

The Geodynamic Context of the Cenozoic Volcanism of the Cap-Vert Peninsula (Senegal)

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Abstract

The Cenozoic alkaline volcanism of the Senegalo-Mauritania sedimentary basin presents an episodic long-lasting volcanic activity from the Eocene-Oligocene boundary up to the Quaternary. Two volcanic episodes are usually distinguished on stratigraphical grounds: a Miocene one and a Quaternary one separated by a period of quiescence of several million years corresponding to the main phase of lateritic weathering. The Tertiary lavas are highly silica-undersaturated alkaline rocks ranging from nephelinites to basanites. They contain nepheline and fassaite-type clinopyroxene in their mineralogy. The Quaternary lavas are more evolved with Hy-normative in comparison to the Tertiary ones; they are composed of basanites and medium to coarser-grained dolerites. The distribution of the REE and other incompatible elements are typical of alkaline lavas with generally strong LREE enrichment without significant Eu anomaly. The Cenozoic Cap-Vert lavas have OIB (oceanic islands basalts)-affinities as shown by their relatively radiogenic Nd and unradiogenic Sr characters closed to the HIMU-OIB. This suggests a HIMU-type end member in the magma sources which is fairly comparable to those erupted in the Canaries and Cape Verde archipelagoes during the same period.

Keywords

Cenozoic, Alkaline Volcanism, Oceanic Islands Basalts, Cap-Vert Peninsula, Senegalo-Mauritania Basin

1. Introduction

The West African Atlantic margin is spotted by three main alkaline volcanic provinces: the Canary Archipelago,

the Cape Verde Archipelago and the Cap-Vert peninsula (Dakar, Senegal). The Cap-Vert peninsula is located at the westernmost part of the Senegalo-Mauritania basin about 1000 km at the east of the Cape Verde Archipelago. The volcanic province (**Figure 1**) which extends further east onshore, is marked by large positive gravity anomalies in the Cap-Vert peninsula (110 mgal) and the Cayar Dome (160 mgal) identified by geophysics offshore [1]. It is subsequent to the opening of the Central Atlantic Ocean during the Lias, and related to the sub-meridional faults and the occurrence of E-W significant transverse fractures corresponding to the extension of oceanic transform faults on the continent.

Reference [2] was the first to suggest two eruptive rock series: one considered of Upper Cretaceous and the other of post-Meso-Nummulitic age. [3] confirmed the existence of these two series, but suggested stratigraphical

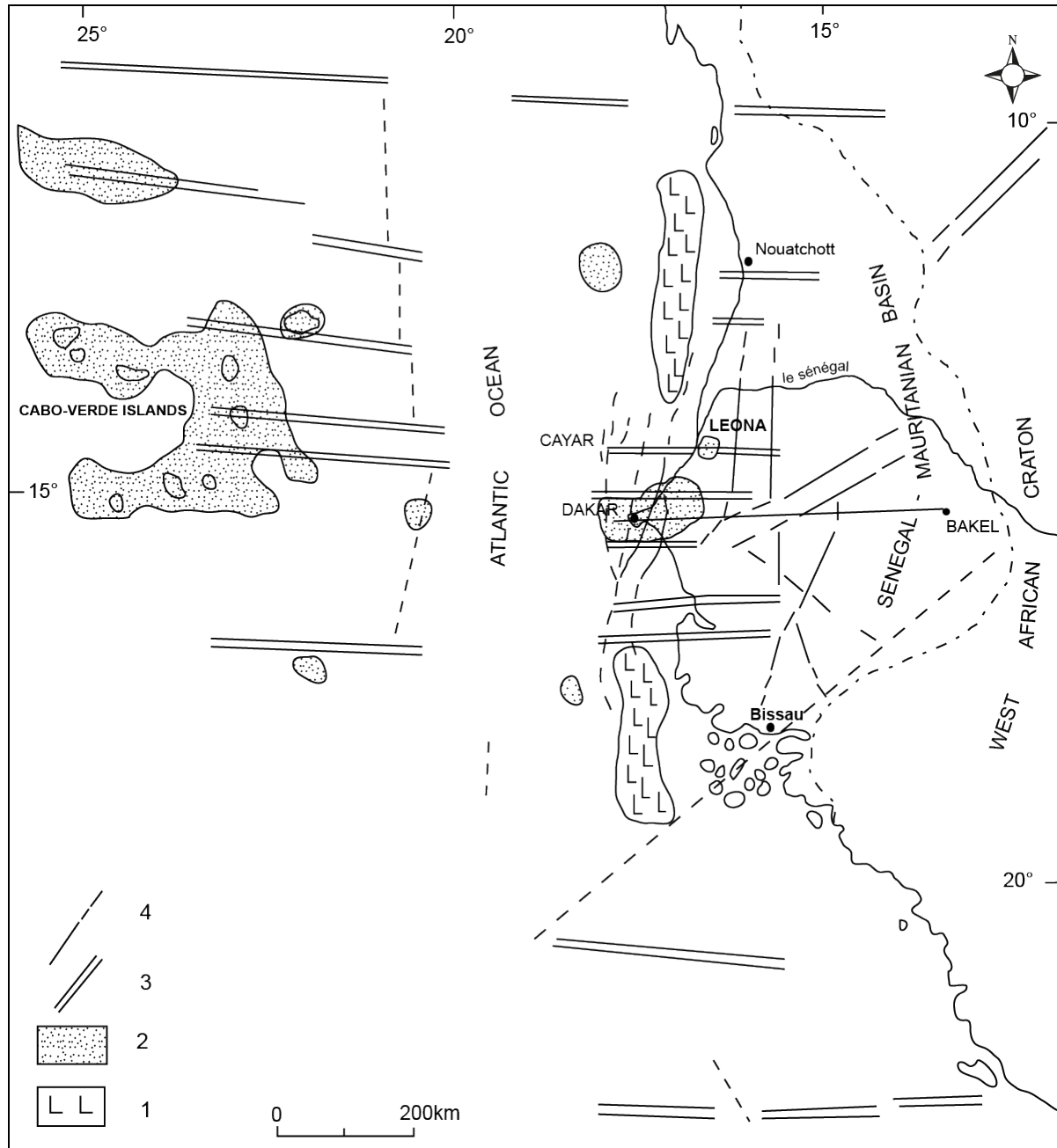


Figure 1. Coastal regions of Senegal: 1: zones of evaporates diapiric structures; 2: zones of regional positive gravimetric anomalies (>40 mgal); 3: Transform faults; 4: faults [4].

grounds during the Miocene age for the first occurrence and an early Quaternary age for the second. Since the 50's, many descriptive studies of volcanic occurrences have been carried out [4].

References [4] [5] described an alkali syenite intrusion detectable only by drilling at Leona village (see [Figure 1](#)). This event can be connected with other activities occurring during the late Cretaceous along the West African Atlantic margin.

Reference [6] distinguished a Tertiary and a Quaternary volcanism separated by a ferruginous lateritic crust of Pliocene age. They presented an improved chronological framework for this volcanism based on K-Ar age determinations. These ages indicate an episodic long-lasting volcanic activity from Eocene-Oligocene boundary up to Quaternary in which the paroxysm is attained during the Serravallian and the Tortonian periods.

On the continental shelf, the activity of the Cenozoic volcanism is marked by intrusive rock and hydrothermal vents in Paleozoic and Cretaceous sediments coinciding with the development of the Cayar Seamount and the volcanic eruptions on the Cape Verde archipelago [7] [8].

Several hypotheses have been advanced to explain the geodynamic significance of this volcanism. [9] [10] interpreted the Quaternary volcanism as an intra-plate volcanism associated with the migration of hot spots activities. This hypothesis is refuted by the absence of gular distribution of radiometric ages across the volcanic province [6]. They interpret the Cap-Vert peninsula volcanism as broadly similar to those of the Cape Verde and the Canary archipelagos by their geodynamic setting age and magmatic characteristics.

This paper deals the interpretation from new geochemical data of the evolution of the Cenozoic volcanism of the Cap-Vert peninsula in relation with its geodynamic environment. The results are discussed and compared with the two other provinces of the Canary and Cape Verde Archipelagos.

2. Geological Setting

The Senegalo-Mauritania sedimentary basin is geologically pretty well known [4] [6] [11]. Sedimentation is related to half-basin tectonic activity which began in the Middle Jurassic time and was active until recent time [12]. Gravimetric studies indicate the existence of a rapid thinning of the continental crust to the West [1]. The oceanic crust appears to open a hundred miles off Dakar area [13]. The basin ([Figure 2](#)) shows a monoclinical structure slightly dipping to the west and cut by sub-meridional normal faults, delimiting horsts and grabens and WNW-ESE faults corresponding to the extension of transform faults on the continent on which is localized the Cape Verde archipelago [11] [14]. These faults delimit the exonded block of the Cap-Vert peninsula that separates the Triassic-Liassic Casamance-Guinea evaporites basins whose deposition coincides with the birth of the rift stage of the Central Atlantic associated with an important phase of tholeiitic magmatic activity [15].

The magmatism acted along ancient zones of crustal weakness, which are related with inland extensions of transform faults. It is associated with two major tectonic events that occurred between the late Lutetian and late Eocene [16], and the Neogene [17]. Two major structures of NNE-SSW and NW-SE directions associated with other secondary NE-SW and NS in the Cap-Vert peninsula are brought out by [18]. These structures are reactivated faults which are cut successively by those of NNE-SSW and NW-SE orientations. In fact, most of those structures are relict faults reactivated during the Alpine tectonic phase until a recent time.

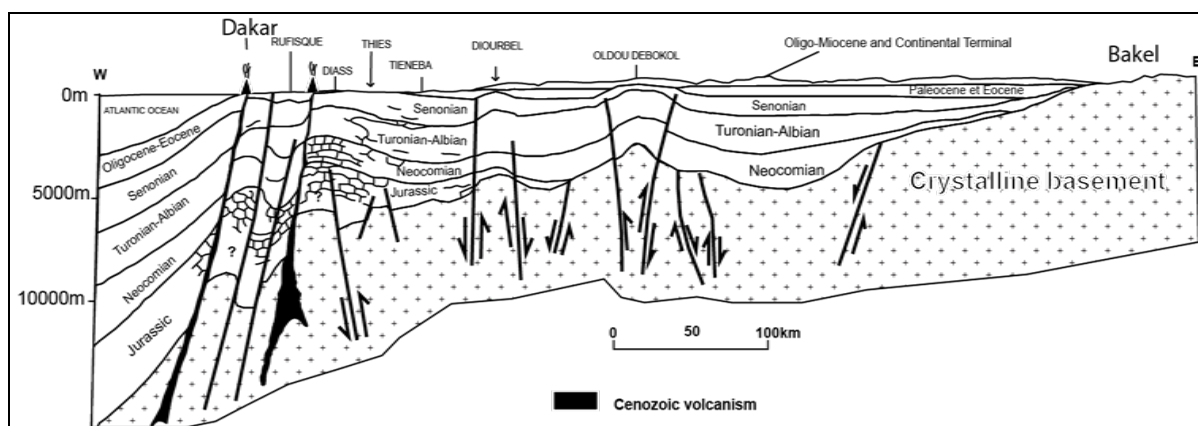


Figure 2. Schematic cross section of the Senegal basin from Bakel (E) to Dakar (W) ([12] modified).

3. Lithological and Petrographical Characteristics

3.1. The Tertiary Volcanism

The Tertiary volcanism consists about thirty small occurrences of hectometric to kilometric extension scattered over an area about 100 km long from Dakar to the east of Thiès (**Figure 3(a)**). Four geographical groups are characterized by their different products:

1) Ankaratrite, nephelinite, basanitelavas flows or sills with columnar structure well spread in the Cap-Vert peninsula (Gorée, Cap Manuel, Iles des Madeleines, Pointe de Fann). The columns are generally vertical and regular shaped with polygonal section and some are bowed toward the edge of the flow;

2) basanite and nephelinitedykes with pegmatitoid veins and tuffs of limited extension in the Rufisque area (Cap des Biches, Diokoul); The dykes oriented N20°, intrude the paleogene limestone sand the contact is marked by a weak thermal metamorphism. The rocks contain numerous vesicles filled of calcite and zeolite elongate NNE to NE trends.

3) Intrusions of basanites and tuffs located at the intersection of WNW-ESE and sub-meridian main fractures in the Ndiass horst area (Khazabe, Thiéo, Bandia);

4) Andin the Thiès region where the main outcrop would correspond to the remains of a lava lake located in a maar [19]. It is a N-S elongated cliff with a limited extension constituted of basanites, dolerite and pegmatitoid-gabbros from the periphery to the inner sides of the pluton.

Petrographical features:

1) Nephelinites with aphyric texture are usually associated with porphyritic (or pegmatitoids) nephelinites with coarser doleritic texture. In the microlitic facies, phenocrystal microcrystal olivine (75% to 90% Fo) are usually corroded by anhyalinemesostasis. The clinopyroxene with fassaite to diopside compositions (Wo 47 - 55 En 30 - 38, Fs 9 - 17) represent the main mineral phase of the rock. An hedral nepheline is associated with needles of apatite and fine grains of olivine and clinopyroxene in the mesostasis. In the porphyritic facies, the clinopyroxenes of fassaite type (Wo 50 - 55 En 29 - 38, Fs 11 - 16) exhibit occasionally hourglass twinning or oscillatory-zonation features. A few tabular minerals of plagioclase (An 50% - 66%) are associated with olivine (66% to 84% Fo). Fine grains of apatite, zeolites, biotite and oxides are abundant in the rock.

2) The basanites are the most representative facies of this volcanism and are frequently associated with nephelinites. The common facies have aphyric texture and may have vacuolar structure with vesicles filled of calcite. The euhedral to subhedral crystals of olivine (67% to 85% Fo) are sometimes surrounded by a thin rim of feldspar. The clinopyroxene with augite compositions (Wo 47 - 52, En 31 - 41, Fs 10 - 15) are corroded by

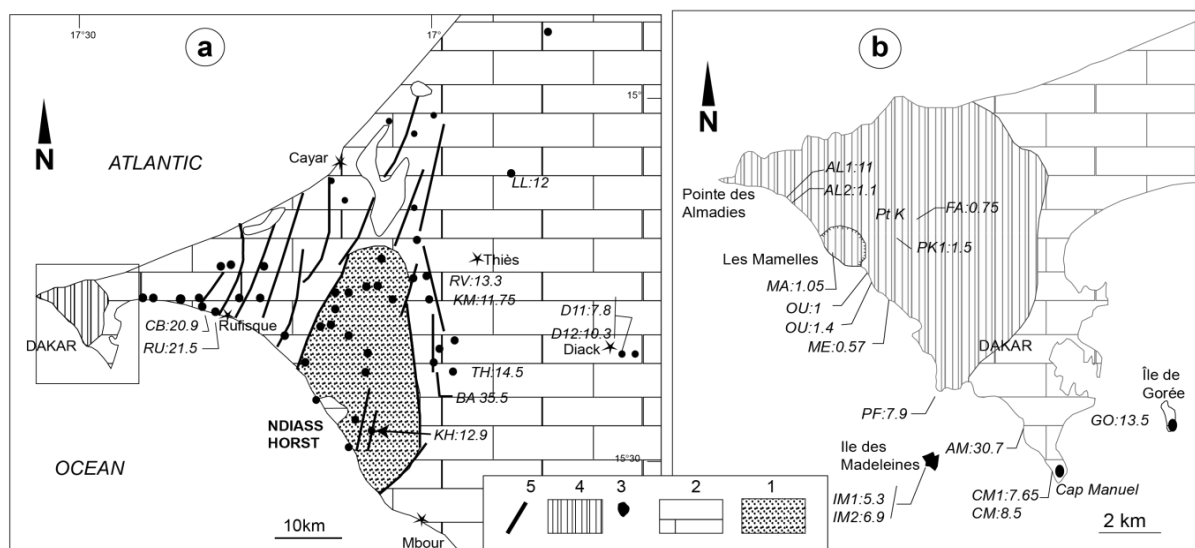


Figure 3. Outcrops of Cenozoic volcanic rocks in Cap-Vert peninsula [6]: (a) Cap-Vert peninsula and Thiès areas; (b) The Cenozoic volcanism of the Head of the Cap-Vert peninsula. 1: Mesozoic province (Ndiass Horst), 2: Tertiary carbonates, 3: Outcrops of Tertiary volcanic rocks dated (RU 21.5, K-Ar ages in Ma) or not dated, 4: Quaternary volcanic province with different K-Ar ages, 5: Faults.

the mesostasis. The microlitic plagioclases (An 52% - 80%) are relatively abundant. Oxides are grouped into fine granules or in inclusion in olivine or clinopyroxene minerals. The hyaline ground mass contains microcrystals of olivine, clinopyroxene, plagioclase and oxides.

3) In the Diack pluton, the basanites, dolerites, and gabbros are arranged into a concentric structure from the periphery to the inner parts of the pluton. In the dolerites, the clinopyroxenes with augitic composition (Wo 44 - 45, En 40 - 44, Fs 10 - 14) and the olivine (60% to 61% Fo) are grouped into the spaces between the plagioclase laths (An 44% - 63%). Oxides are abundant and exhibit a graphitic structure. The gabbros are composed of euhedral olivine (67% Fo) locally surrounded by a fringe of alteration of idding site. The plagioclases (An 44% - 52%) are abundant and partially saussuritized. Abundant oxides are associated with clinopyroxene.

3.2. The Quaternary Volcanism

The Quaternary volcanism is confined at the Head of the Cap-Vert peninsula commonly named Mamelles volcano (**Figure 3(b)**). The flows are interbedded with sand dunes of Quaternary age and laid on the end-Tertiary laterite [4] [20] [21].

From the bottom to the top, the Quaternary volcanism is divided into:

- A lower unit consisting of tuffs and thin flows of olivine basalts known only by drilling;
- An intermediary unit is composed of dolerite sand basalts with a ferruginous fringe of alteration;
- An upper unit composed of volcanic flows corresponding to the Mamelles volcano with several phases of volcanic activities: a) maar deposits established during an initial phase of phreatomagmatic eruption; b) strombolian activity building a cinder cone with emission of lavas at the base of the cone; c) edification of a lake in a large crater by a ring collapse in the cone; d) eruption of doleritic cone-sheet feeding the terminal effusive phase.

These products are structured into four columnar or lamellar flows separated by scories and ferruginized sandy-clay material [22]. They contain centimetric sized vesicles elongated in the direction of the flow and filled with zeolite or calcite material. Nearby the volcanic cone, the basanite flows contain abundant xenoliths of peridotite and gabbro. The basanites are overlaid by two doleritic flows separated by a horizon of alteration consisting of fragments of scories, basanites and dolerites cemented by ferruginous clay material. The upper dolerite has a coarser structure with abundant vesicles exhibiting trails of degassing.

Petrographical features:

The basanites with fluidal texture are composed of olivine (64% to 91% Fo) sometimes surrounded by a rim of idding site. Zoned clinopyroxene of augitic composition (Wo 45 - 50 En 36 - 44 Fs 10 - 15) are associated with abundant plagioclase (An 46% - 76%) in the upper flows. Oxides are usually included in plagioclase or in clinopyroxene crystals or dispersed in the mesostasis.

The dolerites with sub-ophitic to fluidal texture are composed of abundant laths of plagioclase with rare clinopyroxene and olivine crystals. In the upper dolerites, the plagioclase (An 27% - 56%) may represent the only mineral phase where it is associated with augitic clinopyroxene (Wo 31 - 47 En 38 - 49 Fs 11 - 24), olivine (58% - 83% Fo) partially idding sized and Fe-Ti oxides.

4. Geochemical and Isotopic Study

4.1. Analytical Methods

Twenty three samples (present study) associated with eighteen samples ([6], unpublished data) were selected for major and trace element analysis (**Table 1**). Major and trace elements (including REE) were determined by ICP-AES and ICP-MS in CRPG (Nancy, France), following the procedure described by [23]. Nine representative samples were analyzed for Nd and Sr isotopic ratios ([6], unpublished data) in Clermont-Ferrand on a Micromass VG54E mass spectrometer using triple Ta-Re and single Ta filaments, respectively (**Table 2**). The entire process is described by [24].

4.2. Major Elements

The Cenozoic volcanic rocks exhibit distinctive geochemical compositions. The Tertiary lavas are silica-undersaturated (40% - 48%) with $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios values varying between 2.12 and 4.94 except in the porphyritic (or pegmatitoids) nephelinites where these values are more important (7.91 and 40.75). They are characterized by

Table 1. Major and trace elements concentrations (DK samples are from Crévola *et al.*, 1994, unpublished data).

Tertiary volcanism																							
Samples.	1	30	31	32	33	34	35	36	37	38	39	DK18	DK13	DK15	DK14	DK1	DK17	DK16	DK3	DK2	DK6	DK7	DK8
SiO ₂	41.72	41.58	39.26	41.14	42.46	39.39	39.87	38.76	42.33	47.85	47.22	40.46	41.50	39.80	43.34	39.96	45.31	46.91	40.81	40.62	40.60	39.56	47.21
Al ₂ O ₃	11.51	11.71	13.12	11.55	13.49	12.14	12.55	15.91	12.23	13.62	15.95	11.67	12.00	12.80	14.02	12.63	13.20	13.20	12.03	12.96	17.27	11.26	13.55
Fe ₂ O ₃	13.41	12.56	10.42	12.39	11.41	11.57	11.91	12.09	12.37	11.57	11.93	11.67	13.10	11.80	12.03	11.85	11.43	11.14	10.94	11.49	10.39	11.96	11.85
MnO	0.19	0.19	0.17	0.18	0.18	0.19	0.20	0.22	0.20	0.16	0.19	0.19	0.20	2.00	0.19	0.17	0.17	0.16	0.17	0.17	0.17	0.20	0.16
MgO	12.72	12.73	7.69	12.25	9.15	11.71	10.62	5.80	10.77	9.80	3.52	12.07	11.30	11.10	9.26	11.05	11.94	11.23	12.82	11.14	4.90	13.53	9.69
CaO	12.84	12.33	15.95	12.56	12.05	14.97	14.55	13.77	12.32	10.06	8.74	15.38	12.40	14.40	12.72	14.83	11.64	11.99	15.53	14.86	11.08	14.33	10.48
Na ₂ O	2.64	2.73	3.30	2.72	3.46	1.97	2.94	4.69	4.10	2.86	4.86	2.84	3.54	2.83	3.39	3.41	2.83	2.85	3.12	3.29	5.58	3.04	3.16
K ₂ O	0.96	0.85	1.56	0.69	1.00	0.25	0.26	0.12	0.88	0.76	2.02	1.08	0.92	0.27	1.17	7.00	1.14	0.90	0.76	0.68	2.50	0.73	0.64
TiO ₂	2.50	1.82	2.07	1.80	1.96	1.96	2.05	1.99	2.22	1.55	2.49	2.13	2.50	2.04	2.04	2.37	2.14	1.80	1.97	3.08	1.68	1.93	1.43
P ₂ O ₅	0.83	0.90	2.77	0.85	0.84	0.89	1.00	1.59	0.58	0.28	1.02	1.05	0.90	1.05	0.91	0.94	0.58	0.57	0.93	0.76	1.62	1.04	0.51
PF	0.88	1.77	2.61	2.80	2.92	4.31	4.10	5.17	2.37	1.26	1.87	1.84	1.66	4.42	2.66	1.59	0.66	0.76	1.32	1.42	3.61	2.18	1.03
Total	100	99.16	98.92	98.93	98.91	99.37	100	100	100	99.76	99.80	100	100	100.71	101.73	99.48	101.04	101.51	100	100	99.40	99.76	99.71
NaO/K ₂ O	2.75	3.19	2.12	3.96	3.46	7.91	11.12	40.75	4.65	3.78	2.41	2.63	3.85	10.48	2.90	5.01	2.48	3.17	4.11	4.84	2.23	4.16	4.94
Ne'	11.7	10.5	13.7	9.75	10.1	8.63	13.4	21.2	19.2	0	10.6	13	15.3	13	12.5	15.6	7.11	4.43	14.3	15.1	25.58	1.35	13.9
Co	83.3	77.9	82.6	76.6	73.8	69.8	68.2	55.9	78.4	123	49.9	72	76	73	60	82	69	67	74	65	42	64	59
Cr	447	399	99.6	386	217	400	362	12.2	393	467	43	386	358	335	203	258	577	548	577	531	18	356	49
Cs	0.37	0.37	0.26	0.36	0.93	0.39	0.27	0.48	1.26	0.88	1.53	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Hf	5.28	3.30	3.75	3.62	4.55	6.69	4.53	3.05	4.69	2.22	4.67	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb	80.9	61.1	108	61.6	99.8	118	156	236	122	39.1	156	91	119	118	104	96	88	54	103	98	134	46	84
Ni	371	301	105	289	142	217	199	54.4	260	305	50.5	298	293	172	120	210	307	306	269	201	59	236	308
Rb	27.9	23.1	55.6	17.6	26.7	14.2	12.1	8.82	44.4	24.9	63.9	31	30	11	30	23	34	18	23	27	89	24	29
Sr	802	828	1540	872	1997	2732	2799	3571	802	552	843	1583	709	2812	1490	1302	784	694	1073	1011	1774	579	1088
Ta	7.26	4.14	7.45	4.61	6.11	6.81	7.74	11.01	9.88	3.39	11.38	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th	5.27	5.11	9.67	5.44	11.85	10.77	12.17	18.23	5.74	2.20	8.80	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
U	1.25	1.24	2.09	1.28	3.64	2.59	3.18	4.79	1.38	0.53	2.10	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
V	228	191	225	180	196	227	268	314	249	218	232	233	220	242	206	219	242	220	220	284	202	179	197
Y	25	25	38.6	25.9	28.8	29.7	33.6	40.4	24.9	20.6	36.4	29	27	31	31	27	24	23	25	22	33	29	21
Zr	212	152	201	155	222	329	257	257	227	99.2	250	182	228	226	212	165	231	156	200	212	156	89	178
La	45.62	55.40	112.90	57.99	103	87.63	97.77	140	42.32	17.59	65.04	80.90	49.50	88.30	101.00	83.52	47.20	38.40	82.41	84.64	107	44.34	74.00
Ce	88.57	107.70	216.10	113.40	174	164	181.60	252	78.71	34.32	118.30	158	95.2	167	176	155	92.6	77.5	152	101	184.8	74.65	141
Pr	10.43	12.40	23.85	13.05	18.60	18.27	19.71	26.42	8.90	4.08	12.90	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nd	41.61	48.29	89.79	50.68	67.47	67.26	72.25	92.71	34.46	16.79	48.19	66.10	41.60	67.90	67.30	63.27	40.17	34.30	63.12	46.02	72.14	28.67	61.60
Sm	8.44	9.02	15.65	9.54	11.42	11.45	11.92	14.58	6.82	3.78	9.08	9.23	7.75	9.80	10.70	12.25	5.17	5.98	11.75	9.43	13.02	6.20	11.93
Eu	2.73	2.79	4.68	2.90	3.52	3.42	3.65	4.26	2.28	1.37	2.98	2.47	2.15	2.52	2.73	3.51	1.40	1.78	3.26	2.77	3.72	1.88	3.52
Gd	7.42	7.46	12.55	7.57	9.14	9.00	9.60	11.60	6.20	4.02	8.47	7.90	6.81	8.08	8.48	9.77	4.90	5.68	9.18	8.01	10.07	5.73	9.59
Tb	1.02	1.02	1.62	1.08	1.18	1.22	1.28	1.52	0.87	0.62	1.21	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Dy	5.39	5.34	8.38	5.64	6.13	6.21	6.55	7.77	4.73	3.58	6.78	5.68	4.95	6.07	5.87	5.68	4.46	4.21	5.38	4.92	6.71	4.23	6.10
Ho	0.92	0.91	1.37	0.95	1.02	1.05	1.11	1.33	0.82	0.67	1.20	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Er	2.32	2.21	3.36	2.37	2.62	2.67	2.83	3.49	2.05	1.76	3.11	2.32	2.24	2.70	2.67	2.36	1.85	1.88	2.24	2.00	2.94	1.94	2.49
Tm	0.30	0.29	0.43	0.31	0.35	0.37	0.38	0.47	0.28	0.24	0.42	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Yb	1.83	1.79	2.51	1.87	2.10	2.26	2.36	2.92	1.70	1.46	2.66	1.34	1.71	1.89	1.99	1.72	1.14	1.35	1.64	1.44	2.23	1.54	1.81
Lu	0.28	0.26	0.35	0.28	0.31	0.34	0.34	0.42	0.25	0.22	0.38	0.16	0.24	0.24	0.27	0.31	0.14	0.19	0.30	0.25	0.37	0.26	0.29

Table 1 (end) (DK samples are from [6] (unpublished data).

Quaternary volcanism																		
Sample	6	17	25	26	27	28	14	A	16	19	29	18	DK12	DK11	DK5	DK10	DK4	DK9
SiO ₂	48.23	47.54	46.91	47.90	48.24	47.97	50.27	49.35	51.30	50.65	50.51	47.13	48.42	51.72	46.90	49.84	48.20	51.75
Al ₂ O ₃	14.80	15.04	14.60	14.87	14.69	14.66	17.27	14.90	14.72	14.69	15.44	14.82	15.18	15.21	14.92	15.60	15.08	14.66
Fe ₂ O ₃	10.41	10.61	9.81	10.32	10.96	10.82	12.08	11.30	10.44	9.71	10.63	10.26	10.91	10.30	10.46	10.71	10.89	10.91
MnO	0.13	0.14	0.13	0.13	0.14	0.14	0.11	0.15	0.14	0.10	0.12	0.14	0.12	0.12	0.12	0.13	0.13	0.13
MgO	7.88	7.99	7.83	7.40	8.41	8.20	3.52	7.04	7.33	7.39	5.56	7.98	7.18	7.24	8.21	7.26	7.76	7.01
CaO	7.33	8.00	9.42	8.75	8.59	7.91	6.83	8.88	9.01	8.50	9.07	9.07	7.84	8.96	8.32	9.36	8.36	8.73
Na ₂ O	4.06	4.79	4.30	3.89	3.66	4.51	3.78	3.72	3.94	3.78	4.05	4.16	5.05	4.01	4.20	3.84	4.74	3.95
K ₂ O	1.97	1.46	1.52	1.43	1.24	1.68	0.59	1.04	0.69	0.76	0.47	1.45	1.62	0.61	1.43	0.70	1.51	0.63
TiO ₂	2.18	2.13	1.89	1.90	1.81	2.13	1.61	1.70	1.52	1.49	1.55	1.88	2.12	1.35	2.00	1.43	1.86	1.54
P ₂ O ₅	0.69	0.60	0.56	0.59	0.50	0.55	0.30	0.47	0.33	0.34	0.33	0.58	0.53	0.36	0.60	0.34	0.61	0.40
PF	2.66	1.07	1.84	1.97	1.19	0.88	3.63	1.16	-0.04	1.86	1.85	1.69	0.58	nd	2.48	0.57	0.51	0.03
Total	100	99.36	98.80	99.13	99.41	99.43	99.99	99.70	99.39	99.28	99.56	99.15	99.55	99.88	99.64	99.78	99.65	99.74
NaO/K ₂ O	2.06	3.29	2.83	2.72	2.95	2.69	6.37	3.58	5.68	4.97	8.70	2.87	3.12	6.57	2.94	5.49	3.14	6.27
Ne'	2.93	8.01	8.33	2.62	1.29	8.82	0	0	0	0	0	6.52	8.52	0	5.72	0	7.76	0
Co	54.9	56.9	68.3	84.9	68.8	67.5	54.7	57.1	70.5	47.2	60.6	50.8	55	63	51	65	60	60
Cr	238	253	225	239	262	307	274	257	237	215	242	215	246	261	236	244	257	35
Cs	0.66	1.66	0.36	0.43	0.20	0.58	<LD	0.23	<LD	<LD	<LD	0.41	nd	nd	nd	nd	nd	nd
Hf	4.34	4.08	3.45	3.59	3.14	3.81	2.55	2.88	2.15	2.30	2.29	3.73	nd	nd	nd	nd	nd	nd
Nb	66.5	58.2	52.8	53.3	46.1	55.8	30.1	41.2	30.6	31.1	32.1	51.5	56	31	59	27	57	33
Ni	226	231	215	212	237	268	151	218	136	125	116	190	229	146	199	197	227	140
Rb	57.4	17.2	40.9	38	28.2	45	12.3	25.4	15.3	16.9	4.47	37.4	39	17	35	19	44	17
Sr	858	749	772	741	674	714	442	595	466	433	487	742	710	496	768	491	758	451
Ta	5.01	4.54	3.84	3.92	3.20	4.19	1.76	2.71	1.89	1.80	1.86	3.80	nd	nd	nd	nd	nd	nd
Th	4.56	5.23	4.07	4.17	3.51	3.79	2.88	2.87	2.77	3.18	3.16	4.60	nd	nd	nd	nd	nd	nd
U	0.63	1.19	0.79	0.94	0.72	0.86	0.67	0.73	0.48	0.82	0.67	1.09	nd	nd	nd	nd	nd	nd
V	114	141	126	131	136	137	97.2	138	133	122	131	132	145	134	146	47	151	143
Y	18.9	20.2	19.8	20.6	20.4	19.7	23.6	19.9	16.6	16.9	19.1	20.3	19	17	20	42	21	19
Zr	181	161	148	149	132	154	86.1	113	79.4	84.4	87.3	148	143	71	146	74	156	79
La	37.71	34.88	32.84	33.44	30.07	30.80	36.95	27.79	24.36	26.26	26.19	33.88	28.88	24.46	33.80	36.91	33.68	25.65
Ce	68.64	64.48	61.09	61.81	55.47	56.23	52.74	51.44	43.70	47.24	46.39	63.01	51.03	49.13	63.23	38.26	67.13	48.37
Pr	7.92	7.45	7.02	7.15	6.55	6.53	7.84	6.00	4.79	5.18	5.25	7.30	nd	nd	nd	nd	nd	nd
Nd	32.13	30.07	28.05	28.85	26.13	26.89	31.49	24.51	18.55	20.02	20.67	29.40	26.79	18.56	28.39	26.53	28.39	19.49
Sm	7.14	6.65	6.26	6.38	5.82	6.37	7.17	5.37	4.09	4.38	4.66	6.41	6.98	4.69	6.64	6.62	6.89	4.67
Eu	2.48	2.33	2.18	2.22	2.06	2.21	2.53	1.89	1.56	1.62	1.67	2.28	2.25	1.64	2.26	2.22	2.27	1.65
Gd	6.52	6.21	5.64	5.78	5.36	5.69	7.08	5.27	4.26	4.49	4.60	6.08	6.58	4.78	6.20	7.93	6.41	4.75
Tb	0.87	0.87	0.79	0.82	0.78	0.82	1.01	0.76	0.62	0.65	0.69	0.85	nd	nd	nd	nd	nd	nd
Dy	4.31	4.57	4.20	4.37	4.18	4.30	5.37	4.03	3.36	3.58	3.83	4.49	4.35	3.43	4.39	5.54	4.43	3.75
Ho	0.68	0.75	0.71	0.74	0.70	0.71	0.90	0.70	0.59	0.62	0.68	0.75	nd	nd	nd	nd	nd	nd
Er	1.51	1.81	1.71	1.75	1.67	1.68	2.17	1.76	1.45	1.57	1.67	1.82	1.72	1.53	1.70	2.54	1.77	1.61
Tm	0.18	0.23	0.22	0.23	0.22	0.22	0.27	0.22	0.19	0.21	0.23	0.23	nd	nd	nd	nd	nd	nd
Yb	1.01	1.36	1.27	1.34	1.29	1.20	1.65	1.34	1.18	1.25	1.33	1.42	1.11	1.12	1.25	1.61	1.30	1.28
Lu	0.13	0.18	0.17	0.19	0.18	0.17	0.24	0.19	0.16	0.17	0.19	0.20	0.17	0.22	0.21	0.29	0.23	0.23

normative nepheline (9% to 25%) with the exception indoleriticfacies showing normative hypersthene and weakly differentiated with mg numbers ranging from 0.38 to 0.70. On the (Na₂O + K₂O) versus SiO₂ diagram [25], they spread from nephelinites, basanites, tephritesto basalts and hawaiites (Figure 4). The Quaternary lavas are relatively more siliceous (48% - 52%) and more sodic with Na₂O/K₂O ratios values ranging between 2.06 and 8.70. They have low normative nepheline content (1% and 8%) while doleritic facies show normative hypersthene. Their geochemical classification spreads from hawaiites, basalts tottrachy-andesites. They are weakly differentiated with mg numbers ranging from 0.37 to 0.62. The upper dolerites are more aluminous (17.92%), more siliceous (52.17%) and more ferrous (12.54%) than other underlying basanites and dolerites.

The Al₂O₃ exhibits a positive correlation with the degree of silica saturation, whereas MgO, Fe₂O₃^t, CaO, Na₂O, P₂O₅, TiO₂, MnO and Al₂O₃/CaO are negatively correlated with the degree of silica saturation (Figure 5). These variations suggest differentiation processes dominated by clinopyroxene fractionation in the Cenozoic lavas.

4.3. Trace Elements

The concentrations of trace elements exhibit substantial differences between Tertiary and Quaternary rocks. The compatible elements (Cr, Ni, Co, Sc and V) are generally more abundant in Tertiary lavas, indicating various extents of fractionation of ferro-magnesian minerals whereas in the Quaternary lavas, the concentrations of these elements are less abundant.

Table 2. Sr and Nd isotopic datasof Cenozoic volcanic rocks ([6] unpublished datas).

	Ref. Samples	⁽⁸⁷ Sr/ ⁸⁶ Sr) _i	¹⁴³ Nd/ ¹⁴⁴ Nd	εNd
Quaternary volcanism	DK11	0.702994	0.512935	5.79
	DK10	0.703196	0.512805	3.26
	DK4	0.703016	0.512919	5.48
Tertiary volcanism	DK18	0.704076	0.51289	4.92
	DK13	0.703254	0.512971	6.5
	DK14	0.704636	0.512923	5.56
	DK1	0.703191	0.512932	5.74
	DK3	0.703064	0.512898	5.07
	DK8	0.702908	0.51293	5.7

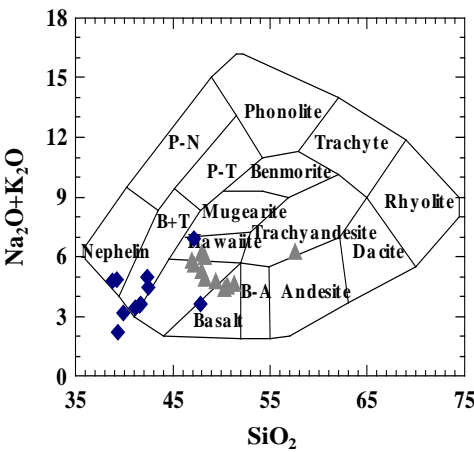


Figure 4. Distribution of Tertiary lavas (diamond) and Quaternary lavas (triangle) on the alkali versus silica diagram [25].

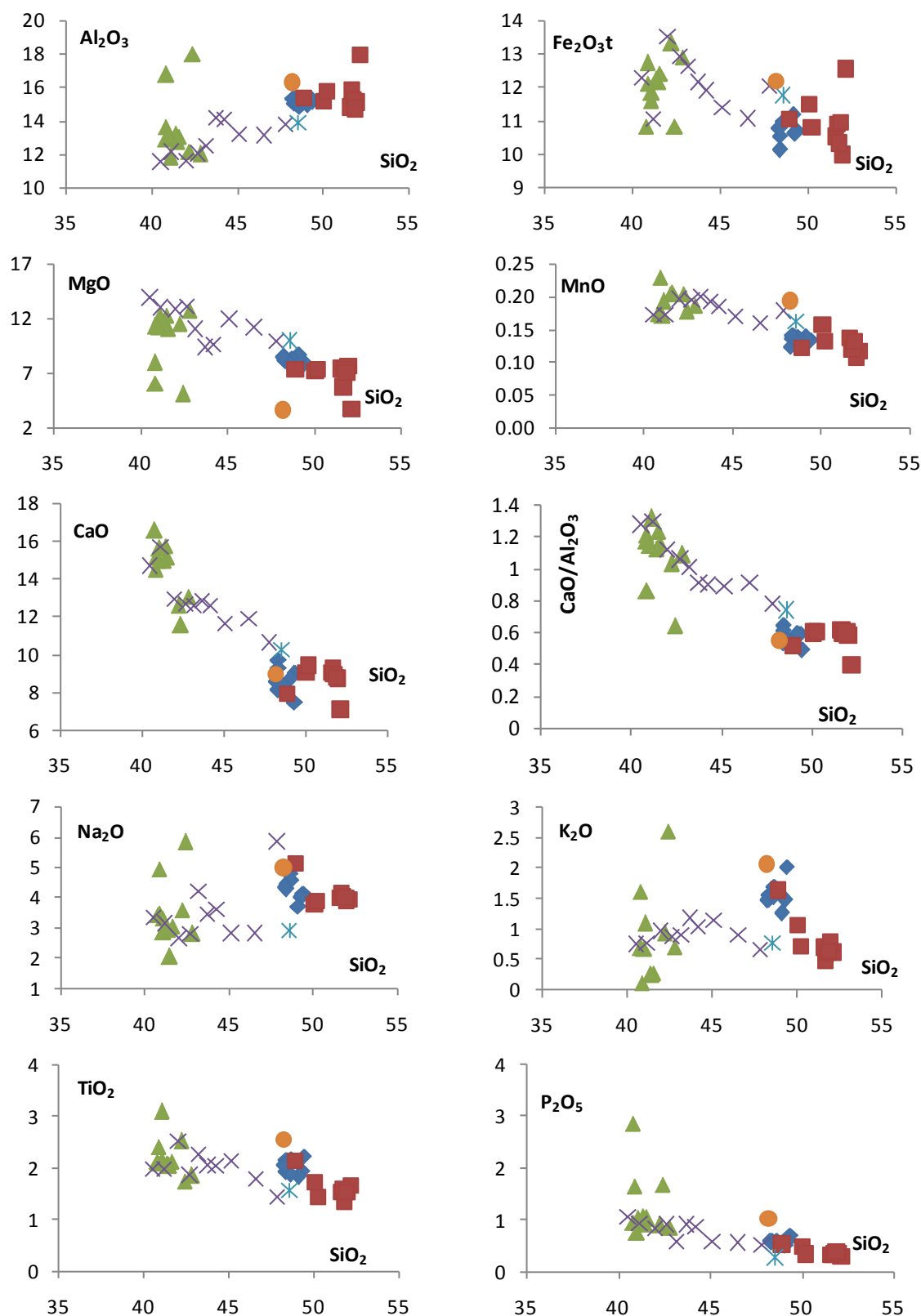


Figure 5. Plots of SiO_2 vs oxides for the Cenozoic volcanic rocks: diamond (Quaternary basanites), square (Quaternary dolerite), triangle (Tertiary nephelinites), cross (Tertiary basanites), asterisk (Tertiary dolerites), round (Tertiary gabbro).

The thorium considered as a strongly hygromagmaphile element shows a positive correlation with the incompatible elements and a negative correlation with the compatible elements (Figure 6). Compatible elements exhibit small variations in the Quaternary rocks whereas the values observed in the Tertiary rocks are notably different according to thorium contents.

The distribution of the rare-earth elements (REE) is typical of alkaline lavas, with generally strong light-REE

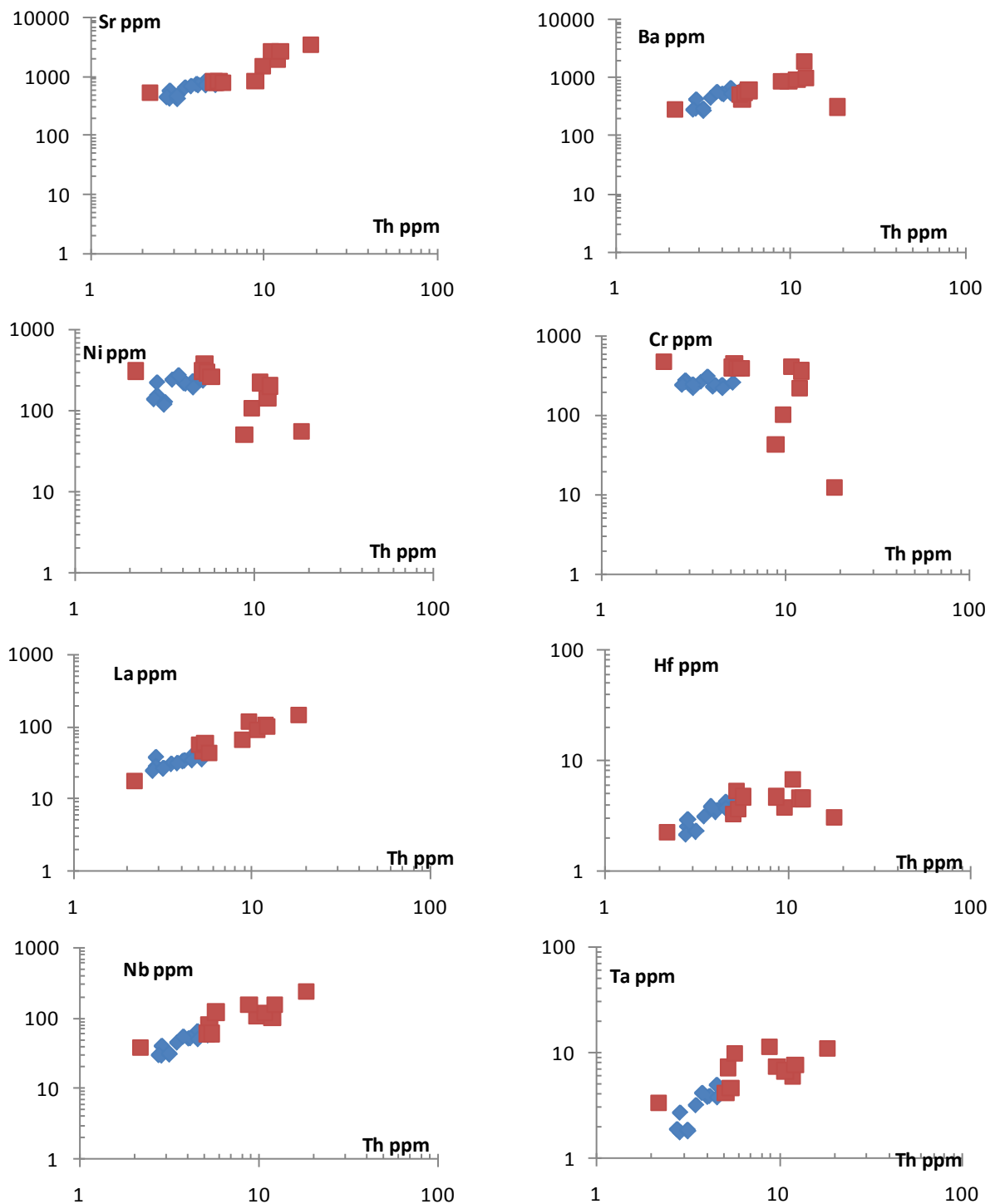


Figure 6. Selected compatible and incompatible elements as function of thorium concentrations of Cenozoic volcanic rocks: diamond (Quaternary rocks), square (Tertiary rocks).

(LREE) enrichments defining regularly sloping patterns without significant Eu-anomaly (**Figure 7**). Tertiary lavas are the most enriched with high values of La_N (120 - 320) and large variations of La/Yb (28 - 60), whereas the Quaternary spectra are much less enriched and more homogeneous with $La_N < 100$ and La/Yb varying from 20 to 27.

The good correlations formerly observed between thorium and trace elements and the parallelism of the representative REE patterns suggest in first approximation a common magmatic source. The Y/N ratios (0.17 - 0.78) and $(La/Yb)_N$ values (8.63 - 34.98) are closed to those alkali basalts where $Y/Nb < 1$ and $(La/Yb)_N > 12$.

The spider-diagrams (**Figure 8**) show a continuous enrichment from Yb to Nb followed by a sharp (in Tertiary lavas) or moderate (in Quaternary lavas) decrease of K and Rb to normalized concentrations. The characters as the Nb culminating patterns, the negative K-anomaly and the LILE enrichment, with low La/Nb , Rb/Nb , K/Nb , Th/Nb , Zr/Nb and Ba/La ratios make them similar to oceanic islands basalts, particularly HIMU-type oceanic basalts [26].

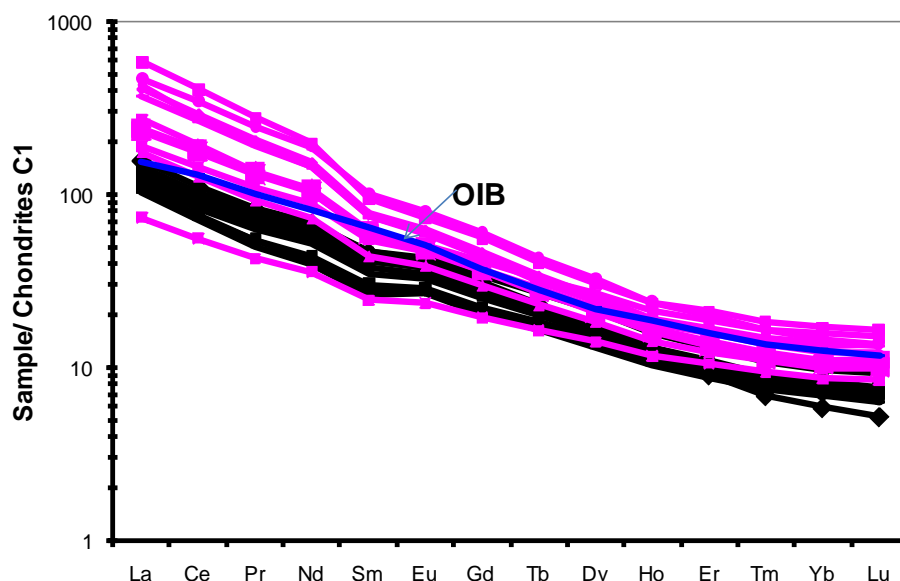


Figure 7. Chondrite-normalized REE patterns of the Cenozoic volcanic rocks: pink (Tertiary rocks), black (Quaternary rocks). Normalizing C1 and OIB (oceanic islands basalts) values from [32].

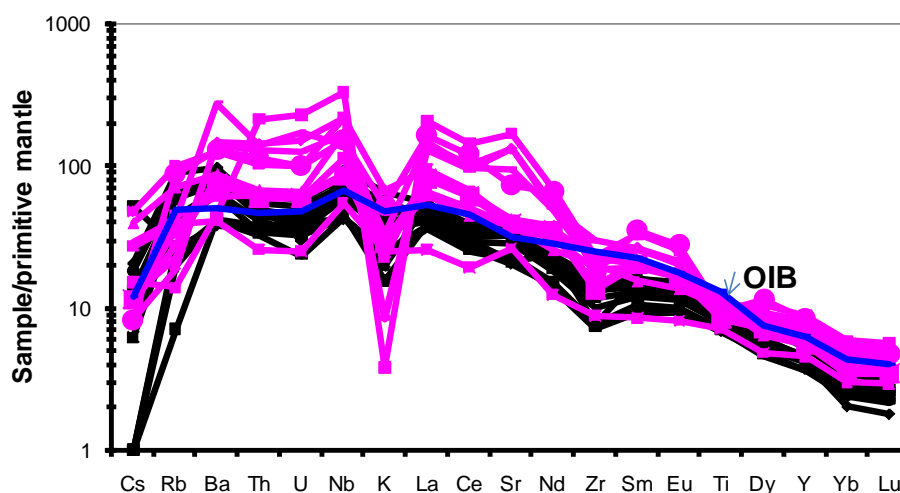


Figure 8. Primitive mantle-normalized trace elements abundance of the Cenozoic volcanic rocks: pink (Tertiary rocks), black (Quaternary rocks). Normalizing primitive mantle and OIB (oceanic islands basalts) values from [32].

The enriched character of the Tertiary rocks compared to the Quaternary rocks could be explained by a sub-continental enriched mantle source or an interaction of metasomatic fluids with the magmatic source just before the melting. The prophyritic (or pegmatitoids) nephelinites which are significantly more enriched than other Tertiary and Quaternary lavas, contained apatite, amphibole, biotite and calcite interpreted as an early interaction of magma with fluid phases rich in H_2O and CO_2 ([19] [27] [28]). The hypothesis of a metasomatized source could be explained by the enrichment of K, Rb, Ba, Sr, LREE and HFSE which are highly soluble in aqueous solutions according to [29]-[31]. Moreover the low values of Hf/Sm ratios in Tertiary (0.21 to 0.63) and Quaternary (0.36 to 0.61) lavas compared to those of primitive mantle (0.695) of [32] are in accordance with metasomatic fluids rich in carbonates [33] [34]. These results are in agreement with the detailed studies on mantle xenoliths and lavas of the Cenozoic Cape Verde archipelagos volcanism which have shown kimberlitic or carbonatitic melts at the origin of metasomatic fluids [35] [36].

4.4. The Isotopic Results

The Nd and Sr isotopes [6], (unpubl. data) of nine samples from the Tertiary and Quaternary volcanism cover the total duration of the volcanic activity and are representative of the groups previously defined (Table 3).

All the Tertiary lavas are characterized by low radiogenic Sr values (0.703064 - 0.703254) and positive ϵNd (+5.07 to +6.5) excepted prophyritic (or pegmatitoids) nephelinites which are more radiogenic Sr (0.704105 - 0.704652) for comparable ϵNd values (+4.92 to +5.56). Moreover, the Quaternary lavas are slightly less Sr radiogenic (0.70299 to 0.70302) with positive ϵNd (+5.48 to +5.79). The quaternary rock DK 10 differs from others, with more radiogenic Sr (0.70320) and less radiogenic Nd ($\epsilon Nd = +3.26$). This high $^{87}Sr/^{86}Sr$ value could be interpreted as reflecting the effects of alteration which modified the magmatic Sr isotopic signatures.

The weak radiogenic strontium and more radiogenic neodymium with positive ϵNd (+3.26 to +6.5) are intermediary between DMM and HIMU OIB-type suggesting an origin from a mantle less depleted than those of ocean ridges basalts (Figure 9). These results are fairly similar of those obtained in the Cape Verde Archipelagos [38].

Several lines of evidence indicate that the studied volcanic rocks did not suffer from significant crustal contamination. The existence of mantle xenoliths and the lack of differentiated lavas suggest that the magmas were not retained long enough within the crust to be contaminated. A possible contamination by lithospheric crust may be considered to explain the increase of silica contents in Quaternary lavas. According to [39], the average Nb/U values for the MORB and OIBs fixed at 47 ± 10 and any increase in this ratio associated with the decrease of uranium values, could be interpreted as the result of a crustal influence. The latest magmatic manifestations during the Tertiary period (Diack pluton) which outcrop at the eastern parts of the volcanic province have relatively high Nb/U ratios (64 - 88) compared to the Quaternary lavas (63 - 106) which are localized at the western parts of the basin at the front of the Atlantic Ocean. In addition, these rocks from Diack pluton have higher values of Zr/U (119 - 288) and Nb/Th (11 - 21) than the other rocks which show no crustal contamination as evidenced by their low Nb/U (45 - 51), Zr/U (53 - 95) and Nb/Th (11 - 12) values (Figures 10(a)-(c)).

5. Discussions and Conclusions

The Cenozoic volcanism of the Cap-Vert peninsula is marked by a magmatic activity spread over 35 Ma, from Late Eocene up to Middle Pleistocene. It belongs to the last magmatic episode known in the western and the northwestern parts of the West Africa during the Permian up to the Quaternary. It is characterized by different periods of activities where no age progression is related to the geographic localization of outcrops as it is shown on the map (cf. Figure 3(a)). This volcanism is moderately to strongly alkaline with sodic affinity and weakly differentiated during his activity. The lack of any evolved products could be explained by a short time residence in the magmatic chamber. However, the Quaternary lavas are more sodic, less alkaline and relatively more differentiated in comparison to the Tertiary one.

The Cap-Vert peninsula volcanism is previously interpreted as an intra-plate volcanism associated with the migration of hot spot activities [9] [10]. On the basis of K-Ar ages data, the Cap-Vert peninsula volcanism is contemporary to the Cape Verde and Canary archipelagos volcanism by their ages of their manifestations and their geodynamic significance [6].

In fact, the evolution of the Cap-Vert peninsula volcanism is characterized by different periods of magmatic activities (Table 3). The early ages of this manifestation are recorded around the Middle Eocene specifically

Table 3. K-Ar ages of the Cap-Vert peninsula volcanic rocks and comparison with Cape Verde (CVA) [38] [41]-[43] and Canary (CANA) [44] [45] archipelagoes duration of volcanism. Samples with asterisk (*) are from the PASMI (unpublished report 2009) and the others from [6].

Ech.	Localization	Petrography	Age (Ma)	Erreur		CVA	CANA
Quaternary							
ME	Mermoz, flow	hawaiiite	0.57	±0.04	Pleistocene		
FA	Fort A, drilling	hawaiiite	0.75	±0.23			
MA	Mamelles, cone sheet	hawaiiite dol.	1.05	±0.2			
AL1	Almadies, flow	hawaiiite dol.	1.1	±0.06			
AL2	Almadies, flow	hawaiiite	1.1	±0.05			
OU1	Ouakam, tuf	hawaiiite	1	±0.1			
OU2	Ouakam, flow	hawaiiite dol.	1.4	±0.2			
PK1	Point K flow	hawaiiite dol.	1.5	±0.1			
DK2003*	Nord Mamelles, flow	basalt	0.593	±0.014			
Tertiary							
IM1	Iles Madeleines, flow	basanite	5.3	±0.3	Tortonian		
IM2	Iles Madeleines, flow	basanite	6.9	±0.2			
DK2025*	Iles Madeleines, flow	basalte	7.29	±0.15			
PF	Pointe Fann, flow	basanite	7.9	±0.4			
CM1	Cap Manuel West, flow	basanite	7.65	±0.4			
CM2	Cap Manuel East, flow	nephelinite	8.5	±0.4			
DK2019*	Cap Manuel, flow	basalt	6.44	±0.14			
DI1	Diack, lava lake	basanite	7.8	±0.5			
DI2	Diack, lava lake	basanite	10.3	±0.6	Serravallian		
M	Keur Mamour, intrusion	nephelinite	11.75	±0.35			
LL	Lam-Lam, sill	basanite	12	±1.5			
KH	Khazabe, intrusion	basanite	12.9	±0.3			
SS	Sen sérère, flow	basanite	13	±0.5			
DK2051*	Cap des Biches	basalt	14.46	±0.31			
RV	Rav. voleurs, intrusion	basanite	13.3	±0.6			
GO	Ile de Gorée, flow	basanite	13.5	±0.4			
DK2042*	Ile de Gorée, flow	basalt	13.03	±0.28	Aquitanian		
TH	Thièo 2, intrusion	nephelinite	14.5	±0.5			
CB	Cap des Biches, sill	basanite	20.9	±0.6			
DK2060*	Cap des Biches	basalt	23.74	±0.5	Oligocene		
RU	Rufisque, flow	nephelinite	21.5	±2			
AM	Anse Madeleines, sill	nephelinite	30.7	±2			
BA	Bandia, intrusion	nephelinite	35.5	±1.5	Mid-Eocene		
Plancktonic foraminifera study give ages between 48 and 45 Ma for the start of the Cap-Vert peninsula volcanism [40]							

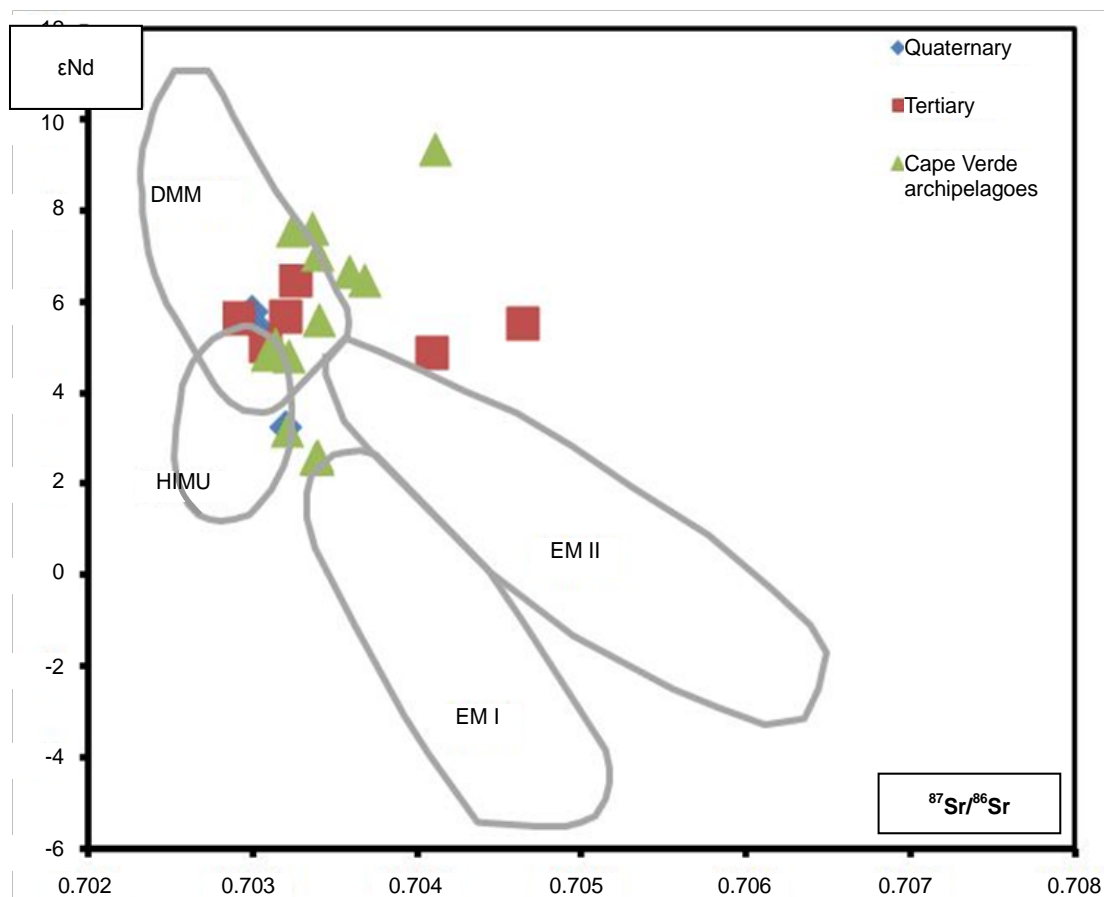


Figure 9. Distribution of Tertiary (III) and Quaternary (IV) volcanic rocks in the $^{87}\text{Sr}/^{86}\text{Sr}$ vs ϵNd diagram (datas of Cape Verde archipelagoes from [38]). The DMM, HIMU, EM I and EMII domains are defined by [37].

between 48 and 45 Ma by [40]. The first manifestation of this volcanism occurred during Oligocene (35 to 20 Ma) and is marked by magmatic intrusions in the Paleocene limestones. The peak of this volcanism is recorded during the Miocene (14 to 5 Ma). It is widely spread in Dakar and the eastern parts of the peninsula, up to Thiès area. The last manifestation is dated during the Pleistocene (1.4 to 0.5 Ma) and is only localized in the Head of Cap-Vert peninsula known as the Mamelles volcano.

The ages recorded in the Cape Verde and Canary Archipelagoes volcanism are relatively more recent in comparison to those observed in the Cap-Vert peninsula. In the Cape Verde Archipelago, the first events of the Cenozoic volcanism are dated around 25.6 Ma in the Old Eruptive Complex of Sal Island [38] [41]-[43]; the paroxysm of his activity was reached during the Miocene (16.3 and 5.6 Ma) and continued during the Quaternary age (1.06 to 0.6 Ma). In the Canary Archipelago, the first manifestations are recorded around 20 Ma in Lanzarote and Fuerteventura Islands; this activity continued in Gran Canaria, Tenerife and La Gomera Islands between 15 to 8 Ma and lately in Palma and Hierro Islands [44] [45].

In the Senegalo-Mauritanian basin, an early plutonicalkaline phase took place in the early Maastrichtian. Then the Cenozoic volcanism began in the Cap-Vert peninsula at the limit Eocene-Oligocene and continued up to 0.6 Ma, while it was still active in Cape Verde (Fogo Island) and Canary Islands (Tenerife and La Palma).

This Cenozoic volcanism is connected to the uplift of lithospheric blocks in response to the Alpine tectonic events occurring in the northwestern Africa. In the Cape Verde and most of the Canary Archipelagoes, the volcanism was at first submarine and becoming subaerial later while in the Cap-Vert peninsula and possibly the easternmost Canary Islands, the volcanism sets on a transitional crust [4] [46] [47].

In fact, in all these three provinces, the Cenozoic magmatism is strongly alkaline and mainly undersaturated, with olivine nephelinites and olivine-melilite nephelinites being fairly common. However, the volcanic series of

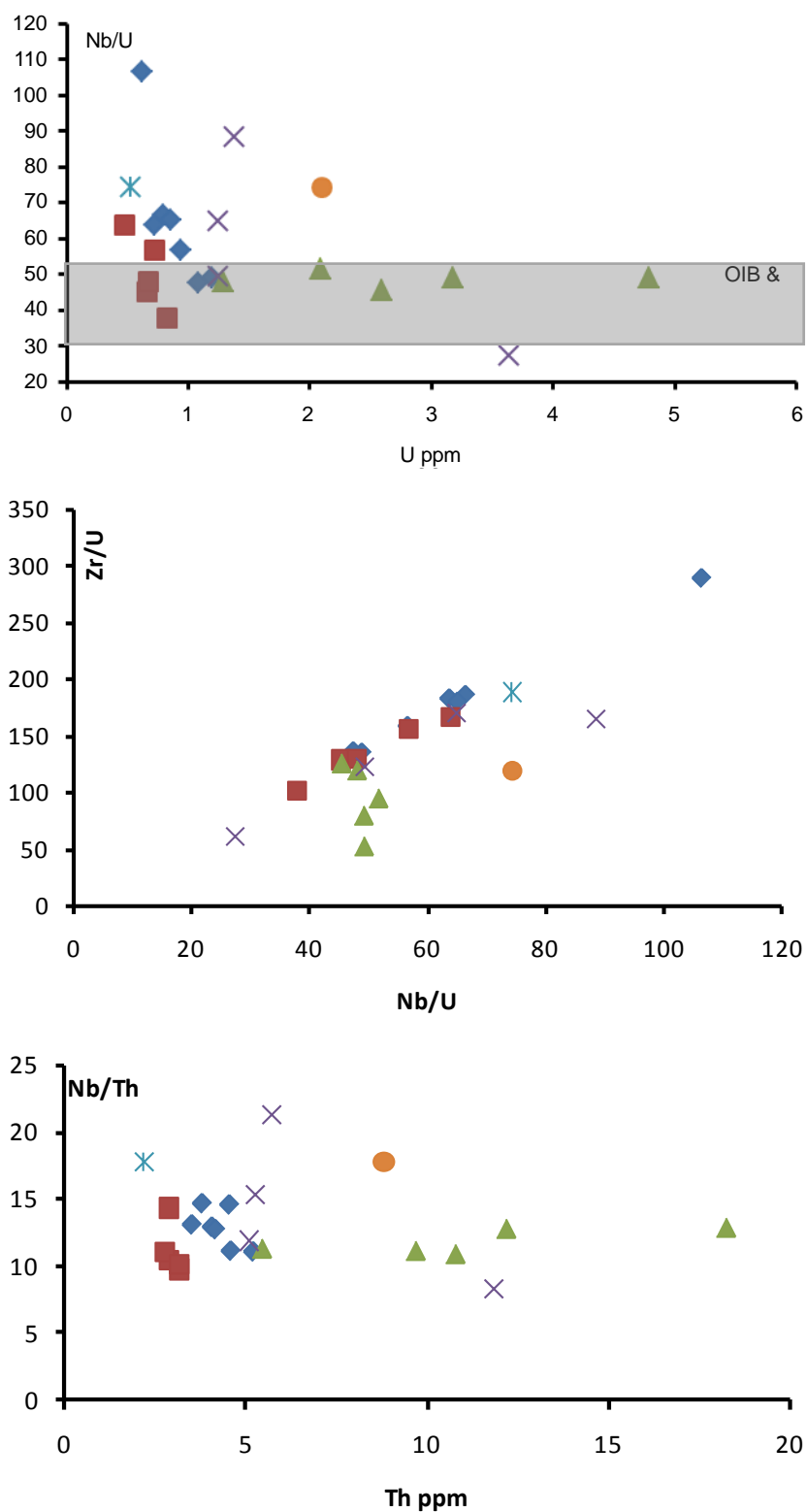


Figure 10. (a), (b), (c)—Incompatible elements ratios evolutions in the Cenozoic volcanism of Cap Vert peninsula: diamond (Quaternary basanites), square (Quaternary dolerite), triangle (Tertiary nephelinites), cross (Tertiary basanites), asterisk (Tertiary dolerites), round (Tertiary gabbro). The shaded portion corresponds to the Nb/U ratios values 47 ± 10 of OIB and MORB values [39].

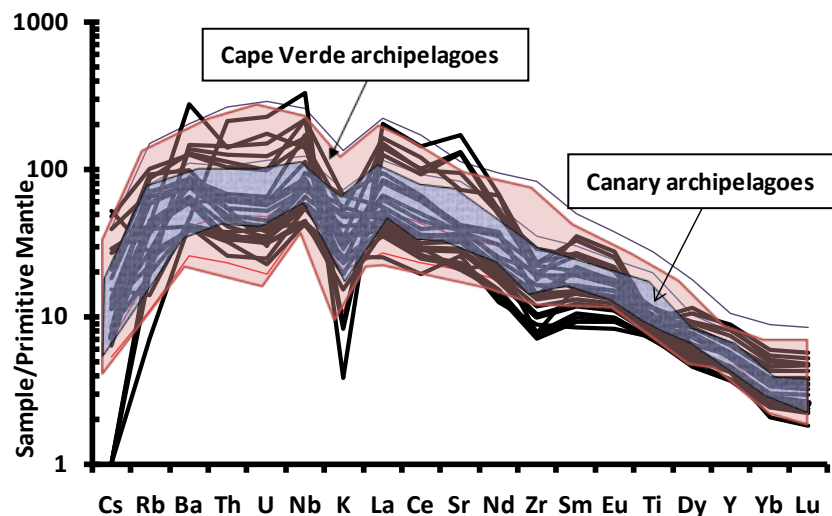


Figure 11. Comparisons of incompatible trace elements concentrations of mafic lavas from the Cape Verde archipelagoes (pink field defined by $n = 26$, $5 < \text{MgO} > 10\%$, [43]. and Canary archipelagoes (blue field defined by $n = 25$, $\text{MgO} > 8\%$, [48]. with the Cap Vert peninsula (present study) normalized to the primitive mantle compositions [32].

the Cap-Vert peninsula remain less differentiated in comparison to the Cape Verde and Canary archipelagoes ones, where mildly alkaline to transitional series are reported [38] [43]. In spite of these differences, they exhibit similar geochemical characteristics as it is shown by the variations of trace elements (Figure 11). Dy/Yb (2.45 - 4.24) and Zr/Hf (33 - 48) ratios are close enough to those obtained in Canary Island (2.8 - 3.6 and 24 - 39) [44] [48] and in Cape Verde archipelago (2.3 - 4.06 and 35 - 69) [41]. Furthermore radiogenic isotopic compositions are characterized by low $^{87}\text{Sr}/^{86}\text{Sr}$ values and high $^{143}\text{Nd}/^{144}\text{Nd}$, suggesting that all these Cenozoic volcanic provinces share fairly a common sub-lithospheric mantle source.

The heterogeneity of the Cenozoic volcanism source in the Cape Verde and the Canary Archipelagoes is widely discussed [38] [43] [48]. In the Cape Verde archipelagoes, this heterogeneity is marked by the contribution of HIMU and DMM component in the magmatic sources of the Northern Islands as it is shown by their high $^{143}\text{Nd}/^{144}\text{Nd}$ values comparable of those observed in Cap-Vert peninsula volcanism, whereas the EM1 component is restricted to the Southern Islands (CVS) sources where the $^{143}\text{Nd}/^{144}\text{Nd}$ values are lower.

The sources of this volcanism are related to the sub-lithospheric plume channeling processes which are beginning at the Triassic-Jurassic stage in the realm of the future central Atlantic Ocean. This process has continued throughout the Cenozoic stage leading to alkaline magmatism along a north-northeast trend with decreasing ages from the Cape Verde archipelago up to Europe [49]. Such a model could explain the early manifestations of this volcanism in the Cap-Vert peninsula as compared to Cape Verde and Canary Archipelagoes.

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