Toward a better understanding of the Late Neogene strike-slip restraining bend in Jamaica: geodetic, geological, and seismic constraints

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Abstract: We describe the regional fault pattern, geological setting and active fault kinematics of Jamaica, from published geological maps, earthquakes and GPS-based geodesy, to support a simple tectonic model for both the initial stage of restraining-bend formation and the subsequent stage of bend bypassing. Restraining-bend formation and widespread uplift in Jamaica began in the Late Miocene, and were probably controlled by the interaction of roughly east–west-trending strike-slip faults with two NNW-trending rifts oriented obliquely to the direction of ENE-trending, Late Neogene interplate shear. The interaction of the interplate strike-slip fault system (Enriquillo-Plantain Garden fault zone) and the oblique rifts has shifted the strike-slip fault trace *c*. 50 km to the north and created the 150-km-long by 80-km-wide restraining bend that is now morphologically expressed as the island of Jamaica. Recorded earthquakes and recent GPS results from Jamaica illustrate continued bend evolution during the most recent phase of strike-slip displacement, at a minimum GPS-measured rate of 8 ± 1 mm/a. GPS results show a gradient in left-lateral interplate strain from north to south, probably extending south of the island, and a likely gradient along a ENE–WSW cross-island profile. The observed GPS velocity field suggests that left-lateral shear continues to be transmitted across the Jamaican restraining bend by a series of intervening bend structures, including the Blue Mountain uplift of eastern Jamaica.

Regional significance of restraining bends

Restraining bends are a relatively common structural and morphological feature along both active and ancient intercontinental strike-slip faults, and occur at a variety of scales ranging from tens of metres to tens of kilometres (Crowell 1974; Gomez *et al.* 2007; Mann 2007) (Fig. 1). Regardless of their scale, interplate 'gentle' or curved restraining bends (Crowell 1974) consist of a convergent fault segment of variable width, geological complexity and topographic elevation, that is misaligned with the direction of the regional interplate slip vector (Mann & Gordon 1996). For example, along the San Andreas fault system, the Transverse Ranges restraining bend occurs at a significant misalignment of about 20° with the regional interplate slip vector between the Pacific plate and North America plate (Fig. 1A). Accommodating about 35 mm/a of right-lateral slip, the San Andreas system is a relatively simple linear boundary along most of its length, but becomes much wider (*c*. 150 km) at the Transverse Ranges, where there are multiple, seismogenic, subparallel thrusts and strike-slip fault strands (Matti & Morton 1993). Restraining bends in intraplate areas of deformation like central Asia are more complex in that that they do not show paired geometries, and they cannot be related in a convincing way to the plate motions (Mann 2007; Cunningham 2007). Instead, reactivation of underlying basement structures seems to play a large role in their evolution.

South of the Transverse Ranges in the Salton Sea and Gulf of California, the trace of the main plate boundary strike-slip fault is again oblique to the direction of interplate slip, but curving in the opposite direction. In this orientation, the misaligned fault trace in this topographically depressed or submarine region is characterized by a broad, 100–150-km-wide zone of oblique opening or 'transtension', which in some areas has progressed to the point of forming localized zones of volcanism or short, oceanic spreading centres (Fig. 1a).

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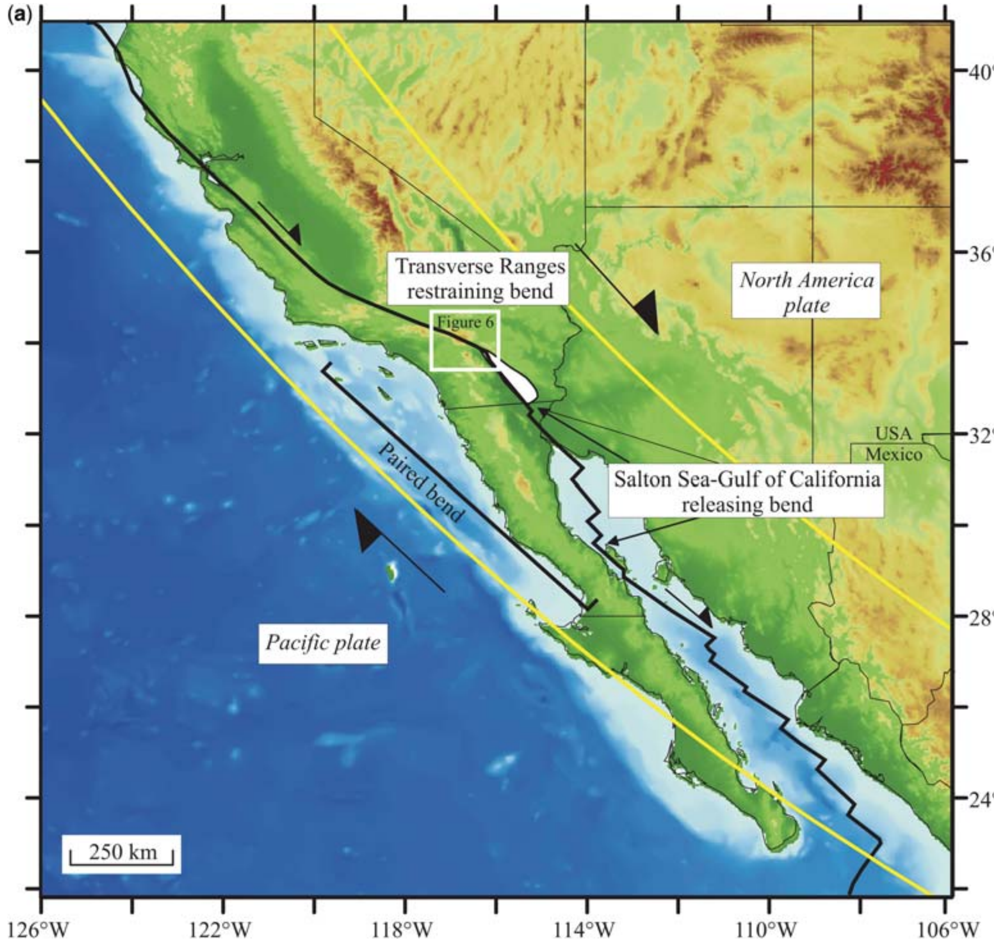

Fig. 1. (**a**) Major restraining and releasing fault bends along the active right-lateral strike-slip San Andreas fault system separating the Pacific and North America plates (direction of plate motion is shown by yellow circles about the pole of rotation from DeMets *et al.* 1994; topographic base is from NASA SRTM data). The Transverse Ranges represent a major restraining-bend segment that is flanked to the south by the Salton Sea–Gulf of California releasing bend (area in white surrounding the Salton Sea is highly extended and below sea-level). The adjacent Transverse Ranges restraining bend and the Salton Sea–Gulf of California releasing bends are termed a 'paired bend'. (**b**) Major restraining and releasing fault bends along the active left-lateral strike-slip northern Caribbean fault system separating the North America and Caribbean plates (direction of plate motion is shown by yellow circles about the pole of rotation from DeMets *et al.* 2000). The island of Jamaica represents a major restraining bend at a right-step in the Enriquillo–Plantain Garden fault zone (EPGFZ) and the Walton fault zone (WFZ). The Jamaica restraining bend is flanked to the west by the West Jamaica releasing bend. The adjacent Jamaican restraining bend and the West Jamaica releasing bend are termed a 'paired bend'. A parallel strike-slip fault zone consists of the Oriente fault zone (OFZ) and the Swan Islands fault zone (SIFZ). The active Mid-Cayman spreading centre (MCSC) is a 100-km-long left-step between the two faults.

The overall effect of the obliquely convergent fault segment in the Transverse Ranges of California and the adjacent obliquely divergent fault segments in the Imperial Valley and Gulf of California is a 'paired bend', or adjacent restraining and releasing-bend segments (Mann 2007). The paired bend gives the southern San Andreas–Gulf of California fault system a gently undulating appearance when viewed on a regional scale (Fig. 1a).

A similar, undulating strike-slip fault pattern composed of adjacent or paired restraining and releasing bends is present along the northern Caribbean plate boundary zone (Fig. 1b). This interplate strike-slip boundary consists of a

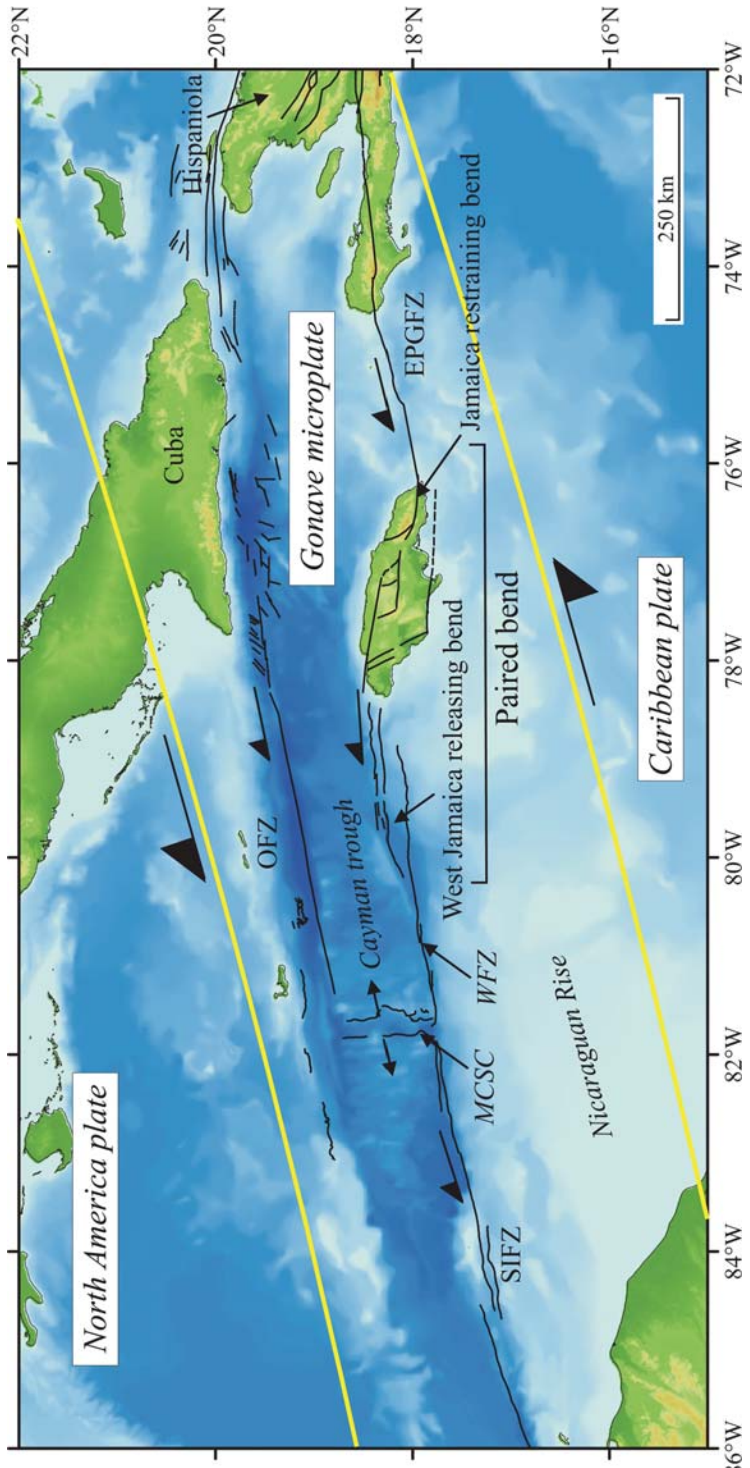

Fig. 1. (*Continued*)

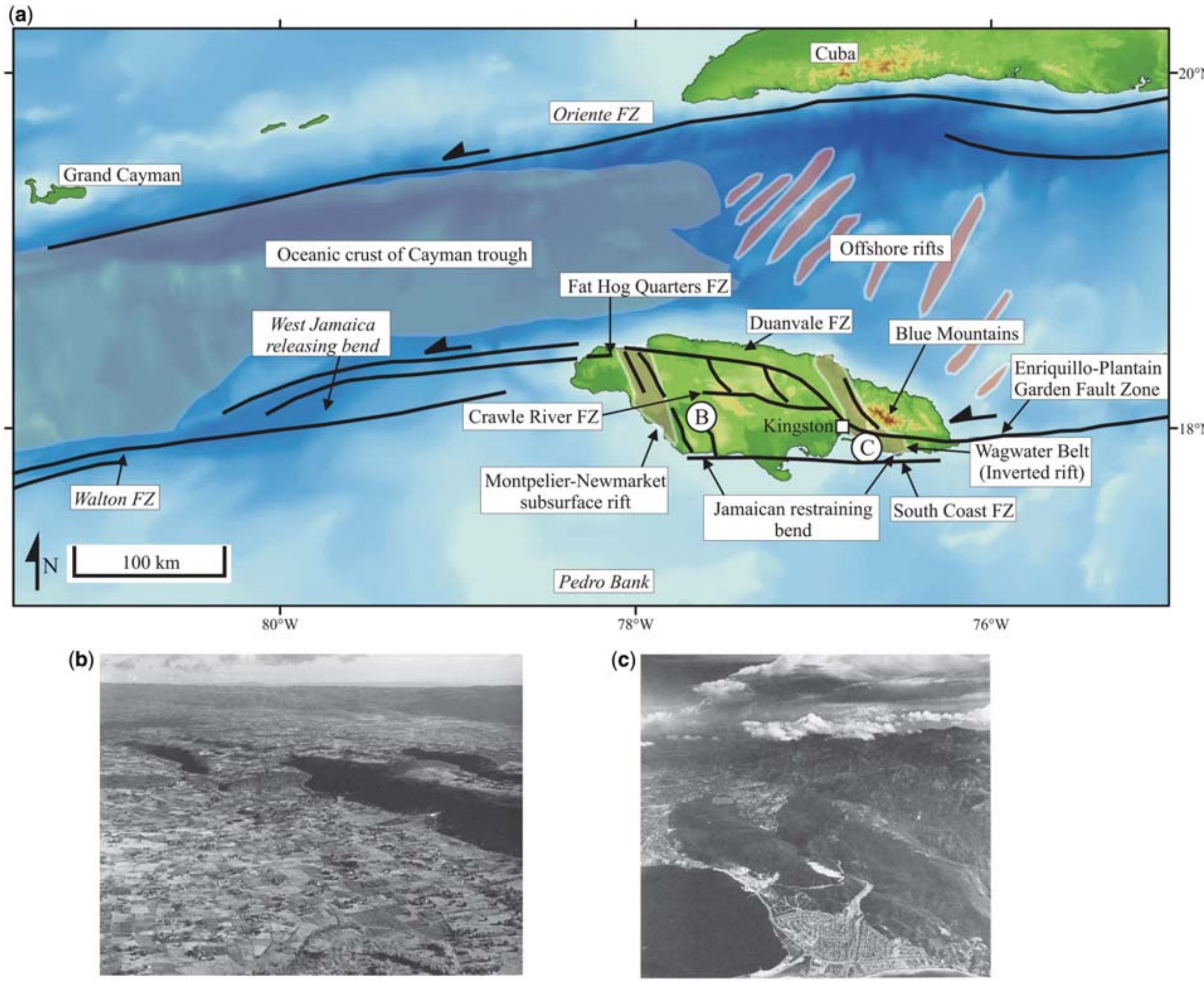

Fig. 2. For caption see p.243.

100–250-km-wide, seismogenic zone of mainly left-lateral strike-slip deformation extending over 3000 km along the northern edge of the Caribbean plate (Burke *et al.* 1980; Calais & Mercier de Lepinay 1990). Prominent restraining bends occur on the islands of Hispaniola (Mann *et al.* 2002) and Jamaica (Mann *et al.* 1985; Rosencrantz & Mann, 1991) (Fig. 2), near the Swan Islands of Honduras along the southern edge of the Cayman Trough (Mann *et al.* 1991), and in northern Central America (Mann & Gordon 1996). Several of these areas constitute paired bends with the familiar undulating fault shape that juxtaposes restraining and releasing bends (Mann 2007) (Fig. 1b).

Swanson (2005) has compiled geological and structural information on gently undulating strike-slip fault traces worldwide. He attributes the adjacent curving traces of strike-slip faults ('paired bends' in this paper) at outcrop to regional scales to adhesive wear, or enhanced friction, along a straight fault plane followed by the nucleation and abrupt lateral shift of the active strike-slip fault to a new parallel fault trace. The deviated fault trace forms a characteristic 5- to 500-km-long, map-view feature of strike-slip faults, which he calls a 'sidewall ripout'. One faulted edge of the deviated 'sidewall ripout' constitutes a releasing bend, whilst the other side constitutes a restraining bend.

Tectonic origin of restraining bends

Two main questions that remain on the origin and evolution of restraining bends are:

(1) what tectonic process is responsible for producing the curvilinear traces in the strike of the fault that ultimately produce alternating restraining and releasing bends; and
(2) how do areas of alternating restraining- and releasing-bend segments evolve with progressive strike-slip displacement?

For the first question, two possible answers are that pre-existing crustal structures influence the strike of the propagating strike-slip fault. For example, a rift or former suture zone might divert the fault from a straight orientation. A second possibility would be that the mechanical properties of the fault itself might cause the fault to lock, accumulate strain, and either form a more curving fault trace (Bridwell 1975) and/or abandon the locked trace and develop an adjacent, parallel fault (Swanson 2005). For the second question, bypassing of bends would appear to be a fundamental property of strike-slip faults as the faults attempt to maintain a straight trace.

In this paper we describe the regional fault pattern, geological setting, and active fault kinematics of Jamaica, from published geological maps, earthquakes and GPS-based geodesy, in order to gain a better understanding of the Jamaican fault restraining bend. Evolution of the restraining-bend faults in Jamaica has important implications for the assessment of seismic risk on this rugged, 10 991 km^2 island with a population of 2.6 million and a long historical record of destructive earthquakes and tsunamis (Wiggins-Grandison & Atakan 2005). An understanding of the present-day stage of restraining-bend development in Jamaica would improve our conceptual basis for understanding those Jamaican faults that might be the source of future large earthquakes.

Tectonic and geological setting of the Jamaican restraining bend

Tectonic setting

The island of Jamaica is one of only two places where strike-slip faults that carry Caribbean–North America–Gonave microplate motion come onshore in the Greater Antilles islands of the northern Caribbean (Cuba, Jamaica, Hispaniola and Puerto Rico) (Fig. 1b). The second place is the neighbouring island of Hispaniola (Haiti and Dominican Republic) where large strike-slip faults are well exposed and can be traced as continuous features for most of the length of the island (Mann *et al.* 1995; Mann *et al.* 1998) (Figs 1b & 2).

Fig. 2. (*Continued*) (**a**) Topography of Jamaica from the NASA SRTM data-set combined with the GEBCO bathymetry of its offshore area. Labelling identifies the major mapped faults onland (Mann *et al.* 1985) and offshore (Rosencrantz & Mann 1991) in the Jamaican paired-bend system. On- and offshore Palaeocene–Early Eocene rift features in Jamaica associated with the east–west opening of the Early Eocene oceanic Cayman Trough are shown in a pale-brown colour. Onland rifts include the now inverted and highly deformed Wagwater Belt of eastern Jamaica, and the subsurface and undeformed Montpelier–Newmarket Rift of western Jamaica. Oceanic crust of the Cayman Trough is shown by the grey area. (**b**) Oblique aerial view (photograph taken by S. Tyndale-Biscoe) of the Spur Tree fault zone of western Jamaica, showing the prominent scarp and plateau-like character of the elevated shallow-water limestone of Oligocene–Miocene age. The location of the photograph is shown by the letter 'B' on the map in (a). (**c**) Oblique aerial view (by S. Tyndale-Biscoe) of the inverted normal fault-bounding the western edge of the deformed Wagwater Belt. Inversion of the Wagwater Belt has induced folding of the adjacent Mio-Pliocene limestones. The location of the photograph is shown by the letter 'C' on the map in (a).

Located in the northern Caribbean Sea at the NW end of the Nicaragua Rise, Jamaica consists of an emergent Cretaceous-age oceanic volcanic arc and volcanogenic sedimentary rocks, overlain by 5–7 km of Tertiary carbonate rocks (Lewis & Draper 1990). Seismic velocities yield an island-arc crustal thickness of 25–30 km, with most locally recorded earthquakes concentrated from depths of 15 to 30 km (Wiggins-Grandison 2003, 2004) (Fig. 3).

At the longitude of Jamaica, Caribbean–North America plate motion of 19 ± 2 mm/a (DeMets *et al*. 2000; Weber *et al*. 2001) is carried by two parallel strike-slip faults, the Oriente transform fault immediately south of Cuba and the Walton/Plantain Garden/Enriquillo faults, which lie 100–150 km farther south (Figs 1b & 2). Mann *et al.* (1995) and Mann *et al.* (2002) postulate that lithosphere between these faults constitutes an independent Gonave microplate that has formed in response to the ongoing collision between the leading edge of the Caribbean plate in Hispaniola and the Bahama carbonate platform. GPS measurements in Hispaniola (Dixon *et al.* 1998; Calais *et al.* 2002; Mann *et al.* 2002) and measurements in Jamaica described by DeMets & Wiggins-Grandison (2007) indicate that roughly half of Caribbean–North America motion (8–14 mm/a) is carried by the Enriquillo–Plantain Garden–Walton faults, consistent with the microplate hypothesis. A key question of major relevance to seismic risk assessment in Jamaica is how strike-slip motion on the Plantain Garden Fault of SE Jamaica is transferred to the island to link with the Walton and other faults making up a large releasing bend west of the island (Figs 1b & 2).

Topographic and geological setting

The Jamaican restraining bend consists of a topographically uplifted area in eastern Jamaica that is bounded at its southern edge by the Enriquillo–Plantain Garden Fault, a transitional area of lower

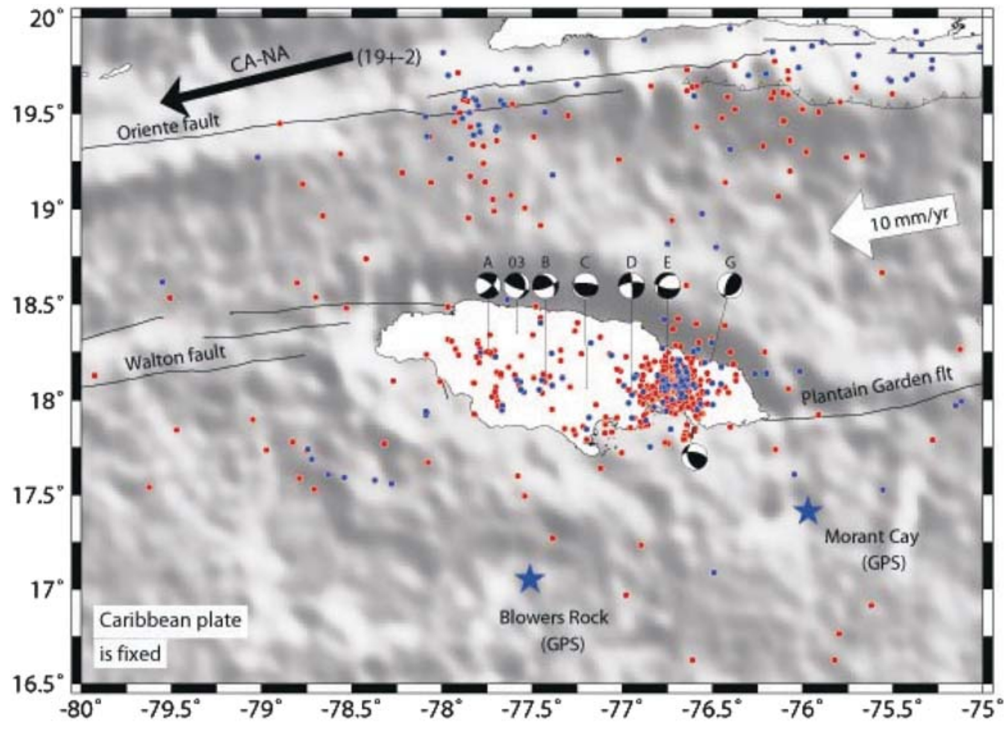

Fig. 3. 1963 to 2004 teleseismicity (blue) and microseismicity (red) of the Jamaica restraining bend on GEBCO bathymetric base map. Micro-earthquakes with magnitudes >1 were recorded by the local Jamaican network (Wiggins-Grandison 2001). Velocities represent motions of the North America plate (black arrow) and the Gonave microplate (white arrow), whose motion is derived from the GPS velocities shown in Figure 4. Faults on and near Jamaica must accommodate a total of 10 (± 2) mm/a of slip. Note that the seismic zone is largely restricted to the island of Jamaica, so the southern edge of the Gonave microplate is believed to lie near the south coast of the island. In-progress GPS sites on Blowers Rock and Morant Cay are therefore assumed to be part of the stable Caribbean plate.

topography in western Jamaica, and an offshore releasing bend, or pull-apart basin, along the Walton fault zone (Rosencrantz & Mann 1991). The West Jamaica releasing bend forms where the plate boundary curves towards a more east–west trend (Figs 1b & 2). Mann *et al.* (1985) and Mann *et al.* (1990) propose that two Palaeogene rifts – that are highly oblique to the EW direction of active plate motion – may be the crustal features responsible for diverting the intersecting plate boundary strike-slip faults from their expected east–west strike directions parallel to the small circles of rotation about the Caribbean pole of rotation (DeMets *et al.* 2000).

In western and central Jamaica, the landscape forms a relatively flat, elevated plateau that exposes karsted Oligocene–Miocene carbonate rocks (Fig. 2b). Faults form prominent scarps in these carbonate lithologies and exhibit topographic relief up to 600 m (Horsfield 1974; Wadge & Dixon 1984; Mann *et al.* 1985) (Fig. 2b). The Palaeogene rifts are subsurface features known from oil exploration both on and offshore of Jamaica (Arden 1975), but in eastern Jamaica, the Wagwater Rift is completely inverted by reverse faulting along its former normal-faulted margins, and elevated into a mountain range (Mann *et al.* 1985; Mann & Burke 1990) (Fig. 2c). Reaching 2.5 km above sea-level, the steep-sided Blue Mountain restraining bend is directly adjacent to the deformed Wagwater Belt and dominates the island's topography and seismicity (Fig. 3d). Its anomalously high elevation and enhanced seismic activity indicate that the Blue Mountains may continue to play an important role in transferring a significant part of the strike-slip displacement northward across the Jamaican restraining bend.

Historic and modern seismicity of Jamaica

Modern records of Jamaican earthquakes date from British settlement of the island in the 1600s. Jamaica has experienced 13 earthquakes of Mercalli intensity VII–X since 1667 (Wiggins-Grandison 2001). The island's most devastating earthquake, a MMI X that occurred on 7 June 1692, caused extensive liquefaction of the island's southern alluvial plains where most of its population was (and still is) concentrated. The 1692 event killed roughly one-quarter of the inhabitants of Port Royal, Jamaica's principal city at the time (Fig. 3). A century ago, the 14 January 1907 Kingston earthquake (MMI IX) killed 1000 and left 90 000 homeless in the capital city. Today, more than one-third of Jamaica's 2.6 million inhabitants and the country's economic base are concentrated in the southern area of the country near the capital city of Kingston (Fig. 2a). Kingston and the surrounding densely populated plains are underlain by thick, unconsolidated alluvium deposited by Jamaica's southward-flowing rivers, and are subject to liquefaction effects and seismic-wave focusing above basinal bedrock topography (Wiggins-Grandison *et al.* 2003). Despite the obvious earthquake hazards, none of Jamaica's Late Holocene faults have been systematically mapped or trenched to reveal which of the main faults may have ruptured during these destructive historical earthquakes.

Teleseisms and relocated microseisms are concentrated primarily along the geomorphically prominent Blue Mountain restraining bend of eastern Jamaica (Fig. 2b), but earthquakes also occur along other topographically prominent faults in the central and western areas of the island (Burke *et al.* 1980; Wadge & Dixon 1984; Mann *et al.* 1985) (Fig. 3). Nearly all relocated earthquakes are found between depths of 12 and 27 km, remarkably deep in comparison with continental settings such as northern and central California, where almost all seismicity is confined above crustal depths of 11–12 km (e.g. Castillo & Ellsworth 1993). Focal mechanisms reveal an island dominated by east–west-directed, left-lateral shear with a lesser north–south convergent component (Wiggins-Grandison 2003; Wiggins-Grandison & Atakan 2005). These focal mechanisms are in excellent agreement with our new GPS velocity field and roughly east–west-trending fold axes that affect the Cretaceous and Tertiary stratigraphic section on the island (e.g. Lewis & Draper 1990).

Initial GPS results for the period 1999–2005

Installation and occupation of an island-wide GPS network was initiated in 1999, and by mid-2001 consisted of the present 20-station network (Fig. 4). By early 2004, all 20 GPS sites had been occupied a sufficient number of times (three to six) over a sufficiently long time-span to define the first-order deformation pattern of the island. The GPS data and velocities presented herein are fully described by DeMets & Wiggins-Grandison (2007), and represent the first description of the island's present velocity field. We summarize these data briefly below and refer interested readers to DeMets & Wiggins-Grandison (2007) for a more complete description and interpretation of these data.

The GPS data were analysed using GIPSY analysis software from the Jet Propulsion Laboratory (JPL); free-network satellite orbits and satellite clock offsets obtained from JPL; a precise point

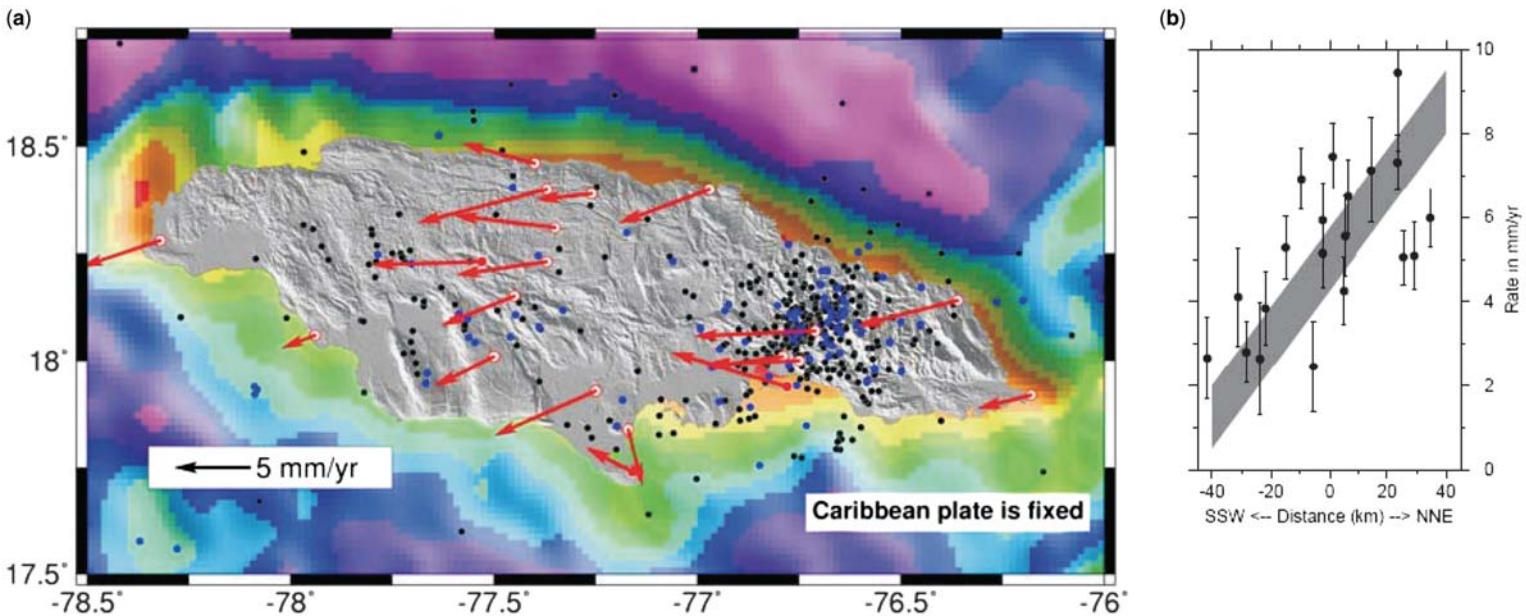

Fig. 4. (**a**) GPS velocity field relative to Caribbean plate (geodetic reference frame is ITRF2000) superimposed on 90-metre Space Shuttle Topographic Radar Mission (SRTM) topography. Velocity uncertainties are omitted for clarity, but are typically $\pm$ 2–3 mm/a at the 1D, 1-sigma level. (**b**) GPS rate components parallel to S75°W projected on to N15°E transect of island. A transect from ENE to WSW (not shown) exhibits a similar gradient.

positioning analysis strategy (Zumberge *et al.* 1997); and resolution of phase ambiguities when possible. Continuous and semi-continuous data at three stations were used to estimate and remove common-mode, non-tectonic noise from all station time series. All of the GPS coordinate time series are well-behaved and have the usual levels of daily scatter (2–4 mm in the northern component, and 3–5 mm in the eastern component). Linear regression of the coordinate time-series yields well-constrained velocities at all 20 GPS sites. Individual site velocity uncertainties are estimated using the Mao *et al*. (1999) algorithm.

Figure 4 shows our most recent GPS velocity field after removing the motion of the Caribbean plate predicted by an angular velocity vector that best fits the velocities of 15 sites in the Caribbean plate interior (DeMets *et al.* 2007). Several useful conclusions can be drawn from the GPS velocity field independent of any modelling. One first-order conclusion is that none of Jamaica moves as part of the Caribbean plate interior (Fig. 4). GPS sites instead move westward relative to the Caribbean plate at a maximum rate of 8 ± 1 mm/a, representing a minimum estimate for Gonave microplate motion relative to the Caribbean plate (Fig. 1b). GPS site directions are uniformly parallel to the southern boundary of the Gonave microplate, indicating that this boundary is dominated by active left-lateral shear as predicted from geological and geomorphological studies (Burke *et al.* 1980; Wadge & Dixon 1984; Mann *et al.* 1985) (Fig. 2b & c).

The velocity field exhibits significant gradients from NNE–SSW and ENE–WSW (Fig. 4), indicating that deformation is two-dimensional. These gradients are a likely consequence of distributed elastic strain from one or more locked faults that transfer slip across the restraining bend. Finally, our data provisionally suggest the existence of a GPS velocity gradient of 2 ± 1 mm/a across the topographically high and seismically active Blue Mountain restraining bend (Fig. 4).

Implications of GPS results for specific faults in Jamaica

If faults in Jamaica are frictionally locked to depths of 20–30 km, as relocated earthquakes suggest (Wiggins-Grandison 2004), then the observed GPS velocity gradients (e.g. Fig. 4) are attributable to elastic strain accumulation and will require detailed modelling to interpret. However, useful inferences can already be drawn without resorting to modelling. With respect to the Caribbean plate interior, the midpoint of the 8 mm/a north–south velocity gradient that we observe occurs just south of the Crawle River left-lateral strike-slip fault zone, close to the latitudinal mid-point of the island (Fig. 2a). Constraints on seafloor-spreading rates across the Cayman spreading centre (Rosencrantz & Mann 1991) (Fig. 1b), and plate circuit closures suggest that Gonave–Caribbean motion cannot be significantly faster than 8–10 mm/a – approximately what we are measuring across Jamaica. Assuming that elastic strain accumulates symmetrically in a laterally homogeneous crust, as seems likely in the thick volcanic arc typical of Jamaican crust, then the fact that the midpoint of our observed velocity gradient occurs in central Jamaica argues against models in which most or all long-term fault slip in Jamaica is focused predominantly along the southern or northern coasts of the island (Fig. 2a).

Modelling will be required to determine whether the data can be used to distinguish between alternative deformation models or possibly a simple single-fault model in which most fault slip is concentrated along faults in central Jamaica. Our data do not appear to be consistent with a model in which faults in the Blue Mountain restraining bend of eastern Jamaica transfer most or all slip from the Plantain Garden fault northward to the Duanvale and Fat Hog Quarters faults along the northern coast of Jamaica, as suggested by Mann *et al.* (1985) (Fig. 2a). Given the topographic and seismic prominence of the Blue Mountains, as well as the prevalence of fault scarps affecting carbonate rocks of Oligocene–Miocene age in the west-central area of Jamaica (Wadge & Dixon 1984) (Fig. 2b & c), this conclusion is an unexpected result (Fig. 2b).

Within the uncertainties, the GPS velocity field (Fig. 4a) and its associated gradients (Fig. 4b) permit partitioning of slip between the east–west-trending Duanvale fault of northern Jamaica; the Crawle River fault zone of central Jamaica; and the South Coast Fault of southern Jamaica (Fig. 2a). Smaller velocity uncertainties are needed to determine whether sudden changes in GPS velocities coincide with any of these faults, as might be expected if any of them are creeping. If, as seems more likely, the faults are locked, then careful modelling will be required to define the range of slip rates and models that are capable of describing the observed site velocities.

From syntheses of satellite imagery and field mapping, various tectonic models have been proposed for Jamaica, including:

(1) a broad, east–west-striking left-lateral shear zone in which several parallel strike-slip faults are active (Burke *et al.* 1980; Wadge and Dixon 1984); and

(2) a right-stepping restraining bend connecting two parallel, left-lateral strike-slip faults (Mann *et al.* 1985).

The widespread microseismicity; fault scarps in Neogene carbonate rocks of the central and western parts of the island (Fig. 2a & b); and two-dimensional gradients in the GPS velocity field, all support a model in which deformation of the island is accommodated by multiple fault step-overs that transfer strike-slip motion across the restraining-bend via a series of intervening active thrust faults. In such a restraining-bend model, slip along the Plantain Garden and South Coastal faults would transfer gradually northward to the Crawle River and Duanvale fault zones, with the summed slip rates for the three faults equalling a minimum of 8 ± 1 mm/a at any given longitude. This model may explain the prevalence of arcuate, north–south-trending, scissor-like scarps that presumably link the east–west-striking strike-slip faults (Wadge & Dixon 1984; Mann *et al.* 1985) (Fig. 4).

Discussion

Combining the GPS and earthquake results with Late Neogene geological data allows a longer term (*c.* 10 Ma) view of how the Jamaican bend continues to evolve and influence the geomorphology, fault kinematics and present-day seismicity of the island (Fig. 3). We propose several stages in the development of the Jamaican paired-bend system (Fig. 5) and compare these stages with better-studied restraining bends along the San Andreas fault system in southern California (Fig. 1a & 6).

Early stages of Jamaican paired-bend development

In our proposed model, the initial stage of paired-bend development occurs when the east–west-striking Enriquillo–Plantain Garden fault zone propagates westward into the Jamaican region and encounters the NE-trending Wagwater and Newport–Montpelier rifts of Palaeogene age (Fig. 5a). The formation of the Enriquillo–Plantain Garden fault zone is attributed to the Miocene–Recent collision between the leading edge of the Caribbean plate in Hispaniola and the Bahama carbonate platform (Mann *et al.* 1995) (Fig. 2a). Formation of the Enriquillo–Plaintain Garden Fault led to the detachment of the Gonave microplate from the NE corner of the Caribbean plate (Fig. 2a). Intersection of the east–west-striking Enriquillo Plantain Garden strike-slip fault with the Wagwater Rift of eastern Jamaica is proposed to have led to its Early to Middle Miocene–Recent inversion and the deviation of the fault trace to a more NW curvature of the fault in eastern Jamaica (Fig. 5b).

A widespread unconformity of Early Miocene age in the carbonate section of Jamaica may date the onset of convergent deformation and uplift in this part of the island (Eva & McFarlane 1979). Green (1977) suggested that continued uplift and strike-slip faulting in eastern Jamaica is marked by a Late–Middle Miocene unconformity. Along the NE coast of Jamaica near Buff Bay, an abrupt facies change occurs between white chalky limestone and grey or brown marl of Late Miocene age (Blow 1969). This facies change may reflect the early inversion of the Wagwater Rift and uplift of the Blue Mountain part of the restraining bend. From the Late Miocene to the present day, uplift has been progressively propagating westward, as shown by the east to west gradient in topographic and erosional level (Fig. 2a). Miocene to Pliocene carbonate rocks around the periphery of the Blue Mountains become progressively conglomeratic in character, and reflect the continued and perhaps accelerated Late Neogene uplift of the Blue Mountains segment of the restraining bend (Horsfield 1974; Mann *et al.* 1985) (Fig. 2a & c).

As the Blue Mountain restraining bend developed, we envision activity along faults in the north-central part of Jamaica, such as the Duanvale fault zone (Figs 2a & 7c). The Duanvale Fault would link the Jamaican restraining bend in eastern Jamaica to the West Jamaica releasing bend (Fig. 2a). In the offshore area of western Jamaica, Rosencrantz & Mann (1991) mapped recent sea-floor fault-breaks roughly parallel to the Duanvale fault-zone. Due to a lack of core data and high-quality seismic-reflection profiles, we have no direct constraints on the age of initiation of the West Jamaica releasing bend but, based on the paired-bend concept, we would predict its age of initiation to be roughly that of the Miocene Blue Mountain uplift, or Early to Middle Miocene.

Later stages of paired-bend development

Earthquakes (Fig. 3) and GPS results (Fig. 4) provide us with insights into how the Jamaican paired bend has continued to evolve to the present day. Recorded seismicity is focused on the area where the Enriquillo-Plantain Garden fault zone intersects the Wagwater inverted rift (Fig. 4). However, a band of earthquakes along the southern coast of the island, along with GPS results, indicates that some left-lateral shearing is accommodated along the southern – rather than northern – parts of the island (Fig. 4). This southern band of east–west-trending seismicity suggests that the previously formed bend structures to the north may be in the initial stages of bypass by the South Coast fault zone, as shown schematically in Figure 5d. Bypass is likely to be a gradual process.

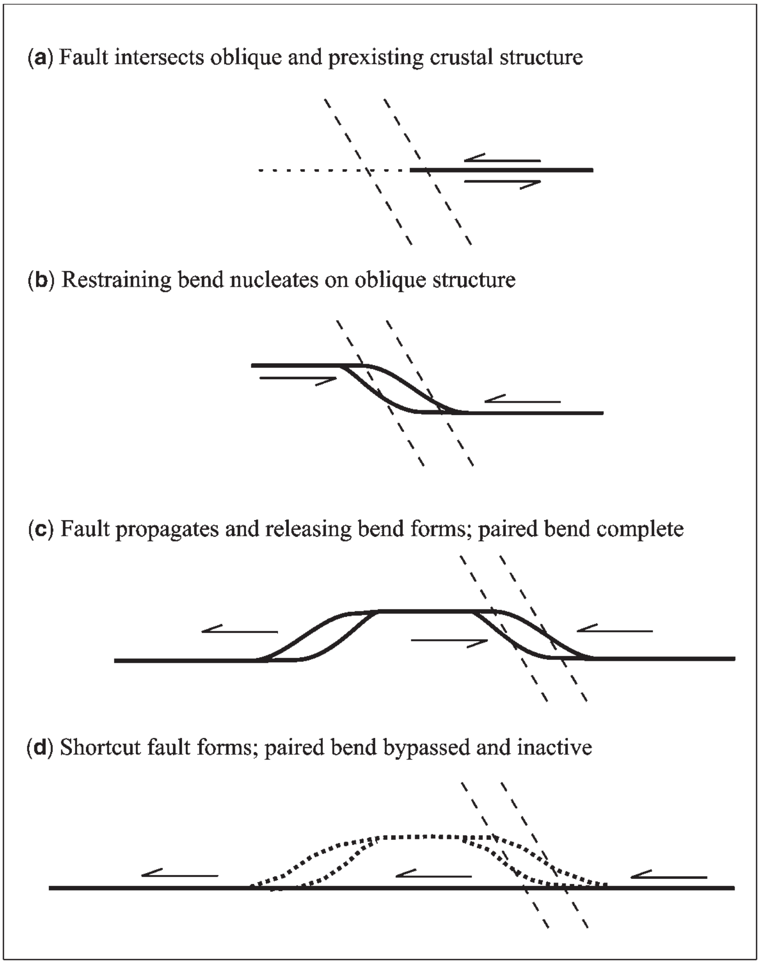

Fig. 5. Proposed conceptual model for the origin and abandonment of a paired strike-slip bend (adjacent restraining and releasing fault segment), based on compilation of information from the Jamaica restraining bend. (**a**) Strike-slip fault intersects an oblique structure. In the case of the Jamaica bend, the oblique structure is a Palaeogene rift basin (cf. Fig. 2a); to our knowledge, no similar type of pre-existing, oblique structure has been recognized beneath the Transverse Ranges of California (cf. Fig. 1a). (**b**) A restraining bend forms and a strike-slip fault continues to propagate. Formation of a restraining bend at the site of the pre-existing rift leads to basin inversion. (**c**) A releasing bend forms as the fault continues to propagate; the commonly observed map view pattern of a 'paired bend' is now complete. (**d**) A bypass fault forms that leads to eventual abandonment of both the restraining and releasing bends in the paired bend. Previous workers have shown that transfer of slip from the bend-impaired trace of the San Andreas to the San Jacinto faults has reached an advanced stage (i.e. modern slip on the San Andreas Fault is 27 ± 4 mm/a, whilst slip on the San Jacinto fault zone is 8 ± 4 mm/a).

Tectonic comparison with the southern California restraining bend

The San Bernardino restraining bend of the southern San Andreas Fault (Fig. 1a) makes an interesting tectonic comparison with the restraining-bend tectonics that we have described in Jamaica (Fig. 6a & b). In southern California, the San Bernardino restraining-bend fault is associated with 3.5-km-high topography. As in the Blue Mountains of eastern Jamaica, the restraining-bend uplift is domal with a very steep, fault-bounded southern edge and a more inclined and gently dipping northern flank (Fig. 6a & b). Palaeoseismological (Matti & Morton 1993) and shorter-term GPS-based studies (Bennett *et al.* 2004) have shown that the curved and topographically elevated San Bernardino and Indio segments of the San

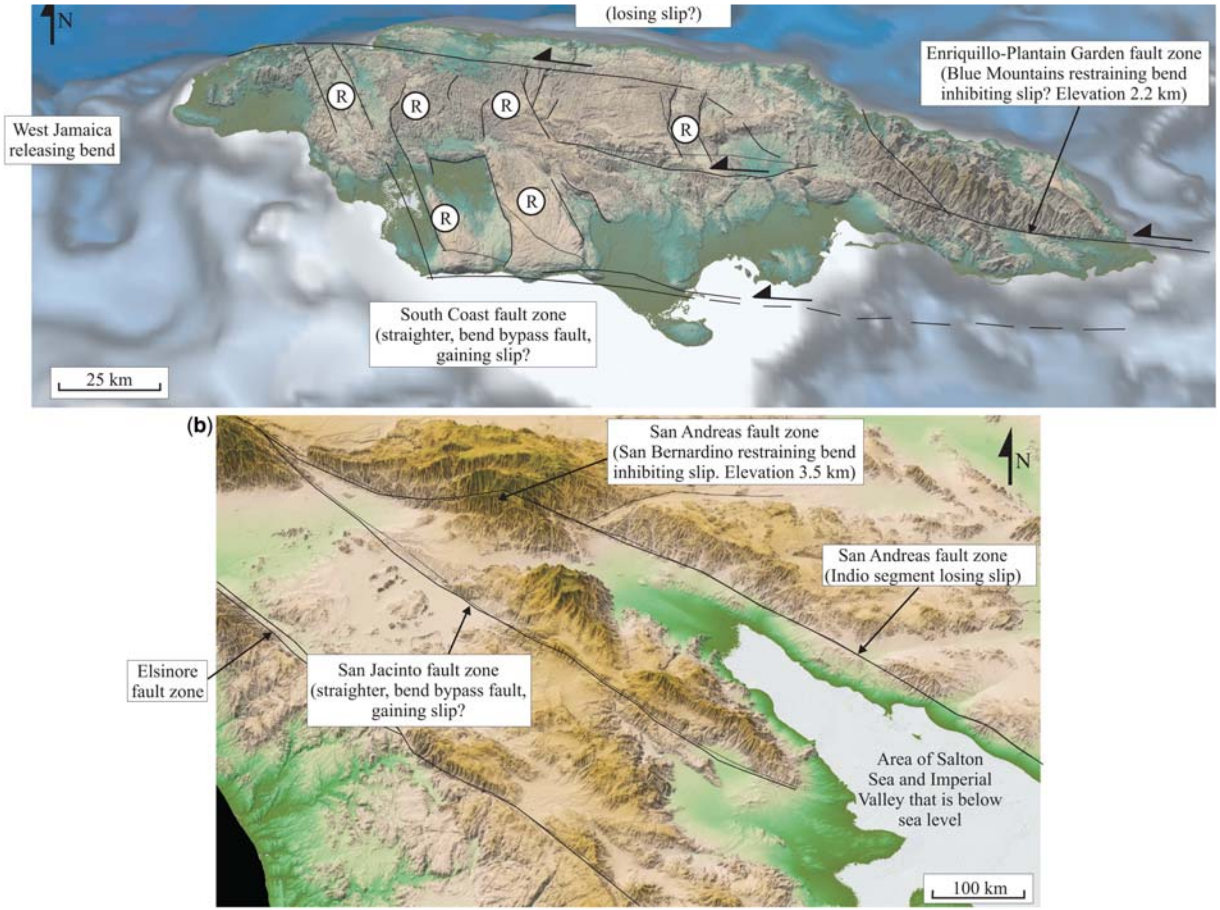

Fig. 6. Comparison of the Jamaica bend with the San Bernardino restraining-bend segment of the San Andreas fault zone and the San Jacinto 'bypass fault' (Bennett *et al.* 2004). (**a**) Earthquakes in southern Jamaica suggest that some of the 8 mm/a of left-lateral shear through Jamaica has shifted to the South Coast fault zone. (**b**) Using geological and GPS data, previous workers have proposed that the inception of the San Jacinto fault zone accompanied the formation of a major restraining bend on the San Bernardino segment of the San Andreas Fault at about 1.5 Ma. This coincidence suggests that the San Jacinto Fault may be acting as a bypass fault that is reducing the rate of strain along the restraining-bend segment (cf. Fig. 7d). This shift may explain the marked difference in seismic strain between the two faults: the San Jacinto Fault has ruptured in several $M > 6$ earthquakes in the last century, whereas the southernmost San Andreas Fault has been remarkably quiescent.

Andreas fault zone are progressively ceding slip to the straighter and topographically lower San Gabriel fault zone. These displacement-rate studies have shown that a change in the slip rate on one fault is matched by an equal and opposite change in the rate on the other (Bennett *et al.* 2004). Hence, there is strong evidence for some level of trade-off, or co-dependence, between the two fault zones. Increased slip transfer will lead to faster slip on the San Jacinto Fault, and eventual abandonment of the San Bernardino restraining bend of the southern San Andreas fault zone. This shift may explain the marked difference in seismic strain between the two faults: the San Jacinto Fault has ruptured in several $M > 6$ earthquakes in the last century, whereas the southernmost San Andreas fault has been remarkably quiescent.

How did the San Bernardino restraining bend nucleate to create the eventual bypass of motion on to the San Jacinto fault zone? To our knowledge, there is no comparable crustal feature like the Wagwater Rift that might have originally led to the curving trace of the San Gabriel fault zone. Swanson (2005) proposed that fault-zone adhesion or increased friction (in the absence of any pre-existing crustal structure) has led to the formation of a 150-km-long and 30-km-wide 'sidewall ripout' structure bounded by the straight San Andreas Fault to the NE and the curved San Gabriel Fault to the SW.

In Jamaica, the geomorphology of the bend area indicates a higher degree of cross-fault relays than in the case of the San Andreas and San Jacinto fault zones (Fig. 6b). On Figure 6b we have marked six, prominent fault-bounded elevations as 'R', or possible relays in which active motion is transferred at stepovers between parallel fault strands. If these relay zones are indeed active, as suggested by their morphology, this observation would indicate that the Jamaican restraining bend is still functioning and has not reached the advanced stage of bypass that has currently been attained by the San Bernardino bend of southern California.

Implications for seismic hazard studies

The proposed model has direct implications for the seismic hazards posed to Jamaica's 2.6 million inhabitants. Figure 7 shows the geographical distribution of the number of times per century that intensities of modified Mercalli VI or greater have been reported in Jamaica from 1880 to 1960 (Shepherd & Aspinall 1980). Like the pattern of recorded seismicity seen on Figure 3, there are higher concentrations of historical earthquakes in the area of the inverted Wagwater Rift of eastern Jamaica and in the subsurface Montpelier Rift of western Jamaica. The close spatial association of the pattern of historical seismicity indicates that these crustal features are an important control on the

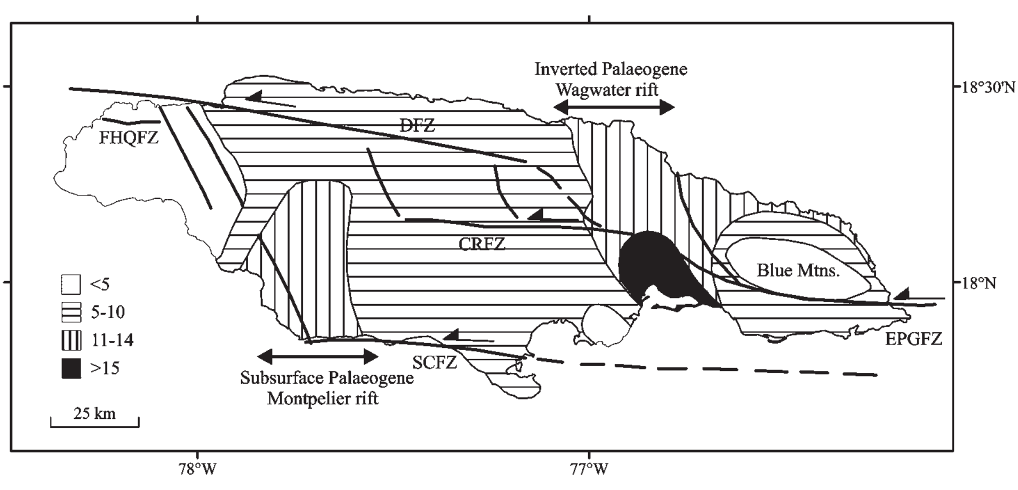

Fig. 7. Geographical distribution of the number of times per century that intensities of modified Mercalli VI or greater have been reported in Jamaica from 1880 to 1960 (modified from Shepherd & Aspinall 1980). Higher concentrations of earthquakes correlate with the area of the inverted Wagwater Rift of eastern Jamaica and the subsurface Montpelier Rift in western Jamaica, and indicate the continued importance of pre-existing crustal structures for the development of paired-bend systems. The areas most affected by the great earthquakes of 1692 and 1907 were along the approximate eastern projection of the South Coast fault zone (SCFZ). A critical question for seismic hazard evaluation is whether motion has shifted to the South Coast Fault or continues to be transferred to more northerly faults like the Crawle River (CRFZ) and Duanvale fault zones (DFZ). EPGFZ: Enriquillo-Plantain Garden fault zone; FHQFZ: Fat Hog Quarters fault zone.

evolution of the Jamaican restraining bend and on the control of present-day earthquakes (Wiggins-Grandison & Atakan 2005).

A key question is whether areas most affected by the destructive earthquakes of 1692 and 1907 were along the approximate eastern projection of the South Coast fault zone, or, alternatively, whether these large earthquakes were related to faulting either in the Wagwater Belt or the adjacent Blue Mountains (Fig. 7). The former scenario would argue for a more advanced bypass stage in restraining-bend evolution (cf. Fig. 5d), while the latter scenario would argue for the continued transfer of slip from the Enriquillo–Plantain Garden fault zone to more northerly faults like the Crawle River and Duanvale fault zones (Fig. 2A). A key avenue of future research will be to identify the presence of Late Holocene faults in both zones, in order to gauge their present level of activity along with their Holocene palaeoseismology.

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