



80-Myr history of buoyancy and volcanic fluxes along the trails of the Walvis and St. Helena hotspots (South Atlantic)

Claudia Adam, Valérie Vidal, Javier Escartin

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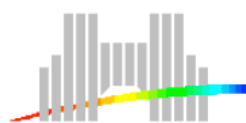
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Abstract: Walvis and St. Helena are the only long-lived hotspot chains in the South Atlantic. Therefore, their characterization is important to constrain the processes associated with mantle plume formation, their temporal evolution, and the interaction with plate and mantle dynamics in the region. We study the temporal evolution of plume buoyancy and magma production rate along both hotspot chains, which are constrained from the swell and volume of volcanic materials emplaced along the chain. The regional depth anomaly is calculated by correcting the 2° bathymetry grid of Smith & Sandwell (1997, *Science*, 277) for thermal subsidence and sediment loading. We separate the topography associated with volcanism and the swell surrounding the hotspot chains using the MiFil filtering method (Adam et al., 2005, *Geochem. Geophys. Geosyst.*, 6). We then estimate the temporal variations associated with both parameters by computing volumes along the hotspot tracks. Neither Walvis nor St. Helena show a 'classical' hotspot behavior. We find that two plumes are at the origin of the St. Helena chain. This study also shows a swell associated with the Circe seamount, supporting the existence of a hotspot NW of the St. Helena trail. The variation in swell and volcanic fluxes suggests temporal variability in the plume behavior at time scales of 10-20 m.y. and 5 m.y., which may be related to oscillations and instabilities of the plume conduit, respectively. Cumulative fluxes in

the area are largest for Walvis and weakest for Circe, and all are significantly lower than that reported for the Hawai'i hotspot.



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Lyon, June 20th, 2007

Dear Editor,

Please find enclosed the revised version of the manuscript entitled "80-Myr history of buoyancy and volcanic fluxes along the trails of the Walvis and St. Helena hotspots (South Atlantic)", by C. Adam, V. Vidal & J. Escartín (Ms. Ref. No.: EPSL-D-07-00106).

You will find in the "Revision Notes" document the detail of changes and answers to the reviewer's comments.

Faithfully yours,

Valérie Vidal
(corresponding author)

Revision Notes for the manuscript

"80-Myr history of buoyancy and volcanic fluxes along the trails of the Walvis and St. Helena hotspots (South Atlantic)"

by C. Adam, V. Vidal & J. Escartín

(Ms. Ref. No.: EPSL-D-07-00106)

Answers to general comments

We agree with the reviewer about the B&W figures, and regret that it cannot provide the clarity of color figures. We choose to represent both the Walvis and St. Helena chains on a single map (Figure 1), instead of two separated figures (like Figure 2), in order to have in a single view both hotspot chains in the South Atlantic, which is our zone of interest. We think this general view provides a more global idea of the bathymetric region, and enhances the parallel between the St. Helena and Walvis chains study.

We corrected the text for the misspelling and the grammar mistakes. In the following, we give answers to the remarks and suggestions of the reviewer on the paper version, and then, to the specific comments in the review.

Answers to remarks and suggestions on the paper version

All page numbers refer to the reviewed version.

- p.3-4: we have added in the introduction a paragraph about the swell origin. See answers to question 1 below.
- p.5, second paragraph. Our reference on the ages reported for the Paraná and Etendeka flood basalts was indeed too old. We updated it, and referred to [Gibson et al., 2006].
- p.9, we gave a more detailed explanation for the unclear point about the choice of the main axis.
- p.10, last sentence, St. Helena swell: we clarified the origin of the swell.
- p.10, Walvis swell paragraph: we explained better why the origin of the oldest swells cannot be related to an intraplate setting phenomena (see answer to question 3).
- p.11, the reviewer would prefer to have the discussion on the accuracy of the tracks deduced from the rotation poles and our choice of the linear trends in the previous section (3. Data analysis). But we are basing this discussion on the swells morphology, which are presented in this section (4. Results). We cannot discuss this argument before describing the swells.
- p.11, we removed the repetitive sentence about the choice of the linear trend.
- p.11, the reviewer noticed that the definition of the buoyancy flux is out of place. We agree with his suggestion and moved it to the end of the Data Analysis section.

- p.12, the reviewer points out that Q_s is only defined in the next section. However, we introduced this variable in the third paragraph of the introduction.
- p.15, we added a part discussing the decorrelation of the phenomena responsible for the 10-20 m.y. and the 5 m.y. variations. See answer to question 5.

Answers to specific comments

1. I would expect a swell beneath Hawaii assuming that it is an active hotspot that may have dynamic support from a plume below. But I would not necessarily expect the same for a ~50 Myr seamount chain. So I am left wondering what this swell actually is. I think readers like myself would benefit from some discussion of the source of such swells in a section in the introduction.

Usually, dynamic topography is related to the youngest part of the hotspot chain (a few hundred meters in height) and associated with vertical forces due to the plume uplift. The swell at older parts of the hotspot chain may have two origins: 1) A thinner than 'normal' lithosphere, due to reheating at the time the lithosphere was overriding the hotspot plume. This effect vanishes through time, as the lithosphere cools and subsides while it is driven away from the plume. 2) Stocking of plume material within or beneath the lithosphere or crust (underplating), which has a permanent effect. Since no underplating has been identified along St. Helena and Walvis chains, and since the dynamic topography is spatially restricted along these chains, right over the present-day location of the plume head, we attribute the main cause of the swell to the long-term thermal effect of the plume.

We have added a paragraph in the introduction to include these explanations in the article.

2. The authors chose to project data on a straight line through the maxima of the calculated swell, rather than along the seamounts in the chain. I don't think that is a problem, but the rationale for this choice and its ramifications could be better discussed. Does this choice affect the final outcome?

We choose indeed a straight line to model the chain main axis and study the evolution of the volcanic and swell fluxes along this. Our choice is based on the fact that the rotation poles models on the region were unsatisfying. We tried to fit at the same time the volcanoes and the swell emplacement to determine this linear trend. Since it is a subjective criterion, there are of course several possibilities, and the use of these several trends could change the final computed volumes. However, the length of the translating box used for computation is large enough (1000 km across-track) to include all topographic features and volcanic root spatial extension belonging to the hotspot. This way, the final volumes are very similar regardless of the 'path' chosen for the calculation.

We have clarified this point in section 3.

3. The authors note that the swells near the continental margin may have a different origin from the other parts of the swell and for this reason, they do not interpret this part of the swell. Again, this choice and the rationale should be discussed a little more. Why is that part of the swell different?

We chose not to interpret the part of the swell at the NE of both St. Helena and Walvis chains because of the irrelevant swell amplitude found, when using the swell computation parameters that are adequate along the main part of the hotspot trends. This result means that it is impossible in this region to interpret the swell as the simple result of the plume expression in an intraplate setting, which predicts a general decrease of the swell amplitude from the younger to the older part of the chain. Moreover, the tectonic analysis of the region shows that the older part of the chains were not formed in an intraplate setting (see section 2.1). Different mechanisms are at stake in the NE part of the hotspot chains, and their interpretation does not enter in the goal of our study.

We have intended to clarify this point in the text (see paragraph after Walvis swell description, in section 4).

4. The authors say that Gough is the likely location of the hotspot. Neither Gough nor Tristan are at the center of the swell. Please explain the choice of Gough a little more.

We do not expect the present-day active volcanism (characterizing the present-day plume head location) to be located at the center of the swell, but at the leading edge of the chain. Indeed, the plume requires some time (typically, a few million years) to influence the thermal structure of the lithosphere, until generating the swell maximum. Hotspot volcanism is associated with the ascent of melt through the lithosphere and to the seafloor, and therefore occurring “upstream” from the swell maximum. Gough satisfies this criterion, which is moreover observed for other hotspots, the French Polynesia being another well-known example [e.g. Adam et al., 2005].

We have added a clarification for this point in section 4, right after the swells description, when justifying the choice of our linear trend.

5. In the discussion, the authors explain the 10-20 Myr variability by breaking up of the plume into blobs because of tilting. Then they describe the ~5 Myr variation as solitary waves in the conduit. The rationale behind this dichotomy is not explained. Please tell the reader why you ascribe one wavelength to one cause and another wavelength to another cause.

We agree that no objective criterion makes it possible to decorrelate the phenomena responsible for the 10-20 m.y. and the 5 m.y. variations. What we want to point out in the discussion are the possible physical mechanisms that could be responsible for such observations.

We clarified this point at the end of section 5.1.

80-Myr history of buoyancy and volcanic fluxes along the trails of the Walvis and St. Helena hotspots (South Atlantic)

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Abstract

Walvis and St. Helena are the only long-lived hotspot chains in the South Atlantic. Therefore, their characterization is important to constrain the processes associated with mantle plume formation, their temporal evolution, and the interaction with plate and mantle dynamics in the region. We study the temporal evolution of plume buoyancy and magma production rate along both hotspot chains, which are constrained from the swell and volume of volcanic materials emplaced along the chain. The regional depth anomaly is calculated by correcting the 2' bathymetry grid of Smith & Sandwell (1997, *Science*, 277) for thermal subsidence and sediment loading. We separate the topography associated with volcanism and the swell surrounding the hotspot chains using the MiFil filtering method (Adam et al., 2005, *Geochem. Geophys. Geosyst.*, 6). We then estimate the temporal variations associated with

both parameters by computing volumes along the hotspot tracks. Neither Walvis nor St. Helena show a 'classical' hotspot behavior. We find that two plumes are at the origin of the St. Helena chain. This study also shows a swell associated with the Circe seamount, supporting the existence of a hotspot NW of the St. Helena trail. The variation in swell and volcanic fluxes suggests temporal variability in the plume behavior at time scales of 10-20 m.y. and 5 m.y., which may be related to oscillations and instabilities of the plume conduit, respectively. Cumulative fluxes in the area are largest for Walvis and weakest for Circe, and all are significantly lower than that reported for the Hawai'i hotspot.

Key words: hotspot, mantle plume, buoyancy fluxes, temporal evolution

PACS: 91.45.Fj, 91.45.Jg, 91.50.Ga, 93.30.Mj

1 Introduction

Hotspot chains are the result of the interaction of stationary zones of mantle upwelling (plumes) with an overlying drifting plate [1]. Two main surface manifestations are generally associated with such a plume-lithosphere interaction: (1) a prominent volcanic chain which displays a linear age progression, as plate motion drags the seamounts away from their zone of emplacement above the plume; and (2) a large positive depth anomaly (typically 100's of kilometers in extent and ~ 100 's of meters in height) called a *swell* [2]. The hotspot swells may be produced by several phenomena. Dynamic topography,

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10 associated with vertical forces due to plume uplift, may generate a swell (a few
11 hundred meters in height) in the youngest part of the hotspot chain, where the
12 lithosphere drifts over the plume head. The swell at older parts of the hotspot
13 chain may have two origins: 1) A thinner than 'normal' lithosphere, due to
14 reheating at the time the lithosphere was overriding the hotspot plume. This
15 effect vanishes through time, as the lithosphere cools and subsides while it is
16 driven away from the plume. 2) Stocking of plume material within or beneath
17 the lithosphere or crust (underplating), which has a permanent effect. Since
18 no underplating has been identified along St. Helena and Walvis chains, and
19 since the dynamic topography is spatially restricted along the youngest part
20 of these chains, we attribute the main cause of the swell to the long-term
21 thermal effect of the plume.

22 The swell is a direct consequence of the buoyant plume upwelling, and there-
23 fore, it is commonly used as the parameter to quantify the hotspot strength
24 [3–5]. However, this parameter is inadequate to study the history of a hotspot
25 chain and the underlying plume dynamics, as the swell amplitude decreases
26 with time due to lithospheric cooling. The volcanic material accumulated along
27 the hotspot chain, which is not affected by this cooling, is a direct record of
28 the volcanic output to the seafloor. However, while being a good indicator of
29 hotspot activity, the volume of extrusives may somewhat underestimate the
30 total melt production, as other processes may operate such as melt entrap-
31 ment in deep lithospheric levels, or lateral melt migration (i.e., lithospheric
32 cracks) and emplacement away from the volcanic chain. The combined analy-
33 ses of both swell and volcanic volumes accumulated along the chain is therefore
34 most adequate and necessary to constrain long-term plume activity [5].

35 In this study, we use the available bathymetric [6], sediment thickness and

seafloor age data [21] to correct for thermal subsidence and sediment loading, and obtain a seafloor depth anomaly around the Walvis and St. Helena hotspot chains. We then separate the swell and volcanic topography components from the residual bathymetry [7]. We then estimate the temporal evolution in production rate of volcanic material Q_v (including both the volcanic edifices and compensating root due to plate flexure) and in the swell flux Q_s . We compare these results with those from Hawai'i [5], the most typical example of a hotspot chain.

2 Tectonic setting

2.1 Description of the Walvis and St. Helena chains

Walvis and St. Helena are the two main hotspot chains found in the South Atlantic. They are formed by wide and continuous zones of diffuse volcanism (oceanic islands, seamounts and small ridges), that locally reach a width of more than 500 km. It is generally considered that these volcanic chains have been created by mantle plumes interacting with the overlying African plate, and that the locus of present-day activity is situated in the proximity of the Islands of Tristan da Cunha for the Walvis Ridge. For St. Helena, the youngest age of volcanism (2.6 Ma) is reported at Josephine seamount [4,8] (see Figure 1). This is consistent with the reported general age progression of volcanism away from the St. Helena and Gough islands and towards the African continent [9,10].

The Walvis Ridge extends WSW some 2800 km from the southwest African continental margin towards the Mid-Atlantic Ridge near Tristan da Cunha

59 and Gough islands (Figure 1). Based on morphological and structural charac-
60 teristics, the chain displays different tectonic settings at the time of volcanic
61 emplacement and loading. The northeastern part (east of 3°E) has a ridge-like,
62 elongated morphology rising 2-3 km above the surrounding seafloor. Large-
63 scale block faulting in this area is prominent, as inferred from the gravity,
64 bathymetry and seismic data [13,14]. Further southwest, the ridge splits into
65 two branches, one trending N-S and a second one trending NE-SW, both
66 composed of individual seamounts and guyots. The N-S trending branch ter-
67 minates near 34°S, whereas the oblique branch continues WSW towards the
68 present-day hotspot location on the eastern flank of the Mid-Atlantic Ridge.

69 The initial manifestation of the Walvis hotspot occurred at the opening of
70 the South Atlantic 130 Ma ago, when it contributed to the emplacement of
71 the Paraná (Southeast Brazil) and Etendeka (southwest Africa) flood basalts,
72 127.5 to 139 Ma old [15]. The hotspot was located initially on the American
73 plate, crossed the axis 80-70 Ma ago, and progressively separated from it to
74 its present-day location on 7 Ma-old African plate.

75 Evidence for this transition from on-axis to intraplate volcanism is found
76 in many geophysical and geochemical observables. The geochemical analy-
77 ses evidence a westward migration of the spreading axis, away from the plume
78 [9,16]. The structural differences between the northeast (oldest) and southwest
79 (youngest) sections of the chain are also reflected in their compensation mech-
80 anisms. While the older part is compensated by over-thickening of the oceanic
81 crust [13,14], the western part is instead regionally compensated by the bend-
82 ing of a lithosphere with an effective elastic thickness of 5-8 km [14]. These
83 different compensation mechanisms reflect the transition with time from a
84 near-axis emplacement with a thin lithosphere and over-thickened crust to an

85 intraplate setting with a thicker lithosphere. This transition is also observed in
86 the mode of volcanic emplacement, that produces a province of intermittent,
87 isolated volcanism rather than a structurally continuous ridge.

88 The St. Helena chain is less well-defined, and is characterized by a broad and
89 ill-defined band of scattered seamounts and volcanic ridges, with a shorter
90 history than that of Walvis, but with a similar progressive separation of the
91 hotspot from the axis. The oldest dated sample along the St. Helena chain
92 is 81 Ma [10], dredged on a seamount situated at the northeastern extrem-
93 ity of the chain (Figure 1). The Cameroon line, northeast of this volcano,
94 seems to form a bathymetric extension of the St. Helena chain into the Gulf
95 of Guinea and linking with the African continent. However, the Cameroon
96 lineament does not show any age progression [17], and therefore cannot be
97 directly linked to a hotspot origin. The origin of the St. Helena chain on the
98 African plate is associated with the emplacement of the Brazilian seamounts
99 on the American plate [10]. Geochemical [16,18] and seismological studies [19]
100 indicate a migration of the St. Helena plume toward the spreading axis. Circe
101 seamount (Figure 1) has been proposed as the site of an active hotspot by
102 Schilling et al. [16]. It is dated at 6.6 Ma, and may be part of a hotspot trail
103 whose present-day location should be some 130 km SW of Circe seamount [8].

104 2.2 Age evolution

105 The distribution of the available volcanic ages (Figure 1) shows a large scatter,
106 with many volcanic edifices located in the same area displaying differences
107 in age of more than 10 Ma. For example, at 34°S, we observe a 44.6 Ma
108 volcanic age between sites dated at 64.4 Ma (south) and 61.6 Ma (north). This

age scattering can be explained by diffuse volcanism, due either to a broad plume (several hundreds of km in diameter) or the presence of a cluster of plumes [9]. Independent geophysical data support the latter hypothesis, since numerous small-wavelength elongated features appear in filtered geoid and topography maps [20], which could indicate the presence of multiple narrow plumes. The likely presence of additional hotspot chains in nearby areas, such as the Circe seamount and proposed associated trail, is consistent with the probable presence of several hotspots [8,16].

Some features uncorrelated with the Walvis and St. Helena plumes have also been reported, as Vema (18 Ma) and 7 East (91 Ma) seamounts south of the Walvis chain. Haxel & Dziak [12] have detected volcano-acoustic signals around a seamount situated on the northern edge of the Walvis track at 5.22°W 32.96°S (see Figure 1). These signals are interpreted as volcanogenic explosions suggesting present-day magmatic activity. The authors support the hypothesis that this phenomenon is not directly related to the Walvis mantle plume, but rather to extensional fracture zones along inactive segments of the chain.

The Walvis and St. Helena chains may have recorded the decrease in velocity of the African plate, that occurred between 19 and 30 Ma [8]. According to O'Connor et al. [8], the migration rate along the St. Helena chain changed from 30 mm/yr to 20 mm/yr at 19 Ma. This change occurred at 30 Ma along the Walvis chain, with a reduction from 31 mm/yr to 22 mm/yr. However, the plate velocity diminution has been computed considering that the chain follows a continuous NW direction [8], without taking into account hotspot tracks deduced from the rotation poles. Moreover, the slowdown is estimated solely on the two younger ages available for each chain, and is therefore poorly constrained.

135 3 Data analysis

136 We first compute the depth anomaly throughout the study area. Using the
137 global age grid of Müller et al. [21] and the GDH1 thermal subsidence model
138 of Stein & Stein [22], we compute the thermal subsidence, which we subtract
139 from the bathymetry [6] (Figure 1). The resulting depth anomaly is then
140 corrected for sediment loading (see [7] for computational details), to obtain
141 the residual bathymetry. In order to test different cooling models, we have also
142 performed the computation with the Parsons & Sclater [23] thermal subsidence
143 model. The results (e.g., flux vs. time estimates) are shifted relative to each
144 other but preserve the variations and their amplitudes [5]. Interpretation of
145 the buoyancy and volcanic flux variations in time are therefore independent of
146 the thermal model used, even if their absolute value remains unconstrained.

147 In order to separate the swell (H_S) and volcanic edifices (H_V) components from
148 the resulting depth anomaly grid, we adapted the MiFil method developped
149 by Adam et al. [7]. This low-pass filtering method effectively removes the
150 topography associated with volcanic edifices from the depth anomaly, and
151 gives the topography corresponding to the swell component H_S , as shown for
152 the St. Helena and the Walvis chains in Figures 2a and 2b, respectively. The
153 volcanic component H_V is thus the difference between the residual bathymetry
154 and the swell component H_S .

155 The H_S and H_V data can then be used to compute both the swell volume
156 and the volume of erupted material (volcanic edifices). The swell volume cor-
157 responds to the volume between the reference depth anomaly (zero) and the
158 swell H_S . To estimate the volume of erupted material, we consider the vol-

159 canic topography, and calculate the associated compensating root. We assume
 160 that the volcanic loading is supported by an elastic lithosphere [26] with an
 161 elastic thickness of 7 km, as deduced from the age of the crust at the time of
 162 loading. Note that the choice of this compensation (regional), rather than a
 163 local (Airy) compensation, does not have a significant influence on the final
 164 results, as the computed volcanic volumes are unchanged [5].

165 We then compute the variation of the buoyancy (Q_S), inferred from swell
 166 volume variations [3], and volcanic (Q_V) fluxes through time for each of the
 167 two volcanic chains in a fashion similar to that of Vidal & Bonneville [5].
 168 We translate a rectangular box of fixed size (1000 km long across-track and
 169 20 km wide along-track) along the main axis of the chains to compute the
 170 variation of the swell and volcanic material along this trend. We chose to
 171 approximate the main axis by the straight traces shown in Figure 2, since the
 172 hotspot tracks calculated from rotation poles [9,24,25] do not match either the
 173 swell or the volcanic chain trends. The length of the computing box, in the
 174 direction transverse to the trend, is taken large enough (1000 km) to include
 175 all the topographic features created by the hotspot and/or all its volcanic
 176 root. Therefore, volume calculations are scarcely affected by using other paths
 177 (e.g. theoretical hotspot track) for our computation instead of the straight line
 178 presented here [5].

179 We also introduce the buoyancy flux (B) temporal evolution along the main
 180 axis trends. The buoyancy flux is commonly used to quantify the rate of swell
 181 formation [3]:

$$182 \quad B = (\rho_m - \rho_w)AV_p \quad (1)$$

183 where ρ_m and ρ_w are mantle and seawater densities respectively, A is the area
 184 of the swell in a vertical plane transverse to the hotspot track, and V_p the plate
 185 velocity in the hotspot frame. B can therefore be written as $B = (\rho_m - \rho_w)Q_s$.

186 4 Results

187 We identify swells associated with both the St. Helena and Walvis chains, and
 188 an additional one associated with the Circe seamount (Figure 2), north of
 189 St. Helena’s trail.

190 **St. Helena swell** - The St. Helena swell is composed of two circular highs,
 191 one centered at longitude 6.5°W , the other at longitude 9°W (Figure 2a). This
 192 observation suggests that two plumes may be at the origin of the St. Helena
 193 chain. It is also interesting to note that the dated volcanoes are located slightly
 194 south of these maxima, indicating a probable influence of weakness zones of
 195 the lithosphere. The strong increase in swell amplitude, northeast of the chain
 196 (>50 Ma), will not be discussed further here, since its origin is not related to
 197 a plume, but more probably to continental processes (see section 2.1).

198 **Circe swell** - The swell has a maximum ~ 400 m amplitude and a 300-400 km
 199 width (Figure 2a). The swell maximum is located 150 km SW of the 6.6 Ma
 200 Circe seamount, which is part of an independent hotspot trail, as suggested
 201 by O’Connor et al. [8].

202 **Walvis swell** - The Walvis chain shows several maxima along its track. The
 203 high associated with the presumed present-day hotspot location has an am-
 204 plitude of ~ 1400 m and a diameter >500 km, with a maximum located NE of
 205 Gough Island and ESE of Tristan da Cunha (Figure 2b). The dated volcanoes

206 are here again located on the edge of the swell and not on its maximum. The
207 middle section of the track, between 28°S and 37°S, shows two adjacent swells,
208 with a somewhat smaller amplitude of ~ 1200 m, and a width of ~ 400 km. The
209 easternmost swell is elongated along a SW-NE direction, whereas the western
210 one has a trend close to the NS direction. Note that both trends are parallel
211 to the volcanic chain.

212 Important swell amplitudes are found in the NE part of both St. Helena and
213 Walvis chains (Figure 2). Considering the ages of the volcanism associated with
214 this part of the chains, these older swells (>50 Ma for St. Helena and >65 Ma
215 for Walvis) have a too important amplitude to be considered as the result of
216 the plume expression in an intraplate setting (see section 2.1). Indeed, after the
217 plume reheating, the lithosphere cools and subsides, and the subsequent mean
218 swell amplitude should decrease. Figure 2 shows that the swell in the older part
219 of both chains does not follow this tendency, thus indicating that other physical
220 processes are at stake. Therefore, the parameters we used to characterize the
221 Walvis and St. Helena hotspot swells are not adequate to characterize the
222 NE depth anomaly, which implies different phenomena, maybe of continental
223 origin, occurring at different spatial scales [27]. Hence, these parts of the swells
224 (>50 Ma for St. Helena and >65 Ma for Walvis) will not be further studied.

225 The hotspot tracks, deduced from rotation poles (displayed in Figure 2b),
226 match only the overall alignment and orientation of the swells along the cen-
227 tral and northeasternmost portions of the chain, but are not consistent with
228 the location of the swell at the southwesternmost end of the chain (Figure 2b).
229 Indeed, all the models choose Tristan da Cunha as the present-day location
230 of the plume, whereas the swell morphology clearly indicates that Gough is
231 the most probable origin. Note that the shift between the plume head em-

232 placement and the swell maximum is a classical feature of a hotspot chain.
 233 Indeed, the plume requires some time (typically, a few million years) to in-
 234 fluence the thermal structure of the lithosphere, and hence generates a swell
 235 whose maximum is located a few hundred kilometers from the present-day
 236 plume head location, in the direction of plate motion (NE, here). On the
 237 other hand, hotspot volcanism is associated with the ascent of melt over the
 238 plume head, through the lithosphere and to the seafloor, and hence occurring
 239 'upstream' from the swell maximum. Gough is therefore the best candidate for
 240 the present-day Walvis plume location. Since the tracks deduced from rotation
 241 poles do not accurately describe the plume trajectory, we choose to describe
 242 it by the linear trends displayed in Figures 2a and 2b. We assume a linear age
 243 progression of volcanism due to the drift of the African plate along them.

244 Figure 3 shows the swell amplitude along the trend, as a function of distance
 245 from the zone of active volcanism. The reported ages of volcanism [9,10] show
 246 an overall age progression, but the large scatter in the data suggests that
 247 the chain formation is complex, with active volcanism extending over a large
 248 area. Distance along the proposed axes of both chains can be used as a proxy
 249 for age if we assume a constant velocity of the African plate of 29 mm yr^{-1}
 250 [8]. O'Connor et al. [8] also report a substantial deceleration of the African
 251 plate speed at 20-30 Ma, but this event is poorly constrained, and is not
 252 systematically observed in other plate motion models [9,24,25]. We thus chose
 253 to extrapolate the volcanic ages along the trend (bottom x -axis in Figures 3
 254 and 4), with a constant migration rate of 29 mm yr^{-1} . We also represent in
 255 Figure 4 the buoyancy flux B , commonly used to quantify the rate of swell
 256 formation (see section 3).

257 The swell along the volcanic chains (Figure 3) does not display the typical

258 decay in amplitude with distance (age) from the present-day position of the
 259 hotspot. We observe instead a maximum in the swell amplitude at ~ 800 km
 260 (~ 30 Ma) and ~ 500 km (~ 15 -20 Ma) along St. Helena and Walvis track,
 261 respectively. Note that the width of the swell profile along the St. Helena track
 262 is due to the presence of two swell maxima, slightly shifted off-axis (see above
 263 section, and Figure 2a). Another large bump is observed along the Walvis
 264 chain, between 35 and 60 Ma. In the next section, we analyse the temporal
 265 variations of the deduced buoyancy fluxes.

266 **5 Discussion**

267 *5.1 Temporal evolution of plume fluxes*

268 **Swell flux Q_s -**

269 The calculated buoyancy fluxes as a function of volcanic age are shown in
 270 Figure 4. For St. Helena, we observe a single wide bump centered at ~ 30 Ma,
 271 whose width can be explained by the presence of two adjacent swells (see pre-
 272 vious section). We observe several maxima in the swell flux along the Walvis
 273 chain: a marked maximum at ~ 10 Ma and two additional ones of smaller am-
 274 plitude at 38 and 54 Ma. These secondary maxima are subdued in Figure 4,
 275 due to the scaling, but they are well-visible on the Walvis swell map (Fig-
 276 ure 2b). The older parts of the buoyancy flux (> 50 Ma for St. Helena and > 65
 277 Ma for Walvis) are not interpreted (see swell amplitude discussion, section 4).

278 The Hawai'i chain, which has a shorter life span (< 45 Ma) than that of the
 279 St. Helena (~ 60 Ma) and Walvis chains (~ 80 Ma), is probably the best

characterized hotspot trail [5], and can be used as a reference in our study. Note that we ignore here the Emperor part, where no swell is reported, and whose volcanic flux is much smaller [5]. Hawai'i shows two important peaks at 3 and 15 Ma. It is important to note that the 3 Ma peak may not be a "real" one since plumes require some time (typically a few million years) to influence the thermal structure of the lithosphere. The swell may then not be totally formed yet at the youngest extremity. Therefore, the age difference between the two peaks in the Hawaiian swell (Figure 4, bottom) could still increase in the next few million years.

Volcanic flux -

The St. Helena chain displays a peak at 10 Ma, preceded by another peak at 30 Ma, in the magma production rate Q_v . Based on both the lack of correlation between variations in Q_v and Q_s (Figure 4), and on the presence of two marked swells (Figure 2a), we propose that the St. Helena trail is formed by two hotspots, instead of a single one. Recent evidence of the existence of two plumes beneath the younger part of St. Helena chain, given by tomography [28], favor this hypothesis.

The Walvis chain also shows a peak at 10 Ma in the magma production rate Q_v , correlated with the main peak in the buoyancy flux profile (Figure 4). This main peak is preceded by two secondary peaks in Q_v , at 39 and 59 Ma, also correlated with two smaller peaks in Q_s at 38 and 54 Ma (Figure 4 and above discussion on Q_s). This correlation between Q_v and Q_s strongly suggests a common origin for both fluxes, with a single plume that peaked in activity at 10 Ma with pulsations 10-20 Ma apart. These pulsations are superimposed on an apparent long-term waning of the plume. We see indeed a progressive

305 overall decrease in Q_v since a maximum at about 60 Ma. This decrease in the
 306 volcanic activity is also apparent in the progressive diminution of the size and
 307 density of seamounts at the seafloor (Figure 1). In comparison, the production
 308 of magma increases drastically during the last 30 Ma for Hawai'i (Figure 4). A
 309 peak is observed at 15 Ma along this chain with a pronounced increase to the
 310 present time, suggesting that the plume is waxing and may have not reached
 311 yet its maximal activity.

312 Both St. Helena and Walvis show short-term variations in magma production
 313 rate Q_v , with a periodicity of about 5 m.y., which has also been reported for
 314 Hawai'i [5].

315 **Evolution of fluxes -**

316 The most significant result of this study is that the Walvis plume does not
 317 appear to be steady state, but rather shows pulsations at 10-20 m.y.. This
 318 periodicity cannot be determined for St. Helena, as it is likely the result of the
 319 activity of two plumes and their temporal variations. A possible explanation
 320 for these pulsations is the tilt of the plume conduit due to large-scale mantle
 321 advection [11,29], as they may develop oscillations if their dip is larger than 60°
 322 [29]. This mechanism has been also invoked to explain the scatter in volcanic
 323 ages along other hotspot chains such as Louisville [30]. In this study, we suggest
 324 that the observed periodicity of 10-20 m.y. may be the first estimate of the
 325 frequency of these oscillations, deduced from observed data.

326 Walvis also shows a marked decrease in volcanic flux Q_v through time which
 327 may reflect a progressive and steady waning of the plume and its associated
 328 activity during the last 60 Ma or more; its extinction could occur in 30 Ma
 329 if this decline continues at a similar rate. The Walvis plume conduit is not

330 imaged by tomography models [31,32], which may be also an indicator of its
 331 weakening and possible extinction. Alternatively, there is a progressive increase
 332 of the age of the lithosphere over which the volcanism is emplaced due to
 333 the migration of the ridge away from the hotspot. The resulting thickening
 334 of the lithosphere with time could play a role in this reduction of Q_v , but
 335 this interpretation is not supported by the lack of such a pattern along the
 336 St. Helena chain.

337 The shorter-term variations with a periodicity of ~ 5 m.y. observed in the
 338 magma production rate Q_v for St. Helena and Walvis (Figure 4) have a too
 339 small periodicity to be associated with a plume tilting phenomenon, which can
 340 sustain tilts up to 60° , depending on the surrounding mantle viscosity [11]. No
 341 evidence of the decorrelation of both the 10-20 and 5 m.y. pulsations can be
 342 affirmed. One possible explanation, however, could be the presence of solitary
 343 waves within the plume conduit [33]. These perturbations have been invoked
 344 to explain both isotopic heterogeneities [34] and a similar 5-7 m.y. periodicity
 345 in volcanism [5] along the Hawai'i chain (Figure 4).

346 5.2 *Total volumes and fluxes*

347 We have computed the cumulative volcanic and swell volumes for the St. He-
 348 lena and Walvis chains, and reported the estimation of swell volume for Circe
 349 in Table 1; owing to the lack of data, we cannot provide an estimate of its
 350 volcanic flux. In Table 1 are also reported the values found for Hawai'i (from
 351 [5]). We have also calculated the mean fluxes along each chain, which we pre-
 352 fer over the present-day values normally reported in the literature, as they
 353 integrate the activity and strength of hotspots over their lifespan.

354 Hawai'i has the greatest mean volcanic and swell fluxes, thus indicating that
355 it is the most vigorous of all the identified plumes. Walvis and St. Helena
356 have similar volcanic fluxes but Walvis' swell flux is three times greater than
357 that of the St. Helena system. As St. Helena results from the combination of
358 two plumes, we can deduce that these are two small ones. The low swell flux
359 associated with Circe suggests that it is a weak and/or small plume.

360 **6 Conclusion**

361 In this paper we have presented the first characterization of the swell and
362 volcanic fluxes and their temporal evolution along the Walvis and St. He-
363 lena hotspot trails. Both hotspot trails are associated with very broad swells,
364 with the volcanic activity slightly offset relative to the swell maxima. For
365 Walvis, the swell maximum shows a marked offset with respect to the pro-
366 posed present-day hotspot location inferred from rotation pole reconstruction
367 (Tristan da Cunha), suggesting that the trajectory of this plume is not accu-
368 rately described by these models. We propose that Gough is the most proba-
369 ble present-day hotspot location. We also find a modest swell associated with
370 the Circe seamount, north of the St. Helena trail, supporting the proposed
371 presence of a hotspot whose location is still undetermined, and an associated
372 volcanic chain.

373 The Walvis hotspot appears to be the result of a single, waning plume, that
374 shows variations in the volcanic and swell flux at a 10-20 m.y. time-scale, and
375 additional, shorter-term variations of about 5 m.y. in the volcanic flux. In
376 contrast, the St. Helena chain appears to be the result of two hotspots, which
377 precludes the interpretation of calculated volcanic and swell fluxes in terms

378 of temporal variability of a single plume. This chain shows also a volcanic
379 periodicity of 5 m.y., similar to that observed along the Hawai'i chain. The
380 10-20 m.y. periodicity may be due to the tilting of the mantle plume conduit
381 under mantle advection, whereas the 5 m.y. variabilities could be explained
382 by instabilities in the conduit itself.

383 The estimation of the mean swell and volcanic fluxes makes it possible to
384 compare the relative strength of the South Atlantic plumes. The strongest
385 is Walvis, followed by the two St. Helena plumes, and probably Circe. The
386 Hawai'i plume (Pacific), which is the reference hotspot in our study, remains
387 the most vigorous among all these plumes.

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483 **FIGURE & TABLE CAPTIONS**

484 **Fig. 1.** Bathymetry of St. Helena and Walvis chains (2' bathymetry grid from
 485 [6]), and published volcanic ages (in million years, from [9,10]). Black lines
 486 indicate the traces used to study the temporal evolution of hotspot fluxes
 487 (see text for discussion). The white and black stars indicate the present-day
 488 location of the Walvis plume inferred by Courtillot et al. [4] and Steinberger
 489 [11], respectively. The white dot on Walvis northern edge indicates the location
 490 of presumed present-day underwater volcanism as inferred from hydrophone
 491 events [12].

492 **Fig. 2.** Calculated swell associated with the St. Helena and Walvis chains.
 493 a) Numbers correspond to age of volcanism in million years [9,10]. b) For
 494 readability, we only report the most recent volcanic ages (< 1 Ma) along
 495 the Walvis chain. Hotspot tracks deduced from rotation poles [9,24,25] are
 496 also reported for comparison (see text). In both maps, the 2500 m isobath
 497 (thin black line) marks the position of the ridge and volcanic islands, and
 498 the bold black line indicates the traces used to study the temporal evolution
 499 of buoyancy and volcanic fluxes along both chains. The filter parameters to
 500 obtain the swell map are $r=45$ km and $R=350$ km for the minimization and
 501 filtering (see [7] for details).

502 **Fig. 3.** Swell amplitude along the St. Helena (top) and Walvis (bottom) trends
 503 (see Figure 1), as a function of distance from the present-day hotspot location
 504 (upper x -axis). Available ages of volcanism (gray arrows and numbers in Ma
 505 [9,10]) and calculated ages assuming a constant velocity (29 mm yr^{-1}) for the

506 African plate (lower x -axis) are also shown along the horizontal axis.

507 **Fig. 4.** Calculated buoyancy (gray) and volcanic (black) fluxes for the St. He-
508 lena (top) and Walvis (middle) chains, as a function of the interpolated age
509 of active volcanism (see text). Gray arrows point the secondary maxima at 38
510 and 54 Ma in the Walvis buoyancy flux (see discussion). For comparison, the
511 buoyancy and volcanic flux for Hawai'i are given in the bottom graph (from
512 [5]). Note the change in vertical scale, for readability.

513 **Table 1.** Total volumes and volume fluxes of volcanic material and swell for
514 Circe, St. Helena and Walvis (this study), and Hawai'i (from [5]). Note that
515 the total fluxes here are calculated as a mean flux along the chain.

Figure 1
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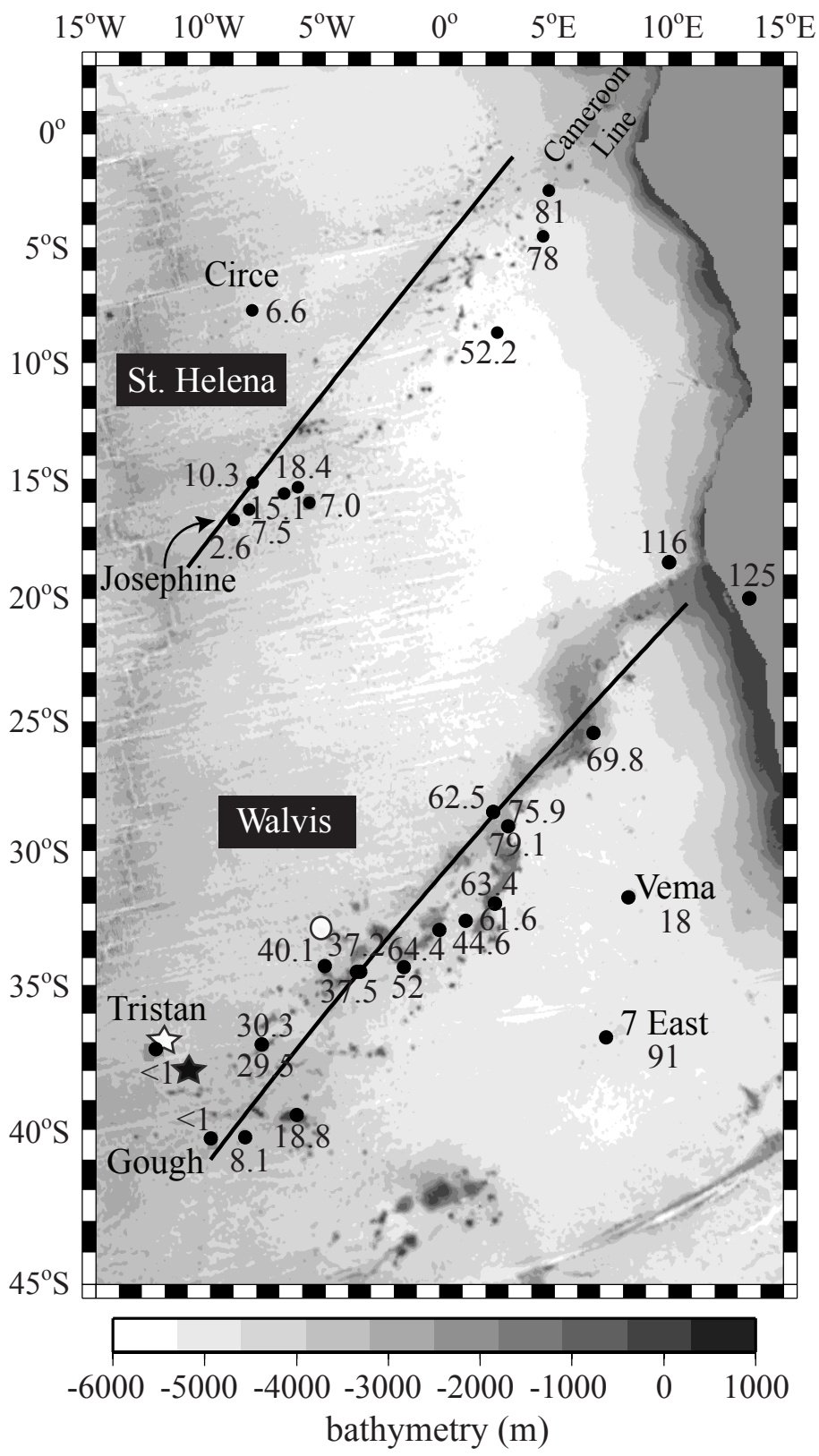


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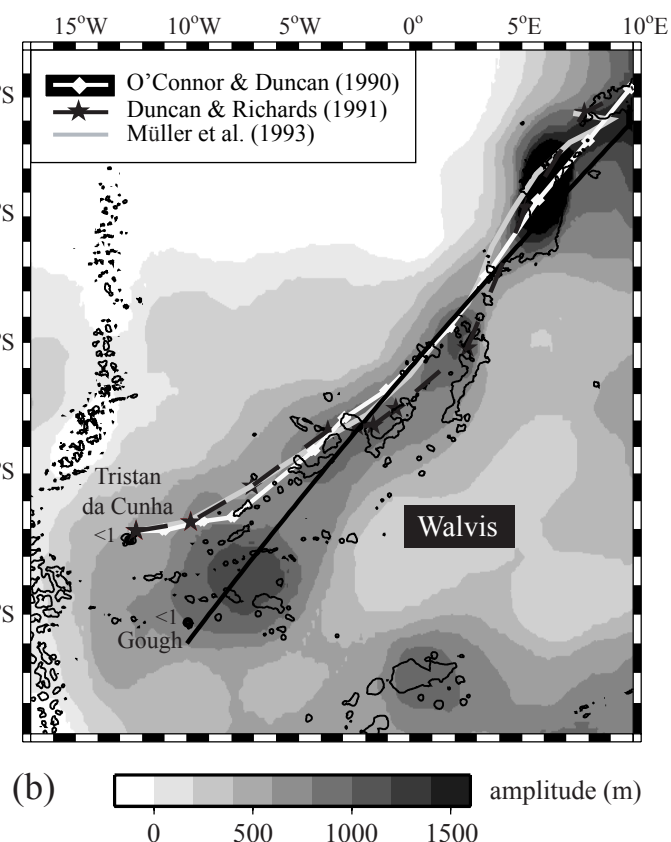
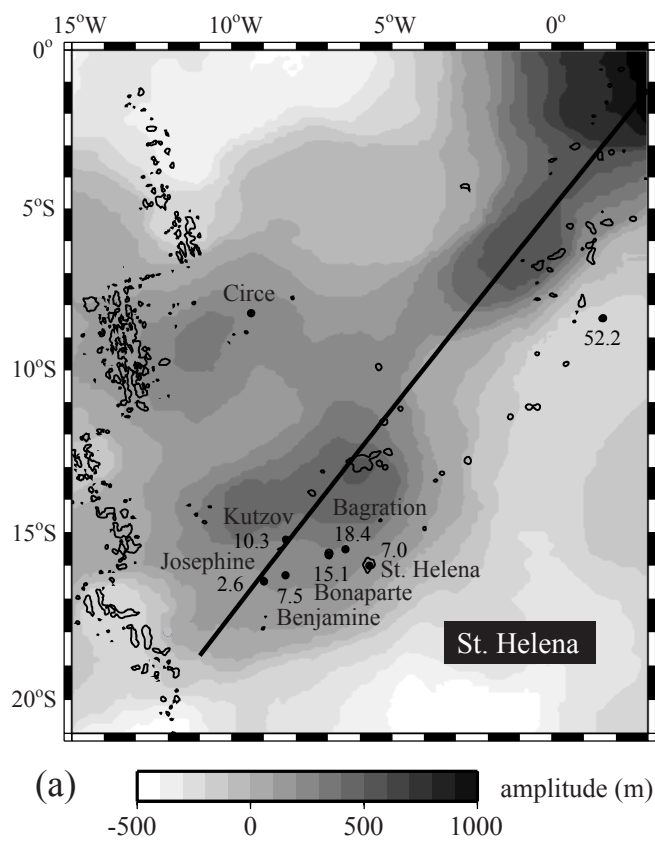


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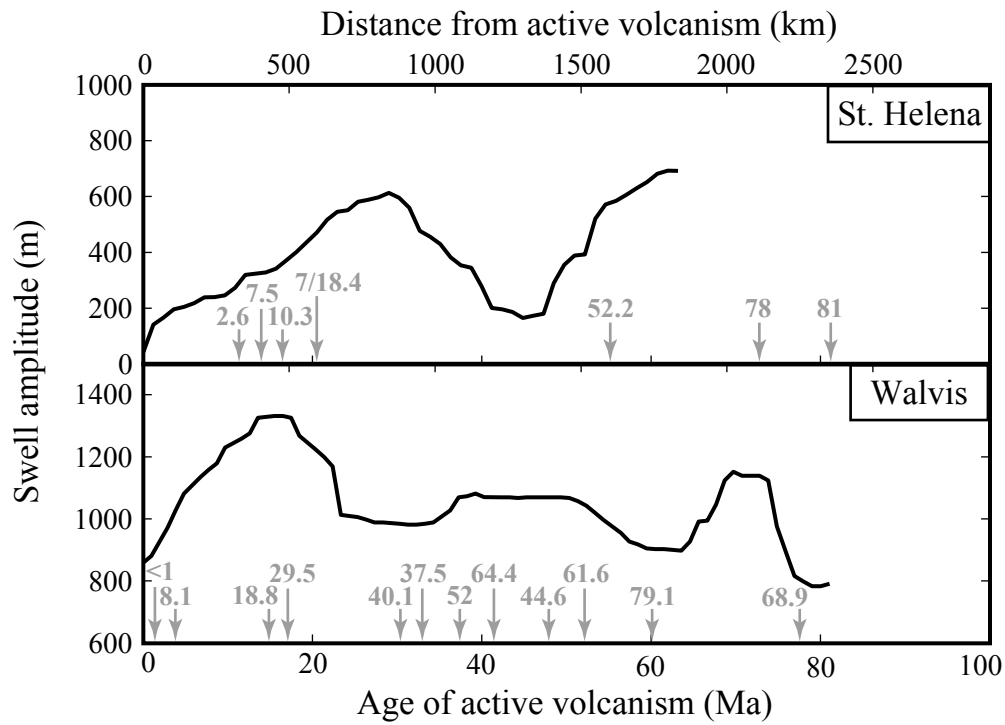
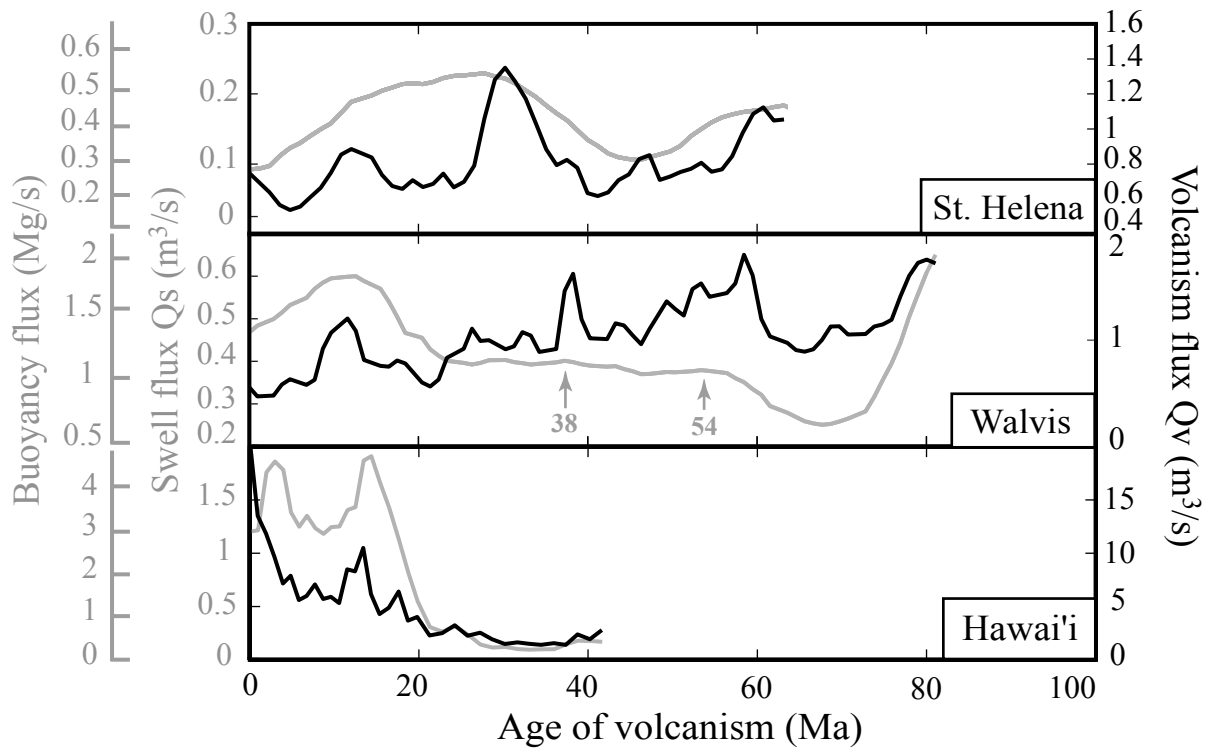


Figure 4
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	Volcanic volume ($\times 10^5$ km ³)	Swell volume ($\times 10^5$ km ³)	Volcanic flux (m ³ s ⁻¹)	Swell flux (m ³ s ⁻¹)	Buoyancy flux (Mg s ⁻¹)
Circe	-	0.65	-	0.09	0.22
St. Helena	11.1	2.33	0.76	0.16	0.37
Walvis	21.4	8.79	1.00	0.41	0.96
Hawai'i	61.8	10.0	4.70	0.76	1.75