# 15. OCCURRENCES OF AIR-FALL VOLCANIC ASH DERIVED FROM THE LESSER ANTILLES ARC AT LEG 78A DRILL SITES<sup>1</sup>

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#### ABSTRACT

Air-fall volcanic ash recovered at Deep Sea Drilling Project Sites 541, 542, and 543 on and east of the toe of the Barbados Ridge delineate middle and late Miocene, early Pliocene, and Pleistocene-Quaternary pulses of explosive volcanism in the Lesser Antilles arc. The ash beds at Site 541 allow precise correlation of intervals repeated by a probable reverse fault at this convergent margin.

## **INTRODUCTION**

This chapter briefly summarizes the occurrence of airfall volcanic ash at three sites (541, 542, and 543) drilled during Leg 78A near the deformation front of the Barbados Ridge complex east of the Lesser Antilles arc (Fig. 1). The ashes are important for establishing the timing of explosive volcanism in the arc, heretofore inferred from geological relationships on the islands (dated only in a general way by sparse biostratigraphic data and radiometric ages) and from surface piston cores east of the arc that document Quaternary explosive eruptions (Sigurdsson et al., 1980). In addition, Site 541 demonstrates the usefulness of ash beds in determining precise vertical offsets along high-angle reverse faults at convergent margins such as this where accretion of sediments is occurring.

## **OCCURRENCE AND LITHOLOGY OF ASHES**

Nearly 250 volcanic ash layers up to 7 cm thick were recovered in cores from three sites drilled during DSDP Leg 78A. Most of these ash layers were recovered at Site 541, near the toe of the Barbados Ridge complex (Fig. 1), where a section was cored continuously from the seafloor through Miocene sediments into a complex zone of deformation coinciding with an active décollement at this convergent margin (Site 541 report, this volume). Fewer ash beds were recovered at Site 542, which is only a few kilometers seaward of Site 541. Recovery of sediments of all types was limited here by discontinuous coring above the décollement. At Site 543, the reference site east of the deformation front of the Barbados Ridge (Fig. 1), a condensed Neogene section containing many ash beds overlies Paleogene and Upper Cretaceous pelagic clays, radiolarian muds, and igneous basement. Scattered ash beds occur below the Miocene into the lower Eocene, but these are much more altered to clays than the younger ashes.

Separate ash occurrences, their age, color, and thickness, are listed in Table 1. The thicker ashes commonly have flat bases and bioturbated tops (Fig. 2). Some ashes are gray, others nearly black. Many have high concentrations of plagioclase, lesser quartz, and minor pyroxenes and opaque minerals owing to density-sorting processes in the atmosphere (e.g., Sigurdsson et al., 1980). None shows evidence of being turbidites or even has significant grading of the type that can also be produced by atmospheric processes.

Coring deformation is severe in the topmost cores, especially in the upper 150 m cored at Site 543. Although the continuously cored section at Site 541 is less disturbed by coring, it is complicated by several faults, as documented by nannofossil biostratigraphy (Bergen, this volume). The faults are evidently high-angle reverse faults produced by the general processes of plate convergence, formation of a décollement further down in the section. and sediment accretion (Moore and Biju-Duval, this volume). The presence of ash beds is also obscured along shear zones that are particularly prominent in Cores 25 to 30 and 40 to 50, the latter cores occurring in the vicinity of the décollement (Cowan et al., this volume). Where coring and tectonic disturbance are minimal, as elsewhere at Site 541, ash beds are useful as indicators of precise correlation of units offset along faults. Figure 3 shows the correlation of ash beds and nannofossil zones (Bergen, this volume) between portions of Tectonic Units A and B, which are the principal repeated intervals above the décollement at Site 541 (see Site 541 report, this volume). The ash beds define a vertical offset of 158.5 m at this interval along the fault. This compares well with the estimate of 156 m calculated by Moore and Biju-Duval (this volume) by adding together individual offsets in the nannofossil biostratigraphy determined by Bergen (this volume).

All the ash beds at Sites 541 to 543 are air-fall ashes, because the bathymetric high of the Barbados Ridge complex isolates the sites from submarine pyroclastic turbidites originating at the arc. This high has existed since the Miocene (Westbrook, 1982). Sigurdsson et al. (1980) have shown that the Quaternary Roseau ash was dispersed in the upper atmosphere over 600 km east of its source on the island of Dominica (Fig. 1). I infer a similar general pattern of eruption, atmosphere dispersal, and submarine deposition for all the Leg 78A ashes, al-

<sup>&</sup>lt;sup>1</sup> Biju-Duval, B., Moore, J. C., et al., *Init. Repts. DSDP*, 78A: Washington (U.S. Govt. Printing Office).

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Figure 1. Location of the Leg 78A drill sites, the Lesser Antilles arc, and the Barbados Ridge complex. The divergence between the Limestone Caribbees and presently active arc at the northern end of the chain is also shown. The heavy dotted line gives the distribution of the 1-cm isopach of the Roseau ash east of its source at Dominica (after Carey and Sigurdsson, 1980).

though the direction and extent of ash dispersal are clearly dependent to some extent on climatic factors that have not been constant since the Miocene.

## TEPHROCHRONOLOGY

A combination of information from Site 541 (postmiddle Miocene), Site 543 (pre-middle Miocene), and a Quaternary piston core 50 km east of Martinique (Sigurdsson et al., 1980) document the frequency of explosive eruptions from the Lesser Antilles arc (Fig. 4). Unfortunately, Quaternary cores from Leg 78A are too disturbed by coring to provide information of this type.

Ages were assigned to ash beds using the nannofossil biostratigraphy of Bergen (this volume) for late Miocene and younger sediments, and the radiolarian biostratigraphy of Renz (this volume) for older sediments. Absolute ages for nannofossil zonal boundaries that are listed in Bukry (1975) and radiolarian zonal boundaries listed in Kling (1982) allowed interpolation of ash beds by depth. Fault repetition at Site 541 is accounted for by separately totalling the number of ash beds in each repeated nannofossil zone, and using the larger number (assuming that the discrepancy results from incomplete recovery and/or core disturbance in one of the intervals).

Major pulses of explosive Lesser Antilles volcanism occurred in the early and middle Miocene, the early Pliocene, and the Pleistocene–Quaternary, with possible minor pulses in the late middle Miocene and latest Miocene (Fig. 4). The early-to-middle Miocene pulse is documented from Site 543, which has been moving toward the Lesser Antilles as the North American Plate has converged on the arc. The ashes are thus probably underrepresented compared with locations such as Site 541, which have remained at a fixed distance closer to the arc since the Miocene (neglecting minor effects of section shortening related to accretion; Moore and Biju-Duval, this volume). Nevertheless, the three major pulses of explosive volcanism coincide with those documented by drilling adjacent to circum-Pacific arcs (cf., Kennett and Table 1. Occurrences of Volcanic Ash at Leg 78A drill sites.

Sample occurrence (core-section, cm level)	Age-z	one	Thickness (cm)	Color	Comments
Hole 451					
2-5, 120			?	Black	Smeared out
3-2, 80 and			2	Grav	Blebs
a3-4, 55			2-3	Gray	Smeared out
<sup>a</sup> 4-3, 140		Pseudo-	2-3	Black	Arched
4-7, 50	1.000	emilianna	<1	Gray ?	Bioturbated
5-2, 60	Pleistocene	lacunosa	?	Gray	Blebs
a5-3, 82	TRistovene		2	Grayish brown	Slightly smeared Bioturbated
a8-2, 33			2	Black	Information
8-7, 43		H. selii	1	Gray	Rive I and
9-2, 40-90		C. mac- intyrei	1	Black	Bioturbated
		-Fault			
10-1, 96		H. selii	1	Black	Crystal ash
a12-7, 30		CN12d	3	Gray	Crystal ash
a12,CC		1. 1953 - 1963	5	Black	12 APR 10 APR 10 APR
13-3, 100		CN12b	<1	Gray	3 laminae
15-5, 120			1-2	Gray	Bioturbated
16-1, 50		Church	<1	Gray	Bioturbated
*16-2, 50 16-3, 28	10000	CNIZa	< 0.5	Grav	Bioturoated
16-3, 130	Pliocene		< 0.5	Gray	
16-4, 90	T noccine		< 0.5	Gray	Bioturbated
16-5, 55			<0.5	Gray	Bioturbated
<sup>a</sup> 16-5, 142			7	Black	
<sup>a</sup> 16-6, 3		CN11b	4 <1	Grav	Bioturbated
16-6, 80			i	Citaj	Bioturbated
17-1, 60			2	Black	Tilted
17-2, 100	-		?		Bioturbated
17-5, 60			?		Bioturbated
a17-6, 50			2	Gray	Rioturbated
17-6, 118			0-5	DIACK	Bioturbated
<sup>a</sup> 18-1, 140		CN11a	7	Black	Tilted
18-2, 90 a18-2, 135			7	Black	Bioturbated
18-4, 35			?	Diate	Bioturbated
18-4, 65			?		Bioturbated
18-5, 55	early		2	Black	Bleb
19-1, 40	Pliocene	CN10c	1	Black	
19-6, 115		CN10b	1-2	Gray	Dispersed by burrowing
a20-1, 119		raun	7	Black	ourioning
<sup>a</sup> 20-3, 15			4	Black	Description
20-3, 77		CNIIa	1-2	Grav	Bioturbated
20-6, 135			?		Bioturbated
20-7, 3			?	Gray	Bioturbated
22-3, 70		CN10c	1-2	Gray	Bioturbated
a22-4, 18		- Fault	2	Gray	Bioturbated
23-2, 80 a23-5 40		CN9b	2	Gray	Bioturbated
25-4, 12			?	Gray	Swirled and mixed
27-1, 90		Deserve	?		Bioturbated
27-2, 80		Barren	2		Bioturbated
27-5, 28			?		Bioturbated
27-6, 140			?		Bioturbated
a28-3, 70		CN9a	10	Gray	Partially bioturbated
29-3, 145	late		?		Disturbed by rotation
29-5, 75	Phocene	CN9b	2	Black	Burrowed
30-3, 45			?		
31-5, 30			?	Black	Bioturbated Disturbed
32-1, 150		CN12a	?	Diack	Bioturbated
32-4, 20-50		Small	?		Bioturbated zone
32-5, 110 a32-6 143		-fault	25	Grav	Bioturbated top
33-3, 80			?	only	Bioturbated
<sup>a</sup> 33-3, 135			4	Black	
33-4, 7		CN11b	2	Black	Bioturbated
33-4, 65			?	Black	1-cm bleb
<sup>a</sup> 33-5, 20			Several	Gray	
34-1, 35-50			?	Gray	Mixed zone
34-1, 90			?	12492350	Bioturbated
34-2, 25			?		Bioturbated
34-3, 25		1	?		Bioturbated
34-3, 40	carly		?		Bioturbated
34-3, 63	Pliocene		2		Bioturbated
34-4, 134		CNI1a	?		Bioturbated
34-5, 15 a34-5, 75		100000	6	Black	Tilted
0.000 B.000 B.0000 B.000 B.000 B.000		1	07/1	0.5676235-0	

Table 1. (Continued).

Hole 451 (Cont.)     3 344, 50 354, 60 355, 160 355, 160 355, 160 355, 160 355, 160 355, 140 357, 160 357, 160 364, 61, 21 414, 55, 74 414, 55, 74 414, 55, 74 414, 55, 74 414, 55, 74 414, 55, 74 415, 257 414, 257, 100 445, 100 40, 100 40	Sample occurrence (core-section, cm level)	Age	-zone	Thickness (cm)	Color	Comments
344, 60       3       Black       Bioturbated top, tilled $351, 60$ 7       Bioturbated       Bioturbated $351, 60$ 7       Bioturbated       Bioturbated $351, 40$ 7       Bioturbated       Bioturbated $351, 40$ 7       Bioturbated       Bioturbated $374, 62$ Miscore       7       Biack       Bioturbated $374, 62$ Miscore       6       Biack       Bioturbated       Bioturbated $374, 62$ Miscore       7       Biack       Bioturbated       Bioturbated       Bioturbated $414, 52, 74$ 0       Barren       1       Green is program       Altered       Altered $444, 62$ early       C. counde       -1       Green is program       Altered $453, 56, 617$ 0       0       7       Biack       Biack       Biack $41, 12, 109$ early       7       Green is program       Altered       Altered $41, 12, 29, 00.00$ 0       CN11a       Green is program       Bioturbated       Bioturbated $31, 39, 64$ early       1       Green is program       Bioturba	Hole 451 (Cont.)				- 00M1071*,	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	a34-6, 50			3	Black	Bioturbated top, tilted
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	34-6, 90			?		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	35-1, 45			?		Bioturbated
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	35-1, 150			ż		Bioturbated
373, 60	35-3, 44		Childre	?		Bioturbated
473.4, 82       3       Greenish prov       Black       Black       Black       Black       Black       Black       Industried full         413.5, 36       413.5, 36       6       Black       Alty moditione         443.5, 30       -       -       -       -       -       -       Alty moditione       -	35-5, 70	8000	CNIOC	1	Grav	Bioturbated
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	a37-4, 82			3	Greenish gray	
3/36, 62, 62, 74, 73, 76         Miscene         Crow         6         Black         Industried furf           441, 35, 70         1         6         Black         Biourbated core         Biourbated core           443, 37, 70         1         Barren         1         Minuted furf         Biourbated core           443, 37, 70         1         Barren         1.5         Black         Ashy modione           443, 30         45, 94         1.5         Black         Ashy modione         Ashy modione           443, 101         extry         C. costade         -1         Gray         Altered           493, 101         extry         C. costade         -1         Gray         Altered           944, 131         molecair         7         Gray         Sheard out and dispersed           943, 90-60         9         S. def.         -1         Biourbated         Biourbated           11, 12-130         7         Gray         Biourbated         Biourbated         Biourbated           11, 12-130         7         Gray         Dispersed         Biourbated         Biourbated           11, 12-130         2         Gray         Dispersed         Biourbated         Biourbated	<sup>437-5,76</sup>	late	CNOb	4	Black	Ricturbated
404, 35-75 414, 35-76 415, 35-74 415, 36-74 415, 36-74 415, 112, 119 50-3, 40 50-3, 30-65         Barcen 2 2 2 2 35, 46-7 1 5, 46-7 1 5, 46-7 1 5, 46-7 1 7 2 1, 122-150 11-1, 122-150 11-	a38-6, 62	Miocene	CINO	6	Black	Indurated tuff
11-1, 20-7, 43-5, 106-110         Description         Barren         Bick         Biddrated turf Biotributed Jone 1           43-5, 106-110         Barren         2         Black         Ashy muditione           43-5, 106-110         Barren         2         Black         Ashy muditione           43-5, 106-110         Barren         2         Black         Ashy muditione           43-5, 107         extry         C. costande         -1         Gray         Altered           49-3, 102         extry         C. costande         -1         Gray         Sheard out and dispersed           90-3, 00-65         s. def.         -1         Gray         Sheard out and dispersed           11-1, 122-10         S. def.         -1         Gray         Black         Block           1-1, 122-10         CN11a         2         Gray         Block         Block         Block           1-1, 122-10         CN11a         2         Gray         Dispersed         Dispersed           1-2, 130-140         CN10c         -2         Gray         Dispersed         Dispersed           1-3, 5-50         cray         Dispersed         -3         Gray         Dispersed           1-3, 5-90         cray         <	40-4, 55-75			?		Bioturbated zone
43.5, 100-110       Barren       1       Tur       Ady mudstone         43.5, 100-110       Barren       2       Black       Ady mudstone         43.5, 100-110       Barren       2       Black       Altered         43.5, 100-110       C. costade       -1.5       Black       Altered         43.5, 100-110       Miccene       -1.5       Black       Altered         44.4, 12, 12, 113       Miccene       -1.5       Shared out and dispersed         50.3, 40       S. def.       7       Steared out and dispersed         1-1, 122-150       7       Gray       Smared out and dispersed         1-1, 122-150       7       Gray       Bisturbated top         1-1, 122-150       7       Gray       Dispersed         1-2, 130-140       0       1       Gray       Dispersed         1-4, 44-8       early       4       Black       Bioturbated top         1-1, 122-130       -2       Gray       Dispersed       1         1-1, 2-2       -2       Gray       Dispersed       1         1-2, 130-140       1       Gray       Dispersed       1         1-1, 12-2       Gray       Dispersed       1       1	*41-3, 20		CN9a	5	Black	Indurated tuff Bioturbated zone
ats. b0-110       Barren       Aday mudstone $435, 80$ 15       Black       15 $435, 80$ 15       Black       Altered $493, 40$ 64, 70       Altered       Altered $494, 10$ Miscene       -1       Gray       Altered $933, 30-65$ 5. def       -1       Sheared out and dispersed $933, 30-65$ 5. def       -1       Sheared out and dispersed $914, 152, 150$ 5. def       -1       Sheared out and dispersed $11, 122-150$ 5. def       -1       Black       Biourbated top $11, 122-150$ 5. def       -1       Gray       Biourbated top $11, 122-150$ -5       CrN1a       Crorey       Dispersed $21, 0+3$ early       4       Black       Biourbated top $12, 125$ CrN1a       Crorey       Dispersed       22 $23, 133-134$ -1       Gray       Dispersed       23 $31, 222, 22$ CrN10b       1       Gray       Dispersed $23, 133-134$ Iate       CrN2b       Co       Gray       Dispersed	43-5, 70		City	i		Tuff
493, 56 493, 115 494, 80 494, 82 494, 82 412, 190-100 812, 90-100 812, 90-100 812, 90-100 812, 90-100 812, 90-100 813, 55-64 812, 190-180 812, 190-18	43-5, 106-110		Barren			Ashy mudstone
	48-5, 56		-	2	Black	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	48-5, 147			1.5	Black	
49-4, 82 49-5, 82 49-5, 812, 119 50-3, 40         Miccent Second Second Second 19-1, 15-20         C. total Mice 5. def. montensi         C. total T T T T T T T T T T T T T T T T T T T	49-3, 40		C costada	<1	Genv	Altered
494, 82 903, 80-05       modelse $\frac{1}{5}$ , $del^2$ $\frac{1}{1}$ , $125-001-1, 122-1301-2, 133-1341-1, 122-1321-2, 123-1341-3, 134-1411-3, 130-1321-3, 130-1311-3, 130-1311-3, 130-1311-3, 130-1311-3, 130-1311-3, 130-1321-3, 130-1311-3, 130-1311-3, 130-1311-3, 130-1311-3, 130-1321-3, 130-1311-3, 130-1311-3, 140-1411-3, 130-1321-3, 130-1311-3, 130-1321-3, 130-1311-3, 130-1321-3, 130-1311-3, 140-1411-3, 150-1311-3, 140-1411-3, 150-1311-3, 140-1411-3, 150-1311-3, 140-1411-3, 150-1311-3, 140-1411-3, 150-1311-3, 140-1411-3, 150-1311-3, 150-1$	49-4, 70	early	C. COMMU	<1	Gray	Altered
abs. 112, 119       State       State       Sheared out and dispersed         303, 40 $\overline{S}$ , $del^2$ $\overline{r}$ Sheared out and dispersed         104, 520 $\overline{r}$ $\overline{r}$ $\overline{r}$ Sheared out and dispersed         114, 122-150 $\overline{r}$ $\overline{r}$ $\overline{r}$ $\overline{r}$ $\overline{r}$ 12, 130-140 $\overline{r}$ $\overline{r}$ $\overline{r}$ $\overline{r}$ $\overline{r}$ 14, 44-8       early       1 $\overline{r}$ $\overline{r}$ $\overline{r}$ $\overline{r}$ $\overline{r}$ 14, 44-8       early       1 $\overline{r}$ <	49-4, 82	Miocene		<1	Gray	Altered
50-3, 50-65     moment     ?     Sheared out and dispersed       *1-1, 12:-150     7     Gray     Smeared out       *1-1, 12:-150     3     Black     Bioturbated       *1-2, 130-140     CN11a     2     Gray     Bioturbated top       *1-4, 20-100     *1-4, 4-44     early     4     Black     Bioturbated top       *1-4, 70-8     *2-1, 6-8     *2-2     Gray     Dispersed       *2-2, 88-92     -2-2     Gray     Dispersed       *2-2, 88-92     -2-2     Gray     Dispersed       *2-2, 88-92     CN10c     -2     Gray     Dispersed       *2-3, 39-40     1     Gray     Dispersed     Dispersed       *3.3, 38-55     CN10b     1     Gray     Dispersed       *1, 40-41     late     CN10b     -7     Gray     Dispersed       *1, 40-111     late     CN10b     -7     Gray     Dispersed       *1, 30-31     early     CN10b     -1     Gray     Dispersed       *1, 30-41     Biot     CN10b     -1     Gray     Dispersed       *1, 40-41     Biack     -7     Gray     Dispersed       *1, 30-31     early     CN10c     1     Gray     Dispersed <td< td=""><td>49-5, 112, 119</td><td></td><td>S del-</td><td>~1</td><td></td><td>Sheared out and dispersed</td></td<>	49-5, 112, 119		S del-	~1		Sheared out and dispersed
Hole 542         7         Gray         Smeared out           81-1, 15-20         7         Gray         Smeared out         Bioturbated           81-2, 90-100         81-3, 55-65         81         Bioturbated, dispersed         Cirginality         Bioturbated, dispersed           81-4, 84-86         early         1         Gray         Dispersed         Bioturbated, dispersed           82-1, 0-8         early         1         Gray         Dispersed         Dispersed           82-1, 0-8         early         1         Gray         Dispersed         Dispersed           82-2, 88-92         CN106         2         Gray         Dispersed         Dispersed           32, 38-65         CN106         1-2         Gray         Dispersed         Dispersed           33, 38-65         CN106         1-2         Gray         Dispersed         Dispersed           14, 140-141         Miccene         CN36         CGray         Dispersed         Dispersed           14, 38-59         CN106         CN106         CGray         Dispersed         Dispersed           14, 140-141         Miccene         CN96         C.1         Gray         Dispersed           14, 140-141         Miccene	50-3, 50-65		montensi	2		Sheared out and dispersed
Bi-1, 15-20         7         Gray         Smeared out Bioturbated, dispensed           1-1, 122-150         3         Black         Bioturbated, dispensed           1-2, 130-100         3         Black         Bioturbated, dispensed           1-1, 152-150	Hole 542	-				
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	81.1.15.00			-		
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	-1-1, 15-20 1-1, 122-150			7 Several	Gray	Smeared out Bioturbated
*1-2, 30-100 *1-3, 35-65 *1-4, 44-48 *1-4, 140-141 *1-2, 47-78 *1-2, 47-78 *1-2, 47-78 *1-2, 47-79 *1-2, 47-79 *				small?		
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	a1-2, 90-100 a1-2, 130-140		Chille	3	Black	Bioturbated top
a) -3, 53 - 65 a) -4, 44 -86 c) -4, 14 -46early Plicocne-1 4Black 4Bioturbated top Dispersed $3-1, 64$ a) -2, 188 -21 a) -2, 188 -21 c) -2, 133 -134 -3, 23, 133 -134 -3, 23, 133 -134 -3, 23, 133 -134 -3, 23, 38 -65 -3, 33, 88 -65 -41, 40 -41 -41, 120 -121 -41, 120 -121 -41, 40 -41 -41, 40 -41 -41, 40 -141CN10b -7<	1-2, 130-140		CIVITA	(originally)	Gray	Bioturbated, dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	a1-3, 55-65			10	Black	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	<sup>a</sup> 1-4, 44-48	early		4	Black	Bioturbated top
	a2-1, 0-8	Photene		>3	Gray	Dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	a2-2, 88-92			>2	Gray	Dispersed
23. 133-1241GrayDispersed31. 20-22 $1-2$ GrayDispersed32. 94-95 $3-3$ , 38-65 $7$ GrayDispersed33.3, 58-65 $7$ GrayDispersed41. 40-41late $<0.5$ GrayDispersed41. 40-41MioceneCN9b $<0.5$ GrayDispersed41. 40-41MioceneCN9b $<0.5$ GrayDispersed43. 140-111 $<10$ $<10$ GrayDispersed12. 130-131 $=arly$ CN11 $<1$ GrayDispersed13. 90-91 $<1$ GrayDispersedDispersed13. 90-91 $<1$ GrayDispersed13. 90-91 $<1$ GrayDispersed24. 130-132 $<1$ CN10c1224. 130-132 $<1-2$ GrayDispersed25. 70-75 $<1$ GrayDispersed24. 130-132 $<1-2$ GrayDispersed3.2, 25-26 $<0.5$ GrayDispersed3.2, 25-26 $<0.5$ GrayDispersed3.4, 51-20Miocene $<10$ GrayDispersed3.4, 51-21 $<0.5$ GrayDispersed3.4, 51-21 $<0.5$ GrayDispersed10. 4, 55-56 $<0.5$ GrayDispersed10. 4, 55-56 $<0.5$ GrayDispersed10. 4, 55-56 $<0.5$ GrayDisturbed10. 4, 55-56 $<0.5$ GrayDisturbed10. 52early $<0.5$ <	2-2, 120-125		CNIOC	>2	Gray	Dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	2-3, 133-134			î	Gray	Dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	3-1, 20-22		Church	1-2	Gray	Dispersed
4-1, 40-41 4-1, 120-121 4-3, 140-141       Inte Miocene       CN9b       <0.5	a3-2, 94-95 a3-3, 58-65		CN10b	7	Gray	Dispersed Bioturbated top
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	4-1, 40-41	late	1000	< 0.5	Gray	Dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	4-1, 120-121	Miocene	CN9b	< 0.5	Gray	Dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Hole 547.4	-		20.5	Olay	Dispersed
1-1, 38-39          1.5       Dispersed         1-3, 38-41       Pliocene        CN11        1.6       Gray       Dispersed         1-5, 20           CN10       Cl       Gray       Dispersed         1-5, 20           CN10       Cl       Gray       Dispersed         1-2, 30-42        CN10       12       Gray       Dispersed           22, 110-111          CN10       Cl       Gray       Dispersed           24, 150-132        1-2       Gray       Dispersed                 Gray       Dispersed	11.00.00				<u> </u>	<b>D</b>
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	1-1, 58-59			<1	Gray	Dispersed
a1-3, 38-41 $cmry$ Pliocene2Gray CN10cBioturbated1-3, 90-91 $cmry$ $cmry$ $cmry$ Pliocene $cmry$ CN10c $cmry$ Black $cmry$ Disperseda1-5, 40-52 $cmry$ $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene2-3, 90-42 $cmry$ $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene2-3, 70-75 $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene3-5, 140-141 a+41, 130-132 $ate$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene3-5, 140-141 a+41, 130-132 $ate$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene3-5, 140-141 a+41, 130-132 $ate$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene3-5, 140-141 a+4, 36-36 $ate$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene3-6, 453 $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene3-3, 85-110 $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ Pliocene $cmry$ <b< td=""><td>1-2, 130-131</td><td>corly</td><td>CN11</td><td>&lt;1</td><td>Gray</td><td>Dispersed</td></b<>	1-2, 130-131	corly	CN11	<1	Gray	Dispersed
1-5, 20-31 a 1-5, 40-52 a 1-5, 40-52 $< 1$ CN10cCiray 12 Gray 10 Gray 1-2 Gray 1-2 Gray 1-2 Gray DispersedDispersed Dispersed2-4, 130-132 2-4, 130-132 2-6, 70-75 3-1, 112-113 3-5, 130-131 3-5, 140-141 4-1, 130-1321-2 1-2 (Gray (Gray) (Gray) 7 (Gray) 7 (Gray) 7 (Gray) 7 (Gray) 7 (Gray) 7 (Gray) 7 (Gray) 7 (Gray) 10 SipersedDispersed (Dispersed) (Gray) Dispersed	a1-3, 38-41	Pliocene		2	Gray	Bioturbated
a) 1.5, 40-52 a) 2.2, 30-42CN10c12Gray 10Bioturbated top Gray $2,2, 110-111$ $2,4, 130-132$ -12Gray $1-2$ Dispersed $2,4, 130-132$ $2,5, 70-75$ 1-2Gray $1-2$ Dispersed $2,4, 130-132$ $3-2, 25-26$ -1-2Gray $1-2$ Dispersed $3,2, 25-26$ $3-2, 83-93$ -1Gray $1-2$ Dispersed $3,4, 12,5-30$ $4+1, 125-30$ $4+1, 130-132$ Iate MioceneCN9aC.16Gray $2-3$ Dispersed $3,4, 10-111$ $10+10-12$ Iate $4+3, 52-36$ CN9aC.17Gray $2-3$ Dispersed $3,4, 52-36$ $4+1, 130-132$ MioceneCN9aC.3Gray $2-3$ Dispersed $4+3, 52-30$ $4+3, 52-36$ MioceneCN9aC.3Gray $2-3$ Dispersed $4+4, 36-36$ $4+4, 36-36$ CN9aC.3Gray $2-3$ Dispersed $4+4, 36-36$ $4+4, 36-36$ CN9aC.1Gray $2-3$ Dispersed $10-4, 42-46$ $10-4, 42-46$ C.5Gray $2-23$ Dispersed $10-4, 42-46$ $10-4, 52-223$ C.5Gray $2-2-3$ Disturbed $10-5, 22-23$ CCGray $2-2-3$ Disturbed $10-5, 22-23$ C25Olive gray $3-3, 85-110$ Ashy mud $2$ $3-4, 50-80$ $3-4, 50-80$ C25Olive gray $3-30$ Ashy mud $3-3, 85-110$ Cmac- $3-3$ 30Olive gray $3-30$ Ashy mud $3-4, 50-80$ $3-4, 595-100$ C2	1-5, 20			<1	Black	Dispersed
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	a1-5, 40-52		CN10c	12	Gray	Bioturbated top
2-4, 10-11C, 1OrayDispersed2-4, 130-1321-2GrayDispersed2-5, 70-751-2GrayDispersed2-6, 70-75-7GrayDispersed3-1, 112-113<0.5	<sup>a</sup> 2-2, 30-42			10	Gray	Top bioturbated
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	2-4, 55-57			1-2	Gray	Dispersed
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	2-4, 130-132			1-2	Gray	Dispersed
3-1, 112-113     3-1, 112-113     C1.5     Gray     Dispersed       3-2, 25-26     3-2, 25-26     -0.5     Gray     Dispersed       3-2, 83-93     7     Gray     Dispersed       3-5, 130-131     -0.5     Gray     Dispersed       3-5, 140-141     late     -0.5     Gray     Dispersed       4-1, 25-30     Miocene     -2.3     Gray     Dispersed       4-1, 36-36     -2.3     Gray     Dispersed       4-4, 36-36     -2.3     Gray     Dispersed       4-4, 36-36     -2.3     Gray     Dispersed       4-4, 36-36     -2.5     Gray     Dispersed       -4, 12-121     -0.5     Gray     Dispersed       -5, 21-221     -0.5     Gray     Dispersed       -64, 52-56     -0.5     Gray     Dispersed       10-4, 62-46     -2.2     Gray     Disturbed       10-4, 52-26     -2.5     Gray     Disturbed       10-4, 52-223     -2.5     Gray     Disturb	2-5, 70-75			7	Gray	Dispersed
3-2, 25-26        <0.5	3-1, 112-113			<0.5	Gray	Dispersed
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	3-2, 25-26			< 0.5	Gray	Dispersed
3-5, 130-131        Small?)         3-5, 140-141       late       <0.5	3-2, 83-93			(several	Gray	Disperseu
$\begin{array}{c c c c c c c c c c c c c c c c c c c $				small?)		
A-1, 23-30 A-1, 23-300 A-1, 23-30 A-1,	3-5, 130-131			< 0.5	Gray	Dispersed
4-1, 130-132       Misocene       <2	a4-1, 25-30	late	CN9a	2-3	Gray	Top dispersed
44, 36-36     <0.5	4-1, 130-132	Miocene	1000000	<2	Gray	Dispersed
3-4, 10-111     C. 33     Gray     Dispersed       10-4, 42-46     <1	4-4, 36-36			<0.5	Gray	Dispersed
10-1, 0-2     <1	5-4, 110-111			<0.5	Gray	Dispersed
10-4, s-2-60     <2	10-1, 0-2			<1	Gray	Dispersed
10-4, 77-79     CV.J.     Onay     Disturbed       10-5, 22-23      <0.5	10-4, 42-46			<2	Gray	Disturbed
10-5, 22-23     <0.5	10-4, 77-79			<0.5	Gray	Disturbed
Iole 453     Sections 1 and 2 have vitric mud representing concentrated ash be disturbed by drilling. Sections 5 7 have dispersed lumps of ash in disturbed vitric-mud matrix.       2     early Pleistocene     Disturbed wirric-mud matrix.       3     early Pleistocene     Disturbed wirric-mud matrix.       3-3, 85-110     25     Olive gray 3-4, 50-80       3-4, 50-80     early early     25       3-4, 50-80     early early     C. mac- intyrei       3-4, 50-80     early early     C. mac- intyrei       3-4, 132-118     Pleistocene     Ashy mud intyrei	10-5, 22-23			< 0.5	Gray	Disturbed
1     early Pleistocene     Sections 1 and 2 have vitric mud representing concentrated ash be disturbed by drilling. Sections 5 7 have dispersed lumps of ash in disturbed vitric-mud matrix.       2     early Pleistocene     Disturbed vitric-mud matrix.       3     early Pleistocene     Disturbed vitric-mud matrix.       3-3, 85-110     25     Olive gray 3-4, 50-80       3-4, 50-80     early early Pleistocene     25       3-4, 50-80     early early 1/3-4, 95-100     C. mac- intyrei       3-132-118     Pleistocene     Intyrei	Hole 453					
Pleistocene 2 early Pleistocene 3 early 3-3, 85-110 3-4, 50-80 3-4, 50-80 4-5 5 C. mac- 5 0 live gray 3-6 10 live gray 10 live gray	1	early				Sections 1 and 2 have vitric mud
2     early Pleistocene early 3-3, 85-110     25     Olive gray 3-4, 50-80     Disturbed vitric-mud matrix. Disturbed humps of ash in a vitric mud matrix. Disturbed through Section 2.       3-3, 85-110     25     Olive gray 3-4, 95-100     Ashy mud Ashy mud ashibit response Dive gray ashibit response Dive gray ashibit response Ashy mud ashibit response Ashy mud		Pleistocene				representing concentrated ash beds disturbed by drilling. Sections 5 to 7 have dispersed lumps of ash in a
Pleistocene early Pleistocene     mud matrix. Disturbed through Section 2.       3-3, 85-110     25     Olive gray     Ashy mud       3-4, 50-80     early     C. mac- intyrei     30     Olive gray     Ashy mud       3-4, 52-138     Pleistocene     intyrei     30     Olive gray     Ashy mud	2	carly				disturbed vitric-mud matrix. Disturbed lumps of ash in a vitric
3     early Pleistocene     Disturbed through Section 2.       3-3, 85-110     25     Olive gray     Ashy mud       3-4, 50-80     early     C. mac-     30     Olive gray     Ashy mud       3-4, 95-100     early     C. mac-     5     Olive gray     Ashy mud       3-4, 51-21,28     Pleistocene     intyrei     3     Olive gray     Ashy mud		Pleistocene				mud matrix.
3-3, 85-110     25     Olive gray     Ashy mud       3-4, 50-80     early     C. mac-     30     Olive gray     Ashy mud       3-4, 95-100     early     C. mac-     5     Olive gray     Ashy mud       3-5, 132-138     Pleistocene     intyrei     3     Olive gray     Ashy mud	3	Pleistocene				Disturbed through Section 2.
3-4, 50-80 early C. mac- 30 Olive gray Ashy mud 3-4, 95-100 early C. mac- 5 Olive gray Ashy mud 3-5, 132-138 Pleistocene intyrei 3 Olive gray Ashy mud	3-3, 85-110	2 resolution		25	Olive gray	Ashy mud
3-5 132-138 Pleistocene intyrei 3 Olive gray Ashy mud	3-4, 50-80	early	C. mac-	30	Olive gray	Ashy mud
5 Onve kiay Asny mud	3-5, 132-138	Pleistocene	intyrei	3	Olive gray	Ashy mud

Table 1. (Continued).

Sample occurrence (core-section, cm level)	Age	-zone	Thickness (cm)	Color	Comments
Hole 453 (Cont.)			6.50	2. 9. 29. 1986	
3.6.15			- 2	Olive area	Ashu mud disturbed
4-1, 40-45			3-4	Olive gray	Disturbed lump
4-1, 55-61			3?	Olive gray	Disturbed lump
4-1, 73-9		]	5-7	Olive gray	Disturbed lump
4-2, 15-25			5?	Olive gray	Disturbed lump
4-3, 140 to			5?	Olive gray	Very disturbed
4-4, 20		CNI2d	12.5	+ g,	
4-4, 120		CIVIZU	2	Olive gray	Disturbed
4-5, 20-40	late		7	Olive gray	Disturbed ashy mud
4-5, 95-100	Pliocene		2	Olive gray	Ashy mud
4-6, 20-30	(2010)01000		?	Olive gray	Disturbed lump
4-6, 139-142			2	Olive gray	Ashy mud
4-6, 147-150			7	Ofive gray	Ashy mud Has dispersed lumps of ash in highly
		CN12b			deformed Sections 1 and 2.
6-6, 125			<1	Dusky yellow	Disturbed
-		CN12a		green	Has dispersed lumms of ach in highly
1		0.50000000			deformed mud in Section 1.
a7-3, 113-116			2-3	Very dark	Bed
1299 DU 010000000000000000000000000000000000			44004	gray	
8-1, 40-50			?	Olive gray	Ashy mud
a <sub>8-1</sub> 148-150			22	Olive gray	Lump
0-1, 140-150			21	black	Cump
<sup>a</sup> 8-2, 8-10	late		1-2	Brownish	Curved bed
9	to early	Forams		black	
a8-2, 90-95	Pliocene	N17-N20	4-5	Brownish	Bed
8-1 5-10			2	Olive grav	Ashy mud
8-3, 20-90			Several	Olive gray	Lumps of ash this interval
8-5, 82-85			?	Olive gray	Ashy mud
9-3, 15-20			5	Olive gray	Ashy turbidite
10					Has numerous ashy patches up to 0.5 cm scattered in Sections 1
122					to 4.
11					Has dispersed ashy spots throughout
a11-3, 127-131			3	Brownish	Undisturbed
12				black	The sector discovered sector and body
13-3 100-110			7	Greenish gray	Disturbed ashy mud
13-3, 130-140			?	Olive	Disturbed ashy mud
13-4, 80-95		Barren	?	Greenish gray	Altered disturbed ashy mud
13-5, 80-117			?	Greenish gray	Altered disturbed ashy mud
-14-1, 33-37			1-2	Black	Bed This had
a14-2, 50-55			5	Dark grav	Bioturbated top
15 and 16			<b>T</b> .	5 an a 8 a)	No distinct ash beds in relatively
A	-				undisturbed Cores 15 and 16.
*17-1, 130-135			5	Black	Bioturbated top
a17-5 32-37	middle	D alata	2-5	Very dark gray	Partly dispersed by bioturbation
a18-1, 57-58	Miocene	D. ululu	<1	Black	rany aspersed by blotarballour
a18-1, 106-108			<2	Black	
a18-2, 113-119			2-3	Black	Partly dispersed by bioturbation
a18-3, 99-100 a18-3, 125-128		V	<1	Gray	Disparsed by burrows
a18-5, 50-56			2-3	Black	Partly dispersed by burrows
a18-5, 85-105	early	0	?	Black	Abundant ash in drilling breccia
a18-6, 8082	Miocene	C. costata	1-2	Black	Dispersed by burrows
419-1, 81-83			1-2	Brownish	Dispersed by burrows
a19-3, 23-27			1-2	Black	Dispersed by burrows
a19-5, 120-123			1-2	Olive black	Dispersed by burrows
<sup>a</sup> 19-7, 5-6			1	Dark gray	Dispersed by burrows
20-4, 10-18			2-3	Very dark gray	May be 2 redistributed
21 and 22					No recovery. Below this, ash is virtu-
	Oligocene				rences as noted.
27-1, 65-66	-		<1		Altered
32-4, 66-68 (?)	middle		<2	Light greenish	Feldspathic mudstone
34-2, 42-43	Eocene		1	gray Greenish gray	Altered
ole 543A			•	Oreclisii gray	Alleid
1	Ouaternary				Core 1 is the mud-line core_very
15 19	()				disturbed, generally vitric mud.
1-2, 85-95			2.0	Olive gray	Ashy mud
1-2, 131-137			3-4	Light brownish	May be Roseau ash
1-4, 20-35			2	Dark gray	Ashy mud
2-1, 86				Turn Punh	Cores 2-10 are Eocene to Campania
2-1, 91	0.000				continuous in cored interval with
2-2, 50	middle				the cores of Hole 543. Cores
2-2, 60	Eocene				543A-2, 3, and 5 contain tiny,
2CC, 15		i			smeetite-rich beds that are proba-
3-1, 21					bly altered volcanic ash. All but
3-1, 29	early		1.4		one are less than 1 cm in thick-
3-1, 64	Eocene	1	2		ness.
3-2, 31-33					

Note: Color is indicated for unbioturbated and undisturbed beds. <sup>a</sup> These ash beds  $\geq 2$  cm in thickness. They are the major ash beds of Figure 4.



Figure 2. Photograph of a typical thick ash bed, with a flat bottom and bioturbated top (Sample 543-18-1, 100-115 cm).

Thunnell, 1977; Cadet and Fujioka, 1980; Cadet, Thisse, et al., 1982; Cadet, Pouclet, et al., 1982). This synchroneity supports a global, plate-tectonic control rather than a local control on arc magmatism (Kennett, 1981). The long hiatus in the late Miocene corresponds with a shift in Lesser Antilles volcanism in the northern part of the arc from sources in the Limestone Caribbees (Fig. 1) to sources in the more westerly arc of presently active volcanoes (Martin-Kaye, 1969; Tomblin, 1975; Westercamp, 1979).

Geochemical and mineralogical studies are currently in progress to evaluate the significance of the ash stratigraphy to the petrological evolution of the Lesser Antilles arc.



Figure 3. Correlation of Site 541 ash beds and nannofossil zones between portions of Tectonic Units A and B, which have been repeated by faulting. The correspondence was first suggested by the similarity in thickness and spacing of pairs of closely spaced ash beds near the base of Core 16 and the top of Core 33. Comparison of the sections above and below demonstrated that seven ash beds, altogether, could be matched in the two intervals. Nannofossil zonal boundaries are from Bergen (this volume).

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Figure 4. Abundances of ash beds (number per 0.5 Ma) plotted versus absolute age. Stippled pattern represents number of major ash beds ( $\geq 2$  cm thick).