Spatial variations in the frequency-magnitude distribution of earthquakes at Soufriere Hills Volcano, Montserrat, West Indies

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Spatial variations in the frequency-magnitude distribution of earthquakes at Soufriere Hills Volcano, Montserrat, West Indies

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Abstract. The frequency-magnitude distribution of earthquakes measured by the *b*-value is determined as a function of space beneath Soufriere Hills Volcano, Montserrat, from data recorded between August 1, 1995 and March 31, 1996. A volume of anomalously high *b*-values ($b > 3.0$) with a 1.5 km radius is imaged at depths of 0 and 1.5 km beneath English's Crater and Chance's Peak. This high *b*-value anomaly extends southwest to Gage's Soufriere. At depths greater than 2.5 km volumes of comparatively low *b*-values ($b \sim 1$) are found beneath St. George's Hill, Windy Hill, and below 2.5 km depth and to the south of English's Crater. We speculate the depth of high *b*-value anomalies under volcanoes may be a function of silica content, modified by some additional factors, with the most siliceous having these volumes that are highly fractured or contain high pore pressure at the shallowest depths.

Introduction

The frequency of occurrence of earthquakes with increasing magnitude can be described as a power law by the equation,

$$log_{10}N = a - bM \tag{1}$$

where N is the cumulative number of earthquakes with magnitudes equal or larger to M, and a and b are constants [*Ishimoto and Ida*, 1939; *Gutenberg and Richter*, 1944). The *b*-value is the slope of the best fit line between the observed number of earthquakes at a given magnitude and the magnitude. It is inversely proportional to the mean magnitude, thus differences in b reflect differences in the average crack length that ruptures in an earthquake.

Values for b are generally close to 1 in much of the earth's crust [*Frohlich and Davis*, 1993; *Morgan et al.*, 1988]. However, in many volcanic areas b is frequently found to be much higher, often closer to 2 (e.g. *Warren and Latham*, 1970]. Factors that can alter the *b*-value include increased heterogeneity of the material [*Mogi*, 1962], an increase in applied shear stress [*Scholz*, 1968; *Urbancic et al.*, 1992], an increase in the effective stress [*Wyss*, 1973], or an increase in the thermal gradient [*Warren and Latham*, 1970].

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In this study we examine spatial differences in relative *b*-values at Soufriere Hills Volcano on Montserrat, West Indies, from data recorded between August 1, 1995 and March 31, 1996 (Figure 1). Between August and October 1995 approximately 1,500 earthquakes were located beneath the volcano, likely associated with the accumulation of magma. These earthquakes covered a broad area of the southern portion of the island of Montserrat (Figure 2) [*Aspinall et al.*, this volume]. The most notable clusters of earthquake hypocenters occurred beneath English's Crater and in an elongate zone to the northeast extending from English's Crater to the Bethel area (August 5 and 6), St. George's Hill (August 13-31, 1995), and Windy Hill (August 25 to September 13) (for geographic locations see Figure 1). From October 1995 through March 1996 magma was actively erupting, forming a lava dome in English's Crater and seismic activity was more concentrated at shallow depth beneath the volcano [*Miller et al.*, this volume; *White et al.*, this volume], although the areas beneath St. George's Hill and Windy Hill remained active throughout the study period.

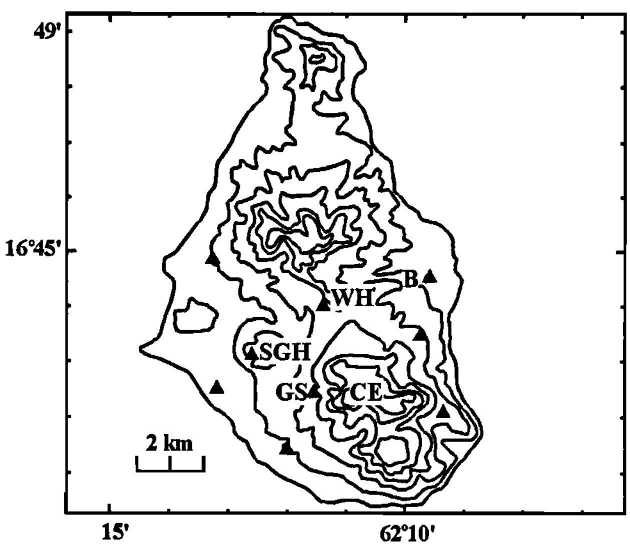

Figure 1. Montserrat seismic network with individual stations shown as triangles from July 1995 to March 1996. Letters correspond to approximate geographic locations referenced in text: CE, Chance's Peak/English Crater; GS, Gage's Soufriere (upper and lower); SGH, St. George's Hill; WH, Windy Hill; B, Bethel.

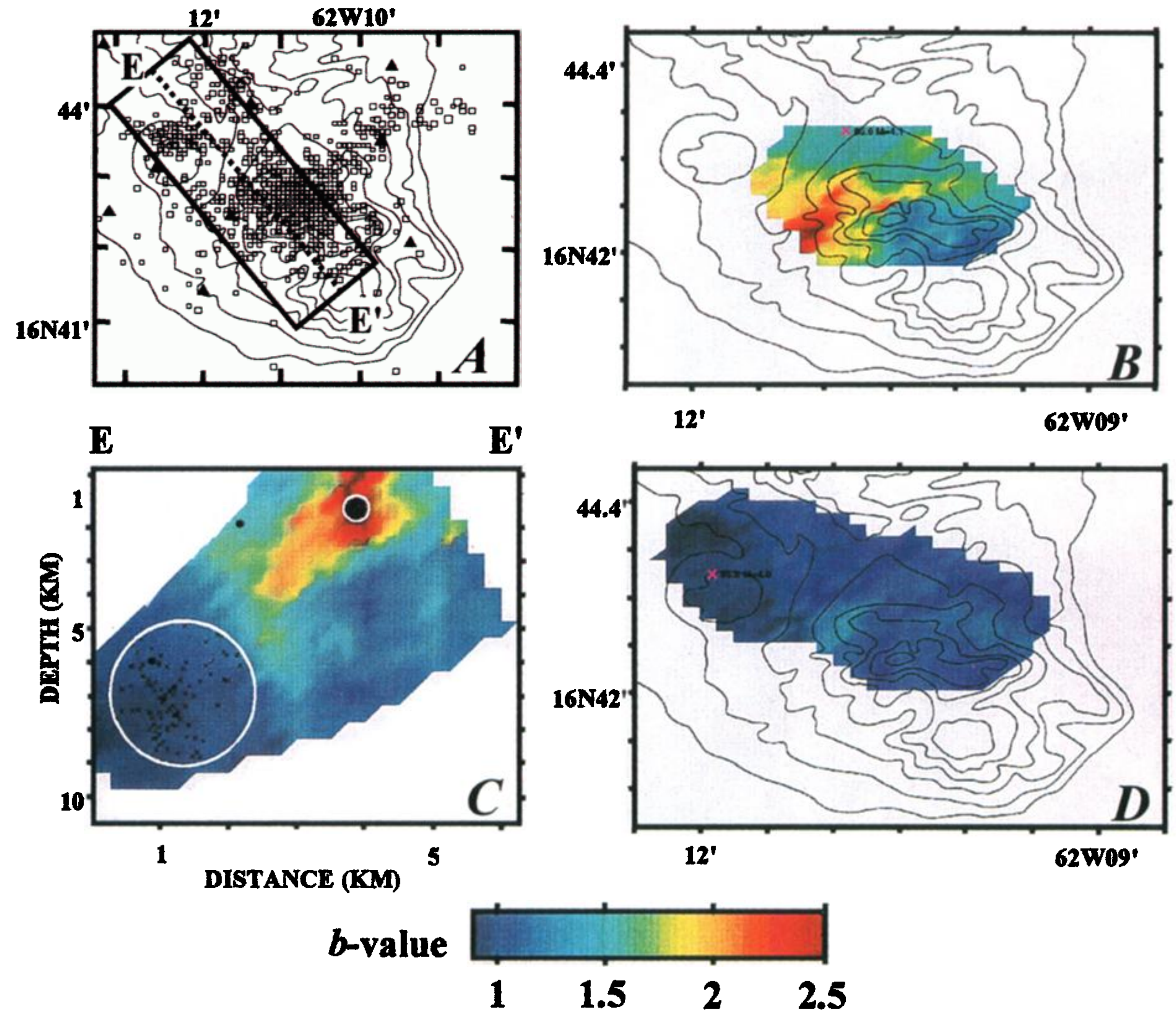

Figure 2. (A) Map of the southern portion of the island of Montserrat showing earthquake epicenters used in this study, seismic stations, and the location of cross-section E-E' (Figure 2C). (B) Map view of b-values for earthquakes above 2.5 km depth. (C) Cross section E-E' showing the distribution of b-values. Circles show locations used to calculate FMDs shown in Figure 3. (D) Map view of b-values calculated for earthquakes at greater than 2.5 km depth. X denotes location of largest earthquake in B and D.

Data

Beginning in late July 1995 the island of Montserrat was monitored by a network of 6 to 9 short period seismic stations (Figure 1). Signals from the various stations were telemetered to a central site and recorded on a PC-based seismic acquisition system similar to that described by *Murray et al.* [1996]. Earthquake hypocenters and magnitudes were determined using the program HYPO71PC [*Lee and Valdes,* 1989] and a velocity model which was derived for Montserrat by trial and error modifications to the velocity model used at Guadeloupe, West Indies [*C. Antenor,* personal communication, 1995]. Magnitudes were determined by coda measurements using the relationship

$$Mb = 2.073*LOG(t) + 0.0018*D - 0.705 \quad (2)$$

where t is the coda duration in seconds and D is the hypocentral distance in km [*Sheperd and Aspinall,* 1983].

The period from August 1, 1995 to March 31, 1996 was selected for this study because the reporting is homogeneous, that is, no changes in magnitude of completeness and no inadvertent changes in magnitude scale, as often encountered in catalogs [*Habermann,* 1982; *Habermann,* 1991], occur in this period. After March 31, the catalog contains a much higher percentage of events without magnitude, such that these data were not useful for this study. During the study period, roughly 4,500 earthquakes were located. For approximately 200 of these earthquakes no coda duration was measured so no magnitude could be determined. An examination of FMD (Frequency Magnitude Distribution) plots suggests the catalog is complete above about magnitude 1.7, resulting in about 1,900 earthquakes used for this analysis. The duration of some of the largest events exceeded the length of the trigger window on the event detection acquisition system, so we calculated magnitudes for these events using the regional Caribbean network, operated by the Seismic Research Unit of the University of West Indies. In total, 16 earthquakes were given a regionally determined magnitude. To maintain consistency, the locations for these events were calculated using only the short-period stations on Montserrat.

Method

The method of b-value estimation used here is identical to that described by *Wiemer and Wyss* [1997], *Wiemer and Benoit* [1996], and *Wyss et al.* [1997]. The *b*-value is estimated at the nodal points of a two-dimensional grid using the N nearest earthquakes. The nearest events are selected on the basis of epicenters in the case of map views, and on the basis of the nearest distance in the projections of the hypocenters onto a vertical plane in the case of cross sections. Consequently, sampling volumes have the shape of cylinders. The nodal separation we use is 0.0025 degrees (roughly 0.25 km) in maps and 0.25 km in cross sections, and N = 100. We restrict the radii of cylinders to a maximum value, R_{max}, beyond which we do not use the *b*-value as it is not based on sufficiently local data. R_{max} was set at 2.0 km.

The *b*-value is calculated using both the maximum likelihood method and the weighted least squares method. The use of both methods allows us to verify that the results are independent of the calculation method. The *b*-value estimates shown in maps and cross sections are calculated with the maximum likelihood method.

Results

The most prominent anomaly is a volume of relatively high *b*-values (red colors) which extends southwest from roughly Chance's Peak/English's Crater to the area of maximum *b*-value anomaly near Gage's Soufrieres (both lower and upper) (Figure 2B). This high *b*-value anomaly is imaged to a depth of about 1.5 km beneath Chance's Peak/English's Crater and to 2.0 to 2.5 km beneath Gage's Soufriere (Figure 2C). A strong zone of relatively low *b*-value (blue colors) is imaged at depths of 3 to 5 km depth beneath St. George's Hill and Windy Hill (Figures 2B and 2C). Another zone of low *b*-values is seen from approximately 2-4 km depth beneath the volcanic edifice, as well as to the south of English's Crater (Figures 2B—2D).

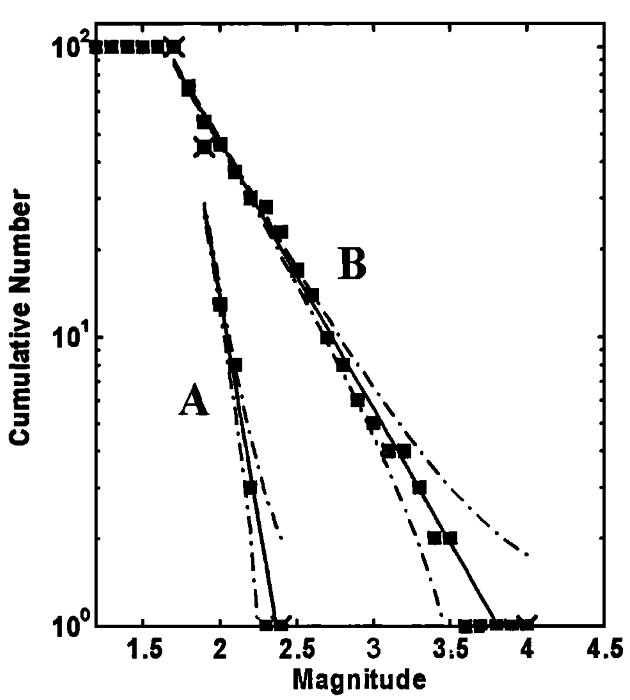

Figure 3. Frequency magnitude distributions from the English's Crater/Chance's Peak/Gage's Soufriere area (A) and from the St. George's Hill/Windy Hill area (B). The sample areas used for each FMD are shown as circles in Figure 2C. The *b*-values are estimated using the maximum least squares method and are 3.07± 0.07 for A and 0.922±0.03 for B.

To demonstrate the difference in observed *b*-values beneath the English's Crater/Chance's Peak/Gage's Soufriere ("volcanic area") and St. George's Hill/Windy Hill ("outlying area"), we have compared FMDs using a 100 event sample in each area. The locations used for these circles are shown in Figure 2C. The volcanic area has a *b*-value of 3.07±0.07, while in the outlying area *b* equals 0.92±0.03 (Figure 3). Both selections closely match the expected Gutenberg-Richter distribution. There is less than a 1 percent chance that the two distributions come from the same population of earthquakes [*Utsu*, 1992]. To verify these results we inspected visually a number of FMDs calculated with 100 events each from the volcanic area with samples from the outlying area, as well as areas south of English's Crater. None of these results varied greatly from the results shown in Figure 3. Based on this test and the spatial and temporal differences of the sample locations, we are confident that the observed distribution of *b*-values at Montserrat is real and not the result of computational artifacts.

For this study we have used an M_c of 1.7. It has been suggested that at many active volcanoes a bi-modal FMD may exist, perhaps as a result of earthquake families at shallow depth [S. Wiemer, personal communication, 1997]. Numerous families of similar earthquakes were observed at Montserrat [*White et al.*, this volume], although the magnitudes are generally smaller than 1.7. Therefore, our study is not strongly affected by this problem.

Discussion and Conclusions

The *b*-values calculated for this study are on average higher than in most other areas, where they range from 0.5 to 1.5. This has been observed in some catalogs as well [M. Westerhaus, personal communication, 1998] and may be a consequence of a compressed magnitude scale, possibly resulting from a number of assumptions we have made in computing magnitudes. Consequently, we consider the *b*-values presented here to reflect relative values and use them only for comparative purposes at Montserrat.

Our results indicate that the *b*-value of earthquakes recorded during the study period shows significant spatial variation on the island of Montserrat. Specifically, the *b*-value at roughly 0-2 km depth beneath English's Crater/Chance's Peak/Gage's Soufriere was found to be much higher than in surrounding areas, especially beneath St. George's Hill and Windy Hill. Possible explanations for these high *b*-values include increased heterogeneity, temperature, and stress conditions. All of these effects are expected at 0-2 km depth beneath Chance's Peak and English's Crater. During the early portion of the study period increased heat flow in the form of increased fumarolic activity was observed as well as the formation of ground cracks [*Aspinall et al.*, this volume]. During the later portions of the study period at both Chance's Peak and English's Crater increased heat flow and rock fracture are expected associated with the eruption of highly viscous andesitic magma. The Gage's Soufriere is an area where high heat flow would be expected as well as highly fractured and thermally altered material associated with the long-term geothermal activity observed there.

There are also a number of possible explanations for the lower *b*-values observed beneath St. George's Hill and Windy Hill, and to the south of English's Crater. We speculate that seismicity here might have been triggered by stress generated by the intrusion of magma beneath English's Crater. We think these areas are likely less fractured and have less thermal alteration than those beneath English's Crater and Gage's Soufriere. These areas of more competent rock could support larger earthquakes, which is reflected in the lower observed *b*-values.

To date, detailed analyses of spatial variation in the FMD have been completed at Mount St. Helens and Mount Spurr in the United States [*Wiemer and McNutt*, 1997] and off-Ito in Japan [*Wyss et al.*, 1997]. At off-Ito, high *b*-regions were found to reflect highly fractured conditions surrounding magma chambers while "normal" *b*-values less than 1 were found surrounding these areas. *Wyss et al.* [1997] suggested that even though basaltic magma ascended through these normal areas, the sizes of the dike systems were likely too small to be imaged by this technique.

We did not attempt to examine possible changes in *b*-values at Montserrat as a function of time, because the catalog was found to be inhomogeneous with respect to magnitude after March 1996. Observations presented by *Miller et al.* [this volume] indicate that much larger earthquakes were recorded at shallow depth beneath English's Crater during later periods of the eruption. We believe that analysis of *b*-values as a function of space and time holds much promise in constraining volcanic processes at active volcanoes.

As at other volcanoes, where *b*-values have been imaged using this technique, high *b*-value anomalies at Montserrat are confined to small volumes with radii of about 1.5 km. However at Montserrat the high *b*-values are seen at very shallow depth (0-2 km), whereas the shallowest anomaly at Mount St. Helens is located at 3 km, at Mount Spurr at 4 km, and at off-Ito volcano below 7 km. A possible explanation is that the relatively viscous andesite (60% $Si0_2$) [*Devine et al.*, this volume] at Montserrat fractures the volcanic edifice to a much higher degree than the basalt at off-Ito, or the basaltic-andesite at Mount Spurr. The exception at Mount St. Helens where a dacite magma (63-65% $Si0_2$) erupts to form a lava dome, may be that *Wiemer and McNutt* [1997) examined data from 1988 through 1996, a period when Mount St. Helens was not in active eruption.

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