AMPHIBOLE COMPOSITIONAL TRENDS IN OVERSATURATED AND UNDERSATURATED ALKALINE PLUTONIC RING-COMPLEXES

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ABSTRACT

Amphiboles from different alkaline ring-complexes, representing both silica-oversaturated and silica-undersaturated petrographic associations, have been studied in relation to their host rocks. Textural, optical and chemical evidence emphasizes major amphibole compositional trends related to host-rock chemistry. In rocks whose agpaitic coefficient is less than 0.9, the Ca + Al^{iv} content of amphiboles is more than 2.5, whereas it is less than 2.5 in agpaitic rocks ($Na_2O + K_2O / Al_2O_3 > 0.9$). This feature is shown firstly by the presence of solid-solution series from kaersutite to hornblende or hastingsite with substitutions $\square$ Ti $\rightleftarrows$ Na^AAl, Ti + O $\rightleftarrows$ Fe^{3+} + OH^- and CaAl $\rightleftarrows$ NaSi predominating in silica-undersaturated rock series and NaAl $\rightleftarrows$ $\square$ Si in basic and intermediate rocks from silica-oversaturated series. Secondly, this feature is shown by the presence of solid-solution series from actinolite or barroisite to winchite, with $CaAl^{iv}$ $\rightleftarrows$ Na Si substitution or to katophorite, richterite and then arfvedsonite with balanced substitutions as $\square$ Fe^{3+} $\rightleftarrows$ $NaFe^{2+}$ and $CaAl^{iv}$ $\rightleftarrows$ Na Si. The first trends are related to early magmatic stages, and the second to late magmatic stages. The absence of (Ca + Al^{iv})-rich amphiboles in agpaitic rocks and an observed break between (Ca + Al^{iv})-rich amphiboles and (Ca + Al^{iv})-poor amphiboles suggest that (Ca + Al^{iv})-rich amphibole stability is controlled by magma alkalinity. One argument is based on the description of a reaction, involving hastingsite and a residual liquid, which results in the crystallization of clinopyroxene and Ti-magnetite, and in the addition of potential analcime to the residual liquid. This alkalinization of the liquid ultimately produces a peralkaline concentrate.

Keywords: amphiboles, alkaline rocks, anorogenic magmatism, differentiation processes.

SOMMAIRE

Cette étude concerne les amphiboles de différents complexes annulaires alcalins, aussi bien sursaturés que sous-saturés en silice, et leurs rela-

tions avec leurs roches hôtes. Des arguments texturaux, optiques et chimiques soulignent l'existence de lignées dans la composition des amphiboles en fonction de la composition chimique des roches. Dans les roches à coefficients d'agpaïcité inférieur à 0.9, le nombre de cations + Al^{iv} des amphiboles est supérieur à 2.5, alors qu'il est inférieur à 2.5 dans les roches agpaïtiques ($Na_2O + K_2O / Al_2O_3 > 0.9$). Ce caractère se traduit d'une part par la présence de solutions solides allant des kaersutites aux hornblendes ou aux hastingsites avec les substitutions principales suivantes: $\square$ Ti $\rightleftarrows$ Na^AAl, Ti + O $\rightleftarrows$ Fe^{3+} + OH^- et Ca Al^{iv} $\rightleftarrows$ Na Si dans les roches sous-saturées en silice, et substitutions du type Na Al $\rightleftarrows$ $\square$ Si dans les roches basiques et intermédiaires des séries sursaturées en silice; et d'autre part la présence de solutions solides allant des actinotes ou des barroisites aux winchites selon des substitutions de deux types: $\square$ Fe^{3+} $\rightleftarrows$ Na^AFe^{2+} et Ca Al^{iv} $\rightleftarrows$ Na Si. Les premières lignées sont attribuées à des stades magmatiques précoces, et les secondes à des phases tardives. L'absence d'amphiboles riches en (Ca + Al^{iv}) dans les roches agpaïtiques et la discontinuité observée entre les amphiboles riches en (Ca + Al^{iv}) et les amphiboles pauvres en (Ca + Al^{iv}) font penser que l'agpaïcité du magma gouverne la stabilité des amphiboles riches en (Ca + Al^{iv}). A titre d'argument, on donne la description d'une réaction impliquant la hastingsite et un liquide résiduel, et produisant du clinopyroxène et de la titanomagnétite ainsi que l'enrichissement en analcime potentielle du liquide résiduel; celui-ci devient alors plus alcalin, ce qui produit en dernier lieu un concentré hyperalcalin.

Mots-clés: amphiboles, roches alcalines, magmatisme anorogénique, processus de différenciation.

INTRODUCTION

Amphiboles are present in many of the rock types found in plutonic bodies from alkaline nonorogenic ring-complexes, those defining a silica-saturated to -oversaturated association as well as those showing silica undersaturation. In both cases, the chemical composition of amphiboles varies considerably from calcic to alkali-rich members according to chemical variations in the differentiating magma and to ther-

TABLE 1. RESULTS OF MAJOR ELEMENT ANALYSES OF ROCKS FROM RING COMPLEXES

PENINSULE RALLIER-DU-BATY

	LL1	L2	P1	P14	DF16	LL14	VA80
SiO_2	64.53	63.48	63.50	68.97	65.82	63.48	63.66
TiO_2	.71	.77	.99	.36	.63	.63	.79
Al_2O_3	16.28	15.67	15.90	14.71	16.13	15.67	17.25
Fe_2O_3	3.25	4.75	2.28	2.28	1.42	2.76	1.39
FeO	1.90	.37	2.42	1.51	2.16	1.80	2.09
MnO	.17	.12	.14	.12	.13	.13	.08
MgO	.35	.15	.60	tr	.25	.45	.56
CaO	.50	.10	.94	tr	.40	.84	1.13
Na_2O	6.20	6.24	5.92	5.87	6.01	5.73	5.68
K_2O	5.92	6.01	6.24	5.14	5.42	6.11	6.44
P.F.	.73	.81	.63	.62	.42	.81	.83
tot.	100.75	98.51	99.83	100.16	98.86	98.61	100.13

CAURO-BASTELICA

	1	2	3
SiO_2	74.72	75.68	71.50
TiO_2	.05	tr	.21
Al_2O_3	13.12	12.12	14.94
Fe_2O_3	.92	1.39	.86
FeO	.72	.82	1.20
MnO	.03	.04	.03
MgO	.02	.04	.20
CaO	.93	.83	1.84
Na_2O	4.47	4.26	4.58
K_2O	4.84	4.76	4.01
P_2O_5	tr	.05	.04
H_2O+	.35	1.75	.72
H_2O-	.16	.06	.11
tot.	100.40	100.56	100.21

ISKOU

	GBH	SGM	77.138	67.78	66.77	61.77	17.77
SiO_2	61.73	61.55	58.34	53.41	51.66	51.33	69.14
TiO_2	1.11	.85	.98	2.85	.87	.55	.27
Al_2O_3	15.48	15.76	18.02	15.88	23.50	24.04	14.26
Fe_2O_3	1.84	2.55	1.78	1.86	1.56	1.44	2.60
FeO	6.18	4.07	5.85	9.72	3.15	2.37	1.73
MnO	.11	.14	.10	.10	.07	.06	.06
MgO	.96	.72	.10	2.52	.91	2.10	.12
CaO	2.84	2.02	3.51	6.32	7.15	10.56	2.02
Na_2O	4.35	4.51	5.59	4.54	5.57	5.33	4.84
K_2O	4.06	4.41	4.58	2.37	1.93	.64	4.75
P_2O_5	.43	.27	.11	.60	.39	.20	.14
H_2O+	.35	1.75	.72	.77	1.07	.60	.77
H_2O-	.09	.39	.13	.04	.18	.07	.10
tot.	99.53	98.99	99.81	100.98	98.01	100.29	100.80

MONTAGNES VERTES

	77.35	MV1	77.60	77.49	77.20	MV2	77-10½
SiO_2	44.52	47.60	60.92	44.22	50.74	61.19	68.34
TiO_2	3.08	2.71	1.80	3.29	1.38	.73	.61
Al_2O_3	18.64	19.44	17.71	19.76	17.31	18.44	13.73
Fe_2O_3	6.62	4.13	4.64	4.74	5.31	2.92	3.35
FeO	6.64	5.44	4.86	5.83	4.29	.81	1.35
MnO	.10	.19	.13	.11	.14	.06	tr
MgO	3.20	3.20	2.56	3.59	1.78	.38	1.65
CaO	10.12	7.93	5.13	10.43	4.76	1.01	.29
Na_2O	3.42	4.79	4.44	3.40	6.31	5.34	4.10
K_2O	1.65	2.67	2.92	1.41	3.94	4.36	5.96
P_2O_5	.44	.77	.08	.36	.64	.29	.19
H_2O+	.83	.82	2.67	2.01	2.26	1.83	.67
H_2O-	.14	tr	.52	.30	.25	.64	tr
tot.	99.10	99.69	98.38	99.45	99.11	97.50	100.24

MONTS BALLONS

	78.31c	78-47	78-20	78-48	78-60b	78-51	78-52	78-64
SiO_2	46.79	57.62	34.40	53.86	45.33	43.47	47.72	57.20
TiO_2	2.35	.55	3.71	1.03	3.02	3.27	2.66	.67
Al_2O_3	16.86	19.49	14.30	19.58	15.52	14.82	18.62	17.80
Fe_2O_3t	9.91	5.68	16.80	6.48	11.78	13.96	9.32	8.51
MnO	.17	.18	.17	.15	.14	.21	.17	.20
MgO	3.36	.53	9.23	1.16	5.91	6.15	3.12	.50
CaO	6.75	2.29	12.46	3.33	8.74	9.46	7.61	2.21
Na_2O	4.57	6.40	3.09	6.14	3.50	3.17	5.03	5.14
K_2O	3.86	6.18	1.60	5.51	2.66	2.90	3.55	6.13
P_2O_5	.72	.21	.84	.34	.76	1.05	.98	tr
P.F.	3.31	1.21	2.15	2.41	1.38	.83	1.32	.77
tot	98.65	100.34	98.75	99.99	98.74	99.49	100.10	99.13

TABLE 2. RESULTS OF MAJOR ELEMENT ANALYSES OF AMPHIBOLES FROM RING COMPLEXES

MAJOR ELEMENT ANALYSES OF AMPHIBOLES FROM THE INTRUSION OF RALLIER-DU-BATY PENINSULA, KERGUELEN

	L1-1	L1-2	L1-3	L1-4	L2-1	L2-2	L2-3	P1-1	P1-2	P14-1	DF16.1	DF16.2	LL14.1	LL14.2	LL14.3	LL14.4	LL14.5	VA80.1	VA80.2	W28.1
SiO_2	42.64	46.09	48.89	45.74	46.73	46.44	46.97	45.98	48.23	47.89	48.54	46.96	51.58	46.41	47.01	48.20	48.36	49.79	45.50	45.68
TiO_2	2.05	2.18	.82	.26	.94	1.34	.96	1.92	.18	.76	.99	1.66	.06	2.05	1.63	.86	.35	.32	1.13	1.15
Al_2O_3	4.34	1.65	.50	.99	3.16	3.19	1.21	2.79	.97	1.21	1.62	1.57	.76	1.80	1.55	1.11	1.06	.90	4.64	3.43
FeO*	30.20	33.03	34.86	35.57	18.96	22.97	32.53	28.97	36.69	35.62	28.68	33.37	22.38	32.34	33.18	34.36	36.52	17.74	25.20	20.80
MnO	1.00	1.33	1.66	2.10	1.35	1.55	1.63	1.12	1.62	1.59	1.21	1.28	1.00	1.07	.92	1.08	1.93	.88	1.14	1.48
MgO	3.87	2.08	.16	.27	10.10	7.48	1.32	5.21	1.15	.34	5.53	1.93	11.62	2.20	1.86	.55	.49	12.91	7.79	11.47
CaO	6.94	4.59	1.01	11.20	7.64	6.90	5.40	5.76	5.66	1.69	5.40	3.89	3.45	5.40	5.03	3.23	8.22	11.61	9.34	8.41
Na_2O	4.68	5.30	8.00	.28	4.65	4.65	4.48	4.85	3.78	7.02	4.91	5.56	6.78	5.58	5.55	6.58	1.92	1.65	2.64	4.83
K_2O	1.62	1.44	1.54	.22	1.17	1.34	1.00	1.23	.55	1.09	1.45	1.30	.89	1.30	1.10	1.56	.25	.17	.63	.82
tot.	97.34	97.69	97.44	96.63	94.70	95.86	94.29	97.83	98.83	97.21	98.33	97.52	98.52	98.15	97.83	97.54	99.10	96.15	98.01	98.07

MAJOR ELEMENT ANALYSES OF AMPHIBOLES FROM THE INTRUSION OF CAURO-BASTELICA, CORSICA

	1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	2-1	2-2	2-3	2-4	2-5	2-6	2-7	2-8	2-9	2-10	3-1	3-2	3-3
SiO_2	41.72	41.63	45.40	44.41	43.84	44.34	44.44	42.43	43.05	44.11	42.76	43.16	41.49	42.67	42.14	45.46	46.02	45.69	41.26	41.93	41.90
TiO_2	1.25	1.23	1.05	1.35	1.40	1.26	1.29	1.44	1.27	1.11	1.38	.80	1.32	.91	1.15	.07	.32	.08	1.48	1.65	1.42
Al_2O_3	1.93	1.67	3.58	3.40	1.66	3.89	3.78	4.00	2.79	2.92	4.27	3.08	4.51	3.12	3.75	.20	.31	.39	7.54	7.50	6.90
FeO	38.27	38.66	35.71	37.34	36.20	36.10	36.10	36.51	39.69	37.21	37.35	36.70	36.87	36.53	35.14	41.00	39.12	40.57	31.73	30.29	32.38
MnO	1.45	1.42	1.27	1.24	1.34	1.62	1.62	1.60	1.89	1.32	1.22	1.41	1.15	1.43	1.28	2.52	2.61	2.59	1.66	1.74	1.79
MgO	.07	.07	.10	.12	.05	.04	.09	.06	.11	.08	.09	.18	.13	.08	.13	.03	.07	.05	2.77	3.09	2.57
CaO	7.78	7.79	8.26	6.59	7.66	7.54	7.20	7.70	5.67	5.82	8.13	7.42	7.88	6.01	6.86	.51	.54	.50	9.45	9.67	9.80
Na_2O	3.45	3.19	2.38	2.44	2.33	2.18	2.13	2.31	2.57	3.19	2.99	2.71	2.99	2.71	2.87	4.01	3.90	2.13	2.13	1.76	
K_2O	.87	.83	.77	.82	.83	.83	.88	.90	.68	.64	.83	.74	.86	.69	.87	.03	.03	.04	.94	.83	.81
tot.	95.22	96.49	98.53	97.71	95.31	97.80	97.53	96.95	94.72	96.40	99.00	96.20	97.20	94.15	94.03	92.69	93.03	93.61	98.96	98.65	99.33

MAJOR ELEMENT ANALYSES OF AMPHIBOLES FROM THE INTRUSION OF ISKOU, AIR, NIGER

	GBH	SGM	138.77	67-78	83.76	74.78	66.77(1)	66.77(2)	78.77(1)	78.77(2)	78.77(3)	61.77(1)	61.77(2)	61.77(3)	61.77(4)	74-78	17-77
SiO_2	42.02	41.19	40.23	43.31	46.05	39.30	42.06	40.94	40.68	38.48	44.60	41.95	43.88	41.27	45.27	41.28	46.71
TiO_2	2.08	2.14	2.18	1.85	1.43	3.10	1.43	1.73	1.23	.79	.43	1.40	.38	4.58	1.11	4.13	1.81
Al_2O_3	7.81	8.27	8.45	7.81	5.53	12.60	7.73	8.85	10.35	13.00	9.33	10.12	9.61	11.84	10.05	11.31	2.05
FeO	25.67	25.76	29.13	23.78	23.94	18.99	26.26	26.82	26.67	26.75	22.47	20.75	21.38	13.00	11.46	15.95	34.08
MnO	.84	.47	.50	.30	.46	.27	.56	.47	.35	.37	.30	.39	.34	.17	.18	.25	.94
MgO	5.20	6.09	3.84	8.12	8.83	8.40	5.94	5.44	4.86	4.17	7.29	8.41	8.31	11.80	14.38	10.60	.93
CaO	9.89	9.92	10.35	9.95	9.71	11.23	10.11	10.37	10.83	10.79	11.39	11.48	11.90	11.30	12.07	10.75	5.56
Na_2O	1.95	1.93	1.79	2.56	1.21	2.36	1.34	1.39	2.00	2.22	1.30	2.12	1.45	2.88	2.16	3.31	4.12
K_2O	1.05	1.19	1.08	.89	.52	1.28	.81	1.01	1.07	.78	.15	.77	.64	.85	.47	.36	1.21
tot	96.51	96.96	97.55	98.57	97.68	97.53	96.24	97.02	98.04	97.36	97.26	97.39	97.89	97.69	97.15	97.95	97.41

	78.522	78-64
SiO_2	38.47	37.55
TiO_2	6.73	3.79
Al_2O_3	11.96	10.46
FeO	14.45	24.16
MnO	.27	1.07
MgO	9.44	5.70
CaO	11.89	10.47
Na_2O	2.64	2.96
K_2O	1.69	1.71
tot	97.48	97.86

AMPHIBOLES FROM MONTAGNES VERTES & MAMELLES

	77-35	MV 1	77.60(1)	77.60(2)	77-49	77.20(1)	77.20(2)	MV2(1)	MV2(2)	MV2(3)	77.03
SiO_2	38.70	40.56	40.39	39.96	40.79	38.33	37.39	38.51	38.76	40.91	43.92
TiO_2	5.21	5.59	6.06	6.32	5.51	1.40	3.01	4.95	3.86	3.59	1.25
Al_2O_3	12.26	12.06	12.19	12.24	11.95	9.11	9.55	8.28	7.07	6.55	7.52
FeO	16.36	16.74	14.74	14.83	12.56	27.0	24.23	28.65	29.79	31.32	23.75
MnO	.28	.50	.29	.30	.12	.84	.77	1.35	1.84	1.59	1.00
MgO	9.83	8.19	8.72	9.44	11.00	5.15	6.35	3.58	1.80	1.96	6.07
CaO	11.33	10.88	11.26	11.32	10.88	9.93	10.36	6.34	7.70	8.00	8.76
Na_2O	2.63	3.31	2.99	3.00	3.29	3.88	3.70	3.18	4.55	4.62	2.89
K_2O	1.56	1.17	1.12	1.13	1.11	1.35	1.33	1.95	1.44	1.48	.59
tot.	98.16	98.80	97.76	98.54	96.61	97.01	96.69	96.79	96.80	100.02	95.75

AMPHIBOLES FROM MONTS BALLONS

	78.31c	78.47(1)	78.47(2)	78-20	78.48(1)	78.48(2)	78.60b	78-51	78.52(1)
SiO_2	35.11	36.50	38.85	37.18	40.61	41.94	39.24	39.45	37.48
TiO_2	7.08	6.66	3.50	8.01	4.03	6.76	5.91	5.54	4.27
Al_2O_3	13.60	13.20	11.98	14.56	14.95	16.22	11.32	11.60	10.80
FeO	12.42	12.68	21.65	11.17	22.65	12.53	16.13	17.49	24.17
MnO	.25	.12	.83	.29	.70	.28	.54	.51	.55
MgO	12.32	11.46	5.87	13.19	5.60	11.42	9.47	7.31	5.21
CaO	13.49	12.41	10.80	10.47	10.75	11.72	10.79	10.52	10.85
Na_2O	2.60	tr	2.88	2.70	3.80	3.64	3.11	3.72	2.48
K_2O	1.46	1.37	1.52	1.61	1.49	1.31	1.35	1.38	1.69
tot.	98.33	96.40	97.88	99.18	97.25	98.40	97.86	97.52	97.50

modynamic conditions (Wilkinson 1961, Ernst 1962, Stull 1973, Cawthorn 1976, Fabriès 1978). At the same time, the role of amphiboles during magmatic differentiation may control the composition of the residual liquid, as has already been described in some volcanic series (Maury 1976, Villemant 1979).

Many studies concerning optical and chemical variations in amphiboles have been published, but unfortunately the control exerted by amphibole in the evolution of alkaline igneous ring-complexes is not well known. In this paper, the chemistry of amphiboles from such complexes located in both oceanic (Kerguelen, Tahiti) and continental (Corsica, Niger, Rhodesia) environments (see Appendix) is compared with host-rock chemistry (Table 1), using new data as well as data from the petrological literature. Thus the petrographic, textural and chemical characteristics of amphiboles (Table 2) enable us to be more specific concerning the role of the different magma-composition trends that were established in relation to the evolution of amphibole composition as magma differentiated.

Here, amphiboles are named according to the recommendations of the I.M.A. (Leake 1978). In the general formula $A_{0-1}B_2C^{vi}_5T^{iv}_8O_{22}$ (OH,F,Cl)$_2$, the tetrahedral sites are filled with Si, Al, then Fe. Our chemical data on amphiboles have been obtained using a microprobe analyzer; concentrations of OH, F, Cl and Fe^{3+} thus are unknown. Amphibole formulae are established on the basis of 13 cations (Si+Al+ Fe^{2+}+Mn+Ti+Mg $= 13$) according to the method of Neumann (1976b). When describing amphibole series in terms of composition, we refer to substitutions such as those described by Fabriès (1978) to derive the most complex formulae from that of tremolite, $\square^A Ca_2 Mg_5$ $Si_8 O_{22}(OH)_2$; the relatively large monovalent cations more or less fill the A sites of the structure. Such substitutions are limited in number: $Fe \rightleftharpoons Mg$, $Fe^{3+} \rightleftharpoons Al^{iv}$, $Na^A Al^{iv} \rightleftharpoons \square Si$, $NaR^{3+} \rightleftharpoons CaR^{2+}$, $Na^A Na \rightleftharpoons \square^A Ca$, $R^{3+} Al^{iv} \rightleftharpoons R^{2+}$ Si, $Ti \rightleftharpoons Si$, and $\square^A Ti \rightleftharpoons R^{3+} Na^A$. According to the standard formula of kaersutite, usually given on the basis of 24(O, OH), we can add another substitution: $Ti + O^{2-} \rightleftharpoons R^{3+} + OH^-$.

AMPHIBOLES IN SILICA-SATURATED TO -OVERSATURATED ROCK SERIES

These petrographic associations contain basic and intermediate rock types (gabbros, monzonites) that have minor proportions of normative nepheline or normative quartz (C.I.P.W. nor-

mative constituents). They also contain differentiated rock types such as syenites and granites in variable proportions; these are enriched in quartz and usually evolve towards increasing peralkalinity.

The complexes of Rallier-du-Baty peninsula, Kerguelen

This association, found in the southwestern part of the main island, consists essentially of five overlapping ring-complexes whose petrography and geochronology are well described (Nougier 1970, Marot & Zimine 1976, Lameyre et al. 1976, Dosso 1977, Dosso et al. 1979, Giret 1980). These complexes contain many different rock types, varying from volumetrically abundant syenites and quartz syenites to granites in minor volumes. Amphiboles are the principal ferromagnesian minerals, occupying from 2 to 5 vol. % of the rocks; they crystallized later than the feldspars and, in some cases, after quartz. Their composition is clearly related to lithology. In syenites, they change gradually from katophorite to winchite and then to ferrorichterite. At the very end of crystallization, ferrorichterite evolves towards alkaline endmembers such as arfvedsonite and riebeckite in a probable solid-solution series (Sundius 1946). In quartz syenites, the amphiboles are zoned from ferrorichterite in the core to arfvedsonite in the rims. Finally, in the granites, amphiboles are not zoned, and their composition lies between end-member riebeckite and endmember arfvedsonite.

For these complexes, the chemical composition of the amphiboles in the syenites and granites is represented by the evolving series katophorite $\rightarrow$ winchite $\rightarrow$ ferrorichterite $\rightarrow$ arfvedsonite, in which the $Fe \rightleftharpoons Mg$ and $NaFe^{3+}$ $\rightleftharpoons CaFe^{2+}$ substitution schemes predominate. The arfvedsonitic composition of the amphibole appears gradually with silica enrichment of the rocks and during a reduction process (Fabriès 1978).

The Iskou ring-complex, Aïr, Niger

This complex forms part of a magmatic anorogenic province known as the Younger granites of western Africa (Black & Girod 1970). General investigations have been reported in geochronological (Karche & Vachette 1976, 1978) and petrographic papers (Black 1965, Black et al. 1967, Bowden & van Breemen 1972, Moreau et al. 1978). Four groups are distinguished, all amphibole-bearing: (1) a
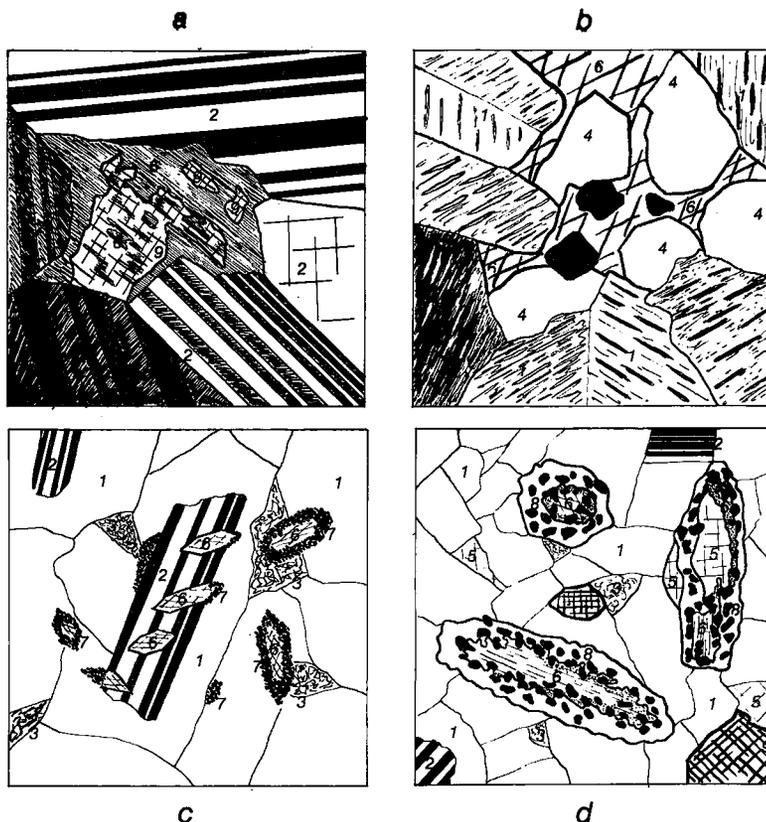
FIG. 1. Different amphibole textures in rocks from ring complexes. (a) Amphibole replacing pyroxene and giving uralitic texture, Iskou, Aïr. (b) Very late amphibole in a peralkaline granite, Cauro-Bastelica, Corsica. (c) Early amphiboles in monzosyenite, Montagnes Vertes, Kerguelen. (d) Coronitic texture of pyroxene + Ti-magnetite, interpreted as an amphibole–liquid reaction product (see text), Montagnes Vertes, Kerguelen. Minerals are: 1 alkali feldspar, 2 plagioclase, 3 nepheline, 4 quartz, 5 analcime, 6 amphibole, 7 oxidation corona, 8 pyroxene + Ti-magnetite corona, 9 pyroxene.

basic association of leucogabbros, monzogabbros and ferrosyenites, (2) a silica-saturated association of quartz-bearing monzonites and syenites, (3) a silica-oversaturated association of quartz syenites and granites, and (4) ferroaugite-bearing syenites.

In basic and intermediate rock types, the amphiboles usually crystallize after plagioclase and the pyroxenes but before alkali feldspar. They generally replace the augitic clinopyroxene in a partly or completely developed uralite texture (Fig. 1a). Their composition evolves from kaersutite in gabbros through hastingsite to ferrohornblende in zoned crystals in leucogabbros, then to a hastingsitic hornblende in quartz monzonite and quartz-bearing syenites. The chemical variations of these calcic amphiboles correspond to a continuous solid-solution series characterized by a decrease in Mg/(Mg+Fe) ratio, Ti and Al and an increase in Si, with substitutions $Ti \rightleftharpoons Si$, $Mg \rightleftharpoons Fe$ and $AlCa^{iv} \rightleftharpoons NaSi$.

In quartz-rich syenites and in granites, amphiboles are commonly associated with late aegirine-augite crystals, and have a sodicalcic composition between the following end-members: ferrobarroisite, ferrowinchite, ferrorichterite and katophorite (Fig. 2).
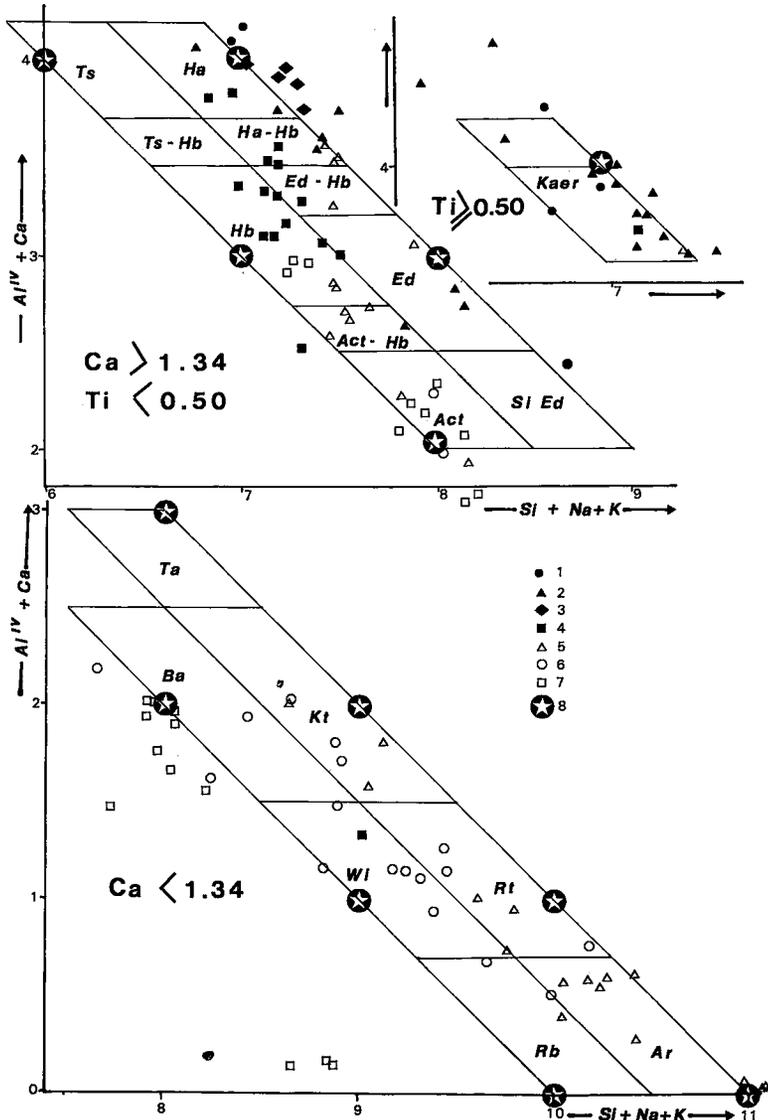
FIG. 2. Amphiboles from nonorogenic complexes plotted in the diagram Ca + Al^{iv} *versus* Si+Na+K: 1 Tahiti, 2 Courbet peninsula and Monts Ballons, Kerguelen, 3 Marangudzi (Borley & Frost 1963), 4 Iskou, Niger, 5 Oslo rift (Neumann 1976a), 6 Rallier-du-Baty peninsula, Kerguelen (Marot & Zimine 1976), 7 Cauro-Bastelica, Corsica, 8 amphibole end-members (Ts tschermakite, Ha ferro- and magnesiohastingsite, Ed edenite, Ta taramite, Kt katophorite, Ri richterite, Ar arfvedsonite, Hb fe- and Mg-hornblende, Ba barroisite, Tr tremolite, Wi winchite, Rb riebeckite, Act actinolite).

The Cauro-Bastelica ring-complex, Corsica

This complex, of Permian age and intruding Hercynian basement (Bonin 1980, Bonin *et al.* 1972, 1973), consists of two principal types of granite, an early hypersolvus granite and a later intrusion of subsolvus granite (Bonin & Martin 1974). There are also two distinctive

chemical trends represented by whole-rock compositions: (1) aluminous, essentially anorthite- or corundum-normative granitic rocks, *e.g.*, the biotite-bearing granites crystallizing as both hypersolvus and subsolvus types; these may contain amphibole-rich xenoliths; (2) an alkaline trend that clearly becomes peralkaline, represented by the amphibole- and fayalite-bearing hypersolvus granites.

In the amphibole-rich enclaves that are interpreted to result from the mixing of major volumes of acid magma with minor volumes of basic magma, the amphiboles are of ferro-hornblendic composition, lying between hastingsite and barroisite end-members. They may belong to a solid-solution series, with substitutions of the following types: $NaAl^{iv} \rightleftharpoons \square Si$ and $CaFe^{2+} \rightleftharpoons NaFe^{3+}$, possibly induced by oxidation (Fabriès 1978). In hypersolvus amphibole- and fayalite-bearing granites, most of the amphibole crystals have a deep green color (which probably reflects variations between ferroedenite and ferrobarroisite compositions) with blue rims of a Na-grunerite, suggesting an outward increase in iron and a decrease in alkalis. Such grunerites are associated with fluorite and annitic micas in an interstitial position or in the rock cavities; this association reveals a late stage of crystallization. Some of the hypersolvus granites contain a blue amphibole as the only ferromagnesian phase; its composition lies between barroisite and winchite. Such substitutions ($Fe^{3+}Al^{iv} \rightleftharpoons Fe^{2+}Si$) may be indicative of a reduction process.

We note that in the Cauro-Bastelica complex, all the amphiboles are iron-rich and aluminum-poor. In granites, sodicalcic amphiboles are always late in appearance; they commonly crystallize after quartz and perthitic feldspars (Fig. 1b). In contrast, calcic amphiboles of ferro-hornblendic composition occur only in the basic, amphibole-rich inclusions.

The anorogenic complexes of the Oslo region

Continental alkaline ring-complexes from the Oslo rift (Barth 1944, Oftedahl 1946, Saether 1962, Dietrich *et al.* 1965, Heier & Compston 1969, Jacobson & Raade 1975, Neumann 1976a) are characterized by two main magmatic pulses: (1) a silica-undersaturated association whose amphiboles will be described in the next section, and (2) a silica-saturated to -oversaturated association of monzonites, nordmarkites and granites. In these, amphiboles constitute two groups depending on rock type. In the alkaline rocks (quartz monzonites and quartz syenites),

magnesian hornblendes show a silica increase that is related to the activity of silica in the magma (Neumann 1976a). In the peralkaline rocks, amphiboles belong to a solid-solution series from subcalcic Na-edenite to magnesioarf-vedsonite, with $CaAl^{iv} \rightleftharpoons NaSi$ the dominant substitution-scheme; these amphiboles show a decrease of Ti, Mg, Ca and Al from core to rim in zoned crystals.

Conclusions

In the silica-oversaturated suites of alkaline plutonic ring-complexes, we can distinguish two groups of rocks on the basis of their amphiboles: (1) Basic and intermediate rock types in which amphibole compositions show a decrease in $Ca+Al^{iv}$ without any increase in the $Si+Na+K$ parameter (Fig. 2). This trend generally evolves from hastingsite to hornblende (Iskou, Oslo), which implies a solid-solution series where the principal substitution can be summarized as $Na^A Al^{iv} \rightleftharpoons \square Si$. Independently of this series, the substitution scheme $Fe \rightleftharpoons Mg$ leads to magnesio- or ferroamphibole types. (2) Differentiated rocks, such as peralkaline syenites and granites, with amphiboles evolving from barroisite to katophorite, to winchite, to richterite and lastly, to arfvedsonite. These solid-solution series issue from balanced substitutions such as $CaAl^{iv} \rightleftharpoons NaSi$ and $\square Fe^{3+} \rightleftharpoons Na^A Fe^{2+}$, with a filling of the A sites by alkalis (essentially Na) under reducing conditions.

The descriptions made above emphasize that Si-enrichment is the main characteristic of amphiboles in both basic and differentiated silica-oversatured alkaline rocks. In order to compare the evolution of rock composition with amphibole chemistry, we have used the von Wolff diagram of normative constituents, described by Johannsen (1939); the diagram enables one to plot minerals and rocks in the same figure (Fig. 3). L represents feldspars and M, silica-saturated ferromagnesian minerals; the line LM is therefore the silica-saturation line separating an upper silica-saturated field from a lower silica-undersaturated field. This diagram shows the progressive silica oversaturation of rocks and the simultaneous Si increase in amphiboles (*e.g.*, Cauro-Bastelica, Rallier-du-Baty, Iskou, Oslo). Note that an overall iron enrichment in conjunction with an Al and Ca decrease is also associated with this feature; in the von Wolff diagram, this is shown by amphibole compositions drawing nearer and nearer to M and rock compositions going further and further from L.
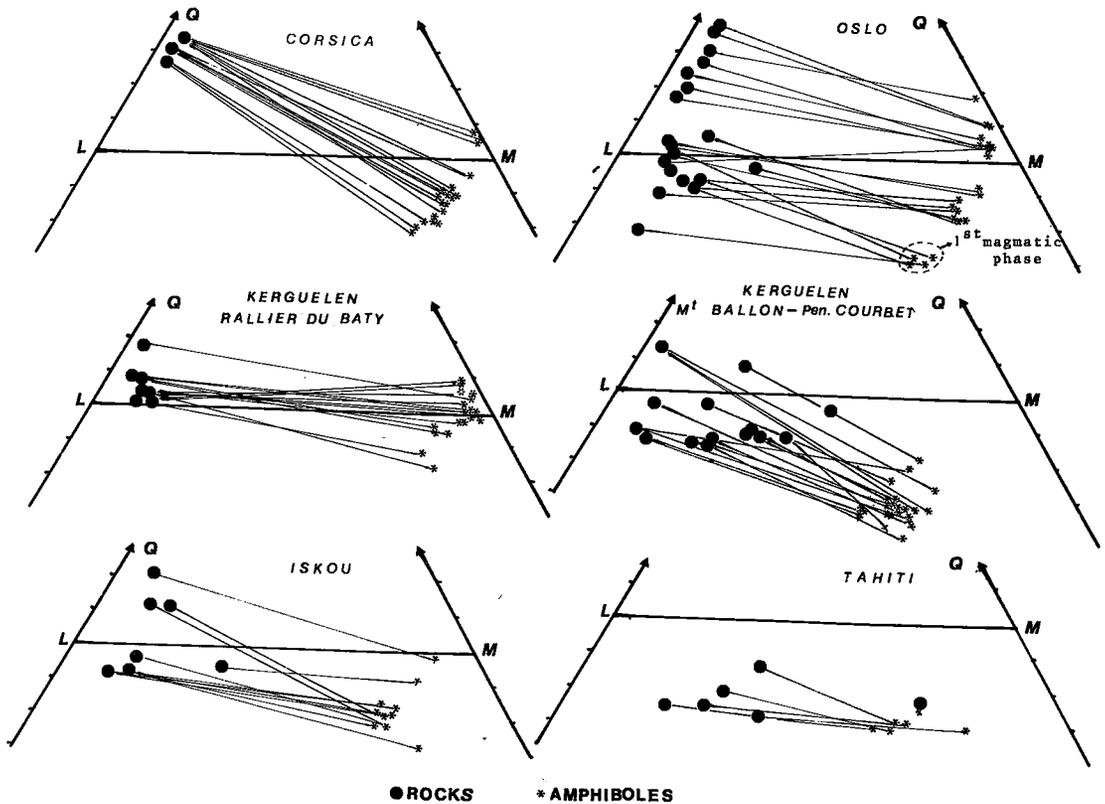
FIG. 3. Amphiboles and their host rocks plotted on the normative von Wolff diagrams. Q quartz, L feldspars, M mafic minerals, Ne nepheline. Some significant tie-lines linking amphiboles and their host rocks have been drawn to aid interpretation.

AMPHIBOLES IN SILICA-UNDERSATURATED ROCK SERIES

These rock associations contain basic to differentiated types in which the nepheline-normative character is always present and sometimes important. These rocks may be separated into two groups: one is weakly silica-undersaturated and evolves towards aluminous differentiates, whereas the other is strongly silica-undersaturated and usually evolves along a peralkaline trend.

Silica-undersaturated rocks from the Olso ring-complexes

In the Oslo region, silica-undersaturated rocks (essexites, plagiofoyaites and nepheline-bearing syenites) were formed during the first main regional magmatic phase. In these rocks, amphiboles may be automorphic or pseudomorphic after clinopyroxene; amphiboles from the two groups are very similar in composition. Neumann (1976a) notes only the $Fe^{2+} \rightleftharpoons Mg$

and $CaAl^{iv} \rightleftharpoons NaTi$ schemes of substitution in these titaniferous hornblendes.

Plutonic rocks from Tahiti

The magmatic history of Tahiti has been the subject of many investigations (Dana 1886, Lacroix 1904, 1910, 1927, Williams 1933, Deneufbourg 1964, Krummenacher & Noetzlin 1966, McBirney & Aoki 1968, Nitechy-Novotny 1975). These authors established the existence of two trends diverging from similar gabbroic compositions. Both trends are silica-undersaturated, but the first is peralkaline and the second is aluminous. These chemical trends mirror closely the volcanic evolution of Tahiti, where there are both trachytic and phonolitic fractionation sequences. Amphiboles are common in each petrographic unit (except in cumulates such as melanocratic gabbros and olivine-bearing pyroxenites), but they are not abundant in transitional rocks between essexites and nepheline-bearing syenites. Their pleochroism is reddish brown to dark brown, and they pre-

sent oxidized rims in differentiated members. All are subsilicic and titanium-rich; the number of cations ranges between 5.53 and 5.98 for Si and between 0.55 and 0.76 for Ti, on the basis of thirteen cations in the T^{iv} and C^{vi} sites. Their chemical composition changes from kaersutite crystallizing in gabbros to ferrokaersutite appearing in the undersaturated syenites. This evolution means an increase in Mn, Fe, Ca and Al with a corresponding decrease in Ti and Mg, according to substitutions such as $(Mn,Fe)^{2+} \rightleftharpoons Mg$ and $CaAl^{iv} \rightleftharpoons NaSi$ (or NaTi).

Kerguelen silica-undersaturated rocks

In the main island of the Kerguelen archipelago, three complexes of this type have been studied: the Monts Ballons in the Central Province of the island and the Montagnes Vertes and Les Mamelles in the eastern peninsula, called Courbet Province. The Monts Ballons ring-complex consists of four successive intrusions emplaced concentrically. A central biotite-bearing gabbro is followed successively by monzodiorite with syenitic variants, then by micromonzonites and syenitic variants containing numerous angular to round enclaves of basic and amphibolitic xenoliths and amphibole xenocrysts; finally, a discontinuous peripheral ring-dyke of nepheline syenite partially encloses this plutonic body (Giret 1979a). Amphiboles are found in most of the rocks in this complex except in the olivine-rich gabbros. They are commonly clustered together in cumulate textures that constitute most of the enclaves in the micromonzonite, an indication of their early crystallization. In these rocks, which closely resemble the plutonic rocks of Tahiti, amphiboles are also very similar, commonly Ti-rich $(0.41 < Ti < 0.80)$ and subsilicic $(5.35 < Si < 6.16)$. Their composition ranges from kaersutite to a composition intermediate between ferrokaersutite, taramite and hastingsite, owing to substitutions already described for amphiboles from Tahiti.

The Montagnes Vertes complex is a small plutonic body 0.8 km across, where an outer zone of chilled or coarse grained gabbro grades imperceptibly through nepheline-bearing monzonites into an inner core of nepheline-bearing syenites (Giret 1978, Giret & Lameyre 1980). Amphiboles, whose early crystallization can be deduced from their common inclusion in plagioclases (Fig. 1c), are rare in the gabbros, but they can occupy up to 14 vol. % in monzonites and syenites. Their evolution is emphasized by a zonation from brown cores to green rims, evidence of a transition from kaersutite to

ferrokaersutite to taramite through substitutions such as $Ti \rightleftharpoons R^{3+}$ Na, $Mg \rightleftharpoons Fe$ and $CaAl^{iv} \rightleftharpoons NaSi$.

In the Montagnes Vertes complex, the general aluminum-enrichment trend expressed by the rock association gabbro–monzonite–nepheline-bearing syenite diverges towards nepheline syenites at the very end of the differentiation sequence. This feature has been related to the breakdown of calcic and sodicalcic amphiboles under magmatic conditions (Giret 1979b). Actually, an early amphibole–liquid reaction (Fig. 1d) is observed in some syenites. The reaction differs considerably from the well-known oxidation under $P(H_2O)$ decrease and a correlative increase in temperature or under $P(O_2)$ increase commonly encountered in volcanic rocks (Coombs & Wilkinson 1969, Merrill & Wyllie 1975). This breakdown that reflects oxidation conditions is also observed in the nepheline-bearing syenites from Montagnes Vertes, and it happens earlier than the crystallization of alkali feldspar, since it concerns only amphibole crystals that are not included in plagioclases (Fig. 1c). The suspected reaction in the other case involves both brown and green amphiboles and leads to clinopyroxene and Ti-magnetite in coronitic textures. The following equation has been established: amphibole + 0.2 Na^+ from liquid 1 → 2 clinopyroxenes + Ti-magnetite + liquid 2. In this reaction the residual liquid (2) is enriched with 0.2 K^+ and 1.3 moles of potential analcime. The amphibole is zoned from hastingsite in cores to ferrohastingsite in rims, with a general cation content of $Si_{6.15}Al_{1.78}Fe_{3.50}Mg_{1.37}Mn_{0.11}Ca_{1.76}Na_{1.19}K_{0.28}Ti_{0.27}$ for $O = 23$. The pyroxene is an aegirine augite (cation content $Si_{1.82}Al_{0.15}Fe_{0.34}Mg_{0.73}Mn_{0.01}Ca_{0.90}Na_{0.05}Ti_{0.05}$ for $O = 6$), and Ti-magnetite has the following composition: Mn_2TiO_4 0.25, Fe_2TiO_4 0.59, Fe_3O_4 0.39. In this reaction, the residual liquid becomes poorer in silica and richer in alkalis by incorporating 1.3 moles of analcime. Consequently, a peralkaline petrographic trend appears, expressed by an increase in modal feldspathoid minerals (from 1 to 8, but in rare cases, up to 13 vol. %) and by the crystallization of sodic pyroxene. Although the crystallization of analcime occurs late [this mineral is not stable at magmatic temperatures except at very high $P(H_2O)$: Wilkinson 1962, 1965, 1968, Roux & Hamilton 1976], we note that the reverse reaction has been obtained experimentally from an olivine- and analcime-bearing dolerite under thermodynamic conditions that are realistic, considering the setting of the Montagnes Vertes pluton [$P(H_2O) = 1$ kbar, $700°C < T < 1020°C$].

In the second complex of the Courbet peninsula, Les Mamelles, located near Montagnes Vertes, gabbros are abundant, and are intersected by a minor volume of syenite and quartz syenite. Arguing on the basis of whole-rock compositions and petrographic data, Giret & Lameyre (1980) offer the following explanation: the silica oversaturation of rocks is produced by amphibole and biotite fractionation from an alkaline magma from which evolved the gabbros. The existence of angular biotite-bearing amphibolitic inclusions in the neighboring basaltic dykes and the scarcity of biotite (less than 2.5 vol. %) and amphiboles (less than 1 vol. %) in gabbros and quartz-bearing syenites and quartz syenites support such a thesis. Amphiboles are partly or completely destroyed by an oxidation process, and analyzed relics belonging to the magnesiohastingsite types have been found in amphibole solid-solution series in the Montagnes Vertes.

Conclusions

With regards to amphiboles, the silica-under-saturated rocks differ from the silica-oversaturated ones. In undersaturated series, amphiboles present some definite characteristics: (1) the presence of Ti-rich amphiboles such as kaersutite in basic and intermediate rock types, (2) chemical composition evolving from kaersutite to hastingsite by way of $Ti + O \rightleftharpoons Fe^{3+} + OH^-$ or $\Box Ti \rightleftharpoons Na^4Al$ substitutions, and from hastingsite to hastingsitic hornblende and to taramite with predominant $CaAl^{iv} \rightleftharpoons NaSi$ substitution (Fig. 2), (3) absence of alkali amphiboles and of Na-rich sodicalcic amphiboles even in the alkaline rock types, and (4) absence of any silica enrichment in amphibole compositions (Fig. 3); all amphiboles are to be found in a very limited area of the von Wolff diagram.

RELATIONSHIP BETWEEN COMPOSITION OF AMPHIBOLES AND OF ROCKS

Von Wolff normative diagrams (Fig. 3) express the close relationship already known (Cawthorn 1976) between silica content of amphiboles and silica activity in the magma constituting the silica-saturated and oversaturated
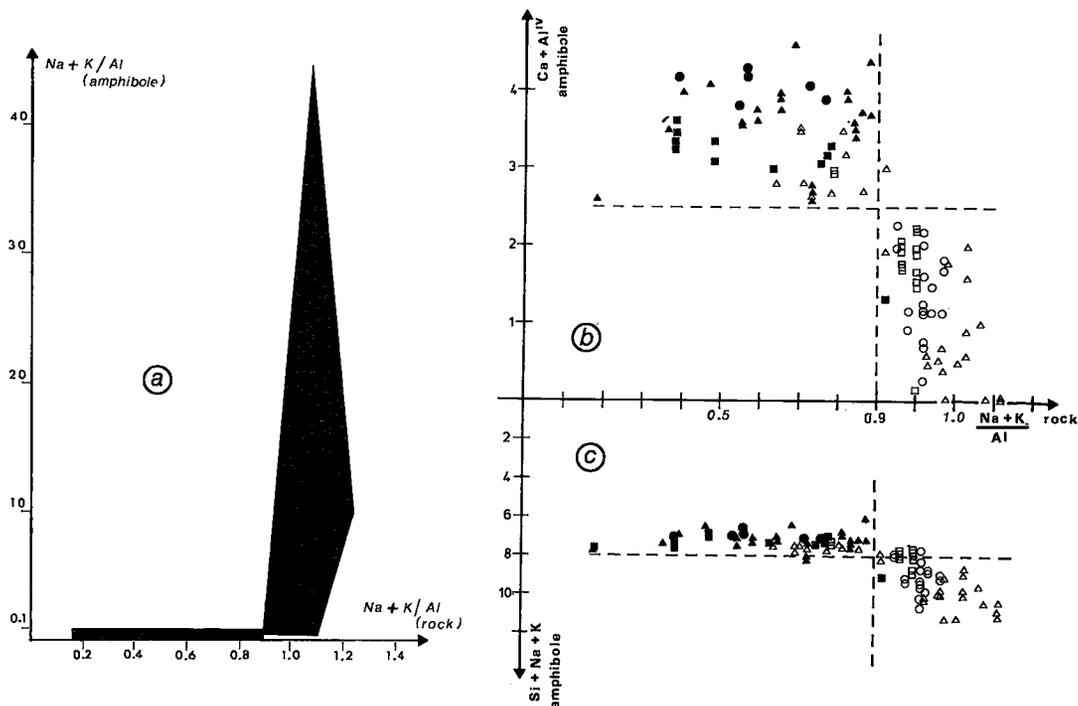
FIG. 4. Linear plots relating compositional variations in amphiboles and their host rocks. (a) Relationship between Na + K/Al in amphiboles and agpaitic coefficient of their host rocks. (b) Relationship between Ca + Al^{iv} in amphiboles and agpaitic coefficient of their host rocks. (c) Relationship between Si + Na + K in amphiboles and agpaitic coefficient in their host rocks.

associations (Corsica, Rallier-du-Baty peninsula, Iskou, Oslo). Such a relationship has been explained in terms of the solubility of Al in the complex amphiboles by Neumann (1976a), who suggested a reaction $Ca_2(Fe,Mg)_4AlSi_7$ $AlO_{22}(OH)_2 + CaAl_2Si_2O_8 \rightarrow Ca_2(Mg,Fe)_3Al_2$ $Si_6Al_2O_{22}(OH)_2 + Ca(Fe,Mg)Si_2O_6 + SiO_2$, showing that silica goes into amphibole and aluminum into plagioclase when the activity of silica in the magma increases, as reflected in our petrographic and chemical data. For the silica-undersaturated rock series, analogous diagrams show that there is no obvious change in amphiboles clustered below line LM and confined to a limited field (Oslo, Tahiti, Monts Ballons, Montagnes Vertes, Les Mamelles). In these series, however, chemical analyses of rocks and amphiboles suggest a close relationship between Ca and Mg contents in rocks and amphiboles with significant correlation coefficients (those for Mg and Ca are, respectively, +0.70 and +0.96 in the Tahiti rock association and +0.96 and +0.81 in the Montagnes Vertes petrographic association).

Other diagrams that take into account the agpaitic ratio of rocks (Fig. 4) suggest the existence of two principal amphibole trends. In Figure 4a, this ratio in rocks has been plotted in terms of the same ratio in amphiboles, and

thus two distinct amphibole populations can be found. To the first group belong amphiboles found in rocks whose agpaitic ratio is less than 0.9; the common characteristic of these amphiboles is a very low $(Na_2O+K_2O)/Al_2O_3$ ratio (less than 0.1). To the second group belong amphiboles from rocks whose agpaitic ratios exceed 0.9; unlike the preceeding amphiboles, these have an agpaitic ratio evolving from 0.05 to 45.0. Such bimodality can be specified in the next diagrams (Figs. 4b, 4c), which clearly separate amphiboles from agpaitic and nonagpaitic rocks in regard to their chemical parameters. Thus, the first group of amphiboles has a $Ca + Al^{iv}$ content greater than 2.5 and a $Si + Na + K$ content less than or equal to 8, whereas the same parameters are less than 2.5 and generally more than 8, respectively, in the second group.

The absence of $(Ca + Al^{iv})$-rich amphiboles in agpaitic rocks suggests the breakdown of such amphiboles when differentiated liquids become peralkaline, which occurs as $P(H_2O)$ decreases or $P(O_2)$ increases (Ferguson 1978) in most observed examples. In the same way, the absence of $(Ca + Al^{iv})$-poor amphiboles where the agpaitic ratio of rocks is less than 0.9 indicates that crystallization of silica-rich amphiboles occurs only in alkaline or peralka-
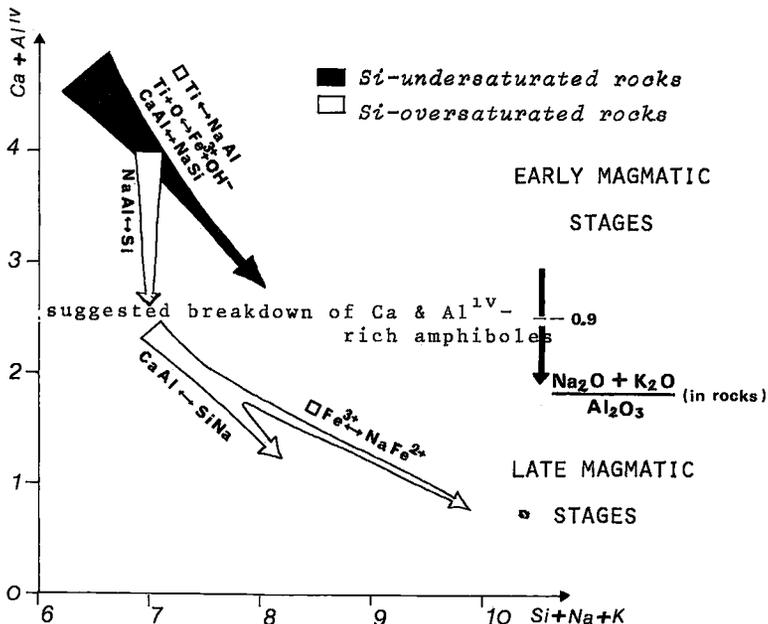
FIG. 5. Schematic representation of the different amphibole compositional trends in alkaline ring-complexes.

line liquids, *i.e.*, in very differentiated magmas. This, added to the previous descriptions (Fig. 1), shows that such silicic and alkali-rich amphiboles crystallize only in very late magmatic stages and even during hydrothermal stages, since their field of stability is controlled by both $P_{volatiles}$ and chemical composition of the magma (Ernst 1962, Charles 1975, Ferguson 1978).

More precisely, and on the basis of petrographic, textural and chemical data, one may infer the existence of different amphibole compositional trends (Fig. 5). With several examples, different compositional evolutionary trends have been established in amphiboles by means of cationic substitutions. Thus, in the silica-saturated and oversaturated associations of alkaline ring-complexes, the predominant substitution in $(Ca + Al^{iv})$-rich amphiboles is $NaAl^{iv} \rightleftharpoons \square Si$, which differs from the silica-undersaturated associations, in which we note a Ti decrease and $CaAl^{iv} \rightleftharpoons NaSi$ as the predominant substitution scheme. In $(Ca + Al^{iv})$-poor amphiboles, which are only encountered in the silica-saturated and oversaturated rock series in this study, the substitution $CaAl^{iv} \rightleftharpoons NaSi$ produces a main trend from which the $\square Fe^{3+} \rightleftharpoons NaFe^{2+}$ substitution gives a bifurcating trend illustrated by the barroisite-to-arfvedsonite evolution. In this schematic representation, $Fe \rightleftharpoons Mg$ substitution occurs independently of any trend.

DISCUSSION

Using experimental data one can infer the considerable importance of physical conditions of crystallization [*i.e.*, T, P(total), P(H$_2$O), f(O$_2$)] controlling amphibole compositions (Boyd 1959, Ernst 1962, Leake 1965, Gilbert 1966, Phillips & Rowbotham 1968, Huebner & Papike 1970a, 1970b, Wones 1970, Holloway & Burnham 1972, Charles 1975, 1977, Helz 1973, 1976, Merrill & Wyllie 1975, Yagi *et al.* 1975, Mitchell & Platt 1978). In the same way but using petrographic and chemical data, Cawthorn (1976) demonstrated that physical conditions govern the partition coefficients of certain elements between amphiboles and magma. However, it is suggested that magma chemistry is the most critical factor (Neumann 1976a, Ferguson 1978).

Although one should consider both physical and chemical parameters together and not separate their specific roles, based on limited experimental evidence, this study establishes close relationships between amphibole compositional trends and the chemistry of their host rocks. Substitutions in amphiboles are controlled essentially by the silica activity of the magma, whereas the $Ca + Al^{iv}$ content of an amphibole depends upon the agpaitic ratio in the rock.

In the alkaline rock series, we suggest the existence of a gap that separates the $(Ca + Al^{iv})$-rich, $(Si + Na + K)$-poor group of amphiboles from the $(Ca + Al^{iv})$-poor, $(Si + Na + K)$-rich group. The first group develops early, commonly earlier than plagioclases, at a magmatic stage. The second develops late, frequently later than alkali feldspars, sometimes later than quartz in a late magmatic stage or during hydrothermal stages, according to Ferguson (1978). Such evidence emphasizes the low probability of a continuous amphibole solid-solution series from hastingsite to arfvedsonite, previously suggested by Frisch (1970). In contrast, our petrographic, chemical and textural data suggest the existence of two solid-solution series, the first being silica-poor ($6.00 \leqslant Si \leqslant 7.01$) and the second silica-rich ($6.76 \leqslant Si \leqslant 8.00$), as shown in Figure 6.

Thus, the role of amphiboles in the magmatic process can be specified. According to Gunn (1972), Cawthorn (1976), Maury (1976) and Helz (1976), the early fractionation of Ca-rich and Si-poor amphiboles induces an increase of Si in the magma, which contributes to the production of silica-rich differentiated liquids (*i.e.*, those of granitic composition) when magmas are silica-oversaturated, and permits the evolution to quartz-bearing rocks from silica-undersaturated magmas. The persistence and breakdown of calcic and sodicalcic amphiboles, as observed in syenites from the Montagnes Vertes intrusion, produce a sodium enrichment in the residual liquid that generates a limited peralkaline trend.
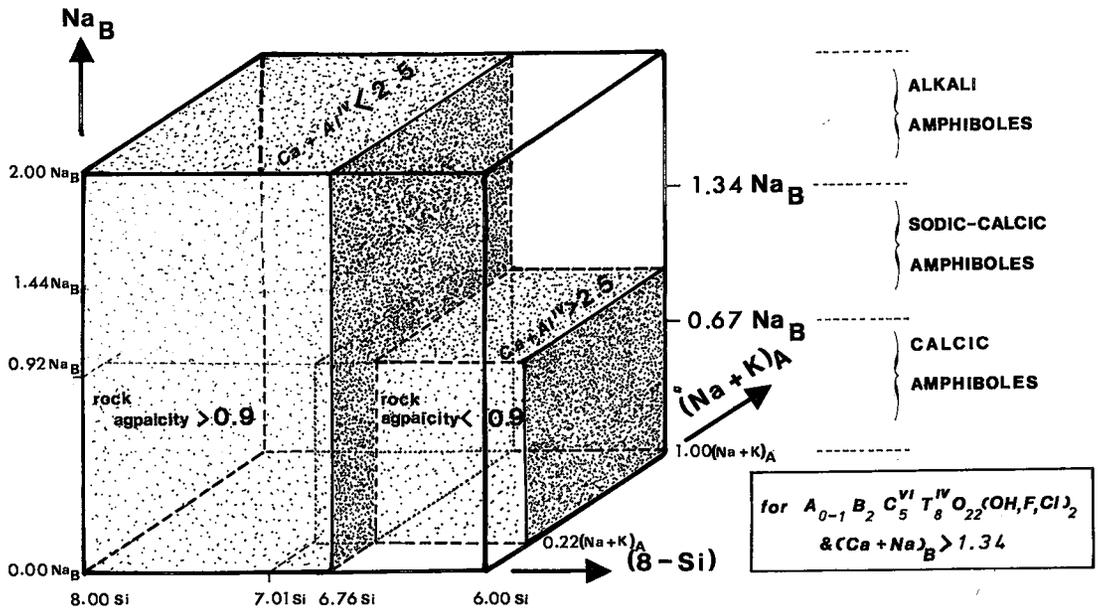
FIG. 6. The two groups of amphiboles in the three-dimensional diagram Na_B, $(Na + K)_A$, Si (Leake 1978).

The translation from French to English has been very kindly done by Mrs. C. Gauthier, teacher of English in the Lycée Fremin (Bondy, France).

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APPENDIX: LOCATION AND DETERMINATION OF AMPHIBOLES AND HOST ROCKS (NEW ANALYSES)

Kerguelen island, Rallier-du-Baty peninsula

Rocks: LL–1 Syenite from the second intrusion of the southern centre; L–2 syenite from the first intrusion in the southern centre; P–1 syenite from the third intrusion in the southern centre; P–14 granite from the fourth intrusion in the southern centre; DF16 syenite from the sixth intrusion in the southern centre; LL14 syenite from the Anse syenite intrusion, fayalite-bearing nordmarkite, and VA80 syenite of the middle centre.

Amphiboles: LL16–1 katophorite, LL16–2 ferrorichterite, LL16–3 arfvedsonite, LL16–4 ferroactinolite, L2–1 & L2–2 same crystal of katophorite, L2–3 ferrorichterite, P1–1 & 2 katophorite, P14–1 arfvedsonite, DF16–1 & 2 same crystal of winchite in the core and rims of arfvedsonite, LL14–1 richterite around a fayalite crystal, LL14–2, 3 & 4 same crystal with ferrorichterite in the core and medium zone and with arfvedsonite in the rims, LL14–5 ferroactinolite, VA80–1 amphibole rimming augite, VA80–2 actinolite, W28–1 actinolite.

Kerguelen island, Courbet peninsula

Rocks: 77–35 gabbro, MV–1 monzogabbro, 77–60 rich kaersutite-bearing monzonite, 77–49 monzogabbro, 77–20 syenite, MV–2 dyke of aplitic microsyenite, 77–103c quartz-poor granite dyke.

Amphiboles: 77–35 ferrokaersutite, MV–1 ferrokaersutite, 77.60–1 & 2 ferrokaersutite, 77–49 kaersutite, 77–20–1 & 2 hastingsite and Mg-hastingsite in the same crystal, MV.2–1, 2 & 3 same crystal of hastingsitic hornblende in the core, grading to taramite in the centre and rim, 103c Mg-hastingsite.

Kerguelen island, Monts Ballons, Province du Centre

Rocks: 78–31c micromonzonite, 78–47 nepheline-bearing syenite, 78–20 amphibole cumulate in monzogabbro, 78–48 nepheline-bearing syenite, 78–60b monzogabbro, 78–51 gabbro, 78–52 monzogabbro, 78–64 nepheline-bearing syenite.

Amphiboles: 78–31c subsilicic kaersutite, 78–47–1 & 2 same crystal of brown kaersutite in the core and green ferrokaersutite rims, 78–20 subsilicic kaersutite, 78–48–1 subsilicic kaersutite, 78–48–2 kaersutite, 78–60b kaersutite, 78–51 taramite, 78–52–1 hastingsite ferrokaersutite, 78–58–2 kaersutite, 78–64 ferrokaersutite.

Niger, Iskou

Rocks: GBH quartz monzonite, SGM quartz syenite, 77–138 quartz syenite, 67–78 monzogabbro, 66–77 leucogabbro, 61–77 leucogabbro, 17–77 alkaline quartz syenite, 83–76 monzogabbro, 78–77 leucogabbro, 75–78 monzogabbro.

Amphiboles: GBH ferrohornblende, SGM ferrotschermakitic hornblende, 138–77 hastingsitic hornblende, 66–77–1 & 2 ferrotschermakitic hornblende, 67–78 ferroedenitic hornblende, 83–76 ferrohornblende, 74–78 FeMg-pargasite, 78.77–1 hastingsitic hornblende, 78.77–2 hastingsite, 78.77–3 ferrohornblende, 62.77–3 kaersutite, 61.77–4 edenitic hornblende, 74–78 FeMg-pargasite, 17–77 ferrobarroisite.

Corsica, Cauro-Bastelica

Rocks: 1 blue soda-grunerite-bearing granite, 2 ferroedenite-, ferrobarroisite- and fayalite-bearing granite, 3 hydrid xenoliths resulting from a mixing of magmas in the biotite-bearing granite.

Amphiboles: 1–1 ferroedenite, 1–3 to 8 ferrobarroisite, 2–2 & 3 same crystal of ferrobarroisite with a ferroedenitic core, 2–1 ferrobarroisite, 2–4, 6 & 7 ferrobarroisite, 2–5 ferroedenite, 2–8 to 10 sodic grunerite, 3–1 to 3 Fe^{2+}-hornblende.