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Ontogeny of islands associated with mantle-plume hotspots and its implications for biogeographical models

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ABSTRACT

Mantle-plume hotspot islands are a common focus of biogeographical studies, and models for the growth of their biodiversity often incorporate aspects of their physical evolution. The ontogenetic pathways of such islands have generally been perceived as simple, comprising successive episodes of emergence, growth, peak size, reduction and elimination. In this paper, we improve knowledge of island development by examining key physical data from 60 islands at eight archipelagoes in equatorial to mid-latitude regions of the Atlantic, Indian and Pacific oceans. Such landmasses achieve their maximum sizes within 200–500 kyrs. However, island longevity varies by up to a factor of 5 and is strongly controlled by the speed of the associated tectonic plate as it moves over the narrow, thermally-elevated conduit where volcanism is focused. At moderate to high speeds (40–90 mm/year; e.g., Galápagos, Hawaii), lifetimes are no more than 4–6 Myrs. In contrast, the oldest landmasses (in the Cabo Verde, Canary, and Mascarene archipelagoes) are built upon slow-travelling plates (<20 mm/year) and date from the Miocene. Notably, Fuerteventura in the Canary Islands, where the rate is *c*. 2.5 mm/year, has existed since 23 Ma. Two processes likely sustain the sub-aerial elevation of these massifs: heat from the plume expands the underlying lithosphere thus increasing its buoyancy, which in turn inhibits cooling-contraction subsidence; protracted magmatic activity counteracts denudation. Furthermore, the Cabo Verde and the Canary archipelagoes sit within dry climatic regions, which likely reduced erosion and mass-wasting. Consequently, two ontogenetic models are presented, one for the edifices on the intermediate- and fast-moving plates, and a second for the constructions on the slow-moving plates. The development path for the former is similar to the schema that is commonly envisaged (see above) and takes place over *c*. 5 Myrs, whereas the one for the latter is rather different and involves quasi-continuous surface renewal plus the maintenance of elevation that lasts for *c*. 10–25 Myrs. The new information should permit a fuller understanding of how a hotspot island's physical development shapes its biota and inform the formulation of related theoretical models.

1. Introduction

The biotic suites on the islands and archipelagoes that result from mantle-plume hotspot volcanism (e.g., Canaries, Galápagos, Hawaii) attract much attention because of their experiment-like properties (Whittaker et al., 2017). They are viewed as relatively uncomplicated natural systems for understanding various important phenomena including new-frontier colonization, speciation-radiation, taxon cycle, ecological release, body-size evolution, species-area relationship, etc. (Wallace, 1880; Losos and Ricklefs, 2009; Santos et al., 2016). The landmasses that host them emerge from the oceans devoid of terrestrial life, and quickly reach their maximum areas and heights, but following the cessation of volcanism they are rapidly lowered and drowned. Stuessy (2006; Fig. 1A) and Whittaker et al. (2007, 2008, 2010; Fig. 1B) considered how biodiversity on such surfaces might change through time in response to immigration, *in situ* speciation, particularly cladogenesis (as opposed to anagenesis), and extinction. Half a decade after its publication, the Whittaker et al. (2008) '*General Dynamic Model*' was scrutinized and refined (Steinbauer et al., 2013). Shortly afterwards, it was expanded to include subduction zone landmasses and rifted continental blocks (Borregaard et al., 2016). Fernández-Palacios et al. (2016) hypothesized how recent sea-level fluctuations induced by the Quaternary glaciation cycles modified the geographical configurations of the islands and archipelagos, and hence their floras and faunas. Other research

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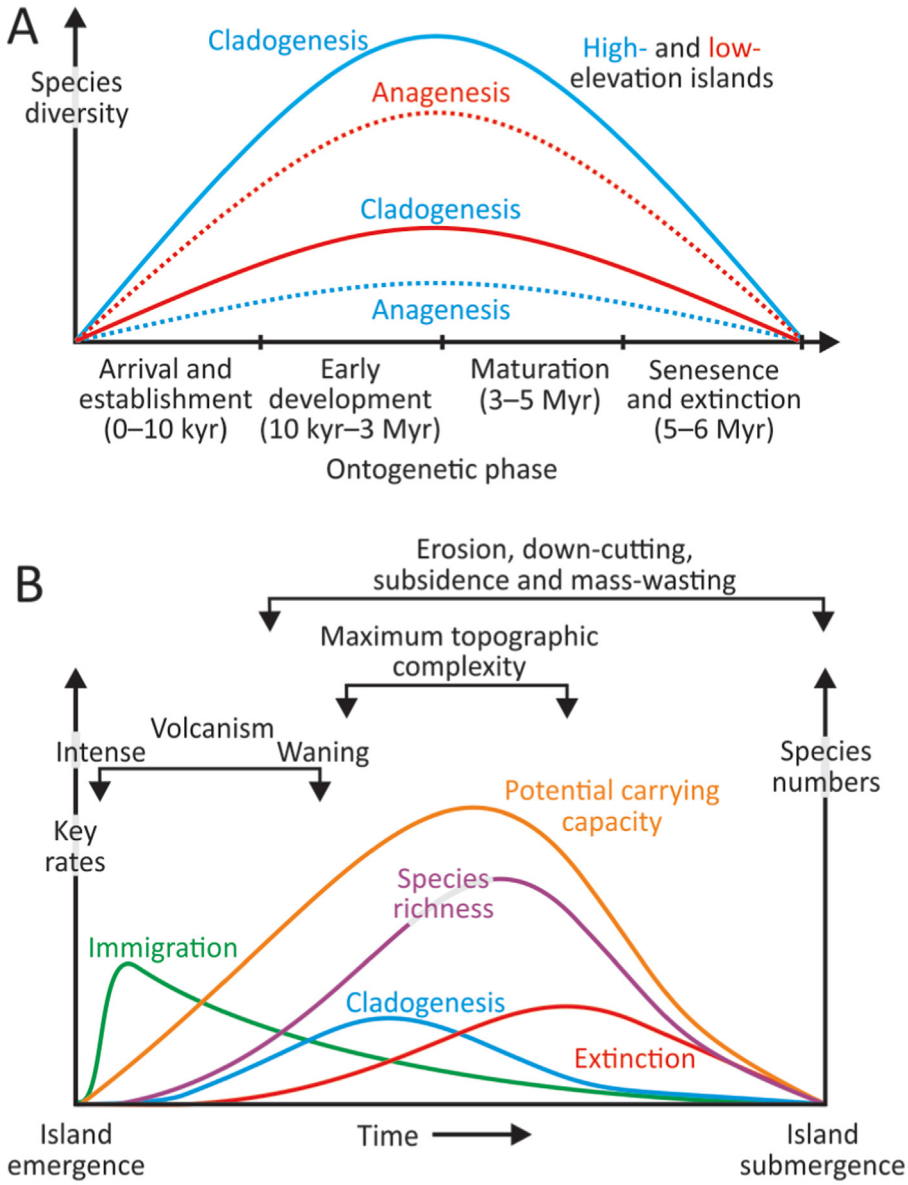

Fig. 1. Two key models explaining the growth of biodiversity on oceanic islands and the role of landmass ontogeny: (A) Stuessy (2006), and (B) *General Dynamic Model* of Whittaker et al. (2007), (2008), (2010) and Borregaard et al. (2016). With both, a critical element is the role that landmass height/availability of ecospaces have in facilitating and stymying cladogenesis. The images were redrafted by JRA, with minor modifications from the originals.

teams have explored allied issues (e.g., Valente et al., 2014, 2020; Pinheiro et al., 2017; Ávila et al., 2019; Cabral et al., 2019; Jõks et al., 2020; Aguilée et al., 2021; Kraemer et al., 2021).

One limitation with the various ontogeny frameworks, which hinders how they might apply to real-life systems, concerns their temporal uncertainties (although see, for example, Cabral et al., 2019, whose modelled landmass exists for 2 Myrs). Whittaker et al. (2008, p.981) explicitly avoided including a scale on their schematic graph; Valente et al. (2014) applied arbitrary units (0–10); Borregaard et al. (2016) were somewhat vague allowing island lifespans to range from 5 to 25 Myrs; Kraemer et al. (2021) disregarded time and instead applied a qualitative 'island maturity' index. We therefore attempt to resolve the ambiguity by way of an exploration of basic geophysical and geochronological data from a large number of mantle-plume hotspot islands that form parts of archipelagoes.

Incidentally, why the plume volcanoes occur where they do is a complicated and contentious issue that has a long history (e.g., Gass et al., 1978; Pollack et al., 1981; Vogt, 1981; Summerfield, 1983; Marzocchi and Mulargia, 1993; Stefanick and Jurdy, 1984; Sleep et al., 1988; Courtillot et al., 2003; Kumagai et al., 2008; Heron et al., 2015). However, the matter is not be reviewed herein as it would be a major, and unnecessary, digression.

2. Methods

2.1. Island selection

Eight mantle-plume island groups (Fig. 2) were used in the analysis: Cabo Verde, Canaries and Mascarenes on the African Plate (Supplementary Data 1: Fig. 1A, B and 1C); Galápagos and Juan Fernández on the Nazca Plate (Supplementary Data 2: Fig. 2A and B); Hawaii, Marquesas and Society on the Pacific Plate (Supplementary Data 3: Fig. 3A, B and 3C). In seven of the archipelagoes the islands form ostensibly straight-line chains with the youngest constructions on/close to the magma source with increasingly older ones further 'downstream'. Cabo Verde is, however, different as it comprises two tracks, a northern one oriented

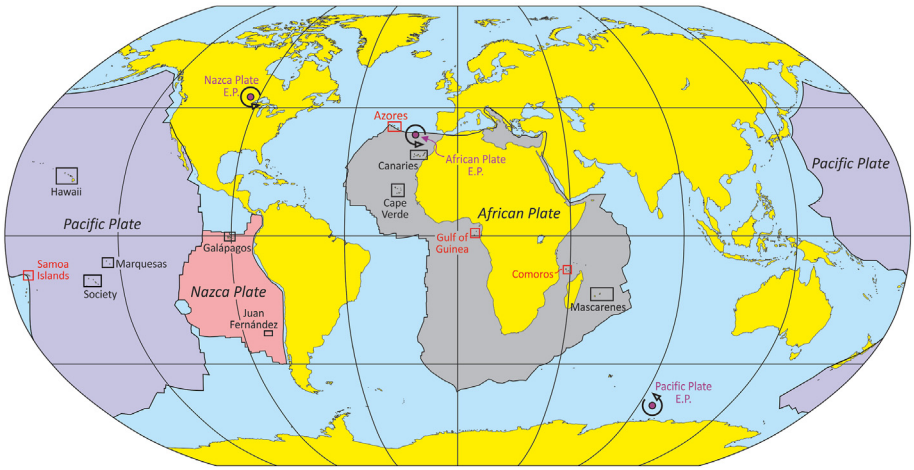

Fig. 2. Locations of the various archipelagoes mentioned in the text. Included in the evaluation are the mantle-plume island groups of Cabo Verde, Canaries, and Mascarenes on the African Plate, Galápagos and Juan Fernández on the Nazca Plate, and Hawaii, Marquesas and Society on the Pacific Plate (all have black lettering and black boxes). Note that a number of other volcanic archipelagoes are omitted (red lettering and red boxes): Azores, Comoros, Gulf of Guinea and Samoa (see text). The purple circles denote the Euler pole locations (all counter-clockwise rotating) for the Nazca plate (49.4°N, 93.9°W), African plate (35.3N°, 17.8°W) and Pacific plate (59.8°S, 97.3°E) based on Wang et al. (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

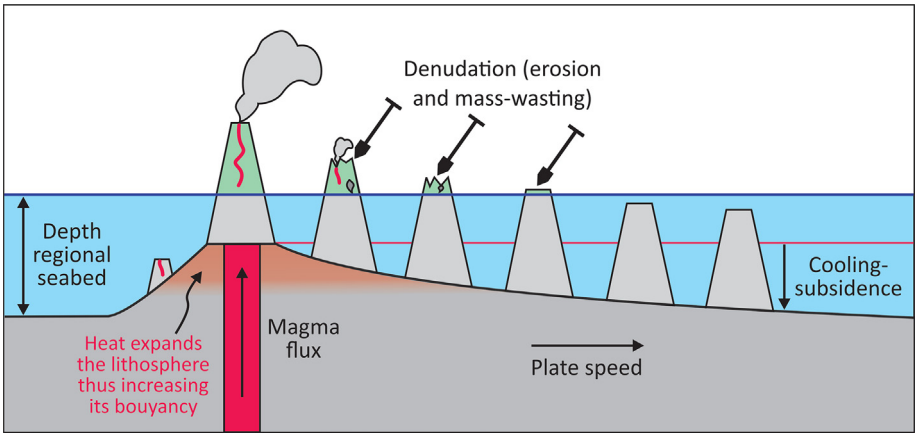

Fig. 3. Summary of the factors controlling the development of mantle-hotspot islands: rate of magma production; depth of the sea-bed; speed of the tectonic plate carrying the edifices over and away from the plume top; denudation (erosion and mass-wasting), and cooling-induced subsidence of the lithosphere. In addition to those works cited in the main text, useful references include Masson et al. (2002, 2008); Geist et al. (2008), Hofmann and Farnetani (2013), and Becerril et al. (2021).

ESE–WNW and a southern one aligned NE–SW (Supplementary Data 1: Fig. 1A; Ramalho, 2011). This rather unusual arrangement results from the uppermost parts of the mantle plume down to *c*. 300 km depth having, at least presently, a double-pronged structure (Figure 10 in Liu and Zhao, 2021). Individual hotspot constructions (e.g., Ascension, Cocos, St Helena) were omitted because the lack of older islands removes the chronological control. Additionally, a number of classic archipelagoes were excluded, even though they are sometimes linked to mantle-plume hotspots. For instance, in the Azores (Fig. 2) a plume is involved but it rises beneath a complex plate junction involving the Mid-Atlantic Ridge and the Terceira Rift (Fernandes et al., 2006; Georgen and Sankar, 2010). Magmatism at the Comoros (Fig. 2) is controlled by a fault that connects to the East African Rift system (Michon, 2016; Famin et al., 2020; Michon et al., 2022; Thinon et al., 2022). Volcanism in the Gulf of Guinea (Fig. 2), and on nearby mainland Africa, has taken place at multiple locations, but there is no age-progression (Njome and de Wit, 2014). There, plume (Saeidi et al., 2023) and non-plume (Belay et al., 2019; Guimarães et al., 2020) explanations have been proposed, but a common thread is for the Congo Craton's northwest edge to guide the ascent of the magma to the Earth's surface thus accounting for the conspicuously straight alignment of the eruption centres that together comprise the 'Cameroon Line'. Samoa (Fig. 2) is linked to a hotspot (Koppers et al., 2008), but the recent activity there results from 'petit--spot' volcanism induced by the localized flexing of the Pacific Plate adjacent to the Tonga Trench (Koppers et al., 2011; Konter and Jackson, 2012; also see Hirano et al., 2006). In summary, the islands in these four archipelagoes are unlike those associated with mantle-plume hotspots, i.e. they lack both a linear arrangement and a systematic age pattern (Wilson, 1963; Morgan, 1971). Hence, the temporal dynamics of these island systems and their fanuas cannot be tested against current dynamic models.

2.2. Data and processing

The development of plume-related volcanic islands is controlled by: (a) regional sea-bed depth, (b) magma flux, (c) intensity of denudation processes (erosion and mass-wasting), (d) speed the edifices are carried over and away from the plume head, and (e) cooling-induced subsidence of the lithosphere (see Fig. 3). Of the five, the second is probably the most intricate, the controls being the plume's temperature, the meltability of the mantle the plume rises through (reflecting its chemistry), and local physical complexities at the base of the lithosphere (Ballmer et al., 2011; Harrison et al., 2017; Garcia et al., 2020). Relevant basic data are: (1) geographical extents of each archipelago, (2) depths of the sub-regional ocean floor the archipelagoes are built upon, (3) peak elevations of the islands, (4) speeds of the tectonic plates, and (5) ages of the oldest landmasses in each archipelago (see Fig. 4 and Table 1). The first were established using *Google Earth Pro*. Regional sea-bed depths were estimated using bathymetric charts generated on the *GeoMapApp* platform (Ryan et al., 2009); despite uncertainties caused by local undulations, it

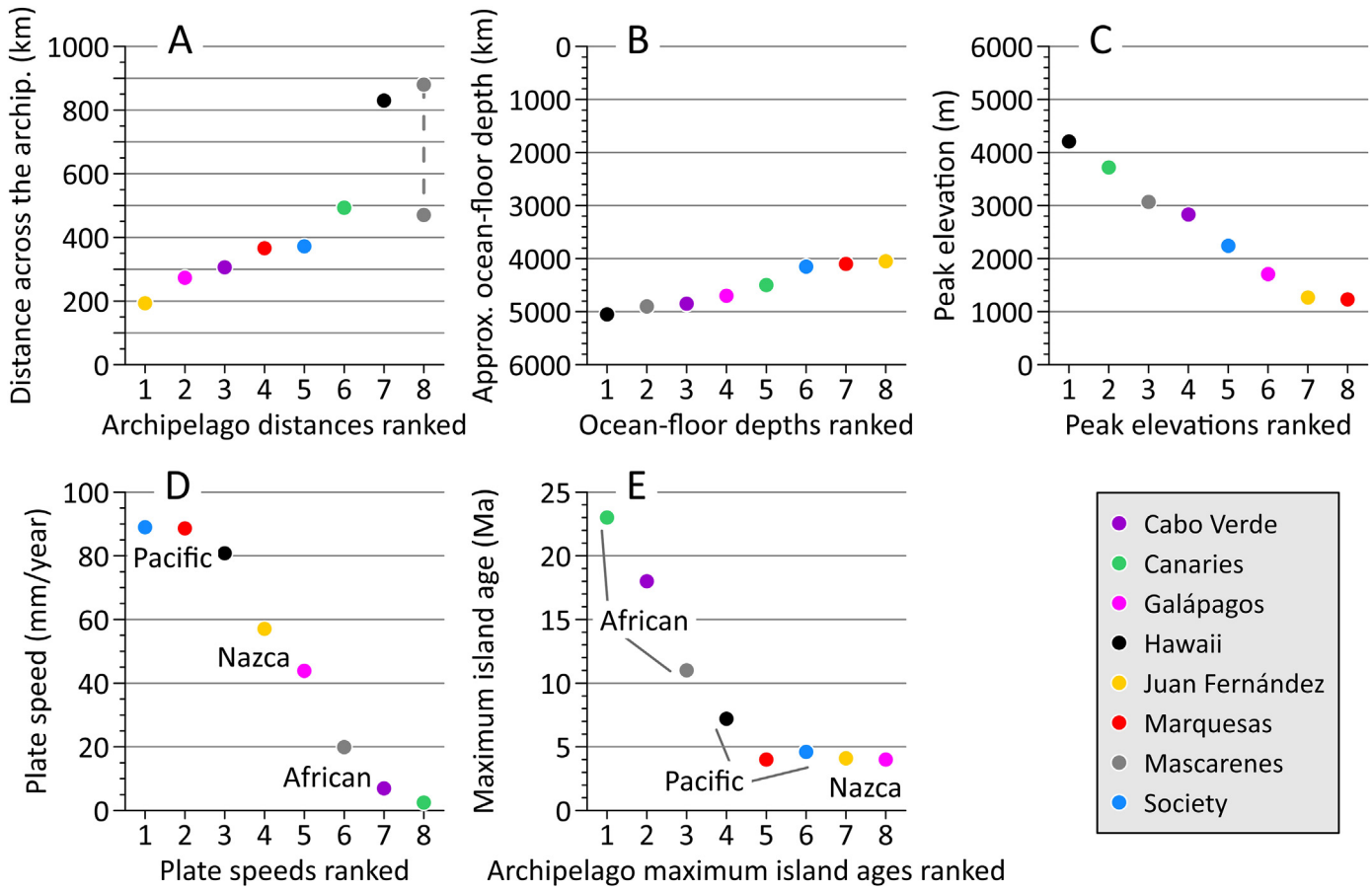

Fig. 4. Plots of five physical parameters associated with volcanic-ocean archipelagoes that have formed above mantle-plume hotspots: (A) geographical extent of each archipelago (Mascarenes also has a 'corrected' value – see text). (B) depths of the sub-regional ocean floor upon which the archipelagoes are built. (C) peak elevations. (D) speeds of the tectonic plates. (E) maximum ages of the archipelago landmasses.

Table 1
Various physical parameter data for the different archipelagoes: extent of the archipelago, depth of the regional seabed, elevation of the highest island, plate speed, and age of the oldest island. For the Hawaii group, Nihoa was included because its peak is 273 m high, although at 0.7 km^2 it is relatively small; Gardner Pinnacles and Necker Island were both omitted as each is < 0.2 km^2 in area and <100 m in height.

	Archipelago Ext.		Sea-bed depth		Peak elevations		Plate speed		Oldest Island	
	Km	rank	m	rank	m	rank	mm/yr	rank	Ma	rank
Cabo Verde	306	3	4850	3	2829	4	6.96	7	18.0	2
Canaries	493	6	4500	5	3718	2	2.51	8	23.0	1
Galápagos	273	2	4700	4	1707	6	43.84	5	4.0	8
Hawaii	830	7	5050	1	4205	1	80.79	3	7.2	4
Juan Fern.	193	1	4050	8	1268	7	57.04	4	4.1	7
Marquesas	366	5	4100	7	1230	8	88.60	2	5.5	5
Mascarenes	880	8	4900	2	3069	3	19.92	6	11.0	3
Society	372	5	4150	6	2241	5	88.97	1	4.6	6

was possible to provide values that are probably accurate to ± 100 m. Elevations and areas were based largely on the compilation of Ali and Meiri (2019), with additional information from the UN Environmental Programme's Island website (http://islands.unep.ch/Tiarea.htm), Clague and Sherrod (2014), and general sources. Plate velocities were taken from Wang et al. (2018; Table 1). Hotspot volcanism sometimes occurs at two or more locations on a plate, and when so then the individual patches of crust the islands are constructed upon will likely be travelling at different absolute speeds, which increase as a function of the angular distance, up to 90°, from the Euler pole (Kearey et al., 2009). Island ages were collated from Ramalho (2011) for Cabo Verde, van den Bogaard (2013) for Canaries, Geist et al. (2014) for Galápagos, Bonacum et al. (2005) and Cousens and Clague (2015) for Hawaii, Lara et al. (2018) for Juan Fernández, Guillou et al. (2014) for Marquesas, Duncan (2009), Quidelleur et al. (2010) and Moore et al. (2011) for Mascarenes, and Uto et al. (2007) for Society. We emphasize that the oldest rocks on an island do not necessarily equate to the landmass's maximum age. First, the materials may have accumulated below the sea and only later did they become sub-aerial. Here, the presence of volcanic 'pillows', indicative of emplacement in aqueous settings, would be a key clue. Second, although the rocks may have been erupted sub-aerially they could have later spent time submerged (e.g., Johnson et al., 2012). In such cases, marine sediments could have accumulated on top of them. The central issue is that the related geology needs to be fully considered.

A higher level of analysis involves identifying the primary factors that, combined, influence/or control the development of the edifices. For

all of the landmasses in each archipelago we examine maximum island age versus plate speed, and peak elevation versus maximum island age.

There are other factors that must also have influenced an island's physical evolution, but quantifying their impacts is effectively impossible. For example, many of the target archipelagoes occupy sub-tropical locations. Consequently, those that have at times in their past been fringed by coral reefs have likely experienced lowered rates of coastal erosion due to the protection such structures provide from wave energy. Notably, today there are significant carbonate growths in the Hawaii, Mascarenes, Marquesas and Society archipelagoes, whereas the Canaries, Cabo Verde and the Galápagos lack such shielding (Spalding et al., 2001). Furthermore, global sea levels have shifted throughout the Cenozoic (e.g., Miller et al., 2020), and the magnitude and frequency of short-period oscillations have also changed, especially in the last 3 Myrs (see also van de Wal et al., 2011; Elderfield et al., 2012). As a consequence, the rates of denudation experienced by the mantle-plume islands must have changed, but whether it involves and an increase or a decrease is not known. Therefore, it is not feasible to assess the influence on the dynamics of the islands' areas and elevations.

3. Results

3.1. Basic findings

3.1.1. Geographical extent of each archipelago

The geographical spread of the islands in each archipelago is shown in Fig. 4A and Table 1. The distances vary from 193 km at Juan Fernández to 880 km at the Mascarenes (although *c*. 470 km if corrected to the Réunion's hotspot's main trace; Hawaii is 830 km).

3.1.2. Typical ocean floor depths

The eight archipelagoes rise from ocean floor that ranges between 4050 m and 5050 m water depths (Fig. 4B and Table 1). The mid-ocean ridges where the crust pieces formed would have been at about 2500 m below the sea's surface. As the newly-formed lithosphere moved away from the spreading centre, it subsided as it cooled and contracted, and thus became less buoyant. Empirical studies (e.g., Parsons and Sclater, 1977; Hillier and Watts, 2005) indicate that the lowering is proportional to the square root of age with *c*. 1 km in 10 Myrs and *c*. 1.8 km in 30 Myrs.

3.1.3. Highest elevations on the volcanic landmasses

The peak elevations within each of the archipelagoes range from 1230 m at Ua Pou in the Marquesas to 4205 m on the Big Island of Hawaii (Fig. 4C and Table 1). Notably, the 3-km range of maximum elevations is appreciably greater than the spread of the depth ranges (1 km; see the previous section).

3.1.4. Plate speeds

The slowest-moving archipelagoes are found on the African plate (Fig. 4D and Table 1, see also Fig. 2), with a range of 2.51 mm/year at the Canaries to 19.92 mm/year at the Mascarenes. Intermediate values are associated with the Nazca plate (43.84 mm/year at Galápagos and 57.03 mm/year at Juan Fernández). The Pacific Plate has the fastest drifting archipelagoes, spanning 80.79 mm/year at Hawaii to 88.97 mm/year at the Society Islands.

3.1.5. Oldest islands

The maximum island ages on the Nazca-plate and Pacific-plate archipelagoes are between 4.0 and 7.2 Mya (Fig. 4E and Table 1). Islands on the African plate are significantly older; 11 Mya in the Mascarenes, 18 Mya in Cabo Verde, and 23 Mya in the Canaries.

3.2. Higher level analyses/examination

3.2.1. Landmass age range and the tectonic-plate speed within the different archipelagoes

The data presented in Section 3.1.5 indicated a considerable spread of oldest island ages. We plotted these values against the local plate speed (Fig. 5 and Table 2). The islands with short maximum lifetimes (typically 4–6 Myrs) are linked to the intermediate- and fast-speed archipelagoes (on the Nazca and Pacific plates). The three African-plate landmass groups are much longer lived, particularly Cabo Verde and the Canaries where the oldest islands are, respectively, 18 and 23 Mya (both Early Miocene). From Fig. 6, the oldest islands in each of the archipelagoes are inversely proportional to local plate speed (slope = −0.465) with a coefficient of determination (R^2) of 0.82.

3.2.2. Landmass areas and their ages within the different archipelagoes

Some authors use area as a proxy for island ontogeny (e.g., Valente et al., 2014; Whittaker et al., 2017). It is therefore useful to note that the areas of similar-age islands in different archipelagoes can vary dramatically, for instance those at Juan Fernández ($\leq$50 km^2) as compared to those at Hawaii (typically *c*. 1000 km^2) (Fig. 7, Table 2). Also, some archipelagoes show a clear decrease in area with age relationship (Society), whereas others do not, that is due either to there being a considerable scatter in the data (Marquesas, Galápagos), or an actual increase in area with age (Canaries). Furthermore, a combination of eustatic shifts, thermal subsidence/uplift and sea-column loading/unloading means that island area can vary greatly over 10^4 years (e.g., Ali and Aitchison, 2014; Fernández-Palacios et al., 2016; Ávila et al., 2019), which is geologically short.

3.2.3. Landmass elevations and their ages within the different archipelagoes

Extra insight into the evolution of the volcanic landmasses can be gleaned from an analysis of their elevations (Fig. 8 and Table 2). In their early stages, the islands on the Nazca and Pacific plates have peaks that are typically 1–2 km high, but within four to six million years they exist no more. In contrast, the ones on the African plate grow to slightly greater altitudes, and are still 1–2 km in elevation even after six million years.

4. Discussion

The primary and processed data reported above demonstrate the markedly different ontogenetic paths for the hotspot archipelagoes on intermediate-to fast-speed, and slow-speed tectonic plates. Here, we explore why this might be the case, as well as related matters, before presenting two models of physical development.

4.1. Quasi-continuous post-emergence volcanism on the older islands in the Mascarene, Cabo Verde and Canary archipelagoes

A feature common to the three slow-moving archipelagoes is that their constituent islands all have volcanism persisting until geologically recently, and in some cases to the present (Mascarenes: Duncan and Hargraves (1990), Duncan (2009), Quidelleur et al. (2010) and Moore et al. (2011); Cabo Verde: Holm et al. (2008) and Ramalho (2011); Canaries: Carracedo et al. (1998). Whilst some islands have hiatuses within their volcanic sequences, a few spanning 3–5 million years, magmatism has always resumed. The issue is reinforced by the review of historical activity on the Canaries by Felpeto and Longpré (2021). Since the late 1500s CE, eruptions have taken place on La Palma in the west (six phases), Tenerife in the centre (four phases), and Lanzarote in the east (two

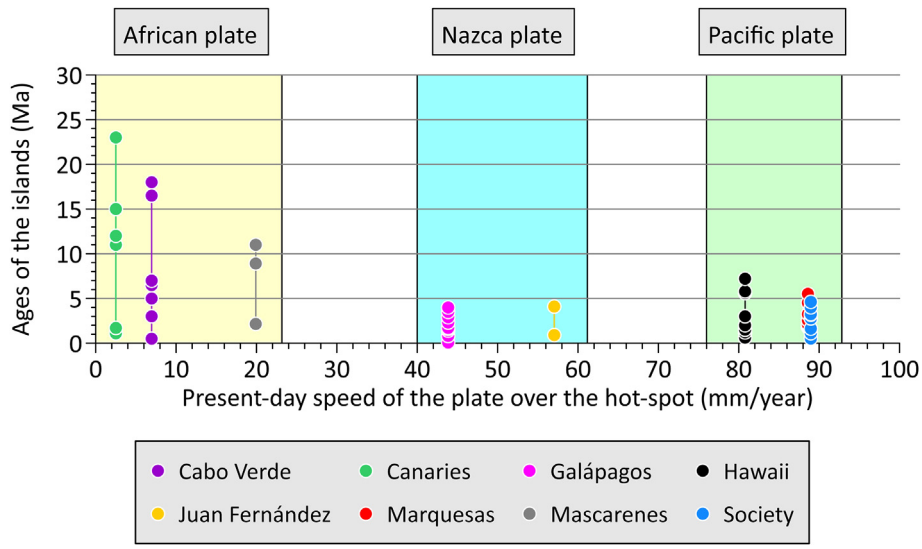

Fig. 5. Plot of island ages versus plate speed for all of the landmasses in each archipelago.

phases). Furthermore, magmatism is not restricted to the 'young' end of the chain. Two aspects feed-in to an appraisal of the ontogenetic paths for such islands. First, there is no obvious termination to the edifice-building and the land-resurfacing that is a fundamental element in some of the theoretical schemes (Fig. 1). Second, the basement beneath the intermediate and older parts of the chains must be reheating periodically thus impeding cooling subsidence (see Detrick et al., 1977; Detrick and Crough, 1978; Clift, 2005). Critically, Cabo Verde and the Canaries sit close to their plate's Euler pole (Fig. 2; Wang et al., 2018) hence their very low velocities. With a slow-moving patch of a plate, it clearly takes an appreciable amount of time before it moves beyond the 'clutches' of the plume (Fig. 3).

4.2. Direct evidence for variable vertical movements on the intermediate-/fast- and the slow-moving archipelagoes

A substantial body of evidence exists for rapid and substantial subsidence on the intermediate- and fast-moving archipelagoes, and a lack of subsidence, and even uplift, on the slow-travelling island groups. Beach- or river-worn cobbles recovered in dredge hauls (Christie et al., 1992), sub-aerial erosion features (Schwartz et al., 2018), and unusual sedimentary accumulations (Ali and Fritz, 2021, pp. 263–265), indicate large-scale sinking of the Galápagos platform (Supplementary Data 2: Fig. 2A) as well as the Carnegie Ridge to the east. For the Hawaii group, Moore (1987) and Moore and Campbell (1987) reported drowned reefs and submerged shoreline-carved terraces to the WNW of the Big Island, as well as on the flanks of the neighbouring Maui Nui platform (upon which Maui, Kahoolawe, Lānai, and Molokai are founded; Supplementary Data 3: Fig. 3A). Furthermore, similar features have been identified on the Oahu massif further along the archipelago (e.g., Faichney et al., 2010). This is very different to what is seen in the archipelagoes of the eastern North Atlantic. In the Canaries (Supplementary Data 1: Fig. 1B), with all of the islands except Gomera, the geology denotes a lack of subsidence and even uplift. Specifically, this includes Miocene–Pliocene pillowed flows, non-recent littoral cones and 'fossil' beaches at numerous localities that are now up to 120 m above sea level (Carracedo, 1999; Meco et al., 2007; Kröchert et al., 2008). On Cabo Verde (Supplementary Data 1: Fig. 1A), there are many examples of the ground having been raised, with values of +100 m being common and on Santiago one record of +450 m (Ramalho et al., 2010b; Johnson et al., 2012, 2018). Ramalho et al. (2010a) attributed the displacements to intrusive activity inflating the ground. Interestingly, Samrock et al. (2022), thought that a trigger for this magmatism, at least on Maio, involved decompression melting induced by mass-wasting of the edifice.

4.3. Issues concerning the relatively dry climates that are associated with the Cabo Verde and Canary archipelagoes

In the *General Dynamic Model* (Whittaker et al., 2007, 2008, 2010; Borregaard et al., 2016), erosion and mass-wasting are both thought to be important in denuding the volcanic edifices. In their scenarios, the processes become important when volcanism has ceased (Fig. 1B). All things being equal, the destruction phase should be more intense where humidity and rainfall are high. Significantly, though, Cabo Verde and the Canaries occupy high atmospheric-pressure regions, the first close to the Sahel of West Africa ('hot steppe'), the second next to the Sahara of North Africa ('hot desert') (Peel et al., 2007). Thus, the dry-air conditions they experience can reasonably be assumed to inhibit their removal. Notably, the other slow-travelling island group, the Mascarenes, occupies a 'tropical rainforest' location, and there the land-surface lowering rates are expected to be higher, which is supported by the elevation versus age data shown in Fig. 8.

4.4. Two new ontogenetic models

The data reported above indicates that the hotspot volcano islands follow two sorts of landmass-development paths. In both, maximum elevation is achieved soon (200–500 kyrs) after emergence. For the islands on the intermediate- and fast-moving plates (40–90 mm/years; Fig. 9A), the lifespans are typically just 4–6 Myrs (Nazca plate and Pacific plate archipelagoes), their simple ontogenies being similar to what is commonly envisaged (e.g., Whittaker et al., 2008, 2017). In contrast, the constructions on the slow-moving African plate (2.5–20 mm/year; Fig. 9B) are very different. There, the islands persist for appreciably longer intervals (11–23 Myrs), with repeated building events and landscape resurfacings, plus there are basement uplifts that are induced by lithospheric heating. The related hypothetical plot in Fig. 9C shows 0.5-Myr-long phases of growth followed by 1.5-Myr-long intervals of rock removal and lowering. Although speculative, it might prove useful to those formulating related biodiversity-growth models. Finally, we note that discussions of island evolution often mention 'hump' shaped paths (e.g., Cabral et al., 2019), although sometimes with a qualifier (e.g., Whittaker et al., 2008). In reality, the two ontogenetic scenarios identified here have steep uprisings followed by long tapers. They can perhaps

Table 2
Age and elevation data for the various islands in each of the archipelagoes. Values for the first have been presented/rounded up to once decimal place. Where information is lacking, the abbreviation 'NK' (not known) is used. Three of the Galápagos islands are excluded ('exc.'): Wolf and Darwin are miniscule; Baltra is an extension of northeastern Santa Cruz, with the intervening channel just 400 m wide. Also, Tahiti in the Society Islands comprises two volcanic massifs, Tahiti Iti and Tahiti Nui (Supplementary Data 3: Fig. 3c), that connect along a *c*. 2-km-wide neck of low ground <20 m high; here, they are treated as separate entities.

Cabo Verde	Age (Ma)	Area (km^2)	Elev. (m)	Canaries	Age (Ma)	Area (km^2)	Elev. (m)
Fogo	0.5	476	2829	El Hierro	1.1	269	1501
Brava	?0.5	67	976	La Palma	1.7	708	2426
S. Antão	3.0	779	1979	La Gomera	11.0	370	1487
Santiago	5.0	991	1394	Tenerife	12.0	2034	3718
S. Nicolau	6.5	388	1340	Lanzarote	15.0	846	671
S. Vicente	7.0	227	725	Gran Canaria	15.0	1560	1949
S. Luzia	?7.0	35	395	Fuerteventura	23.0	1660	807
Maio	16.5	269	436				
Sal	18.0	216	406				
Branco	NK	3	327				
Raso	NK	7	395				
Boavista	NK	620	387				
Galápagos	Age (Ma)	Area (km^2)	Elev. (m)	**Hawaii**	Age (Ma)	Area (km^2)	Elev. (m)
Fernandina	0.06	642	1476	Big Island	0.6	10433	4205
Marchena	0.8	130	343	Kahoolawe	1.2	116	452
Pinta	0.8	60	777	Maui	1.5	1883	3055
Genevosa	0.8	14	64	Lanai	1.5	364	1030
Isabela	0.8	4640	1707	Molokai	2.0	673	1515
Santiago	1.4	585	907	Oahu	3.0	1545	1227
Rábida	1.6	5	367	Niihau	5.6	180	392
Pinzón	1.7	18	458	Kauai	5.8	1431	1598
Santa Cruz	2.3	1012	740	Nihoa	7.2	1	273
Floreana	2.3	173	640				
Santa Fe	2.9	24	259				
Española	3.5	60	206				
San Cristóbal	4.0	558	730				
Juan Fernández	Age (Ma)	Area (km^2)	Elev. (m)	**Marquesas**	Age (Ma)	Area (km^2)	Elev. (m)
Alej. Selk.	1.0	50	1268	Fatu Hiva	1.8	85	1125
Rob. Crus.	4.1	48	915	Mohotani	2.0	15	520
Santa Clara	4.1	2	376	Tahuata	2.1	61	1050
				Hiva Oa	2.6	316	1213
				Ua Huka	3.2	83	884
				Ua Pou	4.5	106	1230
				Nuku Hiva	4.5	339	1224
				Eiao	5.5	44	576
Mascarenes	Age (Ma)	Area (km^2)	Elev. (m)	**Society**	Age (Ma)	Area (km^2)	Elev. (m)
Réunion	2.2	2511	3069	Tahiti Iti	0.5	245	1332
Mauritius	8.9	1865	828	Tah. Nui	1.1	800	2241
Rodrigues	11.0	108	398	Moorea	1.6	134	1207
				Raiatea	2.8	168	1017
				Huahine	3.3	75	669
				Tahaa	3.2	90	590
				B. Bora	4.0	29	727
				Maupiti	4.6	11	380

be best described as door-wedge like.

4.5. *Comparison with the findings of Huppert et al. (2020)*

Huppert et al. (2020) recently postulated a similar link between mantle-plume island longevity and plate speed, in the process noting that the connection had not been previously made (see their Discussion section, p. 3). They proposed that volcanic edifices on the slow-travelling plates were kept aloft due to the underlying lithosphere 'surfing' the mantle-plume swell. However, a key concern is their suggestion of 1–1.5 km of uplift (see their Fig. 2D and E) as it conflicts with the field observations (see Section 4.2) where the raisings are typically an order of magnitude less, at around 100–120 m. We thus infer that the principal mechanism explaining the longevity of the slow-plate islands is instead protracted magmatic activity, both intrusive and extrusive. A second issue with the Huppert et al. (2020) study related to their selection of archipelagoes, notably, the inclusion of the Azores and Comoros. We omit these island groups (see Section 2.1), the first because of its complicated geotectonic setting, that is, a plume beneath the junction of two orthogonal spreading ridges, the latter, for the reason that the volcanism is controlled by a major fault that connects to the East African Rift system. Furthermore, Ascension, Bermuda and St Helena, are included in Huppert et al.'s (2020) work, but as each comprises a single edifice they therefore lack temporal control, which is an element that underpins our study.

4.6. *Implications for diversity growth models for the shallow-marine biotas that are found around the mantle-plume hotspot islands*

Stimulated by the *General Dynamic Model* of island biogeography proposal, biodiversity growth models have since been developed for the shallow-marine faunas that have accumulated around the flanks of the hotspot landmasses (e.g., Pinheiro et al., 2017; Ávila et al., 2018, 2019; also see Hachich et al., 2020). Such assemblages are greatly affected by changes in (i) the habitable area, (ii) ocean currents, and (iii) water-column temperatures, induced by climatic and sea-level shifts, that operate typically on 10^3- to 10^5-year time-scales (also see Obura, 2012; Ludt and Rocha, 2015; Melo et al., 2022). The findings presented herein

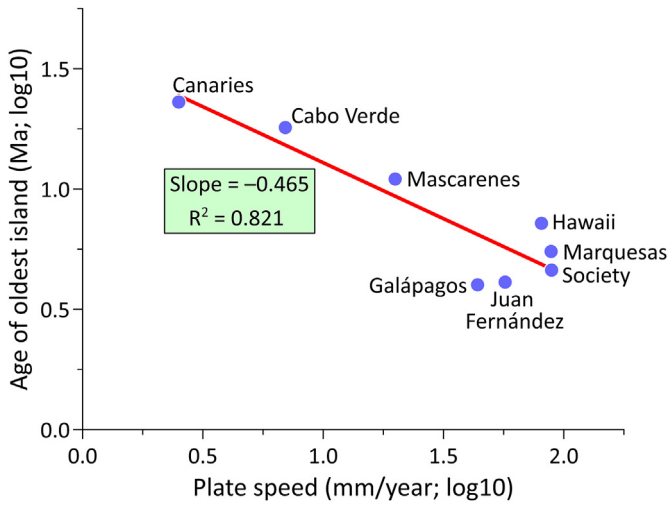

Fig. 6. Plot of island age versus plate speed for the oldest landmasses in each of the archipelagoes. Both axes have been log transformed.

should guide future proposals. At the very least, two ontogeny paths will be needed for the substrates, one for those on the intermediate and fast-speed plates, and a second for those on the slow-speed plates.

5. Conclusions

Analysis of data from 60 individual landmasses in eight archipelagoes leads us to propose two sorts of mantle-plume hotspot islands. Short-lived ones (typically no more than 4–6 Myrs) are located on the intermediate- and fast-moving plates (40–90 mm/year) where the volcanic islands are moved rapidly across and away from their associated plumes. These are found in the Hawaii, Marquesas and Society groups on the Pacific plate, and the Galápagos and Juan Fernández archipelagoes on the Nazca plate. In contrast, substantially older islands (well over 10 million years) are linked to the slow-moving plates (≤20 mm/year). In such cases, protracted landscape rejuvenation takes place plus there is low to negligible subsidence, which likely results from the basements to the edifices remaining longer in the vicinity of the plume, in the process receiving melts and heat over greatly extended periods. The three archipelagoes assigned to this category are Cabo Verde, Canaries, and the Mascarenes. The key features of the two sorts of behavior are encapsulated in the two ontogenetic paths presented in Fig. 9. Together, they have the potential to inform future models of hotspot-island biodiversity through time.

CRediT authorship contribution statement

Jason R. Ali: Conceptualization, Investigation, Visualization, Writing - original draft, Writing - review and editing. Shai Meiri: Conceptualization, Investigation, Writing - review and editing.

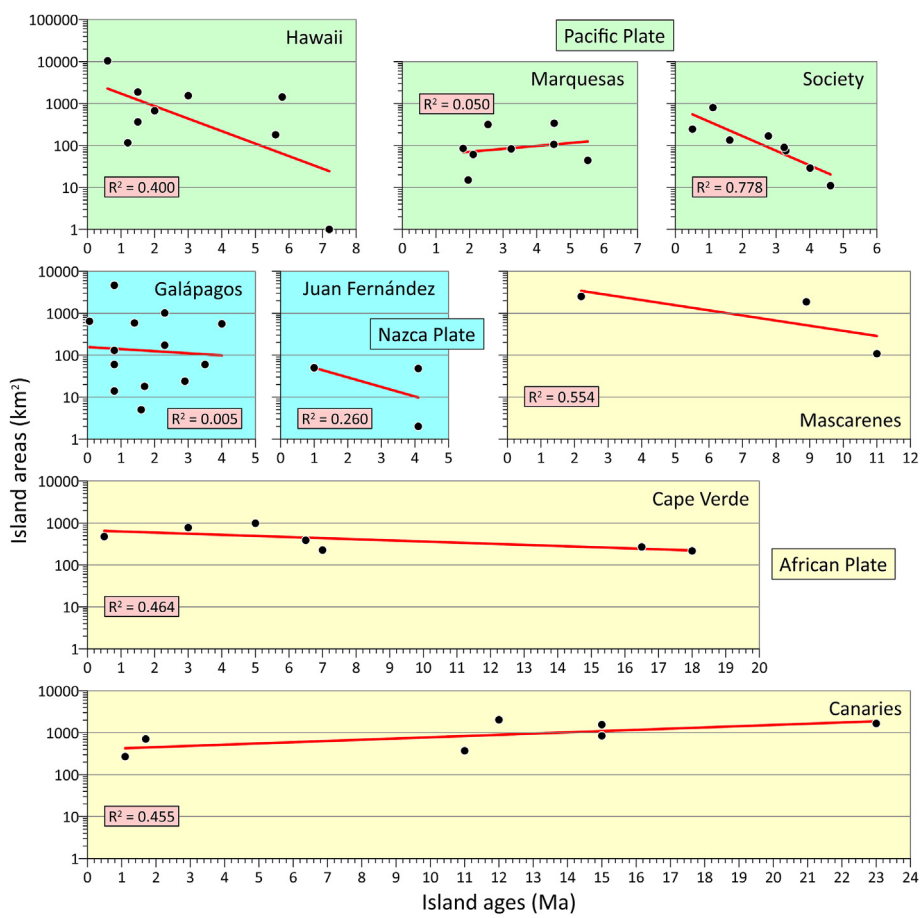

Fig. 7. Plot of island area (log) versus age (normal) for all of the landmasses in each archipelago. Best-fit exponential lines are shown as these would most likely reflect a reduction with time.

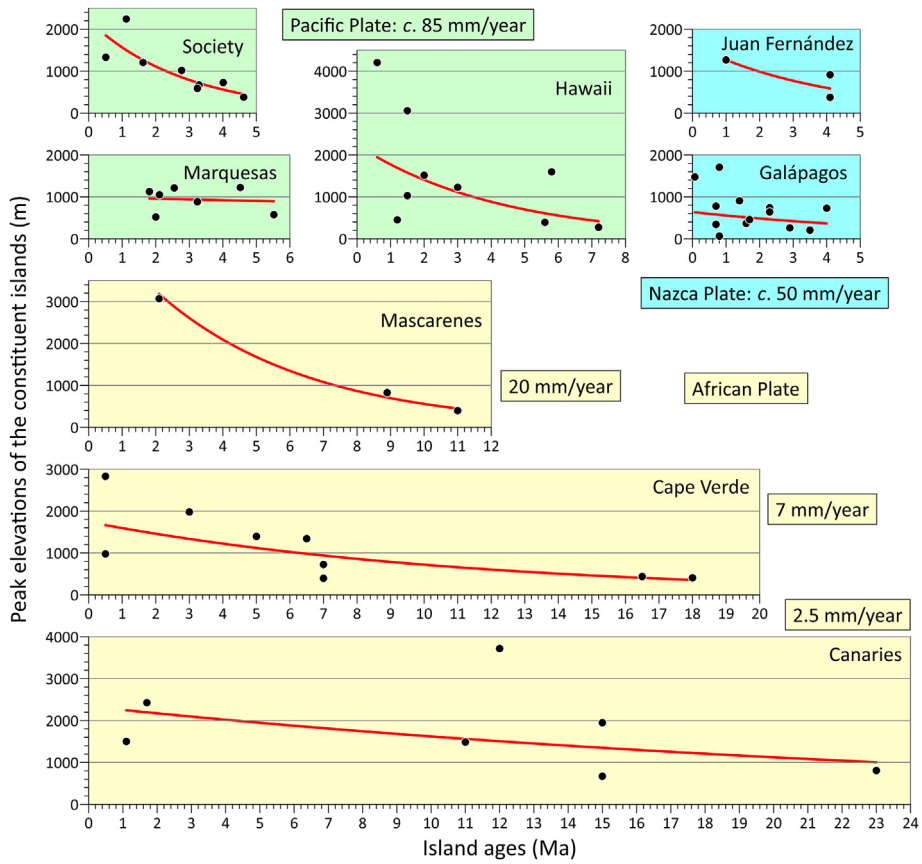

Fig. 8. Plot of island ages versus peak elevation for all of the landmasses in each archipelago. Best-fit exponential lines are shown as these would most likely reflect both the cooling-subsidence and denudation processes.

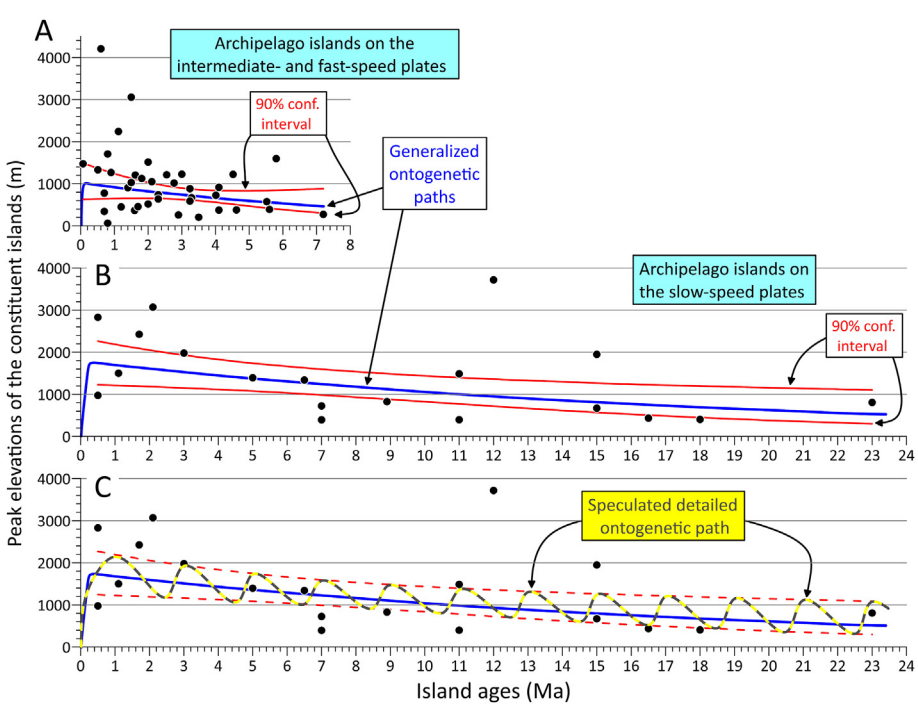

Fig. 9. Ontogeny paths for the different speed archipelagoes. (A) intermediate- and fast-speed. (B) slow-speed (B). Both plots make use of the island-age versus peak elevation data in Fig. 8. The blue traces follow best-fit exponential lines, but close to the origins they turn down sharply to catch the birth of an island (importantly, in neither case does the fitting of a quadratic curve yield a negative parabola). The confidence limits for the data-points are set at 90%. (C) Schematic graph developed from (B) that models multiple eruption and lithosphere-heating events lasting 0.5 Myrs followed by 1.5 Myrs of volcanic quiescence and basement cooling. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All of the data used in this study is presented in the two tables.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eve.2023.100007.

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