Geological evolution of the Caribbean plate: Some critical aspects in the two divergent models

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The Caribbean oceanic basin was initiated with the rifting of the supercontinent Pangaea, opening of the Central Atlantic and drifting of the two Americas about 160 Ma. It had passed through the stages of growth during 160–65 Ma and reached the stages of decline about 60–50 Ma. The plate tectonic evolution of the Caribbean plate is complex. Two different models, i.e. the Pacific model and the Atlantic model are proposed to interpret the growth stages. In particular, the differences revolve on the site of formation of the Caribbean thickened oceanic crust with its flood basalts, if related to a hotspot in the Pacific or to a mantle plume *in situ* in the Atlantic. Some critical aspects in the interpretations in the two models, viz. relationship of the flood basalts with the Nicoya ophiolitic complex at the spreading centre, with the Galapagos hotspot in the Pacific and with the oceanic plateau basalts of mid-Cretaceous super plume are reviewed in the overall context of the on-going general debate on the plume hypothesis.

Keywords: Caribbean plate, oceanic plateau basalts, mantle plume, Pacific and Atlantic models.

The Caribbean plate and the plume-related flood basalts

THE Caribbean is recognized as a small lithospheric plate located between the major plates of North America and South America. It is essentially an oceanic plate and carries on it several islands of different sizes which include some of the islands of the Greater Antilles, Hispaniola, etc. and the islands of the Lesser Antilles, Grenada, etc. The ambient setting of these islands which is a consequence of plate tectonics, provides a scenic beauty to the Caribbean. Good amount of geological work has been carried out on the plate tectonic evolution and the Cretaceous flood basalts of the Caribbean, from which two divergent models on their origin are proposed. The submarine flood basalts of the Caribbean are 15–20 km in thickness and their origin is attributed to a hotspot/mantle plume on either of the models. But the two models differ on the location of the proposed hotspot/mantle plume.

The original idea of hotspot/mantle plume[1,2] was developed later[3] to explain several intraplate volcanic eruptions described as large igneous provinces (LIPS) that include some of the ocean island basalts ex Hawaiian, continental flood basalts ex Deccan, oceanic plateau basalts ex Ontong-Java, etc. The plume hypothesis has been debated extensively in recent years, and the different views on the hypothesis to explain the Phanerozoic LIPS critically reviewed[4]. Further, the possible application of the plume hypothesis to explain certain defined LIPS of the Precambrian has been overviewed[5]. In this context, some of the critical aspects of the two divergent models on the Caribbean and its plume-related flood basalts are reviewed in the article in a framework of plate tectonic setting.

The two models

Extensive work on the Caribbean region has been carried by several researchers during the last two decades and more. The later work has sharpened the differences in the interpretations on its evolution in the two models. The evolution of the Caribbean, particularly during the Late Jurassic–Cretaceous has been visualized differently with two divergent models which are generally referred to as the Pacific model and the Atlantic model. The Pacific model suggests an allochthonous formation of the Caribbean thickened oceanic crust with its flood basalts being formed from the Galapagos hotspot in the Farallon plate of the Pacific Ocean, which later drifted northeastwards into its present position[6–8]. The Atlantic model suggests an autochthonous formation of the Caribbean thickened oceanic crust with its flood basalts being formed between North America and South America, which is related to the openings of the Atlantic Ocean and a mantle plume *in situ*[9–11].

The critical aspects in the two models hinge on the interpretation of the site of formation of the flood basalts and their position relative to the location of the oceanic crust exposed at the Nicoya ophiolitic complex which includes komatiites, basalts, gabbros and plagiogranites in

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Costa Rica, and the basalts show chemical characteristics of ridge basalts[12]. The Pacific model relies on the affinity of the basalts of the Nicoya ophiolitic complex with those derived from the Galapagos hotspot in the Pacific Ocean and on the movement of the Farallon plate during the Cretaceous. The Atlantic model relies on the palaeomagnetic pole path during Jurassic–Cretaceous to fix the position of the basalts relative to the Nicoya ophiolitic complex and on the affinity of the flood basalts to the oceanic plateau basalts (OPB) of *in situ* plume origin.

A brief account of the evolution of the Caribbean based on the reconstruction of the palaeopositions in the two models along with a chronology of the events is given below as a background to the review. Figure 1 gives the present-day setting of the Caribbean plate[13], with some features added. Figure 2 gives the setting at 84 Ma according to the Pacific model[7], with some older faults superposed on it. Figure 3 gives the setting at 72 Ma according to the Atlantic model[11], with superposition of the older spreading ridge since disappeared. Figures 4 and 5 give the plots between select elements of the Caribbean basalts along with the basalts of OPB of Nauru oceanic basins[14].

A brief account of the geological events in the Caribbean region

In the lifecycles of the oceanic basins there are different stages of growth and decline[15]. The Caribbean basin was initiated in the middle Jurassic about 180–160 Ma (Mega = Million, annums) with the rifting of the two Americas and the opening of the Central Atlantic. It had passed through the stages of growth during Late Jurassic–Cretaceous between 160 and 65 Ma.

During this period, its evolution was also influenced by the events in the adjoining region. These include the opening of the Central Atlantic into the Gulf of Mexico along the North Bahamas Fracture Zone (NBFZ), large-scale transcurrent faults with movement along Mojave-Sonora Megashear (MSM) and the Trans-Mexican Volcanic Belt (TMVB) which followed the fractured crustal blocks of North America and brought some blocks of Mexico into the Caribbean region (160–140 Ma)[7], subduction of the Farallon plate on the west coast of America (140 Ma), later on the movement of a part of the Farallon plate along a set of faults carrying the Greater Antilles arc (that includes Cuba and Hispaniola) into the Caribbean (90–70 Ma) (Pacific model; Figures 1 and 2), fracturing of the northern part of South America in Venezuela and Columbia, the opening of South Atlantic and North Atlantic which started at 130 Ma and the consequent westward movement of the Americas.

Internally during the above period of 160–65 Ma, the Caribbean basin had passed through specific stages of growth. These includes the spreading ridge of the Central Atlantic into proto Caribbean (160–80 Ma) with ophiolitic complex of Nicoya in Costa Rica, which probably extended westward into the Farallon oceanic plate; emplacement of 15–20 km thick submarine flood basalts (120–65 Ma) close to the cessation of sea-floor spreading (90–80 Ma) (Atlantic model; Figures 1 and 3); formation of intra-basinal subduction zones of Cuba-Aves Ridge-arc during Aptian–Albian of the Cretaceous (110–100 Ma); northward movement of the micro plates (90–70 Ma), collision of the Greater Antilles arc-trench with Yucatan peninsula of Mexico followed by obduction of ophiolitic complexes during early Palaeocene (65–60 Ma), such as those of Cuba, possibly of Guatemala and Central Mexico along thrust faults; collision of Cuba with the Bahamas platform (60 Ma) resulting in the transfer of the Cuban block to the North American plate, and reorganization of the collided blocks from lateral movements.

By early Palaeocene–Eocene about 60–50 Ma, the Caribbean oceanic basin had reached the stages of decline with the initiation of the presently active arc-trench system of the Lesser Antilles on the east. The Atlantic oceanic lithosphere between the two Americas has been subducting since 50 Ma at a rate of 2 cm/yr beneath the Caribbean plate through the trench dipping west in the mature Barbados Ridge Complex (BRC), which is located 150 km east of the Lesser Antilles volcanic arc (Figures 1 and 3). About 50 Ma, the plate boundaries of the Caribbean were nearly defined with arc-trench systems in the east and west, and transform (strike-slip) faults in the north and south (Figure 1). Since 50 Ma, South and North America have been moving westwards at a rate of about 3 cm/yr, and the Caribbean at a rate of about 2 cm/yr, westwards. Between 50 and 10 Ma, reorganization of some blocks took place within the Caribbean from the lateral movement on the Cayman Ridge strike-slip fault in the north, which is in alignment with an older fault in the adjacent continental crust of America, namely the Montagua–Polo'chic Fault Zone (MPFZ) in Guatemala (Figures 2 and 3). As a consequence of lateral movement on this fault (2 cm/yr), the Chortis block (Nicaragua and Honduras) moved away from the North American plate and joined the Caribbean plate. Hispaniola and Puerto Rico moved eastwards by 10 Ma, at which time the present setting of the Caribbean plate was attained.

Spatial and temporal relation between the Nicoya ophiolitic complex and the flood basalts

From the present-day geological setting of the Caribbean plate (Figure 1), the following may be noted. The Nicoya ophiolitic complex in Costa Rica is located between 0°N and 10°N lat. The flood basalts which occupy the south-western and central part of the Caribbean are located east and northeast of the Nicoya ophiolitic complex. In the Pacific Ocean, the Galapagos hotspot is located close to the equator. The erstwhile Farallon plate of the Pacific

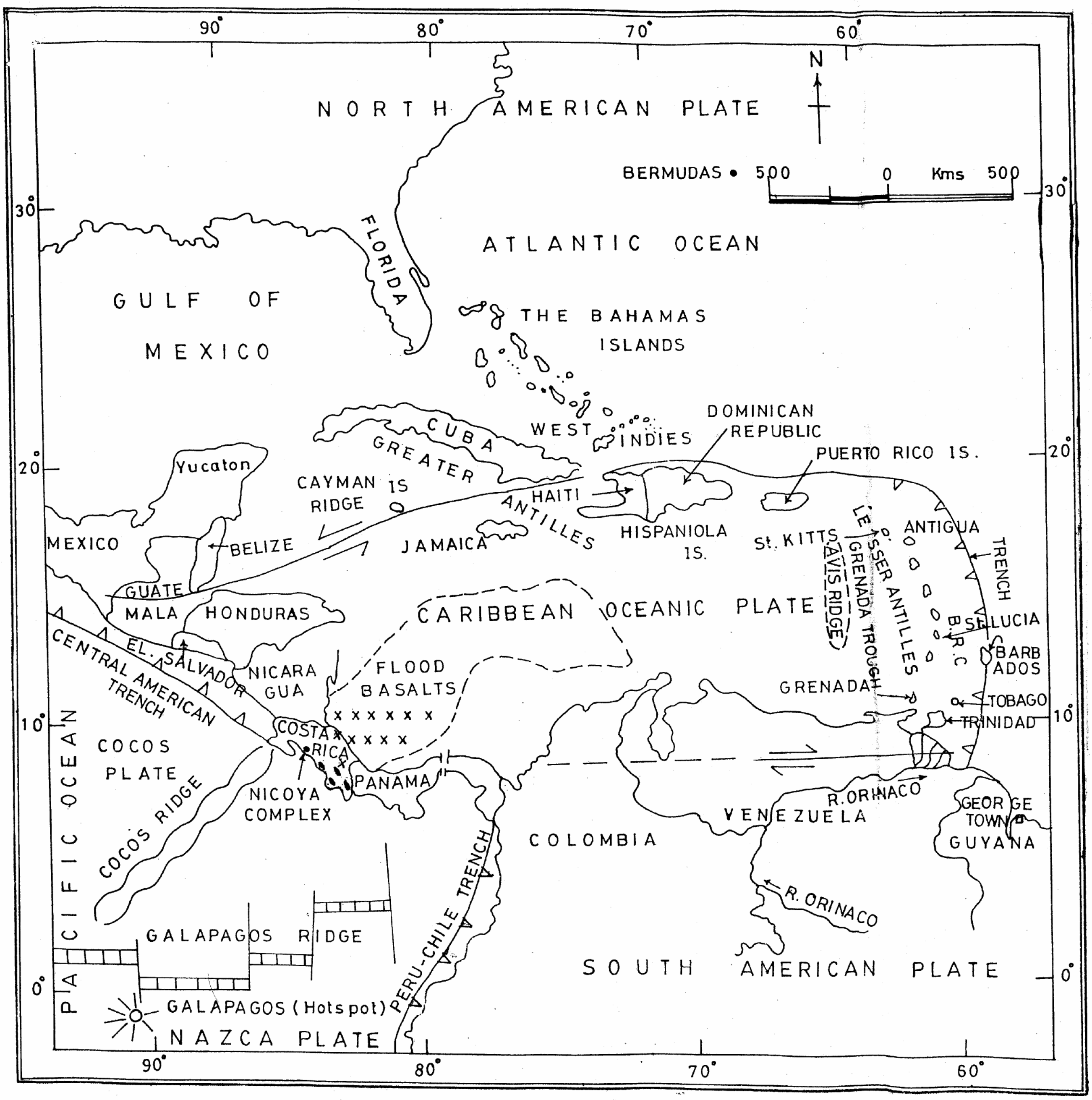

Figure 1. The Caribbean oceanic plate and the regional geological setting at present (compiled from Condie[8] and others). 1 to 4 older fault zones: 1, North Bahamas Fracture Zone (NBFZ); 2, Mojave–Sonora Megashear (MSM); 3, Trans-Mexican Volcanic Belt (TMVB); 4, Montague Polo'Chic fault zone (MPFZ); 5, Cayman Ridge Fault; 6, Nicoya ophiolitic complex. A.R., Avis Ridge; Ch, Chortis block, G.A., Greater Antilles; N.C., North Cuba; N.R., Nicargua Rise; S.C., South Cuba; Y.U., Yucatan block. ●, Ophiolites, X-basalts; ⁚⁚, Disappeared spreading ridge.

was split into two smaller plates known as the Cocos plate and the Nazca plate. The inactive Cocos Ridge located in the Cocos plate trends NE–SW and its northeastern end is located close to the ophiolitic complex of Nicoya.

Figure 3 gives the setting of the protoCaribbean at 72 Ma after reconstruction of the palaeopositions according to the Atlantic model. It shows the locations of the Nicoya ophiolitic complex and the flood basalts in the same relative positions between 0°N and 10°N lat, similar to the present-day setting. This is based on the palaeomagnetic pole data for the basalts of the Nicoya ophiolitic complex in Costa Rica and others in Panama. The contention in the Atlantic model is that if the Nicoya ophiolitic complex was formed from the spreading of the Atlantic ridge from the east as proposed in that model, and if the flood basalts were formed from the Galapagos in the Pacific from the west according to the Pacific model, the basalts should occur west of the ophiolitic complex which is not supported by their present locations, thus maintaining that there was no latitudinal drift in the palaeomagnetic pole path since the Jurassic[16].

It is further argued in the Atlantic model[10,11] that if the Nicoya ophiolitic complex and the flood basalts are assumed to be formed together in the Pacific Ocean, then the restoration of the palaeopositions of the ophiolites during Jurassic–Cretaceous by taking the plate motion vectors on the basis of the Pacific model, will fall far south of the equator which is not supported by the palaeomagnetic drift path.

The temporal relationship between the ophiolitic complex and the flood basalts of the Caribbean is not established in either of the models directly, but is only cited in their stated propositions of linking them to a hotspot outside the Caribbean or to a plume within the Caribbean. The problem is complicated on two accounts. First, the spreading in the protoCaribbean to which the Nicoya ophiolitic complex is related in the Atlantic model, started in Middle Jurassic about 160 Ma, but the ages obtained on the Nicoya complex are between 83 and 90 Ma[17,18]. Secondly, the basalts in and around the Caribbean gave ages ranging from 120 to 65 Ma[19,20].

For different reasons, the two models agree that the older oceanic crust in the Caribbean was consumed at the intra-basinal subduction zones and that the age obtained on the Nicoya ophiolitic complex may be the last episode of spreading. It may be recalled that the intra-basinal subduction zones such as the one on the leading edge of the Greater Antilles arc during Upper Cretaceous (90–70 Ma) moved from south to north within the basin according to the Atlantic model (Figure 3) or was pushed northeastward by the movement of the Farallon plate carrying the flood basalts into the Caribbean (Figure 2). From the age data given above, it appears that the flood basalts of the Caribbean started to form well before (30 Ma) the last episode of the Nicoya ophiolitic complex and continued for some time (15 Ma) after the last episode of the ophiolitic complex.

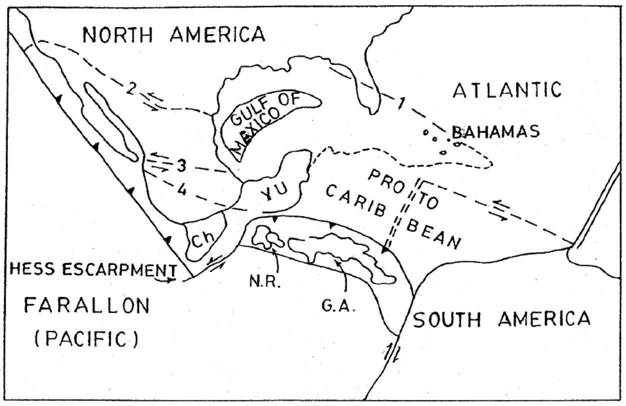

Figure 2. The Caribbean region at 84 Ma (Pacific model; after Ross and Scotese[7]) with older faults superposed. Figure legend same as Figure 1.

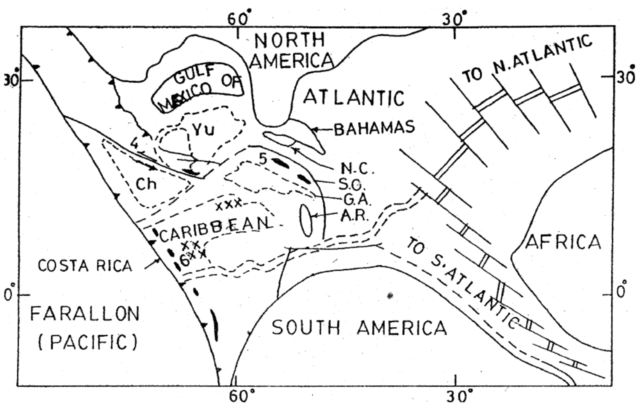

Figure 3. The Caribbean region at 72 Ma (Atlantic model; after Meschede and Frisch[10]), with the disappeared spreading ridge added. Figure legend same as Figure 1.

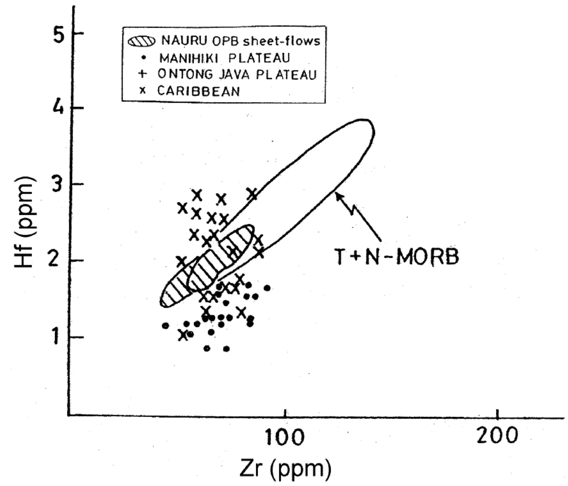

Figure 4. Plot of Zr (ppm) vs Hf (ppm) of the oceanic plateau basalts, including the Caribbean basalts (after Floyd[14]).

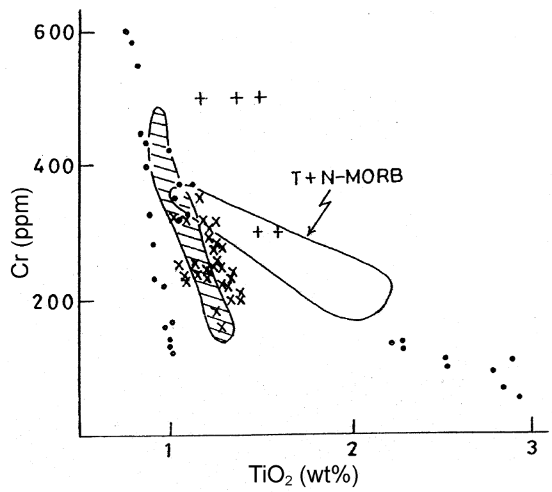

Figure 5. Plot of TiO_2 (wt%) vs Cr (ppm) of the ocean plateau basalts, including the Caribbean basalts (after Floyd[14]).

Flood basalts of the Caribbean and the Galapagos hotspot in the Pacific

The isotopic data of the basaltic rocks from the Caribbean Mesozoic ophiolitic rocks such as the Nicoya complex show similarity to the basaltic rocks formed at the Galapagos hotspot[17]. Therefore, the formation of the flood basalts of the Caribbean took place at the Galapagos hotspot in the Farallon plate of the Pacific and later drifted to the present position according to the Pacific model. Implied in this proposition are that the inactive Cocos Ridge, which is located close to the Nicoya ophiolitic complex (Figure 1) is the trace of the presently active Galapagos hotspot and that the Farallon plate moved northeastward during Late Cretaceous (90–70 Ma) into the Caribbean carrying the flood basalts.

The Atlantic model considers the relation of the Cocos Ridge with the active Galapagos hotspot in a different way. Based on the magnetic, gravimetric and stratigraphic data[21], it is suggested in the Atlantic model that the Cocos Ridge is made up of two components. One component is made up of an abandoned older spreading system which may be a precursor of the Galapagos hotspot and the other is a later overprinted centre of volcanic activity, now represented by Cocos Island volcanism which is related to the presently active Galapagos. The split of the Farallon plate into Cocos and Nazca plates took place around 23 Ma and the oldest rocks of the Galapagos Ridge (Figure 1) are 15–20 Ma in age[22]. Therefore, it is argued in the Atlantic model that the Caribbean flood basalts which are at least 65 Ma in age, could not be derived from the younger hotspot of the Galapagos.

The age of the Galapagos hotspot has not been established with any certainty. In such a case, if one assumes that the inactive Cocos Ridge which is close to the Nicoya ophiolitic complex in Costa Rica was formed as a trace of the presently active Galapagos hotspot, it means a lifespan of 90 Ma or more for the still active Galapagos hotspot. Secondly, if the flood basalts were formed by the older event of the Galapagos and drifted northeastward into the Caribbean, it needed to move 5000 km in a span of 15–20 Ma between 80 and 65 Ma (the age of the youngest flood basalts of the Caribbean) at a plate motion of 30 cm/yr for the Farallon plate. On the basis of these two surmises[11] it is contended in the Atlantic model, the improbability of the Galapagos hotspot linkage to the Caribbean flood basalts.

Affinity of the Caribbean flood basalts with OPB of a mantle plume

Disagreeing with the linkage of the Caribbean flood basalts with the Galapagos hotspot in the Pacific, the Atlantic model[10,11] proposed a linkage of the flood basalts to the OPB of plume origin *in situ*, similar to those of some oceanic basins.

In the Pacific Ocean, the intraplate volcanism represented by the basalts of Nauru basin, Ontong-Java and nearby Maniki basins shows affinity to Mid-Oceanic Ridge Basalts (MORB)[13,23]. The MORB are characterized by low potassium theolitic basalts enriched in Cr, Ni and impoverished in lithophile elements[24]. The basalts which have an intra-plate tectonic setting but affinity to MORB are known as the OPB. In terms of the volume, the OPB appear to be oceanic analogues of continental plateau basalts, but are distinct from the latter which show higher relative enrichment in most large ion lithophile elements (LILE).

The OPB are broadly similar to MORB. But the OPB exhibit some relative enrichment in LILE and in some high field strength elements compared to the normal (N-type) MORB, but this enrichment is matched with transitional (T-type) MORB to a large extent. The Caribbean flood basalts show pillow lavas, flows and sills; petrographically they show quenched, aphyric, phyric types, most of them are rare earth element-depleted, but some are enriched in these[25]. With these variabilities the Caribbean basalts show similarities with N-type MORB, or N + T-type MORB or OPB of other oceanic basins. The chemical characteristics of the OPB of the Nauru, basalts and the Caribbean basalts are discussed with reference to some element ratios[14] which are given in Figures 4 and 5. On the Zr–Hf (ppm) plot (Figure 4), the Caribbean basalts plot in or close to the field of N + T-type MORB, similar to the other OPB. On TiO_2 (wt%)–Cr (ppm) plot (Figure 5), the Caribbean basalts plot along with the other OPB, in a field with an overlap onto the N + T-type MORB but with an enhanced Cr trend, a characteristic of OPB.

The majority of the OPB event took place in mid-Cretaceous[26,27] through a plume during 110–70 Ma. This might be due to certain special tectonic conditions that existed during this period, such as the rapid spreading of the sea-floor, changes in plate motion and widespread lithospheric disturbances[14]. Further, the chemistry of the basalts of the LIPS such as those of Ontong-Java, Caribbean, etc. show wide variation, which reflects the heterogeneous state of the mantle plume source.[3,4].

A general feature of the OPB is that they represent the thickening of the oceanic crust soon after the formation of the underlying oceanic crust basement at a nearby spreading centre, and this is achieved in other OPB basins within 20 Ma after the cessation of the spreading. In the case of the Caribbean, if one takes the age of MO magnetic anomaly at 125 Ma (MO-through M29 designated for pre-Aptian, Cretaceous) and the Ar/Ar isochron age of the flood basalts[19] at 120 Ma, it gives a short interval of 5 Ma between the formation of oceanic crust at the spreading ridge and initiation of thickening of the oceanic crust by flood basalts in the Caribbean. If other ages of the basalts are taken, the situation will be different. It is also suggested that in the case of OPB, including that of the Caribbean, the sheet flows of the basalts were fed via a diffuse complex of numerous short-lived fractures, without affecting the spreading centre[14]. Thus the wide range of ages of the Caribbean basalts vis-à-vis the cessation of the spreading could possibly be explained in the Atlantic model.

Concerted studies and debates on the Caribbean flood basalts and the prognostic trends in the plume hypothesis

The Caribbean and the surrounding areas are one of the actively studied and debated regions in a concerted way to interpret the evolution of the Caribbean plate in a regional framework. Over the years, drilling programmes in the region adjacent to the Caribbean plate, the Deep Sea Drilling Project (DSDP) at Legs 61, 69, etc. and its successor Ocean Drilling Program (ODP) at Leg 170, etc. have contributed useful information. Data from these have enhanced our understanding about the oceanic flood basalts at the spreading centre, the oceanic crust of the Cocos-Nazca spreading system and its relation to the Galapagos hotspot, and the convergent margin off-shore of Nicoya complex in Costa Rica. The Caribbean plate tectonics has been studied by several national organizations in Europe and the two Americas and others as Project 433 under the International Geological Correlation Programme, and the results have been discussed at the special symposium held in Granada, Spain in 2003. At the symposium, the earlier and new advocates of the Pacific model[28] and those of the Atlantic model[29] had sharpened their differences, particularly the former sticking to the idea of the rotation of the Yucatan and the Chortis blocks, and the latter disagreeing with it. The International Research Conference on the Caribbean Plate held in Siguenza, Spain in May–June 2006 discussed various aspects of the two models and the plume hypothesis for the Caribbean flood basalts[30–32]. It was realized at the conference that there are no recognized fracture patterns or magnetic anomaly patterns or a spreading ridge in the Caribbean (excluding the Cayman trough-ridge-strike fault of the Eocene age). The conference also suggested a few ocean drill sites in the Caribbean to resolve the debate on the plume origin of the spreading and the thickened oceanic crust by the flood basalts in the two models.

In recent years the plume, hotspot, the LIPS are being hotly debated which has some bearing on the Carribbean flood basalts. At the Penrose Conference 'Plume IV: Beyond the Plume Hypothesis' held in Iceland in 2003, the earth scientists deliberated with divergent views on the concept of the plume. While a large number of participants criticized the concept of the plume for the origin of mid-plate volcanism, a few others stuck to the conventional definition of the plume and opined that the plume model is the best explanation, for example, for the world's largest plateau basalts of Ontong-Java. At the Chapman Conference on 'The Origin and Impact of LIPS and Hotspots' held in Scotland in 2005, a large number of aspects of the plume, ranging from mantle convection to a meteoritic impact as a trigger were discussed. From the current trends in the debates and reviews[3,4], it appears that a consensus on the plume hypothesis is yet to be achieved. Flexibility on different aspects of the plume, for example, on the source, geochemistry, etc. is cited as an objection to the plume hypothesis by the critics. Large amount data coming from different regions of mid-plate volcanism has probably necessitated a flexibility in the plume hypothesis. Possibly this may itself be a favourable point for greater acceptability in prognosis.

Concluding remarks

The crucial issue in the evolution of the Caribbean plate in the two models is the place of origin and the mechanism of the thickened oceanic crust with flood basalts. The present relative spatial disposition of the Nicoya ophiolitic complex on the west and the flood basalts on the east in the equatorial region, supported by palaeomagnetic pole path for the Jurassic–Cretaceous is a point in favour of the Atlantic model. The temporal relation between the Nicoya ophiolitic complex and the flood basalts of the Caribbean which needs to be substantiated also favours the Atlantic model. Similarity in the chemistry of the flood basalts of the Caribbean with the basalts of N-type/N + T-type MORB or OPB is indisputable. But the *in situ* plume model requires some confirmation about the presence of the radial texture, which is generally associated with the plume basalts. With the general flexibility in the plume hypothesis to explain the mid-plate volcanism of OPB-type, the Caribbean with the Atlantic model with *in situ* flood basalts having short-lived fractures may become yet another example of plume-related OPB and gain greater acceptability in prognosis.

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