

Contrasts in morphology and deformation offshore Montserrat: New insights from the SEA-CALIPSO marine cruise data

C. L. Kenedi,^{1,2} R. S. J. Sparks,³ P. Malin,^{1,2} B. Voight,⁴ S. Dean,⁵ T. Minshull,⁵
M. Paulatto,⁵ C. Peirce,⁶ and E. Shalev^{1,2}

Received 10 May 2010; accepted 7 July 2010; published 7 October 2010.

[1] During the December 2007, SEA-CALIPSO experiment we collected seismic reflection profiles offshore of Montserrat. Off the east coast, we imaged deep fans of volcanoclastic debris from three volcanoes progressively active from ~2 Ma to present. Near-shelf sedimentation rates of 8–9 cm/ka are approximated following cessation of local volcanic activity. The fans were deposited on sediments with apparent dips towards the ESE-trending Montserrat-Havers fault system (MHFS) in southern Montserrat. The MHFS encloses the Soufrière Hills Volcano, has elevated crustal blocks at Roche's Bluff, St. Georges Hill, and Garibaldi Hill, and extends off the west coast. Off the west coast, the N-dip of two faults supports a N-dip interpretation for a major component of MHFS, the Belham Valley fault. We propose that local deformation is affected by stress redistributions consistent with a right-stepping, sinistral *en-echelon* fault system, but the interplay of transtension and magmatism has resulted in complex and evolving stress regimes.

Citation: Kenedi, C. L., R. S. J. Sparks, P. Malin, B. Voight, S. Dean, T. Minshull, M. Paulatto, C. Peirce, and E. Shalev (2010), Contrasts in morphology and deformation offshore Montserrat: New insights from the SEA-CALIPSO marine cruise data, *Geophys. Res. Lett.*, 37, L00E25, doi:10.1029/2010GL043925.

1. SEA-CALIPSO Reflection Profiling and the Geologic/Tectonic Setting

[2] The December 2007, SEA-CALIPSO experiment (Seismic Experiment with Airgun-source – Caribbean Andesitic Lava Island Precision Seismo-geodetic Observatory) at Montserrat, Lesser Antilles, was an onshore-offshore seismic study of the crust and magmatic system under Montserrat and the Soufrière Hills volcano (SHV) [Paulatto *et al.*, 2010; Shalev *et al.*, 2010; Voight *et al.*, 2010]. The experiment included a 48 channel, 600 m streamer, and a 2600 in³ airgun in a seismic reflection survey that explored local submarine deposits and faults and expanded knowledge based on previous seismic and bathymetric studies [e.g., Feuillet *et al.*, 2001, 2002]. We present key results from our

survey and discuss their implications on the local tectonic and volcanic interactions.

[3] As part of the northern Lesser Antilles, Montserrat is the result of oblique subduction accommodated by large scale sinistral strike slip and local, arc-perpendicular normal faulting [Feuillet *et al.*, 2001, 2002] (Figure 1A). Three andesitic volcanic centers dominate Montserrat: Silver Hills (~1–2 Ma), Centre Hills (~0.4–1 Ma), and Soufrière Hills – South Soufrière Hills (~0.3 Ma to present) (Figure 1b) [Harford *et al.*, 2002; Le Friant *et al.*, 2008]. Since 1995, SHV activity has included dome building and collapses that produced onshore and offshore pyroclastic and debris flows and deposits [e.g., Deplus *et al.*, 2001; Le Friant *et al.*, 2004, 2009; Trofimovs *et al.*, 2006; Loughlin *et al.*, 2010].

[4] On and west of SHV, young andesitic domes (<300 ka) and structurally uplifted areas [Harford *et al.*, 2002] are aligned due to normal faulting as part of the extensional Montserrat-Havers fault system (MHFS) [Feuillet *et al.*, 2010]. The MHFS includes an ESE-trending lineament interpreted as the Belham Valley fault (BVF) [Harford *et al.*, 2002] (Figure 1b). Normal faulting continues to the SE of Montserrat with a right step to the Bouillante-Montserrat fault system (BMF) (Figure 1b). Extension with ~N–S trend is prevalent in the region, which Feuillet *et al.* [2010] suggest is accommodated as oblique shear along a series of *en echelon*, mainly NE-dipping normal fault systems including the BMF, MHFS, and the Redonda fault system (RFS) (Figure 1b). We propose that these systems also accommodate minor local shear that has resulted in rotation of older sediments and deformation of the footwall of the BVF and related faults.

2. Data Collection and Processing

[5] As part of the SEA-CALIPSO experiment, the RRS James Cook collected offshore reflection profiles (Figure 1b). The eight GI airgun array was fired every 60 s with streamer signals sampled every 2 ms. The shot interval was 139 m. The data were bandpass filtered between 4 Hz and 64 Hz, stacked, and migrated using sediment velocities from semblance analysis. A low source frequency and long shot interval were selected to maximize the onshore tomography data and were thus less optimal for the reflection study. Six sections are shown in Figures 2–4 (red profile lines, Figure 1b). Time to depth conversions used an average sediment velocity of 2200 m/sec [Paulatto *et al.*, 2010].

3. Volcanoclastic Fans and Faulting Off the Eastern Shelf

[6] The reflection profiles off the eastern shelf are dominated by chaotic sediment packages that are, interpreted as

¹Earth and Ocean Sciences, Duke University, Durham, North Carolina, USA.

²Institute of Earth Science and Engineering, University of Auckland, Auckland, New Zealand.

³Department of Earth Sciences, University of Bristol, Bristol, UK.

⁴Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA.

⁵National Oceanography Centre, University of Southampton, Southampton, UK.

⁶Department of Earth Sciences, Durham University, Durham, UK.

accumulations of volcanoclastic debris. In the profiles, debris is visible as eastward tapering lenses that extend offshore from Silver Hills and Centre Hills (Figures 1b and 2; Lines 7 and 9). The debris from Silver Hills (Line 7) extends ~10 km from the shelf and overlies strata that step down towards Montserrat.

From Centre Hills as well (Line 9), debris onlaps layered sediments that dip westward, from 1.5 s two-way travel time (tw) at km 12 to 2.2 s twt at km 5 (Figure 2). The apparent dip (Line 9) and downward fault-step pattern (Line 7) towards the

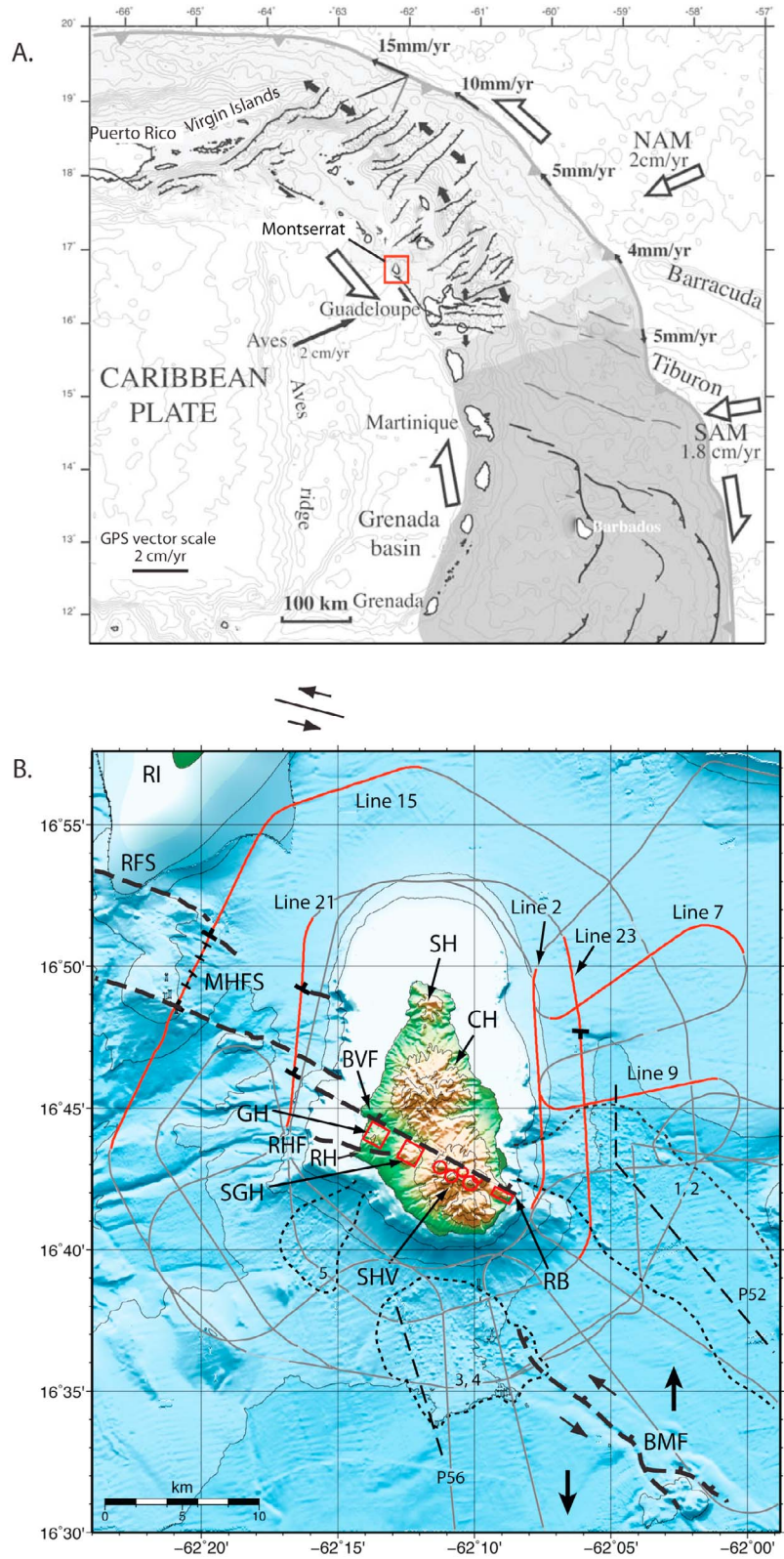


Figure 1

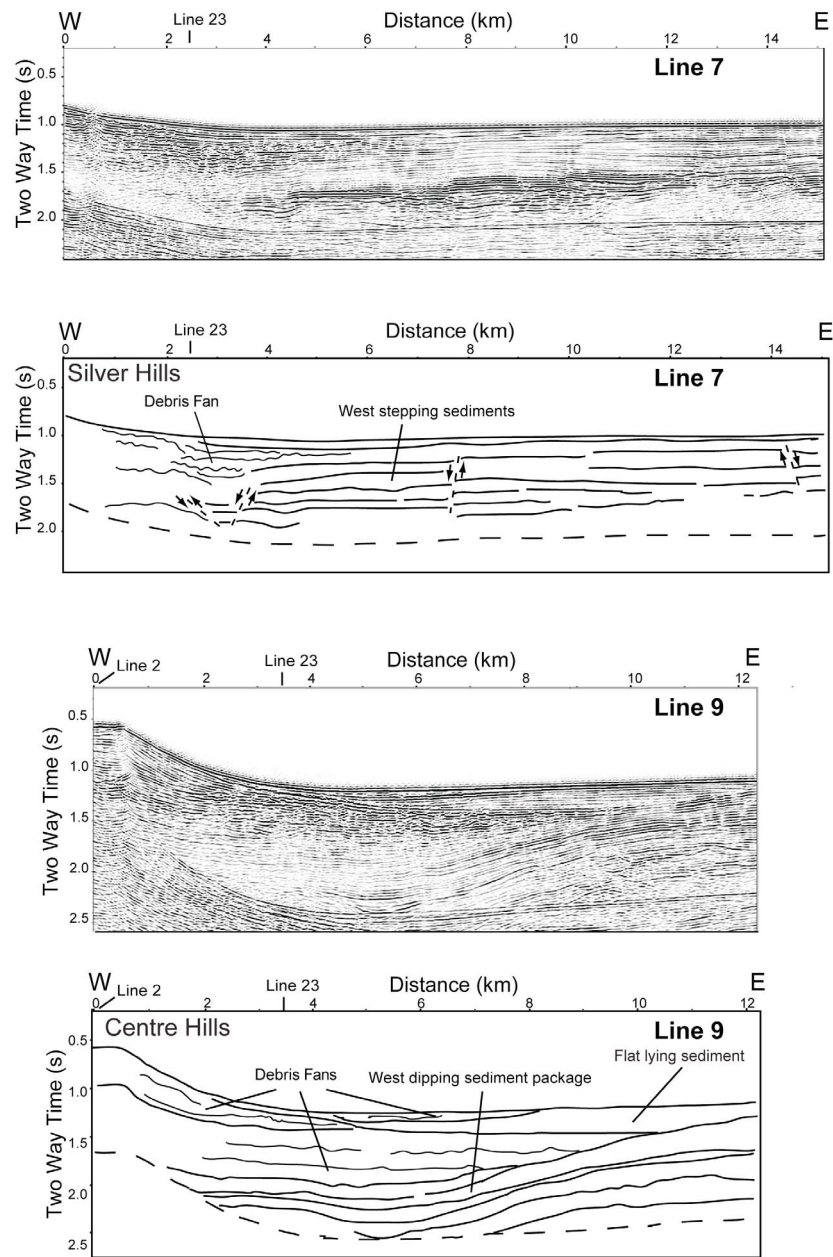


Figure 2. Seismic reflection profiles and annotated interpretations of radial Lines 7 and 9. Solid lines: Strong reflectors and sediment packages. Short dashed lines: Faults. Thin dashed line: Bottom multiple. Intersection with Lines 2 and 23 indicated at top.

Figure 1. (a) Tectonic model of Lesser Antilles, modified from *Feuillet et al.* [2002]. Faults and extension directions described by *Feuillet et al.* [2002]. White full arrows: Motion among North American, South American, and Caribbean plates [*DeMets et al.*, 2000; *Weber et al.*, 2001]. White half arrows: Sinistral and dextral motion along the trench. Thin black arrow: GPS movement at Aves Ridge. (b) Montserrat bathymetry and tectonic model. Grey curved line: Track of the RRS James Cook. Lines in red (7, 9, 2, 23, 15, 21) are discussed in this paper. Red circles: Volcanic centers. Black fault symbols: Normal faults from profiles, apparent dip as indicated. Thick dashed lines: Major fault of the fault systems, including BVF and possible extension to RB. Large black arrows: Extension direction [*Feuillet et al.*, 2001]. Dotted lines: Gravity flow deposits 1–5 of *Le Friant et al.* [2004]. Red squares: Tectonic uplifts Thin dashed lines: Cross sections (P52, P56) along deposits from *Le Friant et al.* [2004]. Orange fault north of the map: inferred from 1985–1986 Redonda earthquake mechanisms [*Girardin et al.*, 1991; *Feuillet et al.*, 2002]. BMF, Bouillante-Montserrat fault system; BVF, Belham Valley fault; CH, Centre Hills; GH, Garibaldi Hill; MHFS, Montserrat-Havers fault system; RB, Roche’s Bluff; RFS, Redonda fault system; RH, Richmond Hill; RHF, Richmond Hill fault; RI, Redonda Island; SGH, St. Georges Hill; SH, Silver Hills; SHV, Soufrière Hills Volcano. Bathymetry map from Institut de Physique du Globe de Paris and M. Paulatto, NOCS.

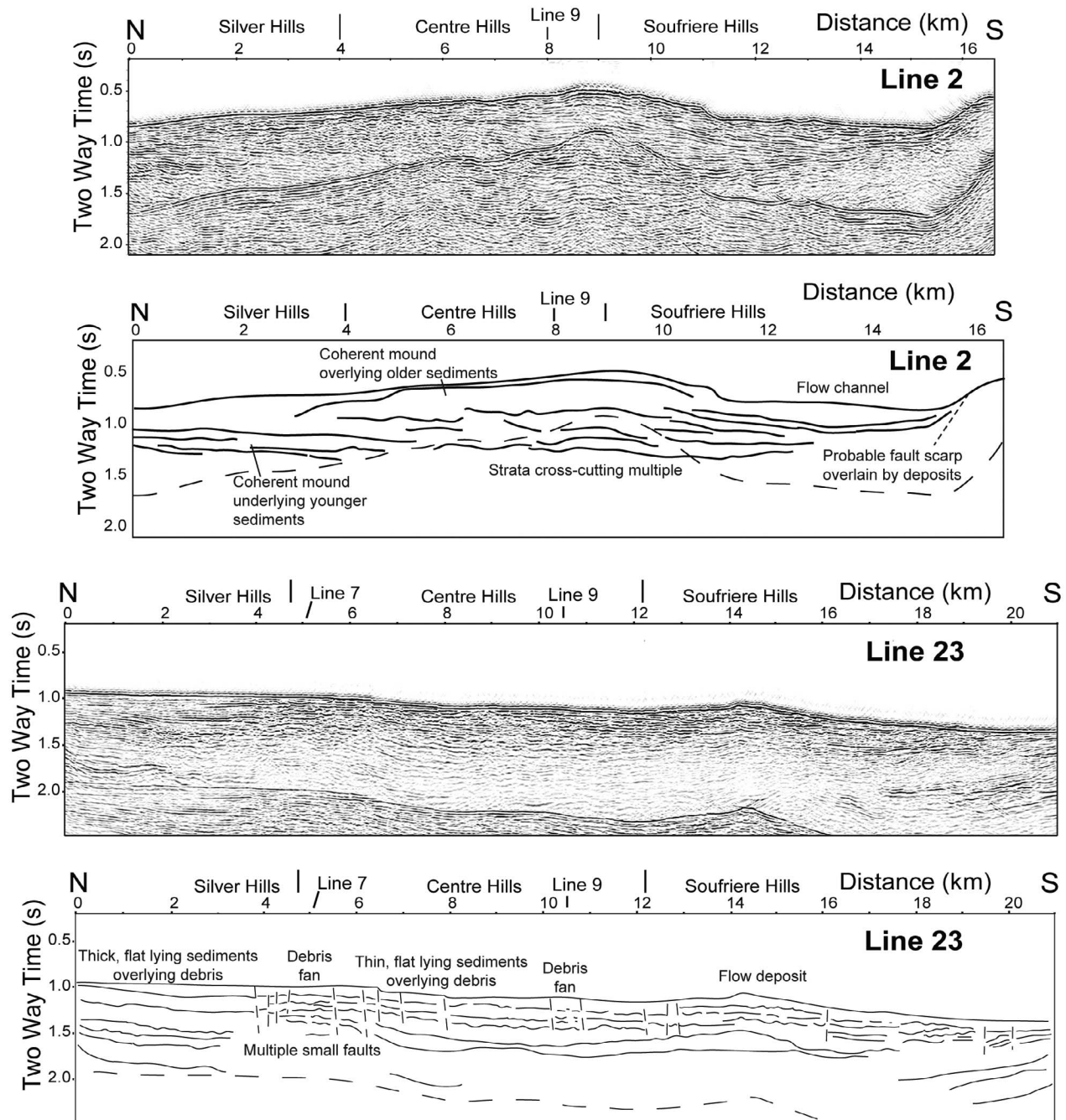


Figure 3. Seismic reflection profiles and annotated interpretations of Lines 2 and 23, parallel to the east coast. Description as in Figure 2. Intersection with Lines 7 and 9 indicated at top. Vertical lines at the top: Boundaries between the major volcanic centers.

island are consistent with either island subsidence or with rotation on the hanging wall of the MHFS faults (Figure 1b).

[7] From Centre Hills the debris lenses have accumulated in stacks, the largest being ~10 km long (Figure 2, Line 9). The lenses are overlapped by and alternate with sub-horizontal strata. We interpret the lenses as submarine fans from emplacements of volcanoclastic flows, caused largely by lava dome collapses and deposited over several hundred ka. Coarse submarine fans have formed in this way during the current volcanism, producing tapering units extending as much as 8 km offshore [Le Friant et al., 2009, 2010].

[8] Where fans are overlain by flat-lying sediment, sedimentation rates can be estimated. We recognize that these rates could be influenced by multiple factors, including minor flows, remobilized deposits, and tephra fallout, but assume that flat sediment accumulation fundamentally marks the cessation of the main volcanic source. Off Silver Hills the largest fan is covered by ~80 m of flat sediments. Silver Hills became extinct at ~1 Ma [Harford et al., 2002], yielding a sedimentation rate of ~8 cm/ka. Off Centre Hills the sediments are ~44 m thick. The Centre Hills became extinct at ~500 ka suggesting a rate of ~9 cm/ka. *Le Friant*

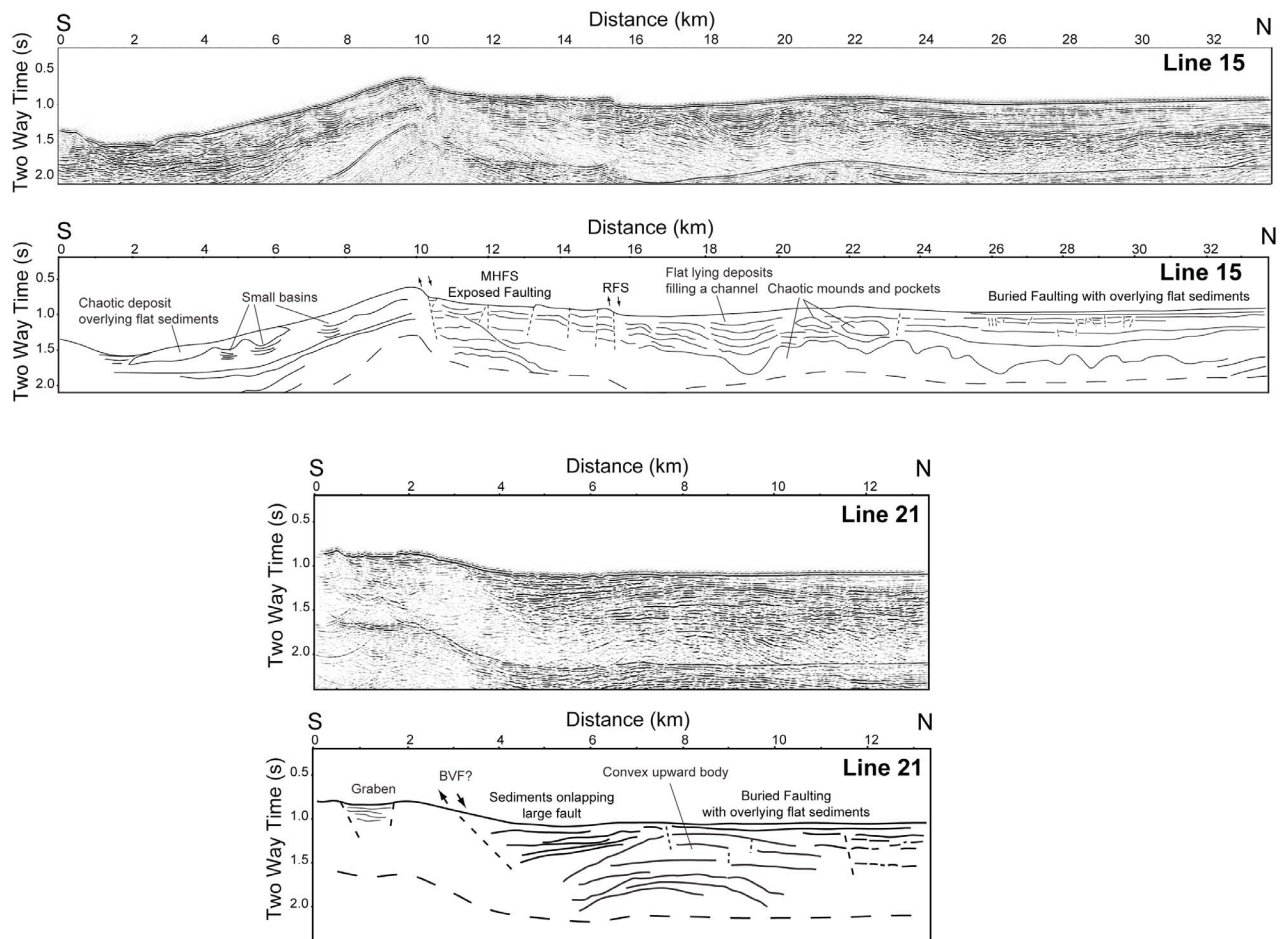


Figure 4. Seismic reflection profiles and annotated interpretations of Lines 15 and 21, off the west coast. Description as in Figure 2.

et al. [2008] report hemipelagic sedimentation rates at a site 60 km offshore as 1–3 cm/ka. At a site ~16 km offshore *Trofimovs et al.* [2010] report a rate of 4–7 cm/ka. Our higher rates are consistent with a persistent, near-shore sediment source.

[9] The N–S reflection profiles off the eastern shelf cut across the debris fans. Approximately 1–2 km offshore (Figure 3, Line 2) a mounded feature is visible just below the sea floor between km 6 and km 11. SHV flow deposits 4–5 km off the shelf are indicated by the mound on Line 23 between ~kms 10 and 20. A 6 km-wide channel is visible in Line 2 at km 11 to 15, which we identify as an embayment associated with a previously described gravity flow [*Le Friant et al.*, 2004] (Figure 1b). The southern slope of the embayment is consistent with the fault scarp north of Roche’s Bluff (Figure 1b) [*Feuillet et al.*, 2010] which subsequently has been modified by landsliding.

4. Exposed and Buried Faults Off the Western Shelf

[10] North-dipping fault scarps offset the ocean floor on profiles approximately 6 and 14 km off the west coast (Figures 1b and 4, Lines 21 and 15). The western scarp offset at km 10 of Line 15 is at least 40 m. The MHFS fault scarp and S-tilted footwall block are clear features as

well on nearby profile gwa058 of *Feuillet et al.* [2010]. To the north several faults break the ocean floor, indicating recent activity. A normal fault-bounded step in the morphology near km 16 on Line 15 is associated with the Redonda fault system (RFS) (Figure 1b). Further north, buried scarps have created basins of folded, syn-rift sediments. Beyond km 23, faulting is buried by ~100 m of flat, basin-filling sediments.

[11] In the south, both profiles reveal complex footwall deformation. At km 4–10 of Line 15 a series of piggy-back basins have formed on the tilted footwall, which is an ascending slope over ~1300 m of elevation. On the elevated footwall of Line 21 (~km 1), a small graben is infilled by subhorizontal sediments (Figure 4).

[12] At km 3 on Line 21, sediments appear to dip to the south and onlap onto a major N-dipping normal fault (Figure 4). This fault is not the same as the principal scarp fault of Line 15, but is *en-echelon* and south of it by ~2 km (Figure 1b) [*Feuillet et al.*, 2010, Figure 2]. The fault may coincide with an along-strike projection of the Belham Valley fault (BVF, Figure 1b).

5. Tectonic Synthesis and Relation to Onshore Deformation and Volcanism

[13] A new tectonic interpretation of southern Montserrat can be proposed by integrating our data with older studies

and the work of *Feuillet et al.* [2010]. We agree with the regional model of *Feuillet et al.* [2010] that the major fault systems (RFS, MHFS, and BMF) are mainly normal and arranged in a right-stepping *en echelon* structure, and also that on the large scale, this section of the arc accommodates regional left lateral shear. We disagree with the interpretation of the onshore features in *Feuillet et al.* [2010] and add a discussion of the SHV feeder dike in relation to the complexity of local tectonic and magmatic stresses.

[14] *Feuillet et al.* [2010] re-introduce the old idea [e.g., *Rea*, 1974] that Garibaldi and St. Georges Hills are volcanic cones, and they suggested the hills were fed by vents in a fissure parallel to the BVF. Notably, the field evidence does not support this hypothesis. St. Georges, Garibaldi, and Richmond Hills are composed mainly of block-and-ash-flow and pumice-and-ash flow deposits, and epiclastic beds [*Harford et al.*, 2002]. The deposit lithofacies are not compatible with vent or near-vent andesite eruption products but most likely have been sourced from SHV. Notably, while the lithofacies are similar to those of modern lava-dome flank environments where original bedding dips $<8^\circ$, exposed beds on Garibaldi Hill have dips up to 50° [*Harford et al.*, 2002]. In addition, 3-D tomography [*Shalev et al.*, 2010] indicates low *P*-wave velocity material under St. Georges and Garibaldi Hills, quite unlike the high velocity cores under SHV and Centre Hills. Thus we conclude that the morphology of these hills is not primary; they are fault-bounded tectonic uplifts that have been deformed by (mostly) normal faults, and deposits have been tilted beyond the sedimentary slope limits.

[15] A closely related issue is the BVF, which, in contrast to *Feuillet et al.* [2010] but following *Harford et al.* [2002], we interpret as a N-dipping normal fault. This is consistent with our interpretation of Garibaldi and St. Georges Hills as tectonic uplifts; in addition, these onshore blocks seem analogous to the prominent elevated footwalls seen offshore on Lines 15 and 21 (Figure 4) (cf. profiles gwa 055 and 058 of *Feuillet et al.* [2010, Figure 3]). The N-dipping fault in our marine profile Line 21 (Figure 4, ~km 3), is aligned with the BVF as an along-strike projection, and the north-dip on the offshore profile supports a similar interpretation for the BVF. Finally, 3-D tomography [*Shalev et al.*, 2010] indicates that the contact of the *P*-wave velocity anomaly boundary under St. Georges Hill dips (very roughly) 50° N.

[16] Regionally, southern Montserrat is part of a transtensional regime with extensional overprinting. Locally, southern Montserrat includes a right-step between the MHFS and the BMF, *en echelon* normal fault systems in sinistral slip; thus uplift may have been encouraged by a minor contractional component [*Deng et al.*, 1986; *Cunningham and Mann*, 2007].

[17] The interplay of transtension, contraction, and magmatism has resulted in evolving stress regimes around SHV and the BVF and related faults, as demonstrated by *Miller et al.* [2010]. Estimates of the orientation of the SHV feeder dike include a NNE trend based on 1995 seismic data [*Miller et al.*, 2010], and a NNW trend based on 1997 ground tilt data [*Hautmann et al.*, 2009]. A way of reconciling these data is to have a dike oriented ~N, which is compatible with a northerly trend of magma-transport-related hybrid earthquakes under SHV [*Miller et al.*, 2010, Figure 2]. A northerly dike trend implies a local E–W axis of minimum compression, which is approximately orthogonal to the MHFS–

BMF regional trend of N–S extension [*Feuillet et al.*, 2001, 2010]. Stresses appear to have been subjected to strong local reorientation. This could be due to some combination of varying pressures caused by the propagation of dikes and evolution of the magma storage system [e.g., *Gudmundsson*, 2006] and to being within a complex fault step [*Oglesby*, 2005].

[18] Based on marine reflection profiles and related onshore data, we conclude that on Montserrat the interplay among local faulting, volcanism, and stresses is very complex. The regional transtensional system of *en echelon* faults [cf. *Feuillet et al.*, 2010] has influenced volcanism, while the local fault step suggests both a component of compression and complicated, evolving stress regimes and fault movements.

[19] **Acknowledgments.** We thank the NSF CD, Geophysics, and I & F Programs, UK NERC, BGS, Discovery Channel TV, and British FCO for funding SEA-CALIPSO. RSJS was supported by a NERC advanced grant. We thank volunteers and crew of RRS James Cook cruise JC19, and Fusion Petroleum Technologies, Inc., for aid in data processing. Special thanks to R. Reichlin of NSF for support of streamer costs, and Brandy Murphy and Lee Ellett of Scripps for excellence in collecting streamer data. The paper was improved with comments from S. Henrys, M. Jancin, J. Rowland, and two anonymous reviewers.

References

- Cunningham, W. D., and P. Mann (2007), Tectonics of strike-slip restraining and releasing bends, *Geol. Soc. Spec. Publ.*, 290, 1–12, doi:10.1144/SP290.1.
- DeMets, C., P. E. Jansma, G. S. Mattioli, T. H. Dixon, F. Farina, R. Bilham, E. Calais, and P. Mann (2000), GPS geodetic constraints on Caribbean–North America plate motion, *Geophys. Res. Lett.*, 27, 437–440, doi:10.1029/1999GL005436.
- Deng, Q., W. Daning, P. Zhang, and S. Chen (1986), Structure and deformational character of strike-slip fault zones, *Pure Appl. Geophys.*, 124, 203–223, doi:10.1007/BF00875726.
- Deplus, C., A. Le Friant, and G. Boudon (2001), Submarine evidence for large-scale debris avalanches in the Lesser Antilles Arc, *Earth Planet. Sci. Lett.*, 192(2), 145–157, doi:10.1016/S0012-821X(01)00444-7.
- Dewey, J. F., R. E. Holdsworth, and R. A. Strachan (1998), Transpression and transtension zones, *J. Geol. Soc.*, 135, 1–14.
- Feuillet, N., I. Manighetti, and P. Tapponnier (2001), Active extension perpendicular to subduction in the Lesser Antilles island arc (Guadeloupe, French Antilles), *Comptes Rendus de l'Académie des Sciences, Series IIA, Earth Planet. Sci.*, 333(9), 583–590.
- 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., et al. (2010), Active faulting induced by slip partitioning in Montserrat and link with volcanic activity: New insights from the GWADASEIS marine cruise data, *Geophys. Res. Lett.*, 37, L00E15, doi:10.1029/2010GL042556.
- 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.
- Gudmundsson, A. (2006), How local stresses control magma chamber ruptures, dykes injections, and eruptions in composite volcanoes, *Earth Sci. Rev.*, 79, 1–31, doi:10.1016/j.earscirev.2006.06.006.
- Harford, C. L., M. S. Pringle, R. S. J. Sparks, and S. R. Young (2002), The volcanic evolution of Montserrat using $^{40}\text{Ar}/^{39}\text{Ar}$ 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.
- Hautmann, S., J. Gottsmann, R. S. J. Sparks, A. Costa, O. Melnik, and B. Voight (2009), Modelling ground deformation caused by oscillating overpressure in a dyke conduit at Soufrière Hills Volcano, Montserrat, *Tectonophysics*, 471, 87–95, doi:10.1016/j.tecto.2008.10.021.
- 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.
- Le Friant, A., E. J. Lock, M. B. Hart, G. Boudon, R. S. J. Sparks, M. J. Leng, C. W. Smart, J. C. Komorowski, C. Deplus, and J. K. Fisher

- (2008), Late Pleistocene tephrochronology of marine sediments adjacent to Montserrat, Lesser Antilles volcanic arc, *J. Geol. Soc.*, *165*, 279–289, doi:10.1144/0016-76492007-019.
- Le Friant, A., C. Deplus, G. Boudon, R. S. J. Sparks, J. Trofimovs, and P. J. Talling (2009), Submarine deposition of volcanoclastic material from the 1995–2005 eruptions of Soufrière Hills Volcano, Montserrat, *J. Geol. Soc.*, *166*, 171–182, doi:10.1144/0016-76492008-047.
- Le Friant, A., et al. (2010), Eruption of Soufrière Hills Volcano, Montserrat (1995–2009) from an offshore perspective: Insights from repeated swath bathymetry surveys, *Geophys. Res. Lett.*, *37*, L11307, doi:10.1029/2010GL043580.
- Loughlin, S., R. Luckett, G. Ryan, T. Christopher, V. Hards, S. De Angelis, L. Jones, and M. Strutt (2010), An overview of lava dome evolution, dome collapse and cyclicity at Soufrière Hills Volcano, Montserrat: 2005–2007, *Geophys. Res. Lett.*, *37*, L00E16, doi:10.1029/2010GL042547.
- Miller, V., B. Voight, C. J. Ammon, E. Shalev, and G. Thompson (2010), Seismic expression of magma-induced crustal strains and localized fluid pressures during initial eruptive stages, Soufrière Hills Volcano, Montserrat, *Geophys. Res. Lett.*, *37*, L00E21, doi:10.1029/2010GL043997.
- Oglesby, D. B. (2005), The dynamics of strike slip step-overs with linking dip-slip faults, *Bull. Seismol. Soc. Am.*, *95*, 1604–1622, doi:10.1785/0120050058.
- Paulatto, M., et al. (2010), Upper crustal structure of an active volcano from refraction/reflection tomography, Montserrat, Lesser Antilles, *Geophys. J. Int.*, *180*, 685–696, doi:10.1111/j.1365-246X.2009.04445.x.
- Rea, W. J. (1974), The volcanic geology and petrology of Montserrat, West Indies, *J. Geol. Soc.*, *130*, 341–366, doi:10.1144/gsjgs.130.4.0341.
- Shalev, E., et al. (2010), Three-dimensional seismic velocity tomography of Montserrat from the SEA-CALIPSO offshore/onshore experiment, *Geophys. Res. Lett.*, *37*, L00E17, doi:10.1029/2010GL042498.
- Trofimovs, J., et al. (2006), Submarine pyroclastic deposits formed at the Soufrière Hills Volcano, Montserrat (1995–2003): What happens when pyroclastic flows enter the ocean?, *Geology*, *34*, 549–552, doi:10.1130/G22424.1.
- Trofimovs, J., et al. (2010), Evidence for carbonate platform failure during rapid sea-level rise; ca 14000 year old bioclastic flow deposits in the Lesser Antilles, *Sedimentology*, *57*, 735–759, doi:10.1111/j.1365-3091.2009.01117.x.
- Voight, B., S. Sparks, E. Shalev, P. Malin, T. Minshull, M. Paulatto, and L. Brown (2010), SEA-CALIPSO active-source seismic experiment probes structure under Soufrière Hills Volcano, WI, *Eos Trans. AGU*, in press.
- Weber, J. C., T. H. Dixon, C. DeMets, W. B. Ambeh, P. Jansma, G. Mattioli, J. Saleh, G. Sella, R. Bilham, and O. Perez (2001), GPS estimate of relative motion between the Caribbean and South American plates, and geologic implications for Trinidad and Venezuela, *Geology*, *29*, 75–78, doi:10.1130/0091-7613(2001)029<0075:GEORMB>2.0.CO;2.

S. Dean, T. Minshull, and M. Paulatto, National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK.
 C. L. Kenedi, P. Malin, and E. Shalev, Institute of Earth Science and Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. (katelk@auckland.ac.nz)

C. Peirce, Department of Earth Sciences, Durham University, South Road, Durham DH1 3LE, UK.

R. S. J. Sparks, Department of Earth Sciences, University of Bristol, Wills Memorial Building, Bristol BS8 1RJ, UK.

B. Voight, Department of Geosciences, Pennsylvania State University, 503 Deike Bldg., University Park, PA 16802, USA.