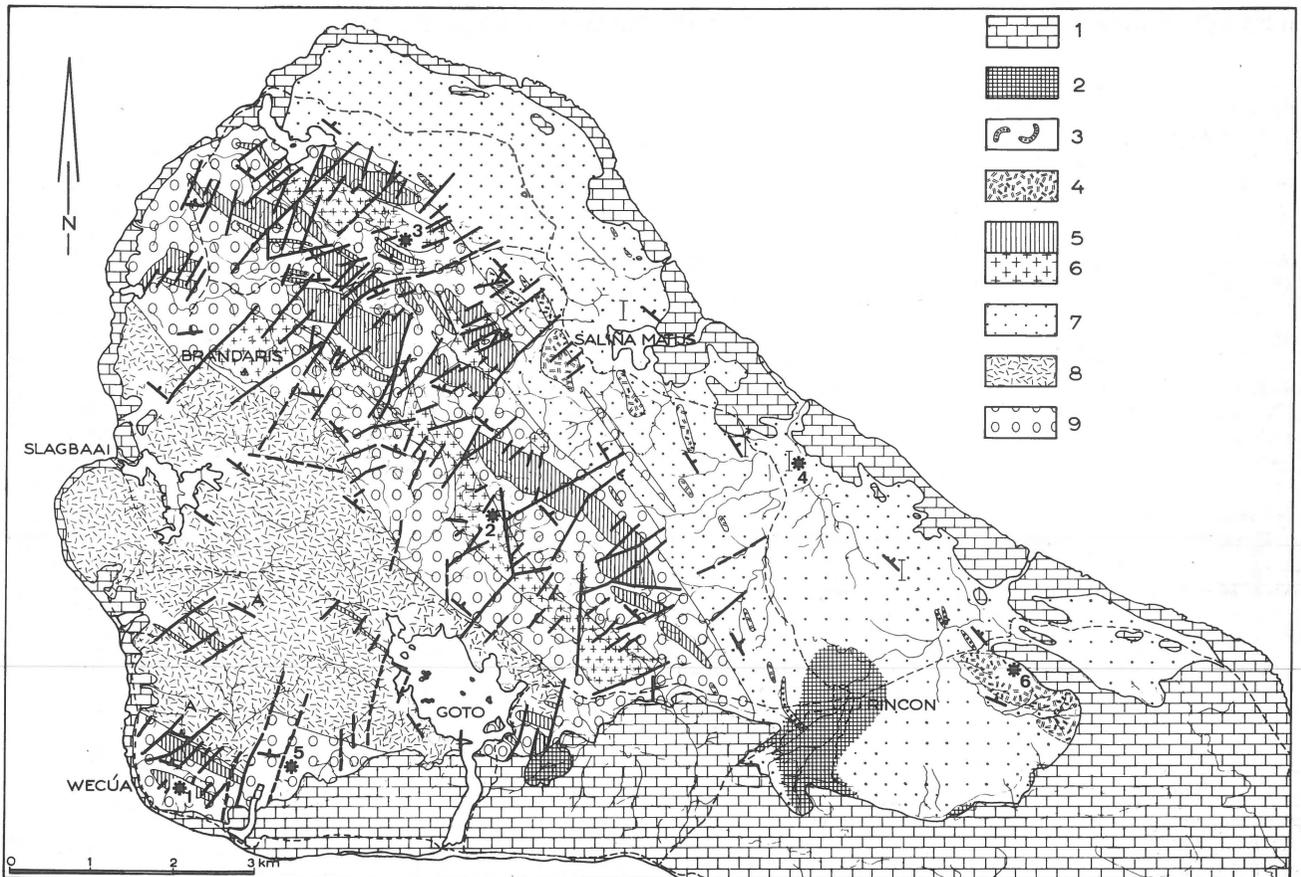


Fig. 3  
Geologic map of N. W. Bonaire (after G. Klaver, unpublished) showing the sampling sites (asterisks with numbers 1 to 6). Legend: 1, Neogene and Quaternary limestones; 2, Eocene limestones and conglomerates; 3, limestones and marls of the Rincon Formation (middle and late Maastrichtian); 4-9, Washikemba Formation; 4, diabase laccoliths; 5, dacitic-rhyodacitic flows; 6, dacitic sills; 7, cherty limestones, pillowed basalts, ash tuffs and (in the upper part) slump conglomerates and turbidites; 8, basalts-diabases (shallow intrusions), lapilli and ash tuffs, cherts; 9, agglomerates and lapilli-tuffs (subaqueous pyroclastic flows). I, inoceramids (Turonian/Coniacian); A, ammonites (late Albian).

## THE LATE CRETACEOUS TIME SCALE

## ANALYTICAL PROCEDURES AND CONSTANTS

The isotopic ages measured in the Washikemba Formation are related to the time scale of the Late Cretaceous proposed by OBRADOVICH & COBBAN (1975). This scale is based upon K-Ar age determinations on 25 biotite/sanidine pairs from 15 individual ammonite zones interspersed in the nearly complete sequence of Late Cretaceous (from late Albion or early Cenomanian through early Maastrichtian) marine sediments in the western interior of North America. Obradovich and Cobban utilized a different set of K constants for the age calculations as the nowadays generally accepted constants used in this study (see next paragraph), so the ages of the stage boundaries were recalculated as follows:

Maastrichtian/Tertiary	66-67 Ma
Campanian/Maastrichtian	72-73 Ma
Santonian/Campanian	84 ± Ma
Coniacian/Santonian	88 ± Ma
Turonian/Coniacian	89 ± Ma
Cenomanian/Turonian	91-92 Ma
Albian/Cenomanian	96 ± Ma

All Rb-Sr measurements were made on whole-rock samples. The Rb and Sr contents and Rb/Sr ratios were determined by X-ray fluorescence spectrometry, using a Philips PW 1450/AHP spectrometer (pressed-powder pellets; mass absorption corrections for both sample and external standard based upon the Compton scattering of the Mo-K $\alpha$  primary beam; VERDURMEN, 1977). For the Rb/Sr ratios the accuracy is estimated at 1.0% down to Rb and Sr contents of about 10 ppm. A number of samples were also analysed for their Rb and Sr contents by isotope dilution techniques; the accuracy is estimated at 1.0% for both Rb and Sr. The isotope measurements were made with a Varian CH5 mass-spectrometer or with a Teledyne SS-1290 mass-spectrometer; both spectrometers are computer-controlled and have a Faraday cage collector and digital output. Repeated measurements over a few years on the NBS-987 Sr(CO<sub>3</sub>)<sub>2</sub> standard give values for normalized <sup>87</sup>Sr/<sup>86</sup>Sr of 0.71006 ± 0.00008 and 0.71008 ± 0.00010 (2 $\sigma$ ), respectively. The accuracy of the <sup>87</sup>Sr/<sup>86</sup>Sr analyses is estimated at 0.05%.

Table I  
K-Ar data and calculated ages

Sample Nr. <sup>1</sup>	K (% Wt) <sup>2</sup>	radiogenic <sup>40</sup> Ar (ppm × 10 <sup>3</sup> )	atmospheric <sup>40</sup> Ar (% total <sup>40</sup> Ar)	calculated age (Ma) <sup>3</sup>
<i>Wecúwa porphyries</i>				
ANT 30	1.45	6.16	47	60.5
ANT 47	0.968	3.89	57	57.0
ANT 49	0.881	4.00	70	64.3
<i>Washikemba porphyries</i>				
ANT 60	0.817	4.49	56	77.6
ANT 63	1.19	6.78	29	80.3
ANT 66	1.35	7.24	20	75.9
<i>Sumpiña porphyries</i>				
ANT 68	1.61	9.04	23	79.4
ANT 71	0.254	1.38	61	76.2
ANT 74	0.675	2.71, 3.15	49, 46	(62)
<i>Poeneitic lava</i>				
ANT 51	5.04	25.2	11	70.9
ANT 52	3.50	14.4	13	58.3
ANT 53	0.164	0.874	44	75.5
<i>Hornblende tuff</i>				
ANT 32, hbl	0.158	0.822, 0.807	63, 60	73.1
ANT 33, hbl	0.132	0.838, 0.839	50, 57	89.4
ANT 34, hbl	0.136	0.844, 0.825	67, 65	86.4
ANT 35, hbl	0.137	0.973, 0.985	51, 49	100
<i>Diabase</i>				
ANT 140	2.15	10.4	64	68.5

<sup>1</sup> Hbl, hornblende; all others, sieve fractions of whole-rocks.

<sup>2</sup> Mean of duplicate analyses.

<sup>3</sup> Errors ± 3% on the basis of estimated errors of 1% for K and 2% for Ar, except for sample ANT 74 of which the radiogenic Ar content was difficult to measure and the reproducibility poor.

K-Ar analyses were made on sieve fractions ( $-250+125 \mu\text{m}$ ) of whole-rocks or separated hornblendes. The K contents were determined by flame photometry with a Li internal standard and CsAl buffer. Argon was extracted in a bakeable glass vacuum apparatus and determined by isotope dilution techniques in a GD-150 mass-spectrometer; all measurements were made by the static method. The accuracy is estimated at 1.0% for K and 2.0% for Ar.

The following constants were used for the age calculations:  $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11} \text{a}^{-1}$ ;  $\lambda^{40}\text{K}_\beta = 4.962 \times 10^{-11} \text{a}^{-1}$ ;  $\lambda^{40}\text{K}_e = 0.581 \times 10^{-10} \text{a}^{-1}$ ; isotopic abundance  $^{40}\text{K} = 0.01167 \text{ atom\%}$  total K.

## RESULTS AND DISCUSSION

The K-Ar data are listed in Table I and the Rb-Sr data in Table II. Figures 4 and 5 show plots of the Rb-Sr and K-Ar data of the Wecúwa and Washikemba & Sumpiña porphyries, respectively.

Except for the hornblendes, all isotopic ages are too young

with respect to the Turonian/Coniacian biostratigraphic age of the upper part of the Washikemba Formation. Widespread resetting of the isotopic systems has thus taken place and it seems obvious to relate this to the low-grade metamorphism shown by the rocks. On the other hand, any metamorphic event must have occurred before the deposition of the Palaeocene or Eocene Soebi Blanco Formation, which has not been affected by the metamorphism. On the basis of the biostratigraphic relationships age boundaries can thus be set to the metamorphism between the boundary Coniacian/Santonian (about 88 Ma) and the boundary Cretaceous/Palaeocene or Palaeocene/Eocene (say, 66 to 54 Ma).

The Rb-Sr data of the Wecúwa porphyries scatter, but four samples display a rough linear correlation corresponding to an age of 54 Ma. Three K-Ar analyses give ages between about 57 and 64 Ma, averaging  $61 \pm 4 \text{ Ma}$ . The ages recorded by the K-Ar and most Rb-Sr systems may be interpreted in terms of an increase in the ambient temperature during an event of low-grade metamorphism in Early Palaeocene time.

One sample of the Wecúwa porphyries (ANT 30) lies significantly above the rough linear array of the other Rb-Sr

Table II  
Rb-Sr data

Sample Nr.	Rb (ppm)	Sr (ppm)	Rb/Sr (Wt/Wt) <sup>2</sup>	<sup>87</sup> Sr/ <sup>86</sup> Sr	<sup>87</sup> Rb/ <sup>86</sup> Sr
<i>Wecúwa porphyries</i>					
ANT 30	17.1 <sup>1</sup>	57.8 <sup>1</sup>		0.70585, 0.70582	
	17.3 <sup>2</sup>	58.1 <sup>2</sup>	0.2985		
ANT 31	17.7 <sup>1</sup>	139 <sup>1</sup>		0.70510, 0.70483	0.8605
	17.8 <sup>2</sup>	136 <sup>2</sup>	0.1314		
ANT 47	9.91 <sup>1</sup>	96.3 <sup>1</sup>		0.70468, 0.70457	0.3746
	10.0 <sup>2</sup>	96.5 <sup>2</sup>	0.1039		
ANT 48	15.4 <sup>1</sup>	60.8 <sup>1</sup>		0.70491	0.2990
	15.6 <sup>2</sup>	61.6 <sup>2</sup>	0.2534		
ANT 49	11.1 <sup>1</sup>	67.7 <sup>1</sup>		0.70462	0.7338
	11.2 <sup>2</sup>	68.7 <sup>2</sup>	0.1637		
ANT 50	15.8 <sup>1</sup>	63.7 <sup>1</sup>		0.70492	0.4745
	16.0 <sup>2</sup>	63.8 <sup>2</sup>	0.2502		
<i>Sumpiña porphyries</i>					
ANT 68	19.1 <sup>1</sup>	85.9 <sup>1</sup>		0.70610	0.6409
	18.9 <sup>2</sup>	85.7 <sup>2</sup>	0.2210		
ANT 69	4.22 <sup>1</sup>	120 <sup>1</sup>		0.70532	0.1010
	4.2 <sup>2</sup>	121 <sup>2</sup>	0.03474		
ANT 70	7.96 <sup>1</sup>			0.70523	0.2967
	8.05 <sup>2</sup>	78.4 <sup>2</sup>	0.1026		
ANT 71	6.11 <sup>1</sup>			0.70523	0.2527
	6.16 <sup>2</sup>	70.6 <sup>2</sup>	0.08736		
ANT 72	22.2 <sup>1</sup>			0.70550	0.6016
	22.4 <sup>2</sup>	108 <sup>2</sup>	0.2080		
ANT 73	19.1 <sup>1</sup>			0.70545	0.5666
	19.1 <sup>2</sup>	97.7 <sup>2</sup>	0.1959		
ANT 74	8.05 <sup>1</sup>			0.70538	0.2696
	8.03 <sup>2</sup>	86.2 <sup>2</sup>	0.09322		

<sup>1</sup> Isotope dilution.

<sup>2</sup> X-ray fluorescence spectrometry. Mean of duplicate analyses.

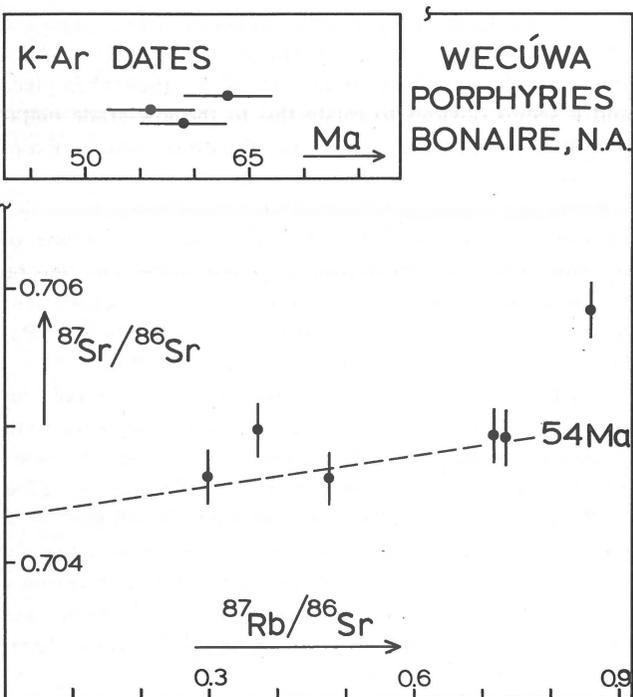


Fig. 4  
Plot of Rb-Sr data and K-Ar ages of the Wecúwa porphyries.

data-points. The rock comes from about the same location as the other samples, so it seems difficult to explain this high point as due to a higher initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio. Possibly, it may be interpreted as reflecting the absence of, or an incomplete, Sr isotopic exchange of this rock with its environment during the metamorphism, so that the old Rb-Sr system was (partially) arrested.

Of the six K-Ar analyses of samples from the Washikemba and Sumpiña porphyries, five lie between about 76 and 80 Ma, averaging  $78 \pm 2$  Ma. A sixth sample has a K-Ar age of about 62 Ma. The Rb-Sr data of the seven investigated samples tend to be correlated according to a line corresponding to an age of 72 Ma.

From the persistency of K-Ar ages of about 78 Ma through the Washikemba and Sumpiña porphyries, which age is also supported by the Rb-Sr systems, it can be concluded that the age of  $78 \pm 2$  Ma has geologic significance. This age is therefore interpreted as reflecting another episode of increased ambient temperature during an event of low-grade metamorphism in Campanian time.

Only one of the investigated samples from the Washikemba and Sumpiña porphyries was sufficiently influenced by the Palaeocene event of low-grade metamorphism to produce a resetting of the K-Ar clock. The Wecúwa porphyries, on the other hand, display a full resetting during this event of all of the investigated K-Ar and most of the Rb-Sr systems. Such a different response towards the metamorphism obviously reflects a somewhat higher intensity of the Palaeocene meta-

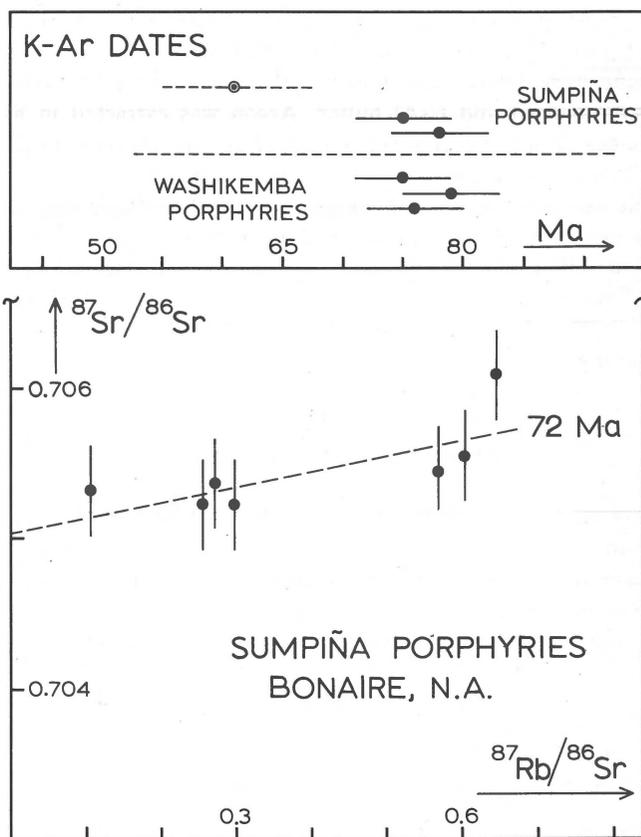


Fig. 5  
Plot of Rb-Sr data and K-Ar ages of the Sumpiña porphyries and K-Ar ages of the Washikemba porphyries.

morphic heating event, which may be related to the deeper level in the crust of the Wecúwa porphyries: in the stratigraphic column of the Washikemba Formation they lie about 2800 m below the Washikemba porphyries and about 4000 m below the Sumpiña porphyries (Fig. 2).

K-Ar ages of 58, 71 and 76 Ma were measured on the poeneitic flow. The highest age falls within the range of isotopic ages displayed by the Washikemba and Sumpiña porphyries, and may thus reflect the inferred Campanian event of low-grade metamorphism. The ages of about 71 and 58 Ma may be interpreted as reflecting partial and complete resetting, respectively, during the Palaeocene event of low-grade metamorphism.

The four hornblendes from the tuffaceous layer in the horizon containing Turonian/Coniacian fossils yield K-Ar ages spreading between about 73 and 100 Ma. This spread may be due to the weathering shown by the samples, but in one sample (ANT 35) the presence of some excess radiogenic Ar may also play a role. Two hornblendes, however, give K-Ar ages averaging  $88 \pm 2$  Ma, which fits very well in the Turonian/Coniacian biostratigraphic age of the tuffaceous layer.

The K-Ar age of  $68.5 \pm 2$  Ma shown by the diabase will approximate the age of the intrusion, as doleritic and dioritic

intrusions with an age of about 70 Ma are also known from Curaçao and Aruba (Z.W.O. Laboratory of Isotope Geology, Amsterdam, unpublished data). It is also possible, however, that we are dealing with a partial resetting of an older K-Ar system due to the Palaeocene event of low-grade metamorphism.

The Rb-Sr data of the investigated samples from the Wecúwa and Sumpiña porphyries point to initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of  $0.7043 \pm 0.002$  and  $0.7051 \pm 0.0004$  ( $2\sigma$ ), respectively. These values do not represent the Sr isotopic composition at the time of the volcanism, however, but they are the result of Sr isotopic redistribution during either one of the two events of low-grade metamorphism. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the extruding volcanics must have been somewhat lower. If we assume ages of about 100 Ma for the Wecúwa porphyries and about 90 Ma for the Sumpiña porphyries, the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the magmas can be calculated at about 0.7039 and 0.7050, respectively. These values lie above the range 0.702-0.703 deduced for the sub-oceanic upper mantle, but fall within the commonly observed variability 0.703-0.705 in the andesitic-dacitic associations of oceanic island arcs (FAURE & POWELL, 1972; FAURE, 1977). For the Sumpiña porphyries, the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio appears to be slightly higher than for the Wecúwa porphyries; this may be explained in terms of some contamination with radiogenic Sr from older sialic rocks or their derivatives (e.g., terrigenous sediments coming from the nearby continent), or to some interaction with sea water. Variations in the Sr isotopic composition of cogenetic magmas in island arcs are not uncommon, however, and appear to be controlled in a complex and not yet fully understood way by factors such as the depth of the Benioff zone, the tectonic setting and the petrogenetic processes by which the magmas were generated from the descending lithospheric plate (FAURE, 1977).

## CONCLUSIONS

Except for the hornblendes with an age of  $88 \pm 2$  Ma, which record the time of the eruption of this tuffaceous material, all K-Ar and most of the Rb-Sr systems in the investigated volcanic and subvolcanic rocks of the Washikemba Formation appear to have been reset by either one of two events of low-grade metamorphism. The first event occurred  $78 \pm 2$  Ma ago (Campanian), some 10 Ma after the deposition of the uppermost part of the Washikemba Formation. For the second event an age of  $61 \pm 4$  Ma can be deduced. The initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the magmas fall within the common range of the andesitic-dacitic associations of oceanic island arcs.

## ACKNOWLEDGEMENTS

Many thanks are due to Prof. Dr. H. J. Mac Gillavry and Mr. G. Klaver, both from the University of Amsterdam, for assistance and helpful discussions in the course of this work. The programme of isotopic dating on Bonaire was undertaken in the framework of a joint research project in the Leeward Netherlands Antilles by the Dept. of Geology, University of Amsterdam, and the Z.W.O. Laboratory of Isotope Geology, Amsterdam. It forms part of the research programme of the 'Stichting voor Isotopen-Geologisch Onderzoek', supported by the Netherlands Organisation for the Advancement of Pure Research (Z.W.O.).

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