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Soufrière Hills eruption, Montserrat, 1995 - 1997: volcanic earthquake locations and fault plane solutions

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Abstract. A total of 9242 seismic events, recorded since the start of the eruption on Montserrat in July 1995, have been uniformly relocated with station travel-time corrections. Early seismicity was generally diffuse under southern Montserrat, and mostly restricted to depths less than 7 km. However, a NE-SW alignment of epicentres beneath the NE flank of the volcano emerged in one swarm of volcano-tectonic earthquakes (VTs), and later nests of VT hypocentres developed beneath the volcano and at a separated location, under St. George's Hill. The overall spatial distribution of hypocentres suggests a minimum depth of about 5 km for any substantial magma body. Activity associated with the opening of a conduit to the surface became increasingly shallow, with foci concentrated below the crater and, after dome building started in Fall 1995, VTs diminished and repetitive swarms of 'hybrid' seismic events became predominant. By late-1996, as magma effusion rates escalated, most seismic events were originating within a volume about 2 km diameter which extended up to the surface from only about 3 km depth - the diminution of shear failure earthquakes suggests the pathway for magma discharge had become effectively unconstricted. Individual and composite fault plane solutions have been determined for a few larger earthquakes. We postulate that localised extensional stress conditions near the linear VT activity, due to interaction with stresses in the overriding lithospheric plate, may encourage normal fault growth and promote sector weaknesses in the volcano.

Introduction

The Soufrière Hills Volcano eruption began on 18 July 1995, the first since European settlement of Montserrat took place in 1632AD [Fergus, 1994], although an eruption (or eruptions) had occurred sometime in the decades prior to that time. In historic times, three notable volcano-seismic crises preceded the present eruption at approximately 30-year intervals: 1897-98, 1933-37 and 1966-67. Few details are available for the first, but the second involved mainly shallow epicentres, associated with four of the volcanic centres but most noticeably Soufrière Hills and St George's Hill [Powell, 1938]. In the 1966-67 volcano-seismic crisis, hypocentres were located across south Montserrat and beneath the Soufrière Hills at depths less than 15 km [Shepherd et al., 1971]. Several episodic swarms of volcano-tectonic earthquakes were detected between January 1992 and the start of the eruption [Ambeh and Lynch, 1996], when monitoring was taken up by the Montserrat Volcano Observatory (MVO).

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The MVO network of short-period (SP) seismometers (Fig. 1) uses mostly 1 Hz vertical component instruments, although 3-component instruments have also been deployed at times. During the crisis the network configuration has been modified, but at least five, and usually eight or more stations have been continuously operational, telemetered to a PC-SEIS data-acquisition system [Lee, 1989] provided by the USGS Volcano Disaster Assistance Program team. Events are inspected routinely by MVO, classified by type [Miller et al., in press] and, when possible, phase arrival time readings are taken. A provisional location is computed using the HYPO71PC program [Lee and Valdés, 1989] for any event classified as a volcano-tectonic earthquake (VT) or impulsive 'hybrid' event for which a quorum of suitable phases is available. Volcano-tectonic events have conventional-looking earthquake signatures with impulsive P- and S-phases and predominant frequencies >5Hz. Lahr et al. (1994) coined the term 'hybrid' for volcano-seismic events which typically have an identifiable P-wave first arrival but a phaseless, lower frequency content (1-4Hz) in the later waveform. By the end of February 1997, when several hundred thousand seismic events had been recorded, the dataset comprised more than 10,000 individual VTs and hybrids, and it is the preliminary phase data from these events which form the basis of the present analysis. In October 1996, the SP network was supplemented by the deployment of a network of five 3-component broadband and three wide-dynamic range SP seismographs (see Fig. 1, and Neuberg et al., in press); data from this new network, however, have not been used here.

Uniform reprocessing of hypocentre locations

The raw seismic event phase readings constitute a fairly heterogeneous dataset: network aperture is small, many earthquakes have very small magnitudes ($M_L \approx 1$), hence low signal-to-noise margins, the network coverage has changed through time, and many different analysts have read and processed the vast number of events recorded. In addition, limited horizontal component data has made determination of S-phase arrivals challenging and, in routine location processing, velocity models and station elevation corrections have not been used consistently over the whole period.

To produce a more homogeneous dataset, a group of 5819 events (data to November 1996) has been iteratively relocated, adjusting station corrections from one run to the next, to minimise overall average *rms* error of the group. In the relocation exercise, a simple velocity model was used, initially adapted for the Montserrat SP network from a model used on Guadeloupe [C. Antenor, pers. comm.]. Individual station elevation corrections have been included, together with an extra velocity layer to the elevation of the top of the mountain allowed hypocentres to be located above sea-level datum. Preliminary runs produced many gross S-phase residuals, mostly early arrivals, and an overall average *Vp/Vs* ratio of 1.44 for the dataset, a value much lower than expected for the conditions. Erroneous early S-phase picks on a vertical instrument is a common problem when near-surface S-P conversions are present, as in the present case. In subsequent runs, Jeffreys' [1961] method was implemented to down-weight any readings with such large non-Gaussian travel-time errors, and the *Vp/Vs* ratio was set arbitrarily

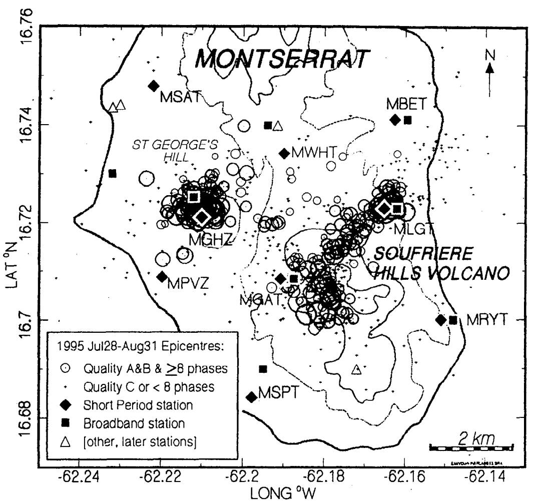

Fig. 1. Seismograph locations and epicentres of volcano-seismic events (mostly VTs) which occurred at the start of the crisis. Three spatial clusters are evident from better quality locations: a linear cluster which advanced southwest from the east coast, shallowing towards the volcano, and nests of earthquakes under St. George's Hill and under the Soufrière Hills volcano (see also Fig. 2).

to 1.70. Azimuthal weighting partially compensated for non-uniform network geometry.

Five full-scale relocation iterations produced a minimum average *rms* of 0.07 sec for all 5819 events. Individual station corrections range from -0.27 to +0.21 sec for P-phases, and from -0.25 to +0.03 sec for S-phases for solutions with HYPO Quality C or better [Lee and Lahr, 1975]. Standard deviations on these average corrections were about 0.1 sec for P and ≥0.2 sec or greater for S-readings, implying relatively large scatter on residuals for such close earthquakes recorded on a small array. Two stations on the volcanic edifice have consistently early P-arrivals, while P-wave arrivals to distant stations in the south and west of the island are systematically late. Nearly all S-phase corrections provide early arrival times, suggesting that misidentified phases have not been fully removed by the Jeffreys' weighting scheme. Proportions of solutions in the trial set achieving HYPO Quality grades are: A, 1% (71 events); B, 35% (2050); C, 37% (2177) and D, 26% (1521). Quality D events are generally ignored in the following discussion.

Using these derived station corrections with the basic velocity model, an additional 3423 seismic events were then processed, giving a complete dataset of 9242 relocated events from 28 July 1995 to 28 February 1997. These range from microearthquakes, some with magnitudes <0 M_L, to felt events approaching magnitude 4 M_L.

Spatio-temporal evolution of the hypocentres

Selected data subsets serve to illustrate the main spatio-temporal features of the VT and hybrid seismicity associated with the eruption. Following the first strong steam venting from the volcano on 18 July 1995, an effective seismograph network was re-established by 28 July 1995, and relocated epicentres of the seismic events (mostly VTs) which occurred in the subsequent 35 days are shown on Fig. 1. Three clusters are evident. One nest of earthquakes lies below St. George's Hill, and another is more directly under the Soufrière Hills volcano itself. A third, elongated cluster appears to have advanced southwestward with time from near the east coast of the island, towards the volcano. Other VT seismicity is diffusely scattered across southern Montserrat during this period: this diffuse activity and the clustering under St. George's Hill mimics the seismicity of earlier volcano-seismic crises in Montserrat [Powell, 1938; Shepherd et al., 1971].

On Fig. 2, oblique views are given for three further periods of activity: a) the early stage, when mainly phreatic venting and mild explosions of steam and ash were taking place; b) an interval associated predominantly with dome building, but with one significant explosion; and c) from November 1996 through February 1997, involving more recent dome growth and occasional big collapses. Quality A, B solutions in Fig. 2a show two of the nests of early VT activity, one at depths 2 - 6 km under the volcano, and the other under St. George's Hill (n.b. a view of the NE-trending linear cluster of Fig. 1 is blocked on this plot). In the period depicted on Fig. 2b, activity under St. George's Hill has diminished, but activity under the volcano has burgeoned and intensified at slightly greater depths than indicated in Fig. 2a. The phalanx of hypocentres under the crater is also expanded upwards to shallower levels, just reaching the surface. By the period of Fig. 2c, activity had become mainly concentrated into a narrow cylindrical volume below the crater, generally no more than 2 - 3 km deep. The majority of these later events are hybrids, rather than VTs.

Variations in hypocentre location parameters over time are shown on Fig. 3. The early, generally dispersed pattern of epicentral positions became increasingly concentrated directly below the volcano crater. The activity also became systematically more shallow, with the general trend of greatest focal depths migrating upwards more than the trend for minimum focal depths. Within all these trends, however, strong short-term spatio-temporal clustering is a feature of the seismic activity [see also Miller et al., in press]. While the detection threshold of the SP network was not invariably uniform over the whole period, the data are, however, representative of observed levels of activity through time, both in terms of numbers of events and their relative locations.

Fault plane solutions

Preliminary fault plane solutions have been derived from a few selected earthquakes (Fig. 4), using P-wave first motion polarities as

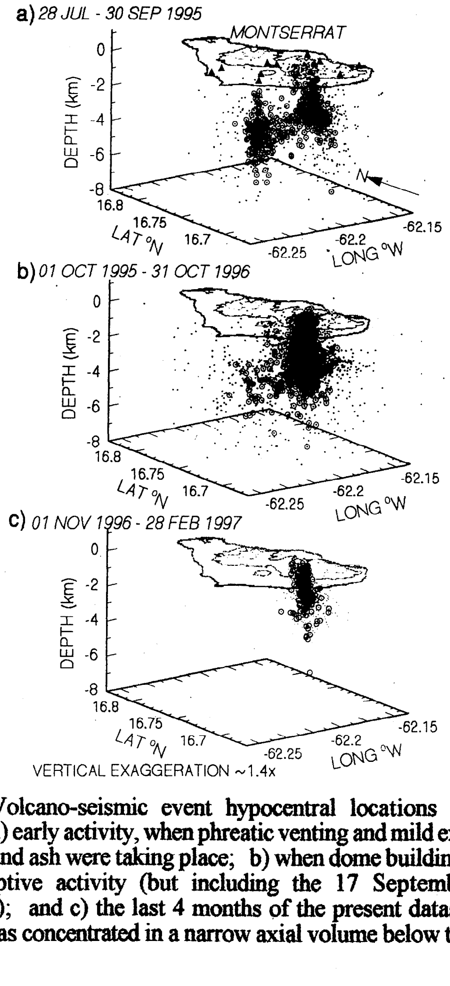

Fig. 2. Volcano-seismic event hypocentral locations for three periods: a) early activity, when phreatic venting and mild explosions of steam and ash were taking place; b) when dome building was the main eruptive activity (but including the 17 September 1996 explosion); and c) the last 4 months of the present dataset, when activity was concentrated in a narrow axial volume below the crater.

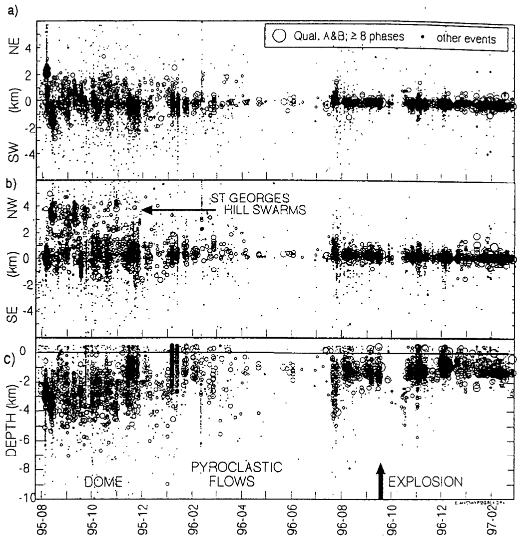

Fig. 3. Location parameters versus time: a) and b) epicentral positions projected on to NE-SW and NW-SE sections through the crater; and c) hypocentral depths. The early, scattered distribution of epicentres evolved into a cluster concentrated below the crater, and became more shallow through time. Short-term spatio-temporal clustering is a marked trait of event occurrences, with some early off-axis clumping, most notably under St. George's Hill. (Sea level = zero depth).

input to the hemisphere search algorithm of Snoke et al. [1984]. Event sizes ranged from about 2.5 to 4 M_L. Solutions '1' and '2', from two of the largest events ($M_L \approx 4$, both on 13 August 1995) in the swarm of felt events under St. George's Hill, indicate reverse-slip and strike-slip movements, respectively. Each mechanism has one steeply-dipping candidate plane striking approximately NE-SW. Solution '3', showing normal fault movement, is for a moderate-sized VT (≈ 2 M_L) which occurred below the northern flank of the volcano on 17 October 1995, at a time when magma effusion at the surface had temporarily stalled. Later on, in February 1996, there was a small swarm of VT's further away from the volcano to the northwest, beneath the southern edge of the Centre Hills. A composite solution (solution '4') of first motions from three events in this sequence shows reverse motion with an oblique component: candidate planes are rotated from those shown for the nearby solutions '1' and '2'. Lastly, solutions '5' and '6' are, respectively, composites of five and three individual hybrid events directly under the mountain in November 1996, when the southern crater rim of the volcano was being distressed. Each of these eight hybrids has the clear appearance of a VT at the start of the seismic signal, with impulsive first motions. Both composite solutions have one plane striking approximately N-S: in solution '6' this plane is steeply dipping, implying possible reverse movement, while the corresponding plane of solution '5' features a slip component which is more oblique-reverse. Except for the three events comprising the composite event '6', which originated at depths of only about 1.4 km below sea-level (ie. 2 km below the crater floor), depths of all other events providing first motion mechanisms are very similar, ranging from 3.1 to 3.5 km below sea-level.

While these fault plane solution data are sparse, their mechanisms can all be interpreted as consistent with elevated radial stresses interacting with regional-scale stresses in the overriding lithospheric plate. As yet, little is known about prevailing crustal stress conditions in Montserrat, and detailed fault mapping for tectonic interpretation is at an early stage. However, a conjectured offset in the local Benioff zone between Montserrat and Guadeloupe [Wadge and Shepherd, 1984], and modelling of forces in subduction zone margins [eg. Whittaker et al., 1992], suggest that such a regime should be compressive. Maximum horizontal stress in the part of the overriding plate which underlies Montserrat would be close to arc-normal (i.e. directed approximately NW-SE) and rapid magmatic intrusion up into the volcano could then create a strain source which may be large enough to produce general uplift flexure. This in turn creates tensile conditions above the intrusion, switching to compressive beyond some critical geometrical distance, and would account for at least some of the diffuse seismicity seen in the early stages of the crisis. It is possible to envisage a realistic stress heterogeneity at depth, such as a vertical dike, generating zones of compressive and tensile differential stresses which depend on depth, distance and azimuth from the intrusion (e.g., Rubin, 1992). Out to a few km range, the magnitudes of these changes can be sufficiently high (e.g. >1 MPa) that conditions for fault slip under the superimposed regional stress field can be either enhanced or quenched, or the style of faulting altered altogether by switching the orientations of the principal stresses. For instance, such circumstances could explain why reverse and oblique mechanisms are possible, and were seen 3 km away under St. George's Hill, at depths where the horizontal compressive stress due to a vertical dike or cylindrical intrusion is greatest. Similarly, extensional conditions can exist at shallower levels, e.g. in the NE quadrant, where a net reduction in the maximum horizontal stress would encourage normal or strike-slip faulting, along the NE linear trend in the first week of August 1995 (see Fig. 1).

Whilst peripheral effects, such as magma-induced groundwater pore-pressure changes propagating to faults at incipient failure [Knapp and Knight, 1977; Delaney, 1982], hydrothermal perturbation by migrating gases, or even magma movement well away from the main edifice, cannot be precluded as causes of the observed seismicity, activity at these particular localities has been a notable feature of previous volcano-seismic crises in Montserrat. However, simple intrusive perturbation of crustal stresses can probably explain the data and other processes, operating otherwise unmanifest at exceptional distances from the known locus of volcanic activity, are not needed. There are two testable consequences of this hypothesis: repeated enhancements of compressive conditions near St George's Hill in recent geological time should have given rise to evident thrust uplift or block tilting in that vicinity; and a preponderance of normal faulting should have been provoked by enhanced extension north-east of the volcano. Recurring activity of the latter kind might have led to the eventual sector failure which produced the open-side to English's Crater.

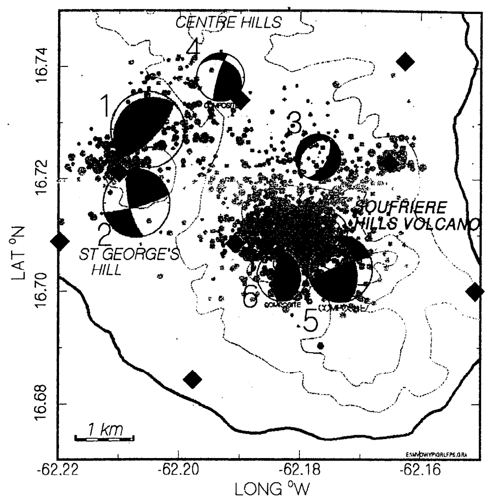

Fig. 4. Lower hemisphere fault plane solutions from selected earthquakes (see text for details). These mechanisms can be interpreted in terms of a co-axial compressive stress increase, centred under the volcano, interacting at critical depths with lithospheric stresses in the overriding plate. (Sizes of beach-balls reflect relative magnitudes, with positions relative to the cloud of all Quality A&B seismicity).

Discussion

This paper draws out the broad features of locations of VT and hybrid earthquake activity during the first 19 months of the eruption. The relocated hypocentres provide little direct evidence for a very shallow magma body beneath the Soufrière Hills volcano, and any large magma body must presumably be located below the main body of seismic activity, at a depth of 5 km or greater. This is consistent with petrological evidence [Barclay et al., in press], which suggests the magma chamber is ≥6 km deep. However, Villasenor et al. [1996], in a hypocentre/velocity structure inversion trial with data from the VT event swarms during August 1995, inferred that the seismically active volume including the NE-SW lateral alignment of hypocentres from the east coast to the volcano had a faster P-wave velocity than its surroundings, an effect said to be consistent with local intrusion on the basis of observations from other volcanic areas. An alternative interpretation, based on the fault plane solutions presented above, is that extensional failure was provoked along that particular line, not by shallow magma migration locally, but by interaction between regional tectonic stresses in the overriding plate and radial stress changes caused by intrusion under the volcano itself.

The ensuing nest of strong activity under St George's Hill, which peaked with more than 38 felt earthquakes in one night (12-13 August 1995), echoed experiences in the earlier Montserrat volcano-seismic crises of 1933-37 and 1966-67. The spatial separation of some of the hypocentres into two clusters, one under St. George's Hill and another under the Soufriere Hills volcano, is reminiscent of pre-eruptive activity recorded in 1991 at Mount Pinatubo volcano, Philippines, [Harlow et al., 1996]. There, most of the seismic energy released during the pre-dome phase occurred as a cluster 5 km northwest of the summit, and this had led to a confusing situation for hazard assessment. With the passing of a few weeks, the locus of activity gradually shifted to a position under the summit of Pinatubo: whereas activity to the NW had occurred at depths of 2 - 6 km (below sea level), the later activity under the volcano clustered above 3 km depth (see Harlow et al. [1996] - Figs. 4, 7, 9). The situation in Montserrat is thus very similar, even in detail (Fig. 2a). At Pinatubo, the NW cluster lay under an area of geologically young fault traces and the VT clustering was conjectured to have been caused by small regional stress changes due to rising magma, triggering movements on pre-stressed near-vertical faults. In Montserrat, the VT clustering under St. George's Hill could, conceivably, have been a response to magma intrusion there (it is an "inactive" volcano), or to some perturbation of its hydrothermal system (although no surface manifestations arose). It is more likely, however, that this energy release was the result of induced local stress changes involving a fault or faults which may have been in a state of incipient failure to begin with. Thus, as an open conduit formed and, as stress conditions presumably re-equilibrated, general seismic energy release in southern Montserrat became much less diffuse, ultimately condensing into a narrow co-axial distribution up to the crater from a depth of about 2 - 3 km. The number of VT events declined, and gave way to increased hybrid and other types of seismic event activity, although small swarms of VTs did occasionally recur, sometimes presaging switches in the locus of dome growth within the crater.

In the months immediately following the end of the period for data used in this study (i.e. after February 1997), there was some diminution in the numbers of locatable events, either as VTs or hybrids, although eruptive activity has continued to increase. However, following a major dome collapse in late June 1997, and an increase in explosive activity since then, there has been some resurgence in seismic activity through to September 1997, including new bursts of VTs and swarms of large hybrids. Eventually, the major scientific challenge will be to recognise symptoms of seismic activity which are indicative of a waning eruption.

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