# Geochemical and Petrological Aspects of Karthala Volcano

# 23

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## Abstract

The eruptive activity at Karthala consists of hypersthene-normative and mildly-alkalic basalts and some hawaiites, with MgO contents varying from approximately 4 % to more than 20 % for oceanites and ankaramites. Most of La Grille volcano's products are basanites and olivine nephelinites, often with a significant proportion of olivine. Although these rocks are silica under-saturated, modally they rarely contain crystals of feldspathoïds. Olivine and augite are the dominant phenocrysts in the Karthala and La Grille lavas (more than 40 % vol. in oceanites and ankaramites). Plagioclase is also present in some phenocryst-rich samples, mainly from the oldest units of the "Karthala ancien" and "M'Badjini" massifs. Plagioclase also occurs in some recent aphyric lavas of the summit caldera. The consistent variations in the Karthala lava compositions observed for both major and trace element contents are in agreement with crystal fractionation or accumulation. Conversely, La Grille lavas do not follow clear fractionation trends. Large variations in incompatible trace elements for a given MgO %, negative correlation between incompatible trace elements and $SiO_2$, and K depletion are symptomatic of magma generation driven by variable degrees of partial melting of a source containing residual amphibole (and/or phlogopite). Mantle-normalized trace elements patterns for Karthala lavas show a pattern typical of Oceanic Island Basalts generated from a mantle source containing garnet and amphibole. The

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Comoros plume represents a “low $^3He/^4He$” hotspot dominated by recycled $^4He$-rich material. Grande Comore Island is located on the ~140 Ma-old oceanic crust of the Somali Basin. All Grande Comore melts represent mixtures between plume-derived and peridotitic lithosphere-derived melts. The compositional variability of alkali basalts from Karthala is consistent with the mixing of plume—and lithosphere-derived melts, with a higher contribution of an EM1 mantle source in the “Karthala actuel” and “Karthala recent” lavas. The “Karthala ancien” and “M’Badjini” units require a source containing a predominantly HIMU component, some enriched EM1, and smaller amounts of a depleted DM component. La Grille lavas more likely reflect a source containing a significant involvement of a DM component, in addition to a HIMU component, and a lower degree of melting.

## 23.1 Introduction

Karthala volcano is the active volcano on Grande Comore, the youngest of the Comoro Islands. The Comoros archipelago is situated at the northern entrance of the Mozambique Channel, between 10°21′ and 13°03′ south and 43°15′ and 45°20′ east. It comprises four volcanic islands (Grande Comore [Ngazidga], Anjouan [Ndzuani], Moheli [Mwali], and Mayotte [Maore]) distributed along a 300 km-long WNW trend (see Bachelery et al. 2016, Chap. 22, Fig. 22.1). This chapter proposes a synthesis of the main geochemical and petrological studies of Karthala volcano, as well as some aspects of La Grille volcano, the second volcanic edifice of Grande Comore Island. More general considerations, concerning the whole archipelago, will also be addressed.

The volcanic units referred to here are those proposed by Bachèlery and Coudray (1993). Very few age determinations are available for the Grande Comore volcanoes, and the lava units cannot be distinguished by petrography alone. A relative chronology has been established on the basis of morphological criteria and on the alteration of the lava flows. “Karthala actuel” unit groups together the historical lava flows (since 1850). “Karthala récent” corresponds to unaltered to little altered lava flows of unknown age, while “Karthala ancien” and “M’Badjini” units are the oldest units, strongly altered, mainly outcropping on the eastern and southern flanks of Karthala volcano. M’Badjini may once have been a separate volcano from Karthala volcano (see Bachèlery and Coudray 1993 and Bachèlery et al. 2016, Chap. 22, for more details).

Lavas from the two volcanoes which comprise Grande Comore have distinct petrological and geochemical characteristics, primarily illustrated by the significant difference in alkali/silica ratios between the two alkaline series. The first works on the petrography of the lavas of the Comoros archipelago were by Voeltzkow (1906), Bauer (1911) and Lacroix (1916, 1922, 1938). More than two decades later, petrological aspects were also broached by de Saint Ours (1960), Thomson and Flower (1971), Strong (1972), and Upton et al. (1974). More recently, Bachèlery and Coudray (1993), Desgrolard (1996), Coltorti et al. (1999), and Radadi Ali (2012) have detailed the petrology of the lavas and xenoliths. The origin of the magmas, their source and their evolution were also studied from a geochemical perspective by Nougier et al. (1986), Class (1994), Späth et al. (1996), Class and Goldstein (1997), Claude-Ivanaj et al. (1998), Bourdon et al. (1998), Class et al. (1998, 2005, 2009), Deniel (1998), Debeuf (2004), and Pelleter et al. (2014).

The alkali basalts of Karthala usually contain a significant proportion of olivine and clinopyroxene phenocrysts (more than 10 %). In this

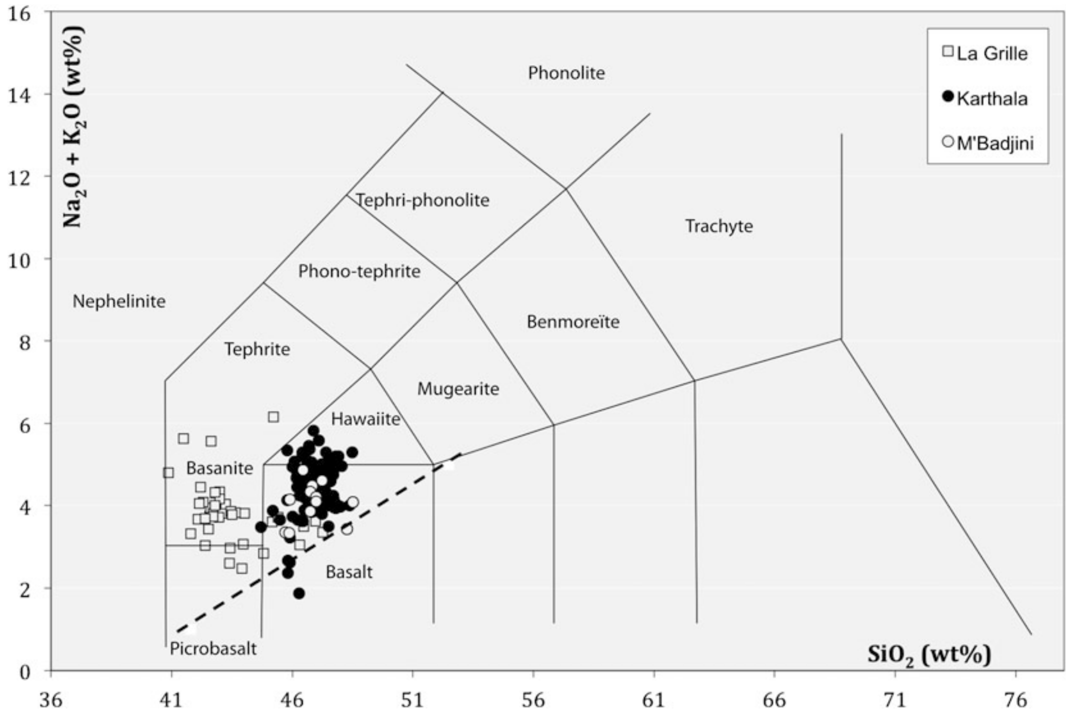

**Fig. 23.1** Total alkalies-silica diagram showing fields of alkaline rock suites from Grande Comore Island. *Fine black lines* delineate the IUGS volcanic rock-type classification redrawn from Le Maitre (1989). *Dashed curve* separates the fields of alkali and subalkali series of Macdonald and Katsura (1964) for Hawaiian basalts. Note that most primitive basic compositions of Grande Comore lavas are either alkaline (Ne-normative) or subalkaline (Hy-normative). Data from Bachèlery and Coudray (1993), Späth et al. (1996), Desgrolard (1996), Class et al. (1998), Deniel (1998)

chapter, we used the rock names recommended by the IUGS (Le Maitre 1989) based on the total alkali/silica diagram for lavas, and on the modal composition of granular rocks. However, as for the Piton de la Fournaise volcano (Boivin and Bachèlery 2009), we choose to use the term oceanite, instead of picritic basalt or picrite, to refer to basalts enriched in MgO by mechanical accumulation of olivine crystals (as opposed to primitive liquids rich in MgO). The term oceanite (Lacroix 1912, 1923) defines a melanocratic variety of picritic basalt made up of numerous large crystals (>20 %) of olivine and a lesser proportion of clinopyroxene, in a matrix enclosing microscopic crystals of augite, olivine, oxides and plagioclase.

Olivine-rich basalts (oceanites) and ol+cpx-rich basalts are characterised by more than 20 % vol. of olivine and/or clinopyroxene phenocrysts. In the Karthala series, most of the historical lavas are alkali basalts with a mean MgO content of about 4–8 %. Olivine-rich basalts (oceanites) and ol+cpx-rich basalts are characterised by higher MgO contents (>8–22 %). Some samples plot in the trachy-basalt field (hawaiite) of the TAS diagram (Fig. 23.1).

## 23.2 Petrography

### 23.2.1 General Aspects

In all the petro-geochemical studies, the moderately alkaline to transitional character of Karthala's magmas, first mentioned by Strong (1972), is highlighted. The Karthala lavas are mainly compose of alkali basalts. They are saturated to slightly undersaturated basalts, picrobasalts and hawaiites (4 wt% normative Ne on average, with rare Hy-normative lavas). The La Grille lavas, the other volcano of Grande Comore Island, are significantly more alkaline and more strongly undersaturated (13 wt% normative Ne on average and 2 wt% normative Lc) than those of Karthala, mainly ranging from basanite to olivine nephelinites. Alkali olivine basalts are rare.

Looking at the entire Comoros archipelago, compositions show a wider range of variations. Several magmatic series can be defined, from strongly silica-undersaturated alkaline magmas known on Mayotte Island (Pelleter et al. 2014), to the transitional magmas already mentioned for Karthala volcano (see Fig. 23.4).

### 23.2.2 Karthala Rock-Types

Depending on the percentage of phenocrysts and on the respective proportions of pyroxene, olivine and plagioclase, several facies have been identified (Bachèlery and Coudray 1993). Olivine, clinopyroxene and plagioclase are generally euhedral to subhedral (polyhedral or skeletal crystals), but rounded and fractured olivine xenocrysts, sometimes with kink bands, can be present in the most porphyric lavas, showing signs of non-equilibrium with the host melt.

Karthala lavas are aphyric basalts, olivine basalts (± clinopyroxene), olivine-rich basalts (oceanites), pyroxene-rich basalts (ankaramites) and plagioclase-phyric basalts. All these mineral parageneses reflect the complexity of the differentiation process involved.

***Alkali aphyric basalts* and *alkali porphyric basalts*** are the most common rock-types at Karthala volcano. The aphyric basalts (less than 5 % mafic phenocrysts—Fig. 23.2a) contain occasional phenocrysts (mm in size) and/or micro-phenocrysts of clinopyroxene and olivine. The olivine basalts, olivine-augite basalts, and augite-olivine basalts are more porphyric (5–15 % mafic phenocrysts—Fig. 23.2b). They contain olivine and/or clinopyroxene phenocrysts, accompanied rarely by small amounts of plagioclase. Clinopyroxene and olivine are the most common phenocryst phases in the porphyric basalts. These crystals are usually euhedral, with minor signs of resorption or skeletal characteristics. Euhedral prisms of augite (mm to cm in size) are common, sometimes in aggregates with olivine or plagioclase. Plagioclase is observed rarely as micro-phenocrysts in the more differentiated compositions. Such compositions are rare among the lava flows of "Karthala actuel" and "Karthala recent", but they can be also found among the historical lava flows (e.g. hawaiite of 1965 in the *Choungou Chahalé* caldera). Plagioclase commonly exists as small microcrysts in the matrix with augite, olivine and Fe–Ti oxides.

***Oceanites*** (***olivine-rich basalts***—Fig. 23.2c) correspond to magmas with a high proportion of large (>1 mm) mafic (olivine + clinopyroxene) crystals (>15 %, with olivine dominant over augite), and a matrix enclosing microscopic crystals of augite, olivine, oxides and plagioclase. Variations in the crystal content of oceanites are due to different degrees of crystal settling or incorporation of olivine and/or augite antecrysts or xenocrysts in a rising basaltic magma. In the TAS diagram, oceanites plot in the "picrobasalt" field ($SiO_2$ <47 %, MgO >18 %, total alkali <2 %), but they do not correspond to true Mg-rich liquids. While olivine is predominant in the olivine-rich basalts, clinopyroxene commonly occurs with the olivine. Only a few samples, mainly from the M'Badjini massif, contain olivine phenocrysts alone. Some samples contain rare small plagioclase phenocrysts.

***Ankaramites*** (***pyroxene-rich basalts***—Fig. 23.2d) are less frequent than oceanites. These melanocratic porphyric rocks (>15 % of mafic megacrysts) have a higher proportion of clinopyroxene than olivine. They contain pyroxene crystals of more than 1 cm in size.

Oceanites and ankaramites can be found among the lava flows derived from eruptive fissures and scoria cones at low altitude along the rift zones, and more commonly from adventive cones scattered on the western slopes of the volcano (e.g. lava flow from the Singani eruption, 1977). They are uncommon at the top of the

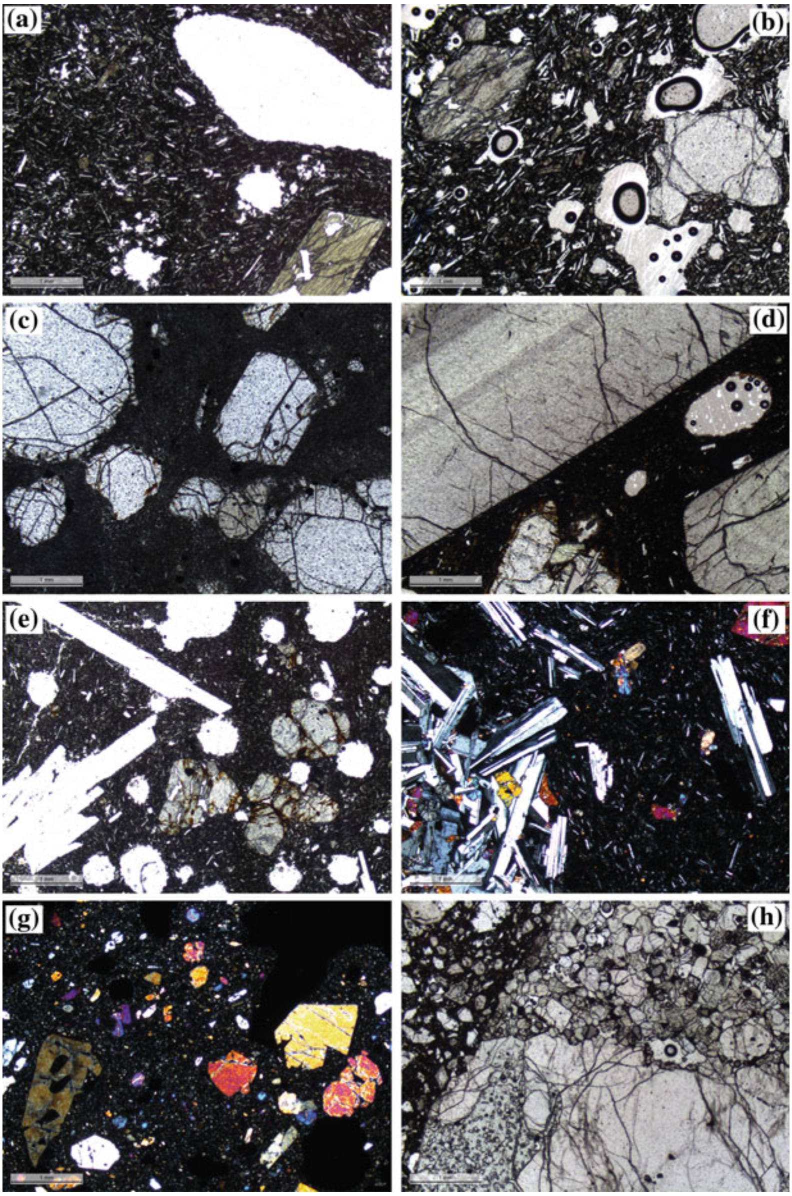

**Fig. 23.2** Sequence of photomicrographs in plane-polarized light (a, b, c, d, e, and h) and cross-polarized light (f and g) showing typical rock samples from the Grande Comore magmatic series. **a** Aphyric basalt from the 1972 eruption of Karthala volcano. Few clinopyroxene phenocrysts are present. **b** Porphyric basalt from the 1977 eruption of Karthala volcano. Olivine and clinopyroxene appear as sub-euhedral phenocrysts. **c** Oceanite from the NW edge of the summit caldera of Karthala. **d** Ankaramite with large clinopyroxene phenocrysts and smaller olivine crystals; "M'Badjini" massif. Note the zonation in the clinopyroxene crystal. **e** Plagioclase-phyric basalt from the "Karthala ancien" unit—Edge of the old caldera of Karthala, alt. 1871 m. Olivine crystals and rare clinopyroxene crystals occur with the large plagioclase laths. **f** Plagioclase-phyric basalt from the "Karthala ancien" unit, ravine N'Gnachentje, east flank of Karthala. The lava encloses a gabbroic xenolith. **g** Basanite from the recent lava flow of Chioundi cone, NE of La Grille volcano. **h** Basanite enclosing a peridotite xenolith. Olivine and clinopyroxene crystals are disseminated in the groundmass of the basanite. In the peridotite, there are large crystals of olivine (and orthopyroxene) adjacent to a mosaic of smaller crystals of olivine and clinopyroxene. Lava flow by Choua-Chandroude Island, La Grille volcano

volcano, but not completely absent. They are also present among the "Karthala ancien" and "M'Badjini" units. The distinction between oceanites and ankaramites is in the relative proportions of olivine and clinopyroxene they contain, although there is a continuum in composition between these two groups of melanocratic lavas. They have incorporated varying amounts of olivine and clinopyroxene crystals during their storage or during their transfer to the surface. Their composition reflects this mixing between an "aphyric basalt" end-member and two "olivine" and "augite" end-members.

***Plagioclase-phyric basalts*** (Fig. 23.2e, f) are only found in the "M'Badjini" and "Karthala ancien" units, at the southern end and eastern flank of Karthala volcano, respectively. Plagioclase is the main mineral phase, frequently associated with clinopyroxene and olivine crystals. Plagioclase crystals are millimeters to centimeters in size. They can occur as squat prisms isolated in the matrix, with many inclusions (mafic minerals and glass), particularly along their edges, but they more commonly form radiating groups in a doleritic texture. Gabbro xenoliths may be present in these plagioclase-rich lavas (Fig. 23.2f).

### 23.2.3 Main Distinctions with La Grille Lavas

Olivine is a ubiquitous mineral in La Grille lavas. Often present in large quantities, the crystals can be euhedral or skeletal, but most are fragmented crystals with signs of resorption resulting from disequilibrium with their host lava (Fig. 23.2g). Olivine is often the only mineral phase present as megacrysts in these lavas; clinopyroxene is rare, and plagioclase never present as phenocrysts. Plagioclase is also often absent from the groundmass, where nepheline may crystallize. These lavas, unlike those of Karthala, often contain xenolithic enclaves of ultramafic rocks (dunites, wehrlites, and lherzolites). The desegregation of these enclaves releases many xenocrysts into the lava (olivine, clinopyroxene, orthopyroxene, and spinel).

Mantle-derived spinel lherzolite and wehrlite xenoliths occur in some La Grille lava flows. Two main sites exist: one near the north coast of the island at Gula Ivoini, the other on the east coast, by N'Droude Island. Coltorti et al. (1999) define three groups on the basis of modal compositions and textures: one group of lherzolites and two groups of wehrlites. Spinel is the only aluminous phase. Textures vary from protogranular to porphyroclastic. In the protogranular lherzolite, olivine and orthopyroxene occur as large crystals (up to 2 mm). Smaller crystals of clinopyroxene and spinel are interstitial or are included within the orthopyroxene. Xenoliths with a porphyroclastic texture are characterized by large crystals of olivine and orthopyroxene, with small neoblasts of olivine and clinopyroxene (Coltorti et al. 1999—Fig. 23.2h).

### 23.2.4 Sandstones and Other Continental Rock Inclusions

Xenoliths of sandstone and other continental rocks have been regularly documented from the Grande Comore lavas. Granite and quartz were first reported by Vienne (1900), and Lacroix (1922) gave detailed descriptions of metamorphic and plutonic rocks found at Anjouan and Mayotte. More recently, Flower and Strong (1969) described sandstone inclusions in the three westernmost islands of the archipelago, and Montaggioni and Nougier (1981) from those of Anjouan. In fact, sandstone xenoliths, as well as crystals of quartz, appear in lavas from all four islands of the archipelago (Debeuf 2004). The most frequent type of sedimentary inclusion in the Comorian lavas is quartzarenite.

The presence of these enclaves was used as an argument in the debate about the nature of the crust underlying the archipelago, suggesting that the Comoros could be underlain by continental crust. According to Nougier et al. (1986), the Comoros are located in the transitional zone between oceanic and continental crust. However, based on the works of Rabinowitz (1983), Coffin et al. (1986), Coffin and Rabinowitz (1987), a consensus exists as to the existence of a Mesozoic oceanic crust (165–130 Ma) in the western Somali Basin. Although sandstone enclaves are common in the Comorian lavas, helium isotope ratios measured on olivine phenocrysts from Grande Comore do not reflect any significant crustal contamination (Class et al. 2005).

## 23.3 Mineral Compositions

As described above, olivine and clinopyroxene are the dominant phenocryst phases in Karthala lavas, and olivine in La Grille lavas. Plagioclase is also present in some phenocryst-rich samples, mainly from the oldest units of the Karthala and "M'Badjini" massifs. Mineral compositions are from the work of Class (1994), Desgrolard (1996), and Radadi Ali (2012).

### 23.3.1 Olivine

Olivine is the main phase in the Karthala lavas. It is always present in the microlites, and is rarely absent as a phenocryst phase. The composition of the olivine crystals ranges from 47 to 88 Fo mol % (Desgrolard 1996). The microlites (<Fo80) are statistically less Mg-rich than the phenocrysts (mostly between Fo83 and Fo87). This abundance of forsterite in olivine phenocrysts is consistent with the low differentiation of the lava.

Olivine phenocrysts are generally equant to tabular and subhedral to euhedral. Most are < 5 mm in the longest dimension, but rare centimeter-sized olivine megacrysts are present in some oceanites. Olivine crystals frequently contain spinel inclusions. They are optically unzoned, except for slight iron enrichment over a few tens of microns near the crystal rims. Kink-banded olivine crystals occur more frequently in the oceanites than in aphyric and olivine basalts.

Electron microprobe analyses show that the cores contain slightly more MgO than the rims. A detailed study of large crystals in the basalts indicates that most are in equilibrium with the host melt (Desgrolard 1996). The composition of the olivine crystal cores ranges from Fo87 to Fo83 (NiO wt% = 0.15–0.35), with no obvious difference between the olivines from olivine-rich basalts and those from aphyric basalts, or those of the rare xenolithic enclaves of ultramafic rocks (dunite, wehrlite). This indicates that these crystals were in equilibrium with primitive or little-evolved liquids.

Olivine-liquid thermometers (Leeman and Scheidegger 1977) applied to some Karthala lavas (Desgrolard 1996) give equilibrium temperatures of between 1190 and 1220 °C and between 1125 and 1172 °C respectively for olivine-rich basalts and aphyric basalts. Similar results were obtained by Radadi Ali (2012).

### 23.3.2 Clinopyroxene

Clinopyroxene is a very common mineral phase in the magmas of the more recent Karthala units. Its frequency is lower in the lavas of "M'Badjini" and "Karthala ancien", and clinopyroxene is rare in those of La Grille. In Karthala lavas, clinopyroxene is always present in the groundmass, and as euhedral phenocrysts in the ankaramites, olivine-rich basalts and aphyric basalts. It frequently appears in olivine basalts. Analyses of clinopyroxene phenocrysts plot in the Mg-rich augite and augite fields of the Enstatite-Ferrosilite-Wollastonite (En-Fs-Wo) diagram, with diopsidic compositions for some phenocryst cores. Compositions are grouped in a small domain around an average composition of En46-Fs9-Wo45. Most of the clinopyroxene crystals display concentric and/or hourglass zoning. The zoning generally corresponds to a decrease in Mg and Cr content and a simultaneous increase in Fe and Ti content from the core to the rim.

The evolution of the Al/Ti and $Al^{VI}/Al^{IV}$ ratios in clinopyroxene are commonly used to determine the pressures of crystallization, with the ratios increasing with increasing

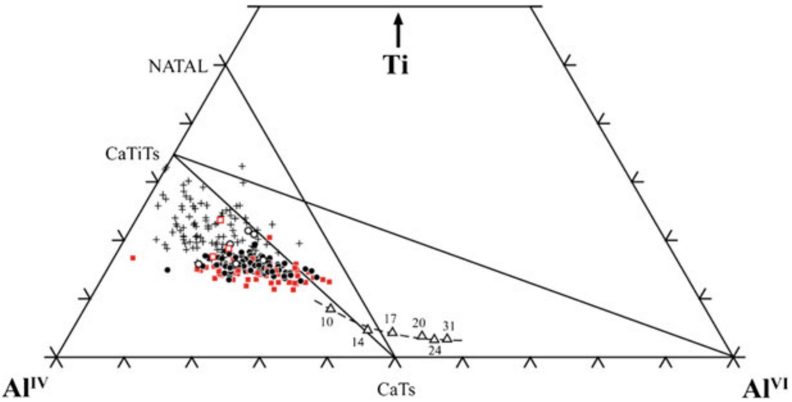

**Fig. 23.3** Evolution of the clinopyroxene type I (*square*) and II (*round*) crystals in the $Al^{IV}$-$Al^{VI}$-Ti diagram. *Solid symbols* and *open symbols* denote crystal cores and rims, respectively. The microlites are also shown with the symbol *plus*. The *triangles* indicate experimental alkaline clinopyroxene compositions for different pressures (in GPa) (in Radadi Ali 2012)

crystallisation pressure. Desgrolard (1996) and Radadi Ali (2012) use these proxies to show that most of the Karthala lava flows derived from a polybaric fractionation process (Fig. 23.3). Radadi Ali (2012) recognizes two types of zonation from a study of clinopyroxenes from the 1977 eruption: (a) normal zonation reflecting a process of fractional crystallization (type I), and (b) oscillatory zonation reflecting more complex changes in the chemical composition of the host melt (type II). Based on measured concentrations of Ti, $Al^{IV}$ and $Al^{VI}$, and experimental data, Desgrolard (1996) determines a crystallization pressure of 8–10 kb for the earliest pyroxenes to shallow level conditions for the majority of the crystals.

From a study of the clinopyroxenes, Späth et al. (1996) suggest that the fractional crystallization processes involved in the differentiation of Comorian lavas were not confined to shallow, sub-volcanic levels, but may have started at depths corresponding to pressures as high as 15 kbar. Such evidence includes the occurrence of complex clinopyroxene crystals with corroded, green cores that are in compositional disequilibrium with their tan-coloured mantles and rims, and have $Al^{VI}/Al^{IV}$ ratios (~0.29–0.55) suggestive of a relatively high-pressure origin. Such crystals have never been described in the Karthala lavas.

### 23.3.3 Plagioclases

While plagioclase microlites appear ubiquitously in the matrix of the Karthala lavas, few lavas contain plagioclase phenocrysts. In the most recent lavas, they appear only as micro-phenocrysts in the most evolved compositions (hawaiites). Plagioclase crystals of a few mm in size are more common in the lava flows from the “Karthala ancien” and “M’Badjini” units.

Plagioclase crystals show no obvious signs of compositional zoning. They occasionally occur in small aggregates, sometimes with augite.

Plagioclase compositions range from An88.8 Ab10.6 Or0.6 to An55.4 Ab41.6 Or2.9 for phenocrysts and micro-phenocrysts. The rims and microlites contain slightly more sodium and potassium (An68.7 Ab29.8 Or1.4 to An49.6 Ab47.5 Or2.9 and An52.3 Ab42.1 Or5.6, respectively). Plagioclase from the “M’Badjini” and “Karthala ancien” lavas are, on the whole, less calcic than those of the “Karthala actuel” and “Karthala recent” units.

### 23.3.4 Oxides

Euhedral chromian spinel commonly occurs as inclusions in olivine, although it is also present as micro-phenocrysts in some of the most mafic samples. These chromian spinels are regarded as having crystallized at elevated temperatures. They may represent a liquidus phase. Their $Cr_2O_3$ composition varies from 49 wt% to 19 wt %. They are characterized by high MgO (between 8 and 12 wt%) and $Al_2O_3$ (between 11 and 16 wt%) contents.

Titanomagnetites are a typical phase of the groundmass with MgO, MnO and $Al_2O_3$ contents up to 3.7, 4.4 and 0.8 wt%, respectively (Radadi Ali 2012). Their composition is rather homogenous, corresponding to Mt8-33 on the magnetite-ulvöspinel line of the $TiO_2$-FeO-$Fe_2O_3$ diagram. Ilmenite is only observed in some gabbros.

## 23.4 Geochemistry

### 23.4.1 Comorian Magmatic Suites

Taking all compositions in the Comoros archipelago into consideration, three trends can be defined on a diagram of total alkali versus silica (Fig. 23.4). Karthala lavas are clearly moderately alkalic, while La Grille lavas are more strongly alkalic and undersaturated. The most silica-undersaturated lavas from the Comoros archipelago correspond to the highly silica-undersaturated trend formed by the lavas of the southern part of Mayotte Island, where basanites, nephelinites, melilitites and phonolites have been recognized, while a moderately silica-undersaturated trend with alkali basalts, basanites, intermediate lavas and phonolites characterise the northern part of the island (Pelleter et al. 2014). Anjouan and Moheli defined intermediate trends from basanites to phonolites, lying between the two trends for Mayotte. Mafic rocks from Mayotte show the widest range of compositions from basalts/basanites and olivine nephelinites to olivine melilitites.

The lavas emitted by the two Grande Comore volcanoes result from a low degree of differentiation, in contrast to lavas on the other islands of the archipelago, where trachytic and phonolitic compositions are present. Only basanites and basic nephelinites are present at La Grille, and Karthala emits mainly alkali basalts and rare hawaiites.

### 23.4.2 Major and Trace Element Variations

La Grille lavas, including the aphyric lavas, are more basic in average bulk composition than Karthala lavas (Strong 1972). Lavas from Karthala show less variation in $SiO_2$ content (45–48.5 wt%) than those from La Grille (from approximately 41–48 wt%). As olivine is a major phase in both Karthala and La Grille lavas, chemical variations can be well illustrated by means of MgO variation diagrams.

Karthala lavas have compositions that are controlled by the crystallisation and accumulation of olivine (+ clinopyroxene), resulting in almost constant major element and compatible and moderately incompatible trace element abundances for a given MgO content. They define linear trends in oxide and trace element versus MgO diagrams (Fig. 23.5), in good agreement with such a fractionation/accumulation evolution process. On most diagrams, a change in slope is observed at 7–8 wt% MgO, possibly indicating a transition between the cumulative (Ol ± Cpx) and non-cumulative lavas.

Conversely, La Grille lavas do not follow clear fractionation trends. Larger variations in incompatible trace elements at a given MgO % and a negative correlation between incompatible trace elements and $SiO_2$ content characterize La Grille lavas. These different behaviours are ascribed to a difference in the composition of the primary magmas of the two neighbouring volcanoes (Strong 1972; Deniel 1998). The variations observed for La Grille lavas suggest that processes other than mineral fractionation/accumulation are predominant in determining the major element variations. Higher MgO content for La Grille lavas is in agreement with the mineralogy of the lavas (high proportion of olivine). Geochemical features of La Grille lavas

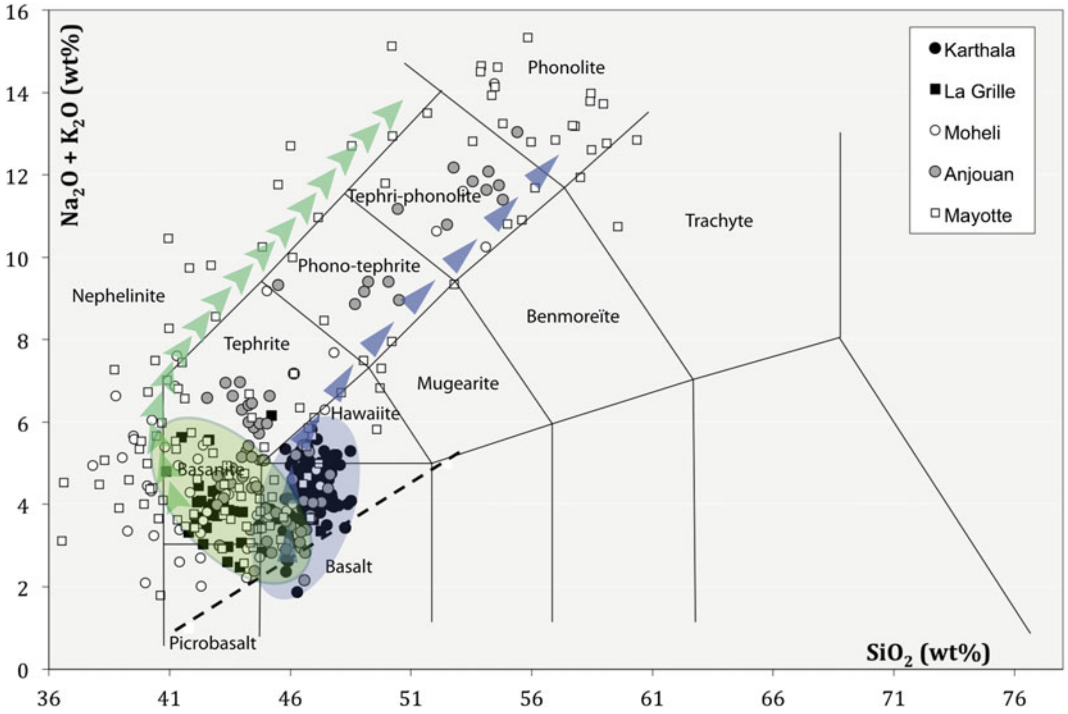

**Fig. 23.4** Total alkalies-silica diagram showing fields of alkaline rock suites from the Comoros Archipelago. *Fine black lines* delineate the IUGS volcanic rock-type classification redrawn from Le Maitre (1989). *Dashed curve* separates the fields of alkali and subalkali series of Macdonald and Katsura (1964) for Hawaiian basalts. Blue and green ovals respectively delineate the compositional fields for Karthala and La Grille volcanoes. *Blue arrows* and *green arrows* respectively show the moderately silica-undersaturated and the highly silica-undersaturated trends for Mayotte lavas. Compositions from Anjouan and Moheli lie between the two Mayotte trends. Data from Strong (1972), Nougier et al. (1986), Bachèlery and Coudray (1993), Späth et al. (1996), Desgrolard (1996), Class et al. (1998), Deniel (1998), Debeuf (2004), Pelleter et al. (2014)

(Mg# of 69–71, Ni content >300 ppm, and Ni/MgO ratios of 25–27) reflect their primitive character (Späth et al. 1996).

As MgO contents are not much higher than 8 % in the non-cumulative Karthala lavas, it seems likely that the Karthala alkali basalts do not represent primitive magmas. The coherent variations in major and compatible trace elements indicate that the evolution of the Karthala suite can be ascribed to low-pressure crystal fractionation/accumulation of olivine and clinopyroxene phases. Lava flows from Karthala volcano show decreasing CaO and transition elements like Ni, Cr, Co, as well as Sc, contents with decreasing MgO content, while $SiO_2$, $Al_2O_3$, $Fe_2O_3$, $Na_2O$, $K_2O$, $TiO_2$, $P_2O_5$ and incompatible trace elements increase. For example, the concomitant decrease of the $CaO/Al_2O_3$ ratio with the decrease in MgO contents is a strong argument for the major removal of Ca-rich pyroxene. This is also well illustrated by the evolution of the composition of Karthala lavas in the $Na_2O$ versus MgO diagram (Fig. 23.6). The good correlation of Sc/Yb with $CaO/Al_2O_3$ (upper right corner of Fig. 23.6) confirms that clinopyroxene fractionation plays a major role in the chemical evolution of these lavas.

Most porphyric lavas have been interpreted as being derived from basalts through olivine and/or clinopyroxene accumulation of antecrysts or xenocrysts, rather than accumulated phenocrysts. These lavas are relatively uncommon in the Comorian volcanic products. Less than 20 % of

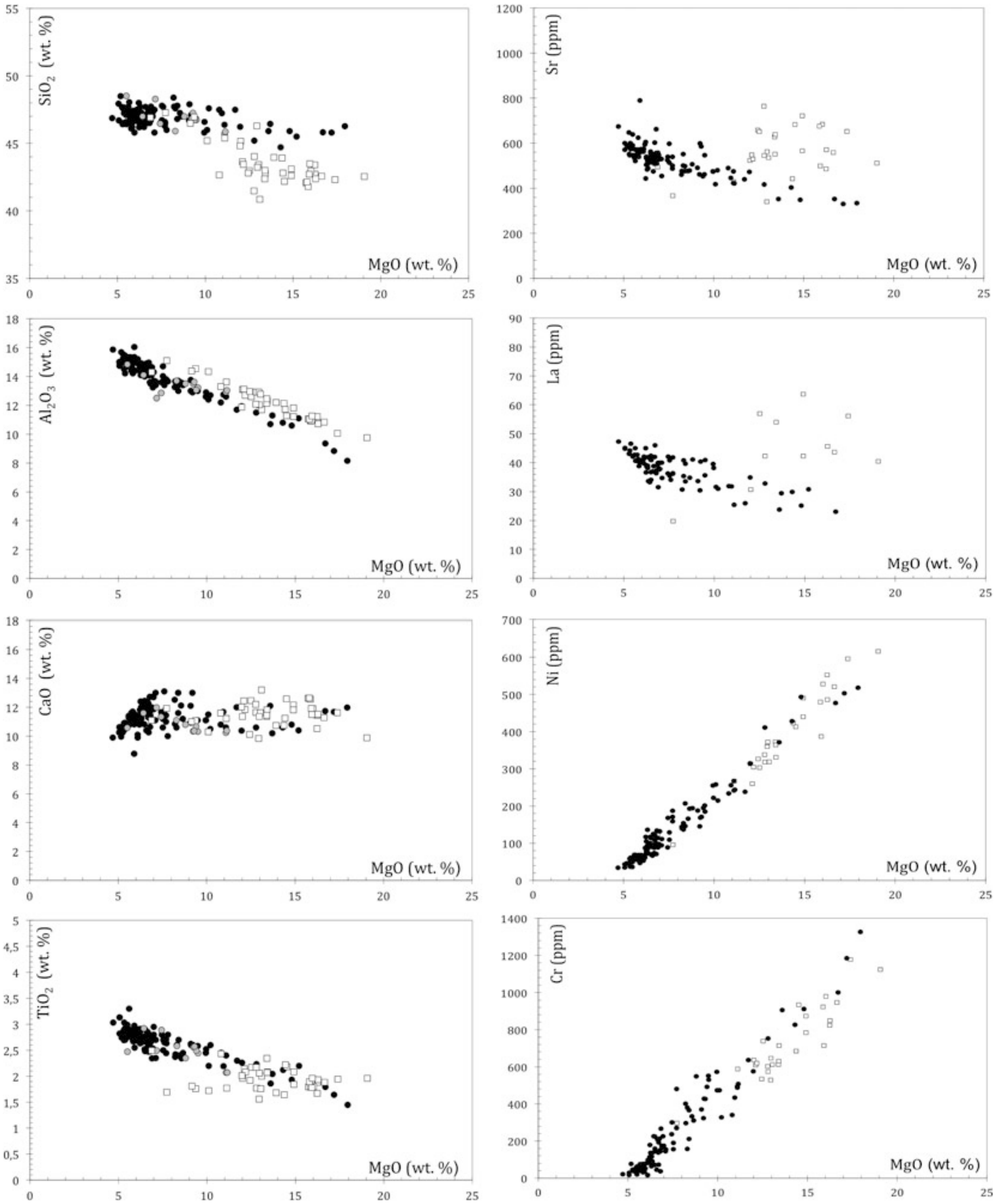

**Fig. 23.5** Major (wt%) and trace (ppm) element versus MgO wt% diagrams for Grande Comore lavas. *Filled circles* Karthala lavas, *open circles* "M'Badjini" lavas, *open squares* La Grille lavas. Data from Bachèlery and Coudray (1993), Späth et al. (1996), Desgrolard (1996), Class et al. (1998), Deniel (1998)

Karthala lavas are highly porphyric (>20 vol. % of megacrystals). They are mainly found among the products issued from the vents at low altitude, and porphyric lavas have erupted only twice during the very short historical record, once in 1872 and the other in 1977.

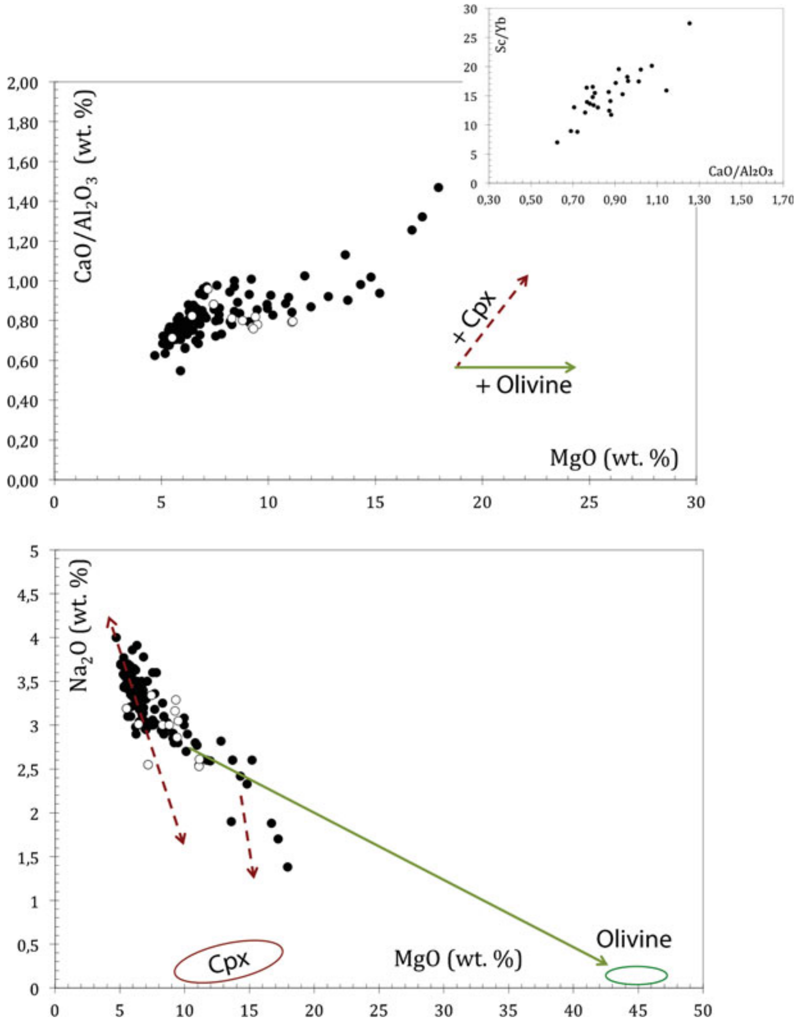

**Fig. 23.6** Clinopyroxene fractionation, and olivine and clinopyroxene accumulation illustrated in CaO/AL$_2$O$_3$ versus MgO (*top*) and Na$_2$O versus MgO (*bottom*) diagrams for Karthala (*closed circles*) and M'Badjini (*open circles*) lavas. Lavas compositions from Bachèlery and Coudray (1993), Class et al. (1998), Deniel (1998), Desgrolard (1996), Späth et al. (1996). Clinopyroxene and olivine compositions from Desgrolard (1996). Plot of the Sc/Yb and CaO/Al$_2$O$_3$ ratios for Karthala lavas (*upper right corner*). Data from Class et al. (1998), Deniel (1998)

### 23.4.3 Mantle Source

It is not possible to evoke the mantle source of Karthala lavas without discussing that of its neighbour, La Grille volcano. Based on trace element and radiogenic isotope compositions (Figs. 23.7 and 23.8), Class and Goldstein (1997), Class et al. (1998), Claude-Ivanaj et al. (1998), and Deniel (1998) show that Grande Comore lavas reflect the interaction of a mantle plume with oceanic lithosphere. La Grille lavas exhibit the most radiogenic $^{143}$Nd/$^{144}$Nd (0.51283–0.51291) and the least radiogenic $^{87}$Sr/$^{86}$Sr (0.70315–0.70336), $^{206}$Pb/$^{204}$Pb (18.98–19.31) and $^{208}$Pb/$^{204}$Pb (38.80–39.15). "Karthala ancien" and "M'Badjini" lavas have the most radiogenic $^{206}$Pb/$^{204}$Pb (19.47–19.86) and intermediate $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd. "Karthala actuel" and "Karthala recent" units exhibit the most radiogenic $^{87}$Sr/$^{86}$Sr (0.70354–0.70396), the least radiogenic $^{143}$Nd/$^{144}$Nd (0.51265–0.51276) and intermediate $^{206}$Pb/$^{204}$Pb (Class et al. 1998; Deniel 1998).

Deniel (1988) proposes that the EM1 and HIMU components are contained within the mantle plume and that the DMM component is located in the oceanic lithosphere. Späth et al. (1996), Class and Goldstein (1997), Class et al. (1998) favour a homogeneous plume with a dominant EM1 signature, and a DMM-HIMU

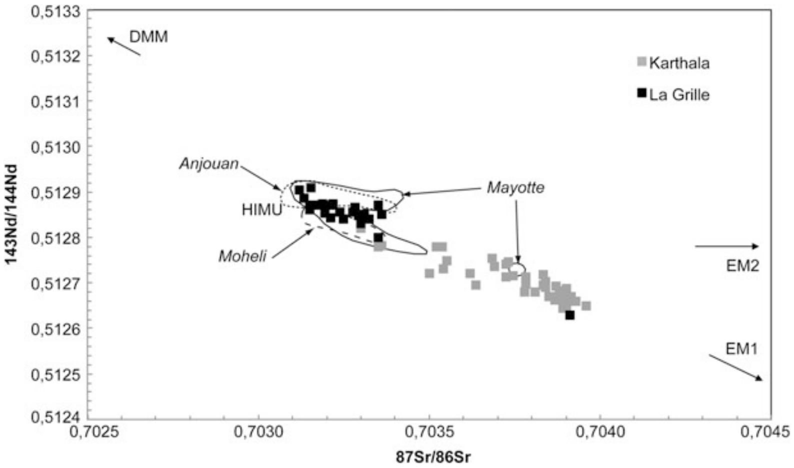

**Fig. 23.7** Sr and Nd isotope variations in lavas from Karthala (*black squares*) and La Grille (*grey squares*) volcanoes in Grande Comore. Composition fields for lavas from Mayotte (*solid lines*), Anjouan (*dotted line*) and Mohéli (*dashed line*) are drawn. Data from Georoc database (http://georoc.mpch-mainz.gwdg.de/georoc/) and Pelleter et al. (2014). The sample from La Grille volcano with a high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratio corresponds to a lava flow emitted at the extension of the north rift zone of Karthala volcano. Karthala lava compositions close to the La Grille field belong to "M'Badjini" and "Karthala ancien" units

oceanic lithosphere. Other geochemical parameters and tracers were used in parallel to depict source composition and melting mechanism of the present activity of the Comoros hotspot. Again using trace elements, radiogenic isotopes and U series, Claude-Ivanaj et al. (1998) suggest that the heterogeneity is due to the lithospheric mantle (DMM-HIMU) whereas the plume is homogenous, as seen in Karthala lavas for $^{87}Sr/^{86}Sr = 0.704$, (Th/U) Kapa ratio = 2.8 and $(^{226}Ra)/Ba = 5000$.

Alkali basalts from Karthala are seen as a variable mixture between plume- and lithosphere-derived magmas. In Sr-Nd–Pb isotope space, the plume end-member lies on the so-called LoNd (low $^{143}Nd/^{144}Nd$) mantle array, considered as a mixing of EM1 and HIMU mantle components (Class et al. 1998; Deniel 1998). Deniel (1998) compares the lavas of the "Karthala ancien" and "M'Badjini" with those of the present Karthala volcano, showing a higher contribution of EM1 mantle source in the most recent products of Karthala than in the past. "Karthala ancien" and "M'Badjini" lavas result from a source containing more of the HIMU component and less EM1, with some DM component. Class et al. (1998) mention two samples of the "M'Badjini" massif whose isotopic compositions are very different to Karthala and other M'Badjini samples, with low-Pb and intermediate Sr- and Nd-isotope ratios that resemble those of La Grille.

La Grille lavas show a more limited range of variations in Sr, Nd and Pb isotopes, at the low-Sr, high-Nd and low-Pb end of the Grande Comore compositional spectrum (Späth et al. 1996; Class and Goldstein 1997; Deniel 1998). They reflect the significant involvement of a DM component, in addition to a HIMU component (with a less clear EM1 contribution). La Grille lavas represent an end-member of the island's compositional array (Fig. 23.7).

If the Dupal isotope anomaly derives from thermal erosion of the Gondwanan lower continental crust within the upper mantle, as found recently for the St. Paul—Amsterdam plateau (Janin et al. 2012), this raises the question of its influence on the Comoros plume impinging on the thinned old crust of the Mozambique canal. The EM1 flavour of the magma source may not have a deep origin, and might instead support the involvement of the upper mantle in the genesis of the magma beneath Grande Comore.

The mineralogy of the mantle source has also been discussed. The existence of residual amphibole (and/or phlogopite) in the lithospheric component of the source of the Comorian magmas has been proposed by Späth et al. (1996), Class and Goldstein (1997), Claude-Ivanaj et al. (1998), Class et al. (1998), and Deniel (1998). The main arguments lie in trace element systematics, such as the relative depletion in K, Rb and MREE. This is particularly pronounced in La Grille lavas, also characterized by the decrease in K/Nb ratio with decreasing degrees of partial melting in the La Grille suite, whereas the K/Nb ratio is relatively constant in the Karthala suite (Class et al. 1998). Smaller or no K depletion in Karthala lavas would thus imply a lower contribution from the amphibole-bearing source (Deniel 1998).

This identification of amphibole in the source region implies that metasomatism took place prior to melting. The existence of hydrous phases lowers the solidus of the lithospheric mantle sufficiently for it to melt when heated up by conduction from under-plated plume material. An episode of metasomatism can be seen in La Grille mantle xenoliths. Coltorti et al. (1999) study mantle-derived spinel lherzolite and wehrlite xenoliths from La Grille volcano. They concluded that there was metasomatised oceanic mantle beneath Grande Comore, due to the migration of a Na-rich carbonatitic melt. The interstitial glass contained in the lherzolite and wehrlite xenoliths has very variable compositions, from very undersaturated to highly oversaturated in silica, and with very high Na contents (up to 14 wt%). Based on the alkali element enrichment (Na) and trace element anomalies (Nb, Zr, and Ti), these authors propose that the metasomatism was due to an "ephemeral" carbonatitic melt. However, no hydrated phases have been found in these mantle xenoliths.

The coupling of isotopes and incompatible trace element ratios in La Grille lavas supports the idea that La Grille magmas formed from variable and low degrees of partial melting of a metasomatised, amphibole-bearing lithospheric mantle source, whereas Karthala lavas represent variable mixtures of plume- and lithosphere-derived melts formed by higher degrees of partial melting. However, Class et al. (2009) discuss the origin of the La Grille melts based on Os isotopes (see also Reisberg et al. 1993). They propose instead that all Grande Comore melts, including the La Grille magmas, represent mixtures between plume-derived and peridotitic lithosphere-derived melts, in order to explain the higher $^{187}Os/^{188}Os$ ratios they observe compared to direct lithospheric mantle melts. The EM1 contribution may also come from that source.

Class et al. (2005, 2009) show that good correlations exist between Sr–Nd isotopes and He and Os isotope ratios. This agrees with the assumption of a mixing of lithosphere-dominated and plume-dominated melts to form the Grande Comore isotope array. The lithosphere-dominated end-member has $^{3}He/^{4}He$ = 6.9 ± 0.15 $R_A$ ($^{3}He/^{4}He \approx 103{,}400 \pm 2{,}200$), while the plume-dominated end-member is characterized by low $^{3}He/^{4}He = 5.2 \pm 0.13\ R_A$ ($^{3}He/^{4}He \approx 137{,}000 \pm 3{,}400$). Thus, the plume end-member of the Comorian volcanism represents a notably «low $^{3}He/^{4}He$» hotspot, dominated by recycled $^{4}He$-rich material (Craig and Rison 1982; Kaneoka et al. 1986; Class et al. 2005). Class et al. (2005) also suggest, based on helium isotope ratios, that the metasomatism of the lithosphere beneath Grande Comore reflects the influence of low degree melts during ocean crust formation.

Mantle-normalized trace elements patterns for Karthala lavas show a typical Ocean Island Basalt pattern (Fig. 23.8). Späth et al. (1996) and Deniel (1998) infer the presence of garnet in the mantle source of Karthala lavas, based on the low HREE concentrations and strongly fractionated REE patterns ($Tb/Yb_N$ = 1.7–2.2 for Karthala lavas, and $Tb/Yb_N$ = 1.5–2.3 for La Grille lavas—Class et al. 1998). From trace element contents and U series, Claude-Ivanaj et al. (1998) conclude that partial melting occurred at the base of old garnet and amphibole-bearing metasomatised

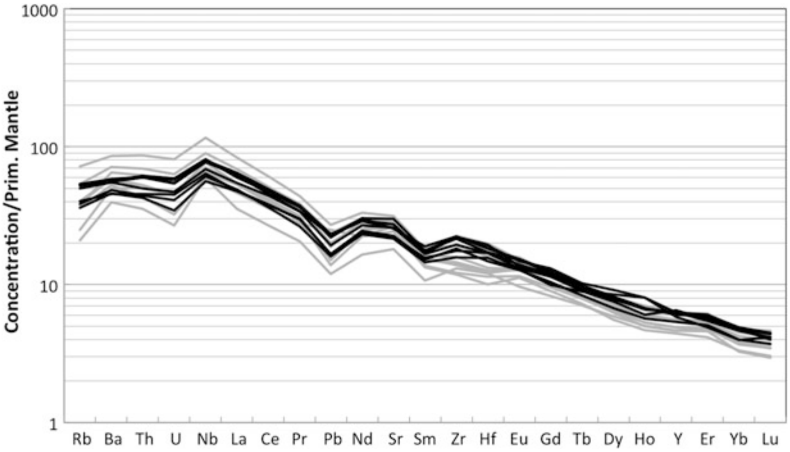

**Fig. 23.8** Conventional primitive-mantle normalized trace element diagram of some representative Karthala (*black lines*) and La Grille (*grey lines*) samples. Data from Georoc database (http://georoc.mpch-mainz.gwdg.de/georoc/)

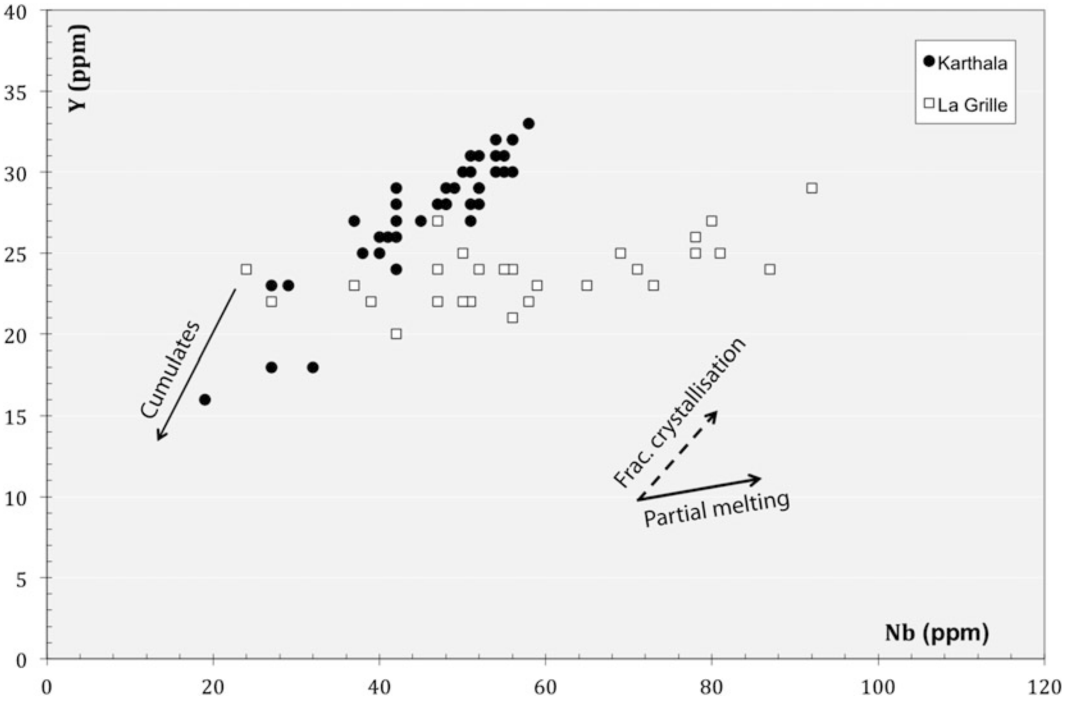

**Fig. 23.9** Y versus Nb diagram for Grande Comore lavas. Data from Class et al. (1998), Späth et al. (1996) (redrawn from Class et al. 1998)

lithosphere at depths greater than 80 km. Class et al. (1998) discuss the presence of residual garnet in the source using the Y versus Nb diagram (Fig. 23.9). While Karthala compositions form a trend highlighting the incompatible behaviour of Y and Nb during fractional crystallisation of olivine + clinopyroxene, those from La Grille are strongly contrasting with the more compatible behaviour of Y during melting in the presence of garnet ($D_Y^{Ol/melt} < 0.01$; $D_Y^{Cpx/melt} \approx 0.5-0.7$; $D_Y^{Grt/melt} \approx 5-10$; $D_Y^{Amph/melt} \approx 0.5-0.7$—White 1997) in the solid residue. However, for Bourdon et al. (1998), as the Karthala source is located at greater depth, the garnet mode in the residue should be greater than for La Grille.

### 23.4.4 Magma Generation

For Späth et al. (1996), the chemical differences between the alkali basalts from Karthala, and the basanites and nephelinites from La Grille may be interpreted as the result of decreasing degrees of partial melting. The more silica-undersaturated basanitic and nephelinitic La Grille lavas may have been produced by relatively small degrees of partial melting of a garnet lherzolite mantle source at depths corresponding to pressures of >25 kbar (~80 km), whereas the moderately alkalic Karthala lavas reflect larger degrees of partial melting of a similar garnet lherzolite or spinel lherzolite source.

Deniel (1998) points out that low $SiO_2$, high $Na_2O$, high concentration of incompatible elements and nepheline normative contents suggest that the lavas from La Grille were produced by lower degrees of partial melting than those of Karthala.

Claude-Ivanaj et al. (1998) also conclude that similar ($^{230}Th/^{238}U$) activity ratios between the two volcanoes may reflect the combined effects of a more garnet-rich residue for Karthala and a smaller degree of melting for La Grille. The smaller modal abundance of garnet in the La Grille source may be due to a shallower depth of melting in the lower part of the lithospheric mantle (80 km depth), where garnet is still present. Therefore, the characteristics of La Grille basanites are consistent with such lavas being generated by small-degree melts of a relatively deep, metasomatised lithosphere.

Class and Goldstein (1997) and Class et al. (1998) also show that basanites from La Grille reflect variable degrees of partial melting of a lithospheric source containing residual amphibole. From the same studies, it has been shown that alkali basalts from Karthala volcano show compositional variations consistent with mixing of plume-derived and lithosphere-derived melts. For Class et al. (1998), Karthala alkali basalts display trace element and isotope variations revealing mixing between a deep mantle plume source and some La Grille-like lithospheric source. This process is inferred to have occurred at the base of the lithosphere where plume melts lower the solidus of the lithosphere and act as metasomatic agents, increasing the temperature and triggering melting. The lithospheric melts then contaminate the primary plume melts. Karthala lavas are a mixture of plume melts and high degree lithospheric melts.

The Ra–Th-U disequilibria (Claude-Ivanaj et al. 1998) indicate that the magma transfer time must be short. The velocity of melts is evaluated to be higher than 10 m/year. Such a velocity is more compatible with quick ascent of melts along well-defined and drained channels rather than through slow percolation.

## 23.5 Summary

Grande Comore magmas, like those of all the Comoro islands, are moderately to highly alkaline, with alkali basalts emitted by the active Karthala volcano, and basanites and olivine nephelinites emitted by La Grille volcano.

Karthala's alkali basalts are aphyric and porphyric lavas, mainly containing olivine and clinopyroxene phenocrysts, while plagioclase phenocrysts are also present in the oldest units of Karthala and M'Badjini. La Grille lavas are undersaturated, with olivine as the only phenocryst phase. High Mg numbers and the occasional presence of mantle-derived xenoliths in La Grille lavas are indications that these lavas are more primitive than Karthala lavas, and may have passed from the mantle to the surface without being stored in a magma reservoir.

Trace element and isotope compositions show a lithosphere-dominated geochemical signature. Magma generation is driven by variable degrees of partial melting of a source containing residual amphibole (and/or phlogopite) and garnet, with the Karthala source probably located deeper than the La Grille source.

Interactions between melts deriving from a metasomatised lithosphere and a shallow mantle plume have been discussed. The alkali Karthala basalts indicate a more pronounced involvement of the mantle plume component. The HIMU component may be present within the DM MORB mantle as known from the global MORB data set. The origin of the EM1 remains controversial: either introduced into the Comorian magmas through delamination or thermal erosion of the lower continental crust during the break-up of Gondwana, that is consistent with the geographic position of the Comoros archipelago near to the continental margins of Africa and Madagascar, or derived from the deeper mantle, source of the thermal plume.

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