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Dyke Swarms of the Paraná Triple Junction, Southern Brazil

Enxame de Diques da Junção Tríplice do Paraná, Brasil Meridional

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ABSTRACT

This work intends primarily to survey the field, mineralogical and petrographic characters of the mafic dykes which occur on a stretch of 650 km along the Southeastern coast of Brazil, between the city of São Sebastião, and the island of Santa Catarina. New chemical and geochronological data are also presented. The coastal dyke swarms are envisaged as the northern and southern arms of a plume-generated triple junction system centered on the Paraná State coast, and related to the initial opening of the South Atlantic. Mafic magma intruded as dyke swarms along three directions: N-S (the southern arm, along the Paraná-Santa Catarina coast), NW-SE (Ponta Grossa arch) and NE-SW (the northern arm along the São Paulo coast). Fifty two dykes, almost all tholeiitic diabases, were mapped and sampled along the south arm coast. The Ponta Grossa arch dykes are chiefly composed of tholeiitic diabases and lesser intrusions of andesitic to rhyolitic composition. Over 240 dykes were sampled and identified along the north arm west of São Sebastião. Lamprophyres are here abundant, followed by diabases, microdiorite porphyries and lesser amounts of trachy-andesite, carbonatite and Precambrian dykes. Special attention was given to the study of lamprophyres, their field appearance relative abundance, mineral and chemical composition, enclaves and relations to neighboring alkaline intrusions.

Palavras-chave: enxame de diques, ocorrências no Sudeste brasileiro, petrografia, quimismo, geocronologia.

RESUMO

Este trabalho tenciona cartografar e descrever as características mineralógicas e petrográficas dos diques máficos que ocorrem ao longo de 650 km da costa sudeste brasileira, entre as cidades de São Sebastião – SP e a Ilha de Santa Catarina – SC. Apresentam-se também novos dados químicos e geocronológicos. Concebe-se o enxame de diques costeiros como constituinte dos braços norte e sul de um sistema de junção tríplice centrado na costa do Estado do Paraná e relacionado à abertura inicial do Atlântico Sul. Magma máfico introduziu-se ao longo das direções: N-S (braço sul, na costa Paraná-Santa Catarina), NW-SE (arco de Ponta Grossa) e NE-SW (braço norte na costa de São Paulo-Paraná). Cinqüenta e dois diques, quase todos toleíticos, foram mapeados e amostrados nas costas do braço sul. No arco de Ponta Grossa também predominam os diabásios toleíticos acompanhados de algumas intrusões riolíticas e andesíticas. Cerca de 240 diques foram mapeados e identificados ao longo do braço norte, a oeste da cidade de São Sebastião. Os lamprófiros, aqui são abundantes, seguidos de diabásios, microdiorito pórfiros e menor proporção de diques pré-cambrianos, carbonatitos e traqui-andesitos. Atenção especial foi dedicada ao estudo dos lamprófiros: sua aparência, abundância relativa, composição mineral e química e relações com intrusões alcalinas.

INTRODUCTION

The Brazilian southern coast is injected by a swarm of predominantly mafic dykes. The past two decades have witnessed an increase on the study of dyke swarms in Brazil, either in the hinterland (Menezes et al., 2001; Sial et al., 1987; Teixeira, 1989, 1990), or along the continental coast (Marques, 2001; Bellieni et al., 1990; Raposo and Ernesto, 1989; Coutinho and Ens, 1992; Coutinho, 1971; Coutinho and Oliveira, 1966; Coutinho et al., 1992; Caruso and Awdziej, 1993; Damasceno, 1966; Garda, 1995; Piccirillo et al., 1990; Comin-Chiaramonti, 1983; Marques et al., 1992; Guedes et al., 2005). As a result, understanding of distribution, density, age, geochemistry and paleomagnetism of mafic dykes has improved markedly. The Brazilian coastal dyke swarms make up three well defined components of the so called Paraná triple junction, which is conceived as plume generated and developed in the lithic and structural sequence, outlined by Burke and Dewey (1973). In this paper, the author is especially concerned with the distribution, petrographic classification and geochemical characterization of 305 mafic dykes which outcrop along the São Paulo, Paraná, and Santa Catarina coast line. 350 samples were sectioned and microscopically studied, 89 of which being chemically analyzed.

The K/Ar geochronological data reported in this paper were obtained from analyses made by CPGeo/IGc/USP.

Methods and sources of chemical analyses are mentioned as footnote in Table 1.

LOCATION AND FIELD FEATURES

The coast surveyed in this study is depicted in Figure 1. The areas where dykes were detected are enlarged and framed in lettered charts. The hiatuses between successive charts were traveled but observations became hampered by existence of beaches, vegetation and dwellings. In addition, stretches of rocky coast could not be reached by sea or land. More detailed maps of the dyke occurrences are presented as charts (Figures 3 and 4A to 4V). Dyke locations and attitudes are plotted and numbered within each chart. Absence of aerial photographs in a proper scale and poor exposures militated against defining dyke prolongations. Some presumed continuity is however indicated by broken lines (e.g., Figure 4B:61).

The description below refers to littoral dykes of the north and south arms of a triple junction system. They are conceived to cross each other in the Ponta Grossa arch domain, Paraná (Figure 2). To simplify representation, coastal dykes in the area have been plotted on either the north or south arm. It must be said, however, that the Ponta Grossa arch is an independent geographic entity, studied by several authors in the fields of paleomagnetism (Raposo and Ernesto, 1989), geochronology (Renne et al., 1996) and isotopic geochemistry (Piccirillo et al., 1990). A survey conducted by Maack (1947), on the feeding dykes of the "trapp of Paraná" informs about the existence of predominant diabase and lesser amounts of diabase porphyry, andesites and possibly a few dacites in the Ponta Grossa arch.

NORTH ARM

The north arm dykes are located in a Precambrian Basement (the Costeiro Complex) which comprises gneisses, granites and amphibolites, striking parallel to the NE mean coast direction. The Complex is part of an ensialic fold belt whose geologic evolution is ascribed to late Proterozoic times. The north arm was intruded along the coast line by over 150 dykes of assorted compositions and ages. Lamprophyre (43%), diabase (42%), microdiorite porphyry (10%) and lesser amounts of assorted "Precambrian" mafics, trachy-andesite and carbonatites make up the dyke assembly. At the north arm's east side, an overwhelming number of dykes strike NE, while at the west side within the Ponta Grossa arch domain, they strike in a NW direction.

Except for a trachyandesite horizontal sheet (Figures 10and 4B:61) and a few other low angled lamprophyre dykes, the swarm is composed of vertical to sub-vertical dykes.

Unlike the massive diabase wide intrusion of Pedrita, Santa Catarina (Figure 12), the thicker dykes are up to 30 m wide and consist of dark grey to black diabase and microdiorite porphyry. They are medium to fine-grained rocks and grade to aphanitic or vitreous black borders. The granitoid wall rocks may show restricted or nil thermal changes at the contact. Diabases are aphyric or porphyritic but rocks of dioritic composition are invariably porphyritic (microdiorite porphyry). Columnar horizontal jointing (Figure 11) is typical of vertical undeformed dykes. Diabase dykes have been seen cutting microdiorite porphyry and a single minette (Figure 13), the sole mica lamprophyre found. The other lamprophyres (camptonite and monchiquite) seem to be more recent. They may cut Precambrian mafics (Figure 15), diabase and even alkaline syenitic intrusions (Coutinho and Melcher, 1973). Small sized xenoliths are sometimes seen inside diabase dykes.

Lamprophyres occur as zoned 0.3 to 2 m. thick dykes, the central parts of which are usually richer in phenocrysts, ocelli and amygdales. Lateral aphyric bands, flow structures and central xenolithic areas have also been observed in some samples. Lamprophyric dykes may be so full of xenoliths as to constitute real intrusion breccias (Figure 15). They carry fragments brought from the deep crust or mantle such as dunite nodules, garnet-sillimanite rocks and granulite.

Presumable Precambrian dykes were distinguished by their metamorphic structure and/or mineral composition. Only tabular intrusions cutting across bedding or foliation were taken into account. Their thickness varies between from 0.5 to 2 m.

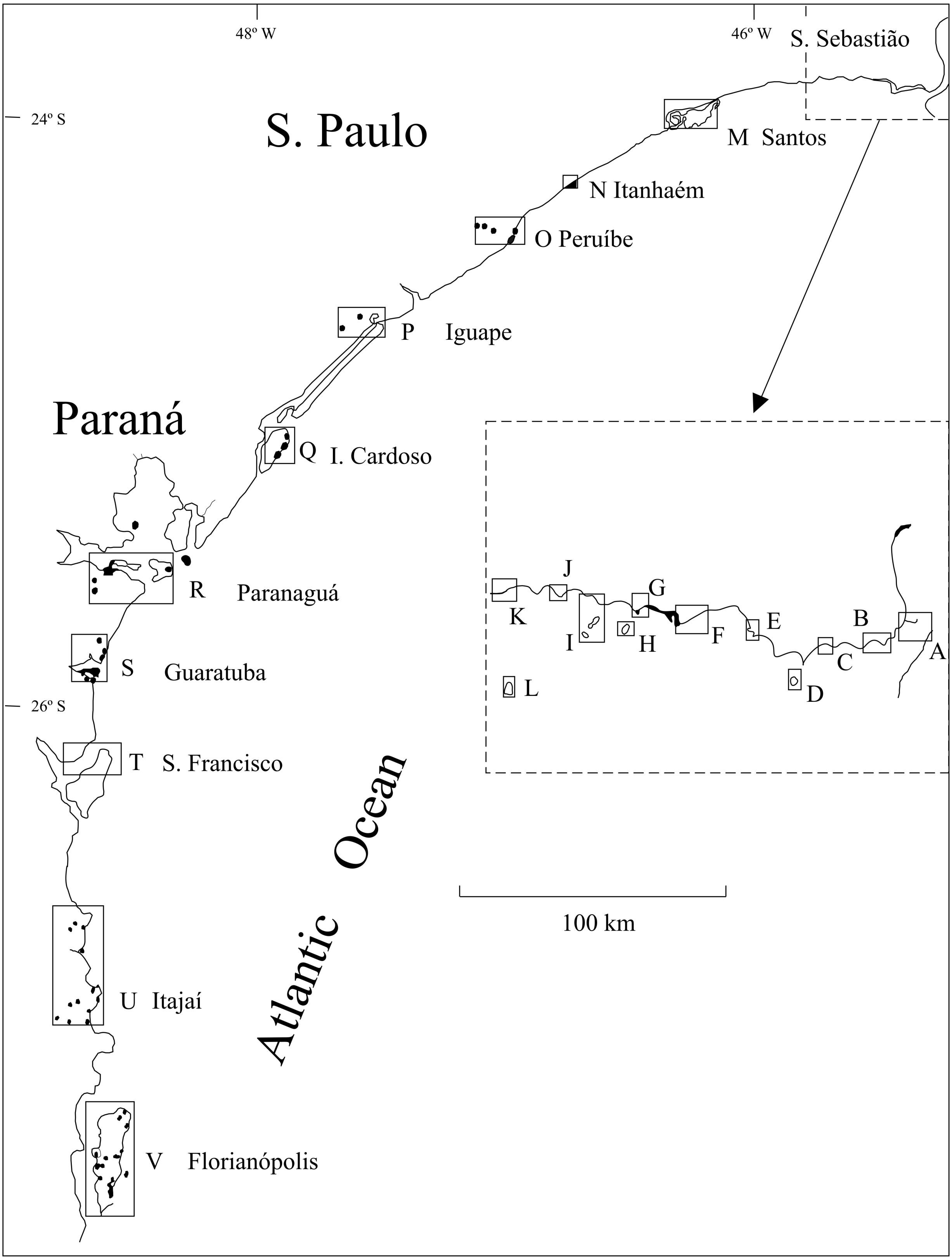


Figure 1. Outline of southern Brazilian coast. Dyke occurrence inside lettered charts.

Carbonatites were mapped in As Ilhas (Figure 4I:19) and Itanhaém (Figure 4N:2) as vertical dykes, 1.5 m the former and 0.5 m thick the latter.

SOUTH ARM

The 59 recorded south arm dykes, cut Precambrian gneissic-migmatitic terrains and low-grade metasedimentary rocks of the Brusque Group, both outcropping along NE-SW belts parallel and diagonal to coast lines. From Paranaguá to São Francisco Island the dykes belong to the Ponta Grossa arch domain and strike NW. Southwards, in the Itajaí and Florianópolis regions, however, the direction changes to NE, parallel to the coastline.

South arm dykes are mainly diabases that can reach a width of about 100 m (Figure 12). They are usually uniformly structured but may show branches and columnar jointing (Figure 11). Their medium to fine-grained aphyric textures grade to narrow aphanitic or vitreous borders.

PETROGRAPHY AND PETROCHEMISTRY

North arm

Trachyandesite

The sheet previously classified as trachyte (Coutinho, 1966) had its name changed to trachyandesite due to its trachytic texture and mineralogy: essential tabular K-rich oligoclase and accessory amounts of quartz, calcite and ore mineral in a trachytic texture (Figure 5A). The sole chemical analysis obtained for this rock (SiO_2 52.5% and $Na_2O + K_2O$ 7.1%) would plot it in TAS diagram (Figure 6) in the field of basaltic trachyandesite.

Diabase

Medium to fine grained diabase is the characteristic petrographic type for the thick dykes that predominate on the west side of the north arm (Figures 4G, 4I, 4J, 4K, 4M). Their texture is intergranular to subophitic (Figure 5B) Except for one occurrence in Ubatuba (Gomes and Ruberti, 1979; Gomes and Berenholc, 1980) no diabase dyke with differentiated granitic parts has been described in the north arm. Calcic plagioclase, usually An_{50-60}, and clinopyroxene (augite and occasional pigeonite), are the predominant mineral phases. Apatite needles, magnetite and/or ilmenite are primary accessories. Quartz or interstitial micropegmatite are commonly found in small amounts. Hornblende and green biotite are deuteric and chlorite, pyrite, epidote, sericite, calcite and leucoxene may appear as secondary products of saussuritization and uralitization. As a whole, considering the mineral and average chemical composition (Table 1), SiO_2 about 50%, low Al_2O_3, rather high iron coupled with relatively low MgO, low alcalies and appreciable TiO_2 as well as the amounts of Q normative (Table 2), it would be safe to say that the north arm diabase belongs to the tholeiitic class with a rather high average TiO_2 content (> 3%). In the TAS diagram of Figure 6, the average diabase would plot in the trachybasalt field.

K/Ar age determined for a Ilha das Couves sample (Figure 4I:31) is 133.1 ± 3 My.

Diabase porphyry

Diabase porphyry, not distinguished from normal diabase occurs as a fine-grained rock in slender dykes mainly in the east side of the north arm (Figures 4B to 4F). Clinopyroxene and/or olivine and/or calcic plagioclase are the usual phenocryst minerals (Figure 5C). Augite has at times, titaniferous

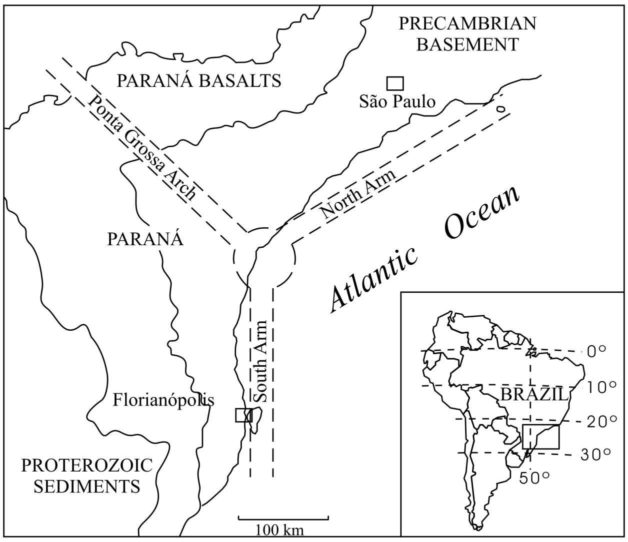


Figure 2. The Paraná triple junction system.

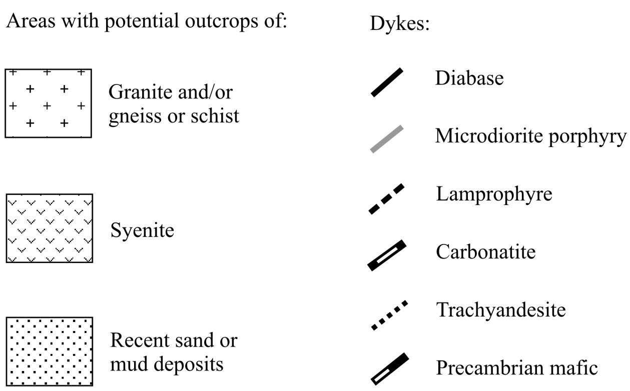
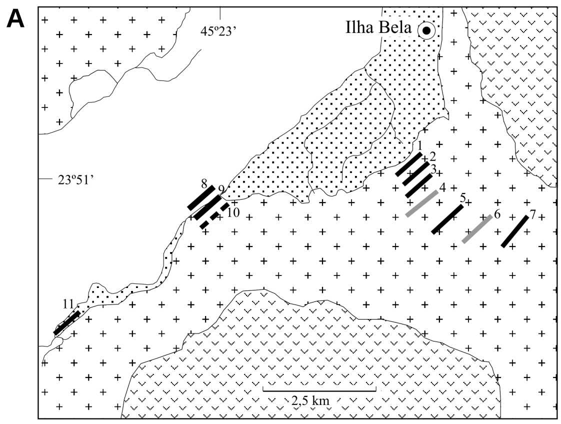
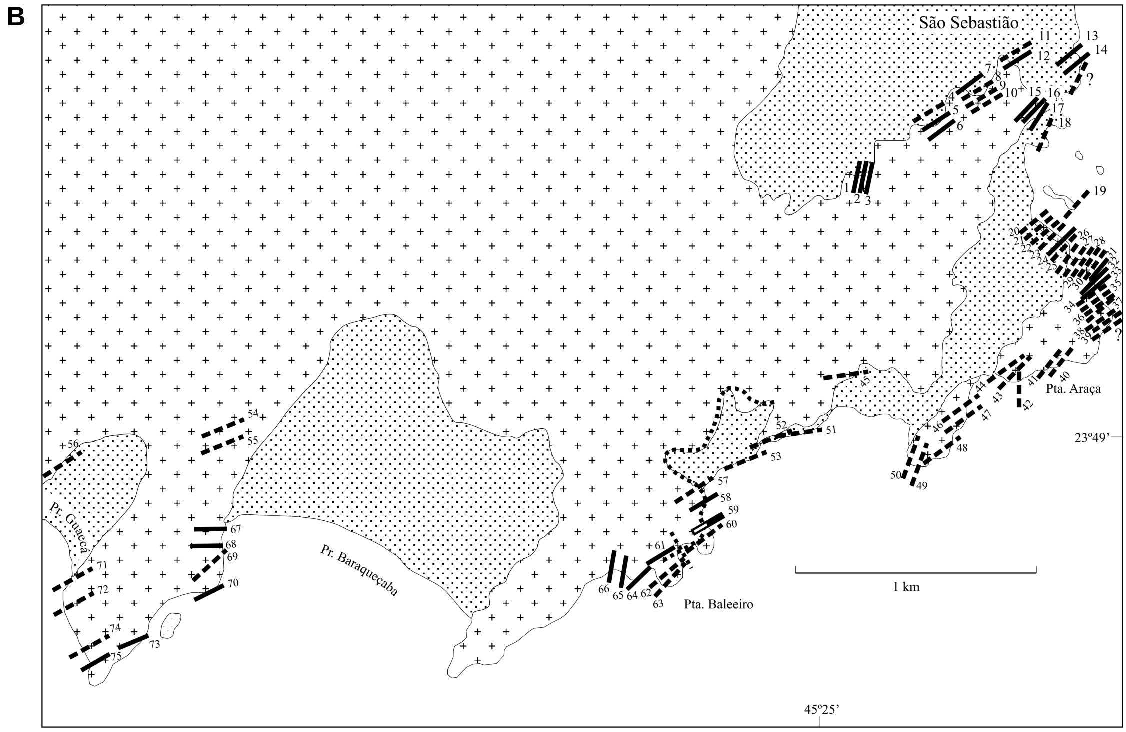
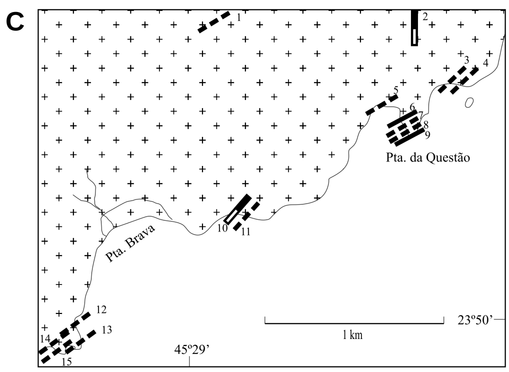


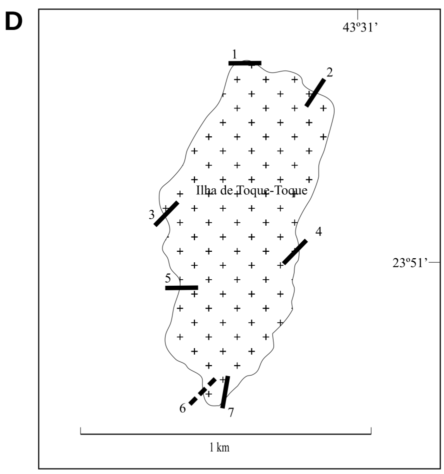
Figure 3. Legends to the lettered charts.

Figure 4. A to V: Figure 1 charts showing regional lithology and mafic dykes location and attitude.









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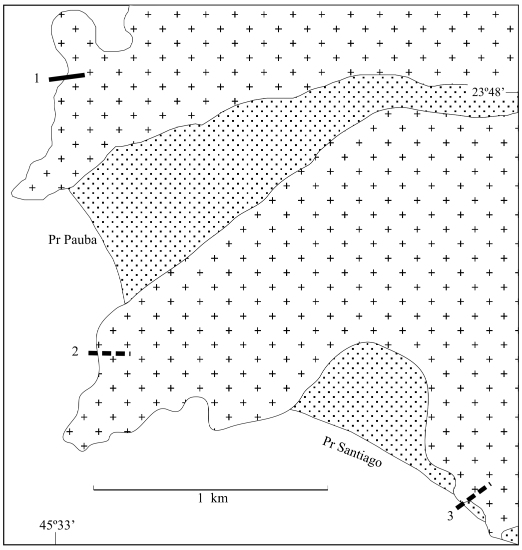
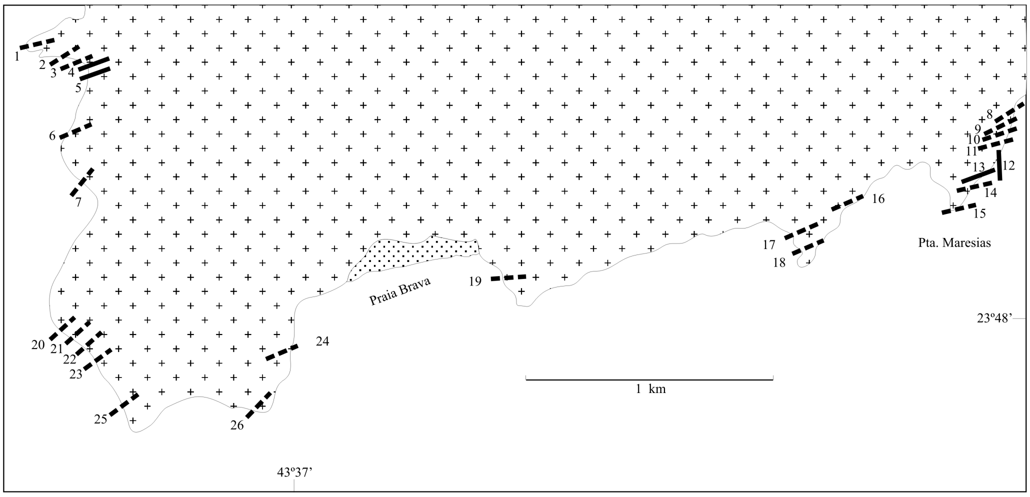

1
23º48'
Pr Pauba
2
Pr Santiago
1 km
3
45º33'

F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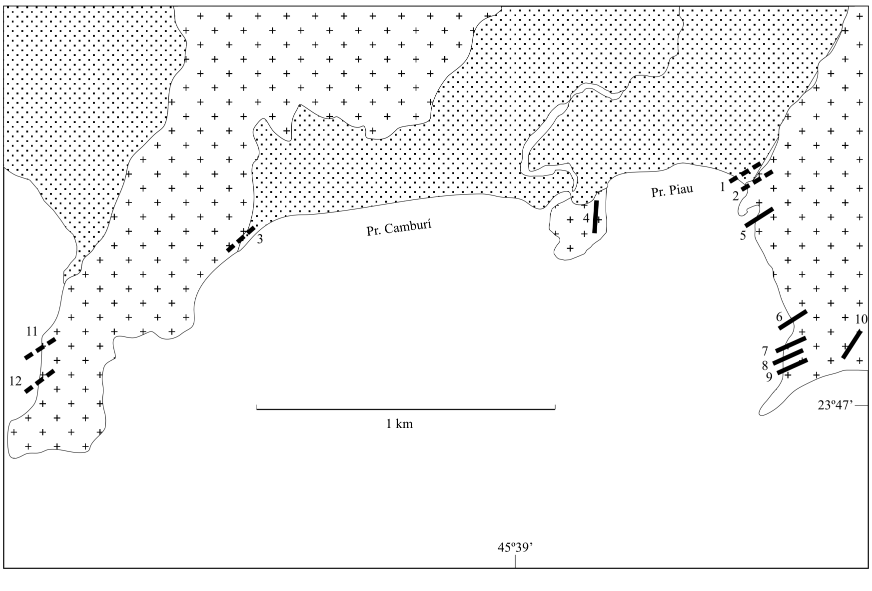
16
17
18
Pta. Maresias
19
Praia Brava
23º48'
20
21
22
23
24
25
26
1 km
43º37'

G


1
2
Pr. Piau
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Pr. Camburi
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10
11
7
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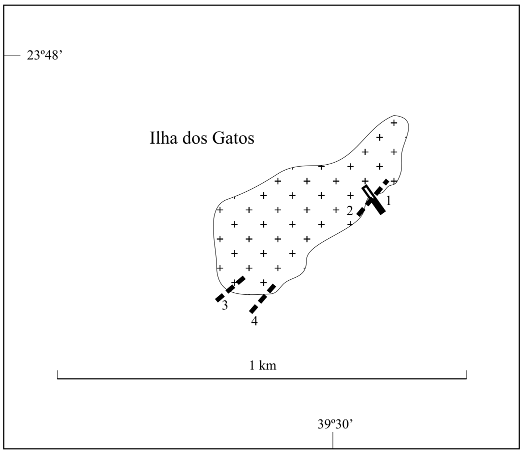
12
1 km
23º47'
45º39'

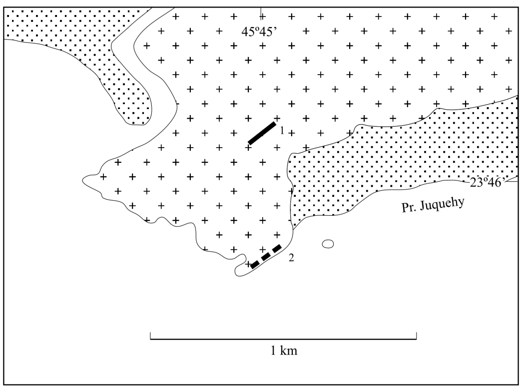
H


23º48'
Ilha dos Gatos
1
2
3
4
1 km
39º30'

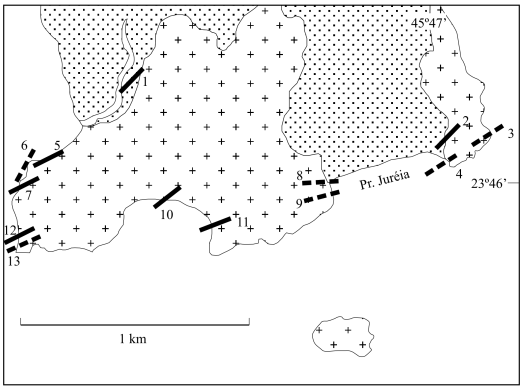
I


As Ilhas
Pr. Sahy
23º47'
As Ilhas
I. das Couves
1 km
45º42'

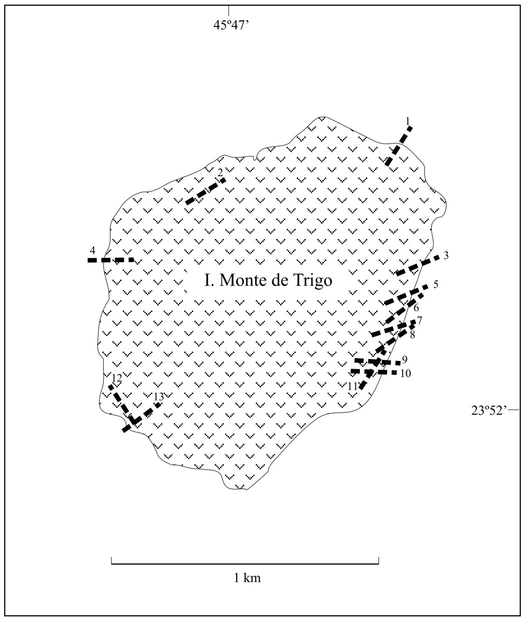
J


45º45'
1
2
23º46'
Pr. Juquehy
1 km

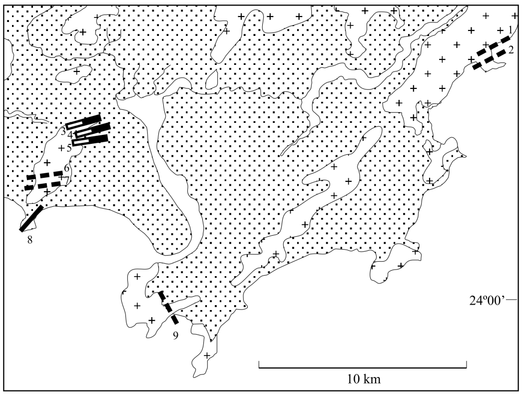
K


45º47'
23º46'
Pr. Juréia
1 km

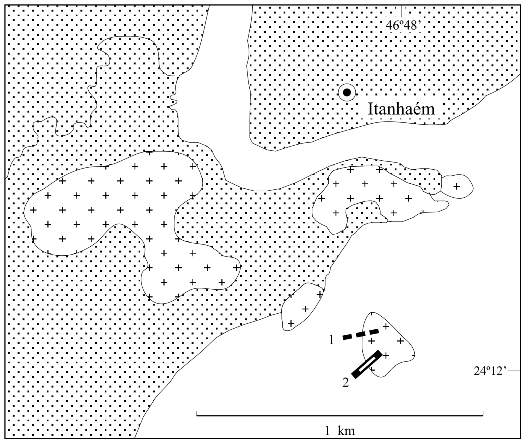
L


45º47'
I. Monte de Trigo
23º52'
1 km

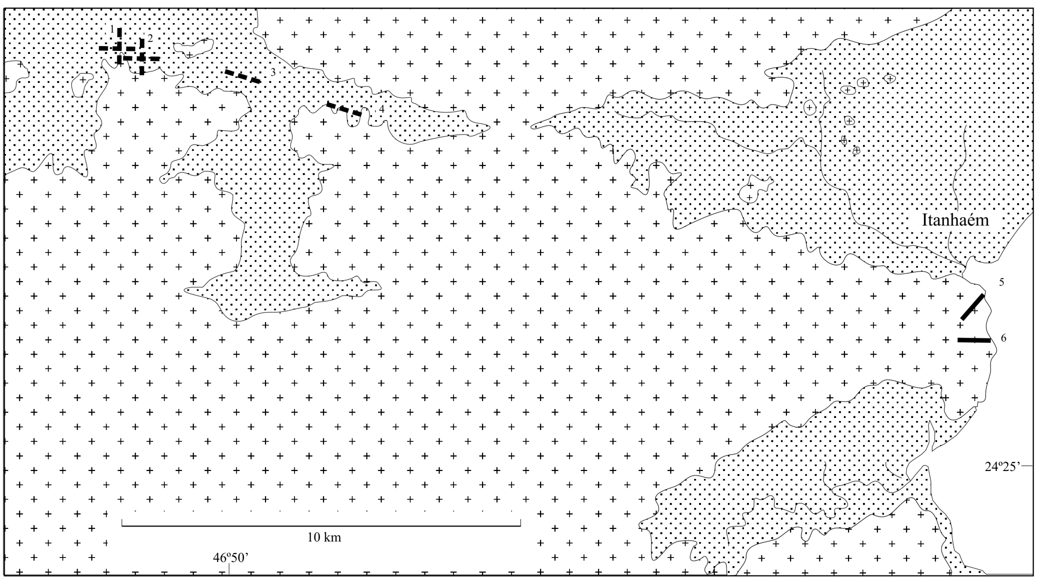
M

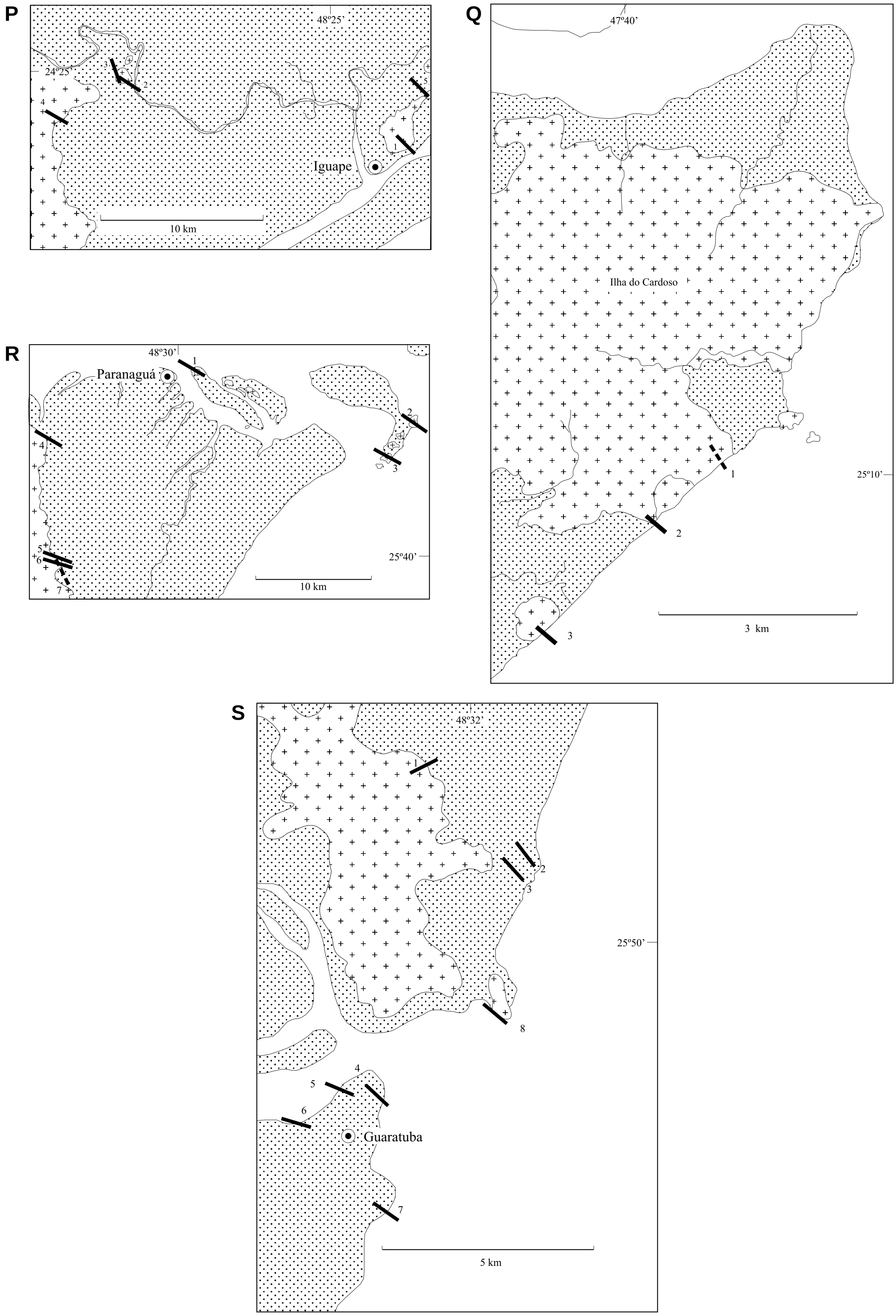

24º00'
10 km

N

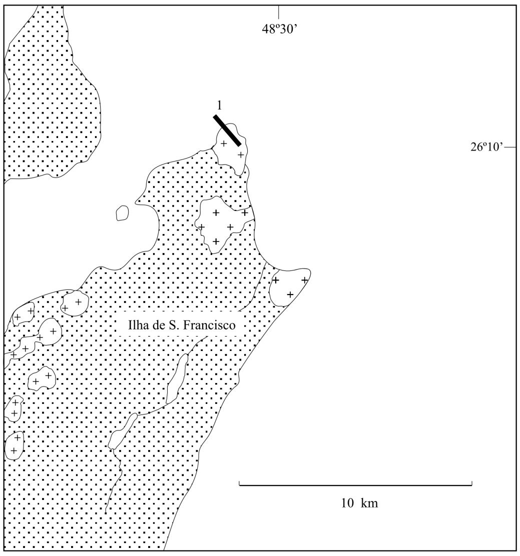

46º48'
Itanhaém
24º12'
1 km

O

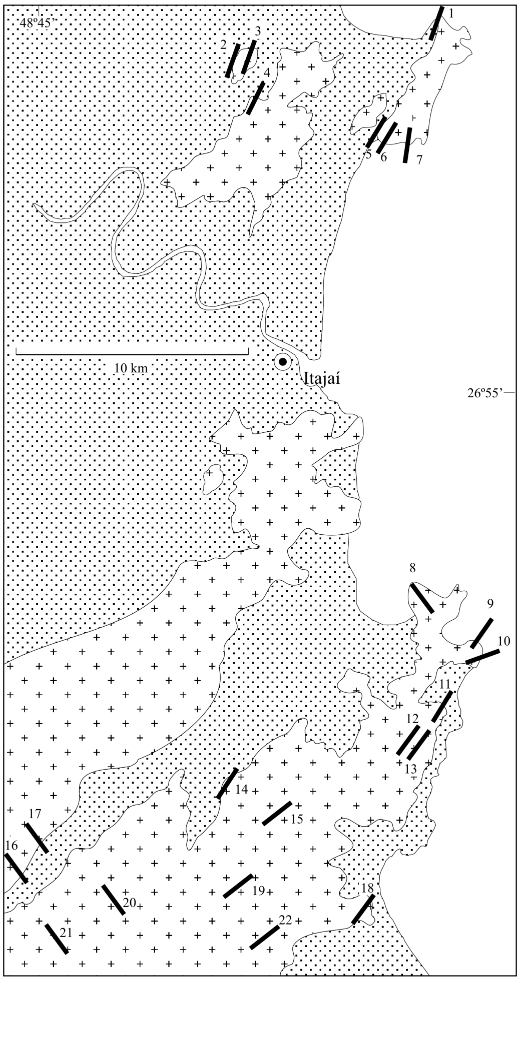

Itanhaém
24º25'
10 km
46º50'


P
48º25'
24º25'
Iguape
10 km
Q
47º40'
Ilha do Cardoso
25º10'
3 km
R
48º30'
Paranaguá
25º40'
10 km
S
48º32'
25º50'
Guaratuba
5 km

T


48º30'
1
26º10'
Ilha de S. Francisco
10 km

U


48º45'
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Itajaí
10 km
26º55'
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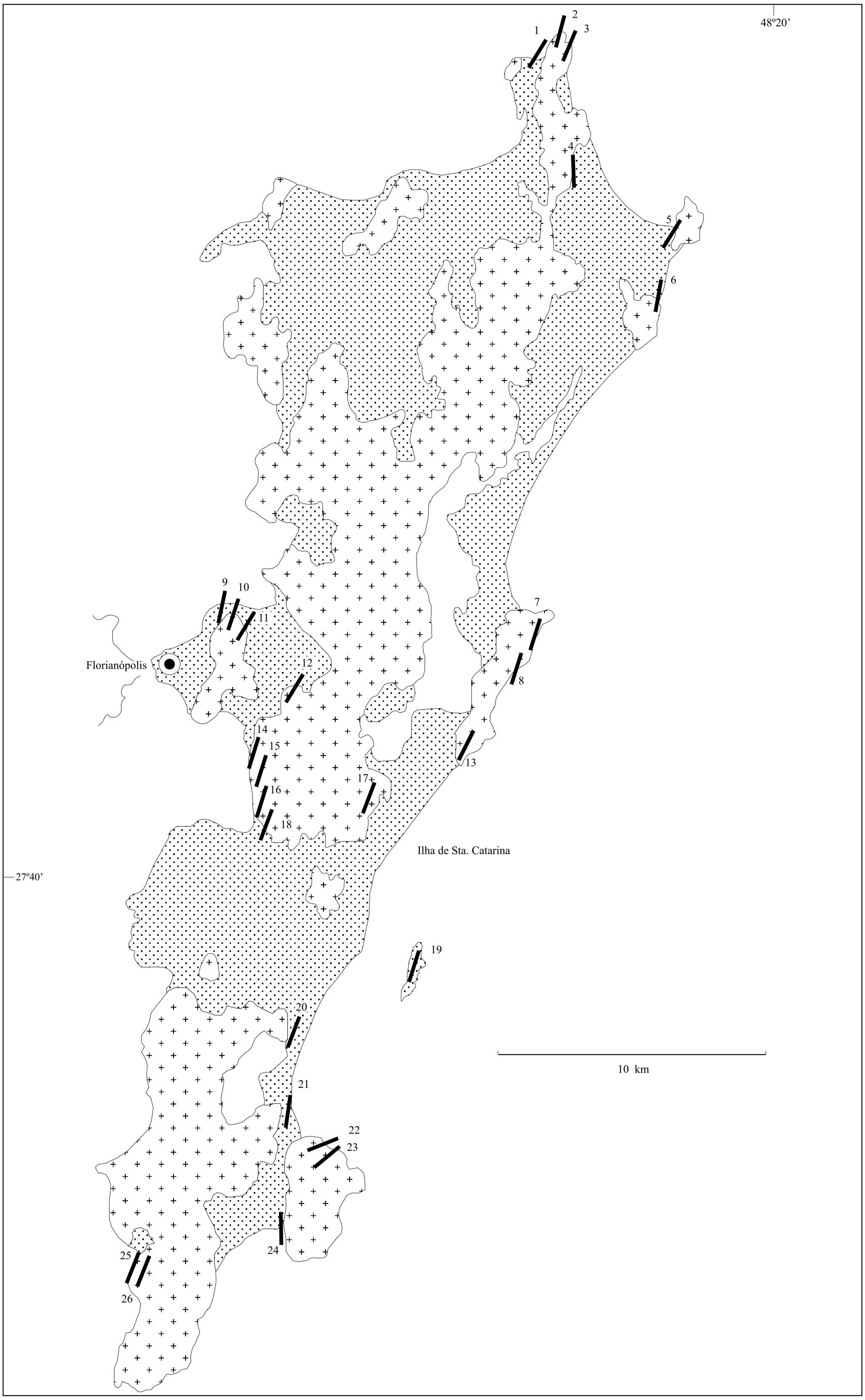
V


48º20'
27º40'
Florianópolis
Ilha de Sta. Catarina
10 km
1
2
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26

Table 1. Chemical analyses obtained from the brazilian southeastern coast mafic dykes. Analysis by ICP and x-ray fluorescence; IGc-USP chem.lab. Atomic absorption: GEOLAB.

Oxide%	Lamprophyre 36 samples			Diabase-N. arm 22 samples			Diabase-S. arm 14 samples			Microdiorite porphyry 14 samples			Carbonatite 3 samples		
	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.
SiO_2	37.47	48.58	42.46	45.80	54.28	50.98	48.78	55.15	51.42	55.00	65.85	58.81	11.61	21.40	20.15
Al_2O_3	7.54	17.16	12.19	12.37	15.80	13.36	11.44	16.69	13.40	12.50	14.40	13.73	1.30	8.70	5.60
MnO	0.11	0.21	0.17	0.12	0.21	0.15	0.17	0.23	0.20	0.10	0.19	0.15	0.30	0.42	0.26
MgO	5.45	15.33	8.89	2.63	6.42	4.18	4.22	5.53	4.42	1.11	4.20	2.60	4.82	13.75	8.06
CaO	6.91	16.70	11.77	5.04	10.51	7.41	3.74	9.42	7.87	2.75	5.60	4.48	25.46	26.04	25.76
Na_2O	0.31	4.10	2.15	2.08	4.68	3.09	2.26	4.10	2.70	2.80	3.70	2.52	0.35	1.30	0.61
K_2O	1.10	6.62	2.08	1.10	3.74	2.15	0.96	3.02	1.63	2.53	4.30	3.90	0.90	3.38	2.36
TiO_2	1.15	5.01	2.59	2.34	4.56	3.58	1.76	4.86	2.85	1.31	2.65	2.05	0.16	2.00	1.32
P_2O_5	0.22	1.83	0.78	0.44	1.29	0.67	0.25	1.02	0.48	0.26	0.86	0.56	3.45	4.00	3.68
Fe_2O_3	0.88	6.75	3.80	2.10	7.29	4.32	2.61	4.56	3.46	1.00	5.36	2.84	0.42	7.20	3.81
FeO	5.46	9.80	7.62	4.64	9.86	7.34	5.57	11.76	9.14	3.53	8.14	5.31	5.60	7.58	6.60
LOIt	1.00	9.16	4.50	0.18	4.82	1.67	0.01	3.74	0.70	0.28	4.91	1.61	-	-	-
CO_2	-	-	-	-	-	-	-	-	-	-	-	-	5.60	33.87	19.62
Sum			99.00			98.90			98.27			98.56			97.83

Trace elements ppm	Lamprophyre 27 samples			Diabase-N. arm 21 samples			Diabase-S. arm 13 samples			Microdiorite porphyry 20 samples			Carbonatite 3 samples		
	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.	Min.	Max.	Aver.
Ba	320	1,661	828	510	1,726	860	228	2,610	716	347	1,437	1,161	600	3,950	2,233
Sr	360	1,517	874	488	1,343	806	124	484	533	212	1,040	697	1,490	3,014	2,799
Zr	120	274	207	135	489	291	141	344	236	208	702	434	74	344	236
Y	6	35	25	27	45	34	25	51	42	23	57	40	36	59	51
Rb	13	86	56	34	128	60	23	99	41	75	147	110	21	126	67
Ni	55	310	163	4	683	90	10	82	46	3	20	11	6	13	9
Cr	70	928	300	4	234	51	10	122	48	4	88	35	4	8	3
Cu	42	146	86	25	215	122	25	257	178	12	203	61	9	25	17
La	15	103	46	16	101	46	16	83	39	36	140	93	170	218	188
Sc	22	42	30	20	101	38	17	41	30	11	33	19	30	36	33
V	196	338	280	43	312	253	124	484	353	20	369	147	30	114	72
Zn	79	113	99	96	489	188	70	135	116	105	198	130	88	117	102
Co	37	100	59	26	109	56	29	122	50	n.d.	n.d.	n.d.	22	22	22
Nb	33	104	63	20	43	31	10	50	24	15	82	53	52	119	78
Ce	36	175	91	80	204	116	17	145	72	59	240	197	309	422	376
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1,955	2,329	2,142
Nd	21	86	52	42	95	66	20	59	43	31	81	62	120	184	160

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Table 2. Representative chemical analyses from lithology groups. Analysis and (modified) norm calculations executed by GEOLAB. **Note 1.** The nine first upper line nominations in the Oxide% table refer to samples from dykes plotted in the different charts of Figure 1. The last three nominations refer to field sample labels of dykes located north of the coast line, outside the charts. **Note 2. D.I.** = Differentiation index.

	Oxide%											
	Lamprophyre				Diabase				Microdiorite Porphyry			
	B-35	**B-56**	**C-8**	**B-45**	**I-5**	**K-5**	**K-2**	**J-1**	**I-3**	**JQ21**	**JQ22**	**JQ78**
SiO_2	43.40	45.50	48.10	39.90	52.10	51.20	50.20	51.30	55.80	57.60	57.30	58.60
Al_2O_3	12.20	8.20	15.00	12.70	13.60	12.80	13.80	13.80	13.60	15.30	14.20	14.40
Fe_2O_3	4.30	3.10	4.60	4.50	3.00	3.00	5.20	4.30	2.80	2.80	4.10	1.00
FeO	6.80	5.60	6.50	6.00	8.40	8.70	7.10	8.00	6.50	5.20	4.70	7.00
CaO	13.60	16.70	8.00	14.70	8.00	9.10	6.20	7.60	5.60	4.80	4.90	4.70
MgO	9.80	15.20	6.20	10.60	4.90	5.30	4.10	4.00	4.20	2.50	3.10	2.50
Na_2O	1.20	1.30	4.10	1.80	2.90	2.70	3.50	2.90	3.20	3.60	3.50	3.40
K_2O	2.30	0.70	1.40	1.30	2.00	1.10	3.00	1.90	4.00	4.30	4.30	4.10
MnO	0.15	0.14	0.20	0.18	0.16	0.16	0.16	0.14	0.16	0.14	0.14	0.14
TiO_2	2.30	1.50	2.20	1.30	3.40	3.50	3.80	4.20	2.50	2.10	2.20	2.10
P_2O_5	0.35	0.22	0.42	0.71	0.49	0.44	0.64	0.60	0.48	0.53	0.46	0.44
CO_2	0.95	0.10	0.35	4.30	0.05	0.05	0.35	0.05	0.05	0.10	0.05	0.20
Sum	97.35	98.26	97.07	97.99	99.00	98.05	98.05	98.79	98.89	98.97	98.95	98.58
	Norm											
	Lamprophyre				Diabase				Microdiorite Porphyry			
	B-35	**B-56**	**C-8**	**B-45**	**I-5**	**K-5**	**K-2**	**J-1**	**I-3**	**JQ21**	**JQ22**	**JQ78**
Q	-	-	-	-	64	89	-	89	66	100	89	153
Cc	22	2	8	100	1	1	8	1	1	2	1	55
Il	30	19	28	17	43	45	49	53	32	27	28	27
Or	25	8	15	14	22	12	13	21	43	46	46	44
Ab	20	21	68	30	47	44	58	47	52	59	57	56
An	78	53	68	84	66	72	48	69	40	47	38	43
Mt	12	9	12	11	12	12	13	13	10	8	9	8
Wo	141	243	61	68	66	83	42	53	49	25	39	27
En	252	387	160	271	124	135	105	101	106	63	79	63
Fs	90	75	92	96	80	82	83	78	68	59	65	61
Di	141	243	61	68	66	83	42	53	49	25	39	27
Hy	201	218	191	299	138	135	146	126	126	97	105	98
Ol	101	109	96	150	-	-	12	-	-	-	-	-
Ne	16	21	7	9	-	-	-	-	-	-	-	-
D.I.	61	50	143	63	133	146	106	171	158	206	184	252

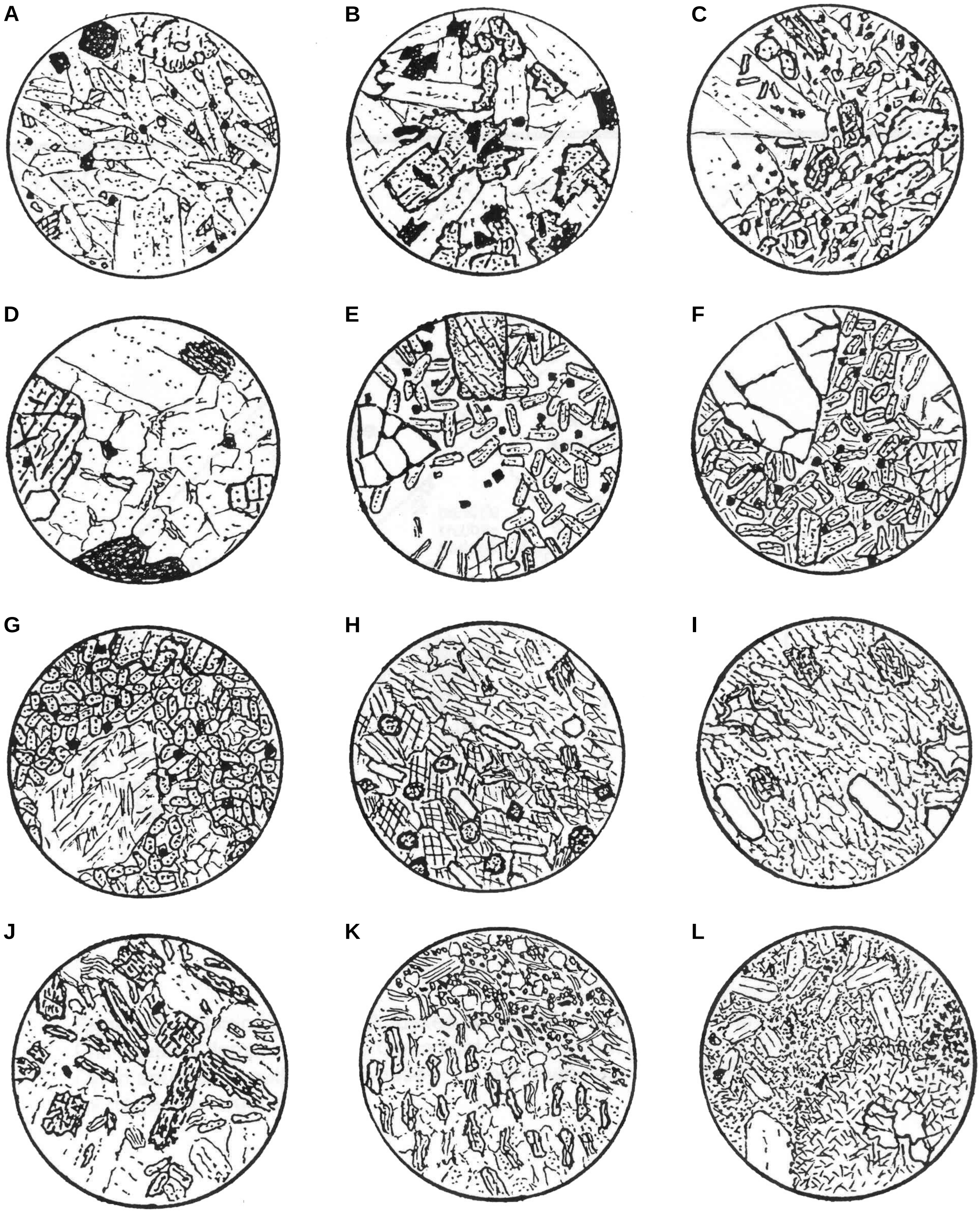

Figure 5. A. Trachyandesite (Figure 4B:61) - Ponta do Baleeiro – Phenocrysts of serpentinized olivine, leucoxenized Ti – magnetite (above) and partly sericitizes andesine shelled by K-feldspar (below). Trachytic groundmas composed of some feldspar, specks of ore and interstial quartz, calcite and siderite. **B.** Diabase (Figure 4O:5) – Peruíbe – fresh sub-ophitic pale-brown augite, labradorite laths and small amounts of quartz and chlorite in interstice. **C.** Diabase porphyry (Figure 4I:26) – Ilha das Couves – fresh labradorite phenocrysts (left), semi alteres hypersthene (upper edge and center) and brownish augite

(right), immersed in an intergranular groundmas of plagioclase, augite, magnetite and ilmenite. **D.** Microdiorite porphyry (Figure 4J:1) – Juquehy – Una – Phenocrysts of andesine (above), augite (left) and magnetite (below) in an panidiomaorphic base of orthoclase-mantled oligoclase, quartz and micropegmatite. Wholly nontronitized hypersthene (upper edge) is a common feature in this rock type. **E.** Lamprophyre Monchiquite (Figure 4I:9) – East of Praia do Sahy – Phenocrysts of Ti-augite (above) and olivine (left). Groundmass composed of Ti-augite, magnetite and some kaersutite in a colorless analcitic base. Ocellus with anacite, biotite, calcite and magnetite (below left). **F.** Lamprophyre camptonite (Figure 4K:6) – East of Praia da Boracéia – Olivine phenocrysts (above). Ocellus with calcite and biotite (above right). Amygdale filled with calcite inside a chloritic border. Groundmass composed of Ti-augite, magnetite and serpentinized olivine. **G.** Ultramafic Lamprophyre ("Ankaranite" – Figure 4A:10) – Ponta da Armação. Corroded Ti-augite (above) and serpentinized olivine phenocrysts (center). Amygdale filled with calcite inside a cholritic border. Ground mass composed of Ti-augite, magnetite and serpentinized olivine. **H.** Carbonatite (Figure 4I:19) – As Ilhas – Shown in the lower half of the slide, is composed of calcite prismatic apatite, phlogopite, rounded garnet aggregates and angular perovskite. The upper half illustrates the dyke´s border belt made up of aligned platy calcite, mafic pseudomorphs and amygdales. **I.** Carbonatite (Beforsite) (Figure 4N:2) – Itanhaém – Texturally similar to the As Ilhas carbonitite. Aligned dolomite platelets surround ferruginous pseudomorphs and amigdales. **J.** Micronorite (Figure 4B:59) – Ponta do Baleeiro – Hypersthene, plagioclase and small grains of horneblende, biotite and iron ore in a hypidiomorphic granular texture. **K.** "Precambrian" dyke: Horneblende, biotite, gneiss + calcite mica schist (Figure 4H:1:2) – Ilha dos Gatos – Rock depicted underneath, a quartz-plagioclase horneblende-biotite gneiss, is the body of a dyke, whose border is a quartz-calcite-mica schist (shows above). **L.** "Precambrian" dyke: Uralitized diabase (Figure 4A:11) – Ilha Bela – Bodies rich with actinolite needles and central diopside aggregated (below right) are immersed in a "blastophitic" groundmass composed of almost totally uratilized diopsidic augite, andesine laths and opaque material (hematite, leucoxene, magnetite).

borders (ca. 3% TiO_2 by EDS). Olivine, (Fo_{82-95} by EDS), may appear fresh or corroded and variably altered to serpentine, talc or carbonate. The matrix is normally composed by plagioclase, pyroxene and Ti-rich ore mineral in fine-grained intergranular or intersertal texture. Low contents of SiO_2 (46 - 51%) and high TiO_2 (> 3%), would make this rock a possible representative of the alkaline diabase clan. Given geologic setting, texture, mineral and chemical composition, diabase porphyries recall closely lamprophyres, to which they seem to be mere variants. Microscopic distinction was based on both the presence of plagioclase phenocrysts and the panidiomorphic texture commonly present in lamprophyre groundmass.

Microdiorite porphyry

Microdiorite porphyry is a petrographic type occurring in dykes along a NE-SW belt called "Bairro do Marisco" by Garda (1995). In fact, they are specially frequent in islands and coastlands (Figure 4I), in what looks to be the south end of that belt. They are also found elsewhere in the north arm. Normal phenocrysts are (Figure 5D): plagioclase (An_{20-50}), augite (sometimes titaniferous) and hypersthene (fresh or altered to nontronite). At times apatite and magnetite appear as microphenocrysts. Ground mass is composed by plagioclase, augite and/or hornblende and/or biotite, ore minerals and, in the more leucocratic types by orthoclase, quartz or micropegmatite. In the TAS diagram (Figure 6), microdiorite porphyry plots in the trachy-andesite and basaltic trachyandesite fields. The average chemical composition and norm make them the most acidic member of the dyke swarm and a hypabissal correspondent of quartz diorite. K/Ar dating for one sample (Figure 4I:7) gave 126.4 ± 1.3 My.

Lamprophyre

This seems to be the prevalent dyke type at the northeast tip of the mapped coast (Figures 4A to 4D). In this paper they fall under the general definition and classification given by Le Maitre (1989) and expanded by Rock (1991). The last author, however says in footnote that "*all* lamprophyres carry phlogopite-biotite, amphibole or both...", an assertive that is denied by the scrutiny of over 130 lamprophyric dykes found in the north arm. As a matter of fact, limited amounts of kaersutitic amphibole are present in some samples, but essential phlogopite–biotite was detected in only one lamprophyre (minette), spotted at the Nova Prata quarry (Figure 4R:7), where it is cut by diabase (Figure 13). The rock presents zoned phlogopite-biotite flakes, euhedral diopside prisms and interstitial matrix of granular sphene, apatite, ore and secondary minerals that fill empty spaces.

The commonest type of lamprophyre belongs to the alkaline class (Rock, 1991) and may be named either camptonite or monchiquite according to the presence or absence of feldspar (plagioclase > orthoclase). By microscopy such distinction was sometimes turned difficult since the feldspars are confined to clouded ocelli or minute interstitial spaces, associated with other minerals (zeolites, clay minerals) of difficult identification. During the microscopic classification procedure, camptonite was the name given to plagioclase-bearing rocks and monchiquite to lamprophyres carrying analcite present in amygdales, ocelli and even as phenocrysts. No other feldspathoid has been easily distinguished. One lamprophyre dyke (Figure 4F:23), is extremely rich in altered olivine and poor in Ti-augite. It was tentatively named polzenite.

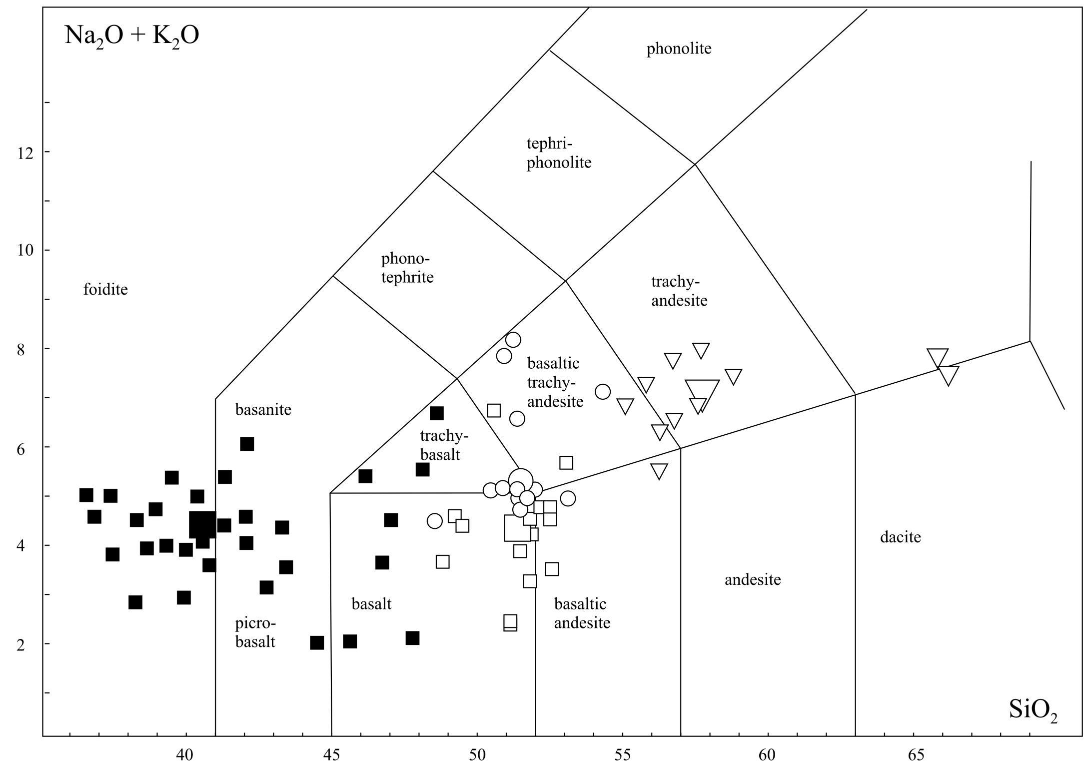

Figure 6. Plotting of the mafic dykes composition in the TAS diagram. Full squares: lamprophyre; open circles: north arm diabase; open squares: south arm diabase; open triangles: microdiorite porphyry; avarages as larger symbols.

The mineral components of lamprophyres are usually Ti-augite, as phenocrysts or prismatic grains in panidiomorphic groundmass. TiO_2 content found by EDS in a phenocryst border is 6.06%. Olivine (Fo_{10-20}) is frequent as phenocryst but it generally appears partially or totally replaced by a variety of minerals: serpentine, talc, carbonate, magnetite, and quartz. Red Ti-amphibole (kaersutite) is sometimes seen as euhedral prismatic phenocrysts, but is usually a minor component of groudmass. Biotite as small red flakes may also be present in accessory amounts.

The usual microscopic appearance of lamprophyres is depicted in Figures 5E and 5F. The clear spot in the first drawing is an ocellus, which in such rocks is usually a concentration of leucocratic minerals; feldspar, feldspathoid (analcite), zeolites and carbonates, often accompanied by primary minerals such as kaersutite and/or biotite. Amigdales are also a common feature of lamprophyres, usually filled with carbonates (siderite on walls, calcite in cores, Figure 5E). Analcite, and a less common similar-looking mineral, may also complete spaces in the cavities.

Some lamprophyric dykes may carry abundant xenoliths (Figure 15) as in the occurrences of Figure 4F:9:16, at the eastern north arm. Some are torn away from the wall rocks, but most come from deep sources and are gathered in the dyke's central parts. Granulites, sillimanite and spinel-hypersthene aggregates, enstatitites, harzburgites and lherzolites, have been identified as xenoliths. They all show signs of hydration, dissolution and eventually melting and mixing. Figure 7, taken from a sample of the occurrence 9 in Figure 4F, illustrates part of such processes: a granulite fragment (60% andesine, 30% quartz, 10% hypersthene, accessory rutile) immersed in an ultramafic lamprophyric magma is seen, under microscopic observation, being melted and corroded. Thin glass films from fused granulite surround xenolithic quartz, whereas basaltic matter crystallizes in cavities (Figure 7, right upper corner). Olivine phenocrysts a few millimeters away from the xenolith contact are fresh, but close to the contact they have been pseudomorphosed into talc, carbonate and microcrystalline quartz. Abundant carbonate also impregnates the immediate surroundings of the xenolith as well as passageways and cavities inside it. So, one is inclined to assume that hot ultramafic lamprophyric magma with high partial pressure of CO_2 and H_2O, was able to dissolve and melt rocks of tonalitic composition in order to produce a basaltic matter before subsequent secondary processes of carbonatization and hydration.

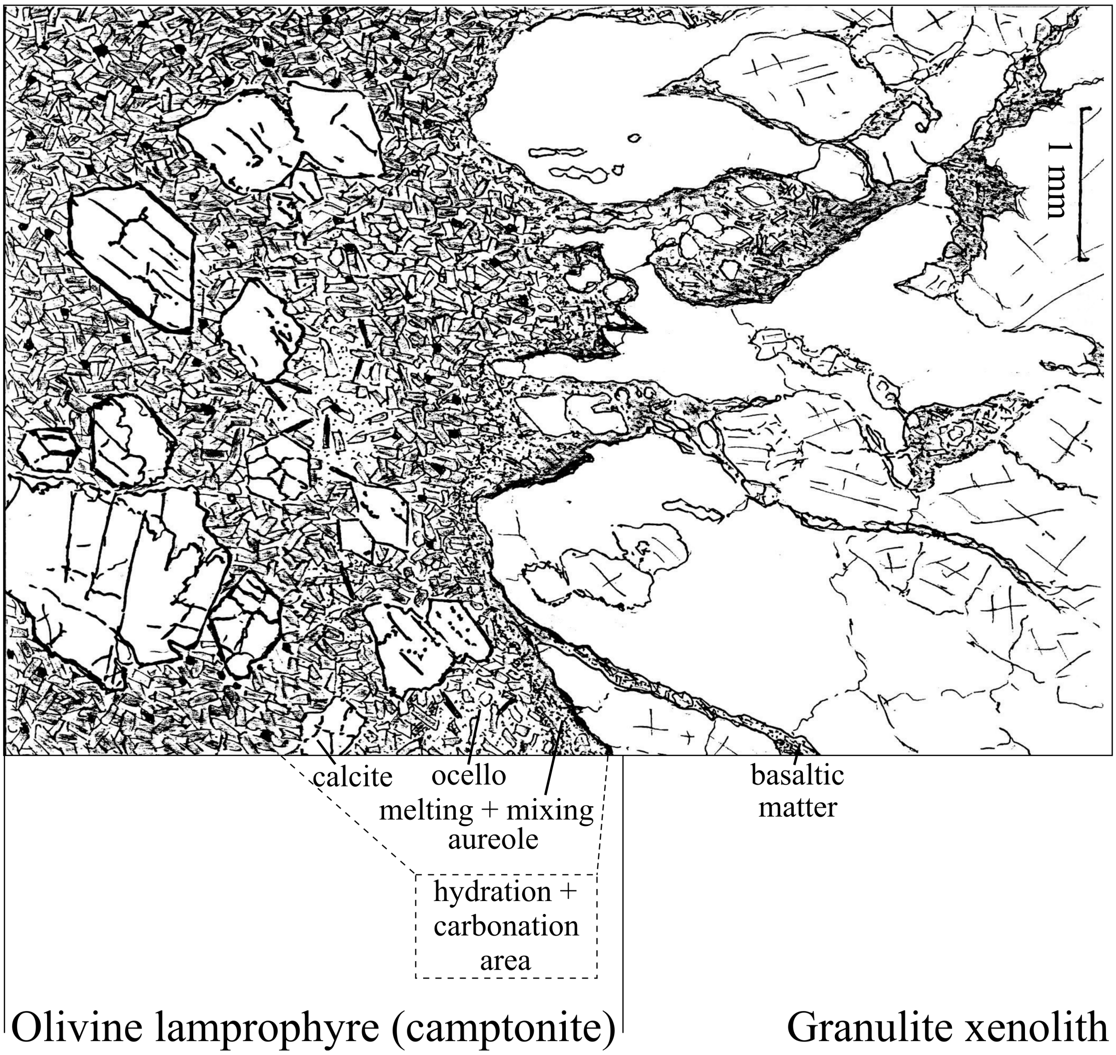

Figure 7. Microscopic view of the lamprophyre-xenolith contacta (occurrence 9, Figure 4F).

As compared to calk-alkali lamprophyre, north arm dykes should be classified as alkali lamprophyres (Nockolds et al., 1979) since they are mostly ultrabasic (Table 1) and have moderate Al_2O_3 and higher contents of MgO and CaO, which is explained by the abundance of augite in their modal composition. They are also distinguished by the presence of normative Ol and Ne (Table 2).

Uncertain K/Ar dating gave 83.3 ± 1.0 My for a fresh lamprophyre (Figure 4M:2), and 147.4 ± 2.5 My (Figure 5B:56) and 132.5 ± 3 My (Figure 4I:29) for somewhat altered samples.

Precambrian dykes

A few still uncertainly dated Precambrian mafic dykes seen along the coastal slopes are described below:

1. Uralitized diabase, exposed in a regular 1 m thick “Mesozoic-looking” dyke at Praia do Veloso, Ilha de São Sebastião. It is composed of uralite, relict andesine and ore in a fine textured rock, rich in amigdales filled with actinolite and epidote (Figure 5L). Low-grade metamorphism and partial recrystallization in shallow environment during the Braziliano cycle, is indicated for its origin. Nevertheless, the possibility for the rock being a Mesozoic diabase modified by unknown deuteric processes, cannot be disregarded.

2. A hornblende-biotite gneiss occurs at Ilha dos Gatos, in a vertical 0.6 m thick discordant dyke, cutting basement gneiss and being cut by a Mesozoic lamprophyre (Figures 4H:1 and 14). This singular rock type, mapped in Figure 8 and microscopically described in Figure 5K, exhibits granolepidoblastic texture parallel to the wall rock gneissosity and is composed by 30% andesine, 5% quartz, 40% hornblende, 20% biotite and ore. The dyke is rimmed by another curious rock: a biotite schist composed by 25% calcite, 25% chloritized phlogopite, 20% quartz, 15% amesite (?), 10% unidentified isotropic mineral and 5% sphene.

3. A micronorite is composed by andesine, hypersthene and smaller amounts of augite, biotite, hornblende and ore. This is a fine-grained rock found as conformable and regular 2 m thick dykes at the Baleeiro peninsula (Figure 4B:59) and other unmapped places. It still preserves its magmatic texture but biotite and hornblende may have been developed by metamorphism. The contact with the host gneiss is transformed into a biotite-hornblende rock. One single chemical analysis was obtained for this micronorite and its data fits in the continental and low potassium tholeiite fields of Pearce and Cann (1973) and also in the sodic tholeiitic series of Middlemost (1975).

4. Hornblende-biotite diorite, found as a contorted dyke at Morro de São Bento, Santos (Figure 4M:3), is a black, medium-grained rock, containing granite xenoliths, and composed of andesine (48%), green hornblende (20%), biotite (22%), titanite (6%), magnetite (3%), apatite, allanite, orthoclase (1%). The rock was dated by K/Ar method as being between 495.2 and 504.5 My.

A K/Ar age of 496 ± 5.6 Ma was obtained for the Ilha dos Gatos dyke. It appears that it would belong to a system of Precambrian dykes occupying fractures in the same general direction followed by the Cretaceous dykes. Such association being proved, it would be reasonable to conceive a tendency for a continental separation 300 - 400 Ma earlier.

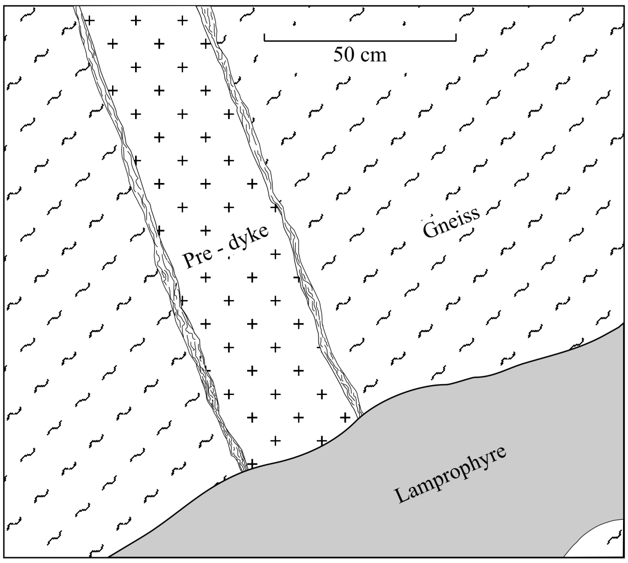

Figure 8. Sketch map of the Ilha dos Gatos occurrence (Figure 4H:1).

Carbonatite

Two carbonite dykes were mapped:

1. In As Ilhas, a 1m thick dyke (Figure 4I:19) has a core of silico-carbonatite (calcite, phlogopite, apatite, phyllosilicates) and borders of beforsite (dolomite, apatite). The silico carbonatite is strongly enriched with incompatible elements (Sr, Ba, Nb, Y, Rb). Its REE content is twice as high as that found in the related lamprophyres. They match the results obtained for little differentiated carbonatites.

2. In Ilha das Cabras, Itanhaém (Figure 4N:2), a dyke about 0.3 m thick may be classified as beforsite. It is made up of oriented (0001) tabular dolomite, apatite, phlogopite, garnet, perovskite and altered mafics (Figure 5H).

The intimate association of the two carbonatites with carbonatized lamprophyres carrying carbonatic ocelli somehow favors the idea of differentiation of lamprophyric magmas leading to a liquid miscibility gap.

South arm

In striking contrast to the rock variety shown by the north arm, the lithology observed from Paranaguá to Ilha de Santa Catarina is thoroughly dominated by only one petrographic type. In fact, medium to fine-grained diabase is the rock type of 55 out of 59 samples collected. No diabase porphyries, lamprophyres, Precambrian mafic rocks or carbonatites were ever spotted at any place in that belt. The four non-diabase samples are: one granophyre (Figure 4V:11), one latite (Figure 4R:1) and two trachy-andesites (Figure 4V:8:14). They came from precarious outcrops of possibly differentiated diabase dykes. Granophyre shows rectangular oligoclase phenocrysts in a fluidal microcrystalline granophyric groundmass of quartz, orthoclase and ore. The latite has diabase texture made up by 30% andesine laths enveloped by 55% micropegmatite, 10% augite and 5% hornblende. This sample, collected in a very thick (50 m) dyke may well represent a leucocratic part of a differentiated diabase dyke. Trachyandesites show resorbed plagioclase autoliths in a trachytic feldspathic groundmass composed primarily of anorthoclase plus amphibole and ore.

Normal diabase exhibits intergranular texture and a variable mode of 45 - 55% andesine-labradorite laths, 10-30% augite grains (here and there with pigeonite), 5 - 10% ore (magnetite, ilmenite), 0-5% interstitial quartz and micropegmatite and 1% apatite. Hornblende and biotite may appear as deuteric accessories. Partial or total saussuritization is not uncommon as well as development of secondary chlorite, epidote and carbonate. Chemical analyses executed in 14 samples enhance their tholeiitic character since they are Q normative and show pigeonite in some modes. Neither Ol nor Ne appear in the norm.

K/Ar ages obtained in 3 samples from Florianópolis (Figure 4V:10) are 146 Ma, 128 Ma and 176.6 ± 1.8 Ma.

CONCLUDING REMARKS

Figure 9 represents the triple junction devised for the studied area.

Its north and south arms became sites of plate movement, fracturing, distention and magma intrusion, and outline the present coast. The third arm (Ponta Grossa arch) failed and became the locus of basaltic activity (Herz, 1977). Normal faulting and rifting occurred at the time and allowed for the intrusion of peralkaline magma as well, which consolidated as stocks of syenite, nepheline-syenite, theralite and others, elsewhere accompanied by carbonatite. In Figure 9, a sequence of black crosses, roughly parallel to the northern coast-line, marks the loci of such stocks.

As to the south arm, only two alkaline intrusions (Lages and Anitapolis) have been reported and located quite far from the coast, westwards.

As it was already stressed, lamprophyres occur only in the north arm. They have been reported (Motoki et al., 1988; Castro et al., 1984) up to the east end of the north arm, and as Figure 9 shows, always near alkaline stocks. In the northern

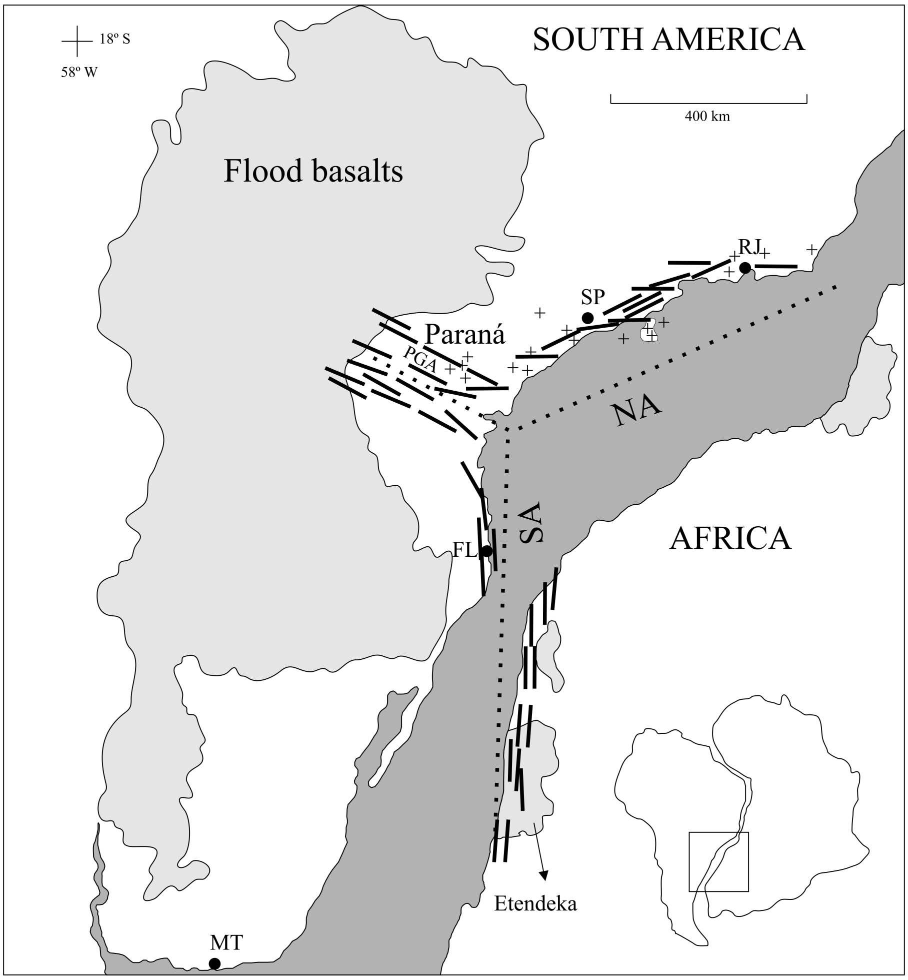

Figure 9. A pre-drift reconstruction of South America and Africa showing the Paraná triple junction and correlation of dykes swarms in both continents. **PGA:** Ponta Grossa Arch; **NA:** North Arm; **SA:** South Arm; **RJ:** Rio de Janeiro; **MT:** Montevideo; **SP:** São Paulo; **FL:** Florianópolis; **Bars:** generalized dyke directions; **Crosses:** alkaline stocks. Distribution and petrography of the Etendeka Formation and correlation with Paraná basalts in Marsh et al. (2001).

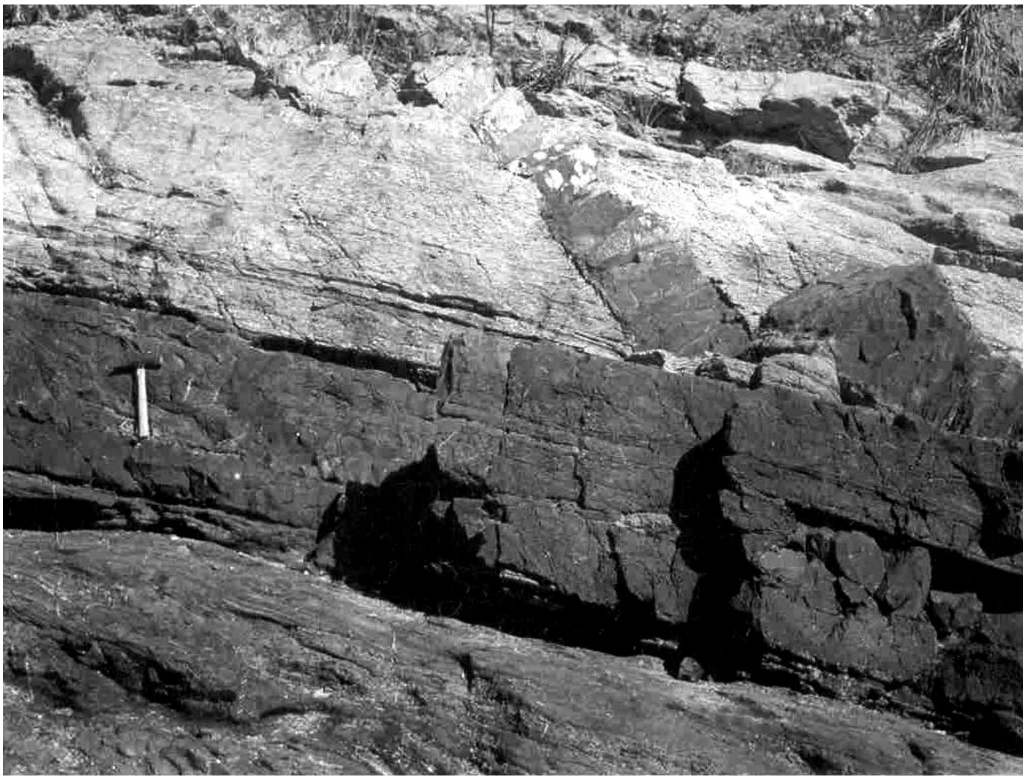

Figure 10. Sub-horizontal trachy-andesite Ponta Baleeiro (Figure 4B:61).

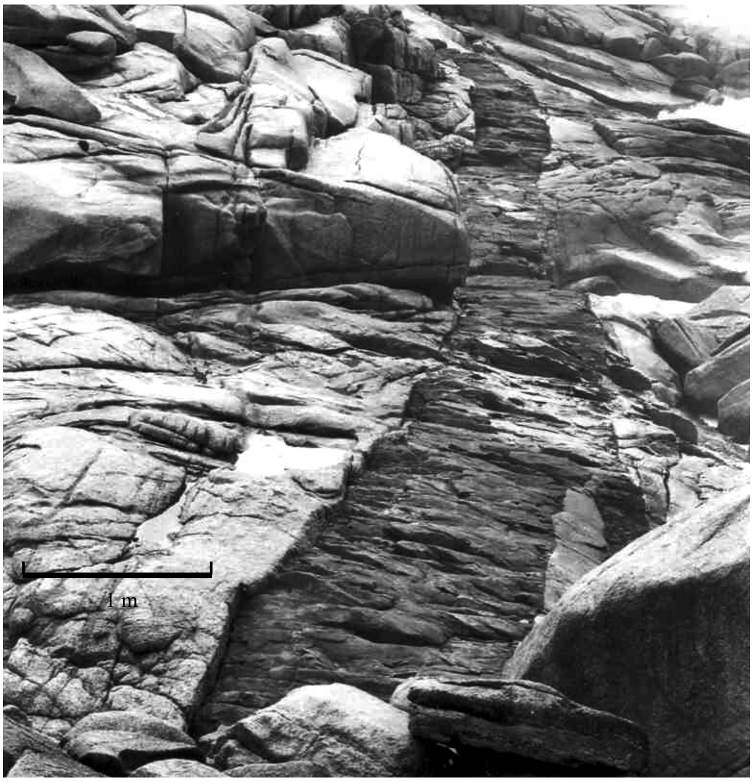

Figure 11. Jointed diabase Ponta Marisco, Ilha Santa Catarina (Figure 4V:24).

Figure 12. Doubled diabase dyke Pedrita, Ilha Santa Catarina (Figure 4V:17).

Figure 13. Curved minette dyke (left), cut by a vertical diabase dyke Nova Prata quarry (Figure 4R:6:7).

Figure 14. Thin Precambrian (593 Ma) dyke, cut by a thicker Cretaceous lamprophyre dyke Ilha dos Gatos (Figure 4H:1:2).

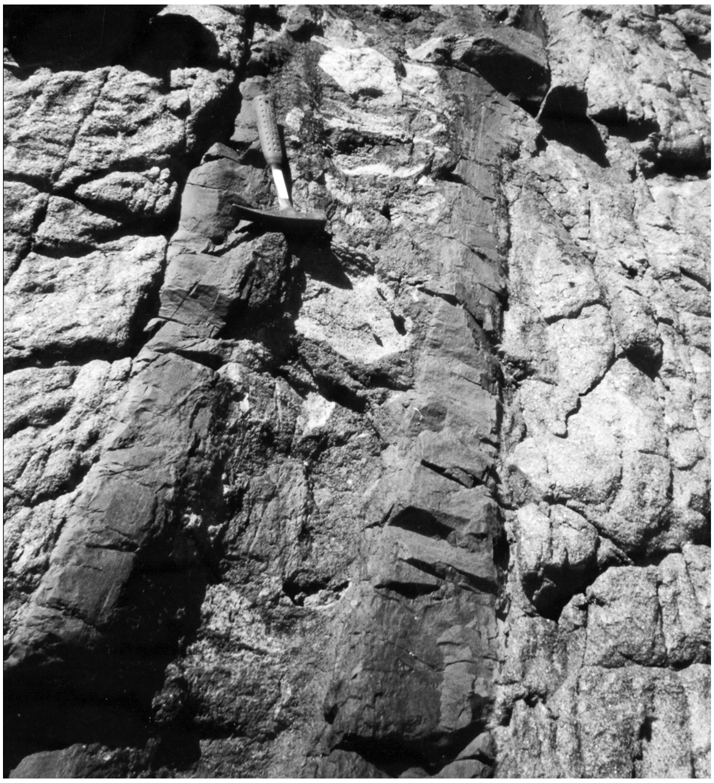

Figure 15. Lamprophyric intrusion breccia, Ponta Maresias (Figure 4F:9).

arm, alkali lamprophyre dykes (camptonite and monchiquite), are especially numerous at the immediate vicinity of the large intrusions of São Sebastião island (Figures 4B, 4C, 4F).

The field evidences lead to the conclusion that the intrusion of lamprophyres along the north arm is genetically related to the original magmas responsible for the formation of stocks of syenitic and nepheline syenitic rock composition.

Figure 9 also depicts the area over which the African Etendeka volcanic sequence and associated intrusions outcrop. The latter injections show a wide variety of shapes that include elongated bodies which are in part dykes running NS parallel to the coast in evident continuity with the Brazilian south arm dyke swarm. The mafic dyke rocks on both sides comprises tholeiites, but according to Marsh et al. (2001), the northern Etendeka mafic rocks show high Ti while the connected southern Brazilian dykes show average medium Ti. In this respect, the north arm high Ti Brazilian diabases (Table 1) and associated intrusions, are better related to the Etendeka igneous province, since the latter also comprehends alkaline and other mafic intrusions including carbonatite, much the same as in the north arm. On the other hand, however, to the author's knowledge, lamprophyres are an exclusive feature of the Brazilian north arm, having not yet been detected in Etendeka.

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