Caribbean Journal of Science, Vol. 49, No. 2-3, 209-221, 2019
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The impact of the submarine volcano Kick ‘em Jenny on benthic foraminifera

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Abstract.—Nothing is known about the impact on marine meiofauna of submarine volcanic eruptions in the Grenada Basin. The benthic foraminiferal fauna is here examined in piston cores taken within ~8 – 38 km of the crater of Kick ‘em Jenny (KeJ), decadal eruptions of which disseminate ash to the NW via the Caribbean Current. Piston core Gs29, taken ~8 km W of the crater, consists of clay-rich material from the *Globorotalia menardii* Zone U, ~500 ka old, probably exposed by slumping. The remaining cores (from proximal to distal: GC59, GC90, GC99 and GC100), taken between 1000 – 3000 m water depth, comprise volcanic ash and are of presumed Holocene age. Recovery from GC59, GC90 and GC99, the last taken 27.3 km NW of the crater, was poor and apparently reflects volcanic ash impact. Recovery from GC100, 38 km NW of the crater and from the basin floor, was rich. Thus, KeJ disrupts seafloor colonization by foraminifera up to 32 – 38 km from the crater. *Bolivina* spp., indicative of low dissolved oxygen concentrations, dominated the assemblage in proximal core Gs29. *Cassidulina* spp. dominated the distal core GC100 assemblage, indicating somewhat higher dissolved oxygen concentrations. This might reflect a long-term change in productivity in the area, or a nutrient-rich surface eddy to the lee of Grenada. Allochthonous, shallow-water foraminifera, recovered throughout cores Gs29 and GC100, were more abundant in the latter. This might indicate that Grenada protects nearshore foraminifera from disruptive hurricanes.

Keywords.— benthic foraminiferal high productivity index; Caribbean Current; Grenada; Lesser Antilles island arc

Introduction

The Lesser Antillean island arc, along the eastern boundary of the ~3,100 m-deep Grenada Basin (Figure 1), has been a locus of volcanic eruptions throughout much of the Cenozoic (Jackson, 2013; Smith et al., 2013). Each volcanic island underwent a submarine phase as it developed. This is evidenced by:

1. The occurrence of blocks of limestone with shallow-water, mid-Eocene age foraminifera on Nevis (Hutton, 1968; Hutton and Nockolds, 1978).
2. Inliers of Late Eocene turbidites (the Tufton Hall Formation) across the northern half of Grenada composed mainly of volcanic lithic fragments (Saunders et al., 1985). The section includes mudstones and marlstones with deep-water trace fossils (*Chondrites*) indicative of water 2000–4800 m deep. Interbedded with these are volcanic arenites containing allochthonous larger foraminifera and coralline algae that indicate the presence of a shallow-water bank in the vicinity of Grenada during Eocene times.
3. An encircling, shallow marine, late Pleistocene limestone around the Brimstone Hill volcanic dome on St. Kitts (Baker, 1985).
4. Saba Bank, which rises to 16 m below the sea surface. This dormant volcanic edifice is now occupied by a rich, benthic foraminiferal fauna (Hofker, 1980).

Despite all these geologically ancient examples, the impact of submarine volcanic eruptions on the Eastern Caribbean marine meiofauna is little known. However, it is known that submarine volcanoes need not be entirely hostile to organisms. Graff et al. (2008) recorded polychaete worms living to maturity close to the summit of the active submarine volcano Kick ‘em Jenny (KeJ; 12.18°N, 61.38°W), in regions of diffuse venting. There they feed on photosynthetic and hydrothermal vent-sourced material. Elsewhere, Molina-Cruz and Ayala-López (1988) reported the distribution and composition of benthic foraminiferal

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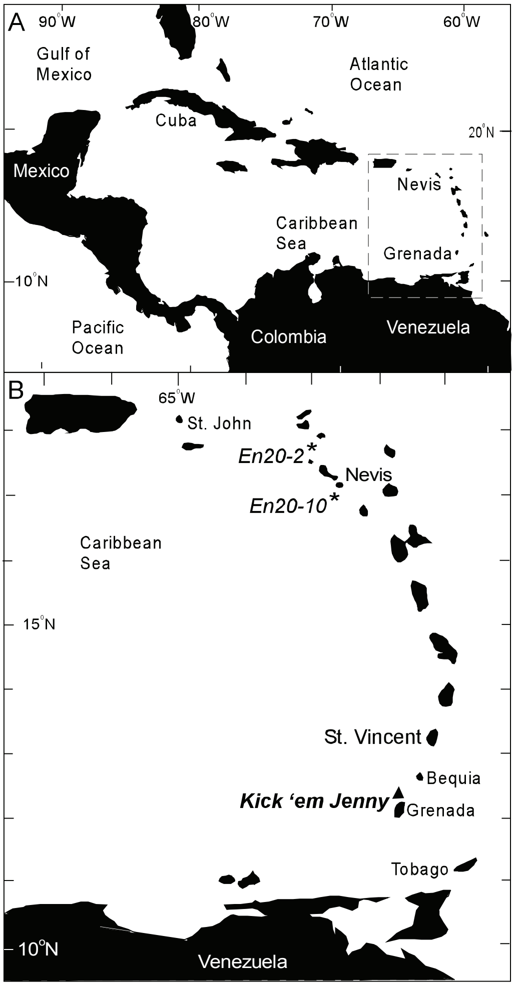

FIG. 1. The eastern Caribbean Sea, showing the locations of Kick 'em Jenny and the Leeward Island cores en20-2 and En20-10.

assemblages at the Guaymas Basin, Mexico. The assemblages near hydrothermal vents suggest that the foraminiferal remains have been affected by a selective dissolution process, only the small species *Bulimina spinosa* (Cushman) and *Bolivina* sp "2" being preserved. Molina-Cruz and Ayala-López (1988) did not, however, report recent volcanic ash in their samples. This paper examines the benthic foraminiferal fauna around KeJ, where ash is common.

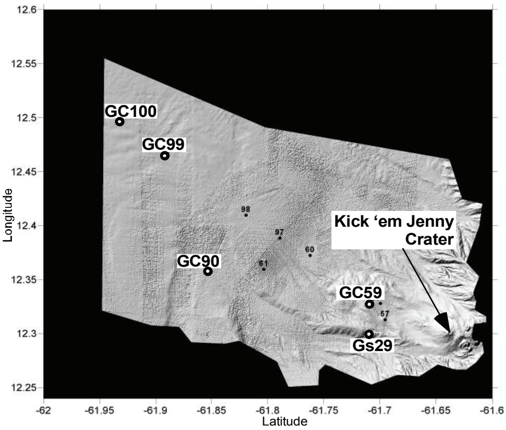

FIG. 2. Kick 'em Jenny and environs, showing the locations of the crater and the cores analysed.

KeJ (Figure 2) is the only active submarine volcano in the eastern Caribbean Sea, located ~8 km N of Grenada (area 344 km^2) and ~8 km W of Ronde Island (8.1 km^2) in the Grenadines. The volcano's name is descriptive. KeJ is located in a channel between two islands were a strong sea current produces large waves. The effect of these waves on ships is said to be comparable to the kick of a donkey, which is locally called a "Jenny".

There have been 14 eruptions at KeJ since its discovery in 1939 (Latchman et al., 2017), making it the most active volcano in the Lesser Antilles island arc (Lindsay et al., 2005). It undergoes two styles of eruption: (a) explosive, tephra-producing eruptions, and (b) effusive, dome-forming lava eruptions (Devine and Sigurdsson, 1995).

It is unknown when precisely KeJ began to form. All lavas sampled from it were erupted during the last century (Huang et al., 2011). Bouysse et al. (1988) suggested that it is a "very young cone (probably only tens or hundreds of years old)". About 1300 m high and 300 m wide at its summit, it currently rises to ~190 m below the sea surface (Carey et al., 2015). Subject to both eruptions and flank collapse, at present it has a horseshoe-shaped structure open to the WNW, toward the lower bathyal to abyssal Grenada Basin, that arose from a single sector collapse event with a volume of ca. 4.4 km^3 and a leading-edge runout of ~14 km (Dondin et al., 2011). This slide event was recently dated at a minimum of 43.5 kyr B.P. using radiocarbon dating from a contact between a carbonate sediment layer and the roof of the landslide deposit (S. Carey, pers. comm.). Eruptions and flank collapse events cause fluctuations in the depth to the summit, which was ~180 m in the early 1970s but decreased during the late 1970s and early 1980s to ~150m, reflecting the growth of a dome within the crater. This dome was destroyed during eruptions in the late 1980s (Shepherd, 1988; Sigurdsson, 1989). Its remains were presumably redistributed NW across the Caribbean Sea by the surface-water Caribbean Current (for details of which, see Chérubin and Richardson, 2007).

The impact of KeJ on the foraminiferal community is unknown, few studies having examined the bathyal and abyssal benthic foraminifera in the eastern Caribbean Sea. Gaby and Sen Gupta (1985) reported the Late Quaternary assemblages in the 4,000 m-deep Venezuelan Basin, west of the Aves Ridge that forms the western boundary of the Grenada Basin. The high abundance of *Cibicidoides wuellerstorfi* (Schwager) in a core taken near the Jungfern sill indicates strong current action at these depths (cf. Lutze and Thiel, 1989). The current’s source is unclear, but it might be an offshoot of the thermohaline Western Boundary Undercurrent, mapped north of the Greater Antilles by Tucholke (1975). The Venezuelan Basin is connected to the Columbian Basin via the narrow, >4000 m deep Aruba Gap, but no such deep connection exists between the Venezuelan Basin and the Grenada Basin.

Sen Gupta et al. (1982) recorded the late Quaternary foraminifera in three cores taken from near 2000 m along the western margin of the Grenada Basin at ~62.5 – 63ºW. The record of benthic foraminifera in these cores spanned the past 127 ka. *Bulimina aculeata* d’Orbigny was the dominant species in two cores, with no apparent glacial-interglacial control over its frequency curve.

Galluzzo et al. (1990) reported the Holocene fauna of the Grenada Basin. Although these authors intimated that the Grenada Basin extends only as far north as the Dominica Passage at ~16°N (Galluzzo et al., 1990, figure 1), Reid et al. (1996, figure 1) suggested that the basin extends as far as 17.7°N. Galluzzo et al. (1990) noted that the basin margins (water depths 1,500 – 2,000 m) are in a mixed water regime strongly influenced by relatively poorly-oxygenated Subantarctic Intermediate Water (SAIW; <4.5 ml/L O_2 at 1,000 m). This water enters the basin from the east and southeast via shallow passages (e.g., the 950 m-deep Dominica Passage; the 980 m-deep St. Lucia Passage; the 890 m-deep St. Vincent Passage and the 740 m-deep Grenada Passage). None of the cores examined by Galluzzo et al. (1990) were taken near KeJ, Core 7614 (12.6°N, 62.4°W) being collected ~120 km to the NW, and Cores 7615 and 7616 being taken west of St. Vincent (~13.2°N, 61.6°W), ~115 km to the north of KeJ. Galluzzo et al. (1990) suggested the Holocene, deep-sea benthic foraminiferal distributions in the basin are related to the spreading of Subantarctic Intermediate Water (SAIW) and Caribbean Bottom Water (CBW) within the basin. A low-oxygen assemblage dominated by *B. aculeata*, *B. alazanensis* Cushman, *Osangularia culter* (Parker and Jones), *Uvigerina auberiana* d’Orbigny and *U. peregrina* Cushman is developed in SAIW between 1,000 and 2,100 m. The CBW assemblage, found in the central portion of the basin below 2,400 m, includes *Cibicidoides wuellerstorfi*, *Eponides tumidulus* (Brady), *Alabaminella weddellensis* Earland, *Gyroidinoides soldanii* (d’Orbigny), *Nuttallides decorata* (Phleger and parker), *Pullenia bulloides* (d’Orbigny), and *PulIenia subcarinata* (d’Orbigny). *Cibicidoides wuellerstorfi* is in the CBW most abundant near the area of CBW entry, in the deep SW portion of the basin. This attests to higher current action in this area. Emery (1972) documented a surface water eddy in the lee of Barbados, to the east of Grenada, in which surface productivity was enhanced, littoral animals with long pelagic larval stages being more abundant in the eddy that elsewhere. It is not yet known if similar surface-water eddies occur in the lee of Grenada and KeJ, where the Caribbean Current flows towards the NW.

Wilson (2008, 2011) examined the benthic foraminiferal fauna in two piston cores collected by Reid et al. (1996) from the northern Lesser

Antilles (Figure 1): core En20-2 (17.8ºN, 63.0ºW, water depth 680 m) and En20-10 (17.0ºN, 63.0ºW, water depth 885 m). These studies present the only quantitative datasets for deep-water foraminifera in the Eastern Caribbean Sea so far published. Both cores yielded throughout (a) a deep-water association (DWA) of middle bathyal benthonic foraminifera and (b) a shallow-water association (SWA) of reefal species. Although these cores were taken only ~150 km apart, En20-2 from the arc platform and En20-10 from the Grenada Basin, they yielded markedly different assemblages. The shallower-water core En20-2 presented an assemblage comparable to that recorded by Galluzzo et al. (1990), *Bulimina* spp. and *Uvigerina* spp. collectively forming 14.7% of the total recovery. These two genera formed only 3.3% of the benthonic foraminifera in the deeper-water core En20-10. *Globocassidulina subglobosa* (Brady) formed only 5.0% of En20-2 recovery but 16.0% of En20-10 recovery, while *Nuttallides rugosa* (Phleger and Parker) was not recovered from En20-2 but was subdominant in En20-10 (8.0% of recovery).

Materials and Methods

Sample Sites

Piston core Gs29 (12.3°N, 61.7°W, water depth 1880 m) was taken NW of Grenada (Reid et al., 1996) and 7.7 km WSW of the KeJ crater, from the flank of the Grenada Basin but within an area characterised as ‘magmatic arc’ by Reid et al. (1996). Core recovery was 5.15 m. However, Reid et al. (1996) having noted that fossil preservation is poor towards the core base, we examine only the uppermost 2 m here. A tephra-fall layer within the core coincides in age with the Ericson Zone U, such that the top of core Gs 29 is older than 500 ka (Reid et al., 1996). The absence of post-U sediment from the core top might result from strong current action preventing deposition during later Pleistoene times, but it might also indicate slumping, perhaps associated with earth tremors, exposing older sediment. Samples were taken from this core every 10 cm.

Comparison is made with four gravity cores (GC59, GC90, GC99 and GC100) up to 80 cm long collected WNW-NW of the KeJ crater, between 1000–3000 m water depths. Precise water depths were not recorded by those collecting the cores. GC59 (12.34°N, 61.71°W) was collected from the shallowest water 8.5 km WNW of the crater and 4.5 km due north of Gs29. Core GC100 (12.49°N, 61.94°W) was collected from the deepest water ~34.4 km WNW of the crater. Core GC90 was taken from 12.36°N, 61.85°W, and GC99 from 12.46°N, 61.89°W, 27.3 km from the KeJ crater. GC59 was taken upslope from the leading-edge of the runout of ~14 km of the slump documented by Dondin et al. (2011) but the other cores were taken west of and beyond the slump edge. The site of the most distal core GC100 lies 33 km from Gs29 and within the Grenada Basin sensu Reid et al. (1996). These gravity cores comprise coarse sand-sized grains of volcanic ash, somewhat diluted by clay and calcareous matter in GC100. Samples from them were not initially taken for micropaleontology, but for volcanological work. Thus, the samples were taken in a somewhat haphazard manner, being recovered from any finer-grained intervals within the cores. Only once it was realised that they contain foraminifera was it decided to use them for micropaleontological work. Some levels were sampled twice, while other samples covered an extended interval (see Figure 3 for an example). For this reason, we do not here try to determine a stratigraphic history for each gravity core, but only to compare the entire assemblages recovered from the individual cores.

Sample preparation

Samples of 10 ml were taken from 1 cm-thick slices of core Gs29. The slices were 10 cm apart, starting at 5 – 6 cm below the seafloor (20 samples). For the gravity cores, samples of ~10 ml were taken from the finer grained intervals. Where horizons in the gravity cores showed marked lateral changes in grain size, two samples were taken from the same horizon.

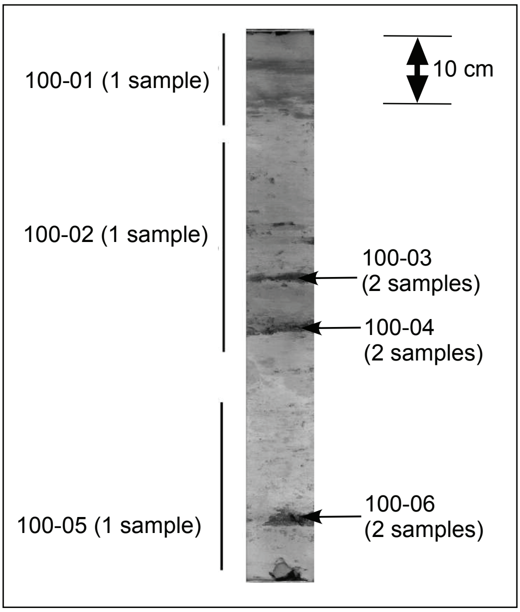

FIG. 3. Locations of samples in core GC59.

Six samples were taken from GC59 and GC99, and nine from each of GC90 and GC100.

All samples were washed over a 63 µm mesh to remove the silt and clay fraction, air dried, and the dried residue spread over a picking tray. Wilson (2008) examined the >125 µm fraction in piston core En20-2, noting that the few species limited to the 63 – 125 µm fraction were few, comprising mostly *Bolivina lowmani* Phleger and Parker and *B. simplex* Phleger and Parker. The abundance of *Bolivina* spp. in the present material required that we pick the entire 63 µm fraction, as exclusion of the finer fraction would have led to the loss of valuable information (Schröder et al., 1987). Specimens were sorted into species that were identified using standard references (Cushman, 1921, 1922; Hofker, 1956, 1976; Phleger and Parker, 1951; Phleger et al., 1953) and mounted onto card microscope slides. We followed Mikhalevich (2014) in regarding the genera *Bolivina* and *Brizalina* as being synonymous.

Statistical Methods

The number of specimens recovered per sample was calculated and the mean abundances for the cores were compared using ANOVA. Cores with very low recovery (mean <100 specimens per sample) were excluded from further statistical analysis. Following the precedent set by Wilson (2008), the specimens were divided into two groups: an allochthonous assemblage of shallow water species, and a presumed autochthonous assemblage of deep water species. The mean percentage abundances of the allochthonous assemblages were compared between the cores with abundant recovery using Student’s *t*-test. Other statistical analyses were restricted to the autochthonous assemblages.

The dominant species in each core was identified, and the mean percentage abundances of these species compared between the cores. The mean percentage abundances of *Planulina ariminensis* d’Orbigny plus *Cibicidoides wuellerstorfi,* used as a proxy for bottom current strength (Singh et al., 2015), were likewise compared.

The benthic foraminiferal high productivity index (BFHP) of Martins et al. (2007) was calculated for cores Gs29, GC100 and the top sample in GC99. This consists of the proportion of the autochthonous, deep-water assemblage as bolivinids, buliminids, *Fursenkoina* spp., *Uvigerina* spp. and *Valvulineria* spp. While it was possible to plot the stratigraphic change in Gs29, only the mean for GC100 and the value for the top sample in GC99 could be plotted.

Hayek and Wilson (2013) introduced a simple quantitative measure, the Assemblage Turnover Index (ATI), which uses changes in species’ proportional abundances to identify intervals of marked community change. For a set of samples from a given site, the ATI for each pair of adjacent samples is defined as $\mathrm{ATI} = \sum \left| p_{i2} - p_{i1} \right|$, in which p_{i1} and p_{i2} are the proportional abundances of the ith species in the lower and upper samples. Wilson et al. (2014) noted that the mean values of ATI through a section is an index of community stability, lower mean values of ATI indicating more stable communities. Low mean ATI does not necessarily reflect an unstressed environment; Wilson et al. (2014) found low mean values in suboxic environments. Here we calculate the mean value of ATI for Gs29. Because of the way the samples were taken from the gravity cores, some horizons being represented by more than one sample, it was not possible to calculate mean ATI for these cores in a stratigraphically meaningful way.

RESULTS

The mean number of total (autochthonous + allochthonous) benthic foraminifera recovered per sample in each core were compared using ANOVA. The means varied widely, ranging from 6 specimens per sample in GC59, taken closest to the KeJ crater, to 242 specimens per sample in GC100, farthest NW of the crater. The mean recovery in Gs29, taken south of the crater, was 219 specimens per sample. GC59, GC90 and GC99 all yielded a mean of ≤ 31 specimens per sample and are excluded from further statistical analyses. However, comparison is made with the uppermost sample in GC90, which yielded 102 specimens. The ANOVA and *post hoc* Tukey's Q showed that the mean recovery per sample from GC100 (range 28 – 398 specimens per sample) and Gs29 (71 – 365 specimens per sample) did not differ significantly.

The allochthonous component consisted principally of (a) *Amphistegina gibbosa* and (b) a species of *Cibicides* with a distinctly flat attachment surface that is presumed to have had a shallow water, epiphytal habit (cf. Langer, 1993). Also recovered were shallow-water miliolids. Student's *t*-test showed that the mean proportions of total foraminifera as allochthonous specimens in Gs29 (allochthonous = 1.4 – 30.0% per sample, mean 12.1%) and GC100 (20.2 – 47.4% per sample, mean 29.5%) were significantly different ($t = 5.36$, $p < 0.0001$, df = 27). Sample 1 from GC99 yielded 28.4% allochthonous specimens, comparable to the mean recovery from GC100. A cautious comparison is made with the percentage abundance of allochthonous specimens in Cores En20-2 (magmatic arc platform; Figure 1) and En20-10 (northernmost Grenada Basin), from which the >125 μm fraction was examined by Wilson (2008, 2011). The percentage of allochtnonous specimens in En20-2 (mean 40.9% per sample) was far higher than that from Gs29 and GC100, while that from En20-10 (mean 24.1%) was comparable to that in GC100.

Gravity Core GC100 yielded 1515 specimens of autochthonous (lower bathyal) benthic foraminifera in 103 species from 9 samples (mean, 168 specimens per sample). Total recovery was dominated by *Cassidulina carinata* Silvestri (36.0% of total recovery; Figure 4A) with lesser *Gyroidinoides orbicularis* d'Orbigny (7.5%), *Cibicidoides pseudoungerianus* (Cushman) (6.1%) and *Cassidulina curvata* Phleger and Parker (5.0%). *Bolivina* spp. formed 2.1% of total recovery, while *Bulimina* spp. formed 2.4% and *Cassidulina* spp. formed 41.7% (Figure 4). *Planulina ariminensis* formed 4.4% of the total recovery.

In contrast, Core Gs29 yielded 3820 specimens of autochthnous (lower bathyal) benthic foraminifera in 88 species from 20 samples (mean, 191 specimens per sample). The fauna in Gs29 was dominated by *C. carinata* (15.3% of total recovery; 1.1 – 32.2% per sample) with lesser *P. ariminensis* (7.5% of total recovery) and *Bolivina lowmani* Phleger and Parker (6.7%). *Bolivina* spp. formed 26.3% of the total recovery, *Cassidulina* spp. formed 15.3% and *Bulimina* spp. formed 2.2%. The autochthonous component in the uppermost sample 1 from GC99 was dominated by *C. carinata* (45.2%), with lesser *Oridorsalis umbonatus* (Reuss)*, Globocassidulina murrhina* and *G. orbicularis* (all 5.5%). *Bolivina* spp. and *Bulimina* spp. both formed 2.7% of the recovery from this sample.

The benthic foraminiferal high productivity index (BFHP) in core Gs29 ranged between 0.178 – 0.591 (mean, 0.349; Figure 4B). In Core GC100, BFPH ranged between 0 – 0.106 (mean, 0.054). These means differed significantly (Student's $t = 8.72$, $p < 0.0001$, df = 28). The BFHP in the uppermost sample from Core GC99 (0.068) was comparable to that in GC100.

The percentage recovery per sample of the autochthonous assemblage as the current indicators *P. ariminensis* and *C. wuellerstorfi* in GC100 ranged between 0.5 – 19.1% (mean,

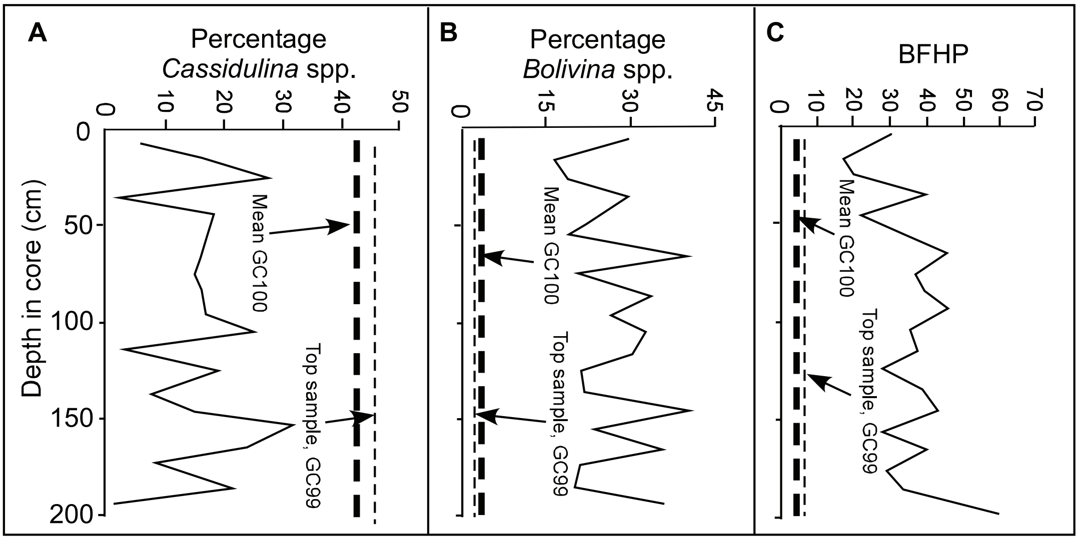

FIG. 4. Selected measures from core Gs29, their mean values in core GC100 (thick dashed line), and values for the uppermost sample in core GC99 (thin dashed line). A. Percentage *Cassidulina* spp. B. Percentage *Bolivina* spp. C. Benthic foraminiferal high productivity (BFHP) proxy.

9.8%), while in Gs29 it ranged between 0 –28.9% (mean, 9.0%). Student's *t*-test indicated that these mean percentages did not differ significantly (t = 0.30, p = 0.76, df = 27).

The Assemblage Turnover Index (ATI) in core Gs29 ranged from 1.04 – 1.81 (mean 1.32). For comparison, the mean ATI in core En20-2 and En20-10 was much lower (0.84 and 0.86 respectively) and did not differ significantly between the cores. In view of the coarser (>125 µm) size fraction examined in the En cores, comparisons between the mean ATI in these and core Gs29 have been made with caution.

DISCUSSION

Wilson (2012) concluded from the faunal differences between cores En20-2 and En20-10 that the northern Lesser Antilles at least comprise an area of considerable complexity with regard to the distributions of Late Quaternary benthic foraminiferal assemblages. He expressed the hope that his observations would lead to further work examining foraminiferal distributions throughout the Lesser Antilles. This study contributes to such further work, demonstrating considerable variation in the benthic foraminiferal community around KeJ and elsewhere in the southern Grenada Basin.

Phleger (1976) suggested that the composition of the benthic foraminiferal fauna at a site is in part a function of primary productivity in near surface waters. The comparative impacts of surface productivity and the dissolved oxygen levels of water flowing into the Caribbean Sea on the benthic foraminiferal assemblage are not yet known. Galluzzo et al. (1990) did not consider the impact of the surficial, high productivity, hypopycnal Orinoco Plume, which enters the Grenada Basin from the SE (Del Castillo et al., 1999; López et al., 2013), when interpreting the bathyal and abyssal foraminiferal assemblages, instead relating the distribution of the Holocene, deep-sea benthic foraminifera in the basin to the flow of Subantarctic Intermediate Water (SAIW) and Caribbean Bottom Water (CBW). The Orinoco plume has subsequently been shown to impact the foraminiferal fauna profoundly (Wilson and Costelloe, 2011; Wilson and Hayek, 2015b), inducing the development of faunas tolerant of a high nutrient loading. Galluzzo et al. (1990) found a low-oxygen assemblage dominated by *Bulimina* spp., *Osangularia culter* and *Uvigerina* spp. along the western edge of the Grenada Basin between 1,000 and 2,100 m, and *C. wuellerstorfi* around the basin centre.

Although *C. wuellerstorfi* attests to strong current action, this species is capable of living in suboxic water (Burkett et al., 2016) at organic carbon flux rates of 0.2 – 15 g m^{-2} yr^{-1} (Altenbach et al., 1999, 2003), suggesting that the Orinoco Plume may impact the benthic foraminiferal fauna over much of the southern Grenada Basin. Martins et al. (2007) noted *B. aculeata* to be indicative of high productivity regions, and its abundance in the western Grenada Basin likewise apparently reflects the influence of the Orinoco Plume. However, Wilson's (2012) core En20-2 presented an assemblage comparable to that the low-oxygen, high-nutrient fauna recorded by Galluzzo et al. (1990), *Bulimina* spp. and *Uvigerina* spp. collectively forming 14.7% of the total recovery, although this core was taken beyond the limits of the Orinoco Plume (Agard and Gobin, 2000). The distribution of foraminifera around KeJ must be interpreted against this background of complex regional variability in the benthic foraminiferal fauna.

The mean recovery per sample was lowest in core GC59, taken closest to the volcanic crater. It is unclear to what extent this reflects the impact of the slump at the site of GC59. However, recovery from cores GC90 and GC99, taken beyond the limit of the slump recorded by Dondin et al. (2011), was also low (mean ≤31 specimens per sample). This apparently reflects the redistribution of volcanic ash from the KeJ crater by the NW-flowing surficial Caribbean Current (Chérubin and Richardson, 2007; Richardson, 2005) which flows at a rate of ~60 cm/s (Molinari et al., 1981). Core GC99, which had an impoverished fauna, was taken ~27.3 km from the crater, whereas GC100, with a rich fauna, was taken ~38 km from it. These distances provide some indication of the limit of the impact of ash from KeJ NW of the crater. It also suggests that the flux of fresh volcanic ash creates an environment inimical to benthic foraminifera, despite the fact that KeJ lies within the high productivity Orinoco Plume. Note, however, that the gravity cores apparently did not come from hydrothermal vent areas comparable to those reported as supporting a foraminiferal fauna by Molina-Cruz and Ayala-López (1988). The paucity of foraminifera in the proximal cores might limit their usefulness for carbon-14 dating of slump deposits.

Reid et al. (1996, p. 90) suggested that poor nannofossil preservation below 2 m in the clay-rich core Gs29 might result from corrosive pore water, possibly because of the decomposition of organic matter rather than any cause related to volcanic activity. This organic matter might be derived from outflow from the Orinoco River, which forms a nutrient-rich, hypoycnal plume near the sea surface (see Agard and Gobin, 2000; Grodsky et al., 2014; López et al., 2013). In view of this potential dissolution, we studied only the uppermost 2 m of this core. The difference in foraminiferal assemblages in Gs29 and GC100 is comparable to the difference in assemblages in En20-2 and En20-10 from the Leeward Islands noted by Wilson (2011) and attests to the small-scale variability of the benthic foraminiferal fauna throughout the Lesser Antillean island arc and Grenada Basin. There are three possible explanations for the dominance of *Bolivina* spp at the site of Gs29 compared to GC100: (1) low dissolved oxygen concentrations, (2) selective dissolution of calcareous foraminifera by hydrothermal activity, and (3) selective dissolution by acids released during the decay of organic matter. There is some support for each of these suggestions.

Kaiho (1994), Murray (2006), Kuhnt et al. (2013) and Moffitt et al. (2014) noted that an abundance of *Bolivina* spp. reflects low dissolved oxygen concentrations. This may be related to a high nutrient flux associated with the Orinoco Plume, possibly augmented by the development of a nutrient-rich eddy to the NW of Grenada (cf. Emery, 1972). If so, then the relative rarity of this genus at GC100 would indicate higher dissolved oxygen concentrations at this site, as is reflected in the difference in the mean benthic foraminiferal high productivity index (BFHP) between these two sites (mean at Gs29 = 0.349, mean at GC100 = 0.053). The distribution of *Cassidulina* spp, which are proportionally more abundant at site GC100 than at Gs29, may support this interpretation of differing productivity and dissolved oxygen concentrations. *Cassidulina* spp. are able to occupy environments with somewhat depressed dissolved oxygen levels (Kaiho, 1994) but thrive in well oxygenated areas also (Mullins et al., 1985). *Cassidulina carinata*, the most abundant subspecies of this genus recovered, is known to have a particularly wide ecological niche (Hayward et al., 2013) suggestive of this being a generalist species *sensu* Wilson and Hayek (2015a).

The abundance of *Bolivina* spp. at the site of Gs29 might reflect selective solution comparable to that noted in hydrothermal areas by Molina-Cruz and Ayala-López (1988), who found "only small species" (*Bulimina* and *Bolivina*). The enhanced dissolution of calcareous microfossils lower in the core (Reid et al., 1996) might support such a conclusion, although it might also reflect dissolution of specimens in acidic waters associated with a rock rich in organic matter (explanation 3 in the list given above). However, the benthic foraminifera recovered from Gs29 did not consist of small species only, as found by Molina-Cruz and Ayala-López (1988), which would suggest that hydrothermal dissolution off KeJ is not as vigorous as in the Guaymas Basin, Mexico. Another factor militates against hydrothermal activity or organic matter being the cause of abundant *Bolivina* spp. in Core Gs29; Kaiho (1994) suggested that species of *Cassidulina* with high porosity tests might related to the difficulty of secreting calcium carbonate. The dominant subspecies of *Cassidulina* recovered here (*C. carinata*) is finely perforate, suggesting that calcium carbonate concentration at the site of Gs29 was not a problem, despite the carbonate dissolution in older sediment at this site noted by Reid et al. (1996).

The reason for the lower dissolved oxygen concentrations at the shallower site Gs29, if this is indeed what is indicated by the abundant *Bolivina* spp. there, is unclear. There are, however, four possibilities. First, it might be related to the development of an as-yet-undocumented eddy in the surface water, comparable to that noted in the lee of Barbados by Emery (1972), inducing high surface productivity and an enhanced organic carbon rain to the site of Gs29. Such an eddy might be expected to influence the summit of KeJ, which currently lies at 190 m below the sea surface, perhaps encouraging the development of the polychaete community reported by Graff et al. (2008) by enhancing surface productivity. Second, it might reflect an eddy in deep-water currents in the lee of Grenada leading to the accumulation of fine grained sediment rich in organic matter, in turn derived from surface productivity within the Orinoco Plume. However, this hypothesis regarding deep-sea currents appears unlikely, the mean percentage abundances of the current indicators *P. ariminensis* and *C. wuellerstorfi* not differing between the cores Gs29 and GC100. Third, palaeoproductivity may have changed over time, the sediment in Gs29 being deposited in Ericson zone U but there being no reason to believe that that in GC100 is older than Holocene. Finally, it is possible that the formation of KeJ during the last few hundred years (Bouysse et al., 1988) has had some impact on the foraminiferal fauna, the sediment in Gs29 being deposited prior to the volcano's formation and that in GC100 after. The precise nature of this influence is unclear, however. We favour the first hypothesis, although we admit that this requires further work.

Saunders et al. (1985) suggested that the shallow-water, larger foraminifera recovered from the Eocene Tufton Hall Formation on Grenada were transported by turbidites. However, this was not the case for the allochthonous specimens (principally *Amphistegina gibbosa*) found in the present study, there being only two thin turbidites in core Gs29 but allochthonous specimens throughout. They may instead have been transported by combined wave and current action during hurricanes and tropical storms. *Amphistegina gibbosa* lives predominantly in fore reef areas (Martin and Liddell, 1988) but has a high susceptibility to transport by wave action (Martin and Liddell, 1991). The comparatively low percentage of allochthonous specimens in Gs29 may have arisen from the mass of Grenada protecting leeward reefs around the island during storms, thus reducing the transport of reefal specimens to the GS29 site. The much smaller Ronde Island would provide little protection for leeward reefs during storms, enhancing transport to the site of GC100.

The mean ATI of 1.32 in core Gs29 was higher than those recorded in cores En20-2 and En20-10, from the Leeward Islands. It is not clear to what extent this reflects the difference in the size fraction examined in these cores. Wilson and Hayek (2015b) examined the >63 µm benthic foraminifera in a piston core, BGT086, taken from the Orinoco fan at a depth of 626 m, within the Orinoco plume. Mean ATI across the entire core was 0.61. This suggests that the benthic foraminiferal community on the fan has been more stable than that recovered from Gs29.

CONCLUSIONS

The benthic foraminiferal meiofauna is impoverished to the NW of the KeJ crater for a distance of 0 – 35 km. This implies that the regular (approximately decadal) input of nutrient-poor ash limits colonisation of the area by foraminifera, despite KeJ lying beneath the high productivity Orinoco Plume.

The benthic foraminiferal fauna recovered includes a considerable allochthonous component derived from fore-reef areas, though this was more abundant in the more distal core GC100. This component is apparently not delivered by turbidity currents, but perhaps transported by wave and current action associated with hurricanes.

The fauna from core GC100, taken NW of KeJ, contains abundant *Cassidulina* spp, while that from Gs29, taken from the south of KeJ, contains many *Bolivina* spp. This is reflected in the higher benthic foraminiferal high productivity (BFHP) index at Gs29. This may be related to an eddy in surface water in the lee of Grenada inducing higher surface productivity and enhancing the rain of organic matter to the seafloor in this area. Alternatively, there may have been a long term change in productivity throughout the entire region.

The densities of foraminifera in samples containing pyroclastic material appear to have potential as a tool for mapping the areal impact of volcanic eruptions on benthic marine meiofauna. However, differences in the composition of the fauna may be related to other factors such as small-scale variations in surface-water productivity.

Acknowledgements.—The authors thank the National Science Foundation grant OCE-0956368 for providing support at the University of Rhode Island for the curation and the distribution of the samples used, and to two anonymous reviewers for their valuable comments. BW acknowledges a contribution towards this work from the Campus Research and Publications Fund of the University of the West Indies. This paper is dedicated to late UWI Emeritus Prof. Trevor A. Jackson, who facilitated this stimulating collaboration.

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