Caribbean Naturalist

No. 54 2018

Origins and Development of Fresh Water Lake, Dominica, West Indies, and Exploratory Study of Traces of Catastrophic Events in its Sediments

Ronald B. Davis, Shirley L. Davis, Dennis S. Anderson, and Peter G. Appleby

The *Caribbean Naturalist* . . .

- A peer-reviewed and edited interdisciplinary natural history science journal with a regional focus on the Caribbean (ISSN 2326-7119 [online]).
- Featuring research articles, notes, and research summaries on terrestrial, fresh-water, and marine organisms, and their habitats. The journal's versatility also extends to publishing symposium proceedings or other collections of related papers as special issues.
- Focusing on field ecology, biology, behavior, biogeography, taxonomy, evolution, anatomy, physiology, geology, and related fields. Manuscripts on genetics, molecular biology, anthropology, etc., are welcome, especially if they provide natural history insights that are of interest to field scientists.
- Offers authors the option of publishing large maps, data tables, audio and video clips, and even powerpoint presentations as online supplemental files.
- Proposals for Special Issues are welcome.
- Indexed and abstracted in Zoological Record, Biologial Abstracts, and BIOSIS Previews. Arrangements for indexing through a wide range of other services, including PROQUEST, SCOPUS, BIOBASE, EMBiology, Current Awareness in Biological Sciences (CABS), EBSCOHost, VINITI (All-Russian Institute of Scientific and Technical Information), FFAB (Fish, Fisheries, and Aquatic Biodiversity Worldwide), and WOW (Waters and Oceans Worldwide), are being pursued.
- The journal staff is pleased to discuss ideas for manuscripts and to assist during all stages of manuscript preparation. The journal has a mandatory page charge to help defray a portion of the costs of publishing the manuscript. Instructions for Authors are available online on the journal's website (www.eaglehill.us/cana).
- Co-published with the *Northeastern Naturalist* (Print ISSN # 1092-6194, Online ISSN # 1938-5307), the *Southeastern Naturalist* (Print ISSN # 1528-7092, Online ISSN # 1938-5412), and *Urban Naturalist* (ISSN # 2328-8965 [online]). Together these journals provide an integrated publishing and research resource for all of eastern mainland North America and the offshore waters and islands from Canada south to the Caribbean region, as well as urban areas worldwide.
- Available online in full-text version on the journal's website (www.eaglehill.us/cana). Arrangements for inclusion in the BioOne database (www.bioone.org, a collaborative effort of Allen Press, AIBS, et al.), EBSCOhost product line, and the Proquest Information and Learning databases (www.il.proquest.com) are being pursued.
- May be ordered through any major subscription service.

Cover Photograph: Coring Freshwater Lake, Dominica, W.I. The improvised platform is tied to shore in triradiate fashion to maintain its position over the deepest part of the original lake basin. Maximum pool mark of present impoundment shows at base of hills in background. Persons left to right: Bryan Bertrand, Dennis Anderson, and Ronald Davis. Bertrand is manipulating coring rods; Davis is operating the winch and cable. Photograph taken by Nickolay Hristov.

CARIBBEAN NATURALIST

The ***Caribbean Naturalist*** (ISSN # 2326-7119) is published by the Eagle Hill Institute, PO Box 9, 59 Eagle Hill Road, Steuben, ME 04680-0009. Phone 207-546-2821, FAX 207-546-3042. E-mail: office@eaglehill.us. Webpage: www.eaglehill.us/cana.

Periodical postage paid in Steuben, ME and additional mailing offices. **Special issue proposals are welcome**. On-line secure subscription ordering: rate per year for Caribbean subscribers - $15 regular, $10 students, $70 organizations; for Non-Caribbean subscribers - $20 regular, $15 students, $90 organizations. **Authors**: submission guidelines are available at www.eaglehill.us/cana. **Co-published journals:** The *Northeastern Naturalist* (ISSN 1092-6194 [print], ISSN 1938-5307 [online]), the *Southeastern Naturalist* (ISSN 1528-7092 [print], ISSN 1938-5412 [online]), and the *Urban Naturalist* (ISNN #2328-8965), journals with separate Boards of Editors. The Eagle Hill Institute is a tax exempt 501(c)(3) nonprofit corporation of the State of Maine (Federal ID # 010379899).

Origins and Development of Fresh Water Lake, Dominica, West Indies, and Exploratory Study of Traces of Catastrophic Events in its Sediments

Ronald B. Davis[1,*], Shirley L. Davis[2], Dennis S. Anderson[3], and Peter G. Appleby[4]

Abstract - We describe the origins and development of Fresh Water Lake on the island of Dominica, West Indies, and interpret indications in its sediment of past disturbances of the catchment by tropical cyclones, earthquake-induced slope failures, and human impacts. The descriptions are based on both the paleorecord and historical record. The lake occupies a small and steep-sided basin at the foot of a volcano and is surrounded by montane rainforest. It was enlarged by construction of a series of increasingly larger dams between 1961 and 1991. Basal contents of a 976-cm sediment core indicate that the lake originated ~730 AD, when a pyroclastic flow dammed a forested stream valley. In the lake's first ~230 years, 436 cm of gravels, sands, and silts accumulated, indicating unstable catchment slopes. The next 340 cm, deposited in the ~935 years to 1896 AD, with high organic content and abundant plant debris from the terrestrial catchment, include evidence of frequent non-anthropogenic disturbances. In the most recent century, 200 cm of relatively minerogenic sediment accumulated, indicating additional destabilization of the catchment, largely due to human impacts. The sediment-accumulation rate peaks at 1990 AD when the final and largest dam was constructed. An exceptionally high ^{210}Pb inventory in the upper part of the core results from a combination of excessive rainfall (~700 cm yr^{-1}), high catchment-erosion, and in-lake focusing. The upper 540 cm of the core contains a series of major negative excursions in the loss-on-ignition profile, each indicating deposition of mixed minerogenic sediment associated with disturbance. We developed informal guidelines for distinguishing between the sedimentary traces of tropical cyclones and terrestrial and subaqueous slope failures at Fresh Water Lake, and applied them to the excursions. However, attributions of the excursions to these different causes contain uncertainties due to lack of real-time data on fluxes of materials to deep-water sites-of-deposition that result from these types of catastrophic events in similar lake/catchment systems.

Introduction

In the mid-1990s, we carried out an exploratory investigation of the sedimentary record of Fresh Water Lake (FWL), high in the volcanic mountainous interior of Dominica, West Indies. Our goals were to determine the age and mode of origin of the lake, its phases of development, and whether its sediment contains traces of earthquake-initiated slope-failures, tropical cyclones, and human impacts. These perturbations, all causes of catastrophic change in the landscapes of Dominica, may

[1]School of Biology and Ecology and Climate Change Institute, University of Maine, Orono, ME 04469, USA. [2]Division of Lifelong Learning, University of Maine, Orono, ME 04469, USA. [3]School of Biology and Ecology, University of Maine, Orono, ME 04469, USA. [4]Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, UK.
[*]Corresponding author - rondavis@maine.edu.

Manuscript Editors: Kam-Biu Liu and Terrence McCloskey

produce similar sedimentary traces, and our additional goal was to determine if we could distinguish between them. We present the results here because of their unexpected and unusual nature, and their implications for studies of lake-sediment records of landscape disturbances and tropical cyclones in forested mountain settings.

Although lakes of volcanic origin with potential for paleoecological study are scarce in the Lesser Antilles, they occur on Guadeloupe, Saint Vincent, and Grenada, in addition to Dominica. Of the few studies of Lesser Antillean sediment records, notable is the work by McAndrews (1996) and McAndrews and Ramcharan (2003) on reconstruction of Holocene vegetation based on pollen analyses at Grenada lakes, and by Fritz et al. (2011) on hydrological variability based on diatom and other analyses at 2 of the same lakes.

Of the 3 natural and catastrophic perturbations that are common in Dominica—volcanic, seismic, and cyclonic—and that may leave traces (disturbance layers) in the sediment of FWL, cyclonic disturbance has attracted the greatest recent attention because of widespread concern that human impacts on global climate may affect tropical cyclone activity (IPCC 2014, Knutsen et al. 2010). To increase our ability to predict future cyclone activity, it is helpful to understand activity in the past, including changes in storm frequency and geographic distributions of storm tracks. As the historical record of past cyclones is limited in time and space (McAdie et al. 2009), extension of the record requires investigation of proxy records including cyclone traces in sediment deposits.

The detection of cyclone traces in sediment has been achieved at many coastal and estuarine water bodies and wetlands subject to overwash by marine storm surges associated with cyclones (e.g., Bertran et al. 2004, Donnelly et al. 2015, Lin et al. 2014). Fewer studies have detected traces in the sediment of lakes removed from direct marine impacts (e.g., Besonen et al. 2008, Brown et al. 2014, Burn and Palmer 2015). With this study, we add to that effort at a very different lake and landscape setting.

Deep-water lake sediments may contain layers of terrestrial sediment and debris attributable to earthquake-induced landslides and debris flows (e.g., Dapples et al. 2002, Doig 1986, Kotarba 1992, Schwab et al. 2009). Moreover, earthquakes can induce subaqueous slumps of shallow-water and slope sediment that is redeposited in deep water (Goldfinger 2009, Kremer et al. 2017, Moore 1978). In addition, widely varying disturbances of lake catchments by humans are recorded as layers in the sediment of lakes (e.g., Brenner and Binford 1988, Davis et al. 2006, Elliot et al. 1995, Zhang et al. 2014).

Dominica and Fresh Water Lake

The Commonwealth of Dominica, located at 15°18'N 61°23'W in the center of the arc of the Lesser Antilles between the islands of Guadeloupe to the north and Martinique to the south (Fig. 1), occupies a mountainous island about 750 km^2 in area (Fig. 2). Like most of its island neighbors, Dominica was formed by volcanic activity, and it bears the distinction of having more live volcanoes than any other island in the eastern Caribbean (Lindsay et al. 2005).

Dominica is seismically active, with frequent earthquakes of magnitude 2–4, and occasional quakes >6.0 (Earthquake Track 2017a, b). Landslides are a frequent occurrence on the island (Caribbean Handbook for Risk-Information Management 2017), and we have observed many recent slide scars on its steep mountains.

Adding to the potential for natural catastrophes, Dominica lies within a main path of entry of Atlantic tropical cyclones into the Caribbean (McAdie et al. 2009). In association with cyclones, the island has experienced excessive rainfall, storm surges, floods, and slope failures, many of them disastrous (Global Facility for Disaster Reduction and Recovery 2017).

Fresh Water Lake is located about half-way between the east and west coasts, and about a third of the way from the southern to the northern tip of Dominica. It is at 754 m above sea level (asl) in a moat between the eastern base of the lava dome Micotrin (Morne Macaque, 1221 m asl), and the rim of a large crater or caldera (Lasne and Traineau 2005, Lindsay et al. 2005; (Fig. 2). This part of Dominica is a major volcanic center, namely, the Micotrin/Morne Trois Pitons group of volcanoes. The volcanic complex and FWL are within Morne Trois Pitons National Park, a World Heritage Site.

Since this volcanic complex erupted to produce extensive ignimbrite deposits 47,400–22,100 years ago (Sigurdsson and Carey 1991), there has been a long period lacking evidence of volcanic activity. Activity resumed only recently: a local

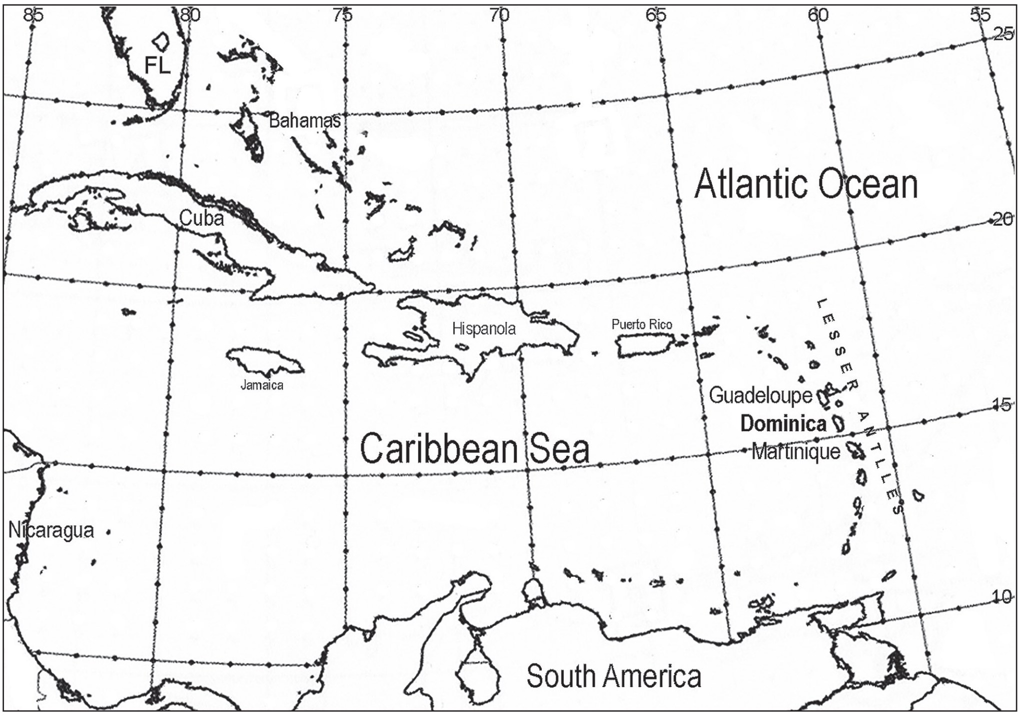

Figure 1. Map of Caribbean region, showing location of Dominica and 2 flanking islands, Guadeloupe and Martinique in the Lesser Antilles. Degrees longitude west and latitude north are given; dots along lines are in 1° intervals. Scale: 1° latitude = 111 km (69.1 mi). Modified from McAdie et al. (2009).

ignimbrite dated 868 AD (2 sig: 769–985; Stuiver et al. 2018) has been found at the village of Laudat on a far side of the Microtin lava dome from FWL (Fig. 2) (Lindsay et al. 2005).

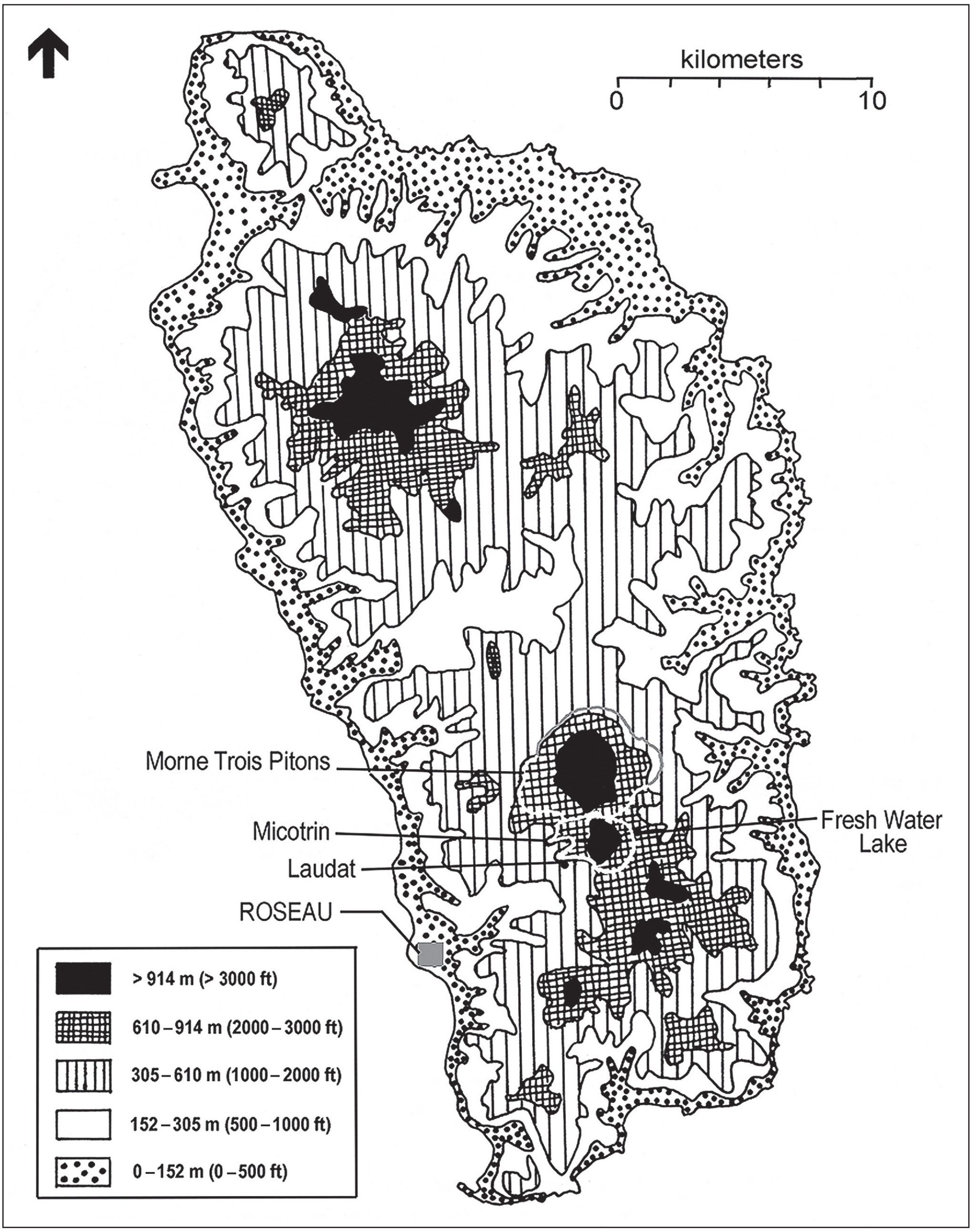

Figure 2. Physical map of Dominica. The bases of the lava domes Micotrin (Morne Macaque) and Morne Trois Pitons are indicated by a white line within the 610–914-m contour, and a gray line in the 310–610-m contour. Fresh Water Lake and the village of Laudat are indicated by small black dots. Modifed from Shankland Cox and Associates (1971).

Fresh Water Lake is at the lower limit of the altitudinal transition between montane rainforest and montane thicket (Beard 1949). Rainfall is extreme at this altitude, as indicated by the few years of available data from the FWL dam site. Annual totals varied from 623 to 751 cm (mean = 685 cm) from 1991 to 1996 (except 1994), with minimum and maximum monthly totals of 22 cm and 116 cm, respectively (Dominica Electricity Services, Ltd. [DOMLEC], Roseau, Dominca, unpubl. data). We conducted our field work during the driest months of January to May, when lake levels are low.

The natural water level of FWL has been raised for hydroelectricity production by a succession of increasingly higher dams starting in 1961, in each case increasing the surface area of the lake. Additionally, water input to the lake has been increased by diverting ("capturing") runoff from adjacent catchments (Table 1).

Methods

History

Little information on FWL that is relevant to our study has been published. To determine impacts of human activities on the lake and its sedimentary record in recent decades, much of it relating to damming and water diversions since 1961, we interviewed present and recently retired General Managers of DOMLEC on 23 January 1996 and referred to the engineering feasibility-analysis by Hanson and Scruton (1984) that led to the most recent and highest damming of FWL during 1989–1991 (Table 1).

Tropical cyclones are a possible cause of disturbance layers in the FWL sedimentary record; thus, we compiled a history of tropical cyclones that have made landfall in recent centuries at Dominica from the several sources cited in the Table 2.

Lake mapping and bathymetric survey

Maps and bathymetry of the natural and dammed FWL were unavailable, except that the rough shape of the small natural lake was depicted as a tiny area on the 1:25,000 topographic map of Dominica (Great Britain Directorate of Overseas Surveys 1960–1978). For that reason, we mapped and surveyed the bathymetry of the dammed lake and used information on the extent to which damming had raised the water level (Table 1) to infer the morphometry of the natural lake. We mapped the maximum pool shoreline in 1996 by sighting compass and 50-m tape, and carried out bathymetric transects along a meter-marked line from inflatable dinghy, using a Secchi disc as a sounding weight. As the water level of the impoundment fluctuated during this process, we standardized bathymetric data to maximum pool level (and shoreline) by determining vertical distance between water level and the dam spillway using an angle gauge and vertical triangulation. To determine lake-surface areas for the full-pool impoundment and the natural lake, we used a fine-scale dot overlay calibrated to map scale.

As subaqueous slope failure is a possible cause of disturbance layers in FWL sediment, we determined steepest mean slopes of the lake bottom on our bathymetric map along lines from the lake's deepest point to the 2 nearest shores, both for the present lake at maximum pool and for the lake prior to damming (4 slopes). We made each determination by solving for the acute angle at the shoreline of a right-angle triangle with its right angle over the lake's deepest point,

Table 1. Recent history of Fresh Water Lake (FWL), based on interviews on 23 January 1996 of General Manager F. Adler Hamlet and then-recently retired General Manager James Daway of Dominica Electricity Services, Ltd. (DOMLEC), supplemented by information from Hanson and Scruton (1984).

Year(s)	Event
1930	Daway said his parents told him that the September hurricane did great damage around the lake.
~1940 to ~1945	Daway said that when he was a youth, the much smaller, natural FWL was shaded by "… big moss-covered trees, and the lake water was much colder than today."
1946	*Oreochromis* sp. (tilapia) were introduced into a previously fishless lake, and "... have done well ever since." "Shrimp" were abundant in the lake prior to the introduction, but not since (Daway).
1957	Daway accompanied surveyor Winsky to sound the lake and found a depth of 15.2 m (50 ft) in the middle.
1961	The first weir (small dam) was built at the lake outlet in 1961 and raised the water level by 1.2 m (4 ft) at full pool (Daway).
1962	An improved weir was built, raising water level an additional 0.9 m (3 ft), a total of 2.1 m (7 ft) above natural-lake level at full pool (Daway).
1962–1976	No modification of weir at FWL outlet (Daway).
1976	Weir at outlet raised to a total of 2.4 m (8 ft) above natural-lake level at full pool (Hamlet).
1976	The Three-streams Diversion was built to supply more water to FWL, resulting in much slumping of the excavated hillside. In the ensuing years, slumped material had to be repeatedly cleared from the channel, and large amounts of it were washed into the lake. There was much "water lily" in FWL prior to the diversion, but not since (Daway).
1979	Hurricane David destroyed so much tree cover in the catchment that FWL water became much warmer, and has remained so up to the 1996 interview, with increased evaporation (Daway)
~1982–1984	Feasibility study for much larger dam carried out. Maximum-pool level (at spillway) to be raised 7.0 m higher than 1976 weir, with such water level to be attained by the end of each rainy season, and then dropping by several meters during each dry season. Upon completion, a marshy wetland will be flooded at what will become the southeast arm of the lake (Hanson and Scruton 1984).
1989	Clarke's River Diversion using 0.5-m diameter pipe to Three-rivers Diversion channel constructed to bring more water to FWL (Hamlet).
1989–1990	All trees in the impending expanded area of FWL dropped in place, and no logs removed or fire used (Hamlet).
1989–1990	Some of downed-tree material removed from the above area, and fire used to reduce volume of debris, contradicting the prior Hamlet entry (Daway).
1989–1991	The much larger dam (Hanson and Scruton 1984) built about 80 m downstream from the former weirs at the original FWL outlet (Hamlet).

with 1 leg from the lake surface to bottom, and the other leg along the water surface to the shore.

Coring

We carried out all coring from an improvised 2.5 m x 2.5 m floating platform secured in position over the deepest point of the lake. For coring soft upper sediment (short-core), we used an improved version of a Davis–Doyle stationary-piston corer (Davis and Doyle 1969) capable of obtaining cores as long as 180 cm in 200-cm long, 6.35-cm inner-diameter clear-acrylic tubes. We sectioned short-cores in the field by upward extrusion in 1.0-cm intervals.

To obtain deeper sediment (long-core), we used a stationary-piston corer with a 140-cm long and 8.9-cm inner-diameter steel coring-tube for obtaining 100-cm core sections. A pair of protruding steel pins on the piston held it in place at the tip of the tube to prevent entry of sediment into the tube during lowering into the coring hole for each successively deeper 100-cm coring thrust. The pins automatically retracted at the outset of a coring thrust so the tube could pass down into the sediment. We used casing to guide the corer back into the same hole, and to prevent slumping of upper sediment into the hole. We performed horizontal extrusion at the shore, where we wrapped and encased each section in a rigid tube for shipping.

Laboratory analyses

We split long-core sections longitudinally in half and sectioned one of the halves in 1-cm intervals. These intervals, and the 1-cm intervals from the short-core were each 29–33 cm^3. We used a 1-cm^3 subsample from each interval for determination

Table 2. List of historic tropical cyclones making landfall at Dominica through 1997 (final coring year). Cyclone event: MH = major hurricane; H = hurricane; TS = tropical storm; TC = type unknown. Sources: 1 = Honychurch (1995), 2 = Walton (2002), 3 = National Hurricane Center (2017), 4 = Chenoweth (2006), 5 = Fraser (2009), 6 = TheDominican.net (2017), 7 = McAdie et al. (2009), 8 = Fontaine (2003), and 9 = Lugo et al. (1983).

Year	Cyclone event	Source	Year	Cyclone event	Source	Year	Cyclone event	Source
1567	TC	1, 2	1806	H	1, 3	1889	TS	7
1666	TC	3	1806	2nd H	3	1889	2nd TS	7
1749	H	4	1809	TS	3	1893	H	7
1753	H	1	1813	H	1, 4	1894	MH	7
1753	2nd H	1	1813	TS	3, 4	1915	H	7
1765	H	4	1814	TS	3, 4	1916	H	3, 7
1766	H	4	1816	H	4	1930	H	7, Table 1
1772	H	3	1817	H	3, 6	1945	TS	7
1779	H	1	1820	H	4	1956	H	7
1780	H	1	1826	H	3	1963	TS	7
1784	H	4	1834	H	1, 3, 4	1970	TS	3
1787	TS	4	1864	H	7	1970	H	3
1787	H	1, 4	1872	TS	7	1979	MH	1, 6, 7, 8, 9
1788	TS	3	1883	MH	7	1981	TS	7
1804	H	5	1888	TS	7	1995	TS	7
						1995	H	7

of percent water and percent loss-on-ignition (LOI; an index of organic content) at 550 °C following Dean (1974). We dried 7-cm^3 subsamples from a series of intervals not used for estimates of plant debris (see below) from the upper part of the core for ^{210}Pb dating.

To estimate amounts of macroscopic plant debris that might indicate catchment disturbances, we extracted it every 4 cm along the core and determined its blotted wet weight. We removed whole plant parts and fragments while gently stirring the sediment and/or teasing it apart in a dish, taking care to minimize breakage, returned adherent sediment to the dish, and transferred the plant parts to a separate dish of wash water. We noted the presence of whole parts and fragments in the general categories: terrestrial broad leaf; graminoid leaf; chunk or splinter of wood, or woody stem; bark; woody root; fern; moss; unspecified plant fiber; unspecified vascular-plant fragment; and peat or peaty soil. We also noted whether any of this material was charred. Although we didn't quantify the numbers of parts in or the weight of separate categories, we tallied categories in order of volume of material. Finally, we transferred the total washed debris to paper toweling to remove all visible surface water before weighing it.

Dating lake sediments

We analyzed dried sediment samples from short-core intervals for ^{210}Pb radiometric dating and for the chronostratigraphic markers ^{137}Cs and ^{241}Am at the Environmental Radioactivity Research Centre, University of Liverpool, UK using the methods of Appleby et al. (1986, 1992). When we discovered that sediment-accumulation rates were so rapid that the short-core was insufficiently deep to complete a ^{210}Pb dating profile, we analyzed deeper samples from the long-core.

Exceptionally high inventories of fallout radionuclides in the upper 200–300 cm of FWL sediment led us to a comparison with fallout inventories in the terrestrial catchment. For this purpose, we collected a 30-cm and a 21-cm soil core near the long-abandoned path, the "Lake Road" (Honychurch 1995), uphill and a short distance north of the lake.

Beta Analytic Inc. (Miami, FL) carried out standard and AMS radiocarbon dating of terrestrial plant macrofossils from 3 key levels in the long-core. These levels represented lake origins (Beta 105964 and 109202) and the rapid transition from largely inorganic to organic (gyttja) sediment (Beta 130512). We calibrated these ^{14}C dates, as well as those we cite from the literature, to calendar years using the CALIB online calibration program by Stuiver et al. (2018). Except when citing an original calibrated date from CALIB, we round-calibrated ^{14}C dates to the closest 10 y. However, we give ^{210}Pb dates to the closest year.

Results

Lake morphometry

After final dam construction and at maximum pool, FWL is irregular in shape with 4 embayments, and has a surface area of 9.5 ha (Fig. 3). The natural FWL basin was largely confined to the northwest arm and central area of the impoundment and had an area of 3.2 ha when it was at high level in the wet season. Apart from the deep basin at its northwest corner, which had an area of only 0.9 ha, the original lake was shallow (Fig. 3). By the end of the dry season, parts of the shallow area would have been replaced by wetland. Before the final dam was built, the eastern part of this seasonal wetland still existed (Table 1).

At maximum pool, FWL had a maximum water depth of 24 m in 1996 (Fig. 3). By subtracting from 24 m the total increase in water level (9.4 m) due to damming (Table 1), we inferred that the maximum depth of the natural lake was 14.6 m. A direct observation of maximum depth of the natural lake in 1957 indicated 15.2 m (Table 1). When we cored the dammed FWL in the dry seasons of 1996 and 1997, maximum water depths were 19.8 m and 18.1 m, respectively.

Steep subaqueous slopes surround FWL's deepest point (Fig. 3). Roughly east of the deepest point, the mean maximum slope is 32º, and roughly west of the deepest point it is 20º. These slopes would have been even steeper prior to damming, 47º and 27º, respectively, suggesting susceptibility to slumping, given a sufficient triggering event.

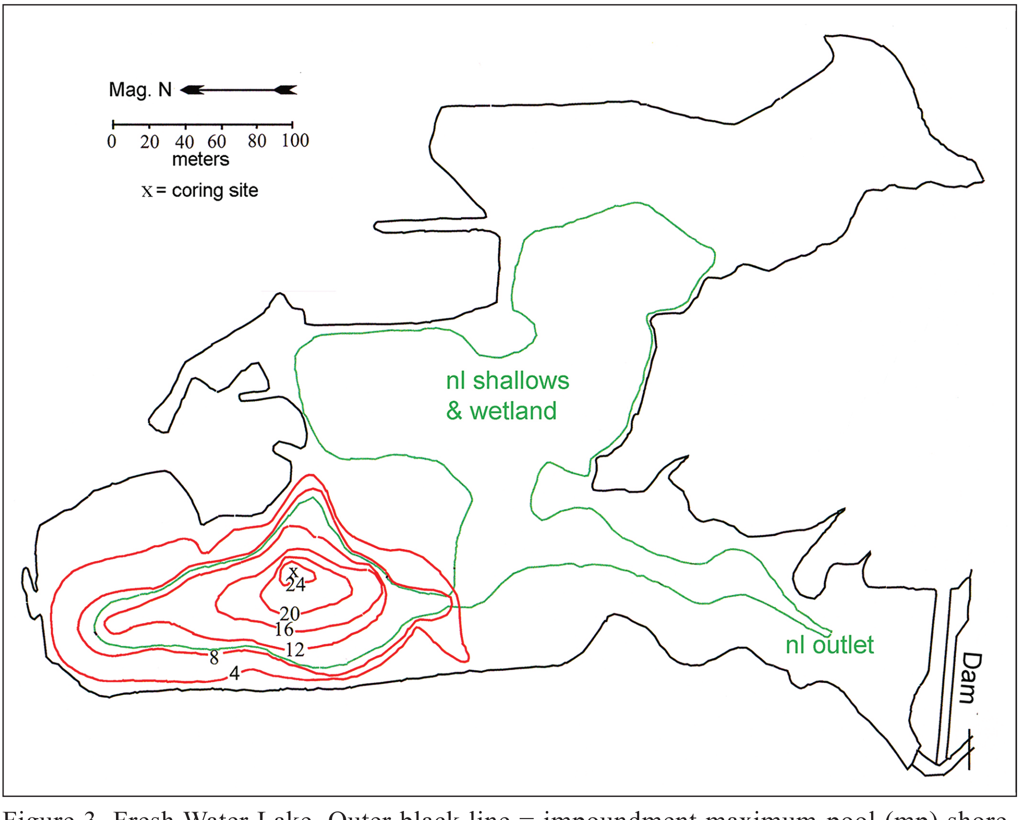

Figure 3. Fresh Water Lake. Outer black line = impoundment maximum-pool (mp) shoreline. Red lines = 4-m isobaths at mp (deep basin only). Green line = full natural-lake (nl) shoreline prior to first damming (Table 1) when lake was 9.4 m shallower. Magnetic north is in February–March 1996. x = coring site.

Sediment cores and core splicing

We obtained a 150-cm–long short-core at the deepest point of the lake on 30 March 1996. From 14 to 24 March 1997, within a few meters of the short-core location, we obtained a long-core in 10 sections, and bottomed out on rock at 976 cm below the sediment surface.

We report results from the short-core for the top 100 cm of sediment, and from the long-core for deeper sediment (Figs. 4–6). Scrutiny of overlapping stratigraphies of LOI and plant debris above and below the 100-cm splice level indicated a close match of the short- with long-cores. The radionuclide results (Figs. 4, 5) support this finding.

^{210}Pb dates and sediment-accumulation rates

Unsupported ^{210}Pb activities in the short-core showed no consistent trend or decrease from the sediment surface to 145 cm, making it likely that the core covered not more than a few decades. In the long-core, ^{210}Pb activities from 104 cm to140 cm were comparable to those of the same depths in the short-core, but below 140 cm decreased steeply with depth, reaching equilibrium with ^{226}Ra at 270 cm (Fig. 4).

In the short-core, ^{137}Cs increased with depth, apart from small irregularities, and reached greatest value in the bottom interval at 145 cm. ^{241}Am occurred only

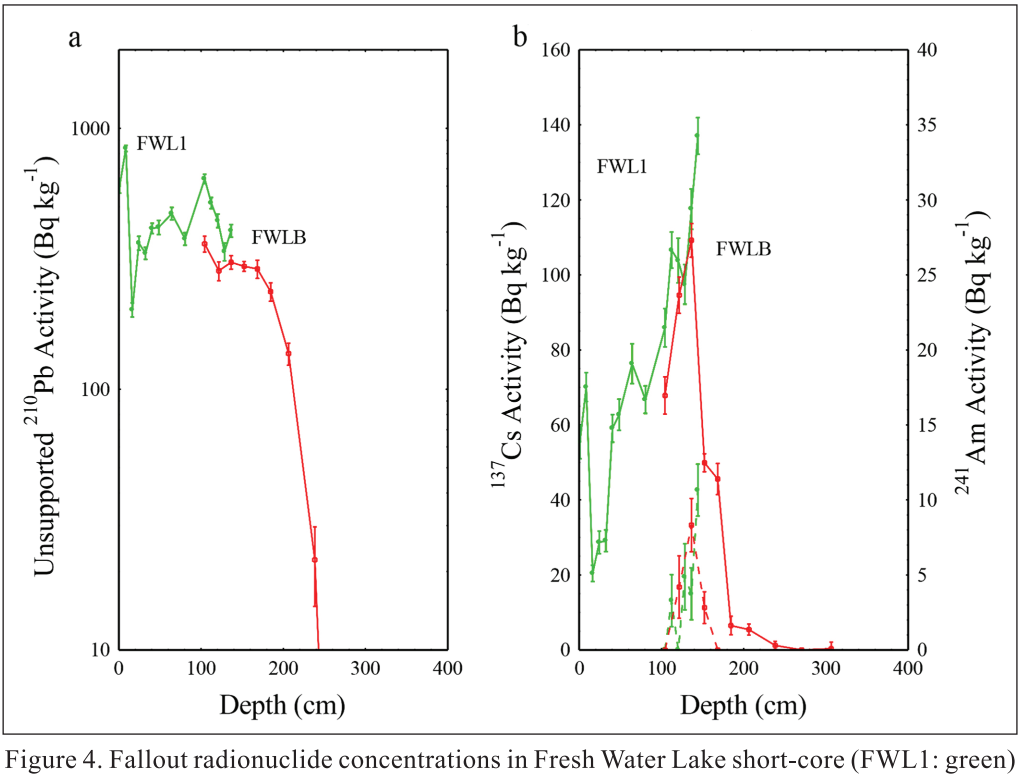

Figure 4. Fallout radionuclide concentrations in Fresh Water Lake short-core (FWL1: green) and long-core (FWLB: red), showing (a) unsupported Pb^{210} activity, and (b) ^{137}Cs (solid) and ^{241}Am (dashed) activities. Data for FWL1 span 0–145 cm, and for FWLB 104–240 cm.

below 100 cm, and had a maximum value at 145 cm. It is typically only detected in sediments dating to the peak bomb-generated nuclear-fallout period of 1962–1964. In the long-core, ^{137}Cs and ^{241}Am have distinct peaks, and date the 137-cm depth as 1963 (Figs. 4, 5), a close match to the short-core. These results support our core-splicing procedure.

We could not use either of the standard ^{210}Pb dating models by itself because of the short period covered by the short-core, and the non-monotonic nature of the ^{210}Pb profile. We followed Oldfield and Appleby (1984) and used the CRS model by anchoring the ^{210}Pb stratigraphy on a $^{137}Cs/^{241}Am$ date of 1963 at the base of the short-core. We present the results as age-depth and sediment-accumulation rate (SAR) curves in Figure 5.

The results indicate a more-or-less uniform SAR of ~0.40 g cm^{-2} y^{-1} (3.3 cm y^{-1}) in the 1960s and 1970s, but much higher rates in the 1980s and 1990s, peaking at 1992–1993 at ~1.1 g cm^{-2} y^{-1} (6.8 cm y^{-1}) (Fig. 5). The low ^{210}Pb and ^{137}Cs concentrations from 12 cm to 36 cm (Fig. 4) are associated with the especially high SAR in 1990–1994 (Fig. 5), during and in the 2 y following construction of the newest and largest dam, and the filling of its reservoir (Table 1). The mean rate since 1963 alone is 0.57 g cm^{-2} y^{-1} (4.4 cm y^{-1}). Much lower rates of ~0.07 g cm^{-2} y^{-1} (~0.6 cm y^{-1}) occurred in the 19th century. Unsupported ^{210}Pb inventories and fluxes were extremely high in these sediment cores. The mean post-1963 ^{210}Pb flux in the short-core is 3937 Bq m^{-2} y^{-1}, and mean pre-1963 flux in the long-core 2832 Bq m^{-2} y^{-1}.

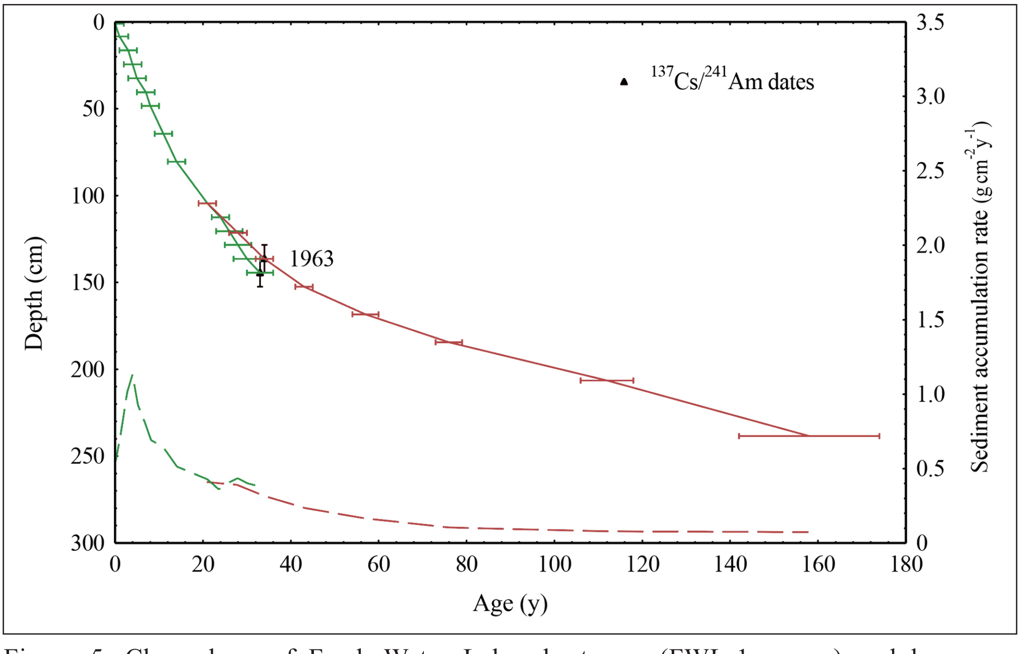

Figure 5. Chronology of Fresh Water Lake short-core (FWL-1: green) and long-core (FWLB: red), showing ^{210}Pb CRS age-depth curves (solid) with 1-sigma ranges on date measurements, and sediment-accumulation rates (dashed). 0 y = 1996. Also shown are the 1963 dates (▲) determined by $^{137}Cs/^{241}Am$ stratigraphy. Splicing of the 2 cores for the composite stratigraphy (Fig. 6) was at 100 cm.

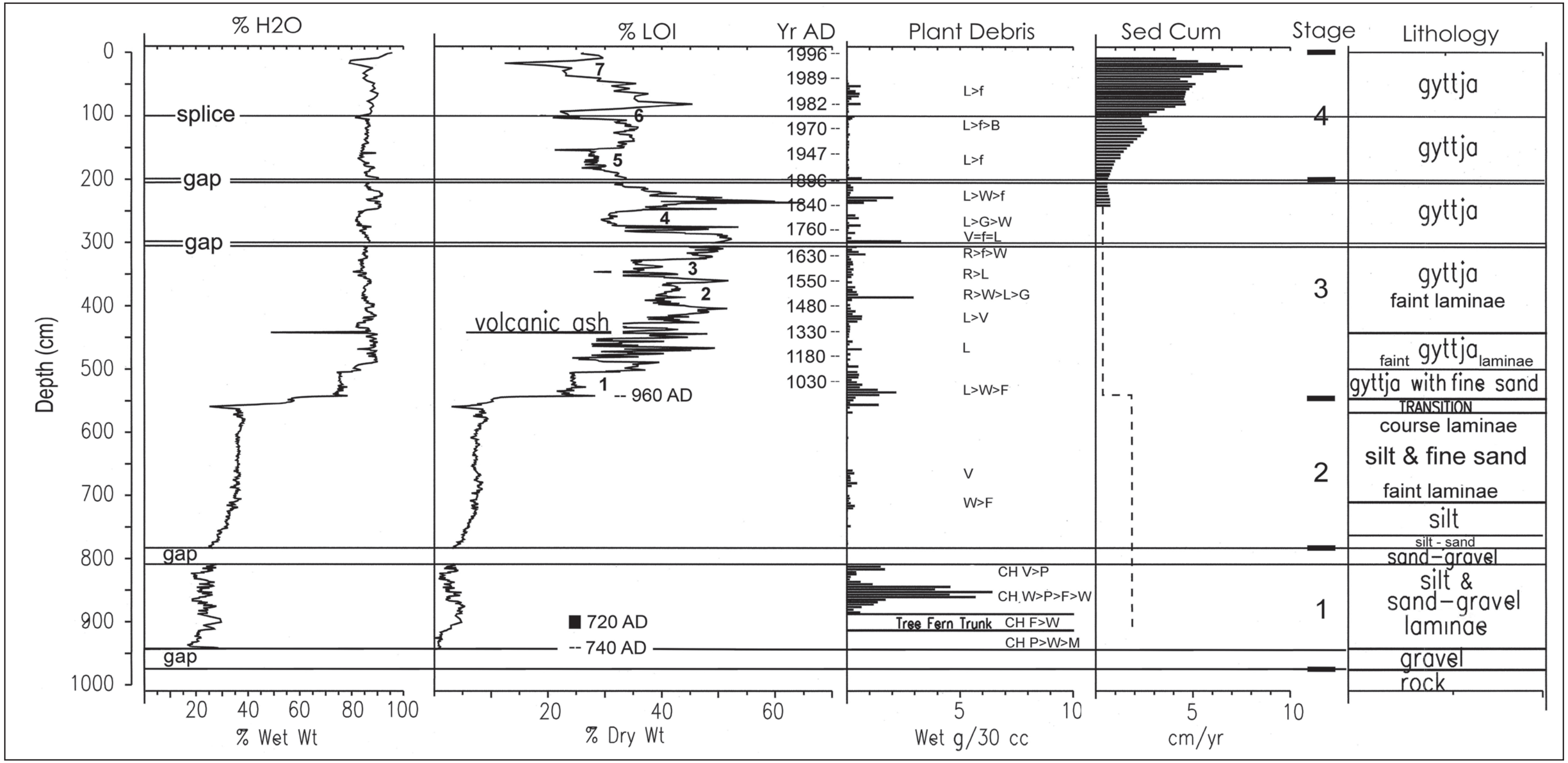

Figure 6. Stratigraphic diagram based on 976 cm of sediment core from Fresh Water Lake. Top meter (short-core) collected in March 1996, deeper part (long-core) in March 1997. Seven selected negative LOI excursions (disturbance layers) are numbered and are interpreted in the text. Derivation of the dates on the right side of the LOI panel is the same as explained at outset of text discussion on the excursions. Details on the three ^{14}C dates (cal yr AD) in the lower part of the panel are given in Table 3. Types of plant debris are: B = bark; F = fern part; f = unspecified plant fiber; G = graminoid-leaf part; L = broad leaf, whole or part; M = moss part; P = peat or peaty soil; R = root; V = unspecified vascular-plant fragment; W = chunk or splinter of wood or woody stem. They are given in order of abundance, e.g., L > W > F, on the plant debris panel. CH = charred. Sed Cum = sediment accumulation rate (SAR). Mean SAR below 240 cm (dashed lines) are anchored to radiometric dates at the beginning and end of each interval. Four stages of lake development are marked off and are described in the results section of the paper.

The 30-cm and 21-cm soil cores yielded very high fluxes of 617 and >722 Bq m^{-2} y^{-1}, respectively. The shorter of the 2 cores did not quite include the entire inventory. At a mean annual rainfall of 6.85 m, the soil-core results correspond to a mean ^{210}Pb concentration in rainfall of ~100 Bq kL^{-1}, comparable to the mean value for sites in the southern US (Environmental Radioactivity Research Centre data base, Liverpool University, UK).

^{14}C dates and sediment accumulation rates

The 2 radiocarbon dates for lake origin, 740 AD from 940–943 cm and 719 AD from 888–908 cm, are inverted, but their sigma ranges broadly overlap, indicating that they are essentially the same (Table 3). We use their average of 730 AD or ~1290 years ago for FWL origin. The date of 961 AD at 540–541 cm has a distinctly separate 1-sigma range from the 2 prior dates, but its 2-sigma range slightly overlaps with them (Table 3). Taking the difference between 961 and 730 AD at face value indicates that it took only about 230 years for the first 436 cm of sediment to accumulate, for an average SAR of 1.90 cm y^{-1}. Rates slow above 540 cm, the average from there to 200 cm (1896 AD) is 0.36 cm y^{-1} (Fig. 6). From 200 cm to the surface, rates are high, again, averaging 1.98 cm y^{-1} (based on ^{210}Pb dating).

Stages of lake development

Four stages of lake-development are clearly shown by the variables plotted in Figure 6. We describe them below, from the bottom of the core upward.

Stage 1, remains of pre-lake ecosystem, and lake origin, 976–783 cm. Above impenetrable rock at 976 cm, and to 943 cm is a dark gray water-washed gravel, only a handful of which we caught, as the rest fell out the bottom of the core tube. From 943 cm to 808 cm is an irregularly and faintly laminated dark gray silt, with

Table 3. Radiocarbon dates from Fresh Water Lake in 1997. Depth is below the sediment–water interface. We follow CALIB (Stuiver et al. 2018) for date calibration. For each median probability calibrated date (Cal y-AD row), we give the 1- and 2-σ (sigma) ranges, and their respective relative areas under the probability distribution (Rel. P).

	Depth (cm)		
	540–541	888–908	940–943
Material dated	Wood	Tree fern stem, charred	Plant fragments and peaty soil, charred
Lab number	Beta-130512	Beta-105964	Beta-109202
Date type	AMS	Standard	AMS
^{14}C y BP (±1 σ)	1070 (± 60)	1310 (± 70)	1260 (± 40)
Cal y-AD	961	719	740
1-σ range	941–1020	652–771	680–773
Rel. P	0.733	1.000	1.000
2-σ range	799–1045	612–883	667–779
Rel. P	0.952	1.000	0.780

some sand and gravel. From this matrix at 908–888 cm we recovered the 7-cm diameter, 20-cm long remains of a tree-fern trunk in vertical position, with some of its surfaces charred. There is an abundance of macroscopic organic remains, mostly wood fragments, but also chunks of peaty soil, some of it charred, and small pieces of charcoal within the inorganic matrix (Fig. 6).

Although there is a gap in our data at 808–783 cm, we can characterize the sediment there as sand and gravel (Fig. 6) because we observed it falling out the bottom of the core tube. Overall, the results for Stage-1 suggest that a catastrophic event involving fire occurred around 730 AD that was responsible for the origin of the lake, and that very rapid sedimentation occurred in the nascent lake.

Stage 2, early lake, 783–540 cm. During this interval, largely inorganic gray silts and fine sands were deposited in the lake. The deposit is, for the most part, irregularly and faintly laminated. Loss-on-ignition increases from 1–5% in Stage-1 to 6–8% in Stage 2; still quite low compared to higher values for samples higher in the core. Macroscopic plant debris is scarce, but what is present consists largely of wood fragments until the transition to Stage 3, when terrestrial leaf remains first appear (Fig. 6).

Stage-3, organically rich, repeatedly perturbed lake, 540–200 cm. This "middle period" at FWL starts at 960 AD, and ends at 1896 AD. At the start, LOI rapidly increases from 6–8% to 25%, is interrupted by a LOI plateau of 26% accompanied by a major spike in plant debris, and then resumes its rapid increase. In the remainder of Stage 3, LOI undergoes high-frequency variation between 30% and 50%, and to 64.5% near the end of the stage. The dark gray-brown sediment (gyttja) is faintly laminated, except for the prominent 7-mm lamina of white volcanic ash at 440 cm. Apart from the exceptional peak in plant debris in the brief Stage-1, it is most abundant and consistently present in Stage-3. This zone's plant debris mainly consists of leaf parts and plant fibers, unlike the largely woody debris of Stages 1 and 2 (Fig. 6).

The average SAR in Stage 3 of 0.36 cm y^{-1} is lower than the average SAR of the combined Stages 1 and 2 by a factor of 5.3. However, the pronounced variations in LOI suggest that major variation in SAR is concealed within its average value. Among the fluctuations in the LOI profile of Stages 3 and 4 are 7 negative excursions that are especially pronounced, and that we have chosen for discussion later. The first 5 of these are flat-bottomed (extended in depth; Fig. 6). Excursions in Stage 3 are at (1) 541–505 cm (plateau); (2) 399–369 cm; (3) 356–327 cm; and (4) 274–237 cm.

Stage-4, instability, siltation, damming, and enlargement of lake, 200–0 cm. Above 200 cm (1896 AD) SAR increases, slowly at first, and then more rapidly to over 7 cm y^{-1} by 35 cm (1990 AD) (Figs. 5, 6). This increase begins well before the first weir (small dam) construction at the lake in 1961 (Table 1). Except for the moderate amounts of plant debris from 80 cm to 52 cm (1980–1987), Stage 4 contains little plant debris, and, on average about 10 percent lower LOI than Stage 3, but LOI varies widely. The 3 major negative LOI excursions in Stage 4 are at (5) 186–151 cm; (6) 104–90 cm; and (7) 38–4 cm (Fig. 6).

Discussion

We have presented evidence bearing on the origin, stages of development, and disturbance history of FWL and its catchment. These results and the following interpretations of them are based on a combination of studies of the paleorecord and the historical record, and they raise several questions that call for further research.

Volcanic origin of Fresh Water Lake, and the early lake

Basal sediments of the core contain charred wood remains and peaty soil (Fig. 6), including charred remains yielding the average calibrated ^{14}C date of 730 AD for lake origin (Table 3). Forest fire is unlikely to occur in these hyperpluvial mountains apart from volcanic events; thus, we infer that at least 1 pyroclastic flow occurred on the FWL side of Micotrin at that time, and the ignimbrite deposit dammed the outlet of a vegetated stream valley to form FWL. This interpretation is also supported by the fact that we cored through a segment of charred tree fern trunk in vertical position, possibly in growing position, and associated with laminated deposits including stream-washed gravels near the bottom of the core. A topographic feature about 200 m south of the pre-dam FWL may provide further support. It rises to the next higher ~15 m (50 ft) map contour above the lake surface and its outlet stream (Great Britain Directorate of Overseas Surveys 1960–1978), and could be part of the formative ignimbrite dam. That supposition needs to be investigated by on-ground geological survey. However, much of the geological evidence for the natural damming of the valley may have been destroyed by construction of the newest and largest human-made dam.

In the ~230 years following lake origin (Stages 1 and 2), sediment with low organic content, absence of leafy plant debris, and very high SAR (period average 1.89 cm y^{-1}) suggest dilution of organic contents by inorganic sedimentation due to unstable subaqueous and/or terrestrial slopes. Siltation could have maintained a turbid water column much of the time, limiting light penetration and primary productivity including by rooted aquatic plants.

Fresh Water Lake's middle period (Stage-3)

We infer from the great increase in LOI and shift to leafy plant debris around 960 AD at the beginning of Stage 3 that the catchment became more fully vegetated, less prone to soil erosion, and the lake less turbid and more biologically productive. However, indications of disturbances are present in the form of saw-tooth variations in the LOI profile (Fig. 6), possibly induced by tropical cyclones and earthquakes. Detailed plant macrofossil and microfossil (e.g., pollen, aquatic diatoms) studies may help to reveal the nature of these short-term disturbances and associated terrestrial and aquatic responses. This period at FWL ends at 1896 AD.

Extreme sediment-accumulation rates, and recent human impacts

From the top of the core downward, ^{210}Pb activity doesn't decrease until 140 cm and then drops steeply to reach equilibrium with supporting ^{226}Ra at 270 cm, and bomb radionuclides ^{137}Cs and ^{241}Am do not peak until 145 cm (Fig. 4). These depths are extreme for lake sediment cores (cf. Davis et al. 1988, 2006). Compared to the average SAR for the 19th century, the 20th century (lake development Stage 4) averages 5 times greater, and the period since 1963 averages 8 times greater.

Sediment-accumulation rates began a sustained increase at the beginning of the 20th century (Figs. 5, 6). During the early 1900s, and before the construction of automobile roads to link the east and west sides of the island, the abandoned path—the Lake Road (Honychurch 1995; L. Honychurch, c/o Dominica Museum, Roseau, Dominica, WI, pers. comm.)—was a major route for east–west travel. It traversed the north side of the FWL catchment. By providing access to tillable soils, Dominicans established gardens and shelters along the side of the path. This activity may explain the early beginning of increasing SAR, well before damming of, and catchment diversions to the lake.

The Three-streams Diversion, built in 1976 (Table 1) further increased siltation of the lake. That construction, and subsequent maintenance of the open channel leading to the lake have mobilized large amounts of silt. In 1997, we observed a prodigious plume of silt entering the northwest corner of the lake, near the coring location, produced by workers clearing vegetation from the channel with machetes.

Sediment-accumulation rate peaked at 1.1 g cm^{-2} y^{-1} (6.8 cm yr^{-1}) in 1993 (Fig. 5). Associated with this peak are low ^{210}Pb and ^{137}Cs concentrations (Fig. 4). These values date only 1–2 y after completion of the newest/largest dam and the filling of its reservoir (Table 1), indicating a major impact of damming on FWL sedimentation.

High radionuclide inventories

Unsupported ^{210}Pb inventories are extremely high in the soil cores, but the ^{210}Pb fluxes we calculated from those cores are comparable to estimates of the atmospheric flux based on mean concentrations in rainwater for the Gulf coast area of the US, suggesting that the high inventories in the FWL catchment are largely attributable to the extremely high rainfall. Additional sampling of ^{210}Pb inventories in soils, and sampling of rainfall for ^{210}Pb concentrations in the FWL catchment would help to consolidate these relationships. The more than 4-fold higher inventories and fluxes in the lake-sediment cores are almost certainly due to a combination of erosive inputs from the catchment and focusing to the deepest part of the lake where we obtained the cores.

Identification of sedimentary traces of cyclones and slope failures

In this section we develop provisional guidelines for the identification of type of natural event responsible for disturbance layers in the sediment of FWL.

Cyclones. Cyclone traces in lake sediment differ substantially from lake to lake and region to region, depending on the type of lake, associated mechanisms of formation of the sedimentary record, and catchment characteristics including topography, soils, and vegetation (e.g., Besonen et al. 2008, Brown et al. 2014, Burn and Palmer 2015). Fresh Water Lake, with its steep, rainforested catchment, is very different from the lake/catchment systems in the just-cited references.

Known impacts of tropical cyclones on forest ecosystems including rainforests in Dominica (Lugo et al. 1983) offer hints at the types of evidence to look for in the

FWL sediment. Severe hurricanes may uproot tall trees, aided by heavy rain that alters soil to promote uprooting, and may also break their trunks, leaving large-size woody debris in place on the landscape (Brokaw and Walker 1991, Everham and Brokaw 1996, Loope et al. 1994, Lugo et al. 1983). But the most widespread and consistent effects of cyclones on rainforests are defoliation (Lugo 2008), stripping of epiphytes, and loss of branches (Brokaw and Walker 1991, Loope et al. 1994), resulting in massive litter-fall (Lugo and Waide 1993). These smaller-size components would more readily be transported by wind and runoff to the lake. However, fresh plant-litter floats, at least for a while, and heavy rain and runoff associated with tropical cyclones, and resultant rapid flushing of the lake may carry much of it through the outlet.

Tropical cyclones also mobilize minerogenic sediment in runoff and may greatly increase sediment discharge (Lugo 2008), including to lakes. We would expect that compared to light plant debris, a greater proportion of dense minerogenic sediment would sink before being swept out the outlet, especially particles larger than clay and fine silt.

Slope failures. Landslides and debris flows on steep, forested terrain are violent events that sweep entire ecosystems with them (Garwood et al. 1979, Varnes 1978), most completely from their central areas, including trees, many of them broken apart, and soil with roots. For this reason, we would expect their sedimentary traces at FWL to contain considerable amounts of broken/fragmented wood including woody roots, as well as leaf fragments, plus much mineral soil. In contrast, tropical cyclones leave bulky wood remains and most soil and roots in place on the landscape, and we propose their sedimentary traces at FWL would contain a lower proportion of woody debris, and a higher proportion of leafy debris. However, on steep terrain, as surrounds FWL, heavy rain from tropical cyclones may occasionally induce landslides and debris flows (Tannehill 1956, Tanner et al. 1991), and such an event would be difficult to distinguish in the sediment from one induced by an earthquake.

Inducement of subaqueous slumps by earthquakes is especially likely at steep lake-bottoms like those in FWL (Goldfinger 2009, Moore 1978). Slump layers have been found in deep-water lake sediments by Doig (1991), Shilts and Clague (1992), and Karlin and Abella (1996), and the subject is summarized by Goldfinger (2009). In cores of deep-water organic lake-sediments, slump layers typically (but not always, cf. Doig 1991) consist of relatively minerogenic sediment, at least in part because, prior to slumping, the sediment had been deprived of organic content by 2 processes: (1) litter processing by shallow-water aquatic invertebrates, and decomposition by aquatic fungi and bacteria (Webster and Benfield 1986), and (2) winnowing/suspension of relatively buoyant organic particles/debris by waves and currents, and redeposition in quiet deep water (Davis and Ford 1982).

Slump layers may appear as couplets or double layers when displaced minerogenic sediment settles out more rapidly than less-dense organic sediment (Doig 1991). The same phenomenon may occur when mixed inputs from terrestrial slope failures and cyclones settle out in the lake. In the rest of this paper, we use the term "couplet" in that sense, and not in reference to a varve or annual couplet as in De Geer (1940).

Cyclone clusters, and their record in lake sediment

When searching paleorecords for traces of individual tropical cyclones, one must consider that cyclones impacting a single site may occur in close succession, more than 1 per season or a small number of years apart. Strings of such closely spaced storms, or cyclone clusters, are separated by periods with infrequent storms. Cyclone clusters on centennial and millennial scales have been identified in coastal paleorecords at several sites across the Caribbean and Gulf of Mexico (e.g., McCloskey and Liu 2013), and from 20th-century historical records on a shorter time scale (Mumby et al. 2011).

The historical record of tropical cyclones making landfall in Dominica (Table 2) contains a major cluster between 1749 and 1837 with no fewer than 19 hurricanes and 5 tropical storms, averaging 3.7 y apart. The exact beginning of the cluster is uncertain, as the record becomes more incomplete prior to the mid-1700s. During the remaining 160-y period covered by the FWL sediment core, only 11 hurricanes and 9 tropical storms made landfall on Dominica, an average of 8.0 y apart.

The likelihood is low of finding traces of most individual cyclones of the 1749–1837 cluster in the FWL sediment. On the one hand, many, if not most of these storms probably didn't greatly impact the FWL catchment, depending on exact storm track, related wind directions, and other factors. On the other hand, for some that did, if closely concurrent, there may not have been sufficient time between storms for vegetation recovery and soil stabilization, and for deep-water sedimentation (including resuspension and focusing) of storm inputs to produce distinctly separate traces in deep-water sediment.

Provisional dating and causal analyses of LOI excursions (disturbance layers)

Dating the LOI excursions is necessary to examine any correlations with tropical cyclones and earthquakes (and associated slope failures) in the historical record. For this purpose, we used 3 approaches. First, we made direct use of the ^{210}Pb chronology from 0 cm (1996 AD) to 240 cm (~1840 AD) (Fig. 5). This period includes excursions 5, 6, and 7. Second, we extrapolated down-core from 240 to 400 cm. For this extrapolation, we applied the average slope (SAR) of 0.62 cm y^{-1} from the 200–240-cm section of the ^{210}Pb age–depth curve (Fig. 5) to the negative LOI excursions. Considering the likelihood that SAR was lower between the excursions, we applied only half that value to the intervening areas. The result is an estimated date of 1480 AD for the 400-cm level. This period includes excursions 2, 3, and 4. Third, to date excursion 1, we used linear interpolation between the 960 AD date at 540 cm (Table 3) and the 1480 AD estimate for 400 cm. Although the first approach took account of SAR differences during and between negative LOI excursions, and the second approach roughly approximates them, the third approach didn't account for them. However, the third approach applies only to excursion 1, and it is anchored to the 960 AD calibrated ^{14}C date at 540 cm.

To identify disturbances during the historical period that are correlated with LOI excursions, we used records of human impacts on the catchment (Table 1), and of cyclones (Table 2) and earthquakes (Earthquake Track 2017a, 2017b; Lindsay et al. 2005) that have impacted Dominica.

Excursion 1. This first negative LOI excursion appears as an interruption or plateau along the steep increase of LOI from 540 cm to 505 cm at the beginning of Stage-3 (Fig. 6), and has a provisional date of 960 to 1090 AD. The preponderance of leafy debris over wood fragments, and an addition of fine sand hint at 1 or more major defoliation events accompanied by enhanced soil erosion of the steep, forested catchment, as might result from 1 or more tropical cyclones. The episode predates historical records in the eastern Caribbean, so we cannot test this hypothesis. As a pulse catastrophic-event, the 35 cm of sediment may have been deposited in a much shorter period than our provisional dating suggests.

Excursion 2. This excursion, from 399 cm to 369 cm, is provisionally dated 1480 to 1530 AD, around the beginning of the historical period in the eastern Caribbean. However, no earthquakes, landslides, or cyclones are on record for Dominica in this period. The excursion's sediment contains several woody root fragments and chunks of wood (Fig. 6), and lesser amounts of leafy debris, evidence more suggestive of terrestrial-slope failure than that from excursion 1. Immediately following the excursion is a brief peak in LOI, coinciding with a peak of woody roots, and lesser amounts of leafy debris. If the approximations we applied to this part of the core for differentiating between the SAR of negative LOI excursions versus intervening periods of high LOI aren't different enough, then excursion 2 could have been deposited in a much shorter period than estimated. It may even be reasonable to propose that the excursion with the following LOI/debris peak constitute a thick couplet produced by a single terrestrial-slope failure.

Excursion 3. The LOI excursion from 356 cm to 327 cm, provisionally dated 1570 to 1620 AD, lacks a peak of plant debris. Of the small amount of debris present, the volume of woody root fragments exceeds leafy debris. Only 1 cyclone is recorded at Dominica around this time, in 1567 (Table 2), perhaps within the excursion period, given likely sediment-dating error. However, the relative abundance of woody root fragments favors a terrestrial slope failure as the cause of the excursion.

Excursion 4. The negative LOI excursion from 274 cm to 243 cm, provisionally dated 1780 to 1830 AD, is not accompanied by a peak in plant debris, but is immediately followed (~1840) by one that largely consists of terrestrial leaf remains, with lesser amounts of wood. This debris is associated with the highest LOI peak (64.5%) in the core (Fig. 6). The 1780–1830 period covers most of the 1749–1837 cyclone cluster (Table 2), and it does not seem possible to determine which individual or group, if any, of these many cyclones might have produced the excursion. However, by applying the same dating proviso here that we applied to excursion 2, the excursion 4 period becomes shorter than indicated by its provisional dating. Further, we may consider the excursion and closely following peaks of organic materials as a thick couplet representing a single event. The dating of the organic peaks at ~1840 closely approximates the 1834 hurricane. That storm (Table 2) was singled out by Honychurch (1995) as especially destructive in Dominica and could account for excursion 4.

Excursion 5. This relatively shallow excursion, from 186 cm to 151 cm, dates by ^{210}Pb to 1918 to 1954. Plant debris is scarce in this sediment, but what is present is largely leafy. There are records of only 1 hurricane and 1 tropical storm making landfall in Dominica in the period (Table 2). The September 1930 hurricane did great damage around FWL (Table 1), but the scarcity of plant debris does not support assigning the cause of the excursion to this storm. At least 2 earthquakes, magnitude ≥6.0, and additional less-powerful quakes affected Dominica in the period (Earthquake Track 2017a, b). In the mid-1990s, we did not observe landslide scars on the slopes above the lake, but they could have been obscured by natural reforestation in the intervening decades, so without aerial or on-ground surveys we cannot eliminate the possibility that they occurred. However, the absence of woody debris, and scarcity of larger than silt-size mineral sediment argues against it. These arguments, and the occurrence of powerful earthquakes point to a slump of subaqueous slope sediment as the most likely cause.

Excursion 6. This brief excursion, from 105 cm to 89 cm, dates by ^{210}Pb from 1976 to 1980. It correlates with the major hurricane, David, in 1979 (Table 2), one of the most damaging hurricanes on record in Dominica (Fontaine 2003, Honychurch 1995, Lawrence 1979). Hurricane David largely destroyed the forest in the FL catchment (Table 1; Lugo et al. 1983). As in excursions 2 and 4, an LOI spike immediately follows it. A layer of plant debris shortly follows the spike, and is virtually contemporaneous with it, given the rapid SAR. These organic layers form a couplet with the minerogenic excursion. The debris layer largely consists of leaf remains, but doesn't have a prominent peak. Excursion 6 also correlates with the 1976 construction of the Three-streams Diversion that mobilized large amounts of mineral soil to the lake. This event, and the ongoing erosional source it created (Table 1) would have diluted inputs of plant debris, suggesting that although the couplet is a product of Hurricane David, the Three-streams Diversion muted its organic layer.

Excursion 7. The excursion from 40 cm to 12 cm, dated 1989–1994 by ^{210}Pb, reaches the lowest LOI value in the upper half of the core and lacks plant debris (Fig. 6). It is correlated with construction in 1989–1991 of the final and by far the largest dam, including the preparation and flooding of a greatly enlarged impoundment area; this project was the most extensive and environmentally damaging project carried out at the lake (Table 1). A hurricane and a tropical storm hit Dominica in this period (Table 2) but, in the mid-1990s, we saw no impacts on the FWL catchment. Additionally, an earthquake of 6.2 magnitude affected Dominica in 1995 (Earthquake Track 2017b), but there was no landslide scar above the lake. Although it appears likely that this final LOI excursion resulted from dam construction and impoundment, an earthquake-induced subaqueous slump could have contributed to it.

Concluding discussion

Critical need for research. Our attempts to determine the causes of disturbance layers in the sediment of FWL encountered several sources of uncertainty. Prominent among these is inadequate knowledge of the effects of catastrophic events in lake catchments on aerial and hydrological transfers of plant debris and sediments to lakes, and the sedimentation of these inputs in lakes. This gap may be filled by long-term monitoring of carefully selected lake/catchment systems in areas with high seismic activity and/or high tropical-cyclone activity, including the monitoring of in-lake sediment dynamics as in Bloesch (1994). Direct observations and real-time data on these processes would facilitate interpretation of paleorecords of catastrophic events in lake sediments and reduce their provisional and hypothetical nature.

Sediment dates. More numerous ^{14}C dates would increase confidence in the dating of LOI excursions at FWL, but the sigma ranges of these dates, especially after calibration, still would limit the close matching of historically dated cyclones, earthquakes, and slope failures with traces in the sediment. This problem is avoided in studying lakes containing annually laminated or varved sediment, as in Besonen et al. (2008). Such lakes should be used whenever possible for fine-scale stratigraphic study of short term events. However, annual layering of lake sediment results from concomitants of seasonality, and requisite conditions for varve formation are more rare in the tropics than in temperate zones (Zolitschka et al. 2015).

Lake selection. Additional aspects of lake selection can simplify interpretation of disturbance layers in the sediment. The location of FWL in an area of both high seismic and cyclonic activity, the steepness of the lake's bottom and terrestrial catchment, and recent major human impacts make it more difficult to determine the causes of disturbance layers in the sediment because of similarities (though there are also differences) in the sediment mobilized by these different kinds of events. For study of lacustrine paleorecords of any one class of events, the selection of study site should strive to minimize influences of other classes of events. Of course, lake choices are more or less limited, depending on geographic area and other factors (Larsen and MacDonald 1993), and compromise in lake selection is likely to remain the rule rather than the exception.

Additional sediment variables. This exploratory work at FWL is limited to only a few, simple, sedimentary variables. Additional variables can facilitate the identification of disturbance layers and their causes. Fine-scale plant macrofossil analysis can clarify vegetational responses to catastrophic events in a lake's catchment (Birks 2001, Cañellas-Boltà 2012), as when a cyclone destroys old growth forest, and it is replaced by successional vegetation. Geochemical changes in lake sediments help to distinguish between different anthropogenic impacts (Davis et al. 1994, 2006). Aquatic-microfossil analyses (e.g., diatoms) can demonstrate shifts in past living populations in response to altered water chemistry due to changing inputs from the terrestrial catchment, in turn helping to reveal past natural and anthropogenic impacts on the catchment (Battarbee et al. 2001).

Acknowledgments

We are thankful to the following individuals: Bryan Bertrand of Laudat, Dominica, provided competent and dependable field assistance, on some occasions under difficult conditions; Nickolay Hristov helped at the lake and field lab and served as project photographer; Lennox Honychurch contributed a valuable historical perspective; and F. Adler Hamlet and James Daway of DOMLEC added historical information. Arlington James, Forest Officer, and Colmore Christian, Director, Commonwealth of Dominica Forestry and Wildlife Division of the Ministry of Agriculture, facilitated this project in many ways. We occupied living, workshop, and laboratory space at Archbold Tropical Research and Education Center, Springfield Estate, in Dominica. Mona George Dill, Manager, and David Lang, Scientific Director, facilitated our operations there. This work was funded by a grant from the Committee for Research and Exploration of the National Geographic Society, and by grant DEB-9527989 from the US National Science Foundation. Much of the fieldwork was carried out during author R. Davis' tenure as a Fulbright Research Scholar in Dominica.

Literature Cited

Appleby, P.G., P.J. Nolan, D.W. Gifford, M.J. Godfrey, F. Oldfield, N.J. Anderson, and R.W. Batterbee. 1986. ^{210}Pb dating by low-background gamma counting. Hydrobiologia 141:21–27.

Appleby, P.G., N. Richardson, and P.J. Nolan. 1992. Self-absorption corrections for well-type germanium detectors. Nuclear Instruments and Methods B71:228–233.

Battarbee, R.W., V.J. Jones, R.J. Flower, N. G. Cameron, H. Bennion, L. Carvalho, and S. Juggins. 2001. Diatoms. Pp. 155–202, *In* P. Smol, H.J.B. Birks, and W.M Last (Eds.). Tracking Environmental Change Using Lake Sediments, Volume 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer, Dordrecht, The Netherlands. 371 pp.

Beard, J.S. 1949. The natural vegetation of the Windward and Leeward Islands. Oxford Forestry Memoir 21. Clarendon Press, Oxford, UK. 192 pp.

Bertran, P., D. Bonnissent, D. Imbert, P. Lozouet, N. Serrand, and C. Stouvenot. 2004. Paleoclimat des Petites Antilles depuis 4000 BP: l'enregistrement de la lagune de Grand-Case a Saint-Martin. Comptes Rendus Geoscience 336:1501–1510.

Besonen, M.R., R.S. Bradley, M. Mudelsee, M.B. Abbott, and P. Francus. 2008. A 1000-year, annually-resolved record of hurricane activity from Boston, Massachusetts. Geophysical Research Letters 35(14):L14705 doi:10.1029/2008GL033950.

Birks, H.H. 2001. Plant macrofossils. Pp. 49–74, *In* P. Smol, H.J.B. Birks, and W.M Last (Eds.). Tracking Environmental Change Using Lake Sediments, Volume 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer, Dordrecht, The Netherlands. 371 pp.

Bloesch, J. 1994. A review of methods used to measure sediment resuspension. Hydrobiologia 284:13–181.

Brenner, M., and M.W. Binford. 1988. A sedimentary record of human disturbance from Lake Miragoane, Haiti. Journal of Paleolimnology 1:85–97.

Brokaw, N.V.L., and L.R. Walker. 1991. Summary of the effects of Caribbean hurricanes on vegetation. Biotropica 23:442–447.

Brown, A.L., E.G. Reinhardt, P.J. van Hengstrom, and J.E. Pilarczyk. 2014. A coastal sinkhole records intense hurricane events. Journal of Coastal Research 30:418–428.

Burn, M.J., and S.E. Palmer. 2015. Atlantic hurricane activity during the last millennium. Scientific Reports 5:12838.

Cañellas-Boltà, N., V. Rull, A. Sáez, O. Margalef, S. Giralt, J.J. Pueyo, H.H. Birks, H.J.B. Birks, and S. Pla-Rabes. 2012. Macrofossils in Raraku Lake (Easter Island) integrated with sedimentary and geochemical records: Towards a palaeoecological synthesis for the last 34,000 years. Quaternary Science Reviews 34:113–126.

Caribbean Handbook for Risk Information Management. 2017. Dominica landslide-inventory map. Available online at http://www.charim.net/dominica/maps. Accessed 13 August 2017.

Chenoweth, M. 2006. A reassessment of historical Atlantic Basin tropical cyclone activity, 1700–1855. Climate Change 76:169–240.

Dapples, F., A.F. Lotter, J.F.N. van Leeuwen, W.O. van der Knaap, S. Dimitridis. and D. Oswald. 2002. Paleolimnological evidence for increased landslide activity due to forest clearing and land-use since 3600 cal BP in the western Swiss Alps. Journal of Paleolimnology 27:239–248.

Davis, M.B., and M.S. Ford. 1982. Sediment focusing in Mirror Lake, New Hampshire. Limnology and Oceanography 27:137–150.

Davis, R.B., and R.W. Doyle. 1969. A piston corer for upper sediment in lakes. Limnology and Oceanography 14:643–648.

Davis, R.B., D.S. Anderson, D.F. Charles, and J.N. Galloway. 1988. Two-hundred-year pH history of Woods, Sagamore, and Panther Lakes in the Adirondack Mountains, New York State. Pp. 89–111, *In* W.J. Adams, G.A. Chapman, and W.G. Landis (Eds.). Aquatic toxicology and hazard assessment: Volume 10. ASTM STP 941. American Society for Testing and Materials, Philadelphia, PA, USA.

Davis, R.B., D.S. Anderson, S.A. Norton, and M.C. Whiting. 1994. Acidity of twelve northern New England (USA) lakes in recent centuries. Journal of Paleolimnogy 12:103–154.

Davis, R.B., D.S. Anderson, S.S. Dixit, P.G Appleby, and M. Schauffler. 2006. Responses of two New Hampshire (USA) lakes to human impacts in recent centuries. Journal of Paleolimnology 35:669–697.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss-on-ignition: Comparison with other methods. Journal of Sedimentary Petrology 44:242–248.

De Geer, G. 1940. Geochronologia Suecica principles. Kungliga Svenska Vetenskapsakademiens Handlingar, Tredje Serien 18(6):1–367.

Doig, R. 1986. A method for determining the frequency of large-magnitude earthquakes using lake sediments. Canadian Journal of Earth Sciences 23:930–937.

Doig, R. 1991. Effects of strong shaking in lake sediments, an earthquake-recurrence interval, Témiscaming, Quebec. Canadian Journal of Earth Sciences 28:1349–1352.

Donnelly, J.P., A.D. Hawkes, P. Lane, D. MacDonald, B.N. Shuman, M.R. Toomey, P.J. van Hengstum, and J.D. Woodruff. 2015. Climate forcing of unprecedented intense-hurricane activity in the last 2000 years. Earth's Future 3:49–65.

Earthquake Track. 2017a. Recent earthquakes near Dominica (earthquakes 4.0^+ mag). Available online at https://earthquaketrack.com/p/dominica/recent?mag_filter=4,%20 http://uwiseismic.com/ScientificAdvisories.aspx. Accessed 13 August 2017.

Earthquake Track. 2017b. Recent earthquakes near Dominica (earthquakes 6.0^+ mag). Available online at https://earthquaketrack.com/mq-mq-petite-riviere-salee/recent?mag_filter=6. Accessed 13 August 2017.

Elliot M.B., B. Striewski, J.R. Flenley, and D.G. Sutton. 1995. Palynological and sedimentological evidence for a radiocarbon chronology of environmental change and Polynesian deforestation from Lake Taumatawhana, Northland, New Zealand. Radiocarbon 37:899–916.

Everham, E.M., III., and N.V.L. Brokaw. 1996. Forest damage and recovery from catastrophic wind. Botanical Review 62:113–185.

Fontaine, T. 2003. Remembering Hurricane David. TheDominican.Net. Volume1, Issue 47, 29 Aug 2003. Roseau, Dominica. Available online at http://www.thedominican.net/articles/david.htm. Accessed 9 January 2018.

Fraser, W.J., Jr. 2009. Lowcountry Hurricanes. Wormsloe Foundation Publication Series, Book 12, University of Georgia Press, Athens, GA, USA. 368 pp.

Fritz, S.C., S. Björck, C.A. Rigsby, P.A. Baker, A. Calder-Church, and D.J. Conley. 2011. Caribbean hydrological variability during the Holocene as reconstructed from crater lakes on the island of Grenada. Journal of Quaternary Science 26:829–838.

Garwood, N.C., D.P. Janos, and N. Brokaw. 1979. Earthquake-caused landslides: A major disturbance to tropical forests. Science 205:997–999.

Global Facility for Disaster Reduction and Recovery. 2017. Disaster-risk management in Latin America and the Caribbean Region: GFDDR Country Notes, Dominica. Available online at https://www.gfdrr.org/sites/default/files/publication/drm-country-note-2010-dominica.pdf. Accessed 13 August 2017.

Goldfinger, C. 2009. Subaqueous paleoseismology, Pp. 119–169, *In* J. Mcalpin (Ed.). Paleoseismology, 2nd Edition. Elsevier, Amsterdam, Netherlands. 629 pp.

Great Britain Directorate of Overseas Surveys. 1960–1978. West Indies, Dominica, 1:25,000 topographic map, Editions 1–4, Tolworth, Surrey, UK.

Hanson, C., and G.H.S. Scruton. 1984. Report: Expansion of hydroelectric-resources feasibility study. Prepared for Government of Dominica by Shawinigan Division of Lavalin International, Montreal, QC, Canada.

Honychurch, L. 1995. The Dominica Story. Macmillan, London, UK. 318 pp.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Fifth Assessment Report of the IPPC, Parts A and B. Cambridge University Press, Cambridge, UK. Part A: 1140 pp; Part B: 670 pp.

Karlin, R.E., and S.E.B. Abella. 1996. A history of Pacific Northwest earthquakes recorded in Holocene sediments from Lake Washington. Journal of Geophysical Research 101:6137–6150.

Knutsen, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, and M. Sugi. 2010. Tropical cyclones and climate change. Nature Geoscience 3:157–163.

Kotarba, A. 1992. High-energy geomorphic events in the Polish Tatra Mountains. Geografiska Annaler. Series A, Physical Geography 74:123–131.

Kremer, K., S.B. Wirth, A. Reusch, D. Fäh, B. Bellwald, F.S. Anselmetti, S. Girardclos, and M. Strasser. 2017. Lake-sediment based paleoseismology: Limitations and perspectives from the Swiss Alps. Quaternary Science Reviews 168:1–18.

Larsen, C.P.S., and G.M. MacDonald. 1993. Lake morphometry, sediment mixing, and the selection of sites for fine-resolution palaeoecological studies. Quaternary Science Reviews 12:781–792.

Lasne, E., and H. Traineau. 2005. Field report on geothermal exploration in Wotten Waven, Dominica. Organization of American States Eastern Caribbean Geothermal Development Project (GeoCaraibes), Report 05. CFG Services, Orléans, France. 111 pp.

Lawrence, M. 1979. Preliminary report, Hurricane David, 25 August–7 September 1979. NOAA National Hurricane Center, Miami, FL. Available online at http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1979-prelim/david/prelim02.gif and http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1979-prelim/david/prelim03.gif. Accessed 9 January 2018.

Lin, N., P. Lane, K.A. Emanuel, R.M. Sullivan, and J.P. Donnelly. 2014. Heightened hurricane surge risk in northeastern Florida revealed from climatological-hydrodynamic modeling and paleorecord reconstruction. Journal of Geophysical Research 119:8606–8623.

Lindsay, J.M., A.L. Smith, M.J. Roobol, and M.V. Stasiuk. 2005. Dominica. Pp. 1–47, *In* J.M. Lindsay, R.E.A. Roberson, J.B. Shepherd, and A. Shahiba (Eds.). Volcanic Hazard atlas of the Lesser Antilles. Seismic Research Unit, University of West Indies, St. Augustine, Trinidad and Tobago, WI. 279 pp. + folder of maps.

Loope, L., M. Duever, A. Henderson, J. Snyder, and D. Jensen. 1994. Hurricane impacts on uplands and fresh-water swamp forests. Bioscience 44:238–246.

Lugo, A.E. 2008. Visible and invisible effects of hurricanes on forest ecosystems: An international review. Austral Ecology 33:368–398.

Lugo, A.E., and R.B. Waide. 1993. Catastrophic and background disturbance of tropical ecosystems at the Luquillo Experimental Forest. Journal of Biosciences 18:475–481.

Lugo, A.E., M. Applefield, D.J. Pool, and R.B. McDonald. 1983. The impact of Hurricane David on the forests of Dominica. Canadian Journal of Forest Research 13:201–211.

McAdie, C.J., C.W. Landsea, C.J. Neumann, J.E. David, E.S. Blake, and G.R. Hammer. 2009. Tropical cyclones of the North Atlantic Ocean, 1851–2006 (with 2007 and 2008 track maps included), 6th Revision. National Climate Data Center, Asheville, NC, USA, and National Oceanic and Atmospheric Administration National Hurricane Center, Miami, FL, USA, Historical Climatology Series 6-2. 238 pp. Available online at http://www.nhc.noaa.gov/pdf/TC_Book_Atl_1851-2006_lowres.pdf. Accessed 21 August 2017.

McAndrews, J.H. 1996. Pollen analyses on Grenada, West Indies. Palynology 20:247 (abstract).

McAndrews, J.H., and E.K. Ramcharan. 2003. Holocene pollen diagram from Lake Antoine, Grenada. XVI INQUA Congress, Program and Abstracts. P. 122 (abstract).

McCloskey, T.A., and K.B. Liu. 2013. A 7000-year record of paleohurricane activity from a coastal wetland in Belize. The Holocene 23:278–291.

Moore, D.G. 1978. Submarine slides. Pp. 563–604, *In* B. Voigt (Ed.). Rockslides and Avalanches, Volume 1. Elsevier, Amsterdam, The Netherlands. 852 pp.

Mumby, P.J., R. Vitolo, and D.B. Stephenson. 2011. Temporal clustering of tropical cyclones and its ecosystem impacts. National Academy of Sciences of USA, Proceedings 108:17626–17630.

National Hurricane Center. 2017. The deadliest Atlantic tropical cyclones, 1492–1996. Available online at http://www.nhc.noaa.gov/pastdeadlyapp1.shtml. Accessed August 2017.

Oldfield, F., and P.G. Appleby. 1984. Empirical testing of ^{210}Pb-dating models for lake sediments. Pp. 93–124, *In* E.Y Hayworth, and J.W.G. Lund (Eds.). Lake Sediments and Environmental History. Leicester University Press, Leicester, UK. 411 pp.

Schwab, J., P. Werner, P. Dulski, E. McGee, N.R. Nowaczyk, S. Bertrand, and S.A.G. Leroy. 2009. Palaeolimnology of Lake Sapanca and identification of historic earthquake signals, Northern Anatolian Fault Zone (Turkey). Quaternary Science Reviews 28:991–1005.

Shankland Cox and Associates. 1971. Dominica: A tourist-development strategy. Planning and Policy Report, Kingston, Jamaica. 239 pp.

Shilts, W.W., and J.J. Clague. 1992. Documentation of earthquake-induced disturbance of lake sediments using subbottom acoustic profiling. Canadian Journal of Earth Sciences 29:1018–1042.

Sigurdsson, H., and S.N. Carey. 1991. Caribbean volcanoes: A field guide to Martinique, Dominica, and St. Vincent. Geological Association of Canada, 1991 Field Trip Guidebooks, Toronto, ON, Canada. 101 pp.

Stuiver, M., P.J. Reimer, and R. Reimer. 2018. CALIB 7.1. Available online at http://calib.org. Accessed 2–8 January 2018.

Tannehill, I.R. 1956. Hurricanes, their Nature and History, Particularly Those of the West Indies and the Southern Coasts of the United States. Princeton University Press, Princeton, NJ. 257 pp.

Tanner, E.V.J., V. Kapos, and J.R. Healey. 1991. Hurricane effects on forest ecosystems in the Caribbean. Biotropica 23:513–521.

TheDominican.net. 2017. Tracing the disruptive power of hurricanes in Dominica. Available online at http://www.thedominican.net/articles/davidtwo.htm. Accessed 20 August 2017.

Varnes, D.J. 1978. Slope-movement types and processes. Pp. 11–33, *In* R.L. Schuster, and R.J. Krizek (Eds.). Special Report 176 Landslides: Analysis and control. Transportation Research Board, National Research Council, Washington, DC, USA.

Walton, T.R. 2002. The Spanish treasure fleets. Pineapple Press, Sarasota, FL, USA. 224 pp.

Webster, J.R., and E.F. Benfield, 1986. Vascular-plant breakdown in freshwater ecosystems. Annual Review of Ecology and Systematics 17:567–594.

Zhang, W., Q. Ming, Z. Shi, G. Chen, J. Niu, G. Lei, F. Chang, and H. Zhang. 2014. Lake-sediment records on climate change and human activities in the Xingyun Lake catchment, SW China. PlosONE 9(7):e102167. Accessed 28 January 2018.

Zolitschka, B., P. Francus, A.E.K. Ojala, and A. Schimmelman. 2015. Varves in lake sediments: A review. Quaternary Science Reviews 117:1–41.