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Magmatism of the troughs behind the New Hebrides island arc (RV Jean Charcot SEAPSO 2 cruise): K-Ar geochronology and petrology

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ABSTRACT

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The chronological, petrological and geochemical studies of lavas dredged from the New Hebrides back-arc troughs allow a new interpretation of the origin of these troughs. In every area, volcanism from the troughs precedes that of the adjacent islands. Four main periods of volcanic activity have been defined: 6.5 to 4.8, 4.1 to 2, 2 to 1 and 1 to 0 Ma. The volcanic affinity is generally orogenic. But some variation exists and two geochemical types (Mg-IAT basalts and hyper-K acid lavas) seem to mark the trough structuration. The succession of the different geochemical types reveals a polyphased and diachronous formation of the troughs from south to north on an arc substratum. Only the Vanikoro area (the most northern one) shows basalts with geochemical characteristics intermediate between MORB and island-arc tholeiites and acid lavas near primitive island-arc lavas, which illustrate the initiation of the arc in this area. So, the New Hebrides back-arc troughs must be considered as intra-arc troughs and are back-arc structures only because of their location at the rear of the active emerging arc.

Outline of the structure

The New Hebrides arc (NH) is associated with the subduction of the Australian plate beneath the North Fiji Basin (NFB). The NH arc is divided into three geological provinces (Mitchell and Warden, 1971): the western one (Santo and Malekula islands), the eastern one (Maewo and Pentecost islands) and the central chain, from Vot Tande to Anatom (Fig. 1). Along the eastern flank of the arc lie several troughs related to tensional stresses. The purpose of SEAPSO 2 cruise (R/V Jean Charcot, 1985) was the study of the back-arc area. It is divided into three tectonic provinces: the Central one, east of Maewo and Pentecost islands, shows compressive features related to the subduction–collision of the d'Entrecasteaux ridges with the NH arc (Collot et al., 1985). North and south of it, discontinuous grabens are developed where volcanism occurs on their flanks and bottoms. These two domains differ from each other in their structure and evolution (Récy et al., 1986).

The southern Coriolis province includes the Vate (VA), Erromango (ERR), Tanna (TA) and Futuna (FUT) troughs. The VA troughs

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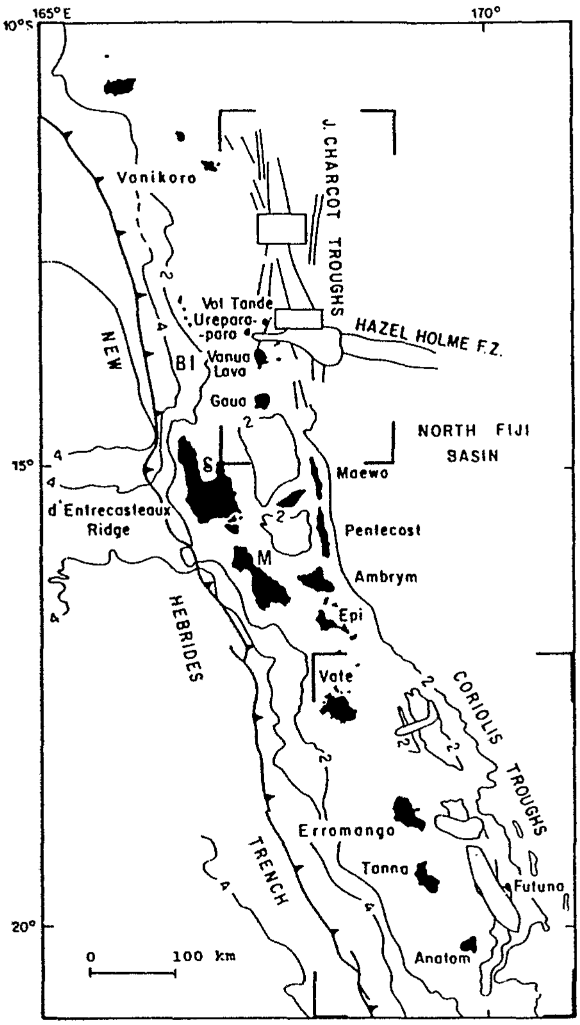


Fig. 1. Bathymetric map of the New Hebrides island arc and back-arc area, from Chase et al. (1983), Monzier et al. (1984), Charvis and Pelletier (1989). The abbreviations mean: *M* = Malekula, *S* = Santo, *BI* = Bank Islands.

are double NNW–SSE grabens; the FUT-TA-ERR trough, N 150° oriented, is bounded by normal faults trending either N 135° or N 165°E (Récy et al., 1986). These grabens are relatively large (up to 40 km in width and 300 km in length) and deep (−2000 to −3500 m).

Dredges locations are given in Table 1 and Figure 2.

– Samples from the Vate trough come from its eastern flank (D26, 27, 28 and 29). Two small isolated cones, located on the northern edge of the trough, were also sampled (D30 and 31).

– Dredge 24 yielded samples from the western flank of the Erromango trough. A small cone, at the northwestern edge of the trough, has also been sampled (D25).

– The Futuna trough has been sampled along its eastern flank (D16, 17 and 19). D20 samples come from an isolated cone on the northwestern flank of the trough. Some small elongated outcrops have also been sampled in the southwestern part of the trough (D21).

The northern Jean Charcot province is characterized by discontinuous, small (5 to 20 km in width) horsts (−1500 to −2000 m) and grabens (−3000 to −3500 m) (Charvis and Pelletier, 1989). The N–S to N 10°E troughs terminate southward against the N 100°E North Fiji Basin Hazel Holme fracture zone (HHFZ) (Chase, 1971). Note that the Vanikoro (VAN) and Vot Tande (VT) areas are situated at the northern and southern end, respectively, of the northern troughs province (Jean Charcot province).

Dredges locations are given in Table 1 and Figure 2.

The VAN trough is occupied by a large composite volcano (ca. 20 km in diameter) sampled from west to east in dredges D1, 2, 3 and 5. The eastern flank of the trough was sampled in dredges D6 and 7.

The VT trough is characterized by a N–S central volcanic ridge (dredge D11). A small isolated cone (D10) lies between this ridge and the eastern flank of the trough. The western flank has been sampled in dredge D12.

The HHFZ was dredged on the southern scarp of its western termination (D14 and 15).

In summary, two main types of structures have been sampled: the trough flanks and the volcanic cones of edifices located on the floor of the trough or on the northwestern flanks. The non-tectonized nature of these volcanic edifices indicates that they were built after the main development of the troughs. Thus, the age of the lavas from these edifices

TABLE 1

Seapso-2 dredges parameters: depth and heading

Box dredge	From	To	Depth	Heading
Vanikoro				
D1	12°12.9'S-126°34.6'E	12°11.9'S-167°34.9'E	−1470 to −940	N 30°E
D3	12°13.5'S-167°40.6'E	12°10.9'S-167°42.1'E	−1350 to −900	N 35°E
D5	12°09.1'S-167°48.5'E	12°08.8'S-167°48.8'E	−1850 to −1650	N 40°E
D6	12°14.7'S-167°50.3'E	12°15.8'S-167°51.0'E	−2450 to −2120	N130°E
D7	12°16.3'S-167°51.8'E	12°16.9'S-167°52.7'E	−2165 to −1930	N110°E
Vot Tande				
D10	13°23.9'S-167°59.7'E	13°24.8'S-167°59.6'E	−2130 to −1800	N220°E
D11	13°20.9'S-167°57.1'E	13°21.7'S-167°55.9'E	−2000 to −1550	N230°E
D12	13°20.9'S-167°49.2'E	13°21.4'S-167°48.1'E	−2200 to −1600	N250°E
D13	13°21.5'S-167°47.7'E	13°21.3'S-167°47.0'E	−1730 to −1400	N250°E
Hazel Holme				
D14	13°40.0'S-168°30.0'E	13°41.6'S-168°28.8'E	−3800 to −2870	N190°E
D15	13°41.0'S-168°29.7'E	13°41.9'S-168°29.6'E	−2900 to −2500	N180°E
Futuna				
D16	19°47.8'S-170°16.5'E		−3320 to −2500	N 30°E
D17	19°47.6'S-170°17.2'E	19°46.8'S-170°18.3'E	−2900 to −2150	N180°E
D19	19°46.3'S-170°19.1'E	19°46.2'S-170°20.6'E	−1750 to −1550	N 90°E
D20	19°25.0'S-169°54.6'E	19°25.6'S-169°55.5'E	−1400 to −1000	N150°E
D21	19°54.1'S-170°17.0'E	19°55.5'S-170°18.6'E	−3280 to −3150	N148°E
Erromango				
D24	18°47.8'S-169°35.1'E	18°47.9'S-169°34.9'E	−1420 to −900	N215°E
D25	18°32.4'S-169°34.3'E	18°31.9'S-169°34.8'E	−910 to −750	N100°E
Vate				
D26	17°38.6'S-169°24.7'E	17°39.4'S-169°25.6'E	−2080 to −1850	N 95°E
D27	17°39.8'S-169°25.5'E	17°39.5'S-169°26.3'E	−1960 to −1200	N 80°E
D28	17°38.4'S-169°26.4'E	17°38.2'S-169°25.8'E	−1270 to −700	N 85°E
D29	17°38.4'S-169°26.6'E	17°38.2'S-169°26.1'E	−980 to −600	N 80°E
D30	17°23.3'S-169°02.5'E	17°23.2'S-169°02.1'E	−1270 to −1200	N270°E
D31	17°23.5'S-169°08.0'E	17°23.6'S-169°09.0'E	−1570 to −1250	N100°E

will give a minimum age of the trough formation.

This study presents data obtained on dredged lavas from the troughs and also on lavas from some of the main volcanic edifices of the NH arc, that are located near the dredged areas. Chronological data allow us to define the order of major magmatic events which occurred during the construction of the arc and that affected the present back-arc area. This information, coupled with petrological and geochemical data for the lavas of the arc-back arc system, can be used to construct a model for evolution in time and space.

Isotopic ^{40}K-^{40}Ar chronology

Analytical procedures

Argon isotopic analyses were performed at the University of Brest, by M.C. Monjaret, H. Bellon and J.C. Philippet.

Whole-rock samples were crushed to pass 20 mesh, and portions finer than 80 mesh were discarded. The remaining fraction was washed in distilled water and then homogenized before splitting into two aliquots. One aliquot was further crushed to pass 100 mesh and was used for K analyses by atomic absorption.

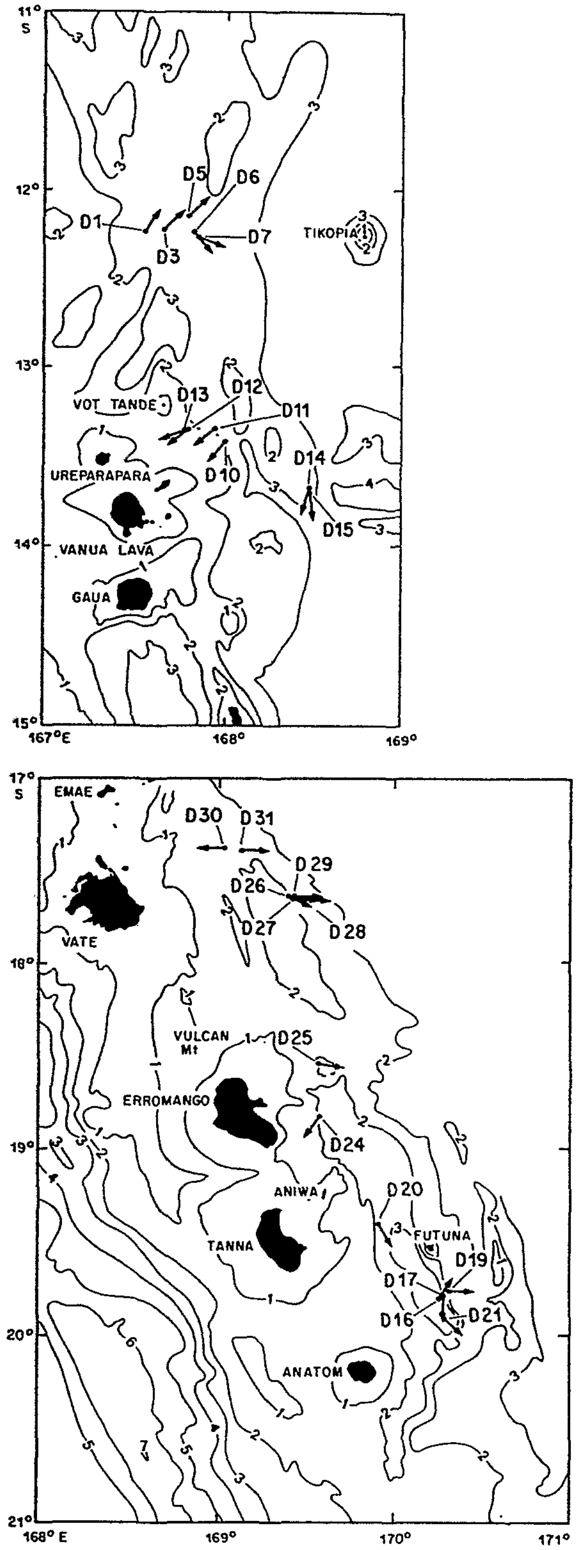


Fig. 2. Locations of dredges in the J. Charcot troughs (upper map) and in the Coriolis troughs (lower map).

Argon extraction was performed by the direct fusion technique under vacuum (10^{-5} to 10^{-7} Torr) using induction heating in a molybdenum crucible. Prior to Ar extraction, samples were baked at 160°C for 48 h under dynamic vacuum. During the fusion under static vacuum, argon, other rare gases, and active gases (hydrogen, oxygen, nitrogen and carbon monoxide and dioxide) were purified. All chemically active gases were gathered on hot titanium sponge collectors, the temperature of which was first raised to 800°C and then lowered to room temperature. The remaining gases were collected on a charcoal trap activated with liquid nitrogen, and were then purified on an aluminium-zirconium getter-pump before their introduction in the mass spectrometer cell. The argon content was measured by isotope dilution. An aluminium foil target containing a known volume of ^{38}Ar, buried as positive ions under a 30-keV energy (Bellon et al., 1981) was added to each sample at the time of weighing and was used as a spike. Consequently, isotope dilution and homogenization were achieved during the fusion of the sample.

Argon isotopes were analyzed in a 180° stainless-stell mass spectrometer. Argon air standards, in the volume range of the samples, were run after each sample measurement in order to make a correction for mass discrimination.

Results

Results are classified in a scale from 1 to 5 according to two main patterns: percentage of $^{40}Ar^*/^{40}Ar_{tot}$ and ^{36}Ar content, presented in Table 2. Of course, these two patterns depend on the age and the K_2O content for every lava.

The $\%^{40}$Ar versus $K_2O\%$ diagram (Fig. 3) does not show a simple linear correlation, but some points with the same K_2O content and belonging to the same age groups have different $\%^{40}Ar^*$. Thus, ages with the higher

TABLE 2

K-Ar isotopic ages of dredged selected lavas of the New Hebrides back-arc troughs. Structural location of samples and isotopic data
Isotopic ages are calculated, using constants by Steiger and Jäger (1977), according to the following formula: $t = 4154.04 \log [1 + 142.69\ (^{40}Ar^*/K)]$. $^{40}Ar^*$ in cm^3; K in g; t in million(s) years (Ma); $^{40}K = 0.01167\%$ of total K in atoms. Analytical uncertainties are estimates as follows: with the percentage of K_2O exceeding 0.1% and $(^{40}Ar^*/^{40}Ar)_T > 15\%$, Inc = 5% of calculated age

Sample	Structural setting	Age (Ma)	Class	$\%K_2O$	$\%^{40}Ar^*/^{40}Ar_T$	^{36}Ar (10^{-9} cm^3/g)	Number	Type
Vanikono								
D7M2	Eastern flank	12.4 ± 0.9	2	0.12	10.1	1.45	2	a
D5M4	Offset eastern cone	3.9 ± 0.6	2	0.27	6.4	1.66	2	f
D5M1	Of the edifice	2.9 ± 0.4	2	0.23	9.6	0.69	2	f
D6M1	Eastern flank	2.6 ± 0.5	3	0.54	11.0	1.24	2	c
D7M4	Eastern flank	2.3 ± 0.2	3	1.20	12.7	2.02	2	e+c
D3M1	Eastern cone	1.8 ± 0.1	1	0.65	12.4	0.90	1	g
D3M3	Eastern cone	1.8 ± 0.3	2	0.38	8.2	0.81	2	f
D3M2	Eastern cone	1.5 ± 0.4	3	0.71	3.7	3.03	3	g
D1M9	Western cone	1.5 ± 0.1	1	0.70	10.1	1.03	1	g
D3M4	Eastern cone	1.1 ± 0.2	2	0.17	6.1	0.32	2	f
D1M3	Western cone	1.1 ± 0.2	2	0.98	7.4	1.46	2	g
D1M8	Western cone	1.1 ± 0.2	2	0.81	8.7	0.98	1	g
D1M5	Western cone	<0.3	2	0.90	3.0	0.98	2	g
Vot Tande								
D11M1	Central ridge	4.9 ± 0.2	2	0.98	16.5	2.66	2	e+c
D11M2	Central ridge	4.8 ± 0.2	2	1.06	22.0	0.98	1	e+c
D12M1	Western flank	2.8 ± 0.1	1	0.66	19.2	0.86	3	d
D10M1	Cone from trough bottom	2.8 ± 0.1	1	0.57	16.1	0.89	1	c
D10M2	Cone from trough bottom	2.7 ± 0.1	1	0.67	15.9	1.04	2	c
Hazel Holme								
D14M1	Southern scarp, basis	5.5 ± 0.4	2	0.26	11.6	1.20	1	a
D14M2	Southern scarp, basis	5.2 ± 0.8	2	0.21	8.9	0.22	2	a
D15M6	Southern scarp, top	4.1 ± 0.2	1	0.69	22.3	1.09	2	b
D15M12	Southern scarp, top	3.5 ± 0.3	3	4.07	13.1	10.22	1	i
Vate								
D27M12	Eastern flank, basis	3.5 ± 0.3	1	0.76	11.7	2.17	2	d
D27M17	Eastern flank, basis	3.4 ± 0.2	1	5.66	34.4	4.00	2	i
D29M6	Eastern flank, top	3.2 ± 0.2	1	1.74	30.5	1.39	1	e+d
D29M3	Eastern flank, top	3.0 ± 0.2	3	4.78	10.7	13.15	1	i
D27M4	Eastern flank, basis	2.4 ± 0.1	1	4.85	32.9	2.61	1	i
D28M1	Eastern flank, middle	2.2 ± 0.2	2	6.50	13.6	10.05	2	i
D27M1	Eastern flank, basis	2.2 ± 0.1	2	4.93	19.0	5.13	2	i
D31M2	Cone at the north of trough	1.5 ± 0.2	3	0.35	5.6	0.95	1	d
D31M1	Cone at the north of trough	1.4 ± 0.2	2	0.44	6.3	0.99	2	d
D30M2	Cone at the north of trough	1.4 ± 0.2	3	0.60	9.3	0.92	2	d
D30M1	Cone at the north of trough	1.1 ± 0.2	2	0.68	7.7	0.99	1	d
D26M7	Eastern flank, basis	0.5 ± 0.1	2	3.64	8.1	2.45	1	h
D26M6	Eastern flank, basis	0.4 ± 0.05	1	3.70	15.2	1.01	2	h
Erromango								
D24M4	Western flank, basis	4.1 ± 0.2	2	0.91	18.2	1.84	2	d
D25M2	Cone on the NW flank	4.1 ± 0.3	3	0.66	13.1	1.95	3	c
D25M4	Cone on the NW flank	4.0 ± 0.6	3	0.60	7.4	3.32	1	
D24M6	Western flank, basis	3.6 ± 0.2	2	0.86	15.3	1.84	2	b
D24M3	Western flank, basis	2.7 ± 0.1	1	3.11	40.3	1.36	1	h
Futuna								
D21M7	Small relief (trough bottom)	6.5 ± 0.5	1	0.36	12.0	1.87	2	d
D21M1	Small relief (trough bottom)	6.1 ± 0.3	3	0.91	17.9	2.76	1	e+d
D17M3	Eastern flank, basis	6.1 ± 0.3	3	1.74	25.0	3.45	2	e
D16M1	Eastern flank, basis	5.2 ± 0.3	3	1.89	27.8	2.79	3	e
D19M1	Eastern flank, bottom	2.6 ± 0.2	3	0.81	10.1	2.06	2	c+d
D20M1	Cone on the NW flank	0.7 ± 0.3	3	0.53	8.2	1.12	2	c
D20M6	Cone on the NW flank	0.7 ± 0.2	1	0.88	5.0	1.20	2	c

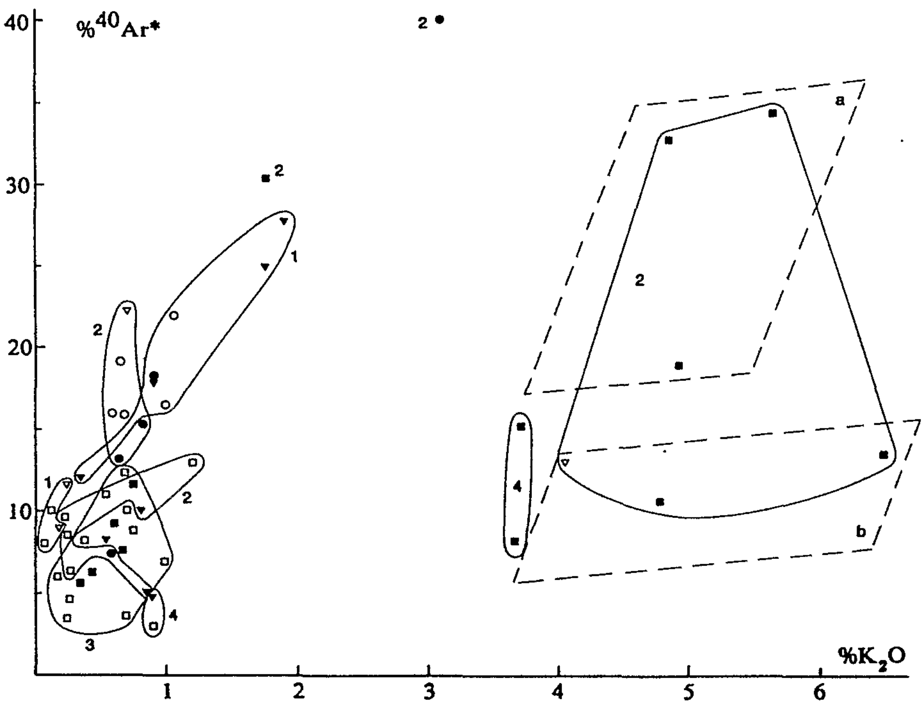


Fig. 3. (%^{40}Ar*/^{40}Ar$_{tot}$) versus K_2O% of lavas from the New Hebrides back-arc troughs.

%^{40}Ar* are better than the others. In the same way, it is possible to establish a classification of ages on the basis of ^{36}Ar content. We also take into account the reproducibility of results for a given sample. Therefore, we have divided the samples into five classes:

– *Class 1* includes the ages of samples with low ^{36}Ar content, high %^{40}Ar*, and thus a good reproducibility.

– *Class 2* includes the ages of samples with a lower %^{40}Ar*, due to a low K_2O content and/or low age.

– *Class 3* includes the ages of samples which are slightly enriched in ^{36}Ar or have a rather low %^{40}Ar*, and which do not show a good reproducibility.

– *Class 4* consists of more problematic ages of samples because of a low K_2O content, a high ^{36}Ar content, or a bad reproducibility despite of a relatively high K_2O content.

– *Class 5* is formed by the ages of samples with a great uncertainty.

We only consider as representative ages those of the three first, and only these ages are used in the construction of the trough histories. The main results are presented in Table 2 and the macroscopic characteristics and the loss on ignition (LOI %) of the analyzed lavas are listed in Table 3.

Coriolis troughs

– Volcanic activity is recorded on the eastern flank of the Vate trough between 3.5 ± 0.3 Ma and 2.2 ± 0.2 Ma. The two small cones on the northern edge of the trough were built up between 1.5 and 1.1 Ma. The most recent lavas come from the base of the eastern flank and are probably fallen blocks.

– Volcanic activity began earlier in the Erromango trough. Samples of this area define an activity phase between 4.1 ± 0.2 and 3.6 ± 0.2 Ma and another stage at about 2.7 ± 0.1 Ma.

– The oldest dated lavas in the southern domain occur in the Futuna trough on small

TABLE 3

Macroscopic characteristics and loss on ignition (1050°C) of the dated samples

	Macroscopic description	LOI%
Vanikoro		
D7 M2	Massive aphyric basalt	0.12
D5 M4	Aphyric basalt with 2.5-mm vesicles; altered rim and 2-mm encrusting	0.31
D5 M1	Aphyric pillow basalt with altered rim and a few vesicles	0.61
D6 M1	Slightly porphyritic pillow basalt with 4-mm vesicles and 5-mm manganesiferous encrusting	0.76
D7 M4	Slightly porphyritic basic andesite with a few vesicles	0.85
D3 M1	Fresh vitreous basic andesite with 2.5-mm vesicles	0.90
D3 M3	Fresh subaphyric basalt with 1.5-mm vesicles	0.37
D3 M2	Comparable with D3 M1 basic andesite	1.22
D1 M9	Fresh slightly porphyric dacite with 3-mm elongated vesicles	0.87
D3 M4	Fresh aphyric basalt with 2-mm vesicles	0.48
D1 M3	Comparable with D1 M9 dacite	1.05
D1 M8	Fresh slightly porphyritic dacite with a few 4-mm vesicles	0.77
D1 M5	Comparable with D1 M9 and D1 M8 dacites	0.84
Vot Tande		
D11 M1	Block of slightly altered massive and porphyritic basalt from a breccia	2.33
D11 M2	Comparable with D11 M1 block, but with oxidized encrusting	0.97
D12 M1	Slightly porphyritic basalt with a few elongated vesicles	0.46
D10 M1	From a volcanic breccia: slightly (plagioclase) porphyritic basalt	0.65
D10 M2	Comparable with D10 M1	0.54
Hazel Holme		
D14 M1	Altered massive and slightly porphyritic basalt	5.18
D14 M2	Comparable with D14 M1 basalt	5.06
D15 M6	Slightly (plagioclases) porphyritic basalt with vesicles	1.41
D15 M6	Grey-brownish, massive and slightly porphyritic andesite	1.98
Vate		
D27 M12	Grey-greenish altered doleritic basalt	6.11
D27 M17	Coarse-grained rock with altered feldspars	0.71
D29 M6	Grey-greenish altered porphyritic (cumulitic) basalt with a few vesicles	7.54
D29 M3	Grey-brown porphyritic dacite with 1-mm rounded vesicles	2.41
D27 M4	Slightly porphyritic	2.80
D28 M1	Coarse-grained rock slightly spilitized	1.94
D28 M1	Dark grey porphyritic dacite with a few 2-mm vesicles	4.32
D27 M1	Pillowed porphyritic basalt with vesicles; manganesiferous rim (thickness = 3 mm)	0.42
D31 M1	Porphyritic basalt (plagioclase + clinopyroxene + olivine) with 5-mm vesicles	0.19
D30 M2	Fresh porphyritic basalt with 1-mm vesicles	0.44
D30 M1	Porphyritic basic andesite (plagioclase + olivine + clinopyroxene) with 2-mm vesicles	0.37
D26 M7	Comparable with D26 M6 dacite	1.98
D26 M6	Very fresh black and vitreous porphyritic dacite	2.49
Erromango		
D24 M4	Highly porphyritic basalt (plagioclase + clinopyroxene + olivine)	0.35
D25 M2	Highly porphyritic basalt (plagioclase + clinopyroxene) with a few 5-mm vesicles	0.01
D25 M4	Highly porphyritic basalt	N.D.
D24 M6	Porphyritic brecciated basalt	1.48
D24 M3	Grey dacite (slightly porphyritic)	1.19
Futuna		
D21 M7	Massive porphyritic basalt	1.56
D21 M1	Highly porphyritic (clinopyroxene + plagioclase + olivine) and massive basalt	1.03
D17 M3	Highly porphyritic (plagioclase + clinopyroxene) basic andesite	3.20
D16 M1	Massive porphyritic (plagioclase + clinopyroxene) basic andesite	4.22
D19 M1	Pillowed basalt with 1-cm encrusted rim	1.73
D20 M1	Fresh highly porphyritic (plagioclase + clinopyroxene + olivine) and vitreous andesite	0.15
D20 M6	Fresh porphyritic basic andesite with 2-mm vesicles	0.18

Note: Linear size of vesicles within lavas is given in millimeters (mm).

southwestern outcrops (6.5 ± 0.5 and 6.1 ± 0.3 Ma) and also on the eastern flank basis (6.1 ± 0.3 and 5.2 ± 0.3 Ma). The top of this flank shows more recent lavas of 2.6 ± 0.2 Ma. The cone on the northwestern flank of the trough contains lavas of 1.7 ± 0.3 and 0.7 ± 0.2 Ma.

The oldest activity in the Coriolis troughs is limited to the Futuna area, between 6.5 and 5.2 Ma. Younger activity is represented in the Erromango area (4.1 Ma) and in the Vate area (3.5 Ma). So, the age of the onset of volcanic activity decreases northward in the Coriolis troughs.

Jean Charcot troughs

- The oldest remnants found in all the New Hebrides back-arc troughs are probably from the eastern flank of the Vanikoro trough: 12.4±0.9 Ma. But these lavas are probably the "remnants" of the substratum of the troughs.

The history of the Vanikoro trough could begin at about 2.9 Ma with the building of a major composite volcano in the center of the trough. This volcano was built between 2.9 and 1.1 Ma from east to west, primarily between 1.8 and 1.1 Ma. In the most western part, lavas are dated at 0.3 Ma.

- Lavas from the volcanic ridge of Vot Tande trough are dated at 4.9–4.8 ± 0.2 Ma. Basalts from the small adjacent cone and from the western flank have comparable ages: 2.7 and 2.8 ± 0.1 Ma.
- Lavas from the Hazel Holme scarp are dated at 5.5 ± 0.4–5.2 ± 0.8 Ma, 4.1 ± 0.2 Ma and 3.5 ± 0.3 Ma.

These results are summarized in Table 2 and Figure 4 and imply the following:

- Excepting two isotopic ages older than 10 Ma, all the ^{40}K-^{40}Ar ages carried out on whole-rock samples scatter between 6.5 and near 0 Ma (in this latter case, only a tendency towards 0 Ma could be defined, this being due to the difficulty of detection of radiogenic argon in very young samples, even if they are fresh and thus suitable for dating).
- The age spectra (Fig. 4) of both the northern and the southern areas (abbreviated N.A. and S.A.) from the troughs and lavas from the islands (Monjaret, 1989), allows a grouping of the results in four main units, here considered as main periods of volcanic activity: (I) – activity prior to 4.8 Ma; (II) – activity between 4.1 and 2 Ma; (III) – activity between 2 and 1 Ma; (IV) – activity younger than 1 Ma.
- Such a subdivision into four groups is easier for the northern area where pauses in volcanic activity are clearly defined. For the southern area, excepting a time break between 4.8 and 4.1 Ma, the activity appears more continuous. Another criterion has been used to isolate the third period from its adjoining periods II and IV: between 2 and 1 Ma volcanic activity occurs almost solely within the islands of the southern area, whereas volcanic activity during the periods II and IV occurred in both geotectonic position, i.e., troughs and islands. A similar pattern characterizes the activity in the northern domain since 4.1 Ma.
- If the activity within islands of the northern area started around 3.5 Ma, the island volcanic activity seems earlier in the southern area where a submarine volcanic stage occurred from 5.8 to 5.3 Ma in Erromango (Colley and Ash, 1971; Bellon et al., 1984). But in the northern and southern domain, the volcanic activity is earlier in troughs than on islands.
- Only two zones VAN and FUT-TA, located at the northern and southern extremities of the whole arc and back-arc system, remain active during the four main periods.
- A southwestern shift of volcanic activity may be noticed during the third period (2–1 Ma) in the two domains, whereas an eastern migration occurred in the southern area during the last period (<1 Ma).

Petrology

88 samples from both geotectonic frameworks, i.e. back-arc and arc areas, were stud-

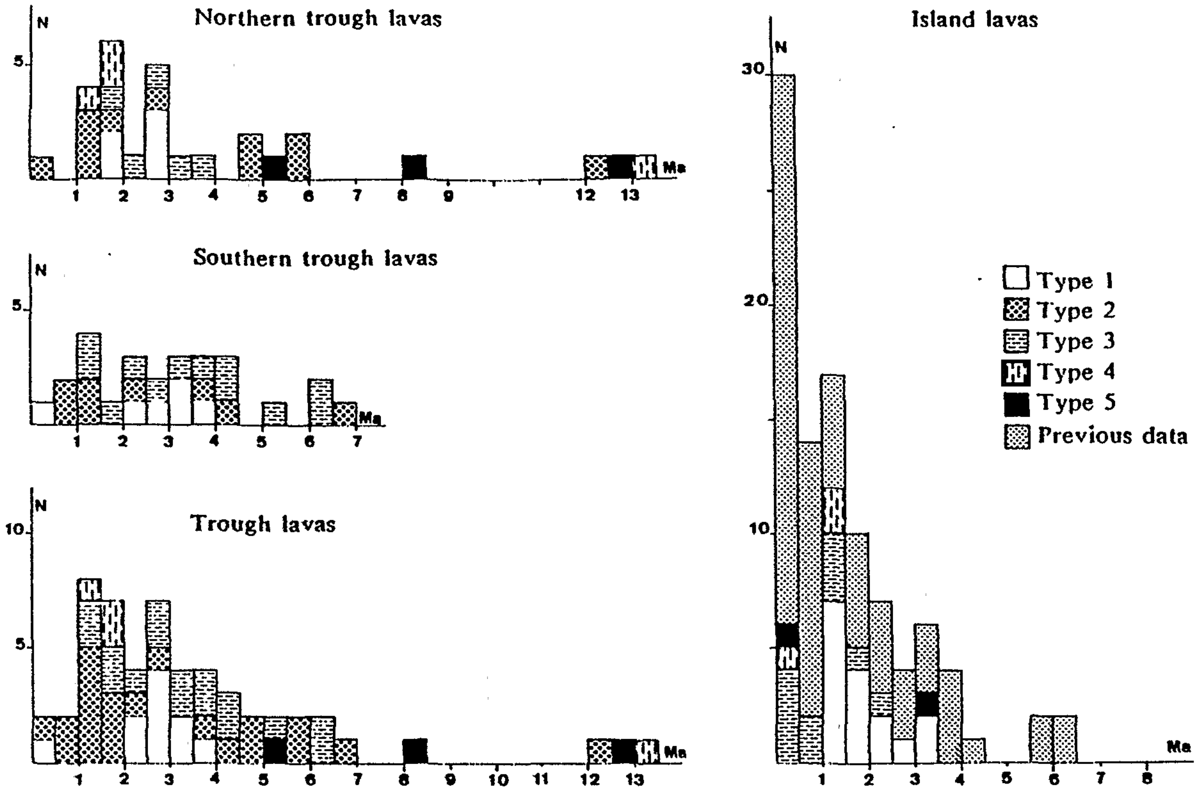


Fig. 4. Histogram of ages of lavas of the New Hebrides back-arc trough.

ied in order to determine their main petrological ad geochemical characteristics.

The dredged lavas show nearly the same SiO_2 range distribution (Monjaret et al., 1987) as do volcanics of the arc (Roca, 1978). Basalts (45–53% SiO_2) clearly predominate (60% of lavas). Basaltic and acid andesites (53–60% SiO_2) represent 13% of lavas, and dacites (SiO_2 >60%) 27%.

Thin-section studies allow a classification of the dredged rocks into two main groups. As opposed to volcanics from the N.A., samples from the S.A. are generally porphyritic (15% phenocrysts: plagioclase, clinopyroxene, ± olivine, orthopyroxene, ferro-titaniferous oxides), to highly porphyritic (50%), the latter showing a cumulate trend (cumulitic basalts and basic andesites from the FUT, ERR and VA troughs). These southern dredged volcanics resemble lavas that crop out in the southern islands when considering the frequency of rock types distribution (cumulitic basalts, basalts, basic andesites and rhyodacites) and the K_2O versus SiO_2 diagram. In contrast, lavas from the northern troughs are quite different from those of the northern islands with respect to their petrology, the abundance of rock types and their K_2O content for the range of silica contents. The majority of trough lavas differ from island lavas with respect to their high vesicularity (generally 20% of rock volume, and, more rarely up to 50%).

Main geochemical features of volcanism

56 lavas from the troughs and 22 from the islands were analyzed by atomic absorption, (J. Cotten analyst, UBO). Nine typical com-

TABLE 4

Geochemical types and representative analyses (major and trace elements analyzed by atomic absorption; J. Cotten analyst, U.B.O.) of erupted lavas in the New Hebrides back-arc trough

	Basic lavas						Acid lavas		
Type:	a MORB	b IAT	c Ti-IAT	d Mg-IAT	e CA	f Intermediate	g PIA	h K-CA	i HK-CA
K_2O	<0.2	>0.5	>0.5	>0.5	>1	0.15–0.4	<1	3–4	4–6.5
TiO_2	1.5	<0.8	1–1.5	1–1.5	<0.8	0.75–1.5	0.75–1.8	0.55–0.65	0.4–0.8
Al_2O_3	16–18	15–18	15–18	15–18	15–18	14.5–17	14.5–16.5	14–15	15–16
MgO	>7	<7	<7	7–12	<7	7–8	1–2.5	1–1.1	0.8–2
Mg#	60–65	<59	<59	66–73	<59	60–66			
Rb	2–3	>6	>6	>6	>10	1–6	7–13	55–70	65–115
Ba	10–65	>65	>65	>65	200–400	45–120	100–180	530–950	600–1050
Sr	160–170	>200	>200	>200	>400	170–270	150–200	260–280	100–300
Cr	>240	<100	<100	160–470	<100	130–260	2–7	<2–5	2–36
Example:	D7M2	D15M6	D10M1	D21M7	D16M1	D5M4	D1M5	D26M6	D27M4
SiO_2	47.00	51.20	49.40	50.20	53.45	50.15	67.00	65.70	63.40
TiO_2	1.36	0.72	1.03	0.50	0.82	0.79	0.86	0.55	0.50
Al_2O_3	17.60	17.05	18.25	13.16	14.72	16.53	14.99	14.36	15.09
Fe_2O_3	1.56	1.50	1.61	1.44	1.44	1.37	0.68	0.71	0.68
FeO	7.96	7.65	8.22	7.37	7.37	6.99	3.46	3.63	3.46
MnO	0.14	0.17	0.16	0.16	0.18	0.16	0.15	0.12	0.12
MgO	8.30	5.45	5.85	10.66	4.57	7.51	1.17	1.05	0.85
CaO	12.22	1.074	10.82	11.58	6.71	12.83	3.27	2.58	2.32
Na_2O	3.20	2.42	2.97	1.73	3.41	2.33	6.12	4.83	4.55
K_2O	0.11	0.68	0.61	0.32	1.84	0.32	0.83	3.70	4.92
P_2O_5	0.05	0.12	0.10	0.08	0.30	0.05	0.25	0.15	0.15
H_2O^+	−0.08	0.78	0.37	1.13	1.99	0.42	0.73	2.16	2.65
H_2O^-	0.24	0.63	0.28	0.43	2.23	0.19	0.11	0.33	0.44
Total	99.74	99.11	99.66	98.76	99.03	99.64	99.62	99.87	99.13
Rb	2	9	7	6	21	4	11	71	97
Ba	10	95	79	52	273	60	165	945	825
Sr	168	266	308	172	411	227	178	277	272
V	167	249	238	216	225	243	38	45	49
Cr	248	51	31	313	60	144	<4	6	2
Ni	139	30	35	127	21	48	<2	<2	1
Co						34	4		7

positions are presented in Table 4. K, Ti, Al and Mg are the most useful discriminant major elements; observed variations of Rb, Ba and Sr, and of Cr and Ni, follow those of the major elements. The geochemical types are defined by their K_2O contents; secondary types are established according to their MgO or TiO_2 contents.

Among the 56 submarine lavas, six types of basic lavas with the following distribution (bracketed number) may be recognized according to this classification:

(a) MORB (mid-oceanic ridge basalt) type, rich in plagioclase: K_2O <0.2% [6].

(b) IAT (island-arc tholeiite) type: K_2O >0.5% [3].

(c) IAT type with higher TiO_2 (1–1.5%) contents [7].

(d) IAT type (K_2O contents) but with larger Mg (MgO = 7–12% and Mg# 66–73) [9] and Cr (160–470 ppm) contents, related to the accumulation of ferromagnesian minerals.

(e) CA (calc-alkaline) type: K_2O >1%; these lavas can also have higher Ti or Mg contents [7].

(f) Type intermediate between MORB and IAT: K_2O = 0.15–0.4%. this lava type is only found in the VAN area [7].

Three types of acid lavas with the following distribution (bracketed number) can be recognized according to the classification of Peccerillo and Taylor (1976): (g) Low-K dacites: K_2O <1% [7].

(i) High-K dacites: K_2O = 3–4% [3].

(j) Hyper-K dacites: K_2O = 4–6% or more; the alkaline enrichment is specially well marked for K_2O [6]. They plot within the shoshonitic field in the K_2O versus SiO_2 diagram.

With the exception of types a (MORB), f (intermediate basalts) and g (low-K acid lavas), lavas found in the New Hebrides backarc troughs are typically orogenic and are very similar to the New Hebrides central chain lavas. Yet, it seems that two geochemical types could be more closely related to the fracture development in the troughs: Mg-IAT and hyper-K dacites.

Volcanic activity through time and space (Fig. 5)

The *oldest remnants* (13–12 Ma) were dredged in the VAN area and clearly have a MORB composition. With respect to their ages and their magmatic affinity, they could be remnants of oceanic basement from that stage of geological development prior to the NH are development. These ages are similar to the ones of the magnetic anomalies 5 and 5A. They are supposed to be present in this area.

During the *first arc-volcanic period* (6.5 to 4.8 Ma), except in the Hazel Holme area where E-MORB is found, volcanism is typically of orogenic affinity; the lavas are Mg-IAT (6.5 Ma) and then CA (6.1, 5.2, 4.9–4.8 Ma). Since no isotopic age has been obtained between 4.8 and 4.1 Ma, this period was probably marked by break in volcanic activity.

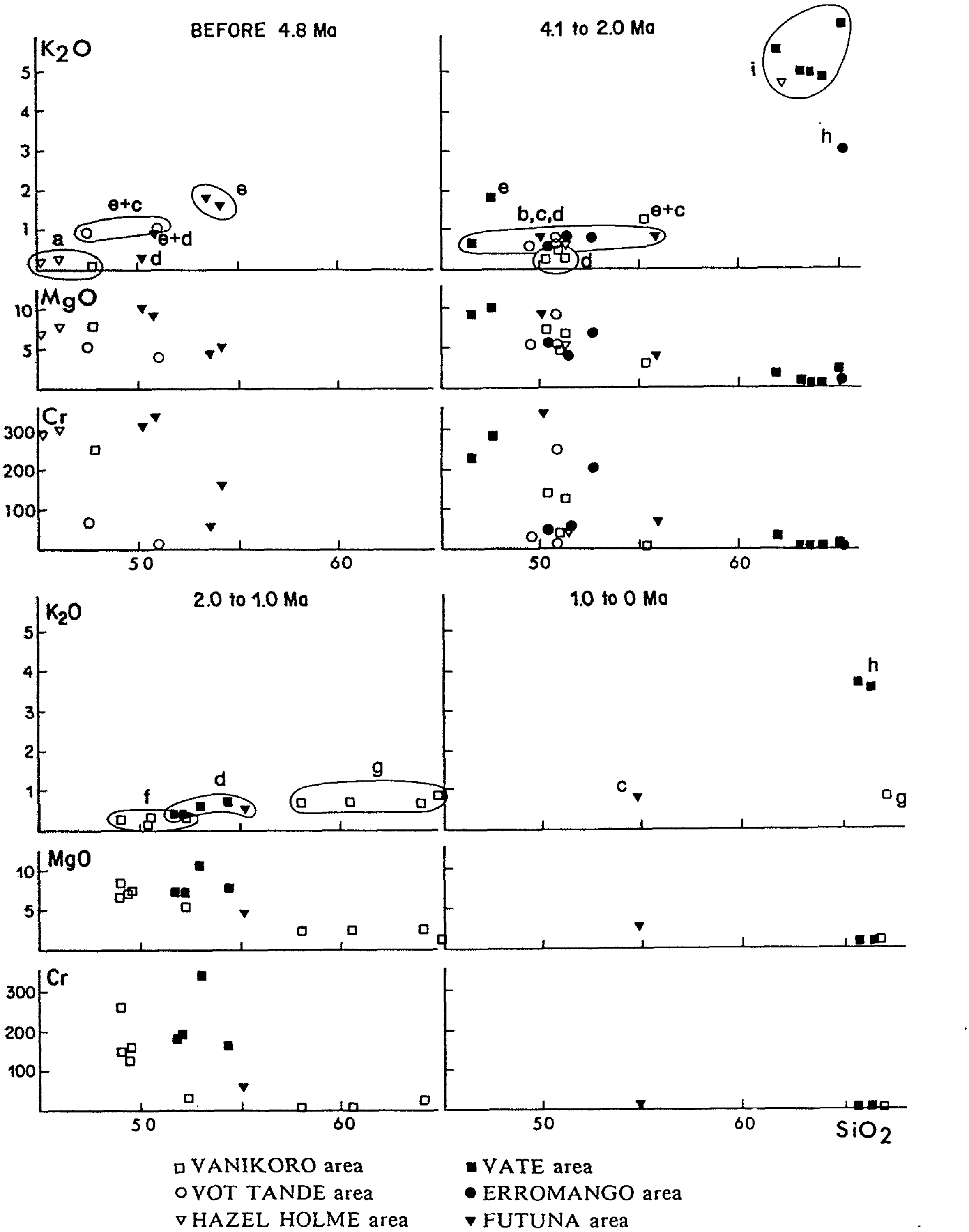
During the *second period* (4.1 to 2.0 Ma) volcanism is recorded in every area and is predominantly of orogenic affinity, almost always IAT, possibly Ti- or Mg-enriched. On the other hand, lavas from the volcanic edifice of VAN trough are basalts intermediate between MORB and IAT. This period is also characterized by the eruption of high-K or hyper-K acid lavas in the southern domain, and corresponds to the onset of building of some islands: Vot Tande (3.5–3 Ma), Mota Lava (2.5 Ma) and Tanna (2.8–2.3 Ma). Lastly, this period is a major stage on Erromango island where four volcanic centers have erupted andesites and pyroclastics around 2.56–2.33 Ma (Bellon et al., 1984).

The *third period* (2.0 to 1.0 Ma) is characterized by volcanic products similar to the second period. However, the VAN area exhibits low-K dacites which are similar to the differentiated lavas erupted in an incipient arc situation (Primitive Island Arc (PIA), Donnelly and Rodgers, 1980). These rocks are clearly distinguished from the others in the K_2O versus SiO_2 diagram (Fig. 5).

The third period is essentially dominated by island building. Thus, the small islands of Mota, Ureparapara and Merig (Mallick and Ash, 1975) were quickly built (1 Ma). The volcanic activity resumed in Gaua (Mallick and Ash, 1975). The volcanic activity is known in Vate (1.6–1.45 Ma), in Erromango (1.2–1.1 Ma) (Bellon et al., 1984), in Anatom (2 Ma, then 1.5–1.2 Ma) and in Futuna [from 2 to 1.8 Ma (Dugas et al., 1976) and at 1.4 Ma].

Also, the island volcanism shows a clear increase of its K_2O content in comparison with earlier episodes.

The *most recent activity* (1.0 to 0 Ma) was scarce in the troughs (VAN, VA and TA areas). It is known in the islands of Vanua Lake, Mota Lava, Mere Lava, Epi (Gorton, 1974), Vate, Erromango (Bellon et al., 1984) and Tanna (Carney and Macfarlane, 1979).



ig. 5. Geochemical diagrams for three discriminant elements: K_2O (%), MgO (%), Cr (ppm) versus SiO_2 (%) contents for the ›ur main periods of activity. The abbreviations for dredged areas are the same as in Figure 1.

Discussion—The New Hebrides troughs: back-arc or intra-arc structures?

Chronological distribution of each rock type

The ages of MORB (type a) (only found in the northern troughs area) are old: 12.4 Ma (VAN area) and then about 5.5 and 5.2 Ma (HH). These lavas could be related either to the opening of NFB or to the basement of the NH arc.

The intermediate (MORB-IAT, type f) basalts restricted to the VAN area were erupted from 2.9 to 1.1 Ma. The late (1.8 to 1.06 Ma and perhaps until recent time) activity is mostly acidic: low-K andesites and dacites. The association of the basalts and the acidic lavas of PIA parentage suggests that the VAN area is the most recent site of arc development in the NH system.

Elsewhere, the activity is of orogenic affinity, though different types may coexist (IAT and CA possibly Ti or Mg enriched). The Mg-IAT and the potassic or high-potassic dacites which could mark the formation of the troughs appear at different times in every area, attesting to a polyphased and complex formation of the troughs.

The formation of the troughs behind the New Hebrides island arc

Trough formation appears to have progressed from south to north. The initial trough development probably formed in the Futuna area at about 6.5–6.1 Ma, then moved at 4.1 Ma to the Erromango area and at 3.5 Ma to the Vate area. Important phases of formation of the Coriolis troughs occurred at 2.7–2.6 Ma (FUT-ERR) and 2.4–2.2 Ma (VA), corresponding respectively to the presumed age of the first formation phase of the Jean Charcot trough, in the Vot Tande area (2.7 Ma) and in the Vanikoro area (2.3 Ma).

The high-K or hyper-K dacites were erupted at different times during the volcanic history (between 3.5 and 2.2 Ma and at 0.6–0.5 Ma) in some specific trough areas (VA-ERR-HH) or islands (Vate). These K-enriched volcanics may be related to arc-transverse faults which perhaps subdivide the arc into several compartments. The uplift process observed on several islands could be further evidence for this fracturing of the arc. The concentration of potassic acidic lavas in the more central zone of the NH arc could be explained by a relation to the subduction–collision of the d'Entrecasteaux ridge. Likewise, the magnesian basalts (type c) have erupted everywhere contemporaneously with normal IAT (type b), being especially abundant in the FUT area.

History of the New Hebrides island arc s.l., the central chain volcanoes and the back-arc troughs

This history is intimately related to the history of the troughs. The remnants of an older arc active before 4.8 Ma are present in the Futuna trough (6.1–5.2 Ma), in the Erromango island (5.3 Ma) and in the Vot Tande trough (4.9–4.8 Ma). During this phase, the building of the arc and that of the trough were penecontemporaneous in the Futuna area.

The arc activity renewed at 4.1 Ma in Erromango island and trough, and continued to 3.6 Ma in this area; activity appeared at 3.5 Ma in Vot Tande island, a time also associated with extension in Vate trough. Subsequently, arc volcanism reached progressively the islands of Tanna, Anatom, Futuna, Gaua, Ureparapara and Merig, and the Vot Tande and Vanikoro troughs.

After 1 Ma, the arc activity began in the inactive Banks islands and the central islands.

Volcanism in troughs and islands/Back-arc and island volcanism

No fundamental geochemical difference exists between the New Hebrides arc volcan-

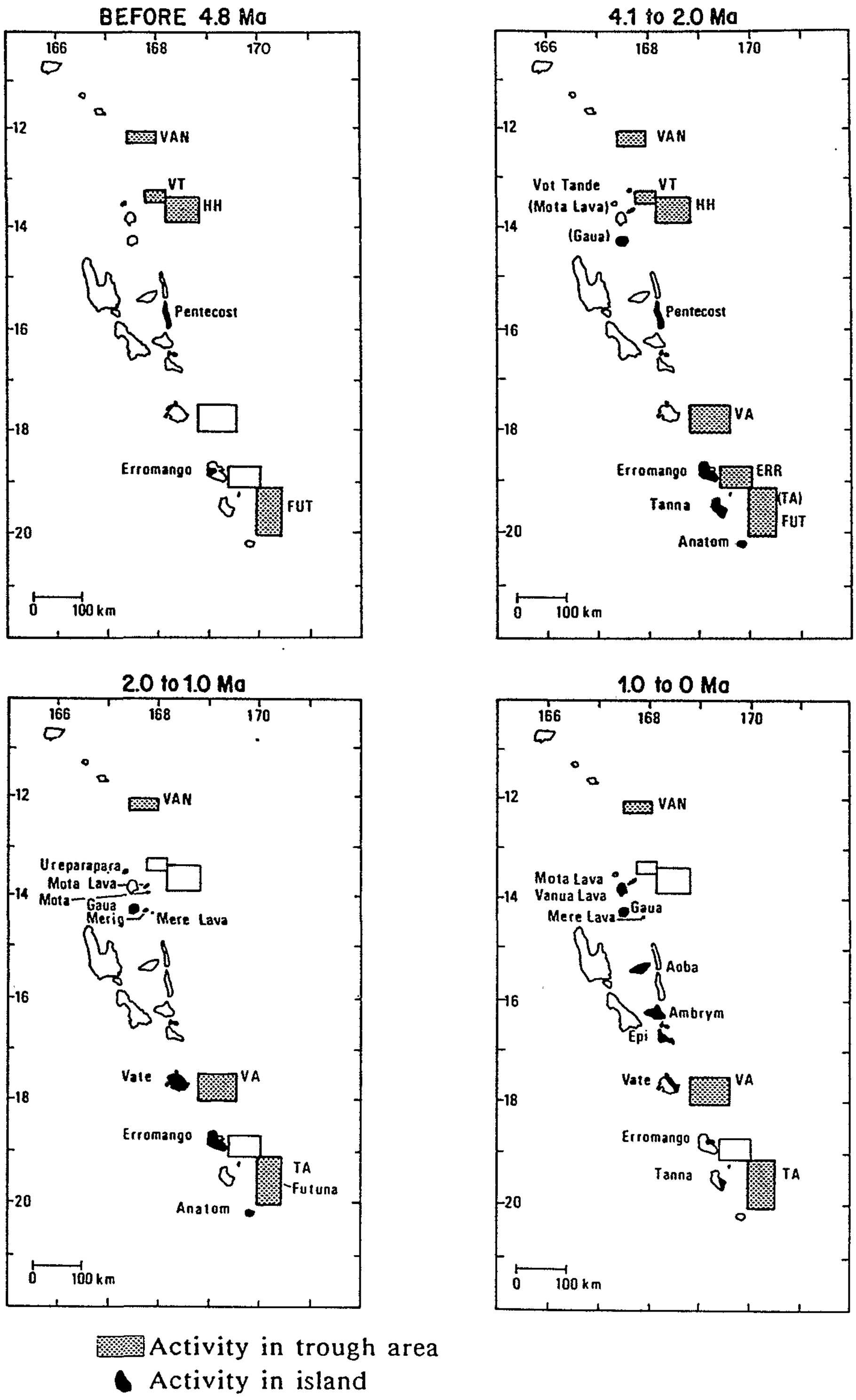


Fig. 6. Volcanic activity through space and time in the New Hebrides arc/back-arc systems. Each map is relative to a period I to IV (surrounded ages). The name of the trough areas or of the islands is only precised when this area or island is showing some activity. Abbreviations for the dredged trough areas: *VAN* = Vanikoro, *VT* = Vot Tande area, *HH* = Hazel Holme area, *VA* = Vate area, *ERR* = Erromango area, *TA* = Tanna area, *FUT* = Futuna area.

ism and the back-arc trough volcanism except for the northernmost area (VAN, which shows original features (basalts intermediate between MORB and IAT, and low-K dacites) and in respect to the relative proportions of Mg-IAT or Mg-CA basic lavas, which are more largely represented in the troughs. So, we consider that the NH back-arc troughs cannot be considered as classical back-arc troughs, such as the Mariana (Karig, 1971) or Bonin troughs (Bandy and Hilde, 1983), characterized by incipient oceanic spreading. They more probably correspond to extensional structures, along which mainly orogenic volcanic products were emitted. Furthermore, the relatively small size of these troughs and their unusual position very close to the arc are specific structural patterns which may partly explain their volcano-tectonic features.

Shifting of the volcanic activity

Figure 6 clearly illustrates a spatio-temporal shifting of volcanic activity from northern troughs (VT–HH) to the Banks islands (Ureparapara–Vanua Lava–Mota–Gaua–Merig) between, respectively, 4.1–2.0 Ma and 2.0–1.0 Ma. This later period is also the time of concentration of the volcanic activity in the southern islands compared to the troughs. In both northern and southern areas, shifting occurred from east to west, i.e. from the back-arc area to the volcanic chain s.s. However, the shifting process has reversed during the last period (1.0–0 Ma) in the southern domain: volcanism is confined to the eastern regions of islands and ends in the troughs (VA–TA).

Conclusion

The New Hebrides back-arc troughs must be considered as intra-arc troughs; they are back-arc structures only because of their location at the rear of the active emerging arc. Volcanism is typically of orogenic affinity, except in the more northern area (Vanikoro trough) which is characterized by volcanic products of a more primitive nature and which could signify the first stages of the arc formation in this region.

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