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Amirante Island Arc in the Indian Ocean: Data on the Initial Island-Arc Magmatism

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Abstract—The Amirante island arc and trench, which compose a parallel arcuate system between Madagascar and the Seychelles microcontinent in the western Indian Ocean, resemble typical island-arc systems only morphologically but differ from them by the absence of seismic activity and an accretionary prism on its landward side, as well as by the composition of the magmatic-basement rocks, which display features similar to those of analogous rocks in mid-oceanic ridges but not island arcs. The structure of basement sections of the island arc is also analogous to the structure of the normal oceanic crust. Rare fragments of two-pyroxene–plagioclase basalts and feldspar-free olivine–orthopyroxene volcanics dredged at some sites reveal mineralogical and geochemical signatures of the products of initial island-arc magmatism. These rocks are thought to have been formed in the Late Cretaceous during the subduction of the oceanic crust of the Somali Basin within the Amirante Trough. The processes resulted from a combination of spreading in the Mascarene Basin with the rotational compression and stacking of the Amirante Basin crust along the boundary between the Seychelles microcontinent and Somali Basin. The termination of spreading and island-arc magmatism was related to changes in the geometry of spreading centers in the western Indian Ocean and the simultaneous development of the modern Carlsberg Ridge at the boundary between the Late Cretaceous and Paleocene.

INTRODUCTION

The Amirante arc in the northwestern Mascarene Basin between Madagascar and the Seychelles microcontinent is a geologically unique structure in the western equatorial portion of the Indian Ocean (Fig. 1). The arc consists of a chain of coral islands, reefs, and rises and is an arcuate ridge, trending roughly from south to north and having steep western and more gently sloping eastern slopes. The ridge extends southwards for more than 500 km and is coupled with the Amirante Trough (>5000 m deep) in the west and the Amirante Basin in the east. The overall morphology of the structure resembles those of island-arc systems in the West Pacific (Northon and Sclater, 1979) but, in contrast to them, is fully aseismic (Johnson *et al.*, 1982; Masson, 1984).

In the northeast, the Amirante Ridge is bordered by the Seychelles Plateau (microcontinent; Girling, 1992), which is a continental block with a Precambrian (~710–650 Ma; Baker and Miller, 1963; Dickin *et al.*, 1986; Plummer, 1995) crystalline basement and a crustal thickness of about 30 km (Girling, 1992; Matthews and Davies, 1966). The rising above the plateau surface Seychelles Islands are made up of Precambrian amphibole-biotite granites, which are intruded by numerous metadolerite dikes of Precambrian age (620 Ma, Plummer, 1995). Dikes and small intrusions of alkaline dolerites, syenites, monzonites, and microgranites of Early Paleocene age are exposed in the western part of the Seychelles (Baker and Miller, 1963; Devey and Stephens, 1992; Dickin *et al.*, 1986; Mart, 1988; Plummer, 1995).

The oceanic basins surrounding the Amirante Arc differ in composition, structure, and the age of their basements as a consequence of the complicated evolution of the local geodynamic environments.

The Somali Basin, situated to the northwest of the Amirante Ridge and separated from it by a large northeast-trending transform fault (Masson, 1984), is characterized by linear M25–M10 magnetic anomalies (160–127 Ma; Kashintsev, 1993; Norton and Sclater, 1979), which suggest that oceanic spreading and the development of the oceanic crust occurred in Late Jurassic–Early Cretaceous time. These magnetic anomalies mark the oldest period of the Indian Ocean opening and the timing of India and Madagascar separation from the African continent (Plummer and Belle, 1995). DSDP Hole 240 in the western Somali Basin recovered basalts with xenoliths of Early Eocene rocks (Erlank and Reid, 1974).

The Mascarene Basin, which flanks the Amirante Ridge in the south, has the oceanic crust of Cretaceous age and supposedly includes blocks of Precambrian granitoids (Carlson *et al.*, 1980). The basin resulted from spreading that began at 100–95 Ma (Plummer, 1996) and caused the separation of the India–Sey-

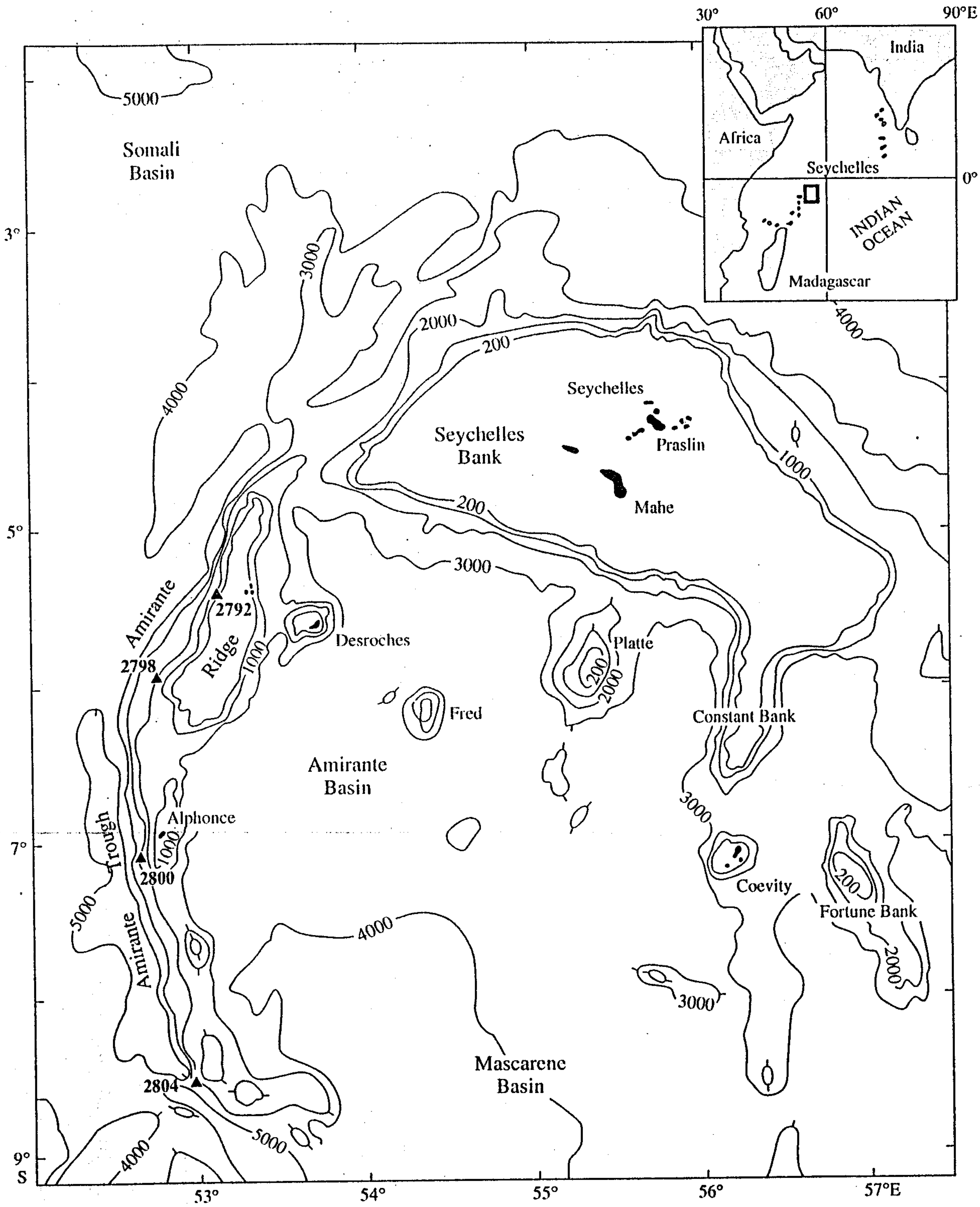

Fig. 1. Bathymetric map and dredge locations within the Amirante Arc (simplified after *Geologicheskoe stroenie...*, 1997). See text for data on the dredging sites shown in the map. Bathymetric contours are in meters.
The inset shows the geological-geophysical study area during Cruise 33 of the R/V *Professor Bogorov* (1990).

chelles block from Madagascar (Fisher *et al.*, 1968; Schlich, 1974; Simpson *et al.*, 1974). The Late Cretaceous age of the oceanic crust of the basin is confirmed by drilling materials. Hole 239 penetrated tholeiitic basalts overlain by Late Senonian sedimentary rocks (Simpson *et al.*, 1974), and Holes 705, 706, and 707 in the eastern Mascarene Ridge recovered tholeiites with ages from the Paleocene to Early Oligocene (Duncan and Hargraves, 1990). According to Plummer (1996), these are sills or lava sheets underlain by a thick pile of pre-Tertiary sedimentary rocks, which are analogous to those retrieved by prospecting holes in the western portion of the Seychelles microcontinent.

Holes drilled within the Amirante Passage, which limits the Amirante Arc in the southwest, recovered sedimentary rocks of Late Campanian and Maastrichtian age, and, hence, the oceanic crust in the area is no younger than 73 Ma (Johnson *et al.*, 1982; Masson, 1984; Masson *et al.*, 1982). To the southwest of the area, in the slopes of Providence Reef, rocks were sampled whose age also corresponds to the Late Cretaceous–Early Paleocene (Wiseman, 1936).

The geological and geophysical studies conducted in 1990 aboard the R/V *Professor Bogorov* have disclosed the magmatic basement of the Amirante Arc beneath its coral edifices (*Geologicheskoe stroenie...*, 1997; Lelikov *et al.*, 1991). It was established that the basement is composed of volcanic and plutonic rocks typical of the normal oceanic crust, a fact that led to ascribing the Amirante Arc to amagmatic arcs and to the concept that the arc itself was produced by the tectonic piling of the oceanic crust (Lelikov *et al.*, 1991). Analogous processes of the arc origin were also conjured by Yu.M. Pushcharovskii (1995). However, dredges at two sites in the northern part of the Amirante Ridge contained volcanic rocks resembling the products of initial island-arc volcanism, and the kaersutite-bearing dolerites found in the southern portion of the ridge are similar to the analogous rocks of the western Seychelles. This paper is focused on a detailed characterization of the rocks of initial island-arc volcanism and on the problem of the genesis of the Amirante Arc.

GEOLOGY

The Amirante Ridge is a chain of islands and submarine rises of the seafloor, which attain elevations of 4500 m above the floor level of the Amirante Basin and 5500 m above the floor of the Amirante Trough. In accordance with its morphology and certain geological and geophysical features, the Amirante Ridge is subdivided into three blocks (segments): Northern, Central, and Southern (*Geologicheskoe stroenie...*, 1997; Lelikov *et al.*, 1991).

The **Northern Block** consists of the Amirante Bank and the small Deroches Ridge, which runs parallel to it (Fig. 1). Seismic data provide evidence that the Amirante Ridge continues northward for approximately 200 km and approaches the Seychelles Plateau from the west (Plummer, 1996), where it is covered by Tertiary deposits. The most elevated parts of the Amirante Bank are crowned by accumulative terraces of low coral islands, all of which are situated on a common volcanic basement. The Northern Block is characterized by a weak magnetic field of different signs with overall low ΔT_a values, which become negative near islands, and a linear orientation of magnetic anomalies (Lelikov *et al.*, 1991). The southern boundary of the block is located at nearly 6° S and runs along a northwest-trending fault.

The **Central Block** of the Amirante Ridge is recognized as a narrow crest extending along a roughly south–north direction. It consists of an *en echelon* chain of small elongated mounds, which sometimes project over the sea surface as small plateaus and flat banks with innumerable small coral islands and reefs on the top. The block is characterized by positive values of its magnetic field with a maximum of 200 nT.

It was established that the Northern and Central blocks are made up of volcanic rocks, such as pillow lavas of clinopyroxene–plagioclase (± olivine) oceanic basalts and dolerite-basalts. Occasional samples from the Northern Block consisted of two-pyroxene–plagioclase basalts and feldspar-free olivine–orthopyroxene volcanic rocks, whose mineral assemblages and chemistry are principally different from those of oceanic basalts.

The magmatic basement of the Northern and Central blocks is overlain by a sedimentary sequence of weakly lithified and poorly sorted rudaceous rocks (conglomerates and gritstones), which consist of variably rounded fragments of basalts and dolerite-basalts (up to 90% by volume) and organogenic limestones with a cement of coarse-grained psammitic material, sometimes grading to gritstone. The cement is carbonate in composition with minor amounts of smectite, zeolites, and, more rarely, chlorite. The composition and morphology of the fragments indicate that they were formed in an littoral marine environment of fragments of the eroded ridge basement (*Geologicheskoe stroenie...*, 1977). The sedimentary succession is overlain by Early Pliocene reef limestones, whose lower extension limit attains depths of 2300–2500 m (*Geologicheskoe stroenie...*, 1997; Lelikov *et al.*, 1991).

The **Southern Block** of the Amirante Ridge is noted for the significant depths of its southeast-oriented crest, with the minimum water depth above attaining 900 m. The boundary between the Southern and Central blocks is drawn along a broad saddle with depths of approximately 3000 m and seems to mark a northeast-trending fault zone (*Geologicheskoe stroenie...*, 1997; Masson, 1984). The magnetic field of the block does not significantly differ from the field of the Central Block and shows a single anomaly with an amplitude of 150–200 nT (*Geologicheskoe stroenie...*, 1997).

Dominating the sequences of the Northern and Central blocks, basalts are scarce in the Southern Block, where they seem to be not so much the products of volcanic eruptions as the chilled (marginal) facies of a dike complex of clinopyroxene, clinopyroxene–amphibole, and amphibole dolerites and fine-grained gabbro in the uppermost portion of the magmatic basement (*Geologicheskoe stroenie...*, 1997). A very interesting rock of the dike complex is kaersutite dolerite (Site 2804), which is mineralogically similar to the analogous rocks of Ile du Nord in the northern part of the Seychelles Plateau.

The dike complex is overlain by a thin succession of weakly lithified conglomerate-gritstone and sedimentary breccia, which consists of fragments of the underlying igneous rocks cemented by coarse sandy material of the same composition with admixtures of smectite, carbonates, and zeolites. The conglomerate–gritstone unit is overlapped by reef limestone, whose lower extension limit corresponds to depths of approximately 2500 m. The dike complex rests on a complex of massive and cumulative gabbronorites and clinopyroxene, clinopyroxene–amphibole, and amphibole gabbro, which were dredged throughout the Southern Block slope up to its foot (*Geologicheskoe stroenie...*, 1997). The gabbroids are associated with small bodies of fully serpentinized peridotite and websterite veins.

Revealed by a Gloria side-scan sonar, a series of closely spaced long lineaments of northwestern trend in the basement of the southern Amirante Ridge resembles analogous structures in present-day spreading mid-oceanic ridges and may be interpreted as a relict structure of a fossil spreading center (Masson, 1984). In the central and northern portions of the Amirante Ridge, this lineament system is pronounced much more poorly, and the local structures seem to trace erosional ravines and tectonic structures in the basement (Masson, 1984).

Hence, the Amirante Ridge is composed of volcanic and intrusive rocks whose composition and structure are similar to those of rocks in the normal oceanic crust of mid-oceanic ridges (*Geologicheskoe stroenie...*, 1997; Lelikov *et al.*, 1991). The upper portion of the Amirante Ridge crust consists of basaltic and dolerite-basaltic pillow lavas and is exposed in the Northern and Central blocks. The lower part of the sequence consists (from bottom to top) of a dolerite and fine-grained gabbroid dike complex, various gabbroids, and, further upward, ultramafic rocks, which were detected in the Southern Block. The predominance of holocrystalline plutonic rocks in the Southern Block and the total absence of mafic volcanics provide evidence for the deeper erosion of this block compared with the Northern and Central blocks. The different erosion depths of the blocks of the Amirante Ridge is also confirmed by the distinct metamorphic grades of the rocks. While the basalts of the Northern and Central blocks are generally metamorphosed to the zeolite facies (top of the pile) and the lower greenschist facies (basement of the volcanic pile), the igneous rocks of the Southern Block are altered under greenschist-facies conditions, i.e., there is a downward increase in the metamorphic grade typical of the oceanic crust.

PETROGRAPHY

Detailed petrographic and geochemical characteristics of volcanic and plutonic rocks composing the basement of the Amirante block are presented elsewhere (*Geologicheskoe stroenie...*, 1997). In this paper, our main concern is only the basaltic component of the oceanic crust of the ridge (we will utilize only data on dredging site 2800 at 7°04.8′ N, 52°38.4′ E, depth 3000–2600 m). We will present detailed descriptions of the unusual, for this section, two-pyroxene–plagioclase basalts and melanocratic feldspar-free olivine–orthopyroxene volcanics from the Northern Block and the kaersutite dolerites dredged from the upper portion of the Southern Block magmatic basement.

The **clinopyroxene–plagioclase (± olivine) basalts** composing the basement of the Northern and Central blocks of the Amirante Ridge have an aphyric, rare-porphyritic texture with the amounts of phenocrysts rarely exceeding 5–7%. The phenocrysts are augite ($Wo_{34}En_{50-52}Fs_{11-14}$) and plagioclase ($An_{85-60}$; Table 1, Sample 2800-1-2). Occasional rhomboidal pseudomorphs of secondary minerals developed most probably after olivine. The groundmass of the rocks is characterized by variable crystallinity, from vitreous with rare clinopyroxene and plagioclase microlites to virtually fully crystalline with minor amounts of volcanic glass. It was determined that the groundmass crystallinity of the basalts increases down the volcanic pile, whose lower parts are dominated by dolerite-basalts and basalts with microdoleritic and doleritic textures. The groundmass clinopyroxene varies from augite to subcalcic augite, and the plagioclase is labradorite (An_{70}). The accessory mineral is titanomagnetite.

The metamorphic alterations in the basalts of the Northern and Central block answer to the zeolite metamorphic facies and involve smectitization of microlites and volcanic glass and the replacement of the latter by iron hydroxides. Smectite in association with zeolites also fills small pores of the basalts and composes thin veinlets. In the basement of the volcanic complex, the metamorphic grade increases to the lower parts of the greenschist facies, as is evident from widespread chlorite and epidote found in the heavy fraction of sediments that were formed by the destruction of the basaltoids (*Geologicheskoe stroenie...*, 1997).

In spite of the generally similar chemistry of the basalts from the Amirante Ridge and the normal tholeiites of mid-oceanic ridges (*Geologicheskoe stroenie...*, 1997; Lelikov *et al.*, 1991), the former have lower concentrations of Sr, Zr, Ba, Y, and, often, TiO_2 (*Geolo-*

Table 1. Microprobe analyses of minerals in basalts of the Amirante Arc

Component	2800-1-2								
	Pl_c^I	Pl_r^I	Cpx_1^I	Cpx_2^I	Pl_1^{II}	Pl_2^{II}	Cpx_1^{II}	Cpx_2^{II}	Cpx_3^{II}
SiO_2	51.18	52.20	48.79	51.38	52.28	53.70	52.18	47.59	49.60
TiO_2	0.00	0.00	1.07	0.52	0.00	0.00	0.71	2.06	1.06
Al_2O_3	31.27	29.94	5.17	3.54	30.68	28.95	3.45	3.79	3.09
Cr_2O_3	0.00	0.00	0.00	0.20	0.00	0.00	0.01	0.00	0.00
FeO	0.62	0.94	8.43	7.27	0.85	1.12	9.44	20.31	18.90
MnO	0.00	0.00	0.04	0.02	0.00	0.00	0.11	0.32	0.30
MgO	0.21	0.27	15.52	15.54	0.30	0.12	8.09	9.64	14.66
CaO	14.07	12.97	19.04	19.87	13.51	10.82	15.76	16.06	11.86
Na_2O	3.21	4.44	0.34	0.06	3.79	5.43	0.02	0.41	0.32
K_2O	0.00	0.05	0.01	0.00	0.00	0.00	0.00	0.02	0.14
Total	100.56	100.81	98.41	98.41	101.41	100.14	99.77	100.20	99.93
X_{Mg}	–	–	0.766	0.792	–	–	0.773	0.459	0.580
X_{An}	0.707	0.631	–	–	0.664	0.524	–	–	–
Wo	–	–	40.4	42.1	–	–	32.6	35.5	25.2
En	–	–	45.7	45.8	–	–	52.1	29.6	43.4
Fs	–	–	13.9	12.1	–	–	15.3	34.9	31.4
Component	2798-1-1								
	Opx_c^I	Opx_r^I	Cpx_c^I	Cpx_r^I	Pl_c^I	Pl_r^I	Cpx_1^{II}	Cpx_2^{II}	Pl^{II}
SiO_2	56.47	55.22	53.40	51.68	46.53	49.96	53.00	54.10	51.88
TiO_2	0.04	0.03	0.14	0.35	0.00	0.00	0.30	0.19	0.00
Al_2O_3	2.02	2.04	2.19	1.50	34.49	34.21	2.24	1.43	30.27
Cr_2O_3	0.40	0.39	0.31	0.00	0.00	0.00	0.00	0.00	0.00
FeO	9.66	9.91	6.68	21.25	0.51	0.64	11.02	13.90	1.14
MnO	0.04	0.05	0.04	0.24	0.00	0.00	0.08	0.19	0.00
MgO	29.05	29.17	18.24	14.01	0.26	0.25	16.04	18.89	0.05
CaO	2.51	2.52	18.73	11.81	17.66	17.25	17.96	12.01	13.55
Na_2O	0.00	0.00	0.01	0.00	1.36	1.72	0.03	0.00	3.81
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.19	99.33	99.74	100.84	100.81	101.03	100.67	100.71	100.62
X_{Mg}	0.843	0.840	0.830	0.540	–	–	0.722	0.708	–
X_{An}	–	–	–	–	0.877	0.850	–	–	0.664
Wo	5.0	5.0	38.0	24.7	–	–	36.7	24.5	–
En	80.0	79.8	51.4	40.7	–	–	45.7	53.5	–
Fs	15.0	15.2	10.6	34.6	–	–	17.6	22.0	–

Note: Samples 2800-1-2 and 2798-1-1 are clinopyroxene–plagioclase and two-pyroxene–plagioclase basalts, respectively; I are phenocrysts, II are microlites in the groundmass; c and r are crystal cores and rims, respectively. Here and in tables below, analyses were carried out by V.M. Chubarov on a Camebax microprobe at the Institute of Volcanology, Far East Division, Russian Academy of Sciences.

gicheskoe stroenie..., 1997; Devey and Stephens, 1992; Fisher *et al.*, 1968).

Two-pyroxene–plagioclase basalts were found only at Site 2798 (5°57.5′ N, 52°45.8′ E, depths 2850–2600 m) in the southern portion of the Northern Block of the Amirante Ridge (Fig. 1) in the form of occasional small (up to 6–8 cm) fragments. These are porphyritic rocks, whose phenocrysts account for approximately

Table 2. Representative microprobe analyses of pyroxene in feldspar-free olivine–orthopyroxene volcanic rock from the Northern Block of the Amirante Arc (Sample 2792-1-9)

Component	1_c	1_r	2_c	2_r	3_c	3_r	4_c	4_r	5_c	5_r	6_c	6_r	7
SiO_2	56.72	55.90	56.33	54.71	54.30	50.64	54.60	52.29	54.67	49.60	53.30	50.84	50.38
TiO_2	0.10	0.11	0.07	0.21	0.37	0.95	0.31	0.51	0.38	0.96	0.45	0.84	0.75
Al_2O_3	1.86	1.75	1.59	3.12	3.77	7.70	3.13	5.29	3.53	7.80	4.44	5.77	8.25
Cr_2O_3	0.63	0.63	0.58	0.11	0.40	0.00	0.83	0.09	0.91	0.37	0.19	0.11	0.00
FeO	9.23	8.96	9.36	11.07	10.33	10.67	10.32	10.30	10.59	9.94	10.95	10.10	11.18
MnO	0.01	0.03	0.01	0.05	0.11	0.02	0.05	0.10	0.05	0.01	0.05	0.02	0.09
MgO	31.34	30.87	30.06	26.66	25.09	15.81	26.11	21.03	25.88	15.30	23.09	18.79	15.18
NiO	0.08	0.04	0.05	0.00	0.01	0.00	0.03	0.01	0.03	0.00	0.02	0.00	0.00
CaO	1.78	1.98	1.98	3.74	5.12	13.97	4.18	10.06	5.01	15.48	8.04	13.10	14.50
Na_2O	0.00	0.00	0.01	0.71	0.0	0.00	0.00	0.00	0.00	0.06	0.00	0.01	0.76
K_2O	0.01	0.01	0.01	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09
Total	101.76	100.28	100.05	100.46	99.50	99.76	99.56	99.68	101.05	99.52	100.53	99.58	101.18
X_{Mg}	0.858	0.860	0.851	0.811	0.812	0.725	0.818	0.785	0.813	0.733	0.790	0.768	0.708
Wo	3.4	3.8	3.9	7.6	10.6	31.5	8.6	21.2	10.2	34.8	16.5	27.8	32.7
En	82.9	82.7	81.8	75.0	72.6	49.7	74.8	61.8	73.0	47.8	65.9	55.5	47.6
Fs	13.7	13.5	14.3	17.4	16.8	18.8	16.6	17.0	16.8	17.4	17.6	16.7	19.7

Component	8	9	10_c	10_r	11	12	13_c	13_r	14	15	16	17	18
SiO_2	48.66	47.87	49.51	51.65	48.86	50.15	48.80	49.64	49.15	49.58	49.43	51.15	50.24
TiO_2	1.13	1.06	0.98	0.82	0.91	0.84	1.17	0.88	1.07	0.98	1.08	0.85	1.00
Al_2O_3	8.86	9.03	8.85	14.21	9.60	6.86	8.91	7.48	8.61	7.49	8.55	7.64	7.05
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.07	0.00
FeO	10.70	11.37	9.75	11.12	11.83	11.02	12.02	9.95	9.71	9.45	11.76	8.64	10.20
MnO	0.05	0.00	0.02	0.00	0.03	0.03	0.08	0.02	0.06	0.01	0.04	0.05	0.06
MgO	14.63	13.66	14.76	9.45	13.07	17.85	13.82	15.88	14.09	15.40	14.75	16.52	16.33
NiO	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
CaO	16.49	16.49	15.88	12.77	15.65	12.58	15.74	15.57	16.04	16.74	15.05	15.55	14.26
Na_2O	0.06	0.14	0.36	0.86	0.38	0.01	0.31	0.76	0.55	0.03	0.05	0.00	0.00
K_2O	0.00	0.00	0.03	0.98	0.15	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Total	100.58	99.64	100.14	101.86	100.48	99.39	100.85	100.18	9.31	99.68	100.71	100.47	99.14
X_{Mg}	0.709	0.682	0.730	0.602	0.663	0.743	0.672	0.740	0.721	0.744	0.691	0.773	0.740
Wo	36.5	31.2	36.1	36.9	36.3	27.3	35.5	34.3	37.1	36.8	33.6	34.4	31.7
En	45.0	42.8	46.6	38.0	42.2	54.0	43.3	48.6	45.4	47.0	45.9	50.7	50.6
Fs	18.5	20.0	17.3	25.1	21.5	18.7	21.2	17.1	17.5	16.2	20.5	14.9	17.7

Note: (1, 2) Orthopyroxene phenocrysts in (1) varioles and (2) matrix; (3–6) pyroxene microlites with Ca-poor cores and Ca-rich rims from (3, 4) varioles and (5, 6) matrix; (7–18) clinopyroxene from rims around pseudomorphs after the Ca-poor pyroxene cores of microlites.

Table 3. Microprobe analyses of chrome spinel in feldspar-free olivine–orthopyroxene volcanic rock from the Northern Block of the Amirante Arc (Sample 2798-1-9)

Component	1	2	3	4	5	6	7	8
SiO_2	0.07	0.03	0.03	0.05	0.02	0.01	0.02	0.14
TiO_2	0.13	0.17	0.19	0.18	0.30	0.18	0.71	0.64
Al_2O_3	11.52	14.84	13.25	13.96	18.32	14.51	16.47	16.78
Cr_2O_3	57.11	52.61	55.40	55.26	47.76	50.88	46.40	46.82
Fe_2O_3	3.71	5.30	4.04	3.51	6.23	5.12	8.31	6.55
FeO	15.33	14.64	13.81	14.53	16.40	15.83	17.38	16.72
MnO	0.35	0.27	0.29	0.28	0.25	0.40	0.28	0.31
MgO	12.05	12.91	13.25	12.95	12.44	11.58	11.72	11.84
NiO	0.00	0.13	0.00	0.05	0.01	0.03	0.00	0.01
ZnO	0.01	0.06	0.05	0.02	0.00	0.00	0.05	0.04
Total	100.28	100.96	100.31	100.73	101.73	98.54	101.34	99.85
Cr/(Cr + Al)	0.769	0.704	0.737	0.726	0.636	0.702	0.654	0.652
$Mg/(Mg + Fe^{2+})$	0.584	0.611	0.631	0.614	0.575	0.560	0.546	0.558
$Fe^{3+}/(Fe^{3+} + Fe^{2+})$	0.179	0.246	0.208	0.178	0.255	0.225	0.301	0.261

Note: Chrome spinel: (1–4) in pseudomorphs after olivine phenocrysts, (5) in pseudomorph after the core of a Ca-poor clinopyroxene microlite, (6–8) from the vitreous matrix.

10% of the rocks by volume and are orthopyroxene, clinopyroxene, and plagioclase. The orthopyroxene crystallized as large (up to 5 mm) prismatic crystals, which are usually fully replaced by aggregates of brown iron hydroxides. Its relics correspond to bronzite in composition ($Wo_5En_{80}Fs_{15}$; Table 1, Sample 2798-1-1). Clinopyroxene phenocrysts are smaller (no larger than 0.5–1.0 mm) and consist of augite of variable composition (Table 1). Plagioclase phenocrysts are elongated crystals (up to 0.5–0.8 mm long) of bytownite (An_{85-88}; Table 1). The texture of the groundmass is hyalopilitic and, in places, spherulitic; the groundmass consists of microlites of augite and subcalcic augite ($Wo_{23-35}En_{53-58}Fs_{18-22}$), labradorite ($An_{66}$), titanomagnetite, and variable amounts of volcanic glass, which is replaced by smectite, carbonate, and iron hydroxides. Rare veinlets, pores, and amygdules are filled with smectite, sometimes in association with zeolites.

Analytical data indicate that the two-pyroxene–plagioclase basalts differ from the clinopyroxene–plagioclase varieties by lower concentrations of TiO_2 (0.54 wt %), alkali oxides, LILE, HFSE, Cr, Ni, and Co (*Geologicheskoe stroenie...*, 1997).

Feldspar-free olivine–orthopyroxene rock 'was found as a single small (2.5 cm) fragment in a dredge sample from Site 2792 (5°23.8′ S, 53°03.1′ E, depth 3100 m; Fig. 1). This is a massive rock with rare pores and scarce olivine and orthopyroxene phenocrysts in fully altered volcanic glass. The rock has a variolitic texture, with round black varioles ranging from a few fractions of a millimeter to 3–4 mm and cemented by a yellowish gray vitreous cementing mass. Varioles are equally distributed over the rock and account for 20% of its volume.

Olivine and orthopyroxene phenocrysts amount to 3–5% and occur in both varioles and the cementing mass. The olivine composes small (no larger than 0.8 mm) euhedra, which are fully replaced by smectite. The orthopyroxene occurs as euhedral prismatic crystals up to 1 mm, whose composition ranges from bronzite (En_{82-83}) in the cores to pigeonite in the margins (Table 2). Olivine and orthopyroxene phenocrysts contain crystalline inclusions (up to 0.1 mm across) of accessory high-Cr spinel, whose composition is very close to chrome spinel from volcanics of the boninite series (Table 3).

Microlites in varioles and the cementing mass attain 0.05–0.3 mm and consist of pyroxene. Its composition varies, and its crystal cores are often replaced by secondary minerals. Relict patches in the cores of the microlites are composed of pigeonite or, more rarely, subcalcic augite ($Wo_{9-10}En_{72-74}Fs_{17}$) and surrounded by rims of commensurable size of calcic pyroxene, whose composition corresponds to augite or subcalcic augite ($Wo_{21-37}En_{38-62}Fs_{15-21}$, Table 2). The assemblages of the phenocrysts, the structures of pyroxene microlites in the groundmass, and the high-Cr composition of the accessory spinel make these rocks similar to volcanics of the boninite series.

Kaersutite dolerites (Site 2804: 8°33.6′ N, 52°56.5′ E, depth 4200–3750 m) occur relatively rarely among rocks of the dike complex, which consists mainly of clinopyroxene and clinopyroxene–amphibole dolerites and is exposed in the upper part of the magmatic basement of the Southern Block. The rocks

Table 4. Microprobe analyses of minerals in kaersutite-bearing dolerite from the Southern Block of the Amirante Arc (Sample 2804-3-22)

Component	Cpx^1	Cpx^2	Pl_c	Pl_r	Hb^1	Hb^2	Hb^3	Ilm
SiO_2	5.69	53.01	57.32	60.17	43.07	51.82	55.93	0.00
TiO_2	0.27	0.18	0.04	0.00	5.23	0.71	0.19	48.09
Al_2O_3	1.60	0.89	26.81	25.69	10.76	3.46	0.92	0.00
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	7.46	8.78	0.44	0.69	11.65	10.15	8.23	51.63
MnO	0.00	0.09	0.00	0.00	0.00	0.06	0.09	1.37
MgO	16.41	13.48	0.03	0.05	14.09	18.47	20.53	0.01
CaO	19.29	23.32	9.32	7.12	11.70	11.76	11.65	0.25
Na_2O	0.47	0.63	6.66	7.66	3.03	1.12	0.33	0.00
K_2O	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Total	99.19	100.38	100.62	101.39	99.53	97.55	97.87	101.35
X_{Mg}	0.797	0.733	–	–	0.682	0.764	0.805	–
X_{An}	–	–	0.563	0.340	–	–	–	–
Wo	40.2	47.7	–	–	–	–	–	–
En	47.7	38.3	–	–	–	–	–	–
Fs	12.1	14.0	–	–	–	–	–	–

contain clinopyroxene and kaersutite, which occurs as individual prismatic crystals and partial pseudomorphs after or incomplete rims around pyroxene grains. The clinopyroxene is present in the form of rare phenocrysts up to 1.5 mm, which consist of augite with salite marginal zones (Table 4). Most of the dolerites have a doleritic or, in places, sheaf- and fan-shaped textures and consist of kaersutite, plagioclase (An_{56} in the cores and An_{34} in the margins), and ilmenite. The mineral assemblages of the rocks and their mineral chemistry are similar to those of analogous rocks in the Early Paleocene alkaline complex of Ile de Nord in the western Seychelles.

GENESIS OF THE AMIRANTE ARC AND INITIAL ISLAND-ARC MAGMATISM

The origin of the Amirante Arc and the Amirante Trough remains largely uncertain. It was hypothesized that the Amirante Arc and Trough compose an island-arc system, whose morphology resembles those of typical island-arc systems off active continental margins of the West Pacific Ocean (Lelikov *et al.*, 1991; Pushcharovskii, 1995; Fisher *et al.*, 1968; Norton, Sclater, 1979). However, the Amirante Arc differs from them by the absence of a notable accretionary prism (Fig. 2), the absence of seismic activity, and by the composition of rocks, whose mineralogy and geochemistry are closer to those of oceanic basites rather than of island-arc rocks. Gravimetric data (Miles, 1982) indicate that the gravity field over the Amirante Arc and Trough only partly resembles the gravity anomalies of mature subduction zones. The Amirante Trough seems to mark only nascent subduction, which causes the insignificant mass deficient of this structure and merely weak compression (Damuth and Johnson, 1989; Miles, 1982).

Based on recent seismic and bathymetric data and mapping materials on the Amirante Arc obtained with a side-scan sonar, Masson (1984) concluded that compression and the development of a subduction zone can be proposed only for the southern segment of the Amirante Arc, which is situated within the Mascarene Basin. The latter was formed by Late Cretaceous spreading. The northern part of the arc is spatially related to a large transform fault zone between the Somali Basin, which has a pre-Late Cretaceous crust, and the Mascarene Basin, whose crust is of Late Cretaceous age.

The variations in the crust composition and thickness with the transition from the Amirante Ridge to the Seychelles Plateau, the mass deficit beneath the Amirante Trough, and the mass excess in the eastern Amirante Arc led Mart (1988) to suggest that the Amirante Arc was produced in the Early Paleocene, when the Seychelles continental block was separated from India and collided with the oceanic crustal block of the Mascarene Basin. Mart proposed that subduction processes within the Amirante Trough initiated alkaline magmatism, which manifested itself in certain islands in the western Seychelles at approximately 65 Ma (Devey and Stephens, 1992; Dickin *et al.*, 1986; Plummer, 1995).

The most exotic hypotheses relate the genesis of the Amirante Arc and Trough to the impact of a large heavenly body (Alt *et al.*, 1988; Chatterjee, 1992; Hartnady,

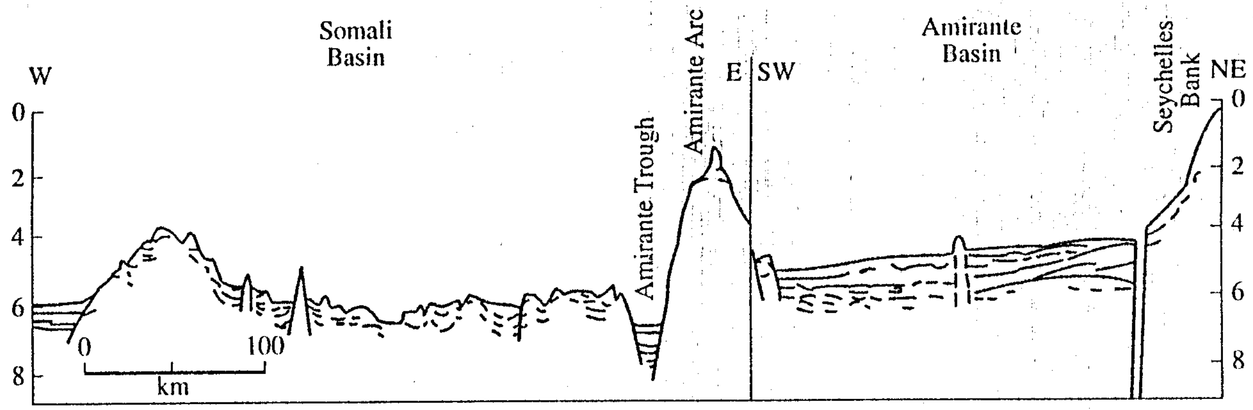

Fig. 2. Seismic reflection profile across the Somali Basin, Amirante Arc, and Amirante Basin (Mart, 1988). The vertical axis is the two-way time (in seconds). Note the absence of an accretionary prism near the Amirante Arc.

1986). However, this idea is in conflict with the absence of an ubiquitous Early Cretaceous unconformity in the deposits of the Seychelles microcontinent (Plummer, 1996). Seismic data and the materials of prospecting drilling suggest that the largest stratigraphic hiatus is dated at the Middle Triassic–Early Cretaceous, and the overlying Late Cretaceous and Tertiary rocks are flat-lying and only weakly deformed (Damuth and Johnson, 1989; Plummer, 1996).

The most feasible model for the origin of the Amirante Arc and Trough during the Late Cretaceous separation of the Seychelles Plateau from Madagascar was recently put forth by Plummer (1996) and Plummer and Belle (1995) (Fig. 3). According to this model, the onset of separation between the Seychelles microcontinent and Madagascar is dated at 100–95 Ma and occurred along a system of two unparallel transform faults. Sinistral displacements along the faults resulted in the Amirante pull-apart basin and shaped the eastern portion of Madagascar and the western contour of the Seychelles Plateau (Plummer, 1996). Having no linear magnetic anomalies (Fig. 4), the Amirante Basin was formed, according to this model, not by spreading (as is currently usually hypothesized) but by the compensation of sinistral strike-slip motions along the transform fault zones (Figs. 3b, 3c). To the south of the Amirante Basin, sinistral motions along convergent transform faults resulted in a narrow pull-apart basin between Madagascar and the Mascarene Ridge (Fig. 3c). The basin was an embryo of the present-day Mascarene Basin, which shows close similarities with analogous pull-apart basins in the Gulf of Aqaba and the Dead Sea (Girdler, 1990). At approximately 85 Ma, this narrow pull-apart basin in the continental crust was affected by rifting (Schlich, 1982) and experienced the onset of spreading and the development of the newly-formed oceanic crust of the Mascarene Basin with a well-pronounced system of linear magnetic anomalies (Fig. 4).

The evolution of a spreading center in the Mascarene Basin and continuing sinistral strike-slip displacements along the transform fault between the Somali Basin and the Seychelles–India continental block created favorable conditions for counterclockwise rotational compression along the boundary between the two structures and eventually resulted in the origin of the Amirante Arc and the Amirante Trough in the Late Cretaceous, at approximately 80 Ma (Fig. 3d) (Plummer, 1996). The spreading conditions in the Mascarene Basin and the rotational compression conditions at the boundary between the Somali Basin and the Seychelles–India continental block did not change, according to Plummer (1996), throughout the Late Cretaceous (80–65 Ma) and ceased to exist as late as the Early Paleocene (Figs. 3e, 3f) in response to a change in the geometry of spreading centers in the western Indian Ocean and the origin of the present-day Carlsberg Ridge (Kashintsev, 1993; Plummer, 1996).

Hence, there are good reasons to believe that the initial island-arc magmatism that produced the two-pyroxene–plagioclase basalts and feldspar-free olivine–orthopyroxene volcanics dredged from the Amirante Ridge occurred in the Late Cretaceous, when the counterclockwise rotation of the Seychelles–India continental block caused a rotational compression at its boundary with the Somali Basin and the subduction of the ancient oceanic crust of this basin into the Amirante Trough.

The origin of the Carlsberg Spreading Ridge in the Early Paleocene and the related separation of the Seychelles block from India were associated with active tholeiitic volcanism, which resulted in the Deccan flood basalts with an age of 60–70 Ma in India (Devey and Stephens, 1992; Gallet *et al.*, 1989; Plummer, 1995) and in the volcanic piles exposed at the western termination of the Seychelles Plateau (Devey and Stephens, 1992; Girling, 1992). According to Girling (1992) and Shor and Polland (1963), this succession formed a continuous cover over the whole pre-Late Cretaceous basement of the Seychelles Plateau and attained a thickness of approximately 2 km. The rocks were dated at 70.9 ± 1.1

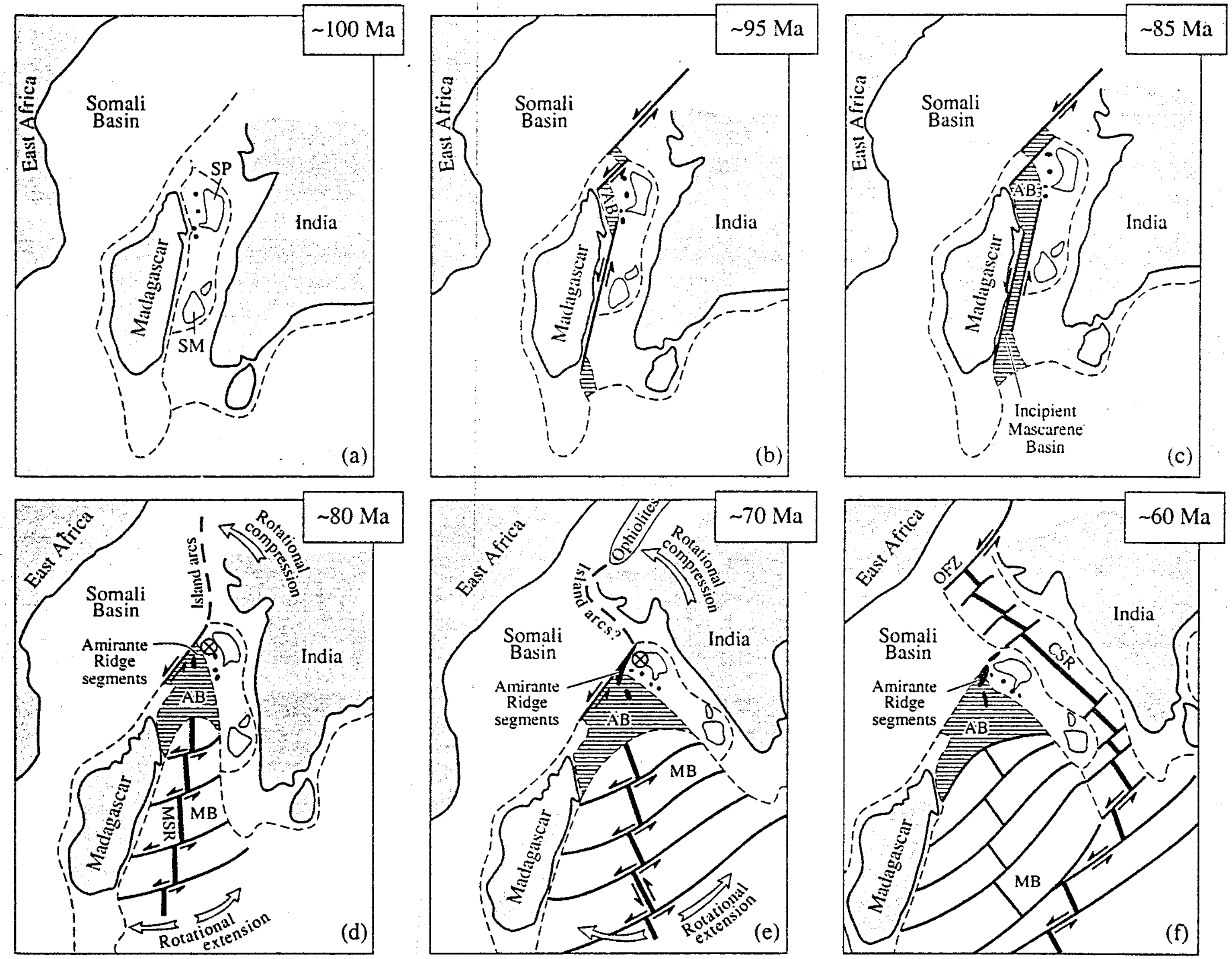

Fig. 3. Paleogeographic evolution Seychelles–Madagascar rift zone and the development of the Amirante and Mascarene basins, Amirante Arc, and the Amirante Trough (Plummer, 1996).

AB—Amirante Basin, CSR—Carlsberg Spreading Ridge, MB—Mascarene Basin, MSR—Mascarene Spreading Ridge, SM—Saya de Malha Bank, SP—Seychelles Plateau (microcontinent), OFZ—Owen Fracture Zone, X—rotation axis.

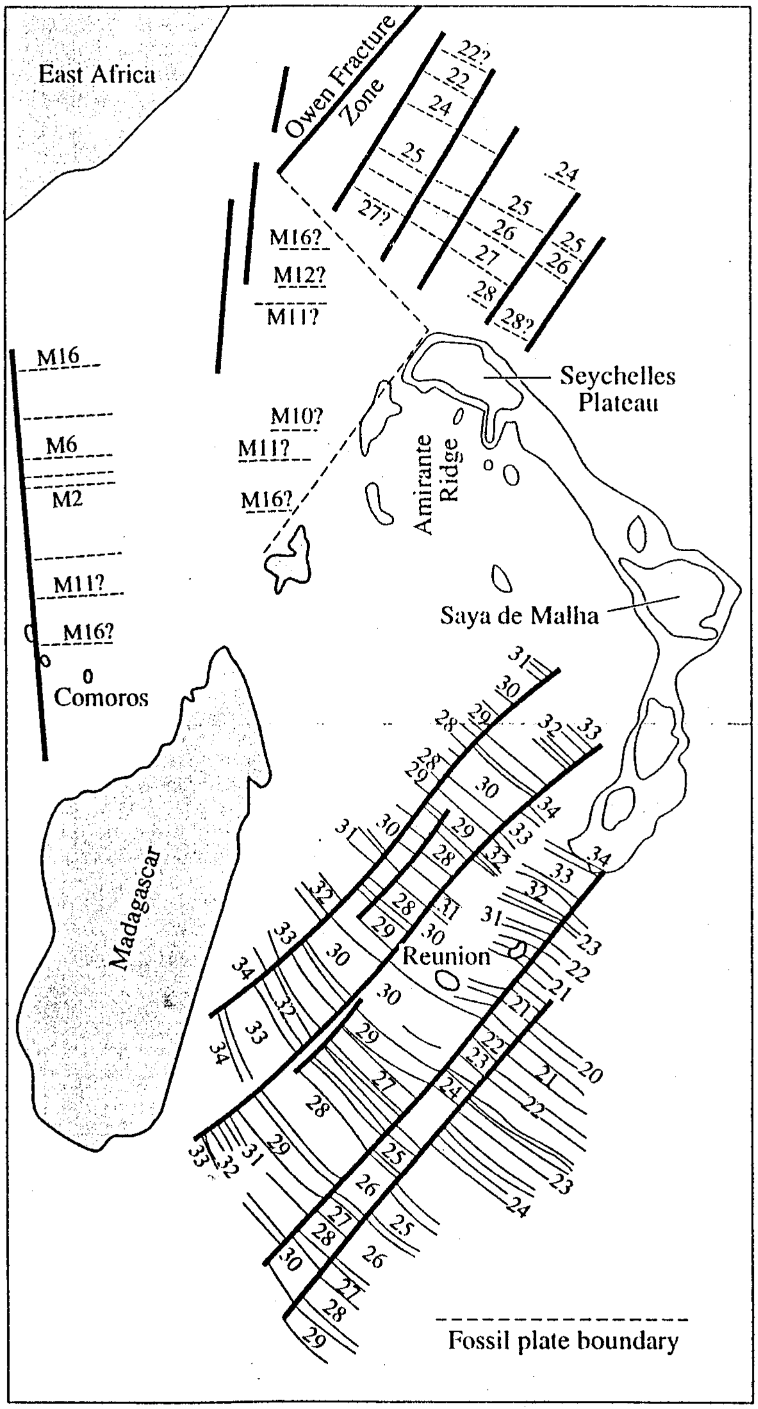

Fig. 4. Paleomagnetic anomaly identifications from the Mascarene and eastern Somali basins (Masson, 1984; Plummer, 1996).

and 77.6 ± 1.6 Ma, which is close to the age of tholeiite dikes (69.1 ± 1.7 and 73.5 ± 2.2 Ma) in Praslin Island in the Seychelles Archipelago (Dickin *et al.*, 1986; Plummer, 1995). The latter rocks are geochemically analogous to the Deccan flood basalts (Devey and Stephens, 1992). The active tholeiitic magmatism was followed (with a brief 1–5-Ma interlude; Devey and Stephens, 1992) by the intrusion of small subvolcanic and intrusive bodies of alkaline dolerites and syenites, which are widespread in the western part of the Seychelles Plateau and in the Deccan Plateau in India. The striking geochemical similarities between the alkaline rocks of the two areas and their similar crystallization ages (~65 Ma; Dickin *et al.*, 1986) suggest that they were derived under similar conditions, which seem to have been created during magmatic processes at transform fault zones cutting across the Carlsberg Spreading Ridge (Kashintsev, 1993; Devey and Stephens, 1992) but not due to the movement of the Seychelles–India continental block over a hotspot in the western part of the Comoros Archipelago (Duncan and Hargraves, 1990; Emerick and Duncan, 1982) or by the subduction of the oceanic crust of the Mascarene Basin within the Amirante Trough (Mart, 1988).

The fact that dredging samples from the upper portion of the Southern Block in the Amirante Ridge contain kaersutite-bearing dolerites (*Geologicheskoe stroenie...*, 1997) mineralogically similar to the analogous rocks from Ile de Nord in the Seychelles led us to suggest Early Paleocene alkaline magmatism in the Amirante Arc.

Hence, the complicated and long-lasting geotectonic evolution of the Seychelles–Amirante area made it a unique geologic structure in the Indian Ocean. We realize that many aspects of the scheme proposed for the evolution of the Amirante Arc, the development of a subduction zone along the Amirante Trough, and the initial island-arc magmatism in the Amirante Ridge remain disputable and call for further detailed investigations, although the scheme was developed on the basis of the latest geological and geophysical data (*Geologicheskoe stroenie...*, 1997; Lelikov *et al.*, 1991; Plummer, 1996).

CONCLUSION

The Amirante Arc and Trough, which compose an arcuate system between Madagascar and the Seychelles microcontinent, are morphologically and geophysically similar to island-arc systems in the West Pacific Ocean but differ from them by a fully aseismic character, the absence of an accretionary prism, and by the composition of the rocks, whose mineralogy and geochemistry are analogous to those of oceanic-crust basites but not island-arc rocks. The stratigraphic top of the arc magmatic basement consists of pillow lavas of clinopyroxene–plagioclase (± olivine) tholeiites and dolerite-basalts, which are metamorphosed to the zeolite facies and are exposed in the Northern and Central blocks. Deeper portions of the sequence consist of a dolerite and fine-grained gabbro dike complex and, further downsection, massive and cumulative gabbro, gabbronorite, and, then, ultramafic rocks, which crop out in the southern part of the arc. The predominance of holocrystalline plutonic rocks in the southern part of the arc and the higher metamorphic grade (up to the greenschist facies) of these rocks point to the deeper erosion of this portion of the arc compared with its northern and central parts.

The two-pyroxene–plagioclase basalts and feldspar-free olivine–orthopyroxene volcanics found in the northern part of the Amirante Arc are mineralogically and geochemically distinct from the mafic rocks of the oceanic crust and resemble the products of initial island-arc magmatism.

The genesis of the Amirante Arc and Trough remain a matter of vivid discussion. According to currently predominant hypotheses, these structures, which have a magmatic basement of Late Cretaceous rocks of the normal oceanic crust, compose an island-arc system that resembles typical arcs only morphologically. However, some gravity anomalies of the Amirante Arc and Trough led Mart (1988), Masson (1984), and Miles (1982) to propose the possible limited subduction of the Cretaceous oceanic crusts of the Mascarene Basin within the Amirante Trough. Later, summarizing newly obtained geological and geophysical evidence, Plummer (1996) concluded that the Amirante Arc and Trough were created at 80–70 Ma within the Amirante pull-apart basin. The latter was produced by sinistral strike-slip motions along a system of unparallel transform faults between Madagascar and the Seychelles microcontinent. Spreading processes and the development of the oceanic crust of the Mascarene Basin in the Late Cretaceous caused the rotational compression at the boundary between the Seychelles microcontinent and the Somali Basin with an older oceanic crust (Plummer, 1996), tectonic piling of the oceanic crust of the Amirante Basin, and the origin of the Amirante Arc and Trough, along which the subduction of the oceanic crust of the Somali Basin and initial island-arc magmatism can be suggested. The products of this magmatism were the two-pyroxene–plagioclase basalts and feldspar-free olivine volcanics found in dredging samples from the northern part of the Amirante Ridge. The processes terminated at 65 Ma in response to changes in the geometry of spreading centers in the western part of the Indian Ocean and the development of the present-day Carlsberg spreading ridge.

REFERENCES

Alt, D., Sears, J.M., and Hyndmann, D.W., Terrestrial Maria: The Origin of Large Basalt Plateaus, Hotspot Tracks and Spreading Ridges, *J. Geophys. Res.*, 1988, vol. 93, pp. 647–662.

Baker, B.H. and Miller, J.A., Geology and Geochronology of the Seychelles Islands and Structure of the Floor of the Arabian Sea, *Nature* (London), 1963, vol. 199, no. 4891, pp. 346–348.

Barazangi, M. and Dorman, J., World Seismicity Map of ESSA Coast and Geodetic Survey Epicentres Data for 1961–1967, *Bull. Seismol. Soc. Am.*, 1969, vol. 59, pp. 369–380.

Carlson, R.L., Christebsen, N.J., and Moore, R.P., Anomalous Crustal Structures in Oceanic Basins: Continental Fragments and Oceanic Plateaus, *Earth Planet. Sci. Lett.*, 1980, vol. 51, no. 1, pp. 171–180.

Chatterjee, S., A Kinematic Model for the Evolution of the Indian Plate Since the Late Jurassic, *New Concepts in Global Tectonics*, Chatterjee, S. Hotton, N., Eds., Lubbock: Texas Tech. Univ. Press, 1992, pp. 33–62.

Damuth, J.E. and Johnson, D.A., Morphology, Sediments and Structure of the Amirante Trench, Western Indian Ocean:

Implications for Trench Origin, *Mar. Petrol. Geol.*, 1989, vol. 6, pp. 232–242.

Devey, C.W. and Stephens, W.E., Deccan-Related Magmatism West of the Seychelles–India Rift, *Magmatism and the Causes of Continental Break-Up*, Storey, B.C., Alabaster, T. and Pankhurst, R.J., Eds., *Geol. Soc. Spec. Publ.*, 1992, no. 68, pp. 271–291.

Devey, C.W. and Stephens, W.E., Tholeiitic Dykes in Seychelles and the Original Spatial Extent of the Deccan, *J. Geol. Soc. London*, 1991, vol. 148, pp. 979–983.

Dickin, A.P., Fallick, A.E., Halliday, A.N., *et al.*, An Isotopic and Geochronological Investigation of the Younger Igneous Rocks of the Seychelles Microcontinent, *Earth Planet. Sci. Lett.*, 1986, vol. 81, no. 1, pp. 46–56.

Duncan, R.A. and Hargraves, R.B., ^{40}Ar, ^{39}Ar Geochronology of Basement Rocks from the Mascarene Plateau, the Chagos Bank, and the Maldives Ridge, Eds. Duncan, R.A., Baseman J., Peterson L.C., *et al.*, *Proc. Ocean Drill. Progr. Sci. Results, 115. College Station, TX (Ocean Drilling Program)*, 1990, vol. 115, pp. 53–61.

Emerick, C.M. and Duncan, R.A., Age Progressive Volcanism in the Comoros Archipelago, Western Indian Ocean and Implications for Somali Plate Tectonics, *Earth Planet. Sci. Lett.*, 1982, vol. 60, no. 3, pp. 415–428.

Erlank, A.T. and Reid, D.L., Geochemistry, Mineralogy, and Petrology of Basalts, Leg 25, DSDP, *Initial Rep. DSDP*, Simpson, E.S.W., Schlich, R., Eds., Washington: U.S. Gov. Print. Off., 1974, vol. 25, pp. 543–551.

Fisher, R.L., Engel, C.G., and Hilde, T.W.C., Basalts Dredged from Amirante Ridge, Western Indian Ocean, *Deep-Sea Res.*, 1968, vol. 15, no. 5, pp. 523–534.

Fisher, R.L., Johnson, G.L., and Heezen, B.C., Mascarene Plateau, Western Indian Ocean, *Bull. Geol. Soc. Am.*, 1967, vol. 78, no. 10, pp. 1247–1266.

Francis, T.G.J. and Shor, G.G., Seismic Refraction Measurements in the N.W. Indian Ocean, *J. Geophys. Res.*, 1966, vol. 71, no. 2, pp. 427–499.

Gallet, Y., Weeks, R., Vandamme, D., and Courtillot, V., Duration of Deccan Trap Volcanism: A Statistical Approach, *Earth Planet. Sci. Lett.*, 1989, vol. 93, no. 2, pp. 273–282.

Geologicheskoe stroenie Amirantskoi dugi v Indiiskom okeane (Geological Structure of Amirante Arc, the Indian Ocean), Lelikov, E.P., Ed., Vladivostok: Dal'nauka, 1997.

Girdler, R.W., The Dead Sea Transform Fault System, *Tectonophysics*, 1990, vol. 180, no. 1, pp. 1–13.

Girlling, C.M., Hydrocarbon Habitat of the Seychelles Microcontinent Related to Plate Tectonics and Paleogeography, *Proc. Indian Ocean Petroleum Sympos. Victoria, Seychelles*, Plummer, P.S., Ed., 1992, pp. 223–231.

Goslin, J. and Patriat, P., Absolute and Relative Plate Motions and Hypotheses on the Origin of Five Aseismic Ridges in the Indian Ocean, *Tectonophysics*, 1984, vol. 101, nos. 3–4, pp. 221–224.

Hartnady, C.J.H., Amirante Basin, Western Indian Ocean: Possible Impact Site of the Cretaceous / Tertiary Extinction Bolide?, *Geology*, 1986, vol. 14, pp. 423–426.

Johnson, D.A., Berggren, W.A., and Damuth, J.E., Cretaceous Ocean Floor in the Amirante Passage: Tectonic and Oceanographic Implications, *Marine Geol.*, 1982, vol. 47, no. 3/4, pp. 331–343.

Kashintsev, G.L., Magmatism, Geological History, and Geodynamics of the Indian Ocean Floor: Late Jurassic–Paleocene, *Geotektonika*, 1993, no. 3, pp. 55–68.

Lelikov, E.P., S"edin, V.T., Badredinov, Z.G., *et al.*, New Geological Data on the Amirante Arc, Indian Ocean, *Dokl. Akad. Nauk SSSR*, 1991, vol. 320, no. 4, pp. 946–951.

Mart, Y., The Tectonic Setting of the Seychelles, Mascarene and Amirante Plateaus in the Western Equatorial Indian Ocean, *Marine Geol.*, 1988, vol. 79, no. 3/4, pp. 261–274.

Masson, D.G., Evolution of the Mascarene Basin, Western Indian Ocean, and the Significance of the Amirante Arc, *Marine Geophys. Res.*, 1984, vol. 6, no. 4, pp. 365–382.

Masson, D.G., Kidd, R.B., and Roberts, D.G., Late Cretaceous Sediment Sample from the Amirante Passage, Western Indian Ocean, *Geology*, 1982, vol. 10, no. 5, pp. 264–266.

Matthews, D.H. and Davies, D., Geophysical Studies of the Seychelles Bank, *Philos. Trans. Royal. Soc. London, Ser. A*, 1966, vol. 259, no. 1099, pp. 227–239.

Miles, P.R., Gravity Models of the Amirante Arc, Western Indian Ocean, *Earth Planet. Sci. Lett.*, 1982, vol. 61, no. 1, pp. 127–135.

Norton, I.O. and Sclater, J.G., A Model for the Evolution of the Indian Ocean and the Breakup of Gondwanaland, *J. Geophys. Res.*, 1979, vol. 84, no. 12, pp. 6803–6830.

Plummer, P.S., Ages and Geological Significance of the Igneous Rocks from Seychelles, *J. Afr. Earth Sci.*, 1995, vol. 20, no. 2, pp. 91–101.

Plummer, P.S., The Amirante Ridge/Trough Complex: Response to Rotational Transform Rift/Drift between the Seychelles and Madagascar, *Terra Nova*, 1996, vol. 8, no. 1, pp. 34–47.

Plummer, P.S. and Belle, E.R., Mesozoic Tectono-Stratigraphic Evolution of the Seychelles Micro-Continent, *Sediment. Geol.*, 1995, vol. 96, no. 1, pp. 73–91.

Pushcharovskii, Yu.M., Tectonics of the Indian Ocean, *Geotektonika*, 1995, no. 4, pp. 73–91.

Rabiniwitz, P.D., Coffin, M.F., and Falvey, D., The Separation of Madagascar and Africa, *Science*, 1983, vol. 220, no. 4592, pp. 67–69.

Schlich, R., in *The Indian Ocean: Aseismic Ridges, Spreading Centers and Basins*, Nairn, A.E. and Stehli, F.G., Eds., New York: Plenum, 1982, pp. 51–147.

Schlich, R., Sea Floor Spreading History and Deep-Sea Drilling Results in the Madagascar and Mascarene Basins, Western Indian Ocean, *Deep-Sea Drill. Proj., Initial Rep.*, Simpson, E.S.W., Schlich, R., Eds., Washington, DC: US Gov. Print. Off., 1974, vol. 25, pp. 663–678.

Scrutton, R.A., Hemptonsyall, W.B., and Peacock, J.H., Constraints on the Motion of Madagascar with Respect of Africa, *Marine Geol.*, 1981, vol. 43, nos. 1–2, pp. 1–20.

Shor, G.G. and Polland, D.D., Seismic Investigations of Seychelles and Saya de Malha Banks, Northwest Indian Ocean, *Science*, 1963, vol. 142, no. 3588, pp. 48–49.

Simpson, E.S.W., Schlich, R., *et al.*, *Deep-Sea Drill. Proj., Initial Rep.*, Washington, DC: US Gov. Print. Off., 1974, vol. 25.

Wiseman, J.D.H., The Petrology and Significance of a Rock Dredged from a Depth of 774 Fathoms, Near to Providence Reef, Indian Ocean, *Trans. Linn. Soc. London*, 1936, vol. 19, ser. 2, pp. 437–443.