GeoResJ 1–2 (2014) 1–7

Contents lists available at ScienceDirect

GeoResJ

journal homepage: www.elsevier.com/locate/GRJ

Reconstructing the link between the Galapagos hotspot and the Caribbean Plateau

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ARTICLE INFO

Article history:
Available online 6 March 2014

ABSTRACT

Most authors agree that parts of the Caribbean plate are an igneous Plateau underlain by Farallon lithosphere that was trapped in between the North and South American plates. However, the origin of the thickened crust is debated. The theory of oceanic plateaus forming as magmatic outpouring related to a plume arrival became prominent when Large Igneous Provinces could be traced back to hotspots. The present-day proximity of the Galapagos hotspot made it an obvious candidate for associating its plume head arrival with the formation of the Caribbean Plateau. However, it was shown that in a fixed or moving Indian-Atlantic hotspot reference frame, plate reconstructions predicted the Galapagos hotspot a thousand or more kilometres away from the Caribbean plate at the time of Plateau formation (~88–94 Ma). Here, we calculate the goodness of fit for the Pacific hotspot reference frame and the recently developed Global Moving Hotspot Reference Frame. We show that both frames lead to good correlations between the paleo-positions of the Caribbean Plate and the Galapagos hotspot, when a docking time of the Caribbean plate to South America of 54.5 Ma is assumed. As this result is consistent with abundant evidence that lends support for a Galapagos hotspot origin of the rocks that form the Caribbean Plateau, proposed alternative mechanisms to explain the thickened crust of the Caribbean Plateau seem to be unnecessary. Finally, based on our model, we also derived an age distribution of the lithosphere underneath the thickened crust of the Caribbean Plateau.

Introduction

The Caribbean Sea is a complex tectonic system with numerous components. Because of the lack of sea-floor anomalies, the origin of these components is widely debated. The largest and perhaps most controversial component is the Caribbean Plateau that makes up the bulk of the Caribbean seafloor (Fig. 1). This Plateau is a large igneous province of up to 20 km thick crust [1] and it is predominantly between 88 and 94 Ma old (Fig. 1) [2,3]. The mechanism and place of formation of this Plateau is still the focus of debates. While the Caribbean Plateau is often referred to as the Caribbean Large Igneous Province (CLIP) or the Caribbean-Colombian Plateau, these terms also refer to regions that have been accreted onshore [4]. As such, we will use the term Caribbean Plateau to focus on the submarine section of the Plateau.

Agreement exists that the Caribbean Plateau was built on top of a piece of former Farallon lithosphere that was trapped in between North and South America [6,3]. To accommodate the Farallon lithosphere between the Americas, westward subduction initiated in either the Lower [7,8] or Upper Cretaceous [9,3] at a transform boundary [8] or alternatively subsequent to polarity reversal [3,7]. Subduction initiated either as a response to the collision of the Caribbean Plateau with the Great Antillean Arc [10,11,5] or possibly because of a change in the spreading rate of the Mid-Atlantic Ridge [7,8].

Disagreement remains on the causal mechanism for the thickened crust of the Caribbean Plateau. One theory invokes that the Caribbean Plateau formed above the rising plume head of the paleo-Galapagos hotspot and is due to the associated volcanic outbursts [10,6], analogous to the creation of the Ontong-Java Plateau above the Louisville hotspot [12]. This is supported by geochemical studies of the Caribbean Plateau, which suggest an impact of a plume head at the base of the lithosphere [13–16]. It was also noted that only plume melts have the required temperature to

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http://dx.doi.org/10.1016/j.grj.2014.02.001
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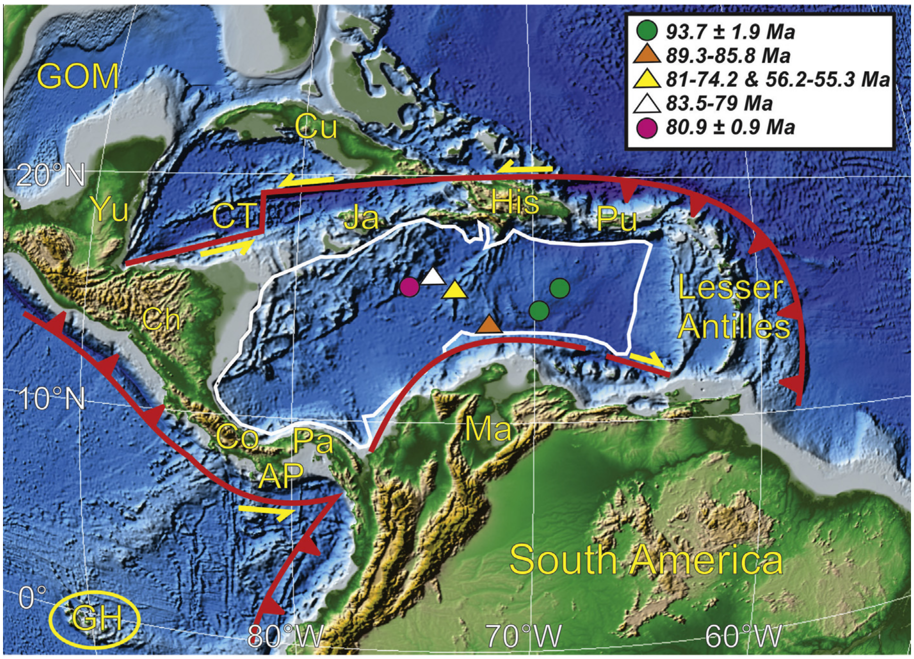

Fig. 1. Overview of the Caribbean Sea. Plate boundaries are indicated in red. At present-day the northern plate boundary is characterized by transtension and the southern boundary by a complicated transpressional regime [5]. Subduction zones along the Lesser Antilles arc and Central America form the plate boundaries on the western and eastern edges of the region, respectively. White outline shows the extent of the Caribbean Plateau [1]. Circles (radiometrically dated) and triangles (not possible to be radiometrically dated) indicate dredge sample locations. Sample ages are given in insert box [2]. Abbreviations: Galapagos hotspot (GH), Maracaibo Block (Ma), Panama (Pa), Azuero Peninsula (AP), Costa Rica (Co), Chortis Block (Ch), Yucatan Block (Yu), Jamaica (Ja), Cuba (Cu), Hispaniola (His), Puerto Rico (Pu), Cayman Trough (CT), Gulf of Mexico (GOM).

generate the lavas on the Caribbean Plateau [17,11]. Furthermore, the basalts from the Galapagos hotspot have a deep mantle signature combined with other complexities associated with depleted mantle and recycled oceanic crust consistent with the Caribbean Plateau basalts [18]. Finally, the short duration of the bulk formation of the Caribbean Plateau suggests plume-induced melts [2].

Nevertheless, Pindell et al. [19] have challenged this theory for two reasons: the first being the patchy record of accreted hotspot tracks between 21.2 and 51.9 Ma, probably lost due to subduction under Central and South America with only one sample from the southern Azuero Peninsula (Fig. 1) leading to an age of 32.8 ± 0.5 Ma in this range [20]; and secondly, because of the thousand kilometres between the Galapagos hotspot and the reconstructed position of the Caribbean Plateau at the time of formation predicted by reconstruction models that are based on fixed or moving Indian-Atlantic hotspot reference frames [19,21]. These difficulties have led Pindell et al. [19] to propose a model in which the Atlantic asthenosphere upwelled through a remnant slab window caused by westward subduction of the proto-Caribbean spreading centre.

It was shown, however, that the basalts from the Plateau have radiogenic isotopes and trace-element ratios showing similarity to deep mantle sources that are inconsistent with ambient shallow mantle upwellings, such as beneath a slab-window [2]. Additionally, Pindell and Kennan [7] demonstrated that when using a fixed Pacific hotspot reference frame [22], a good fit between the paleo-Galapagos hotspot and the reconstructed position of the Caribbean Plateau at the appropriate time of Plateau formation (~94–88 Ma) can be reached.

Thus, as the available geochemical evidence points to the rising plume head of the paleo-Galapagos hotspot as the source of the Caribbean Plateau rocks, we revisit Pindell and Kennan's [7] observation here and develop a new reconstruction model using two recent reference frames for the Pacific hotspots: Wessel and Kroenke [22] and Doubrovine et al. [23]. The necessary assumptions to reach a good correlation between the paleao-Galapagos hotspot and the Caribbean Plateau between ~94 and 88 Ma are outlined in sections 'Reconstructing the Caribbean' and 'Correlating the positions of the Galapagos hotspot and the Caribbean Plateau'. In addition, we show how these reconstructions can be used to derive an age-grid for the former Farallon lithosphere underneath the Caribbean Plateau in section 'Age-grid'. In section 'Seismic tomography', we address the regional tomography. Finally, in section 'Discussion' we discuss our findings, which are summarized again in the conclusions (section 'Conclusion').

Reconstructing the Caribbean

To calculate the relative positions in our kinematic model, we used 4D Plates [24] and assumed that the Caribbean Plateau has a Pacific origin, being fixed to the Farallon plate and at some point 'docked' between the Americas. Here, docked refers to the point in time when the Plateau detached from the Farallon plate, and was wedged between North and South America and as a result became fixed to South America. Prior to docking, the following plate circuit was used: Caribbean Plateau – Farallon Plate – Pacific Plate – Antarctica – Africa, with South and North America moving relative to Africa. For ages older than 83.5 Ma, the Pacific Plate – Antarctica circuit is broken [21] and we reconstructed the Americas and associated blocks assuming that their position is given by the moving Atlantic-Indian Hotspot frame [25]. In order to reconnect the circuit, we assumed that there is no relative motion between this frame and Pacific hotspot reference frame of Wessel and Kroenke [22], the latter giving the relative positions of the Pacific plate to the frame. For times older than 100 Ma, we use the paleo-magnetically-derived true polar wander corrected reference frame of Steinberger and Torsvik [26]. This reference frame is necessary for the age-grid derivation (see section 'Age-grid'), but does not affect the correlation between the Caribbean Plateau and the Galapagos hotspot (see section 'Correlating the positions of the Galapagos hotspot and the Caribbean Plateau').

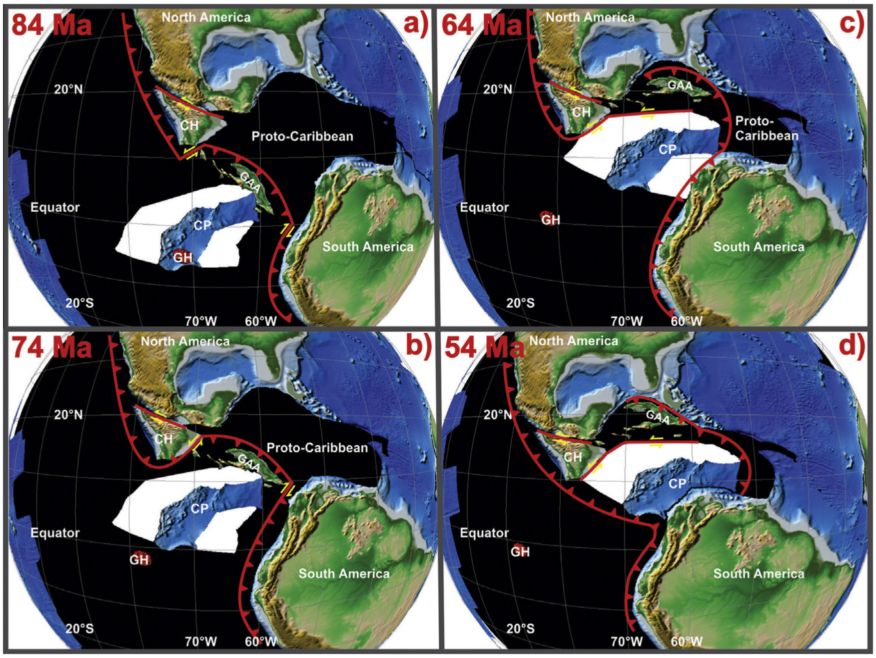

Fig. 2. Caribbean plate reconstructions, in which the Caribbean Plate (CP) is composed of the Caribbean Plateau (shaded relief) and associated parts of the Farallon plate (in white) that have either been subducted or obducted. The reference frame of Wessel and Kroencke [22] is used in this model. Topography is shaded by present-day relief (black indicates seafloor that has since subducted). Abbreviations: Great Antillean Arc (GAA), Chortis Block (CH), Galapagos hotspot (GH). (a) 84 Ma: the Farallon lithosphere crosses the paleo-Galapagos hotspot at the south-western edge of the present-day Caribbean Plateau. The proto-Caribbean seafloor is being subducted by a north-eastward retreating subduction zone. Farallon/Phoenix lithosphere is subducted beneath western North and South America, respectively, and continues to do so in the following time slices. Transform motion occurs between the Chortis Block and North America (see section ‘Reconstructing the Caribbean’ for a possible alternative suggested by Moran-Zenteno et al. [30]). (b) 74 Ma: the Caribbean Plateau resides on top of the Farallon plate and moves away from the paleo-Galapagos hotspot. Further north-eastward retreat of the Great Antillean Arc as well as some northward subduction under the Yucatan block occurs. Transform motion took place along the north-western South American margin. (c) 64 Ma: the Farallon/Caribbean Plate was moving mostly eastward implying transform motion along the south-eastern edge of the plate and northern South America, consistent with unconformities identified on the islands offshore South America [29]. Further subduction retreat of the Great Antillean Arc. (d) 54 Ma: the Caribbean Plateau was fixed to the bulk of South America and subduction initiated across the northern margin in response to convergence between North and South America. Also, transform motion and compression between north-western South America (Maracaibo Block) likely occurred since then, as the block is characterized by an independently moving complicated strike slip regime. It is suggested to be the source of the present-day transpressional regime [5].

For the various blocks in the Caribbean (Fig. 1), we based our Euler rotations on those provided by Ross and Scotese [27] with the few exceptions noted below. Firstly, unconformities underlying volcanics on some of the islands surrounding the Caribbean plate [28,29] are indicative for a subduction polarity reversal that supposedly occurred sometime in the Late Cretaceous after the present-day Caribbean Plateau had collided with the Great Antillean Arc [11]. Ross and Scotese [27] model this event to occur at 100 Ma. However, we held the Great Antillean Arc (restricted to Cuba, Hispaniola, Jamaica and Puerto Rico) fixed with respect to North America until 86.5 Ma: implying north-eastward subduction of former Farallon lithosphere along the western boarder of the arc until this time, consistent with recent suggestions of Hastie et al. [3]. The subduction reversal is followed by the consumption of the Proto-Caribbean seafloor by the retreating subduction zone to the north–east as well as transform-fault motion between the edges of the arc and North and South America.

To the west of the Plateau, the reconstruction of the Chortis Block remains debated [30]. The rotation poles of Ross and Scotese [27] were used, placing the Block adjacent to North America. However, the Chortis Block could have equally been treated as part of the Great Antillean Arc with a paleo-position further to the west and adjacent to the Great Antillean Arc [30]. In line with previous suggestions [31–33], the collision of Cuba with the Bahamas platform was set to be in the Early Eocene (51 Ma), followed by the onset of seafloor spreading in the Cayman Trough (49 Ma – present-day). Our reconstruction of the Caribbean Sea is presented in Fig. 2.

Correlating the positions of the Galapagos hotspot and the Caribbean Plateau

The major uncertainty we want to test is the relative positions of the Caribbean Plateau and Galapagos hotspot at the time of former’s formation. In order to do so, we varied the ‘docking’ of the Caribbean Plateau between North and South America in two reference frames. For the Galapagos hotspot we assumed either a Pacific fixed hotspot reference frame [22] or the Global Moving Hotspot

Table 1
Distance between the Caribbean Plateau and Galapagos hotspot at 89 ma based on different docking times and reference frames.[a]

Docking time (Ma)	Doubrovine et al. [23] (km)	Wessel and Kroencke [22] (km)
5.0	4865	5150
10.0	4565	4850
20.0	3600	3900
30.0	2540	2810
40.0	1600	1850
50.0	340	450
54.5	490	190
60.0	925	650
65.0	1280	990
70.0	1770	1500
75.0	2270	2000

[a] The distance was measured between the orange triangle (sample dated between 89 and 85.8 Ma) from Fig. 1 and the centre of the Galapagos hotspot polygon (red) as shown in Fig. 4.

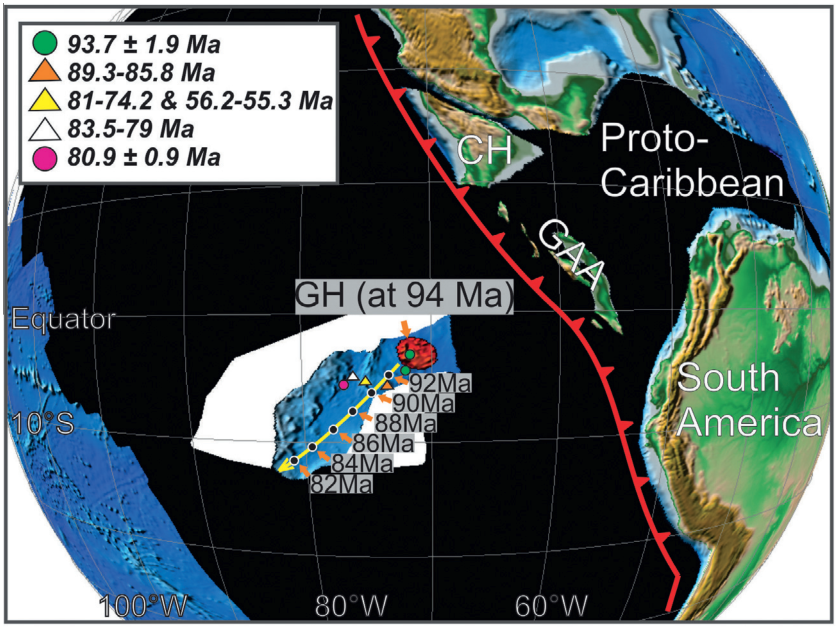

Fig. 3. Coincidence of the Galapagos hotspot (red) and the Caribbean Plateau-polygon at 94 Ma, assuming a fixed Pacific mantle reference frame [22] for the Galapagos hotspot. The white shaded area refers to the portion of Farallon lithosphere that was subducted after it has entered the opening gap between North and South America (see Fig. 2). The yellow arrow and associated points indicate the motion path and timing of the Galapagos hotspot relative to the Caribbean plate (present-day bathymetry is shown). Circles and triangle indicate the same sample datings as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

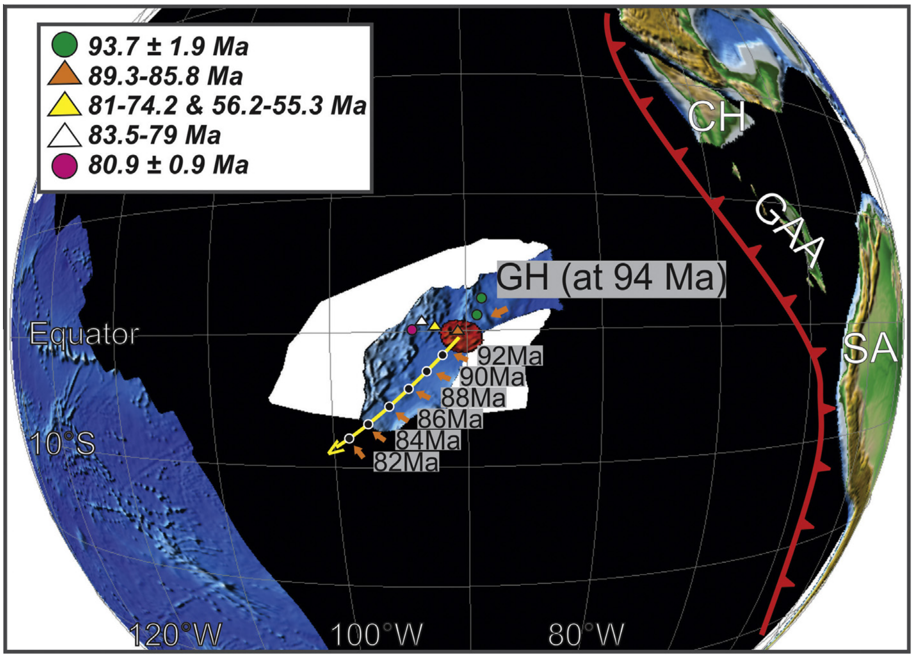

Fig. 4. Coincidence of the Galapagos hotspot (red) and the Caribbean Plateau-polygon at 94 Ma, using the global moving hotspot reference frame of Doubrovine et al. [23]. Labels are as in Fig. 2. Note the shift in longitude as a consequence of this reference frame relative to the fixed Pacific hotspot reference frame of Wessel and Kroencke [22]. Note also that the general agreement between the locations of the Caribbean Plateau and the Galapagos hotspot is very similar in both explored reference frames (compare to Fig. 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Reference Frame of Doubrovine et al. [23]. In the former case, as explained in the Caribbean Reconstruction section above, we fixed the moving Indian-Atlantic hotspot frame to the Pacific one for times older than 83.5 Ma. In the latter case, we used the absolute positions for Africa and the Pacific. For the Pacific rotations, the stage rotations of Wessel and Kroenke [22] were applied from 90 Ma. The extent of the Caribbean Plateau is based on that of Mauffret et al. [1].

In both reference frames, the Plateau's relative position to the Galapagos hotspot between 94 and 88 Ma is very sensitive to changes in the timing of the docking age as shown in Table 1. Very young docking ages place the Plateau thousands of kilometres away from the Galapagos hotspot, as others have reported [19,21]. However, for a narrow range of docking ages the Plateau crosses over the position of the Galapagos hotspot at ages closely matching those of the dated dredge samples shown in Fig. 1. For either model, docking ages between 50 and 60 Ma gave reasonable fits for the geochemical data, with the Wessel and Kroenke [22] model giving distances between 190 and 650 km while Doubrovine et al. [23] gave distances between 340 and 925 km.

Within this time block, there was a switch from divergence to convergence between North and South America at 54.5 Ma [34]. Using 54.5 Ma as the docking age, the Plateau crosses the Galapagos hotspot at the presumed age of formation (88–94 Ma) for either reference frame. The virtual hotspot trail for the reference frames of both Wessel and Kroenke [22] and Doubrovine et al. [23] using this docking age are shown in Figs. 3 and 4, respectively, while the rotation parameters are presented in Table 2. Both reference frames lead to an age progression of increasing ages west to east as well as locating the Plateau above the hotspot for the reported sample ages between about 81 and 94 Ma. Note, however, that the massive basaltic flows thought to make up the Caribbean Plateau [2] would not be point-source eruptions (as it appears from the small number of collected samples) but would cover large areas, making a precise correlation difficult.

Table 2
Rotation poles for the Caribbean Plateau-polygon.

Time (Ma)	Finite rotation			Fixed plate (plate ID)
	latitude (°)	longitude (°)	angle (°)	
Based on a fixed Pacific hotspot reference frame [22]				
0.0	0.0	0.0	0.0	South America (201)
54.5	0.0	0.0	0.0	South America (201)
54.5	67.6642	144.355	50.6645	Farallon Plate (902)
105.0	67.6642	144.355	50.6645	Farallon Plate (902)
Based on a global moving hotspot reference frame [23]				
0.0	0.0	0.0	0.0	South America (201)
54.5	0.0	0.0	0.0	South America (201)
54.5	68.75	142.37	52.43	Farallon Plate (902)
105.0	68.75	142.37	52.43	Farallon Plate (902)

Age-grid

To derive an age-grid based on the assumptions described in the previous section, we rotated the Caribbean Plate/Plateau-polygon to the location of the mid-ocean ridge that once formed the plate boundary between the Pacific and Farallon plates [21]; and found it touches the ridge at ~105 Ma in either model, although we used the reference frame of Wessel and Kroenke [22] to be consistent with the reconstruction in Fig. 2. Fig. 5 shows the reconstructed polygon with the paleo-age grids of Müller et al., [35]. The age distribution covered by the rotated polygon was extracted and then rotated back to the present-day position, adding the intervening 105 million years to the grid (Fig. 6). According to our model, the oldest parts underneath the Caribbean Plateau are located in the east and are approximately 144 Ma old.

Seismic tomography

Duncan and Richards [12] noted the concentration of hotspots in the area of high geoid residuals. With the advent of high resolution seismic tomography, the underlying anomalies or Large Low Shear Velocity Provinces (LLSVPs) at the base of the mantle could be correlated with these hotspot locations [37]. In both cases, the

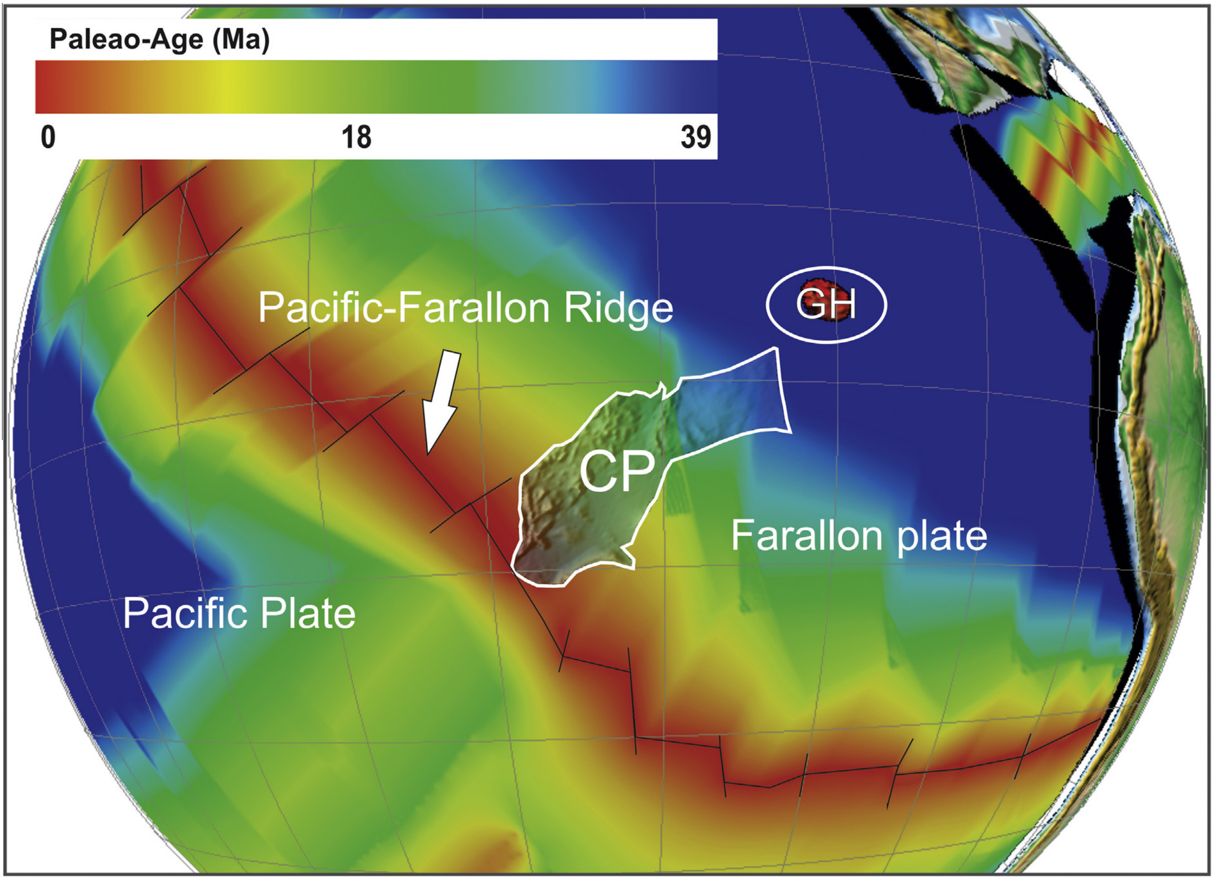

Fig. 5. The paleo-age-grids of Müller et al. [35] were used to extract the age distribution covered by the rotated Caribbean Plate/Plateau polygon to the former Pacific-Farallon ridge. Based on the reconstruction model presented in Fig. 2, the Caribbean Plate/Plateau polygon touches the ridge 105 Ma ago. Note that the absolute positions are given here by a paleo-magnetically derived true polar wander corrected reference frame [26].

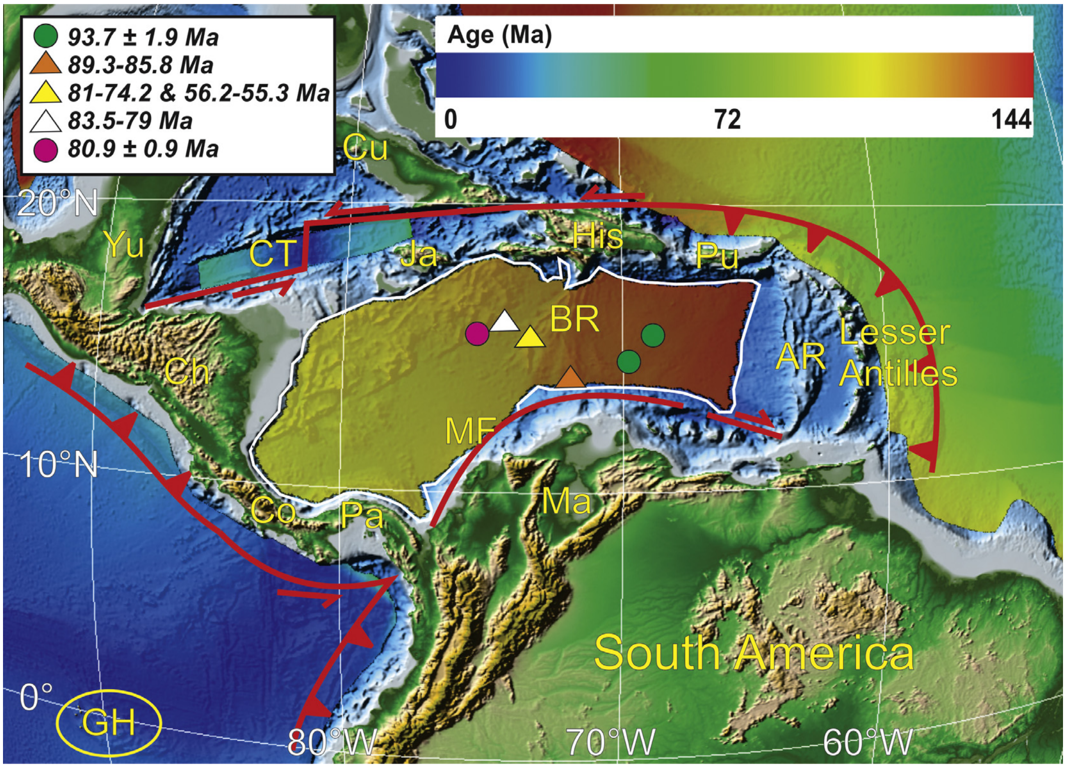

Fig. 6. Present-day age distribution of the former Farallon lithosphere underneath the Caribbean Plateau, based on paleo-age-grids of Müller et al. [35] (see text for a discussion and Fig. 5). For the Pacific, Cayman Trough, Gulf of Mexico and the Atlantic, the age distribution according to the age-grids of Müller et al. [36] is shown.

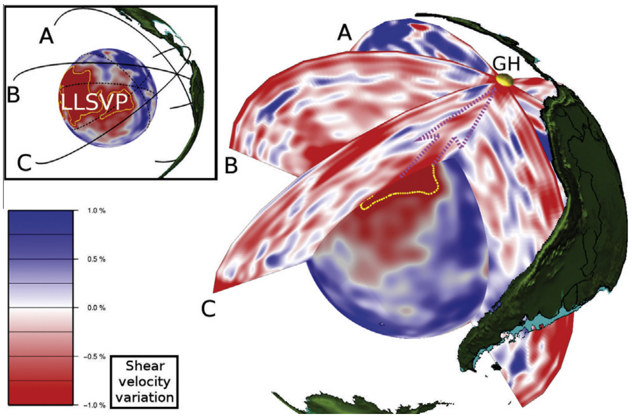

Fig. 7. Shear-wave velocity anomalies from the S40RTS model [39] at 2800 km depth with three cross-sections (A–C) showing shear-wave velocity variations. Insert shows the 2800 km anomalies with the traces of the top (solid black line) and bottom (dashed black line) of the cross-sections for reference. The −1.0% anomaly at 2800 km depth is highlighted by a dashed yellow line and indicates the Large Low Shear Velocity Province (LLSVP) underneath the Pacific. The dashed purple line indicates a tilted anomaly from the LLSVP to underneath Galapágos hotspot (GH) located at the yellow dot. National boarders and topography (down to 500 m depth) are shown for reference. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Galapagos hotspot lies on the edge of the eastern most extent of the Pacific geoid anomaly [12] and the Pacific LLSVP (Fig. 7, insert). With vertical mantle transit times of 150 million years [38], it is likely that the arrival of the Galapagos plume ~88–94 million years ago would still be seen in mantle tomography. In Fig. 7, a large upwelling can be observed tilting from the eastern extent of the Pacific LLSVP to the northeast and continuing upwards to the base of the Galapagos hotspot (purple arrow in Fig. 7).

Discussion

The relative distance between the Galapagos hotspot and the Caribbean Plateau at the time of large igneous province formation is largely dependent on the docking age of the Caribbean Plateau, as shown in Table 1, with 54.5 Ma giving a relatively small offset as well as coinciding with the change in relative motion between the Americas. However, the idea of Pindell and Kennan [7] that the relative drift between the Indian-Atlantic and Pacific hotspot reference frames might be responsible for the apparent mismatch in locations is also significant. Here, we used the recent Global Moving Hotspot Reference Frame (GMHRF) of Doubrovine et al. [23] as well as the Pacific hotspot frame [22]. The latter frame gives a better fit of the position of the Galapagos hotspot relative to the Caribbean Plateau for our docking age of 54.5 Ma. While we could tune the docking age to improve the fit of the GMHRF, the derivation of this timing from the initiation of convergence between the Americas gives an external constrain to the reconstruction.

Using two reference frames reduces the uncertainty of our conclusions, although such uncertainties remain because of the uncertainties in Wessel and Kroenke [22] for ages >90 Ma and in the GMHRF for ages between 50 and 80 Ma [23]. In addition, our paper does not prove a causal relationship between the Galapagos hotspot and the Caribbean Plateau, but removes one of the main plate kinematic objections to such a theory.

Finally, recent debate has focused on whether the correlation between the LLSVP edges and hotspot locations mean that deep mantle upwellings are tilted from the centre of the LLSVPs or occur at the edges and proceed straight up in the mantle [37,40]. In the mantle tomography presented here, there appears to be a tilted upwelling from the centre of the eastern extent of the Pacific LLSVP, agreeing with the former suggestion.

Conclusion

We have shown that a good correlation between the relative positions of the Galapagos hotspot and the Caribbean Plate at the time of Caribbean Plateau formation (main phase: 88–94 Ma) can be reached in the Pacific [22] as well as in the Global Moving Hotspot Reference Frame [23]. The docking time of the Caribbean Plateau to South America proved to be critical in this regard and best fits were reached when a timing of 54.5 Ma was assumed. Interestingly, this timing is coincident with the switch from divergence to convergence between the Americas, possibly implying some long-wavelength consequences. Our findings are consistent with abundant geochemical evidence. Therefore, alternative mechanisms to explain the formation of the Caribbean Plateau, such as asthenosphere inflow through slab windows, seem to be unnecessary.

Finally, our model enabled us to derive an age-grid of the former Farallon lithosphere underneath the Caribbean Plateau. This grid will be useful for various geodynamic investigations, including the calculation of the regional present-day dynamic topography.

Acknowledgments

The presented work was funded by a research Grant from Statoil AS. The authors thank Statoil AS and Kalkulo AS for the use of 4D Plates. HPB acknowledges funding from the DFG SAMPLE SPP. We appreciate constructive comments of Esteban Gazel and an anonymous reviewer. We are also grateful to editor Scott King for his careful reading and his suggestions to improve the original paper.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.grj.2014.02.001.

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