

The Volcanism of the Comoros Archipelago Integrated at a Regional Scale

Laurent Michon

Abstract

The development of the Comoros archipelago in the Mozambique channel has been diversely interpreted since the 1970s. The two end-member causes are, on the one hand, a deep mantle plume that developed a hotspot track from the Seychelles Plateau to the Grande Comore, and, on the other hand, a lithospheric deformation that reactivated transform faults and controlled the magma path. The present work first surveys the sparse geological, geophysical and geochronological data available for this archipelago, re-evaluates the age of the magmatic activity and integrates this evolution at a regional scale. Combining realistic magma production rates, the volume of each edifice and the geochronological, it is showed that the magmatic activity started first in Mayotte about 20 Ma and second, almost simultaneously, in Anjouan, Mohéli and Grande Comore about 10 Ma ago. This magmatism, coeval with magmatic periods in areas surrounding the Mozambic channel, the southern East African rift and Madagascar, is organised in three periods since Late Oligocene. Magmatic provinces are now superimposed with seismic zones and graben structures. In consequence, the Comoros archipelago is tentatively interpreted as part of the East African rift rather than related to a distinct deep mantle plume.

Keywords

Comoros archipelago · Magmatism · Hotspot · Rift · Mozambique channel

L. Michon (✉)

Laboratoire Géosciences Réunion, Université de La Réunion, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, UMR 7154 CNRS, 97744 Saint Denis, France
e-mail: laurent.michon@univ-reunion.fr

1 Introduction

The origin of intraplate magmatism and the related volcanoes is a long-lasting debate (Morgan 1972; Sleep 1990; Anderson 2000; Courtillot et al. 2003). On the one hand, non-plate boundary magmatism results from deep mantle ascent rooted in the transition zone or at the core mantle boundary, producing flood basalts and/or linear chains of extinct volcanoes (Morgan 1972; Sleep et al. 1988). On the other hand, all intraplate volcanism is explained by shallow, plate-related stresses that fracture the lithosphere and cause volcanism along these fault zones (Anderson 2000). A reconciling classification proposes that intraplate volcanoes stem from three mantle sources lying at different depths (Courtillot et al. 2003). Primary plumes (e.g. La Réunion and Hawaii) would originate at the core mantle boundary. Superswells in the lower mantle would feed secondary hotspots from the transition zone (e.g. Samoa and Tahiti). Finally, tertiary hotspots would result from asthenospheric convections caused by lithospheric deformation.

In such a scientific debate, the volcanoes of the Comoros archipelago were diversely interpreted in the past decades (Morgan 1972; Hajash and Armstrong 1972; Upton 1980; Emerick and Duncan 1982; Emerick 1985; Nougier et al. 1986; Späth et al. 1996; Class and Goldstein 1997; Class et al. 1998; Courtillot et al. 2003). The aim of this paper is first to review the different interpretations, second to re-evaluate the age of the magmatism and third to integrate it at a regional scale.

2 Volcanoes of the Comoros Archipelago

The Comoros archipelago, located in the northern Mozambique channel between the northern tip of Madagascar and Mozambique, is composed of 4 volcanic islands aligned along a WNW-ESE direction (Fig. 21.1). From east to west, they

correspond to Mayotte, Anjouan, Mohéli and Grande Comore. Including the Geiser and Leven Banks whose volcanic origin was confirmed by the volcanic rocks dredged on the submarine flanks (Daniel et al. 1972), the overall volcanic alignment remarkably displays the different erosion stages of hotspot volcanoes (Darwin 1842, Fig. 21.1c). Geochronological data seems to corroborate the diachronous magmatic activity, starting in Mayotte at least 10.58 Ma ago, in Mohéli and Anjouan around 3.9 and 5 Ma ago, respectively, and finally in Grande Comore since 0.13 Ma (Hajash and Armstrong 1972; Emerick and Duncan 1982, 1983; Nougier et al. 1986; Debeuf 2004; Table 21.1; Fig. 21.2). It is worth noting that a syenite xenolith dated at 11.1 Ma in Anjouan (Montaggioni and Nougier 1981; Nougier et al. 1986) suggests an early phase of magmatic activity coeval with the volcanism of Mayotte (Nougier et al. 1986). For Mayotte, a maximum age of 15 Ma was estimated for the onset of the magmatic activity on the seafloor (−3300 below sea level) (Nougier et al. 1986). Magmas emitted in the Comoros archipelago belong to the typical silica-undersaturated, alkaline series (Strong 1972; Flower 1973; Nougier et al. 1986). Their isotopic composition indicates a mixing between the Indian Ocean lithosphere and deep mantle sources showing affinities with the HIMU and EM1 components (Emerick 1985; Späth et al. 1996; Class and Goldstein 1997; Class et al. 1998; Deniel 1998; Debeuf 2004). At the scale of the archipelago, lavas from the active Karthala volcano (Grande Comore), which are the less undersaturated and have a distinct isotopic signature (EM1), would result from a higher degree of mantle partial melting than for the other volcanoes (Späth et al. 1996; Class et al. 1998).

Whether the volcanic activity developed on an oceanic or continental crust remains unclear. The presence of sandstone xenoliths in lavas of Mayotte, Anjouan, Mohéli and Grande Comore was first interpreted as evidencing a continental nature of the underlying crust (Lacroix 1922; Flower and Strong 1969). However, magnetic

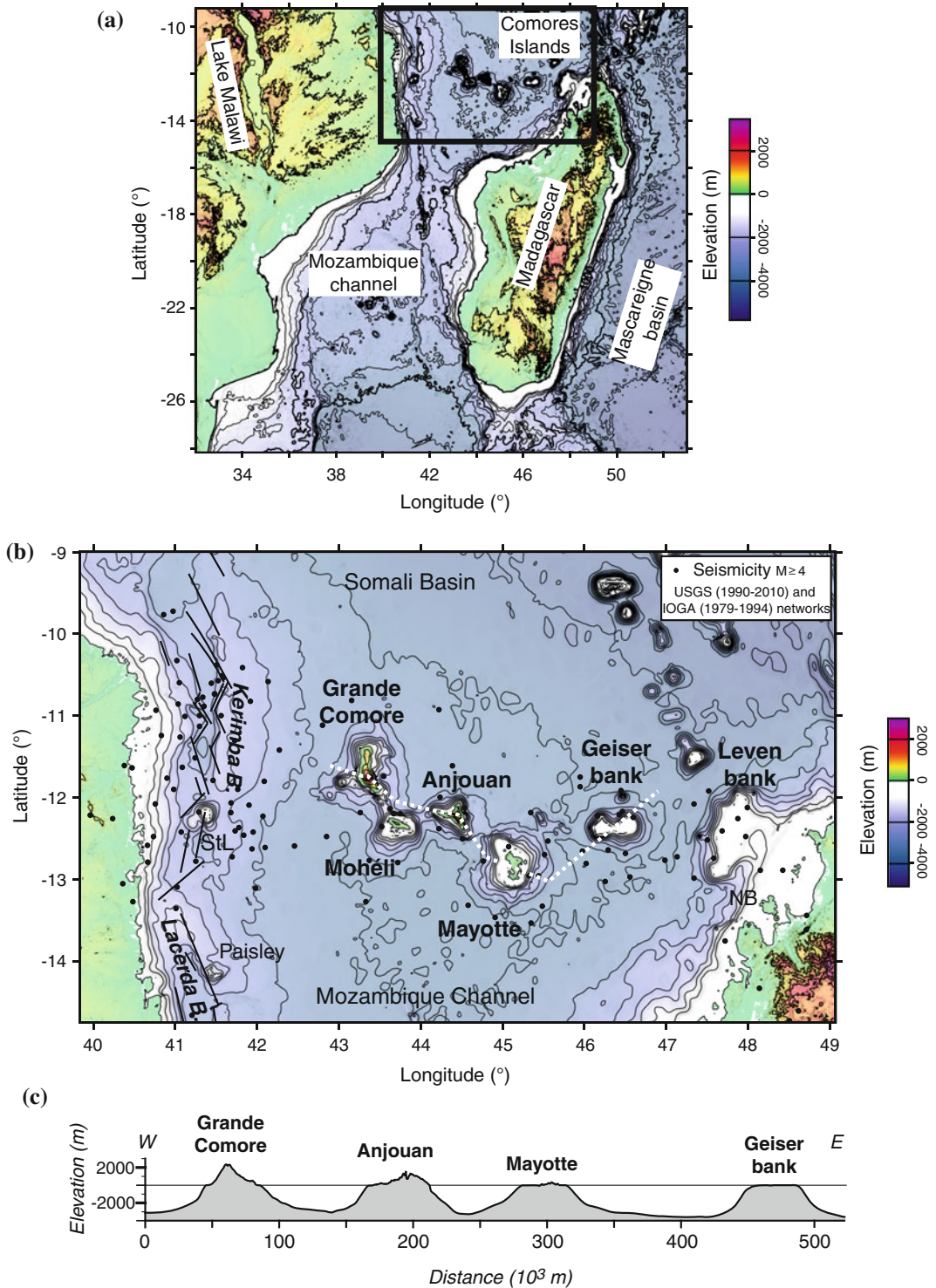


Fig. 21.1 **a** Location of the Comoros archipelago, between the northern tip of Madagascar and Africa. **b** The archipelago is composed from east to west of Mayotte, Anjouan, Mohéli and Grande Comore. Geiser and Leven banks are submarine reliefs of volcanic origin (Daniel et al. 1972). Saint Lazare (*StL*) and Paisley

seamounts also correspond to submarine volcanoes related to the Kerimba and Lacerda basins (Mougenot et al. 1989). *Black lines* account for Miocene to Quaternary faults related to the Kerimba and Lacerda basins (after Mougenot et al. 1989). *NB* Nosy Be. **c** Topography along the volcanic track

Table 21.1 Geochronological dating of the volcanic rocks of the Comoros archipelago

Location	Latitude	Longitude	Age (Ma)	Sample name	Reference
Mayotte	-12.9	45.133	10.58	M41	a
Mayotte	-12.75	45.08	7.7	samp. 16	b
Mayotte	-12.75	45.08	7.7	samp. 92	b
Mayotte	-12.75	45.08	7.1	samp. 110	b
Mayotte	-12.75	45.08	6.9	samp. 31	b
Mayotte	-12.989	45.151	6.11	M140	a
Mayotte	-12.75	45.08	5.9	samp. 12	b
Mayotte	-12.71	45.1	5.28	samp. MA-29	c
Mayotte	-12.71	45.1	5.26	samp. MA-30	c
Mayotte	-12.75	45.08	5	samp. 22	b
Mayotte	-12.999	45.142	4.98	M137	a
Mayotte	-12.75	45.08	4.9	samp. 116	b
Mayotte	-12.67	45.0567	4.41	M112	a
Mayotte	-12.649	45.0385	4.36	M104	a
Mayotte	-12.673	45.05	4.2	M109	a
Mayotte	-12.75	45.08	4.03	samp. 46	b
Mayotte	-12.98	45.113	3.97	M132	a
Mayotte	-12.949	45.162	3.95	M39a	a
Mayotte	-12.881	45.214	3.91	M38	a
Mayotte	-12.647	45.022	3.79	M108	a
Mayotte	-12.94	45.1	3.75	samp. MA-81	c
Mayotte	-12.86	45.1	3.65	samp. MY13-1	d
Mayotte	-12.84	45.107	3.64	M55	a
Mayotte	-12.94	45.1	3.41	samp. MA-82	c
Mayotte	-12.74	45.23	3.4	samp. MY1-1	d
Mayotte	-12.975	45.202	3.4	M93	a
Mayotte	-12.75	45.08	3.3	samp. 149	b
Mayotte	-12.75	45.08	3.3	samp. 147	b
Mayotte	-12.75	45.08	3.3	samp. 112	b
Mayotte	-12.77	45.1	3.27	samp. MA-68	c
Mayotte	-12.72	45.08	3.25	samp. MA-25	c
Mayotte	-12.91	45.1	3.24	samp. MA-73	c
Mayotte	-12.75	45.08	3.23	samp. 03	b
Mayotte	-12.75	45.08	3.1	samp. 117	b
Mayotte	-12.75	45.08	2.7	samp. 126	b
Mayotte	-12.94	45.175	2.55	M87	a
Mayotte	-12.944	45.124	2.52	M95	a
Mayotte	-12.75	45.08	2.5	samp. 93	b
Mayotte	-12.9	45.084	2.43	M46	a
Mayotte	-12.75	45.08	2.4	samp. 138	b

(continued)

Table 21.1 (continued)

Location	Latitude	Longitude	Age (Ma)	Sample name	Reference
Mayotte	-12.737	45.144	2.39	M97	a
Mayotte	-12.777	45.23	2.32	M4	a
Mayotte	-12.77	45.18	2.31	samp. MA-37	c
Mayotte	-12.75	45.08	2.2	samp. 83	b
Mayotte	-12.75	45.08	2.15	samp. 85	b
Mayotte	-12.841	45.125	2.13	M82	a
Mayotte	-12.75	45.08	2	samp. 87	b
Mayotte	-12.67	45.09	2	M25	a
Mayotte	-12.991	45.109	1.95	M115	a
Mayotte	-12.75	45.08	1.85	samp. 06	b
Mayotte	-12.75	45.2	1.59	samp. MA-59	c
Mayotte	-12.76	45.1	1.49	samp. MA-38	c
Mayotte	-12.75	45.08	1.49	samp. 144	b
Mayotte	-12.72	45.2	1.42	samp. MY3-1	d
Mayotte	-12.809	45.189	1.41	M56	a
Mayotte	-12.736	45.19	1.3	M123	a
Mayotte	-12.804	45.193	0.8	M58	a
Mayotte	-12.762	45.099	0.78	M59	a
Mayotte	-12.783	45.234	0.15	M53	a
Anjouan	-12.15	44.3	11.1	samp. AN14	b
Anjouan	-12.15	44.3	3.9	samp. AN08	b
Anjouan	-12.24	44.32	1.52	samp. AJ-28-1	d
Anjouan	-12.15	44.3	1.5	samp. AN02	b
Anjouan	-12.17	44.41	1.18	samp. AN-11	c
Anjouan	-12.17	44.38	0.39	samp. AJ-21-1	d
Anjouan	-12.15	44.3	0.36	samp. AN01	b
Anjouan	-12.15	44.3	0.36	samp. AN04	b
Mohéli	-12.25	43.66	5	samp. MO12	b
Mohéli	-12.25	43.66	3.2	samp. MO10	b
Mohéli	-12.25	43.66	2.75	samp. RH-32	c
Mohéli	-12.33	43.84	1.89	samp. RH-22	c
Mohéli	-12.33	43.84	1.53	samp. RH-21	c
Mohéli	-12.28	43.71	1.14	samp. RH-42	c
Mohéli	-12.25	43.66	0.71	samp. RH-33	c
Mohéli	-12.29	43.77	0.62	samp. RH-36	c
Mohéli	-12.25	43.66	0.56	samp. MO04	b
Mohéli	-12.25	43.66	0.48	samp. MO05	b
Grande Comore	-11.85	43.49	0.13	samp. 35G	c
Grande Comore	-11.62	43.27	0.01	samp. GC1-1	d

a Debeuf (2004), *b* Nougier et al. (1986), *c* Emerick and Duncan (1982, 1983), *d* Hajash and Armstrong (1972)

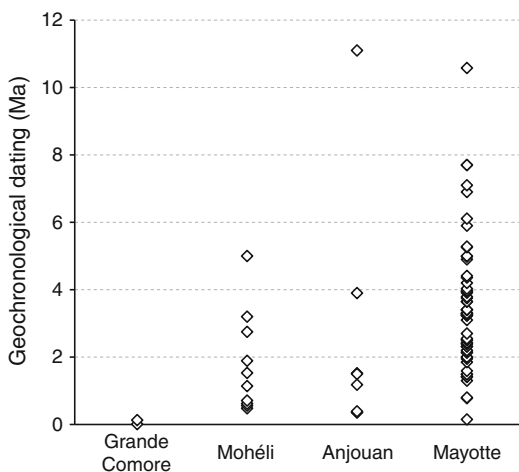


Fig. 21.2 Age of the volcanism in the Comoros archipelago. Geochronological dating from Hajash and Armstrong (1972), Emerick and Duncan (1982, 1983), Nougier et al. (1986), Debeuf (2004)

data suggest that the Comoros archipelago lie on a Late Jurassic to Early Cretaceous oceanic lithosphere resulting from the North-South opening of the Somali Basin (Rabinowitz et al. 1983; Coffin and Rabinowitz 1987). The sedimentary rocks could then correspond to xenoliths of sedimentary rocks resulting from erosion of continental units stemming from either the Davie Ridge (Leclaire et al. 1989) or the Karoo formations cropping out on the eastern or western coasts of Africa or Madagascar, respectively. In such a plausible scenario, the occurrence of the 0.175 km² sandstone massif cropping out in the subaerial central part of Anjouan (Debeuf 2004), about 3500 m above the sea floor, requires additional processes than upward magma transport to be uplifted to its present structural level. Whatever the nature of the crust, seismological data clearly show that the volcanic edifices stand on a seismically active zone connecting the northern extremity of Madagascar in the east to the African coast in the west (Bertil and Regnault 1998; Rindraharisaona et al. 2013) (Fig. 21.1b). This seismicity develops in a regional E-W extensive setting (Grimison and Chen 1988; Foster and Jackson 1998; Heidbach et al. 2008).

3 Hotspot and Rift-Related Interpretations of the Magmatism of the Comoros Archipelago

Three main interpretations have been put forward to explain the magmatism of the Comoros archipelago. Their main difference stands on the source of the magmatism. First, the intraplate volcanism together with the island alignment was interpreted as arising from a deep mantle plume (Morgan 1972). The hotspot impingement, about 40–50 Ma ago below the Seychelles Plateau, would have produced a NNE-SSW volcanic alignment formed by the Amirantes arc, the Farquhar isles and the Comoros archipelago (Emerick and Duncan 1982; Emerick 1985). The plume hypothesis would be supported by the lack of “any significant zone of seismicity” (pp. 417 in Emerick and Duncan 1982) and the EM1 and HIMU signatures of the volcanic rocks (Emerick 1985; Späth et al. 1996; Class et al. 1998). However, in such a model the northwest orientation of the volcanic alignment is hardly compatible with the migration of the African plate toward the NNE (Müller et al. 1993).

Thus, opposite views, involving lithospheric processes instead of deep plumes, have been invoked to explain the development of the magmatism. The Comoros archipelago would represent the surface expression of either a very slowly spreading ridge, similar to the tholeiite and alkali olivine basalt islands at the southern end of the Red Sea (Upton 1980), or the reactivation of lithospheric transform zones (Nougier et al. 1986). Whatever the lithosphere dynamics, the magmatism could be linked to the asthenosphere and be a passive response to forms of lithospheric breakup (Courtillot et al. 2003).

I showed that several lines of evidences can be used to support the hotspot or tectonic origins of the Comoros archipelago. Instead of proposing an additional interpretation, I present a re-evaluation of the age of the magmatism, I compare it to the surrounding volcanic areas and integrate it in the regional geodynamic setting.

4 Discussion

4.1 Onset of the Volcanism of the Comoros Archipelago

The age of 15 Ma proposed for the beginning of the magmatism in Mayotte has been inferred for a magma production rate of $0.5 \text{ m}^3 \text{ s}^{-1}$ (Nougier et al. 1986), which corresponds to a mean value determined for some of the most active volcanoes worldwide (between 0.26 and $0.69 \text{ m}^3 \text{ s}^{-1}$; Wadge 1980). Yet, this value is one order of magnitude larger than the magma emission rate defined for the current shield building stage of Karthala volcano (Grande Comore), between 0.04 and $0.06 \text{ m}^3 \text{ s}^{-1}$, from the activity of the last two centuries (Bacheléry 1999). Such production rates for Karthala correspond to intermediate values; between those of moderately active hot-spot volcanoes like La Gomera, Terceira, Santo Antao or Sao Miguel (production rates around $1\text{--}7 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$) and those related to active to very active hotspots like Kilauea, Mauna Loa and Piton de la Fournaise (production rates between 0.3 and $1.6 \text{ m}^3 \text{ s}^{-1}$; Crisp et al. 1984; Gerlach 1990; White et al. 2006).

Assuming an average long-term production rate of the Comoros archipelago in the same range as the current magma emission rate of Karthala, $0.05 \text{ m}^3 \text{ s}^{-1}$, and considering the total volume of each edifice from the sea floor, I determined a duration of the magmatic activity of around 10, 3.5, 5.5 and 9 Ma for Mayotte, Anjouan, Mohéli and Grande Comore, respectively. Added to the oldest subaerial geochronological ages of each edifice (Emerick and Duncan 1982; Nougier et al. 1986; Debeuf 2004), these results suggest a beginning of the magmatic activity in Mayotte, Anjouan, Mohéli and Grande Comore around 20, 7, 10.5 and 9.1 Ma ago, respectively. Thus the magmatism of the Comoros archipelago probably initiated 5 Ma earlier than initially proposed. Furthermore, as mentioned above, an early activity of Anjouan likely started as early as 11.1 Ma (Nougier et al. 1986). In consequence, I propose that the

magmatic activity begun first in Mayotte about 20 Ma ago and second, almost simultaneously, in Anjouan, Mohéli and Grande Comore between 9 and 11 Ma (Fig. 21.3).

4.2 Regional Distribution of the Volcanism

Integrated at a regional scale, the magmatism of the Comoros archipelago shows strong petrological and geochemical similarities with the undersaturated alkaline basalt and basanite series emplaced in northern Madagascar and along the Kerimba and Lacerda basins (Daniel et al. 1972; Mougénot et al. 1989; Melluso and Morra 2000). Conversely, they present distinct chemical and isotopic compositions than the Neogene magmas emitted in central Madagascar around the Alaotra graben, which are explained by smaller degrees of partial melting of an heterogeneous mantle lithosphere (Melluso et al. 2011) (Fig. 21.4).

The most remarkable point is the timing of the magmatic activity in and around the Mozambique channel. Geochronological data suggest the occurrence of three periods of magmatic activity since the Upper Oligocene (Fig. 21.3). The first period, which developed in late Oligocene, is documented in the Rungwe volcanic province, the southernmost volcanic occurrence related to the East African rift (Roberts et al. 2012b), and in Central Madagascar (Piqué 1999; Bardintzeff et al. 2010). Only a few volcanic manifestations can be linked to this event. The second period of activity started around 20 Ma ago and lasted about 3–4 Ma. The magmatism resumed in the Rungwe volcanic province (Rasskazov et al. 2003) and in Central Madagascar (Piqué 1999; Bardintzeff et al. 2010). It also probably initiated in Mayotte as estimated above from the magma production rates. After a lull of 4–6 Ma, the activity drastically spread over the Mozambique channel and the surrounding areas, forming the third, largest period of activity (Fig. 21.3). The former Rungwe and Central Madagascar provinces were reactivated

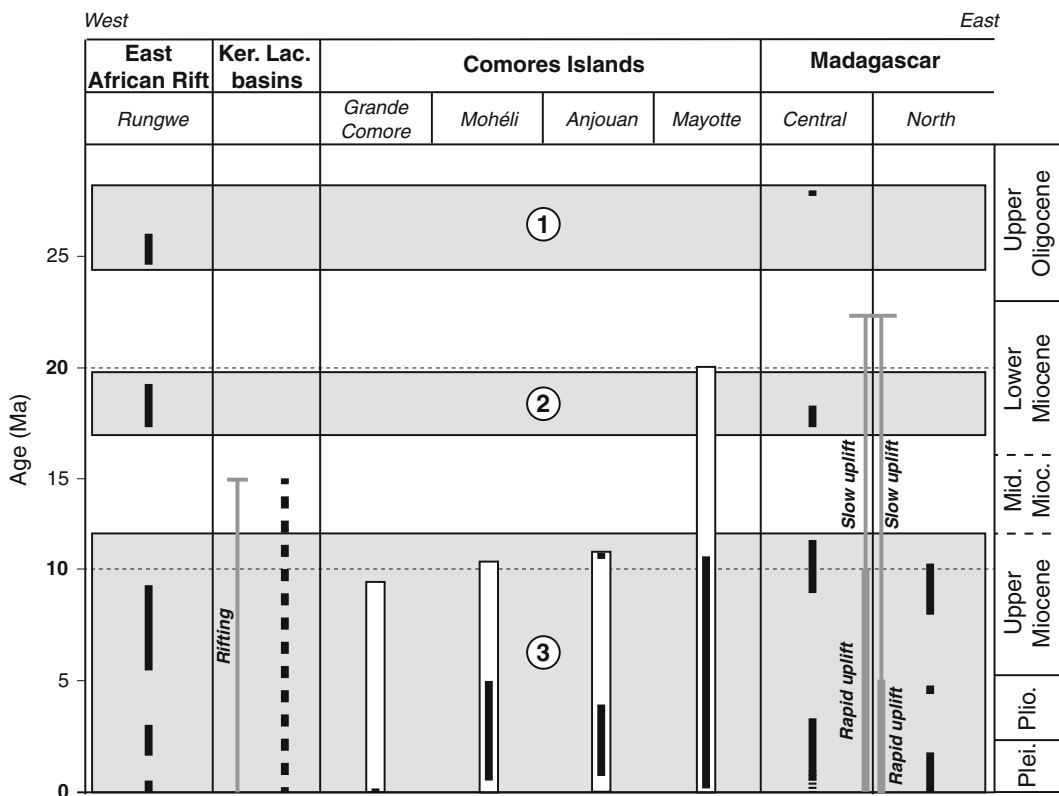


Fig. 21.3 Synthesis of the age of the volcanism (*black bars*) in the Comoros archipelago and the surrounding volcanic provinces. See Fig. 21.4 for location. Geochronological dating from Hajash and Armstrong (1972), Emerick and Duncan (1982, 1983), Montaggioni and Nougier (1981), Nougier et al. (1986), Ebinger et al. (1989, 1993), Rasamimanana et al. (1998), Piqué (1999); Bardintzeff et al. (2001, 2010), Rasskazov et al. (2003), Debeuf (2004), Cucciniello et al. (2011), Roberts et al.

(2012a). *White bars* account for the newly estimated activity for the different edifices of the Comoros archipelago. 1, 2 and 3 identify the different periods of volcanism that developed at a regional scale. Rifting of the Kerimba and Lacerda basins is dated by Mougénot et al. (1986a). The uplift of Madagascar is determined from river profile analysis (Roberts et al. 2012b). See text for explanation

(Ebinger et al. 1989, 1993; Bardintzeff et al. 2010). Moreover, volcanic activity appeared almost simultaneously in the southwest and north parts of Madagascar and in the Anjouan, Mohéli and Grande Comore (Emerick and Duncan 1982, 1983; Nougier et al. 1986; Rasamimanana et al. 1998; Debeuf 2004; Bardintzeff et al. 2010; Cucciniello et al. 2011). Additionally, oceanographic data indicate magmatic occurrences in the Kerimba and Lacerda basins since the middle Miocene (Mougénot et al. 1986a, 1989).

To sum up, the temporal distribution of volcanism of the Comoros archipelago shows striking similarities with the adjacent volcanic

provinces, suggesting a narrow genetic link at regional scale.

4.3 The Magmatism of the Comoros Archipelago Integrated in the Regional Geodynamics

The Neogene magmatism that developed in the Kerimba and Lacerda basins, in the East African rift and in Madagascar is spatially superimposed to an active seismicity linked to an overall E-W extension (Grimison and Chen 1988; Bertil and Regnault 1998; Foster and Jackson 1998;

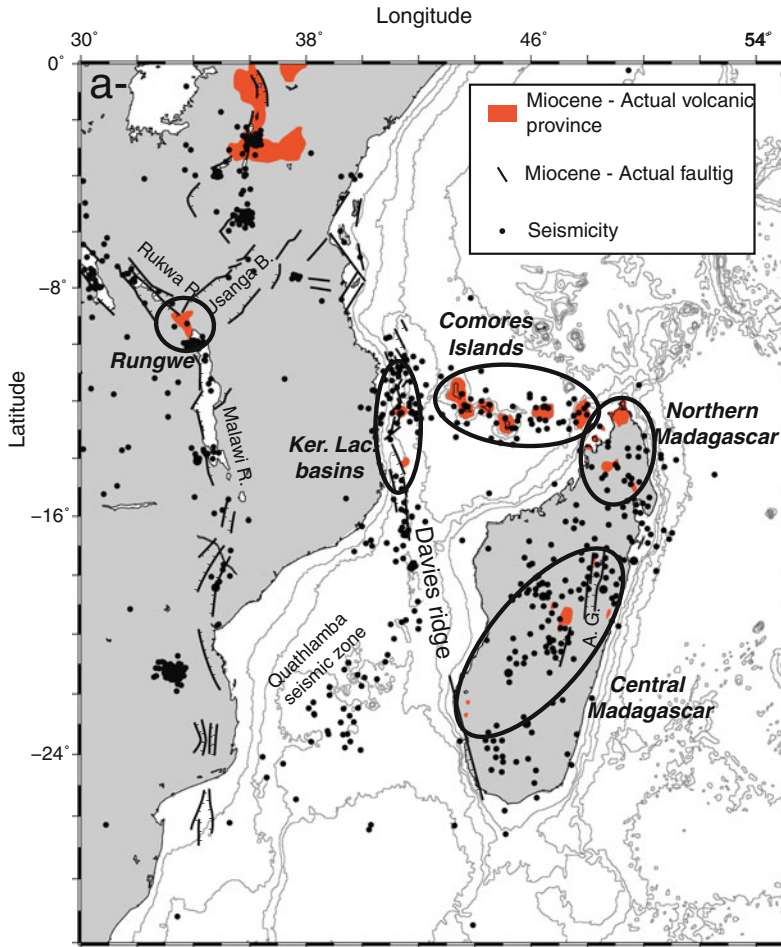


Fig. 21.4 a Distribution of seismic activity, volcanism and normal faults active from the Miocene to the actual. Earthquakes from the Institut et Observatoire de

Géophysique d'Antananarivo (IOGA) (Bertil and Reignoult 1998). A.G. Alaoetra graben

Delvaux and Barth 2010; Rindrarahaona et al. 2013). These seismic zones are associated with graben structures initiated in Late Oligocene or Late Miocene (Rukwa rift; Ebinger et al. 1989; Roberts et al. 2012a), Middle Miocene (Kerimba basin; Mougénot et al. 1989) and Pliocene (Madagascar; Laville et al. 1998; Kusky et al. 2010). This entire system of grabens would correspond to the southeastward continuity of the East African rift (Mougénot et al. 1986b; Piqué 1999; Stamps et al. 2008).

The Comoros archipelago is also located in an active seismic zone. However, very few data

allow a precise determination of the stress regime that affected this seismic band. No obvious tectonic structures have been identified and only rare focal mechanisms suggest a present strike slip stress regime (Delvaux and Barth 2010). It is worth noting that this stress field is consistent with the Plio-Quaternary transpression described along the N150 trending faults of the Kerimba basin (Mougénot et al. 1986a, 1989). Strike slip and transpression, if any, could explain the occurrence of uplifted blocks like the sandstone one in Anjouan and extension along NE-SW faults (Debeuf 2004).

In consequence, considering the spatial and temporal distribution of the seismic activity, the magmatism and the tectonic structures, I propose that the volcanism of the Comoro Islands do not result from a distinct deep hotspot but instead primarily stems from lithospheric deformation in the general context of the East African rift.

5 Conclusion

The main points of this review can be summarized as follows:

1. The magmatism of the Comoros archipelago has been diversely interpreted in the past decades as the result of a deep mantle plume or lithospheric deformation. It is thus a classical example that fed the debate on the origin of intraplate ocean volcanoes.
2. The age of Comoros archipelago is very likely older than previously considered and did not migrated linearly. Magmatism in Mayotte probably started about 20 Ma ago whereas Anjouan, Mohéli and Grande Comore may develop almost simultaneously about 10 Ma ago.
3. The magmatic activity was coeval with that developed in Madagascar and in the Rungwe volcanic province. At a regional scale, three different periods of activity can be distinguished. All these provinces are spatially superimposed to a current seismic activity.
4. The Comoros archipelago is consequently interpreted as the result of a lithospheric deformation in the general context of the East African rift rather than the surface expression of a deep mantle plume.

References

Anderson DL (2000) The thermal state of the upper mantle; no role for mantle plumes. *Geophys Res Lett* 27(22):3623–3626

- Bachèlery P (1999) Le fonctionnement des volcans boucliers. Exemples des volcans de La Réunion et de la Grande Comore. Habilitation à Diriger des Recherches, Université de la Réunion, 239 pp
- Bardintzeff JM, Liégeois JP, Bonin B, Bellon H, Rasamimanana G (2010) Madagascar volcanic provinces linked to the Gondwana break-up: geochemical and isotopic evidences for contrasting mantle sources. *Gondwana Res* 18(2–3):295–314. doi:10.1016/j.gr.2009.11.010
- Bertil D, Regnoul JM (1998) Seismotectonics of Madagascar. *Tectonophysics* 294(1):57–74
- Class C, Goldstein S (1997) Plume-lithosphere interactions in the ocean basins: constraints from the source mineralogy. *Earth Planet Sci Lett* 150:245–260
- Class C, Goldstein SL, Altherr R, Bachèlery P (1998) The process of plume–lithosphere interactions in the ocean basins—the case of Grande Comore. *J Petrol* 39(5):881–903
- Coffin MF, Rabinowitz PD (1987) Reconstruction of Madagascar and Africa: evidence from the Davie fracture zone and western Somali basin. *J Geophys Res* 92(B9):9385–9406
- Courtillot V, Davaille A, Besse J, Stock J (2003) Three distinct types of hotspots in the Earth's mantle. *Earth Planet Sci Lett* 205:295–308
- Crisp JA (1984) Rates of magma emplacement and volcanic output. *J Volcanol Geotherm Res* 20(3):177–211
- Cucciniello C, Melluso L, Morra V, Storey M, Rocco I, Franciosi L, Grifa C, Petrone CM, Vincent M (2011) New Ar ages and petrogenesis of the Massif d'Ambre volcano, northern Madagascar. In: Beccaluva L, Bianchini G, Wilson M (eds) *Volcanism and evolution of the African lithosphere*, vol 478. *Spec Pap Geol Soc Am*, pp 257–281
- Daniel J, Dupont J, Jouannic Ch (1972) Relations Madagascar-Archipel des Comores (Nord-Est du Canal du Mozambique). Sur la nature volcanique du Banc de Leven. *C R Acad Sci Paris* 274:1874–1877
- Darwin C (1842) *The structure and distribution of coral reefs*, 2nd ed. Smith Elder and Co, London, 95 p
- Debeuf D (2004) Etude de l'évolution volcano-structurale et magmatique de Mayotte (Archipel des Comores, Océan Indien): Approches structurale, pétrographique, géochimique et géochronologique. Unpublished Ph. D. thesis, Université de La Réunion, 243 pp
- Delvaux D, Barth A (2010) African stress pattern from formal inversion of focal mechanism data. *Tectonophysics* 482(1):105–128. doi:10.1016/j.tecto.2009.05.009
- Deniel C (1998) Geochemical and isotopic (Sr, Nd, Pb) evidence for plume-lithosphere interactions in the genesis of Grande Comore magmas (Indian Ocean). *Chemical Geol* 144:281–303
- Ebinger CJ, Deino AL, Drake RE, Tesha AL (1989) Chronology of volcanism and rift basin propagation:

- Rungwe volcanic province, East Africa. *J Geophys Res Solid Earth* 94(B11):15785–15803
- Ebinger CJ, Deino AL, Tesha AL, Becker T, Ring U (1993) Tectonic controls on rift basin morphology: evolution of the Northern Malawi (Nyasa) Rift. *J Geophys Res Solid Earth* 98(B10):17821–17836
- Emerick CM (1985) Age progressive volcanism in the Comores Archipelago and northern Madagascar. PhD thesis, Oregon State University, 195 pp
- Emerick CM, Duncan RA (1982) Age progressive volcanism in the Comores Archipelago, western Indian Ocean and implications for Somali plate tectonics. *Earth Planet Sci Lett* 60(3):415–428
- Emerick CM, Duncan RA (1983) Errata to Age progressive volcanism in the Comores Archipelago, western Indian Ocean and implications for Somali plate tectonics. *Earth Planet Sci Lett* 62:439
- Flower MFJ (1973) Petrology of volcanic rocks from Anjouan, Comore Archipelago. *Bull Volcanol* 36:238–250
- Flower MFJ, Strong DF (1969) The significance of sandstone inclusions in lavas of the Comores archipelago. *Earth Planet Sci Lett* 7:47–50
- Foster AN, Jackson JA (1998) Source parameters of large African earthquakes: implications for crustal rheology and regional kinematics. *Geophys J Int* 134(2):422–448
- Gerlach DC (1990) Eruption rates and isotopic systematics of ocean islands: further evidence for small-scale heterogeneity in the upper mantle. *Tectonophysics* 172(3):273–289
- Grimison NL, Chen WP (1988) Earthquakes in the Davie Ridge-Madagascar region and the southern Nubian-Somalian Plate boundary. *J Geophys Res* 93:10439–10450
- Hajash A, Armstrong RL (1972) Paleomagnetic and radiometric evidence for the age of the Comores archipelago, west central Indian Ocean. *Earth Planet Sci Lett* 16(2):231–236
- Heidbach O, Tingay M, Barth A, Reinecker J, Kurfeß D, Müller B (2008) The World Stress Map database release 2008. doi:10.1594/GFZ.WSM.Rel2008
- Kusky TM, Toraman E, Raharimahefa T, Rasoazanamparany C (2010) Active tectonics of the Alaotra-Ankay Graben System, Madagascar: possible extension of Somalian-African diffusive plate boundary? *Gondwana Res* 18(2–3):274–294. doi:10.1016/j.gr.2010.02.003
- Lacroix A (1922) La constitution lithologique de l'archipel des Comores. *C R XIIIème congrès Int Géol Bruxelles* 2:949–979
- Laville E, Piqué A, Plaziat JC, Gioan P, Rakotomalala R, Ravolonirina Y, Tidahy E (1998) Le fossé méridien d'Ankay-Alaotra, témoin d'une extension crustale récente et actuelle à Madagascar. *Bull Soc Géol Fr* 169(6):775–788
- Leclaire L, Bassias Y, Clocchiatti M, Segoufin J (1989) La ride de Davie dans le Canal de Mozambique: approche stratigraphique et géodynamique. *C R Acad Sci Paris* 308:1077–1082
- Melluso L, Morra V (2000) Petrogenesis of Late Cenozoic mafic alkaline rocks of the Nosy Be archipelago (northern Madagascar): relationships with the Comorian magmatism. *J Volcanol Geotherm Res* 96(1):129–142
- Melluso L, le Roex AP, Morra V (2011) Petrogenesis and Nd-, Pb-, Sr-isotope geochemistry of the Cenozoic olivine melilitites and olivine nephelinites (“ankaraitrites”) in Madagascar. *Lithos* 127(3–4):505–521. doi:10.1016/j.lithos.2011.08.003
- Montaggioni L, Nougier J (1981) Les enclaves de roches détritiques dans les volcans d'Anjouan (archipel des Comores). Origine et interprétation dans le cadre de l'évolution du canal de Mozambique. *Bull Soc Géol Fr* 7:595–601
- Morgan WJ (1972) Deep mantle convection: plumes and plate motions. *Am Ass Petroleum Geol Bull* 56:203–213
- Mougenot D, Virlogeux P, Vanney JR, Malod J (1986a) La marge continentale au Nord du Mozambique; résultats préliminaires de la campagne Md40/Macamo. *Bull Soc Géol Fr* 2(3):419–422
- Mougenot D, Recq M, Virlogeux P, Lepvrier C (1986b) Seaward extension of the East-African rift. *Nature* 321:599–603
- Mougenot D, Hernandez J, Virlogeux P (1989) Structure et volcanisme d'un rift sous-marin: le fossé des Kérimbas (marge nord-mozambique). *Bull Soc géol Fr* 5(2):401–410
- Müller RD, Royer JY, Lawver LA (1993) Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. *Geology* 21(3):275–278
- Nougier J, Cantagrel JM, Karche JP (1986) The Comores Archipelago in the western Indian Ocean: volcanology geochronology and geodynamic setting. *J African Earth Sci* 5:135–145
- Piqué A (1999) The geological evolution of Madagascar: an introduction. *J Afr Earth Sci* 28(4):919–930
- Rabinowitz PD, Coffin MF, Falvey D (1983) The separation of Madagascar and Africa. *Science* 220(4592):67–69
- Rasamimanana G, Bardintzeff JM, Rasendrasoa J, Bellon H, Thouin C, Gioan P, Piqué A (1998) Les épisodes magmatiques du Sud-Ouest de Madagascar (bassin de Morondava), marqueurs des phénomènes de rifting crétacé et néogène. *C R Acad Sci* 326(10):685–691
- Rasskazov SV, Logachev NA, Ivanov AV, Boven AA, Maslovskaya MN, Saranina EV et al (2003) A magmatic episode in the western rift of East Africa (19–17 Ma). *Russ Geol Geophys* 44(4):317–324
- Rindraharisaona EJ, Guidarelli M, Aoudia A, Rambolamanana G (2013) Earth structure and instrumental of Madagascar: implications on the seismotectonics. *Tectonophysics* 594:165–181. doi:10.1016/j.tecto.2013.03.033
- Roberts EM, Stevens NJ, O'Connor PM, Dirks PHGM, Gottfried MD, Clyde WC et al (2012a) Initiation of the western branch of the East African Rift coeval

- with the eastern branch. *Nat Geosci* 5(4):289–294. doi:[10.1038/ngeo1432](https://doi.org/10.1038/ngeo1432)
- Roberts GG, Paul JD, White N, Winterbourne J (2012b) Temporal and spatial evolution of dynamic support from river profiles: a framework for Madagascar. *Geochem Geophys Geosys* 13(4). doi:[10.1029/2012GC004040](https://doi.org/10.1029/2012GC004040)
- Sleep NH (1990) Hotspots and mantle plumes: Some phenomenology. *J Geophys Res* 95(B5):6715–6736
- Sleep NH, Richards MA, Hager BH (1988) Onset of mantle plumes in the presence of preexisting convection. *J Geophys Res* 93:7672–7689
- Späth A, le Roex AP, Duncan RA (1996) The Geochemistry of Lavas from the Comores Archipelago, Western Indian Ocean: petrogenesis and Mantle Source Region Characteristics. *J Petrol* 37(4):961–991
- Stamps DS, Calais E, Saria E, Hartnady C, Nocquet JM, Ebinger CJ, Fernandes RM (2008) A kinematic model for the East African Rift. *Geophys Res Lett* 35(5):L05304. doi:[10.1029/2007GL032781](https://doi.org/10.1029/2007GL032781)
- Strong DF (1972) Petrology of the island of Moheli, western Indian Ocean. *Geol Soc Am Bull* 83(2):389–406
- Upton BGJ (1980) The Comores archipelago. In: Nairn AEM, Stehli FG, Churkin M (eds) *The ocean basins and margins*, vol 6. Plenum Press, New-York, pp 21–24
- Wadge G (1980) Output rate of magma from active central volcanoes. *Nature* 288:253–255
- White SM, Crisp JA, Spera FJ (2006) Long-term volumetric eruption rates and magma budgets. *Geochem Geophys Geosys* 7(3):Q03010. doi:[10.1029/2005GC001002](https://doi.org/10.1029/2005GC001002)