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Building the Cape Verde Islands

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Chapter 2
The Cape Verde Archipelago

2.1 Introduction

The Cape Verde Archipelago, also known as the Cape Verde Islands or simply the Cape Verdes, is a group of islands situated in the North Atlantic approximately at latitudes between 14°40′ and 17°30′ N and longitudes between 21°30′ and 25°30′ W of Greenwich (see Fig. 2.1). The islands lie 450–600 km off the western coast of Africa at the approximate latitude of the Cape Verde promontory in Senegal, from which they take their name.

The archipelago was discovered in 1460 AD by Portuguese sailors exploring the west coast of Africa. Human settlement started soon after but suffered numerous setbacks from the hardships imposed by the arid climate. Now, the archipelago comprises the Republic of Cape Verde. Nine of the ten islands are inhabited, hosting a population of ~450,000 inhabitants.

The origins of the Cape Verde Archipelago are attributed to the long-term mid-plate volcanism associated with the Cape Verde hotspot. The volcanic activity probably started in the Oligocene/Miocene and extended well into the Holocene. Historical eruptions are unknown except on Fogo, a highly active volcano whose last eruption occurred in 1995.

2.2 Geography of the Archipelago

2.2.1 Geomorphology

The archipelago is composed of ten islands and eight minor islets arrayed in a west-facing horseshoe. The islands are traditionally divided into the Barlavento (windward) group, comprising the islands of Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and Boa Vista, and the Sotavento (leeward) group, comprising Maio, Santiago, Fogo, and Brava. However, a close look at the

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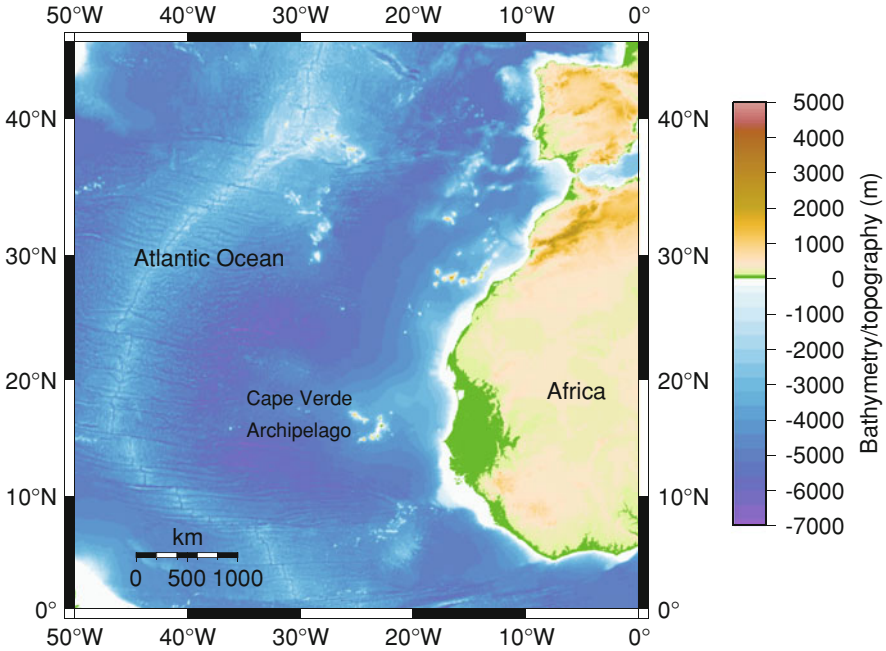

Fig. 2.1 Location of the Cape Verde Archipelago. Elevation data from Amante and Eakins [1]

regional bathymetry suggests a different division based on the coalescence of the submarine pedestal of the islands' edifices: it seems that the archipelago is composed of a "northern chain", comprising the islands of Santo Antão, São Vicente, Santa Luzia, and São Nicolau, and a "east-to-southern chain", comprising Sal, Boa Vista, Maio, Santiago, Fogo, and Brava (see Fig. 2.2). For simplicity, hereafter we will refer to the latter chain only as the "southern chain". Fogo and Brava form a partly detached edifice, because their pedestals coalesce with Santiago slightly above the 3,000 m isobath, which is significantly deeper than elsewhere. We consider Fogo and Brava as part of the southern chain, however.

In the southern chain, the bathymetry reveals the presence of a shallow area between Boa Vista and Maio, known locally as the João Valente Bank or João Valente Shoals. This feature, whose flat summit is just 14 m below the present sea-level, probably corresponds to a former island whose top has been truncated by marine erosion, i.e., it is probably a guyot. In the northern chain, the islands of São Vicente, Santa Luzia, and the Islets of Ilhéu Raso and Ilhéu Branco (to the ESE of Santa Luzia) probably constitute a single elongated edifice, as suggested by the bathymetry. These were probably "separated" by recent sea-level rise, as attested by the shallow channels existing between these islands, which barely reach 20 m depth.

The bathymetry also reveals that several seamounts are present in the vicinity of the main islands. Most of these seamounts correspond to volcanic edifices that never reached sea-level, since flat topped morphologies seem to be rare. Among the

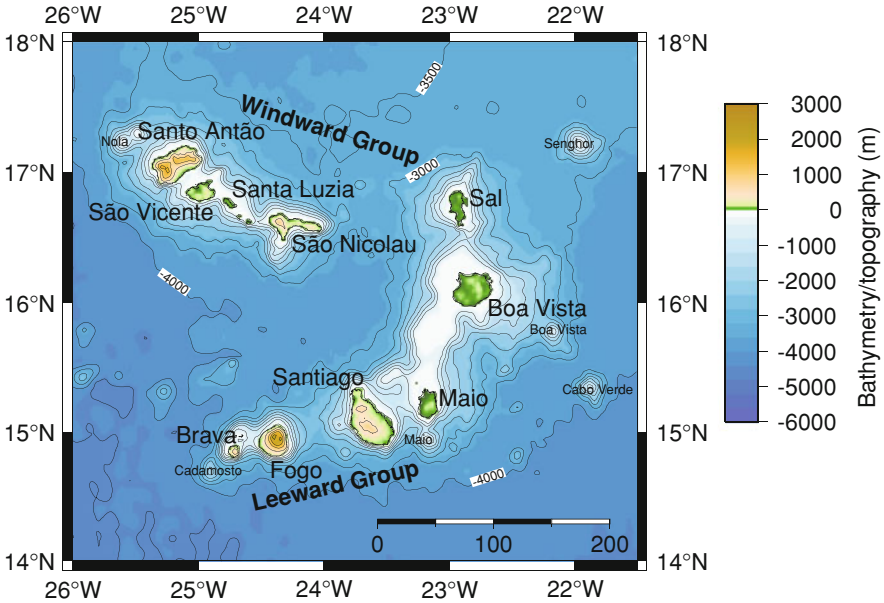

Fig. 2.2 Relief of the Cape Verde Archipelago. Contour lines are in m. Note the contrast in relief between the eastern and western islands. The western islands tend to exhibit higher reliefs than the eastern ones, denoting younger landscapes in the former and denuded topographies in the latter. Note also the north–south asymmetry in the insular platforms of the islands, with more extensive platforms in the northern part of the edifices. Elevation data from Amante and Eakins [1]

Table 2.1 Cape Verde area by island (in km^2)

Southern chain from E to W						Northern chain from E to W			
Sal	B. Vista	Maio	Santiago	Fogo	Brava	S. Nicolau	S. Luzia	S. Vicente	S. Antão
216	620	269	991	476	67	388	35	227	779

most important seamounts lying in the vicinity of the Cape Verde Islands we highlight: the Senghor Seamount (~100 km to ENE of Sal), the Boa Vista and Cabo Verde Seamounts (ESE of Boa Vista), the Maio Seamount (S of Maio), the Cadamosto Seamount (WSW of Brava), and the Nola Seamount (WNW of Santo Antão)—see Fig. 2.2.

The archipelago's total land area corresponds to about 4,068 km^2 unevenly distributed among the islands. The largest island (Santiago) is 991 km^2 as opposed to the just 35 km^2 covered by the smallest island (Santa Luzia) (see Table 2.1). Inter-island distances vary from just 8 km (between São Vicente and Santa Luzia) to 270 km (between Santo Antão and Maio).

There is a contrast in relief between the eastern and western islands (see Figs. 2.2, 2.3 and Table 2.2). The eastern islands of Sal, Boa Vista and Maio are low and flat-lying and their maximum elevations are under 450 m above sea-level (asl).

Fig. 2.3 Morphological types of edifices. Note the contrast in the surface morphology of these three edifices. Maio (in the E) is the oldest edifice with a flat lying erosive morphology. Santiago represents an intermediate stage, where the morphology of the (shield) edifice is still perceptible, despite being cut by deep valleys. Fogo (in the W) is a young stratovolcano with a preserved morphology, only interrupted by the east-facing caldera-collapse scar

Table 2.2 Islands' maximum elevation distribution (in m asl)

Southern chain from E to W						Northern chain from E to W			
Sal	B. Vista	Maio	Santiago	Fogo	Brava	S. Nicolau	S. Luzia	S. Vicente	S. Antão
406	387	436	1,394	2,829	976	1,340	395	725	1,979

Their general landscape is old and denuded, and erosive landforms prevail. Their only relief is normally a few isolated residual morphologies, normally erosion-resistant phonolitic edifices, or the cones formed during the last post-erosional eruptive stage. These constitute razed edifices whose relief has been levelled mostly by periods of partial immersion, where wave-cut erosion dominated. The morphology denotes the late post-erosional stage. Conversely, the western islands generally exhibit higher relief and reach elevations that frequently surpass 1,000 m asl. Their landscape is young and the primary volcanic forms are still perceptible. Edifices in an early post-erosional stage, like Santiago and Santo Antão, still exhibit the overall shield morphology despite being cut by deep valleys. The still active volcano of Fogo, with an elevation of 2,829 m asl and the highest point in the archipelago, corresponds to a stratovolcano whose morphology is only interrupted by the east-facing caldera-collapse scar, now partially masked by the construction of the new summit cone. This volcano is still in its main building stage and erosive features are rare.

2.2.2 Climate and Erosional Regime

The Cape Verdes enjoy a tropical oceanic climate. Annual temperature variation is small and ranges from 19 to 29°C. However, since the archipelago is part of the

Sahelian arid belt, rainfall levels are lower than in other West African countries. This condition imposes an arid to semi-arid regime with scarce but concentrated rain during a "wet season" from August to October. Annual precipitation barely reaches 260 mm/a and is also unevenly distributed due to orographic effects. Rainfall is normally confined to short but heavy downpours associated with tropical storms, inducing a torrential regime to fluvial erosion. These episodic but strongly erosive flow conditions, when combined with the prominent topography of younger volcanic landforms, lead to a deeply incised drainage pattern characterised by deep canyons and narrow gorges. It is indeed remarkable how these ephemeral streams, which are probably active erosive agents for only a minute fraction of the average year, are capable of such erosive power. The deep canyons testify to their powerful effects [2]. In addition, the arid conditions also favour overland flow and soil wash which, together with slope mass wasting, contribute to the high load transported by the drainage system and lead to increased erosive power. However, as soon as the stream leaves the steep and narrow flow channel, the erosive and transport capability of the stream wanes, leading to the formation of large alluvial fans when the geomorphic conditions are propitious. In denuded islands, and due to the lack of relief, drainage often assumes a different pattern. Drainage, in these areas, is normally characterised by braided systems and incipient meanders with low lying channels. During storms, riverine flow frequently bursts the channel banks and mantles large areas with the entrained sediments it carries. This, together with high overland flow and soil wash, leads to a barren and dusty landscape covered in thin layers of outwash deposits whose finer elements are easily remobilised by the wind.

The islands are subjected to a normally persistent northeasterly wind, inducing an energetic marine erosion regime with asymmetrical characteristics. Coastlines facing the prevailing winds are thus more energetic and endure higher erosion rates. This leads to an asymmetrical erosive topography with higher sea cliffs and more extensive insular platforms (below sea-level) in the northern slopes of the volcanic edifices (see Fig. 2.2). The more rapid coastline retreat in the northern shores also influences the drainage base level, leading to steeper stream profiles and increasing the erosive power of stream flow on the northern slopes.

2.3 Geodynamical Setting

The Cape Verde Islands lie on the African tectonic plate, a plate that has moved very little in the last 30 Ma in relation to the hotspot reference frame [3, 4]. Moreover, the pole of rotation for the African plate seems to be located in the vicinity of the Cape Verde Archipelago, further contributing to the fixity of the archipelago relatively to the underlying hotspot [5]. This might explain why the Cape Verde Islands are arranged as a cluster rather than a single linear chain. For whatever reason, we may consider the archipelago stationary relative to its melting source [6–8]. This situation

enables the study of plume/plate interactions without the complication of plate movement [7].

Despite its proximity to the African mainland, the Cape Verde Archipelago clearly lies on oceanic lithosphere. This is directly confirmed by the presence of underlying Mesozoic ocean floor at the nearby IODP sites [9, 10]. It is indirectly confirmed by the presence of seafloor spreading magnetic anomalies mapped across the region surrounding the islands, with the Cretaceous Magnetic Quiet Zone lying eastwards of these islands [11, 12]. According to Williams et al. [12], the Neogene volcanic episode creating the Cape Verde Archipelago did not mask the original texture and fracture zones of the Mesozoic seafloor, attesting to fact that these islands lie on oceanic crust. Seismic investigations also suggest an underlying oceanic crustal and mantle structure [8, 13, 14]. The underlying lithosphere is interpreted to be between 120 and 140 Ma old, as suggested by the presence of the Mesozoic seafloor spreading magnetic anomalies M0–M16 [11, 12, 15] (see Figs. 2.4 and 2.5). Thus, if no thermal rejuvenation occurred, the islands lie over thick and cold lithosphere that has reached its asymptotic properties [16]. In fact, it seems that the features of the original Mesozoic seafloor in the nearby area of the islands are still discernible, suggesting that no regional reheating occurred [12].

The disposition of the Cape Verde Islands along two apparently different trends, one NW–SW and other NE–SW, is suggestive of a possible relationship with fracture zones [12, 13, 17]. Mata et al. [18] suggested that the linear arrangement

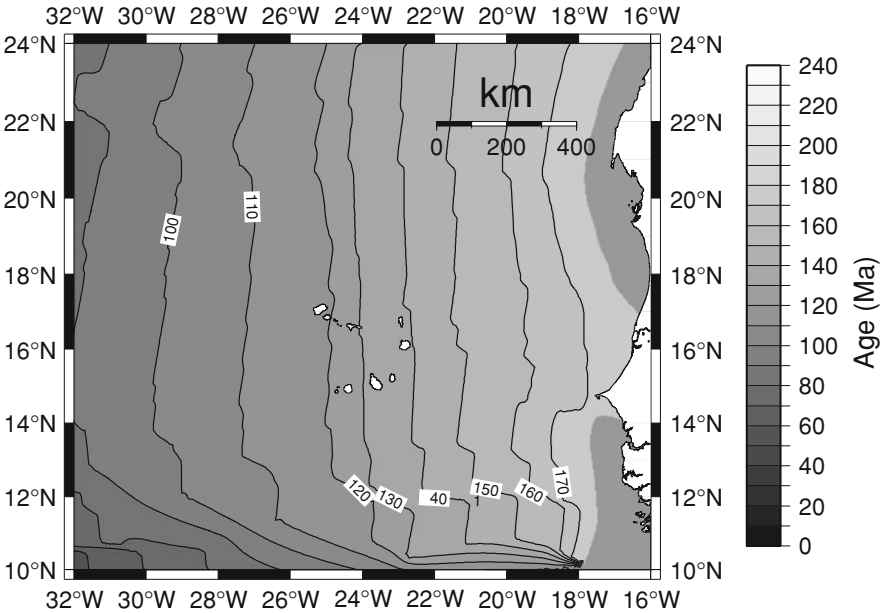

Fig. 2.4 Age of the lithosphere in the vicinity of the Cape Verde Archipelago. Note that the islands lie on 120–140 Ma old lithosphere. Data from Muller et al. [15]

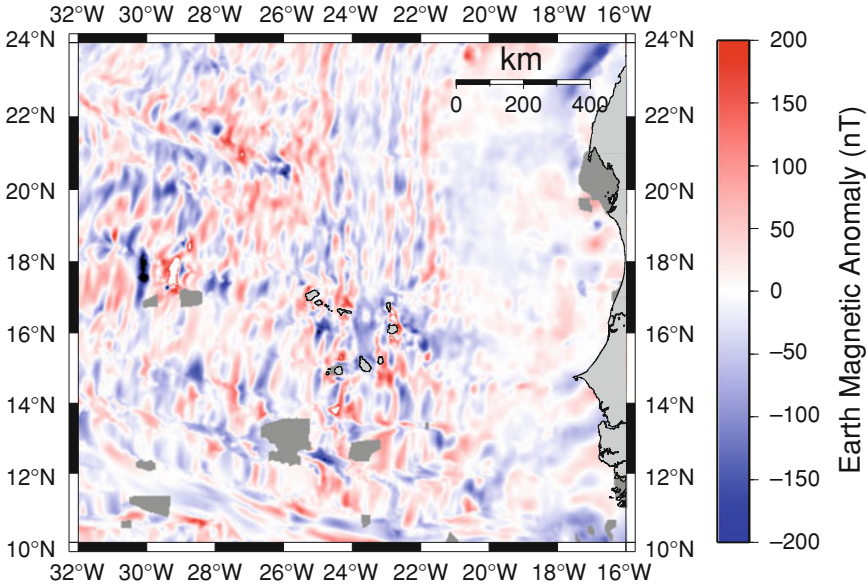

Fig. 2.5 Seafloor spreading magnetic anomalies in the vicinity of the Cape Verde Archipelago. Data from Maus et al. [19]

of the Cape Verde Islands in two distinct chains may result from the interaction between the hotspot and deep fractures. However, this geometry may be fortuitous since there is no clear evidence for the islands being located preferentially along fracture zones [12].

2.4 The Cape Verde Rise and Islands

The Cape Verde Islands rest upon one of the most prominent features in the NE Atlantic: the Cape Verde Rise [9]. The Cape Verde Rise is a large smooth dome-shaped swell, spanning almost 10° in latitude and reaching depths as shallow as ~3,000 m [9] (Fig. 2.6). When compared to the expected depth for the age, the Cape Verde Rise stands in excess of 2,000 m above the reference value, making it the largest bathymetric anomaly in the world's oceans [6, 20–22]. The origins of the Cape Verde Rise are still controversial, but it is widely accepted that this feature is associated with the Cape Verde hotspot volcanism [6, 20, 21]. The stratigraphic record inferred from the existing IODP sites strongly suggests that the rise is the result of a broad uplift in excess of 2,000 m that occurred sometime around the Oligocene/Miocene transition or the Early Miocene [9, 10].

The volcanic activity associated with the Cape Verde hotspot probably started sometime in the Late Oligocene or Early Miocene. This seems to be the age of the oldest exposed lavas in the archipelago that are unequivocally associated with hotspot activity [23]. Likewise, this is also the suggested age for the formation of

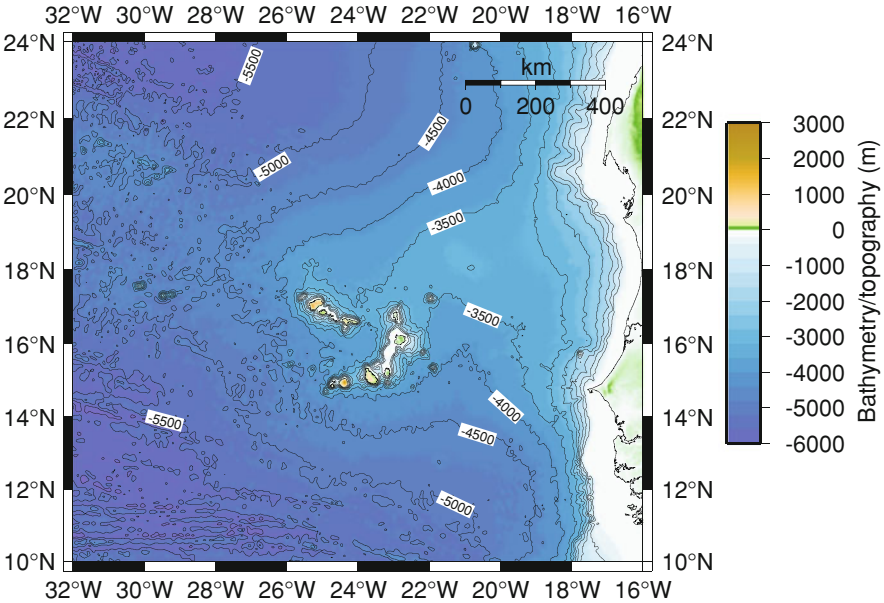

Fig. 2.6 Map of the Cape Verde Rise. Contour lines in meters. Elevation data from Amante and Eakins [1]

the Cape Verde Rise, as inferred by the sedimentary record offshore the Cape Verdes [9, 10]. However, the activity was not continuous and not all the islands were formed at the same time. It seems that Sal, Boa Vista and Maio were formed first, as attested by their surface geology and published geochronology (see Fig. 2.7). Around 10–8 Ma ago, volcanism seems to have started further west, creating the basement complexes of Santiago, São Nicolau and Santo Antão. Soon after a vigorous period of activity resumed, leading to the voluminous shield-building stage of Santiago and possibly the entire northern chain. Sal experienced post-erosional volcanic activity as well, and possibly the basement complexes of Fogo and Brava were created by that time. This vigorous Miocene/Pliocene period of activity is well documented in the sediments of the Cape Verde Rise [9, 10]. The bulk of the archipelago, consequently, seems to have been formed towards the end of the Neogene [24]. Holocene volcanism has been reported on several islands, but historical volcanism is not known except on Fogo. The highly active volcanic centre of Pico do Fogo has erupted every 20 years, on average, since the discovery of the archipelago [25, 26].

Oceanic intra-plate volcanism is normally dominated by low-viscosity magmas with relatively low levels of entrapped volatiles. As a consequence, effusive activity normally prevails, leading to the generation of broad shield-type edifices. These edifices may assume an elongated or star-shaped morphology due to occurrence of fissure eruptions along preferential directions or rift arms, but the main factors controlling these geometries are still poorly understood. More towards the end of

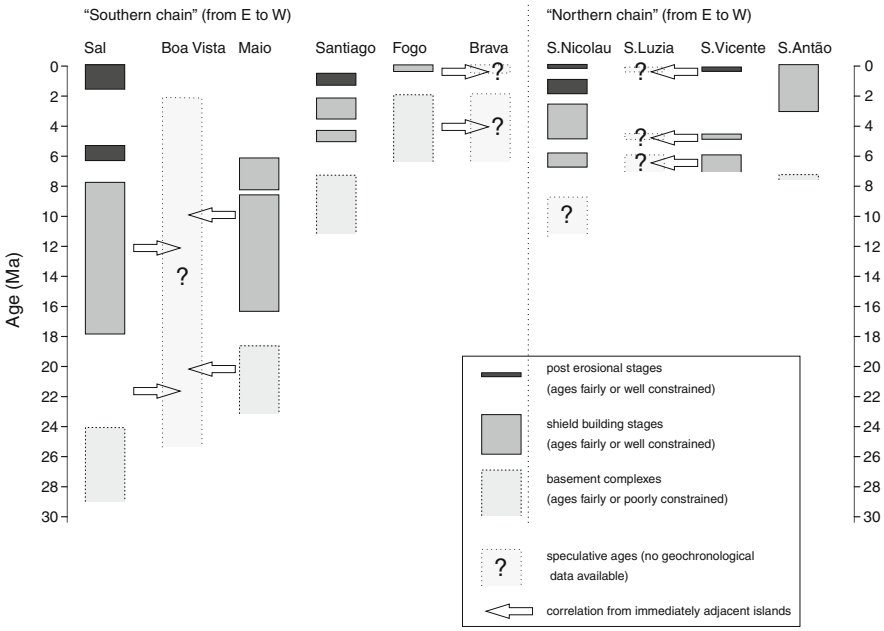

Fig. 2.7 Age distribution of exposed volcanic/intrusive products across the Cape Verde Archipelago. Modified from Holm et al. [24] and based on the geochonological data of Bernard-Griffiths et al. [27], Mitchell et al. [28], Torres et al. [23], Plesner et al. [29], Jørgensen and Holm [30], Duprat et al. [31], Holm et al. [24], Foeken et al. [32]. Note the possible age progression of the oldest exposed rocks in the southern chain and the approximately synchronous extrusion of all the islands composing the northern chain

each eruptive cycle, the eruption of more evolved magmas may sporadically occur, leading to the formation of stratovolcanoes. However, these are normally rare.

The petrological array of lavas extruded in the vast majority of oceanic islands is normally dominated by alkali basalts and their derived products. The Cape Verdes are no exception and the overwhelming majority of their lavas correspond to undersaturated lithologies; silica-saturated lithologies are extremely rare [2]. However, what sets apart the Cape Verde magmatism from those of the other Atlantic archipelagos is the presence of intrusive and extrusive carbonatites (normally calcio-carbonatites) in at least five of the ten islands that compose the archipelago [30, 33]. The carbonatites, once thought to be confined to the basement complexes of the islands, actually occur in the mature stages of some of the islands [33].

According to Kogarko [34], the vast majority of the Cape Verde lavas can be classified in two main differentiated series: (1) a high-alkali series comprising picrites, high-Mg foidites, low-Mg foidites and phonolites; (2) a moderate alkalinity series comprising picrobasalts, basanites, tephrites, tephrophonolites, phonotephrites, phonolites and trachytes. The lavas are thus dominantly relatively primitive lavas, generated by low degrees of partial melting at considerable depths [7, 35].

The presence of plutonic cores within the basement complexes of the edifices is also a notable characteristic of the Cape Verdes. Unsurprisingly, these lithologies are only well exposed in the denuded edifices. They are better represented on Boa Vista, Maio, São Vicente and Brava, but they also occur on Sal and Santiago [33, 36–42]. Their chemistry is normally not much different from their extrusive counterparts and comprise lithologies ranging from gabbros to syenites [39]. The plutonic bodies may correspond to the top of shallow magma chambers unearthed by deep levels of erosion.

Volcanic activity is not a continuous process, neither on short or long time scales. During the periods between individual eruptions or, more importantly, during the longer-term periods of volcanic quiescence, erosion and sedimentation prevail. The Cape Verde's volcanostratigraphic record shows that quiescence usually lasts from 1 to 4 Ma, but occasionally may last up to 6 Ma. This condition seems to be normal in the context of the Atlantic islands, and may be the result of the hotspot's fixity and/or the thick lithosphere above it. The outcome of such periods of erosion and sedimentation is usually well represented in the geological record of the islands, either by massive deposits of lahar or extensive marine carbonates. It is not surprising, then, that many islands exhibit considerable volumes of sedimentary formations in their stratigraphy, or thin but extensive sedimentary cover on its surface.

Another defining feature of Cape Verde is the significant inter-island differences in the surface geology across the archipelago. These differences mostly reflect the different ages of the edifices and/or the level of erosion experienced by the islands. However, differences may also arise from rather different structural controls on the volcanism (fissure vs central eruptive style) and different uplift/subsidence histories.

A complete overview on the volcanostratigraphy of each island is presented on Chap. 5, with the available age constraints. Simplified geological maps are also presented in that chapter.

2.5 A Heterogeneous Mantle Source

The partial melting occurring in the mantle beneath oceanic islands is perceived to be the result of adiabatic decompression of plume and asthenosphere components in the ascending flow [43]. Thus, ocean island lavas, and particularly the more primitive basalts, are thought to generally reflect the geochemical properties of the source and the physical conditions prevailing during melting [43]. Since plumes are considered the most effective probe of mantle reservoirs, ocean island basalts have been extensively studied for the last three decades in order to provide insight on mantle chemical properties [44].

From the advent of the hotspot theory, the origin of the Cape Verde Islands is believed to involve volcanic activity associated with an underlying mantle plume [45]. The Cape Verdes are thus viewed as the surface manifestation of a process

that taps a deep mantle reservoir [18, 24, 45–48]. As in many other hotspots, though, the mantle source associated with the Cape Verde volcanism seems to be heterogeneous [7, 24, 29, 30, 45–48]. In fact, the Cape Verde has been suggested to be an extreme example of a zoned mantle plume [7, 24].

A general overview of the petrology and the variation of basaltic rocks seems to confirm that these are quite similar on the different islands [45, 46]. The suite of lavas that characterise the bulk of the Cape Verdean volcanism seems to reflect parental magmas that correspond to high-Mg foidites, picrobasalts and basanites [34], indicating a low degree of partial melting of mantle peridotite at considerable depth [35]. The occurrence of carbonatites on many islands of the archipelago additionally suggests that the mantle source is CO_2-rich [7]. However, despite this apparently common source, the variation found in the isotopic compositions of lavas from different islands requires that the magmatism had different source regions on different islands [30, 45, 46].

A characteristic of the Cape Verde magmatism is the occurrence of significant intra-island and inter-island radiogenic isotope variations, reflecting temporal and spatial changes in the mantle source [7, 47]. The heterogeneity of the Cape Verde mantle source was first shown by Gerlach et al. [45], using Sr–Nd–Pb isotopes. These authors highlighted the differences between the Southern and Northern Islands, and interpreted them as a mix of three isotopically distinct end-members: (1) Depleted MORB Mantle (DMM); (2) a HIMU-like end-member; and (3) an EM1-like end-member [47]. According to Gerlach et al. [45], the northern islands reflect a strong HIMU (high time-integrated U/Pb) component, possibly supplemented by trapped DMM material, while the southern islands reflect an EM1-like signature possibly due to mixing.

More recently, Doucelance et al. [47] suggested that the intra-island variability in the Pb–Sr–He isotope composition found in Cape Verde requires at least five distinct end-members for the source of the archipelago's basalts. According to these authors, the northern islands reflect a signature resulting from recycled oceanic crust and long term storage, with variable amounts of entrained mixed material. In contrast, the southern islands, though also requiring the presence of recycled oceanic crust and long term storage, additionally have an isotopic signature that is strongly influenced by subcontinental lithospheric mantle, yielding EM1-like trace element patterns [47]. São Nicolau is somehow slightly different from the other northern islands, and requires the assimilation of unaltered Jurassic MORB [47]. However, it has been shown that the oceanic lithosphere plays an important role in controlling the geochemical signature of ocean island basalts, altering their original major and trace elements compositions via its age/thickness, and suggesting that shallow-level interactions need to be taken into account [44].

The isotopic variations seem not to be confined to the basaltic lithologies. Jørgensen and Holm [30] suggested the existence of two distinct HIMU sources within the Cape Verde plume, in order to explain the contrasting isotopic signatures between basalts and carbonatites. According to Jørgensen and Holm [30], the isotopic signatures found in the lavas of São Vicente suggest an evolution from a deep-seated plume-dominated source to a significantly depleted mantle source at

higher levels. Carbonatite contamination of younger basaltic magmas is also proposed by Jørgensen and Holm [30]. Noble gas isotopic compositions of carbonatites also suggest a relatively undegassed source, possibly from the lower mantle [48].

2.6 Summary

The Cape Verde Islands constitute an archipelago generated by Neogene oceanic hotspot volcanism, standing on the broad bathymetric anomaly known as the Cape Verde Rise. The archipelago's stationary position with respect to the melting source, makes it an ideal place to study plume/plate interactions without the complexities imposed by plate movement. The nature of the volcanism is essentially effusive, corresponding to alkaline and silica-undersaturated lavas generated by partial melting at deep levels, and associated with a heterogeneous mantle source. The islands exhibit significant differences in their surface geology, mostly due to differences in the age, erosion level and uplift/subsidence histories experienced by the edifices.

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