GEOLOGICAL NOTE

Prehistoric Stratigraphy of the Soufrière Hills–South Soufrière Hills Volcanic Complex, Montserrat, West Indies

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ABSTRACT

The Soufrière Hills and South Soufrière Hills volcanoes are morphologically distinct but petrologically similar. The history of the complex is subdivided into seven episodes. The Soufrière Hills subunit I (≤175 ka) has deposits of Pelean style with ignimbrites of Plinian style abundant near its top. This is followed by deposits from the South Soufrière Hills (~130 ka) that represent open-crater St. Vincent–style activity. Soufrière Hills subunits II–V (~112,000–~400 BP) return to more characteristic Pelean activity; at ~22,000 BP, block-and-ash flow deposits containing abundant clasts of vesicular andesite dominate. Age dating shows that renewed activity began just before European settlement in 1632 CE. This activity, including the ongoing eruption, is typical of the dominant eruptive style of this volcano for the last 175 ka.

Online enhancements: figures.

Introduction

Fieldwork that includes the logging of an almost continuous section of the east coast sea cliffs of Montserrat from Roche's Bluff to Spanish Point conducted before and during the initial nonexplosive phases of the most recent, and ongoing, eruption of the Soufrière Hills volcano chronicles the eruptive history of the Soufrière Hills (SH)–South Soufrière Hills (SSH) complex. Many of the studied outcrops reported here have since been buried by the products of this eruption. The stratigraphy of the SH was previously described by Rea (1974) and Wadge and Isaacs (1988), and Rea (1974) also described the SSH. A summary of the eruptive history of the SH was presented in earlier paper by Roobol and Smith (1998), and here we present new data for SSH and reinterpret the stratigraphy of the SH-SSH complex in light of recent age dates (Harford et al. 2002) and the detailed observations of the deposits associated with the current eruption sequence (e.g., Young et al. 1998; Druitt and Kokelaar 2002). Our new composite stratigraphy of the SH-SSH complex is based on excellent exposures in the east coast sea cliffs of Montserrat (figs. 1, 2) augmented by more than 50 stratigraphic sections measured around the flanks of the volcano (figs. 5, 6, available in the online edition).

Pyroclastic Stratigraphy and Eruptive History of the SH-SSH Complex

The classification, terminology, and symbols used on the stratigraphic sections for the deposits of the SH and SSH centers described below are largely based on work by Smith and Roobol (1990) for Mount Pelée, Martinique, and Roobol and Smith (2004) for Saba and St. Eustatius. The SH center is composed of four domes (Gages Mountain, Chances Peak, Galways Mountain, and Perches Mountain) with gently dipping aprons of unconsolidated

Manuscript received June 17, 2005; accepted September 14, 2006.

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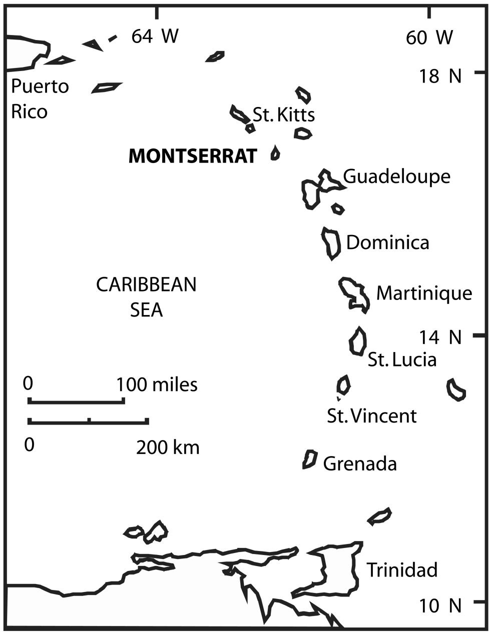
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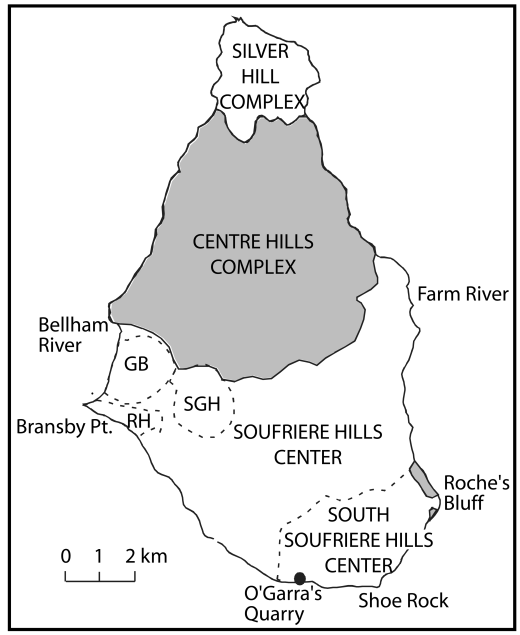
SILVER
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Roche's
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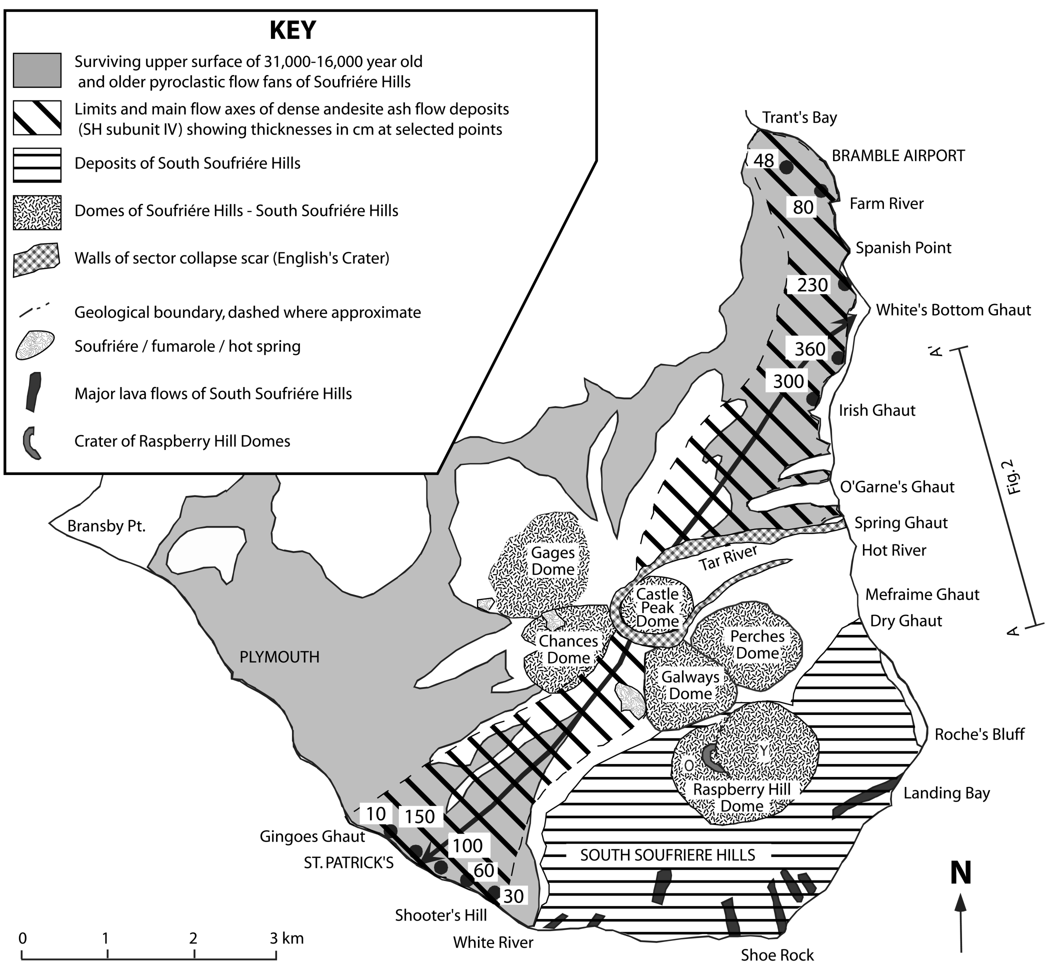
O'Garra's
Quarry
Shoe Rock


KEY
Surviving upper surface of 31,000-16,000 year old and older pyroclastic flow fans of Soufriére Hills
Limits and main flow axes of dense andesite ash flow deposits (SH subunit IV) showing thicknesses in cm at selected points
Deposits of South Soufriére Hills
Domes of Soufriére Hills - South Soufriére Hills
Walls of sector collapse scar (English's Crater)
Geological boundary, dashed where approximate
Soufriére / fumarole / hot spring
Major lava flows of South Soufriére Hills
Crater of Raspberry Hill Domes
Trant's Bay
BRAMBLE AIRPORT
48
80
Farm River
Spanish Point
230
White's Bottom Ghaut
360
300
Irish Ghaut
A'
Fig. 2
A
O'Garne's Ghaut
Spring Ghaut
Hot River
Bransby Pt.
Gages
Dome
Tar River
Castle
Peak
Dome
Mefraime Ghaut
Dry Ghaut
Perches
Dome
Chances
Dome
PLYMOUTH
Galways
Dome
Roche's Bluff
O
Y
Raspberry Hill
Dome
Landing Bay
10
150
Gingoes Ghaut
100
ST. PATRICK'S
60
30
SOUTH SOUFRIERE HILLS
Shooter's Hill
White River
Shoe Rock
N
0
1
2
3 km

pyroclastic deposits radiating away from the superstructure toward the northeast and southwest. A fifth dome—Castle Peak, which was contained in the steep-walled elliptical sector collapse scar of English's Crater—has now been overtopped and buried by the new domes (1995–present; fig. 1).

Our sea cliff stratigraphy of the SH (fig. 2) has been subdivided into five subunits—I, II, III, IV, and V (equivalent to units I, II, and III; marker G; and latest prehistoric deposits of Roobol and Smith 1998). Subunit I is lithified, subunit II is lithified to weakly lithified, subunit III is weakly to nonlithified, and subunits IV and V, as well as those from the present eruption (subunit VI), are completely unlithified. Although deposits from the present eruption are separated here from those of subunit V, stratigraphically they would represent a single subunit.

The SSH center is bounded by the White River in the west and tributaries of Dry Ghaut in the north (fig. 1). It has a summit crater open to the east, which is occupied by the Raspberry Hill dome complex of two nested domes, the oldest in the west and the youngest in the east.

The stratigraphic data from the SSH is based on a reconnaissance survey of the southern coast of Montserrat combined with the logging of detailed stratigraphic sections from the lower White River and O'Garra's Quarry. In addition, deposits believed to belong to the SSH are exposed on the Atlantic coast, in the vicinity of Mefraime Ghaut (figs. 2, 6). As with the SH, most, if not all, of the outcrops logged by us for the SSH have now been buried by deposits from the present eruption.

Although the adjacent SH and SSH centers are morphologically distinct, their radiometric ages allow us to infer that their stratigraphies represent a nearly continuous record of volcanism in southern Montserrat. Figure 3 shows the interpreted evolution of the SH-SSH complex through time.

"Ancient" Soufrière Hills (Fig. 3A). The core of the complex, exposures of which are found on Garibaldi, Richmond, and St. George's hills on the southwest side of the island, appears to be composed mainly of altered, dense andesite block-and-ash flow deposits and their reworked equivalents characteristic of Pelean-style activity. The $^{39}Ar/^{40}Ar$ ages of these deposits from Garibaldi Hill (282 ± 8 ka) and a high-temperature plateau age of 434 ± 50 ka, thought to represent the minimum age for the xenocrystal component of Gages dome (Harford et al. 2002), suggest that the complex has been active for more than 400 ka.

Soufrière Hills Subunit I (Fig. 3B–3D). Subunit I is exposed in a paleohill beneath a prominent unconformity in the lower sea cliffs on either side of Irish Ghaut but extending mainly to the south (figs. 2, 4). The lowest exposed bed is a coarse-grained, clast-supported, ash-poor block flow overlain by a dense andesite surge deposit capped by a prominent paleosol. Above the paleosol is a sequence of nine white ignimbrite and pumiceous surge deposits of andesitic composition, with a single pumiceous lapilli and ash fall layer at their base. Within the exposed ignimbrite succession, there are two local unconformities. Overlying the ignimbrites but separated from them by a prominent unconformity is a sequence of dense andesite block-and-ash flow deposits containing lenses rich in semivesicular andesite clasts. This succession is, in turn, overlain by another sequence of ignimbrites, the lower units of which contain large channel-fill deposits of coarse, dense, angular lithic-lag breccias with clasts up to 300 cm and clast-support structures. Lag breccias are composed of clasts representing a wide variety of rock types, some of which are hydrothermally altered. A weighted mean $^{39}Ar/^{40}Ar$ age of 174 ± 3 ka was obtained from the lowest exposed block-and-ash flow deposit from this subunit (Harford et al. 2002).

Subunit I contains deposits from a variety of eruptive styles. The lowest exposed deposits (fig. 4) are characteristic of Pelean-style activity. Following an eruptive hiatus, the style of activity changed to that of open-crater Plinian eruptions, as indicated by the occurrence of pumiceous falls, flows, and surges (figs. 3*B*, 4) that, following a significant time break, are succeeded by a second period of Pelean activity (fig. 3*C*). Gages dome (151 ka) and its associated pyroclastic deposits, which are now exposed on the west side of the dome near Dyer's Village (Rea 1974), probably were emplaced during

Figure 1. Regional map of Lesser Antilles (*top left*) showing location of Montserrat and an outline map of the main volcanic complexes on Montserrat (*top right*). *Bottom*, detailed map of southern Montserrat showing areal extent of the deposits from the South Soufrière Hills and Soufrière Hills volcanic centers (modified from Roobol and Smith 1998). *O* = older two-pyroxene basalt dome of the South Soufrière Hills; *Y* = younger two-pyroxene andesite dome of the South Soufrière Hills. Location of east coast sea cliff section shown in figure 2 is indicated on map.

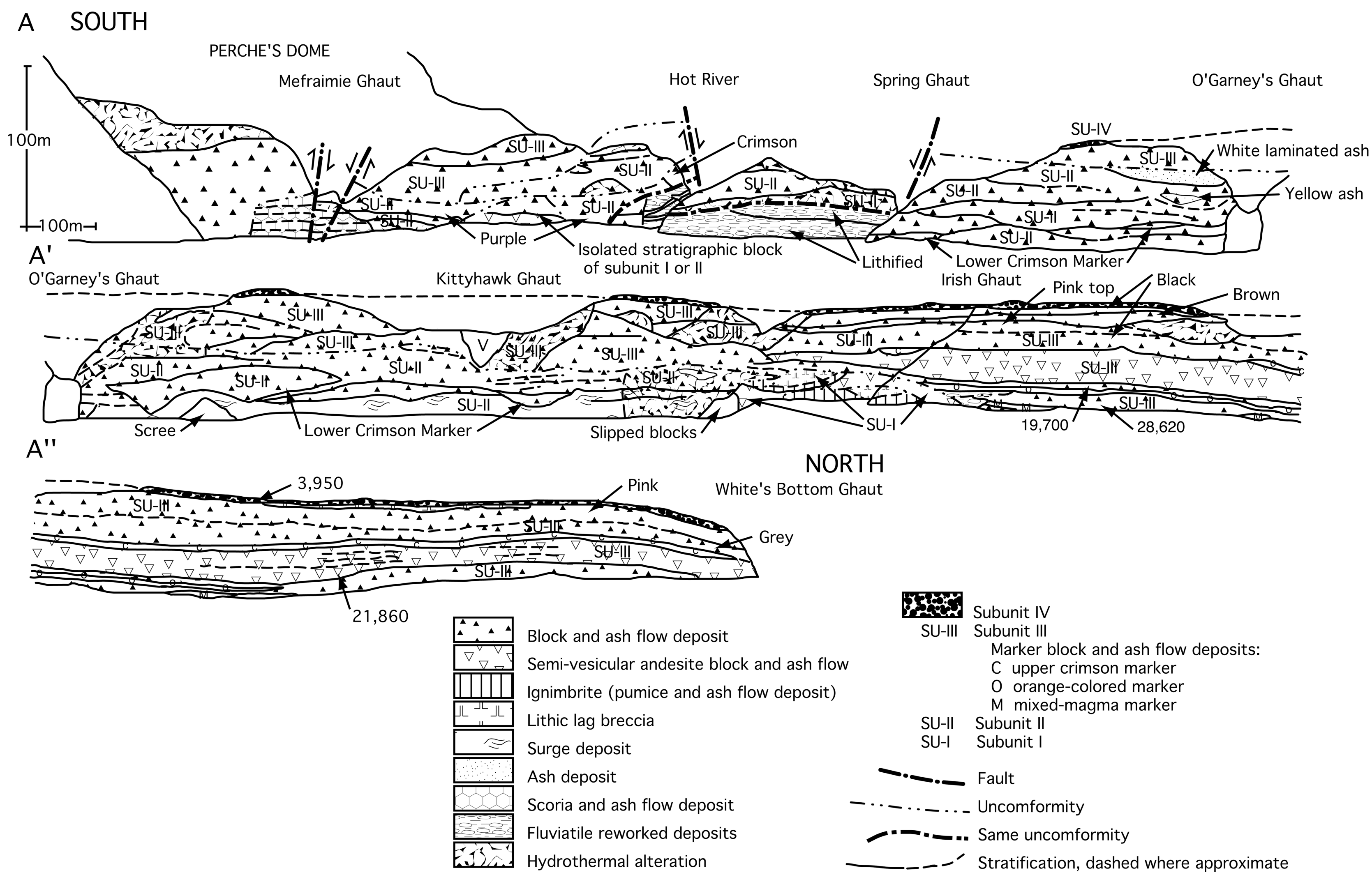


Figure 2. Detailed stratigraphic profile of the 4.6-km sea cliffs between Roche's Bluff and White's Bottom Ghaut as seen from the sea. Irish Ghaut is hidden in this perspective behind a small headland, so it is not seen as a valley on the profile. Note that the profile predates the present eruption and that recent deposits now bury large sections of it. $^{39}Ar/^{40}Ar$ ages from Harford et al. (2002); ^{14}C dates from table 1. (Profile has been modified and expanded from that presented in Roobol and Smith 1998.)

this Pelean episode. The final eruptive products of subunit I (fig. 3*D*) show a return to open-crater Plinian activity with the eruption of pumice and ash flows. The presence of lithic lag breccias in the lowest deposits of this Plinian episode suggests that the upper flanks of the volcano were destroyed during explosive eruptions (Roobol et al. 1987). Because these lag breccias are overlain by ignimbrites, it is probable that open-crater Plinian eruptions continued for some time after this destructive episode.

The 174-ka age obtained from a dense andesite block-and-ash flow deposit in subunit I cannot be correlated with the age of any known dome. We infer that the source for many of the block-and-ash flow deposits in this and other subunits must have been a dome (or domes) that was subsequently destroyed or buried by new eruptions.

South Soufrière Hills (Fig. 3E). The stratigraphy of the SSH is dominated by the presence of scoriaceous lapilli and ash fall, scoria and ash flow, and scoriaceous surge deposits (fig. 6). Other types of deposits, including block-and-ash flows, dense andesite surges, pumiceous lapilli and ash falls, and mudflows, make up only a minor portion of the measured stratigraphies. Within this pyroclastic succession are a number of lava flows, indicating that the SSH has undergone both explosive pyroclastic eruptions as well as effusive eruptions. Some of the lavas appear to have been fed by parasitic dikes rather than to have erupted from the central vent.

In O'Garra's Quarry, the succession is composed of a sequence of scoria and ash flows, scoriaceous surge deposits, and scoriaceous fall deposits, with the latter becoming more abundant upsection. Many of the flow deposits occur as valley fills with irregular lenslike outcrops. Within the succession are a number of local unconformities as well as a single well-developed paleosol, which separates an upper unit of basaltic fall (Rea's Basaltic Cinder Zone), flow, and surge deposits from a lower unit that also contains dense andesite flow and surge, and pumiceous fall deposits (Rea 1974). Interbedded in this pyroclastic succession are at least three lava flows usually characterized by reddened scoriaceous tops and bottoms.

The SSH deposits near Mefraime Ghaut on the east coast can be subdivided into six lithified scoria and ash flow units with intercalated scoriaceous lapilli fall layers similar to the upper unit described from the south coast (fig. 6). The deposits assigned to the SSH are separated from those of the SH by a prominent unconformity. Following the highly explosive phase that produced the Plinian eruptions at the end of subunit I, activity shifted toward the southern flank of the complex with the eruption of the deposits that now form the SSH. These deposits have been $^{39}Ar/^{40}Ar$ dated at 131 ± 7 ka (Landing Bay), 130 ± 5 ka (Roche's Bluff), 129 ± 14 ka (Shoe Rock), 128 ± 17 ka (Roche's Bluff), and 128 ± 27 ka (White River Pyroclastic Fall series; Harford et al. 2002), suggesting that the center was built during a relatively short period of time (2–5 ka) at around 130 ka. The majority of deposits associated with this unit are quite distinct from the deposits erupted before and after, and they mainly represent the products of open-crater St. Vincent–style activity of basaltic/basaltic andesite composition, although a few deposits representing andesitic Pelean- and Plinian-style activity are also present in the lower part of the section. The absence of any stratigraphic discontinuities above and below these latter deposits suggests that they were also erupted from the SSH. The extrusion of the domes of Raspberry Hill probably occurred at the end of the explosive phases.

Soufrière Hills Subunit II (Fig. 3F). SH subunit II, which outcrops only to the south of the ignimbrite paleohill, forms the lower half of the sea cliff section and increases in thickness to the south (fig. 2). This subunit is composed of at least 12 lithified andesitic block-and-ash flow deposits (fig. 4) that locally show yellow and orange areas of hydrothermal alteration. Near Irish Ghaut, a discontinuous outcrop of ignimbrite forms the lowest exposed deposit (fig. 4). From Irish Ghaut south to O'Garne's Ghaut, however, the lowest part of the exposed succession is composed of a thick sequence of andesite surge deposits that are overlain by a discontinuous but prominent crimson block-and-ash flow deposit (lower crimson marker unit; fig. 2).

Between Mefraimie Ghaut and Spring Ghaut at the southern end of the cliff section, subunits I and II are well exposed and overlie two separate paleohills of unknown stratigraphic position (fig. 2). The southern paleohill is composed of block-and-ash flow deposits, some of which contain semivesicular andesite clasts similar to those described from subunit I. The northern paleohill is composed of andesitic fluviatile conglomerates of unknown age.

Subunit II represents a return to Pelean-style activity. The majority of the deposits comprising this subunit represent the products of Pelean-style eruptions, although minor, discontinuous outcrops of ignimbrite do occur locally. Dated deposits within this subunit include Galways dome (112 ka) and a block-and-ash flow deposit exposed in the east coast sea cliffs (75 ka; Harford et al. 2002).

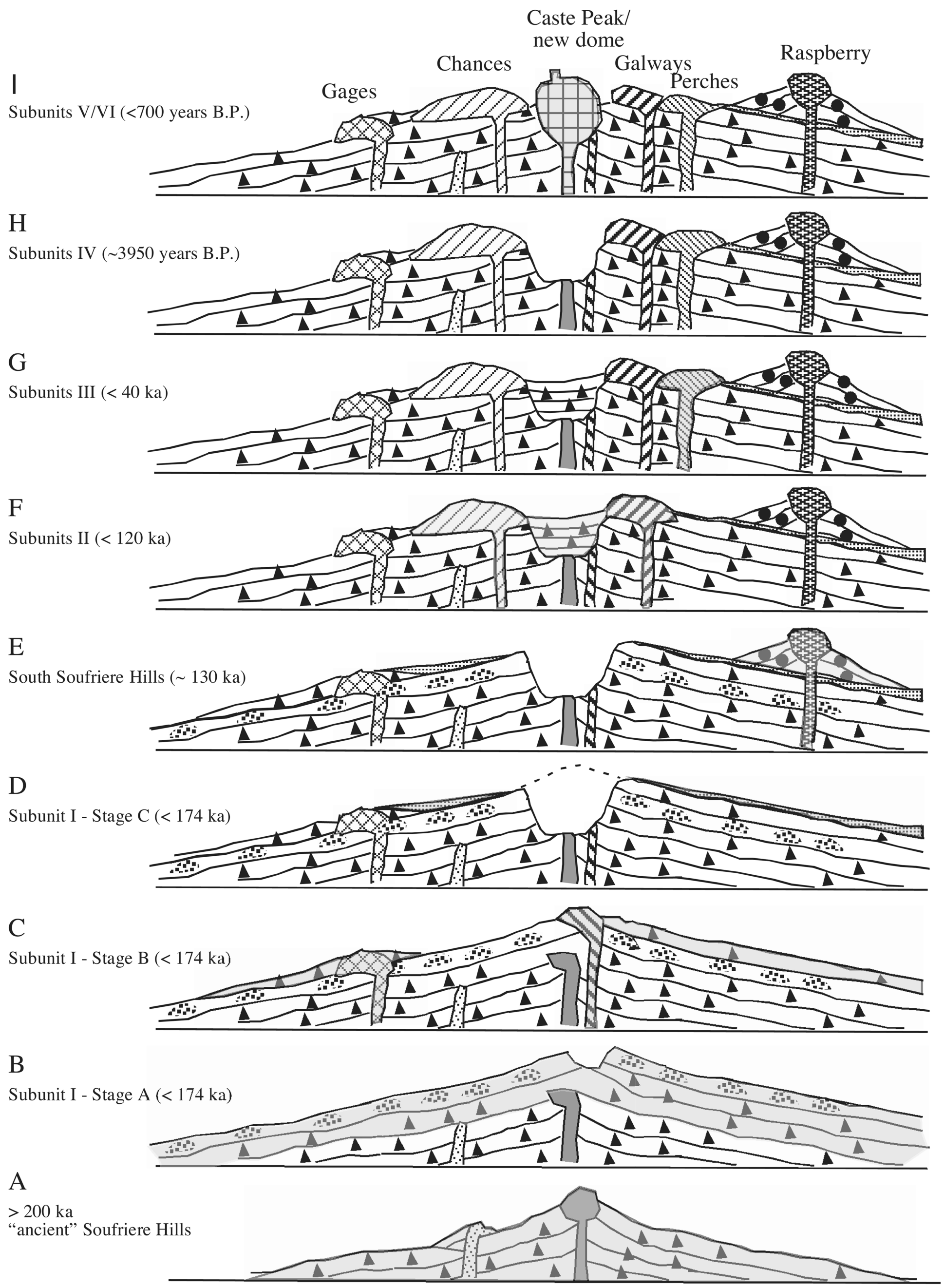


Figure 3. Development of the Soufrière Hills–South Soufrière Hills complex (diagrammatic sections running approximately NW-SE). Deposits produced during a particular stage shown by light shading. *A*, "Ancient" Soufrière Hills (>200 ka). *B*, Soufrière Hills subunit I (≤174 ka) showing open-crater stage during which eruption of ignimbrites occurred. *C*, Soufrière Hills subunit I (<174 ka) showing central dome during Pelean-type eruptions; Gages dome (~151 ka) possibly extruded at this time. *D*, Soufrière Hills subunit I (<174 ka) showing the effects of destruction of upper flanks of volcano as evidenced by occurrence of lithic lag breccias. *E*, South Soufrière Hills (~130 ka) showing development of South Soufrière Hills by eruptions from vent on southern flank of Soufrière Hills. *F*, Soufrière Hills subunit II (<120 ka) showing eruptions dominated by Pelean-style eruptions; probable extrusion of Galways and Chances Peak domes during this period. *G*, Soufrière Hills subunit III (<40 ka) showing evolution dominated by Pelean-style eruptions; extrusion of Perches dome during this period. *H*, Soufrière Hills subunit IV showing effects

Although dominated by Pelean-style eruptions, subunit II also contains three relatively thick pyroclastic fall units (fig. 2). The uppermost deposit is a sequence of five pyroclastic fall layers (from base to top): a brown pumiceous lapilli and ash fall (25 cm thick); two scoriaceous lapilli and ash fall layers with an intermediate ash fall layer (173 cm thick); and a fine-grained lithic ash fall (60 cm thick; fig. 4). This fall sequence overlies an incipient paleosol, and the upper fine-grained lithic ash fall is cut by the prominent unconformity that separates stratigraphic subunit II from stratigraphic subunit III (fig. 4). With the exception of the scoriaceous lapilli and ash fall deposits from the SSH, thick pyroclastic fall deposits are not common in the stratigraphy of this complex. The 500- and 600-cm thicknesses of the lower two fall units suggest that they represent major periods of explosive activity, which is significant when compared with the maximum cumulative thickness of the present eruption (slightly more than 43 cm over a 5-yr period; Bonadonna et al. 2002). The uppermost sequence of fall deposits contains beds of basaltic scoriaceous lapilli and ash similar to the pyroclastic fall deposits of SSH, but their stratigraphic position at the top of subunit II suggests that they most likely are associated with eruptions from SH rather than SSH. The occurrence of these fall deposits suggests the presence of an open crater at the end of subunit II.

Soufrière Hills Subunit III (Fig. 3G). Subunit III is present along the entire 4.6-km sea cliff section and dominates the stratigraphy of the sea cliffs at the north end between White's Bottom Ghaut and Irish Ghaut (fig. 2). It unconformably overlies both older subunits, and its base rises in the sea cliffs toward the south.

Subunit III consists of approximately 20–30 block-and-ash flow deposits with associated surge deposits dipping seaward at angles of 2°–5°. Although dense andesite clasts are the dominant lithic component of the majority of these deposits, in a number of block-and-ash flows, angular and more vesicular clasts, referred to here as semivesicular andesites, are abundant. Where both dense andesite and semivesicular andesite clasts occur in the same deposit, the latter are concentrated at the tops of the flows. In the east coast sea cliffs, the deposits containing semivesicular andesite clasts are especially prominent toward the middle of the section where they form a single distinct horizon (fig. 2). Similar deposits have also been described from outcrops of subunit III from the west coast and from the more poorly exposed northern margin of the SH (fig. 5), suggesting that the SH has erupted semivesicular andesite a number of times during subunit III. These deposits are similar to those produced during the current eruption by the fountain collapse of Vulcanian eruption columns (Cole et al. 2002; Druitt et al. 2002).

Three prominent marker beds can be traced along the cliffs within subunit III. The lowest marker bed exposed near the base of subunit III (fig. 2) is a 100-cm-thick, comingled block-and-ash flow deposit containing rare blocks up to twice the thickness of the deposit. The other two marker beds are an intermediate unit composed of an orange block-and-ash flow deposit and an upper unit formed by a crimson block-and-ash flow deposit. These two marker units form the lower and upper boundaries of the block-and-ash flow deposits containing the semivesicular andesite clasts exposed in the east coast sea cliffs.

Subunit III has yielded 23 radiocarbon ages ranging from 16,630 ± 150 to 31,580 ± 230 BP (table 1; Rea 1974; Baker 1985; Wadge and Isaacs 1988; Young et al. 1996). The lowest marker bed within this subunit has yielded an age of 17,010 ± 60 BP, which is too young for its stratigraphic position near the base of the subunit (figs. 2, 4). This discrepancy can be accounted for only by contamination (Harkness et al. 1994). Two $^{39}Ar/^{40}Ar$ ages (38 ± 8 and 24 ± 1 ka) have also been obtained from this subunit (Harford et al. 2002). The older overlies the lowest marker unit, confirming the age discrepancy. The younger is from a block-and-ash flow deposit that was interpreted by Roobol and Smith (1998) to belong to subunit II. This new age now places this deposit in the overlying subunit III (fig. 2).

Subunit III indicates a return to Pelean-style eruptions following another quiescent period. These block-and-ash flow and associated surge deposits can be subdivided by paleosols and local unconformities into at least five eruptive sequences. The source for at least some of the block-and-ash

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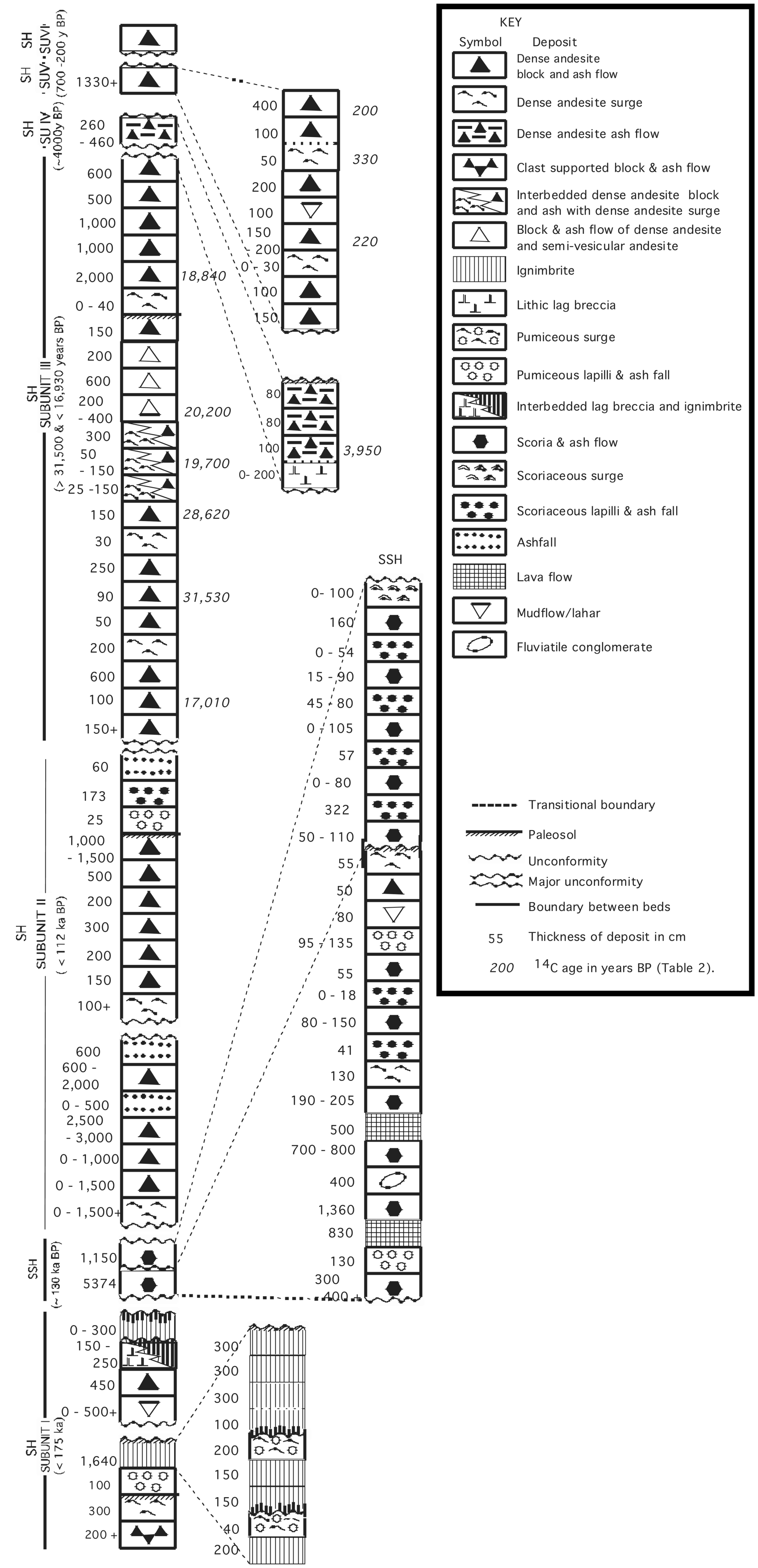
of sector collapse of east flank of edifice to produce English's Crater after eruption of dense andesite ash flows. *I*, Soufrière Hills subunits V, VI (<800 BP) showing extrusion of Castle Peak and new dome and associated pyroclastic deposits.


KEY
Symbol Deposit
Dense andesite block and ash flow
Dense andesite surge
Dense andesite ash flow
Clast supported block & ash flow
Interbedded dense andesite block and ash with dense andesite surge
Block & ash flow of dense andesite and semi-vesicular andesite
Ignimbrite
Lithic lag breccia
Pumiceous surge
Pumiceous lapilli & ash fall
Interbedded lag breccia and ignimbrite
Scoria & ash flow
Scoriaceous surge
Scoriaceous lapilli & ash fall
Ashfall
Lava flow
Mudflow/lahar
Fluviatile conglomerate
Transitional boundary
Paleosol
Unconformity
Major unconformity
Boundary between beds
55 Thickness of deposit in cm
200 14C age in years BP (Table 2).
SH SUV•SUVI (700 -200 y BP)
SH SU IV (~4000y BP)
SH SUBUNIT III (> 31,500 & < 16,930 years BP)
SH SUBUNIT II (< 112 ka BP)
SSH (~130 ka BP)
SH SUBUNIT I (< 175 ka)
SSH
18,840
20,200
19,700
28,620
31,530
17,010
200
330
220
3,950

flows was probably Perches dome, which has been dated at 24 ka BP (Harford et al. 2002).

Soufrière Hills Subunit IV (Fig. 3H). Subunit IV is unique because it is solely composed of dense andesite ash flow deposits. It outcrops as a thin fan extending along the east coast for a distance of 4.5 km from Trant's Bay, north of the Bramble airport (destroyed during the present eruption), south to the Hot River, reaching a maximum thickness of 360 cm between Spanish Point and Irish Ghaut. A similar deposit, believed to be coeval, forms the topsoil along the southwest coast of the island between Gingoes Ghaut and Shooter's Hill, where it reaches a maximum thickness of 150 cm (fig. 1). At its maximum development on the east coast, subunit IV consists of three pyroclastic flow deposits. The lowest flow has a coarse-grained lag breccia of variable thickness that contains angular blocks of dense hornblende andesite up to 50 cm in diameter at its base. In Irish Ghaut, the ash-rich upper part of this lowest flow contains fragments of carbonized wood dated at 3950 ± 70 BP (table 1).

Although the deposits from subunit IV are not well preserved on the upper flanks of the SH, their gravity-controlled paths of descent can readily be inferred from the topographic maps, indicating the probable source area. Both fans appear to originate within what is now the arcuate collapse scar of English's Crater in the vicinity of the buried Castle Peak dome. The distribution of the fans of subunit IV, however, can be explained only if they originated before the formation of English's Crater and from a source at an elevation higher than the present-day Chances Peak, that is, from the summit of the pre–sector collapse volcano.

An indication of the form of this pre–sector collapse volcano can be obtained by projecting back the existing remnant slopes preserved as the northern and southern sides of the present-day volcano and that are now abruptly truncated by the sector collapse scar. We infer that before the sector collapse, the ancient Soufrière Hills was approximately 1200 m high.

Subunit IV is interpreted to have been erupted before the formation of English's Crater; thus, its age of 3950 ± 70 BP provides a maximum age for the formation of the edifice collapse of the SH. The triggering of this sector collapse could have been produced by edifice inflation of the superstructure of the SH (Lipman and Mullineaux 1981) or by the explosive decompression of a pressured dome (Sparks et al. 2002; Voight et al. 2002), with failure localized in regions weakened by hydrothermal activity (Lopez and Williams 1993; Reid et al. 2001). The Tar River and Cow Hill New Soufrières, located on the northern rim of the sector collapse scar, probably represent remnants of the hydrothermally weakened eastern wall destroyed during this collapse. Although debris flow deposits from this sector collapse are not preserved in the east coast sea cliffs, they have been recognized offshore in marine surveys (Deplus et al. 2001). No deposits have been identified between those assigned to subunits III and IV, which implies a 12,000-yr eruption hiatus, although small-volume eruptions might have occurred, and the deposits subsequently may have been removed by erosion.

Soufrière Hills Subunit V (Fig. 3I). Subunit V, the youngest prehistoric pyroclastic deposits on Montserrat, is composed of a succession of thin, fine-grained, ash-rich block-and-ash flow and surge deposits identified only in the Tar and Hot rivers as remnant veneers along the walls of ghauts (sections now buried by the recent pyroclastic deposits). Best exposures were in the lower reaches of the Hot River, near the coast, where a 1.3-m section was measured (fig. 4). The abundant charcoal (logs up to 3 m long) in these deposits yielded radiocarbon ages that range from 435 to 200 BP (table 1; Young et al. 1996). A single age of 770 BP (Young et al. 1996) also probably belongs to this subunit. Age variations suggest that subunit V results from several periods of volcanic activity. The older ages (770 BP, 435–420 BP), including their standard deviations, are definitively before the settlement of the island in 1632 (Fergus 1994) and pose no difficulty in interpretation. The youngest ages (290–200 BP), including their standard deviations, however, do pose a problem, since many yield calendar ages after the settlement of the island. As the source charcoals for all of these young dates are contained within pyroclastic flows and surges, there is no doubt that they are all of volcanic origin. One simple explanation is that an eruption occurred after the island was settled by Europeans but that it went unrecorded. Such an event must, however, have been large enough for pyroclastic flows to reach the coast and thus should have been seen by anyone

Figure 4. Composite stratigraphic section for the South Soufrière Hills–Soufrière Hills complex. (Modified and expanded from Roobol and Smith 1998.)

Table 1. Radiocarbon Ages from Pyroclastic Deposits from the Soufrière Hills Center

Sample number	Location	Measured ^{14}C age (BP)	Conventional ^{14}C age (BP)[a]	Calendar calibrated date[b]	Type of deposit	Stratigraphic unit (subunit)
MN 961-63	Lower Hot Ghaut	200 ± 60	200 ± 60	1670 CE	Block-and-ash flow	V
MN 961-60	Lower Hot Ghaut	220 ± 50	220 ± 50	1665 CE	Block-and-ash flow	V
MN 954-22	Tar River	240 ± 50	240 ± 50	1660 CE	Block-and-ash flow	V
MN 953-2	Tar River	270 ± 50	270 ± 50	1650 CE	Block-and-ash flow	V
MN 954-21	Tar River	290 ± 50	290 ± 50	1645 CE	Block-and-ash flow	V
MN 961-64	Lower Hot Ghaut	330 ± 60	330 ± 60	1525 CE	Dense andesite surge	V
MN 953-27	Tar River	360 ± 50	360 ± 50	1505 CE	Block flow	V
MN 954-15	Tar River	420 ± 50	420 ± 50	1455 CE	Block-and-ash flow	V
MN 961-57	Lower Hot Ghaut	420 ± 50	420 ± 50	1455 CE	Fluviatile reworked block-and-ash flow	V
MN 961-8	Irish Ghaut	3950 ± 70	3950 ± 70	2460 BC	Dense andesite ash flow	IV
MN 961-2	Sea cliffs between White's Bottom Ghaut and Irish Ghaut	17,010 ± 60	16,980 ± 60		Mixed-magma block-and-ash flow	III
MO 10	Dyer's Village	17,670 +1150, −1340			Block-and-ash flow	III
MO 13	White's Estate	18,450 ± 450			Dense andesite surge	III
MO 17	Fort Ghaut	18,600 ± 550			Dense andesite surge	III
MN 961-72	White's Bottom Ghaut	18,840 ± 70	18,820 ± 70		Block-and-ash flow	III
MN 961-14	Sea cliffs between White's Bottom Ghaut and Irish Ghaut	19,700 ± 310	19,700 ± 310		Block-and-ash flow	III
MO 1	Fort Ghaut	19,970 ± 340			Block-and-ash flow	III
MN 95-19A	Sea cliffs between Spanish Point and Tuitt's Bottom Ghaut	20,200 ± 180			Semivesicular andesite block-and-ash flow	III
MO 15	Road to Galways Soufrière	20,800 ± 650			Block-and-ash flow	III
MN 95-33	Sea cliffs between White's Bottom Ghaut and Irish Ghaut	21,860 ± 200			Semivesicular andesite block-and-ash flow	III
MN 961-51	Sea cliffs between White's Bottom Ghaut and Irish Ghaut	28,620 ± 1050	28,620 ± 1050		Block-and-ash flow	III
MN 961-52	Sea cliffs between White's Bottom Ghaut and Irish Ghaut	31,580 ± 230	31,580 ± 230		Block-and-ash flow	III

Note. All ages determined by Beta Analytic, except MN 95-19A and MN 95-33, which were analyzed at the USGS Radiocarbon Lab, Menlo Park, California.

[a] Conventional ^{14}C ages have been calculated after normalization of $^{13}C/^{12}C$ ratios to −25 per thousand.

[b] Calendar calibrated date determined from the intercept of the conventional ^{14}C age with the calibration curve.

on the east coast. The other explanation is that the dated charcoals are contaminated by younger humic acids and microscopic rootlets and thus actually represent an eruption before settlement. Contamination of these samples by younger material might explain the young ages for one or perhaps two of the dated samples. Table 1 shows, however, that five samples from two different localities yielded young ages. Similar young ages were also obtained by other workers who used different dating laboratories. At present there is no satisfactory explanation for these young ages.

In summary, these young dates together with their standard deviations suggest that the SH possibly erupted around 1475 CE and again between 1536 and 1561 CE (average age of 1547 CE), just before the European settlement of the island in 1632 CE (Fergus 1994). This conclusion is supported further by the observation that the first maps of Montserrat show cultivated land almost to the top of the SH (Fergus 1994). Such a distribution is consistent with an eruption just before the settlement of the island because an eruption probably would have destroyed much of the tropical rainforest on the upper slopes of the SH, making the land there easier to clear. Similar examples of agricultural use of recently denuded volcanic areas have been described in Martinique (Smith and Roobol 1990) and Saba (Roobol and Smith 2004).

The deposits of this subunit are petrographically similar to the Castle Peak dome, with which they are probably associated. The apparent absence of any deposits definitively associated with this eruption outside of a very narrow sector of the volcano's eastern flank (within the sector collapse scar) suggests that the Castle Peak eruption, unlike the current eruption, was dominated by the quiet extrusion of a dome with only minor pyroclastic activity.

Soufrière Hills Subunit VI. Subunit VI represents the deposits from the present eruption. These are dominated by block-and-ash flow and associated surge deposits, together with subordinate thin ash and lapilli fall deposits. Some of the flow and surge deposits contain, in addition to dense andesite clasts, abundant clasts of vesicular andesite. These latter deposits were observed to form from fountain collapse of Vulcanian eruptions through the actively growing Pelean dome (Druitt et al. 2002). The deposits from the current eruption blanket all the flanks of the SH. Descriptions of the history of the eruption and its deposits are found in reports by Young et al. (1998) and Druitt and Kokelaar (2002).

Discussion. The stratigraphy of the SH-SSH complex indicates that Pelean-style activity has dominated its eruptive history. The fact that the existing domes (Gages, Chances Peak, Raspberry, Galways, Perches, Castle Peak, and post-1995 domes) are not confined to one site but are located in all sectors of the complex's superstructure (figs. 1, 3), however, suggests that the active vent and, thus, possibly its deeper magmatic pathway have shifted with time. Major unconformities within the stratigraphy, thought to represent significant periods of quiescence, also suggest that volcanic activity probably was not continuous over the >400,000 yr of evolution of the SH-SSH but occurred instead as periods of intermittent activity spanning several thousand years, separated by long periods of dormancy. It is possible that each significant renewal of activity was accompanied by a shift in the position of the active conduit. The active vent/conduit currently is located within English's Crater, and over the last ~700 yr, it has produced Castle Peak dome and the post-1995 domes together with their associated pyroclastic deposits, subunits V and VI. The time period between the end of subunit III (~16,000 BP) and the renewed late prehistoric activity (~800 BP) may be used to estimate the length of quiescence. Although the deposits from subunit IV were formed around 4000 yr ago, these deposits are unique for the SH-SSH and probably do not really signify a reactivation of "normal" activity, so we infer that "typical" activity did not begin until ~800 yr ago. If this interpretation is correct, then the most recent dormant period spanned ~15,000 yr, whereas the preceding active period spanned ~22,000 yr. We conclude from stratigraphy and available radiometric dates that the current active period of intermittent eruptions could last for several thousand years before SH again lapses into another long quiescent period.

Comparison with the Present Eruption

Characteristic features of the present eruption of the Soufrière Hills that began on July 18, 1995, and continues today include (1) multiple episodes of growth and collapse of domes (Watts et al. 2002), (2) generation of dense andesite block-and-ash flows by explosive and gravitational collapse of these domes (Calder et al. 2002; Norton et al. 2002), (3) generation of pyroclastic flows of vesicular andesite by fountain collapse of Vulcanian eruption columns (Clarke et al. 2002; Cole et al. 2002; Druitt et al. 2002), (4) generation of debris avalanche deposits associated with failure of part of the southern flank of the volcano (Voight et al. 2002; Ritchie et al. 2002; Sparks et al. 2002), and (5) generation of relatively thin pyroclastic fall deposits ranging from fine-grained phreatic ashes to thin fall deposits rich in pumiceous lapilli produced by sub-Plinian explosions (Bonadonna et al. 2002).

As this is the first historic eruption of the SH-SSH complex, one may ask how typical of past activity is the present eruption. The growth of domes and the generation of dense andesite block-and-ash flows have dominated the present eruption of the SH. Considering both the abundance of dense andesite block-and-ash flows throughout the stratigraphy of the SH-SSH and the occurrence of older domes such as Gages, Galways, Perches, and Castle Peak, it would appear that dome growth and the production of associated pyroclastic deposits have also been integral parts of essentially all eruptive activity for the SH-SSH complex over its >400-ka history. The only major exceptions were the times when Plinian eruptions from an open crater produced the sequences of ignimbrites in subunit I and the open-crater St. Vincent–style activity associated with the formation of the South Soufrière Hills, although even this activity terminated with the extrusion of the Raspberry Hill domes. Pyroclastic flows of vesicular andesite produced by the fountain collapse of Vulcanian eruption columns have also been observed to form during the present eruption. These deposits are similar to those termed here semivesicular andesite block-and-ash flows, which have been described from subunits I and III, and are particularly abundant in the latter. It is apparent that all of the flow deposits described from the present eruption have their counterparts in the stratigraphic record.

During the present eruption, phreatic explosions, sub-Plinian eruptions, Vulcanian explosions, and dome collapse have all produced fall deposits. All of these deposits are fine grained and ash rich. Similar deposits have not been described stratigraphically. In fact, prehistoric fall deposits are usually coarser, poorer in fine ash, and thicker than those from the present eruption. Thus, although block-and-ash flows similar to those generated by the present eruption dominate the prehistoric stratigraphy of the Soufrière Hills, their associated fall deposits have not been observed. Such differences suggest differences between present and past Pelean-style activity or, more probably, that the thin, fine-grained ashes produced by the present eruption are very susceptible to erosion, so that their prehistoric counterparts have not survived to be incorporated into the stratigraphic record.

Although the present eruption of the SH can be regarded as an example of a Pelean-style eruption, there are notable differences between the present eruption on Montserrat and the eruption of Mount Pelée. For example, during the 1902–1905 and 1929–1932 eruptions, the coarse pyroclastic flows affected only a relatively narrow sector (~30°) of the flanks of Mount Pelée. In contrast, the coarse pyroclastic flows from the present eruption of the SH cover a sector of >270°. The difference in the extent to which the flanks are affected in these two eruptions is very much a result of the morphology of the summit of the volcano. The 1902–1905 and 1929–1932 eruptions of Mount Pelée both formed on the west side of Morne Macouba, which shielded much of the northern and eastern flanks of the volcano from pyroclastic flows. These flows were directed almost exclusively westward because the 1902 and 1929 domes overtopped the rim of the crater. In contrast, the SH eruption has produced a series of domes that have at different times overtopped almost the entire rim of English's Crater, resulting in pyroclastic flows that have descended in many directions. SH-SSH prehistoric eruptions also had areal distributions that appear to have affected most of the volcano's flanks. In summary, the present eruption appears to be very similar to past activity. Differences noted here between the characteristics of Pelean-style eruptions and their deposits on Mount Pelée and those of SH, however, require that hazard assessment for other volcanoes characterized by Pelean-style deposits should be conditioned based on the present eruption of the SH and the generally poor preservation of fine ash fall deposits characteristic of explosive events.

ACKNOWLEDGMENTS

This work was supported by grants from the National Science Foundation (EAR-7717064, EAR-9527273, OEDG-01119934, EAR-0507334); the National Aeronautics and Space Administration (NCC W-0088); the Puerto Rico Power Authority; the University of Puerto Rico; and California State University, San Bernardino. A. Rheubottom, E. Quinones, K. Rowley, and E. Rivera assisted in field and laboratory work, and D. Martinez and J. Fryxell helped in drafting. We especially thank S. Young for showing us the excellent sections in the Hot River. Special thanks go to the Montserrat Volcano Observatory and its staff for essential logistical support, and A. Grouche and J. McMahon are thanked for helicopter support. We would like to dedicate this article to the memory of G. P. L. Walker, who led us into the study of pyroclastic stratigraphy.

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