Neotectonics of Hispaniola: plate motion, sedimentation, and seismicity at a restraining bend

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The pattern of Neogene faulting, volcanism, and sedimentation in Hispaniola helps to resolve a problem that arises in attempting to determine the direction of Caribbean plate motion from earthquakes alone, namely: How well do earthquake mechanisms define plate motion? Hispaniola occupies a compressional north-step or restraining bend in the generally east-west-trending Motagua-Cayman Trough–Puerto Rico Trench fault system which marks an active plate boundary zone (PBZ) of left-lateral strike-slip motion between the North America and Caribbean plates. Four areas are distinguishable in Hispaniola from field mapping and from the interpretation of satellite imagery and conventional aerial photographs. Two of these areas consist of active left-lateral strike-slip fault systems that roughly define the northern and southern coasts of the island. The structure of both fault systems suggest a roughly east-west-trending direction of relative plate motion consistent with previous findings. The intervening area consists of en echelon mountain ranges thrust up at the restraining bend from the early Miocene. A Pleistocene volcanic province within this area is interpreted as defining a diffuse extensional fault termination of the southern strike-slip fault zone. The fourth area in eastern Hispaniola is interpreted as being underthrust by discontinuous fragments of lithosphere in response to convergence at the restraining bend. It appears possible that thinner, young island arc lithosphere may be more prone to subduction than to “escape” or “flaking”, processes that are more important in older, more buoyant lithosphere.

1. Introduction

Recorded seismic events enabled Molnar and Sykes [1] to establish the identity of the Caribbean as a rigid lithospheric plate defined on its northern and southern margins by strike-slip plate boundary zones or “PBZ’s” [2] and on its east and west by convergent boundaries and volcanic arcs (Fig. 1). Most of our knowledge of Caribbean plate motion has come from the study of PBZ earthquakes over the last two decades and from marine geologic surveys of the 1400 km long Cayman Trough pull-apart [3] (Fig. 1). The precise distribution, direction and rate of Caribbean plate motion is important in earthquake prediction and in identifying areas of seismic risk as well as constraining active motions of adjacent plates and tectonic reconstructions. Present-day Caribbean motion is assumed by some workers [4] to have been steady and has been extrapolated into the past to form a basis for reconstructions as old as Eocene.

Various methods of determining North America–Caribbean relative plate motion have yielded significantly different results (Table 1). Caribbean–South America relative plate motion is generally inferred indirectly from the relative motions of Caribbean–North America and North America–South America plate pairs. Variation in these results shown in Table 1 and Fig. 1 can be attributed to regional inferences based on local areas of PBZ deformation. In particular, slip-vector analysis of earthquakes may reflect local inter-
Fig. 1. Plate tectonic setting of Hispaniola (CARIB = Caribbean plate; NOAM = North America; SOAM = South America; COCO = Cocos). Dashed lines represent direction of North American left-lateral strike-slip motion about a pole of relative motion suggested by Jordan [7] and Minster and Jordan [8] (lines labelled 1) and Sykes et al. [4] (line labelled 2). Slip lines labelled 1 are based mainly on earthquake slip vectors and fault strikes from the Cayman Trough pull-apart (shown in grey) and Central America and Suggest Mountains of Hispaniola (hatched area) result from plate convergence at a north-step or restraining bend in our east-west left-lateral strike-slip plate boundary zones. Slip lines labelled 2 are based mainly on earthquake slip vectors in the Hispaniola–Puerto Rico (PR) area and suggest northeasterly to east-northeasterly plate convergence in this area. Black thrust symbols indicate subduction zones with volcanic arcs; uncolored thrust symbols indicate convergent zones without associated volcanic arcs.

We here describe Neogene deformation in Hispaniola as providing a way of resolving problems inherent in interpreting a seismic record that is short and contains substantial earthquakes only indirectly related to plate motions. Hispaniola is a compressional north-step or restraining bend in the principal displacement left-lateral strike-slip fault zone of the North American–Caribbean PBZ (Motagua–Swan–Oriente–Septentrional–Puerto Rico Trench Fault Zones) (Fig. 1). The island provides the largest onshore area of this PBZ deformation system outside Central America (Fig. 1). We discuss the late Neogene geologic record within the framework of the new seismic data presented here and draw comparisons to similar strike-slip restraining bends in California, New Zealand and Lebanon.
TABLE 1
Determinations of present-day Caribbean motion relative to North America

<table>
<thead>
<tr>
<th>Reference</th>
<th>Rate</th>
<th>Direction</th>
<th>Method of calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molnar and Sykes [1]</td>
<td>0.5 cm/yr at</td>
<td>–</td>
<td>empirical relationship between seismicity and slip rate (Brune [5]).</td>
</tr>
<tr>
<td></td>
<td>Lesser Antilles Arc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molnar and Sykes [1]</td>
<td>2.2 cm/yr at</td>
<td>N80 ° E</td>
<td>rate from closure of velocity triangle for NOAM, Cocos, CARIB: direction from earthquake mechanisms</td>
</tr>
<tr>
<td></td>
<td>Lesser Antilles Arc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isacks et al. [6]</td>
<td>2 cm/yr</td>
<td>–</td>
<td>rate based on downdip length of seismic zone in Lesser Antilles arc</td>
</tr>
<tr>
<td>Jordan [7]</td>
<td>angular rate of 0.20 ± 0.07 °/Ma</td>
<td>pole at 60 ° N, 116 ° E</td>
<td>combination of earthquake slip vectors, Cayman Trough spreading rate and closure of velocity triangle for NOAM-CARIB-COCOS</td>
</tr>
<tr>
<td>Minster and Jordan [8]</td>
<td>1.94 cm/yr</td>
<td>essentially same pole as Jordan [7] (see Fig. 1)</td>
<td>combination of earthquake slip vectors, Cayman Trough spreading rate</td>
</tr>
<tr>
<td>Sykes et al. [4]</td>
<td>3.7 ± 0.5 cm/yr over 7 Ma</td>
<td>N70 ° E in northeastern Caribbean; pole at 66 ° N, 132 ° W (see Fig. 1)</td>
<td>rate from configuration of seismic zone in Puerto Rico and Lesser Antilles; direction from earthquake slip vectors</td>
</tr>
</tbody>
</table>

- Authors note that rate does not include aseismic slip or seismic moments for thrust faults.
- Principal source of error is the small angular separation between Cocos Pacific and Cocos–Americas plates.
- Rate calculation assumes constant plate motion over 10 Ma.
- Slip vectors used by Jordan [7] from Hispaniola, Puerto Rico Trench and area south of possible NOAM-CARIB-SOAM triple junction are excluded.
- Five out of seven earthquake slip vectors used to determine direction of plate motion arc from Puerto Rico Trench and northern Lesser Antilles; rate calculation assumes constant plate motion over 10 Ma.

2. Four structural areas in Hispaniola

The physiography of Hispaniola consists of alternating valleys and mountain ranges which are mostly defined by active reverse or sinistral strike-slip or oblique-slip faults (Fig. 2A). Cretaceous to Eocene island arc and platform carbonate rocks are typically found in the cores of mountain ranges at higher (> 1000 m) elevations while the valleys contain thick sequences of Tertiary and Quaternary sedimentary rocks [9].

Field mapping and interpretation of LANDSAT, SEASAT-SAR radar images and conventional aerial photographs indicate two areas of active, through-going left-lateral strike-slip faults that roughly follow the north and south coasts of the island (Fig. 2A). The west-central part of the island consists of high ground bounded by dominantly reverse faults along the edges of the uplifted mountain ranges. The eastern part of the island is relatively much lower than the rest of the island and does not appear too affected by active faulting (Fig. 2A). We first describe the neotectonic characteristics of each of the four zones and then attempt an overall interpretation of the structure and seismicity of the island.

3. Strike-slip faulting in northern Hispaniola

The northern zone of strike-slip faulting consists primarily of the Camu and Septentrional Fault Zones of the northern Dominican Republic and constitutes a 50 km wide, 300 km long landward extension of the Oriente strike-slip fault zone of the Cayman Trough and the oblique-slip faults of the Puerto Rico Trench (Fig. 1). Both the Camu and Septentrional Faults are convex to the south and change strike from 090 ° to 115 ° (Fig. 2A). The two faults bound the highest topographic
Fig. 2. Summary of neotectonic structures of Hispaniola which have developed since the Miocene and their relation to historical seismicity: A. Topography, recent faults, and recent volcanic centers; B. Historical seismicity from Kelleher et al. [11]; C. Strain ellipse showing types of structures predicted in a left-lateral strike-slip plate boundary zone with east-west relative plate motion; D. Schematic map of major structural features produced since the Miocene in Hispaniola by North America–Caribbean relative plate motion. Mountain ranges approximate anticlines but are thrust bound at their edges. Motion is transformed between the two strike-slip fault zones by northwest-southeast extensional “pull-apart” structure across the west-central part of the island. We interpret this as a bypass response to locking across the northern convergent strike-slip fault zones.

block of the Cordillera Septentrional where elevations reach 1249 m along a ridge parallel and 2–3 km north of the Septentrional Fault Zone (Fig. 2A). The Camu Fault Zone is much less topographically distinct than the Septentrional which forms a fault line scarp as steep as 400 m over 2 km in the central section. The Septentrional Fault Zone is marked by a single prominent fault scarp along its central and eastern trace and forms a remarkably straight contact between Quaternary alluvium and Tertiary sedimentary rocks of the southern Cordillera Septentrional (Fig. 2A). The fault trace exhibits geomorphic features characteristic of active strike-slip faults such as shutter ridges, aligned drainage, vegetation contrasts, en echelon folds, beheaded and skewed alluvial fans and uphill facing scarps [10]. Side-look radar imagery reveals low scarps in alluvium where the fault crosses alluvial plains. The single fault trace splays into at least two sub-parallel traces in the western Dominican Republic (Fig. 2A). The northern splay contains a 10 km long “push-up” area of compressional deformation at a 2.5 km right-step in the strike-slip faults trace (Fig. 2A). The sharpness of the fault trace near the push-up (area indicated in Fig. 2A) suggests the possibility of a
historical rupture perhaps during the 1842 earthquake [11] (Fig. 2B). The southern splay trends almost due west along the flood-plain of the Rio Yaque del Norte and projects westward along the coast of northern Haiti (Fig. 2A). This splay is marked in the alluvium by a strong vegetation contrast where the faulting has acted as a downslope barrier to groundwater migration.

The concentration of high ground on the north sides of the Camu and Septentrional Fault Zones, the occurrence of push-up structure, and a locally thick (possibly 4 km or more) Plio-Pleistocene clastic section south of the Septentrional Fault Zone [9] all suggest that west-northwesterly sections of these faults are “transpressional”: that is, they have a significant component of convergence (Fig. 2C). Northeast-trending, secondary extension has occurred north of the Camu Fault Zone and formed at least two Quaternary grabens near Bahia Maimon and Rio Yasica [12,13] (Fig. 2A). Convergence across the westernmost section of the Septentrional Fault Zone may have resulted in the splaying and in the progressive abandonment of the northern splay.

The age and offset of the Septentrional and Camu Fault Zones are poorly known. Both faults truncate rocks of Miocene age [12]. Overthrusting along the Septentrional Fault Zone appears to have been initiated in the Pliocene based on the evidence of the age of sediments accumulated on the overthrust valley block south of the fault [9]. Eberle et al. [13] have suggested a left-lateral offset of 100 km on the Septentrional Fault Zone to match areas of alluvial gold deposits in the Cordillera Septentrional and eastern Hispaniola.

4. Strike-slip faulting in southern Hispaniola

Recently a major throughgoing strike-slip fault zone has been identified stretching from south-central Hispaniola to southeastern Jamaica where displacement appears to be relayed northward at a major restraining bend [14]. The fault extends to western Jamaica and may merge with the southern edge of the Cayman Trough (Fig. 1). We have named the continuous part of this fault the Enriquillo–Plantain Garden Fault Zone on the basis of its extreme landward segments in eastern Jamaica and central Hispaniola. Parts of this fault zone have been recognized from historical [11] and present-day [4] earthquakes.

In south-central Dominican Republic and eastern Haiti, the Enriquillo–Plantain Garden Fault Zone is a remarkably straight and narrow zone of deformation which trends due east. The fault trace cannot be followed into eastern Hispaniola (Fig. 2A) and is locally obscured by alluvium in the sub-sea level Enriquillo Valley of the Dominican Republic (Fig. 2a) whose floor is dynamically depressed by en echelon secondary thrusts associated with east-west strike-slip displacement [15] (Fig. 2C). At higher elevations, the fault trace exhibits typical strike-slip geomorphic features such as travertine mounds, fault springs, uphill facing scarps, and offset drainage. In eastern Haiti, the fault trend changes abruptly from 090° to 099°, a strike it maintains to eastern Jamaica (Figs. 1, 2A). The west-southwesterly fault trace in southern Haiti is interrupted by two Quaternary pull-apart basins at Clonard and Mirogoane Lakes and is locally marked by one very prominent fault valley near Leogane [16]. En echelon extensional structures are also inferred from bathymetric maps of the offshore continuation of the fault in the Jamaica Passage, the marine strait separating eastern Jamaica and southwestern Haiti [16] (Fig. 1). Right-steps of the fault trace in southwestern Haiti and eastern Jamaica, are marked by local topographic uplifts caused by convergence at “push-ups” or restraining bend segments (Fig. 2A). In these compressional segments, the single strike-slip fault splays into a series of thrust and reverse faults which are topographically less prominent. Local elevations reach 2–3 km (Fig. 2A).

The existence of pull-aparts and the fault trough structure of the 099°-trending section of the Enriquillo–Plantain Garden Fault Zone in Haiti and the Jamaica Passage suggest that this west-southwesterly section of the fault is “transstensional”, that is, it has a significant component of divergence [16] (Fig. 2C). A northeast-trending graben in Port-au-Prince Bay north of the fault [17] and in Azua Bay south of the fault (Fig. 2A) as well as northwest-trending restraining bend or “push-up” segments are all consistent with this hypothesis.
The total offset on the Enriquillo–Plantain Garden Fault Zone appears to be about 10 km based on the offset of Cretaceous rocks in Jamaica. The age of initial fault movement appears to be early Pliocene when secondary deformation associated with the fault completely disrupted a later Miocene deep marine basin in the Enriquillo–Cul-de-Sac Valley of the Dominican Republic and Haiti [18,19].

5. Deformation of the west-central mountain ranges of Hispaniola

The west-central part of Hispaniola consists of en echelon, sinuous mountain ranges with elevations reaching a maximum of 3 km in the Cordillera Central of the Dominican Republic (Fig. 2A). Uplift of the ranges has occurred along northwesterly trending reverse and thrust faults which over-thrust the floors of neighboring valleys and generally occur near the 500 m topographic contour (Fig. 2A). Mapping along the major fault zone, which separates Cretaceous rocks of the Cordillera Central from sedimentary rocks of the San Juan Basin to the south (Fig. 2A), has shown that east-west-trending segments of the fault zone have a large strike-slip component whereas more northwesterly trending segments are reverse faults associated with overturned and intensely thrusted beds [20]. North-south seismic profiling across the southern edge of the San Juan Basin between two of the ranges indicates a synclinal structure for the basin and the presence of imbricate reverse faults dipping southwards at 45° [21] (Fig. 3; line of section shown in Fig. 2A). Uplift of the northwestern margin of the Cordillera Central occurs along at least three mapped faults all of which are convex to the northeast (Fig. 2A). The Bonao Fault Zone forms the most prominent topographic scarp and delineates the northeastern boundary of the highest region of the Cordillera Central (Fig. 2A). The Hatillo Fault Zone (Fig. 2A) is a thrust dipping at approximately 30° to the southwest and carrying what are thought to be older metamorphic rocks northwards over Cretaceous to early Tertiary [22]. The Hispaniola Fault Zone is an Oligocene age strike-slip fault which juxtaposes metamorphosed mafic volcanic rocks on its south from quartz-albite-sericite-epidote-chlorite metamorphosed rocks on its north over a distance of 170 km [22]. The west-northwesterly segment of

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Fig. 3. Interpretation of north-south Vibroseis seismic reflection line across the San Juan Valley (from Nemec [21]). Over 2 km of high-energy fanglomerates of Mio-Pleistocene age have filled the synclinal basin and record the uplift of the Cordillera restraining bend to the north.
the Hispaniola Fault Zone north of the Cordillera Central is marked by a narrow graben of folded Oligocene elastic rocks believed to have been deposited in an asymmetric depression along an active strike-slip fault [23]. The northwesterly striking segment of the Hispaniola Fault Zone is occupied by a wedge-shaped ultramafic body with reverse faults on both sides dipping eastward at 75–80° and westward at 50–65° [24]. The ultramafic rocks are interpreted as the upfaulted basement of the Oligocene strike-slip basin which is preserved to the north. This hypothesis is consistent with the observation that northwesterly faults are thrusts and that more easterly trending faults have more of a strike-slip component (Fig. 2C).

6. Recent volcanic province of Hispaniola

Four areas of recent volcanic rocks have been identified in central Hispaniola (Fig. 2A). The easternmost volcanic center consists of a northeast-trending belt of domes and valley fillings of andesites, rhyolites, and basalts. K-Ar ages range from 2 Ma B.P. to less than 0.5 Ma B.P. (latest Pliocene to late Pleistocene) [25]. Most of the volcanic eruptions appear to have occurred along northeast-trending, presumably normal, faults which are orthogonal to the trend of the reverse faults bounding the southern edge of the Cordillera Central (Fig. 2A).

The western three volcanic centers consist mostly of basalt flows [25] (Fig. 2C). Basalt flows erupted at the eastern center overlie sedimentary rocks of Plio-Pleistocene age. The outcrop pattern of two of these mafic volcanic centers is also elongate to the northeast and again suggests eruption along northeast-trending normal faults (Fig. 2C). The center near the west coast of Haiti occurs along the landward extension of a recent northeast-trending graben in Port-au-Prince Bay (Fig. 2C).

7. Deformation of eastern Hispaniola

Most of eastern Hispaniola is low in elevation, covered by Neogene marine shelf sediments indicating limited regional uplift and is relatively unaffected by recent faulting (Fig. 2A). High ground exposing Cretaceous rocks is found only in the north and may reflect secondary compressional uplift along the southern edge of the South Samana Bay Fault Zone (Fig. 2A).

8. Neotectonic synthesis

We interpret structural pattern of strike-slip faults, grabens, and thrust-bound mountain ranges (shown in Fig. 2A and schematically in Fig. 2D) as indicating that Hispaniola occupies a 250 km wide belt of left-lateral shear deformation resulting from east-west relative motion of the North America and Caribbean plates (Fig. 2C). East-west faults, such as the eastern part of the Enriquillo–Plantain Garden Fault Zone (Fig. 2A) are strike-slip faults (Fig. 2C). West-northerly trending faults, such as those in the Septentrional and Camu Fault Zones, are transpressional or convergent strike-slip faults (Fig. 2C). West-southwesterly trending faults, such as those in the western part of the Enriquillo–Plantain Garden Fault Zone (Fig. 2A), are transtensional or divergent strike-slip faults (Fig. 2C). Northwesterly trending faults, such as the Hatillo, Hispaniola, and Bonao Fault Zones (Fig. 2A), are reverse or thrust faults (Fig. 2C). The trend of recent volcanics is northeasterly and they are locally associated with northeasterly trending normal faults (Fig. 2C). Recent grabens also trend northeast (Fig. 2A).

The dominance of reverse and convergent strike-slip faults in northern and west-central Hispaniola suggests that this part of the island constitutes an asperity or restraining bend in the east-west North American–Caribbean plate boundary zone (Fig. 1). The origin of the asperity is attributed to the interaction of Miocene and younger east-west strike-slip faults with west-northerly striking rocks formed in island arcs of Cretaceous to Eocene age. Oligocene strike-slip faults of which the Hispaniola Fault Zone (Fig. 2A) is the most prominent represent an early stage in the evolution of the North America–Caribbean PBZ. We interpret the Enriquillo–Plantain Garden Fault Zone, which more closely parallels the east-
west direction of plate motion (Fig. 2A), as a bypass fault which is relieving the locking and uplift across the northern and central parts of the island (Fig. 2D). Motion is transformed between the two strike-slip fault zones by northwest-southeast extension across the west-central part of the island. This interpretation suggests a pull-apart origin for the Pleistocene volcanic province of central Hispaniola (Fig. 2D). Superposition of the northeast-trending volcanic centers on northwest-trending thrusts and reverse faults bounding the Cordillera is predicted in an east-west strike-slip system (Fig. 2C) and is consistent with the crosscutting relationships of mountain fronts and volcanic centers (Fig. 2A). An intriguing relationship exists between active extension indicated by recent volcanism and grabens and active compression indicated by mountain ranges and seismicity.

9. Shallow seismicity and its relation to crustal structures in Hispaniola

The present-day seismicity of Hispaniola consists of a broad belt of earthquakes which range in depth from 0 to 115 km. Two bands of shallow seismic activity (< 70 km) are present: a northern band roughly parallels the Orient–Septentrional–Camu–Puerto Rico Trench Fault Zones and events on it have been concentrated in northeastern Hispaniola and the Puerto Rico Trench [4]. A more diffuse southern band of activity is developed from Jamaica to southern Hispaniola and roughly parallels the Enriquillo–Plantain Garden Fault Zone. The two bands of shallow earthquake activity appear to merge in eastern Hispaniola and extend as a single belt to the Lesser Antilles island arc.

The record of historical earthquakes in Hispaniola and Puerto Rico dates back to the 16th century and closely corresponds to the present-day strike-slip fault pattern [4,11] (Fig. 2B). A zone of ruptures in the 19th and 20th centuries extends roughly parallel to the Septentrional–Puerto Rico Trench Fault Zones. The extended rupture zone of the 1842 earthquake corresponds closely with the west-northwesterly convergent section of the Septentrional Fault Zone and is compatible with the idea of sudden energy release along a 300 km segment following a period of locking across the fault plane. Recent scarps in the western Dominican Republic may have formed during this event (Fig. 2A).

A second belt of smaller, historical rupture zones of the 18th and 19th centuries coincides with the Enriquillo–Plantain Garden Fault Zone [11] and is compatible with reduced frictional slip on a fault zone that is parallel or slightly oblique to the direction of plate motion (Fig. 2C). The younging of ruptures eastward suggests a time-space migration of seismic slip, which began in October of 1751 in the Dominican Republic, moved westward across Haiti in the 18th and 19th centuries, and perhaps culminated in Jamaica during large earthquakes there in the 20th century (Fig. 2B).

10. Deep seismicity and its possible relation to crustal structures in Hispaniola

A belt of intermediate depth earthquakes (70 < h < 140 km) extends from the Lesser Antilles arc as far west as the outcrop of the Bonao Fault Zone in central Hispaniola and events in this belt are particularly concentrated in eastern Hispaniola [4] (Fig. 2A). Detailed seismic work has shown that intermediate depth earthquakes from the northern Lesser Antilles arc to the western end of Puerto Rico are associated with a continuous underthrust slab [4]. Intermediate earthquakes from the western end of Puerto Rico to central Hispaniola are associated with the deformation of discontinuous slab fragments and slip vectors of earthquakes change orientation from approximately easterly (northeast of Puerto Rico) to southwesterly and southerly (in eastern Hispaniola) (arrow in Fig. 2B). Historical rupture zones in eastern Hispaniola and Puerto Rico are subcircular [11] (Fig. 2B) and are consistent with intermediate-focus earthquakes presently occurring above subducted slabs in these areas.

A seven-station seismograph network installed by one of us (T.M.) in the north-central Dominican Republic in December 1979 suggests two diffuse zones of intermediate-depth earthquakes that dip steeply to the southwest beneath the Cordillera
Fig. 4. Comparison between restraining bends (A) along the San Andreas Fault system between the Pacific and North American plates (the Transverse Ranges) and (B) along the Dead Sea Fault system between the Sinai (Levant and Arabia plates (the Lebanon Ranges)). Slip lines about published poles of rotation are indicated: 1 = Minster and Jordan [8]; 2 = Woodford and McIntyre [40]; 3 = Le Pichon and Franchette [43]; 4 = Garfunkel [41]. Pole positions determined from fault strikes from only one side of the restraining bend (e.g., 2, 4) yield directions of plate motion which are inconsistent with much of the geology of the plate boundary zone.

Central (area west Bonao and La Vega) to depths of 115 km [26,27]. Although both seismic zones have not yet been well defined, preliminary data suggests that both zones are between 30 and 50 km thick and are separated by an approximately 30 km wide aseismic zone. Both zones extend to depths of 115–120 km. The upper 50 km of the eastern zone is relatively aseismic and cannot be confidently correlated to any surface structure, although it is in the general vicinity of the westernmost Puerto Rico Trench near Samana (Fig. 4). The western zone is better defined by a more dense occurrence of events that suggests a fairly uniform seismic zone from the surface to maximum depths of 120 km. The upper part of the western zone approximately coincides with mapped southwesterly dipping reverse and thrust faults (Hatillo, Hispaniola, Bonao Fault Zones) (Fig. 2A). Above and to the west of the western zone in the Cordillera Central is a relatively dense zone of
hypocenters that range in depth from 30 to 0 km (Fig. 4).

The two seismic zones are speculated to be slabs of relatively young (Cretaceous–Eocene) island arc lithosphere which are being subducted along northwest trending thrust and reverse faults that accommodate shortening in the restraining bend. Although more seismic work and geologic mapping will be necessary to better define the slabs and their surface extensions, subduction appears to occur in a more or less southwesterly direction perpendicular to the strikes of known reverse faults in central Hispaniola (i.e., Hispaniola, Hatillo, and Bonao Fault Zones) and the westernmost Puerto Rico Trench. Earlier workers have previously pointed out the “island arc” structure of eastern Hispaniola (e.g., [1] and [31]) but have not interpreted the structure as a product of convergence at a strike-slip restraining bend. The latter interpretation is supported by two observations: (1) earthquake slip vectors appear to locally diverge from an approximately east-west direction north of Puerto Rico to a southwest direction (Fig. 2B) perpendicular to the strike of mapped reverse and thrust faults in eastern Hispaniola (Fig. 2A); and (2) the areas above the underthrust slabs are topographically low lying (Fig. 2A) and are not characterized by a large number of shallow earthquakes. Low topography is consistent with the idea of local convergence being accommodated by underthrusting rather than lithospheric shortening and thickening—the deformation style found farther west in the topographically higher parts of central Hispaniola (Fig. 2A).

11. Discussion

Structural and seismic data suggests that Hispaniola occupies an active restraining bend or asperity in the east-west North America–Caribbean strike-slip plate boundary zone (Fig. 1). The restraining bend structure of the island has important implications for plate interactions in this area as well as for tectonic processes occurring at restraining bends.

11.1. Direction of Caribbean plate motion

Several tectonic models have been proposed for the Neogene tectonics of Hispaniola. None have reconciled the apparent convergence of the Caribbean and North America plates suggested by intermediate-depth earthquakes in eastern Hispaniola and the east-west strike-slip motion predicted from plate calculations [7] and from east-west Neogene strike-slip offset in the Cayman Trough [3] (Fig. 1). Most models have emphasized convergence over strike-slip because of: (1) lack of firm evidence for strike-slip faulting in the northeastern Caribbean (with the exception of the en echelon pattern of Cordillera in central Hispaniola) [28,29]; (2) the superficial resemblance of the east-west-trending, landward-dipping Puerto Rico and Muertos Trenches to active Pacific convergent margins [30]; (3) the strong southerly component of earthquake slip vectors suggesting north-south plate convergence [1,4,31] (Fig. 2B); and (4) closure of the North America–Africa–South America relative plate motion circuit which suggest Neogene relative convergence between the Americas across the Caribbean [32,33].

Our observations suggest that convergence in Hispaniola is related to secondary northwest-southeasterly compression resulting from the interaction of east-west relative plate motion with older west-northwesterly trending island arc structures (Fig. 2D). Neogene interaction has produced an asperity or restraining bend in northern Hispaniola which is being partially bypassed by a new, more slip-parallel strike-slip fault that was initiated sometime in the Pliocene (Fig. 2D). Shortening in eastern Hispaniola is accommodated by subduction of what is thought to be island arc lithosphere to depths of at least 115 km (Fig. 4). Slip vectors from earthquakes in this zone trend perpendicular to local northwest-trending thrusts and arc structures established by the Eocene and are therefore probably not reliable indicators of the overall direction of Caribbean–North America plate motion (Fig. 2B). Better long-term indicators of plate motion are convergent and divergent strike-slip fault systems and associated secondary structures (Fig. 2D) which have developed since the Miocene (that is over the last 6 Ma) and indicate an almost
exactly east-west direction of relative plate motion (Fig. 2C). The east-west direction of plate motion indicated by these geologic structures agrees well with slip lines about the pole of relative motion calculated by Jordan [7] and Minster and Jordan [8] using a combination of earthquake slip vectors and fault strikes mostly from margins of the Cayman Trough (Fig. 1). Our study of plate motion in Hispaniola has independently arrived at the same conclusion as Minster and Jordan [8] who eliminated earthquake slip vectors from the Hispaniola and Puerto Rico Trench area because “the data show internal scatter and the stress and strain fields are complex”.

Our data suggests that N70°E direction of Caribbean relative motion suggested by Sykes et al. [4] (Fig. 1) may partly reflect intraplate deformation at the Hispaniola restraining bend. However, the number of local mechanisms in the Hispaniola and Puerto Rico areas is still quite limited and further progress can be expected in determining the direction of plate motion using earthquakes.

11.2 Early development of the Hispaniola restraining bend

The history of uplift related to restraining bend formation in Hispaniola is recorded by the stratigraphic relationships and compositions of coarse clastic sediments eroded from uplifted areas and preserved in surrounding basins. Moreover, bend formation was accompanied by a rapid acceleration of clastic sedimentation rates.

There is good stratigraphic evidence for the early uplift of the Hispaniola bend from both the northern (Cibao Basin) and southern flanks (San Juan Basin—cf. Fig. 3—and Enriquillo Basin) of the Cordillera Central. Two large, apparently undeformed Miocene alluvial fan complexes are found along the northern edge of the Cordillera Central in the Cibao [34]. The triangular shape and fining northwards of both fans into the Cibao Basin indicates the early uplift of the northern edge of the Cordillera Central by at least the late Miocene, the approximate age of the basal clastic rocks [35]. The basal unconformity of the eastern fan clearly truncates sediments as young as late Oligocene [34]. The fans consist of well-rounded to sub-rounded clasts of tonalite, greenstones, felsic tuffs and vein quartz that suggest a deep level of late Miocene erosion of the Cordillera Central.

On the southern edge of the Cordillera Central, an influx of clastic sediments derived from the erosion of an arc terrane occurred in: (1) early Miocene on the north flank of the central Plateau in Haiti [19] and its eastward continuation into the San Juan Valley of the Dominican Republic [20]; (2) late medial Miocene (Tortonian–Messinian) in the Enriquillo–Cul-de-Sac Valley [18,19,36] (Fig. 2A). This depositional history is consistent with and reflects the progressive post-early Miocene uplift of a restraining bend centered on the present-day Cordillera Central. The slightly younger age for the onset of clastic sedimentation on the south flank of the Central Plateau of Haiti and the Enriquillo–Cul-de-Sac Valley is consistent with southward progradation of a clastic wedge derived from the Cordillera Central. A very rapid sedimentation rate of 60 cm/1000 years can be derived from detailed paleontologic on the late Miocene clastic succession of the eastern Enriquillo–Cul-de-Sac Valley [36].

11.3 Comparison of Hispaniola with other restraining bends

Restraining bends or compressional asperities are found along most active strike-slip fault systems and occur on a variety of scales. Major bends (that is, fault separations of roughly 100 km) have been described in the Transverse Ranges of southern California [37], the southern Alps of New Zealand [38], and the Lebanon Ranges of Lebanon [39] (Fig. 4). It is interesting to briefly compare the neotectonics of Hispaniola, which lies entirely within island arc lithosphere with the active tectonics of these other bends which are better studied and lie within continental lithosphere.

All of the bends result in major deflections (15–30°) of the principal displacement strike-slip fault zone of their associated PBZ and result in crustal shortening and topographic uplift of area measured in thousands of square kilometers (Fig. 4). Some workers have made regional inferences
on the direction of plate motion, which have failed to recognize the importance of the restraining bend fault segment within the framework of the entire PBZ [40,41]. Fault strikes from only one side of a major restraining bend yield pole positions which are much closer to the PBZ and are inconsistent with much of the PBZ geology (cf. [42,43] for discussions) (Fig. 4).

A variety of deformational mechanisms have been suggested to occur at active bends; all may lead to faulting and substantial earthquakes which are only indirectly related plate motion (Fig. 5). Different mechanisms, which have been suggested to occur at the Transverse ranges bend (Fig. 5), include: (1) sideways *escape* of triangular continental fragments [44]; (2) *bypassing* of the bend area by more rectilinear faults [37]; (3) *flaking* of sheetlike masses or crustal flakes or less than lithospheric thickness [45]; and (4) incipient *aseismic subduction* [45]. Mechanisms proposed for the Southern Alps restraining bend include: (1) a steady-state balance between *erosion and uplift* on reverse faults [46]; (2) *subduction* [47]; and (3) *flaking* [48].

Rapid erosion and acceleration of sedimentation rates frequently occurs during uplift of restraining bends and has become particularly well understood for the Transverse Ranges of California [49].

Data presented here suggest that three of the above processes, bypassing, uplift, and subduction, dominate at the Hispaniola restraining bend, which unlike the above examples, lies wholly within relatively young (Cretaceous to latest Eocene) island arc lithosphere. It appears possible that thinner, younger island arc lithosphere may be more prone to subduction than to escape or flaking processes that are more important in older more buoyant lithosphere.

Fig. 5. Proposed deformational mechanisms which have been suggested to occur at restraining bends; all may lead to faulting and earthquakes related to internal plate deformation at the bend and not to relative plate motion. Mechanisms B and C appear to be occurring in the relatively young (Cretaceous–Eocene) island arc lithosphere of Hispaniola.

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