GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L00E15, doi:10.1029/2010GL042556, 2010

Active faulting induced by slip partitioning in Montserrat and link with volcanic activity: New insights from the 2009 GWADASEIS marine cruise data

Nathalie Feuillet,[1] Frédérique Leclerc,[1] Paul Tapponnier,[1,3] François Beauducel,[1] Georges Boudon,[1] Anne Le Friant,[1] Christine Deplus,[1] Jean-Frédéric Lebrun,[2] Alexandre Nercessian,[1] Jean-Marie Saurel,[1] and Valentin Clément[1]

Received 15 January 2010; revised 19 March 2010; accepted 25 March 2010; published 30 April 2010.

[1] New high-resolution marine data acquired aboard R/V *Le Suroît* was used to map active normal faults offshore Montserrat in greater detail. The main faults of the Montserrat-Havers fault zone have cumulative scarps up to 200 m high, and offset sedimentary layers by hundreds of meters. They are arranged in a right-stepping, *en echelon*, trans-tensional array, which confirms that they accommodate the left-lateral component of motion resulting from slip partitioning of oblique convergence along the volcanic arc. They cut across Montserrat's recent volcanic complex. Faulting and fissuring exerted control on the position of andesitic domes, which are aligned along the N110°E average fault trend. The ≈10 km-long fault segments that cross the island could produce damaging, M ≈ 6 events comparable to the shallow, 16 March 1985, Mw~6.3 earthquake that ruptured a submarine, N140°E striking, left-lateral fault near Redonda. **Citation:** Feuillet, N., et al. (2010), Active faulting induced by slip partitioning in Montserrat and link with volcanic activity: New insights from the 2009 GWADASEIS marine cruise data, *Geophys. Res. Lett.*, *37*, L00E15, doi:10.1029/2010GL042556.

1. Introduction

[2] While best known for catastrophic volcanic eruptions (e.g., Mount Pelée, 1902; Soufrière Hills, 1995-present), the Lesser Antilles arc is a dangerously seismic region. The largest known earthquakes (M ≥ 7.5), which ruptured the subduction interface between the North-American and Caribbean plates only 4 years apart in the mid-19th century (11/01/1839; 8/02/1843) destroyed Fort-de-France (Martinique) and Pointe-a-Pitre (Guadeloupe), respectively, with thousands of victims [*Robson*, 1964]. Smaller, damaging events (e.g., Mw = 6.3, 21/11/2004 Les Saintes earthquake; M = 6.3, 16/03/1985, Redonda earthquake, NW of Montserrat) have ruptured shallower faults in the overriding volcanic arc [*Feuillet et al.*, 2002; *Beauducel et al.*, 2005; *Girardin et al.*, 1991].

[3] To better understand and document the sources of such earthquakes, off- and onshore surveys were undertaken along the arc since 1998. The multibeam bathymetry and 6-channel seismic reflection profiles of the 1998 AGUADOMAR cruise on board IFREMER's R/V *l'Atalante* [*Deplus et al.*, 2001] helped map two distinct sets of active normal faults (Figure 1). The faults of the first set bound 100 km-long, 50 km-wide, arc-perpendicular half-grabens that disrupt the fore-arc reef platforms [*Feuillet et al.*, 2002, 2004]. The faults of the second set are arranged in a trans-tensional, right-stepping, *en echelon* array that follows the inner edge of the arc (Figure 1). At plate scale, *Feuillet et al.* [2002] interpreted the inner-arc array and fore-arc grabens to form a sinistral horsetail, absorbing the trench-parallel component of motion between the North-American and Caribbean plates east of the Virgin Islands and left-lateral South Puerto Rico fault zone (Figure 1, inset). The two fault systems contribute to accommodate plate-scale slip-partitioning along the northeastern arc. Using the Caribbean North America Euler pole consistent with recent GPS measurements [*López et al.*, 2006], the trench parallel component of slip increases northwestwards with the curvature of the Caribbean plate edge, from ≈ 4 mm/yr in Martinique to ≈ 17 mm/yr in Saba (Figure 1, inset). The existence of numerous cross-arc active faults, which reflects CCW bookshelf faulting, however, makes it unlikely that the fore-arc forms a distinct micro-plate, as inferred by the above authors.

[4] The new marine data acquired in 2009 during the GWADASEIS cruise yields more detailed insight into the geometry of active faulting offshore Montserrat. Here we present preliminary results from this cruise, and a refined local volcano-tectonic model. Our discussion focuses on active faults near Montserrat, and on their link with volcanism.

2. GWADASEIS Cruise

[5] From 23 February to 27 March 2009, we surveyed the Lesser Antilles volcanic arc aboard French R/V *Le Suroît* between St Lucia and Saba. Multibeam bathymetric coverage (EM300 echo-sounder) provided digital elevation models (DEM) with a vertical accuracy of 2 m at 1000 m depth. 154 high-resolution (72 channels) seismic reflection profiles were acquired at high angle to the inner-arc. The data were filtered, stacked and migrated on board, after NMO correction, using Seismic Unix. The seismic reflection profiles without interpretation are shown in the auxiliary material (Figure S1).[4] Other datasets (EM300 imagery,

[1]Institut de Physique du Globe de Paris, UMR 7154, CNRS, Paris, France.
[2]Laboratoire de Recherche en Géosciences, UMR 8053, Université des Antilles et de la Guyane, CNRS, Pointe-à-Pitre, France.
[3]Now at Earth Observatory of Singapore, Nanyang Technological University, Singapore.

0094-8276/10/2010GL042556

[4]Auxiliary materials are available in the HTML. doi:10.1029/2010GL042556.

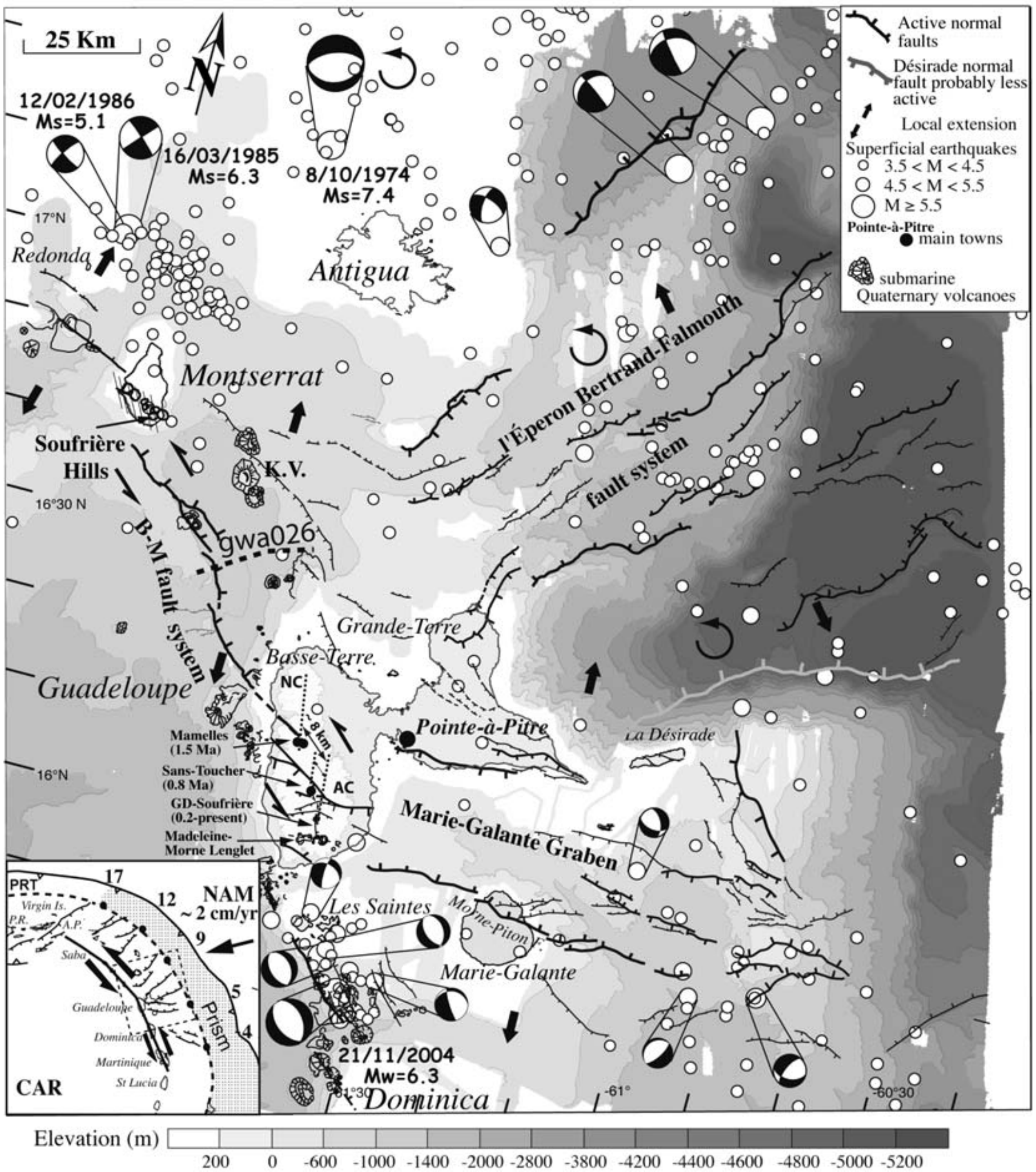

Figure 1. Seismotectonic map of the northern Lesser Antilles arc. Topography and bathymetry redrawn from AGUADOMAR cruise DEM and IGN data. Contours at 200 m interval. Active faults in black with ticks from *Feuillet et al.* [2004]. Double black arrows: local direction of extension. White dots: 1981–2006, shallow (<30 km) seismicity from IPGP observatories. Focal mechanisms from *Stein et al.* [1982], *McCann et al.* [1982] and *Dziewonski et al.* [2000]. Volcanic complexes ages in Basse-Terre from *Samper et al.* [2007]. Circular arrows: Counterclockwise (CCW) rotation of blocks. KV, Kahouanne Volcano. Sinistral offsets of Mamelles and Sans Toucher volcanoes compare to the Soufrière dome are indicated by black dashed lines with a double arrow. The numbers in kilometers indicates the offsets. Inset: simplified map showing the link between the *en echelon* inner arc fault system and the subduction with the trench parallel component of shear increasing from 4 to 17 mm/yr between Martinique and Saba (black dots with numbers, considering the new Caribbean (CAR) North American (NAM) Euler vector of *López et al.* [2006]). Black line with arrows: inner *en echelon* fault system with slip probably increasing northwards. Hatched area: subduction prism; A.P, Anegada Passage; P.R, Puerto Rico; PRT, Puerto Rico trench. Black line with triangles: accretionary prism frontal thrust. Dashed black line: main negative gravity anomaly corresponding to the lesser Antilles backstop from *Bowin* [1976].

high-resolution sonar imagery, Chirp 3.5 kHz, sediment cores, etc…) will be discussed elsewhere.

3. Active Faulting Offshore Montserrat

[6] To map active fault scarps and recent submarine volcanic edifices from the DEM, we used the approach described by *Feuillet et al.* [2002, 2004]. The faults are also defined in section by the seismic profiles. The names of the main physiographic features are from *Bouysse et al.* [1984]. New structures are named after localities on the closest islands.

[7] Figure 2 shows the overall seafloor morphology and pattern of active faulting around Montserrat. South of the

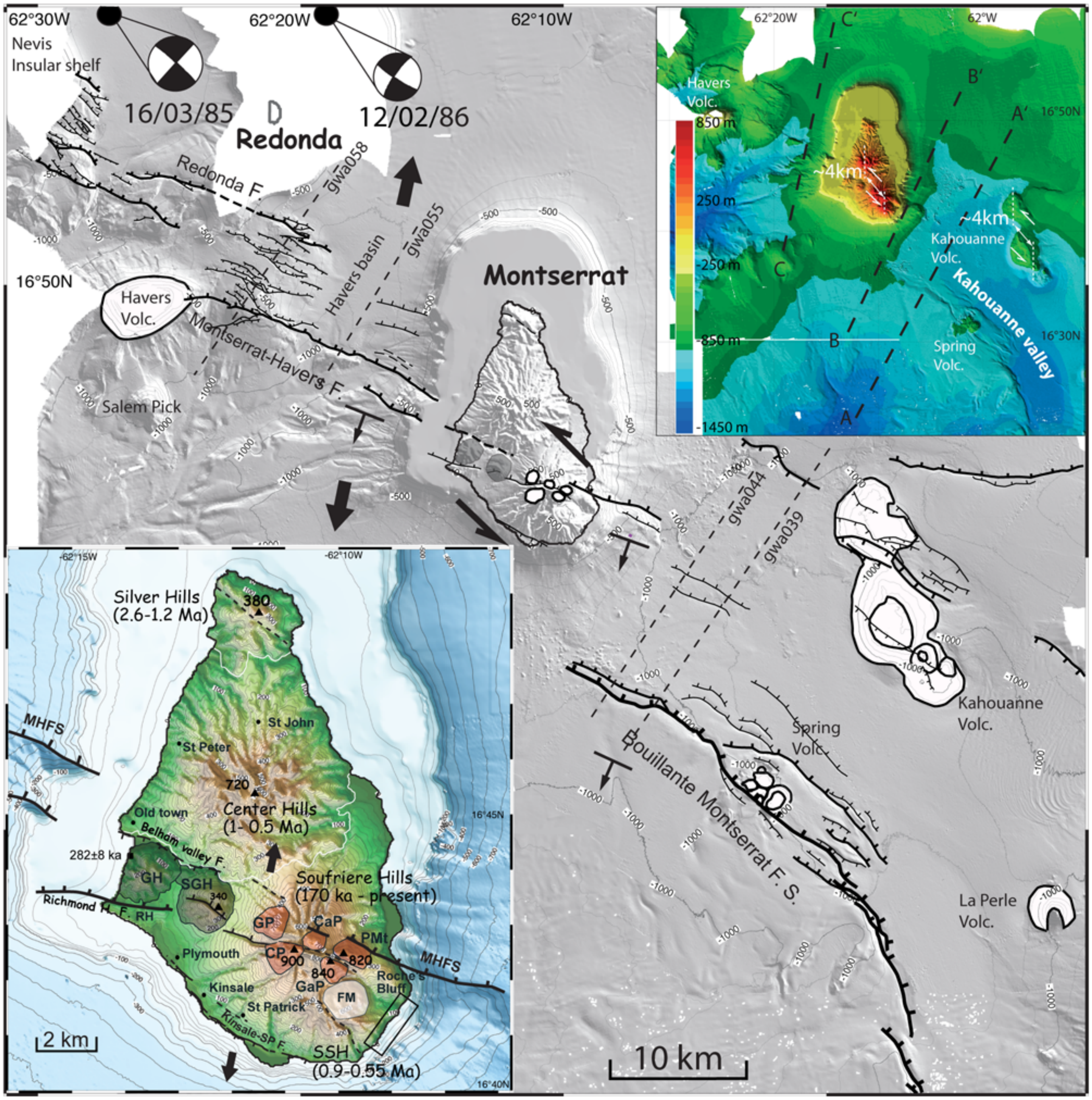

Figure 2. Seismotectonic map of Montserrat. Topography and insular shelf bathymetry from *Le Friant et al.* [2004]. Bathymetry from AGUADOMAR and GWADASEIS cruises. Contours at 100 m interval. Active faults as in Figure 1. Seismicity from PDE USGS. Focal mechanisms as in Figure 1. Double black arrows: local direction of extension. Large scale Sinistral shear direction is indicated. Half black arrow with bars: regional scale tilt of the MHFS footwall. Dashed lines with names: location of seismic profiles of Figure 3. In white, submarine volcanoes. Top right inset: N225°E illuminated bathymetry and topography. Sinistral offsets of volcanic complexes are indicated by white dashed lines with a double arrow. The numbers in kilometers indicates the offsets. Dashed black lines: location of bathymetric profiles shown in Figure S2. Bottom left inset: Volcano tectonic map of Montserrat. Volcanic complexes ages from *Harford et al.* [2002]. In orange, Soufrière Hills domes: CaP, Castle Peak; CP, Chances Peak; GaP, Galways Peak; GP, Gages Peak; PMt, Perches Mt. In white, South Soufrière Hills dome: FM, Fergus Mount. In grey: GH, Garibaldi Hill; SGH, St Georges Hill. Kinsale-SP F., Kinsale-St Patrick fault; MHFS, Montserrat Havers Fault System; RH, Richmond Hill; SSH, South Soufrière Hills Inferred or less active faults are indicated by dashed lines. Black box: Location of Figure S3.

island, the west side of the Kahouanne valley is bounded by the northeastward-dipping Bouillante-Montserrat Fault System (BMFS), which extends all the way to Basse-Terre and is composed of 10–20 km-long, N130 ± 20°E trending, normal fault segments arranged in a right-stepping *en echelon* pattern, with scarps up to 200m-high. Bathymetric profile AA′ (Figure S2) shows that the BMFS controls the regional seafloor morphology, separating two

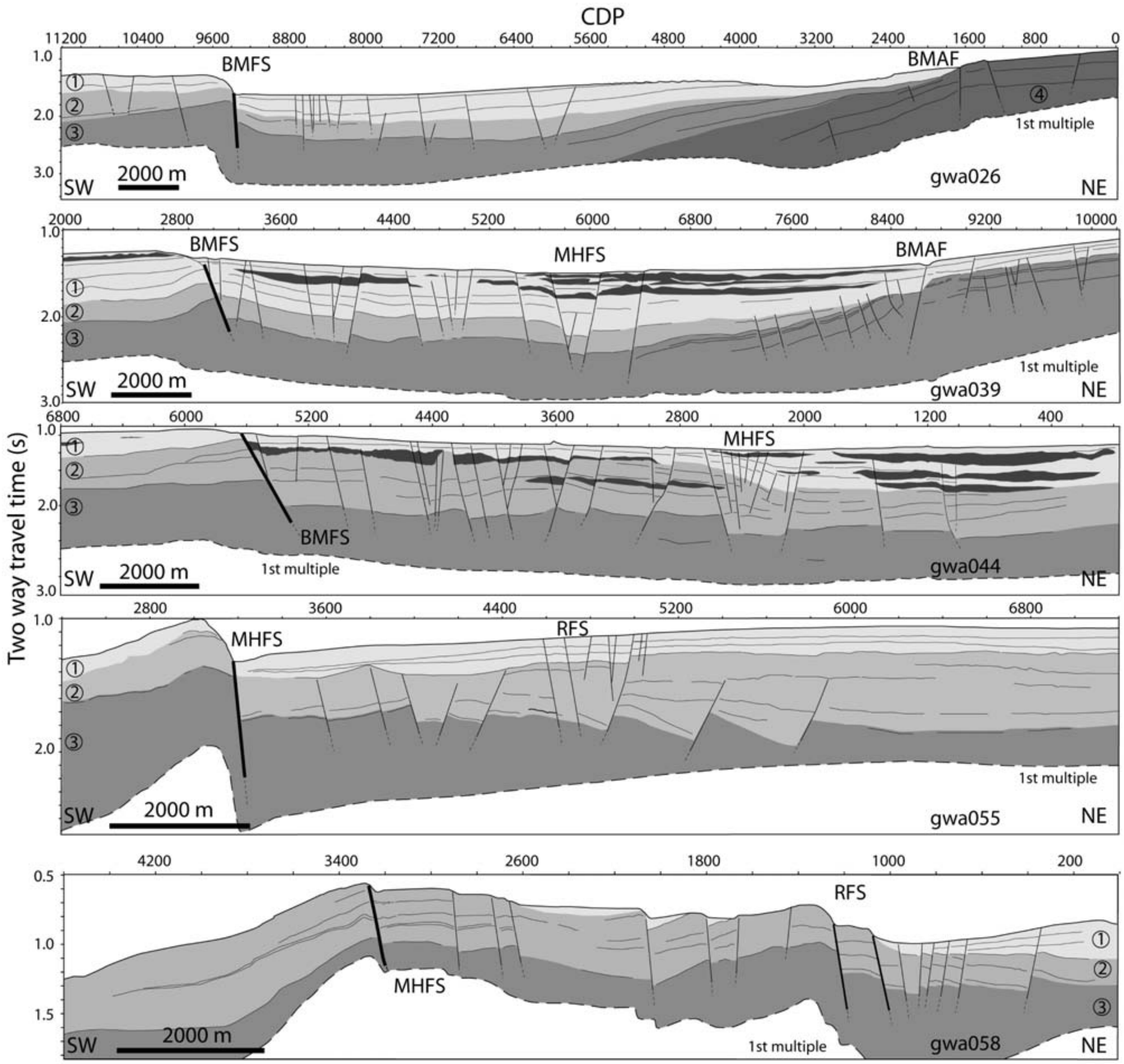

Figure 3. Interpretation of 72 channel high-resolution seismic profiles (see profiles in Figure S1). Location on Figures 1 (gwa26) and 2. In grey with numbers: principal sedimentary units identified between major, continuous reflectors along entire profiles. Units vary along BMFS-MHFS strike and are not correlated from a profile to another. The faulted darker grey lenses are chaotic deposits (probably Montserrat debris avalanches deposits, [*Le Friant et al.*, 2004]). CDP, common depth point; BMFS, Bouillante Montserrat fault system; BMAF, Bouillante Montserrat antithetic fault; MHFS, Montserrat Havers fault system; RFS, Redonda Fault System. Dashed line: first multiple. Bold lines are larger faults.

crustal blocks tilted ≈ 1° southwestwards (see also seismic profile gwa026 (Figure 3)). Thus, the Kahouanne valley is a typical half-graben, filled by a several hundred meters-thick wedge of sediment layers whose SW dips increase with depth, and the NE-dipping BMFS was active during sedimentation, progressively tilting more sedimentary units of increasing age. Using a mean seismic velocity of 2200 m s^{-1} in sediments yields throws ≤ 400 m for sedimentary unit 3, and > 1000 m for the lowest, most tilted unit.

[8] Many smaller faults associated with the BMFS' master-fault extend to the base of the Kahouanne sedimentary sequence, but fast sedimentation has prevented the growth of high cumulative seafloor scarps. Such scarps are in fact too small to be seen in the EM300 bathymetry. Küllenberg cores in the Kahouanne basin show fine, alternating, pelagic, turbiditic and tephra units [*Beck et al.*, 2009]. Close to Montserrat, additional chaotic units (darker gray on Figure 3) are inter-bedded within this fine sequence. That they are seen only on profiles gwa39 and 44 implies that they are probably Soufrière Hills' debris avalanches [*Le Friant et al.*, 2004]. Even the most recent ones are cut by the faults, attesting to ongoing Quaternary tectonic activity. Because sedimentation rates are as yet unknown and may vary in space and time, the vertical throw rates on the faults remain unconstrained. Nevertheless, sedimentation rates in a sequence including large

avalanches might reach tens of cm/kyr, implying throw-rates of tenths of mm/yr on the larger faults. Offsets of the shallowest sediments and seafloor on one CHIRP profile (Figure S1) confirm current fault-slip. On profiles gwa039 and 055, many faults cutting units 2 and 3 north-east of BMFS and Montserrat-Havers fault system (MHFS) are capped by younger, un-deformed layers, implying south-westward shift of recent faulting. The BMFS scarp height decreases towards the northwest. South of Montserrat, it is covered by, and terminates beneath, a huge avalanche deposit [*Le Friant et al.*, 2004]. We interpret this north-westward decay to result from transfer of slip, across a right step-over, to the SW-Montserrat fault zone (Kinsale, St-Patrick faults) and MHFS.

[9] Southeast of Montserrat, the MHFS is characterized by a narrow, densely faulted zone (profile gwa44 (Figure 3)). On the other side of the island, the MHFS cuts and offsets the insular shelf. Farther west, in the Havers basin (Figure 2), the master-fault is marked by a ~200 m high scarp and off-sets by ≈ 400 m the deepest visible sediment interface (profile gwa055, unit 3). Here, the MHFS separates and tilts gently southwestwards two basement blocks, as does the BMFS on profile gwa26 (Figure S2). While most minor faults north of MHFS on profile gwa055 are un-conformably covered by the finer strata of upper unit 1, many well-preserved scarps on shallower, relatively sediment-free vol-canic seamounts are mapped farther west (Figure 2; profile gwa58 (Figure 3)). We interpret this more densely faulted zone, east of the Havers volcano, to accommodate the right-stepping transfer of motion between the MHFS and the ~N110°E-striking, NE-dipping Redonda fault system (RFS).

[10] Even at the largest scale, the three master-fault systems (BMFS, MHFS and RFS) are arranged in a right-stepping *en echelon* pattern. At all embedded scales there-fore, the geometry of the inner-arc fault array requires a left-lateral component of motion parallel to the trench. Such trans-tensional faulting is consistent with ~N–S extension, as in the Guadeloupe archipelago [*Feuillet et al.*, 2002].

4. Faulting Onshore and Link With Volcanism on Montserrat

[11] The volcanic island of Montserrat is composed of four main eruptive complexes emplaced at different times in the last 2.5 Ma [*Harford et al.*, 2002] along an overall NNW trend (Figure 2). The youngest volcanic complexes of Soufrière Hills began to form at least ~170 ka ago in the southeastern part of the island, south of the Centre Hills. The multi-epoch volcanic construction of Montserrat, together with strong tropical rainfall, erosion and weathering, make the morphology of the island quite complex.

[12] Nevertheless, the southern part of Montserrat is clearly structured by several N110 ± 10°E striking fault scarps, parallel to offshore faults, all of them part of the MHFS. The south-facing, Belham Valley scarp (BVF) limits the Centre Hills complex to the South. The north-dipping, morphologically clearer, Richmond Hill fault (RHF) bounds the Richmond Hills towards the north [*Chiodini et al.*, 1996]. It then steps and extends farther eastwards north of Chances and Galway Peaks. This latter fault zone bounds the steepest, NNE side of the 820–900 m-high active volcano. It con-tinues southeastwards to crosscut Montserrat's eastern shore just north of Roche's Bluff, where small normal faults are exposed on outcrop [*Harford et al.*, 2002]. Deposits origi-nally emplaced in a shallow-marine environment on the 300 m-high Roche's Bluff hill have been uplifted tens to hundreds of meters [*Harford et al.*, 2002] by normal slip on the MHFS. The sea cliff along the eastern shore of the South Soufrière Hills also exposes several NW-striking normal faults within the MHFS footwall (Figure S3). Finally, along the southwest coast of the island, debris flows and fluvial fans are truncated by linear, right-stepping cliffs, which we interpret to mark the surface expression of south-dipping normal faults (Kinsale and St Patrick faults).

[13] The ~200 Kyrs to present Soufrière Hills complex's volcanic domes are aligned along a ~N110°E trend, which suggests that they formed on a fissure of this orientation. Although the origin of the Garibaldi Hill (282 kyrs-old) and St Georges Hill domes is debated [*Harford et al.*, 2002], they were likely fed by vents aligned along an adjacent, parallel fissure, in a way comparable to the Madeleine-Morne Lenglet vent alignment in Basse-Terre [*Feuillet et al.*, 2002]. That the most prominent young normal faults and volcanic alignments of Montserrat share the same general trend and lie where the regional MHFS crosses the island indicates that they are the co−located consequence of NS crustal extension.

[14] Overall, the striking resemblance, both in age and structure, between the volcanic complexes of Montserrat and Basse-Terre suggests that they have been shaped by similar processes, among which tectonic faulting along the inner arc array clearly played a key role.

5. Conclusion and Discussion

[15] The GWADASEIS marine cruise data thus confirms that Montserrat's young volcanic complex lies on the inner arc system of WNW/ESE-striking, mostly northeast-dipping, active normal faults arranged in a right-stepping *en echelon* array that has been interpreted to accommodate the component of left-lateral shear due to partitioning of oblique convergence along the northern Caribbean subduction zone [*Feuillet et al.*, 2002]. Active volcanic complexes appear to be markers of such ongoing, large-scale, trans-tensional motion. In Montserrat, the ancient Centre and Silver Hills volcanic centers are located ≈ 4 kilometers northwest of the most recent South Soufrière and Soufrière Hills (Figure 2, inset). The submarine Kahouanne volcanic complex, which is crosscut and left-laterally displaced by a fault system antithetic to the BMFS, displays an analogous geometry. Similarly, in Guadeloupe, the BMFS separates the older volcanic complex (Northern, Axial Chain, 2.8–0.6 Ma [*Samper et al.*, 2007]) from the Grande-Découverte recent complex (200ka–present). Specifically, the 1.46 ± 0.03 Ma [*Samper et al.*, 2007] Mamelles domes and the summit of the ancient, fault-truncated Sans-Toucher (≈800 ka), are located ≈4 km and ≈8 km, respectively, northwest of the Soufrière active dome.

[16] In all cases, the older complexes, to the north, have therefore been shifted sinistrally by a minimum of ≈4 km (Figure 1). Plausible ages of such a finite displacement, derived from dating of the volcanic edifices, may be used to place bounds on the rate of the left-lateral component of motion. If one assumed, for instance, that this displacement accrued since the final demise of the ancient volcanic cen-ters (≈800 ka in Basse-Terre), the corresponding rate would

be about 5 mm/yr, a value locally in keeping with plate-scale kinematic boundary conditions. This would also indicate that the inner arc fault zone might not be much older than 1 Ma. Given the dating uncertainties, however, smaller rates and older ages, by a factor of at least 2, are equally possible. One issue that remains puzzling is the position of the presently active volcanic centers at the southern end of each individual volcanic chain, perhaps due to another component of motion of the upper (Caribbean) plate relative to deeper, more steady sources of magma.

[17] The MHFS cuts Montserrat island right along the alignment of domes and vents of the recent volcanic complex and thus must have controlled the upward rise of magmas through fissures parallel to the faults of that system. The normal faults, which are typically 10–20 km long, are capable of generating shallow earthquakes with magnitude ≥ 6 near or beneath the island, implying seismic as well as volcanic hazard. Such an event (Les Saintes, 21 November 2004) recently ruptured part of the inner-arc, *en echelon* system south of Guadeloupe [*Beauducel et al.*, 2005] (Figure 1). The 16 March 1985 Redonda earthquake and it main aftershock (12 February 1986), both of them strike-slip events north of the RFS, are another example. The distribution of aftershocks (Figure 1) and focal mechanisms imply ruptures of N140°E-striking planes, compatible with the overall left-lateral faulting geometry and NS orientation of the regional minimum horizontal stress. Finally, earthquakes rupturing faults near active volcanoes may induce static or dynamic stress changes in their plumbing systems that promote volcanic unrest or eruptions [*Hill et al.*, 2002], a circumstance that should be taken into account in regional volcanic hazard assessment.

[18] **Acknowledgments.** We thank the captains, officers and crew of R/V *le Suroît* (IFREMER). We are grateful to Barry Voight for helpful discussions and critical reading of the manuscript. Special thanks to B. Mercier de Lepinay who helped for the Chirp processing. We are also grateful to two anonymous reviewers, whose comments contributed to significantly improve the paper. This study was supported by the ANR CATELL-RISKNAT CNRS-INSU program. This is IPGP contribution 2634.

References

Beauducel, F., et al. (2005), The M_w 6.3 earthquake of Les Saintes (Guadeloupe) on November 21, 2004, paper presented at IAVCEI European Seismological Commission Annual Workshop, Saint-Claude, Guadeloupe, 19–24 Sept.

Beck, C., et al. (2009), Co-seismic sedimentary increments within the Lesser Antilles Arc. Preliminary results from GWADASEIS coring campaign, paper presented at Association des Sédimentologistes Français Conference 2009, Rennes, France, 25–31 Oct.

Bouysse, P., P. Andreieff, M. Richard, J. C. Baubron, A. Mascle, R. C. Maury, and D. Westercamp (1984), Géologie de la ride d'Aves et des pentes sous marines du nord des Petites Antilles, esquisse bathymétrique à 1:1,000,000 de l'Est-caraïbe, *B. R. G. M. Rep.*, *93*, 141 pp.

Bowin, C. (1976), *Caribbean Gravity Field and Plate Tectonics*, *Spec. Pap. Geol. Soc. Am.*, *169*, 79 pp.

Chiodini, G., R. Cioni, A. Frullani, M. Guidi, L. Marini, F. Prati, and B. Raco (1996), Fluid geochemistry of Montserrat Island, West Indies, *Bull. Volcanol.*, *58*, 380–392, doi:10.1007/s004450050146.

Deplus, C., A. Le Friant, G. Boudon, J. C. Komorowski, B. Villemant, C. Harford, J. Segoufin, and J. L. Cheminée (2001), Submarine evidence for large-scale debris avalanches in the Lesser Antilles Arc, *Earth Planet. Sci. Lett.*, *192*, 145–157, doi:10.1016/S0012-821X(01)00444-7.

Dziewonski, A. M., G. G. Ekstrom, and N. N. Maternovskaya (2000), Centroid-moment tensor solutions for October–December, 1999, *Phys. Earth Planet. Inter.*, *121*, 205–221, doi:10.1016/S0031-9201(00)00156-4.

Feuillet, N., I. Manighetti, P. Tapponnier, and E. Jacques (2002), Arc parallel extension and localization of volcanic complexes in Guadeloupe, Lesser Antilles, *J. Geophys. Res.*, *107*(B12), 2331, doi:10.1029/2001JB000308.

Feuillet, N., P. Tapponnier, I. Manighetti, B. Villemant, and G. C. P. King (2004), Differential uplift and tilt of Pleistocene reef platforms and Quaternary slip rate on the Morne-Piton normal fault (Guadeloupe, French West Indies), *J. Geophys. Res.*, *109*, B02404, doi:10.1029/2003JB002496.

Girardin, N., M. Feuillard, and J. P. Viode (1991), Réseau régional sismique de l'arc des Petites Antilles: Sismicité superficielle (1981–1988), *Bull. Soc. Geol. Fr.*, *162*, 1003–1015.

Harford, C. L., M. S. Pringle, R. S. J. Sparks, and S. R. Young (2002), The volcanic evolution of Montserrat using ^{40}Ar/^{39}Ar geochronology, in *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*, edited by T. H. Druitt and B. P. Kokelaar, *Geol. Soc. London Mem.*, *21*, 93–113.

Hill, D. P., F. Pollitz, and C. Newhall (2002), Earthquake-volcano interactions, *Phys. Today*, *55*, 41–47, doi:10.1063/1.1535006.

Le Friant, A., C. L. Harford, C. Deplus, G. Boudon, R. S. J. Sparks, R. A. Herd, and J. C. Komorowski (2004), Geomorphological evolution of Montserrat (West Indies): Importance of flank collapse and erosional processes, *J. Geol. Soc.*, *161*, 147–160, doi:10.1144/0016-764903-017.

López, A. M., S. Stein, T. Dixon, G. Sella, E. Calais, P. Jansma, J. Weber, and P. LaFemina (2006), Is there a northern Lesser Antilles forearc block?, *Geophys. Res. Lett.*, *33*, L07313, doi:10.1029/2005GL025293.

McCann, W. R., J. W. Dewey, A. J. Murphy, and S. T. Harding (1982), A large normal-fault earthquake in the overriding wedge of the Lesser Antilles subduction zone: The earthquake of 8 October 1974, *Bull. Seismol. Soc. Am.*, *72*, 2267–2283.

Robson, G. R. (1964), An earthquake catalogue for the eastern Caribbean, *Bull. Seismol. Soc. Am.*, *54*, 785–832.

Samper, A., X. Quidelleur, P. Lahitte, and D. Mollex (2007), Timing of effusive volcanism and collapse events within an oceanic arc island: Basse-Terre, Guadeloupe archipelago (Lesser Antilles Arc), *Earth Planet. Sci. Lett.*, *258*, 175–191, doi:10.1016/j.epsl.2007.03.030.

Stein, S., J. F. Engeln, D. A. Wiens, K. Fujita, and R. C. Speed (1982), Subduction seismicity and tectonics in the Lesser Antilles arc, *J. Geophys. Res.*, *87*, 8642–8664, doi:10.1029/JB087iB10p08642.

F. Beauducel, G. Boudon, V. Clément, C. Deplus, N. Feuillet, F. Leclerc, A. Le Friant, A. Nercessian, and J.-M. Saurel, Institut de Physique du Globe de Paris, UMR 7154, CNRS, Case 89, 4 Place Jussieu, F-75252 Paris CEDEX 05, France. (feuillet@ipgp.jussieu.fr)

J.-F. Lebrun, Laboratoire de Recherche en Géosciences, UMR 8053, Université des Antilles et de la Guyane, CNRS, BP 592, F-97159 Pointe-à-Pitre CEDEX, France.

P. Tapponnier, Earth Observatory of Singapore, Nanyang Technological University, 50 Nanyang Avenue, N2-01a-09, Singapore 639798. (tappon@ntu.edu.sg)