Data Descriptor: Sixty-one thousand recent planktonic foraminifera from the Atlantic Ocean

Leanne E. Elder1, Allison Y. Hsiang1,2, Kaylea Nelson1, Luke C. Strotz1,3, Sara S. Kahanamoku1,4 & Pincelli M. Hull1

Marine microfossils record the environmental, ecological, and evolutionary dynamics of past oceans in temporally expanded sedimentary archives. Rapid imaging approaches provide a means of exploiting the primary advantage of this archive, the vast number of fossils, for evolution and ecology. Here we provide the first large scale image and 2D and 3D shape dataset of modern planktonic foraminifera, a major microfossil group, from 34 Atlantic Ocean sediment samples. Information on more than 124,000 objects is provided, including general object classification for 4/5ths of the dataset (~99,000 objects). Of the ~99,000 classifications provided, more than 61,000 are complete or damaged planktonic foraminifera. Objects also include benthic foraminifera, ostracods, pteropods, spicules, and planktonic foraminifera test fragments, among others. This dataset is the first major microfossil output of a new high-throughput imaging method (AutoMorph) developed to extract 2D and 3D data from photographic images of fossils. Our sample preparation and imaging techniques are described in detail. The data provided here comprises the most extensive publicly available archive of planktonic foraminiferal morphology and morphological variation to date.

| Design Type(s) | image analysis objective • observation design • biodiversity assessment objective |
| Measurement Type(s) | two-dimensional spatial region • morphology |
| Technology Type(s) | imaging method • morphometry |
| Factor Type(s) | geographic location |
| Sample Characteristic(s) | Foraminifera • North Atlantic Ocean • marine sediment • South Atlantic Ocean |

1Department of Geology and Geophysics, Yale University, Yale 06520, USA. 2Department of Bioinformatics and Genetics, Swedish Museum of Natural History, Stockholm 810 90, Sweden. 3Biodiversity Institute and Department of Ecology and Evolutionary Biology, University of Kansas, Kansas 66045, USA. 4Department of Integrative Biology and Museum of Paleontology, University of California, Berkeley, CA 94720, USA. Correspondence and requests for materials should be addressed to P.M.H. (email: pincelli.hull@yale.edu).
Background & Summary

Paleontology and evolutionary biology are in the midst of a revolution driven by the proliferation of three-dimensional imaging technologies\(^1\)\(^2\). Nano- to micro-CT scanning and synchrotron-based tomography provide powerful tools for addressing questions of ontogeny, morphology, ecology, and phylogeny through submicron-scale volumetric resolution of fossils\(^1\)\(^3\)\(^5\). Population-level studies of 3D-morphological evolution have remained relatively rare, however, due to the time and data intensive nature of these approaches\(^5\). To address this gap, we have developed a high-throughput approach for extracting 2D and 3D shape information from photographic images called \textit{AutoMorph}\(^6\)\(^7\) and have used this technique to generate extensive image and shape data for modern planktonic foraminifera.

Planktonic foraminifera are mixotrophic protists with calcium carbonate tests found primarily in the sunlit layers of the global ocean\(^6\)\(^9\). Due to their abundant fossil record and importance in paleoceanographic research, planktonic foraminifera and other microfossil groups (i.e., coccolithophores, radiolarians, and diatoms) have been the focus of many (semi-)automated approaches for extracting information on factors like size, 2D shape, calcite thickness, and species\(^10\)\(^–\)\(^13\). Despite this long history of extensive imaging, there are few shared datasets consisting of the primary data (i.e., original images and measurements) of the many of millions of microfossil measurements and images made to date (see \url{http://data.nhm.ac.uk/dataset/henry-buckley-collection-of-planktonic-foraminifera}), likely due to difficulty of sharing large files in the past\(^14\). Even the growing number data aggregators and archives like iDigBio, MorphBank, MorphoBank, and Figshare, have remits and/or storage limitations that preclude the storage of large datasets like the one we described here. This data sharing gap is important because it precludes the data being re-used for other purposes, including documenting the range of morphological variation within planktonic foraminiferal species.

Here we provide an extensive image library of modern planktonic foraminifera, with accompanying 2D and 3D coordinate data and morphometric measurements from Atlantic Ocean core top sediment samples. Images of 61,849 complete and damaged planktonic foraminifera are provided along with accompanying 2D and 3D morphometric data for nearly all objects (i.e., 57,304 of the complete and damaged planktonic foraminifera provided were successfully extracted for 2D and 3D shape). Images and shape data for another ~37,000 classified objects is also provided in categories including planktonic foraminiferal fragments, pteropods, ostracods, etc. (see Methods for further details). We have withheld the object identities for 1/5th of the entire sample set (24,846 of the ~124,000 total objects) so that these images can be used as the test set for automatic image recognition algorithms (i.e., machine learning).

We primarily sampled morphological variation in the North Atlantic for practical and theoretical reasons. The vast majority of the roughly fifty morphological species of extant planktonic foraminifera are found in all ocean basins and hemispheres\(^15\)\(^\text{–}\)\(^16\), with morphological and genetic differentiation across environmental gradients\(^9\)\(^\text{–}\)\(^17\). Thus, while the dataset presented here primarily describes North Atlantic variation, it should be broadly representative of global variation in community morphology. From a practical perspective, we sampled in the Atlantic in order to obtain the best-preserved fossils. The Atlantic Ocean has far more well-preserved, carbonate-rich deposits, due to younger (i.e., less acidic) bottom waters and shallower average depths than the Pacific and Indian Oceans\(^18\)\(^\text{–}\)\(^19\). Preservation was important to ensure that we captured variation in morphology arising primarily from processes acting on living, rather than dead\(^20\)\(^\text{–}\)\(^21\), foraminifera.

Fossils were imaged and shapes extracted using automated slide scanning and a high-throughput image processing pipeline (\textit{AutoMorph}), developed in-house to rapidly extract 2D and 3D shape information from light microscopic images\(^6\)\(^7\). Because the \textit{AutoMorph} pipeline is relatively new, we describe in detail our sampling and imaging protocols for samples dominated by planktonic foraminifera. Relevant usage notes for this dataset are also provided. The \textit{AutoMorph} software is available and frequently updated on GitHub (\url{https://github.com/HullLab}), and the images and shape data are available on Zenodo (\url{http://doi.org/10.5281/zenodo.165514}). The publically available dataset presented here provides the most extensive images, 2D and 3D shape documentation of the range of morphological variation observed in recent planktonic foraminifera to date, and provides a baseline for considering variation in morphology across both time and space.

Methods

Sample Selection and Preparation

Discerning the relative importance of environment, preservation, and biotic interactions on patterns observed in fossil assemblages often requires considering individual fossils in the context of their sedimentary environment and broader sample assemblage\(^22\). With this in mind, we imaged entire assemblages of fossils and sedimentary constituents from our 31 core top sediment sites from the North Atlantic and three core top sites from the South Atlantic (Fig. 1). Sites were chosen so as to span the five major planktonic foraminiferal faunal provinces identified by previous authors\(^15\), utilizing splits of core top fossil collections from B.H. Corliss (University of Rhode Island), R.D. Norris (University of California, San Diego), and M.J. Henehan (Yale University) (Table 1). Additional core top samples obtained from the Lamont-Doherty Core Repository for this study were dried, washed with deionized water over a 63μm sieve, and dried again at 50°C (see also Table 1). Sites and samples are from water depths above ~ 4000 m and had good to excellent preservation. To directly test for preservational effects, a few sites were selected along bathymetric depth transects (see Water Depth in Table 1). 'Depth Interval'
(depth below the sediment-water interface) varied from a minimum of 0-0.5 cm core depth to a maximum of 0-3 cm (Table 1), with broader depth ranges generally corresponding to a greater amount of geological time captured by the sample. Some of the core tops provided by B.H. Corliss had age estimates determined on the basis of benthic foraminifera oxygen isotopes (Table 1).

All core top samples were sieved to obtain the >150 μm fraction. The >150 μm fraction was then subsampled with a micropaleontological microsplitter down to ~5000 objects (primarily composed of planktonic foraminifera). Subsampled objects were arranged and lightly glued to plain black micropaleontological slides using a binocular stereo microscope (Fig. 2). Foraminifera were oriented with the umbilical side facing up, and fragments and ostracods were oriented with the concave side up. We aimed to mount ~1000 objects per slide, in order to prevent adjacent objects from touching, for a total of between 3–6 prepared slides for each subsample of ~5000 objects. In all, 155 slides were prepared from the 34 sites (Table 2 (available online only)).

Imaging

Prepared slides were imaged using a 5-megapixel Leica DFC450 digital camera mounted on a Leica Microsystems DM6000M compound microscope with a drive focus and motorized x-y scanning stage. The microscope system is controlled by Surveyor Software (Version 7.0.1.0, Objective Imaging Ltd) run on a Dell computer (3 TB Solid-State Drive, 3.7 GHz processor) coupled to an OASIS-blue 3 Stage Controller (Objective Imaging Ltd) and a 5-megapixel Leica DFC450 digital camera. Three slides were prepped and scanned at a time using Surveyor’s multi-slide scanning mode (i.e., Navigator mode), which allows for multiple user defined scanning regions and variable background heights. Under our imaging pipeline, every slide scan generates a stack of raw slide images (called planes) at different z-axis heights. The number of planes per slide depends on the z-step size and the z-range (i.e., vertical extent of the volume imaged). All slides in this study were imaged with a z-range of 950 μm and a z-step size of 31.1 μm. Every slide region defined in Navigator was imaged and saved as a series of BigTIFFs: one BigTIFF for every z-plane through the slide and a single extended-depth-of-field (EDF) composite image. The BigTIFF image format is an extension of the more common Tiff file format, but is designed for large images (>4GB). In this study, all slides were imaged with a 5x objective and illuminated with dark field lighting.

Figure 1. Map of sample locations. Sites investigated in this study, shown with Yale Peabody Museum (YPM) site numbers. Additional site information provided in Table 1.
Table 1. Metadata for collection and locality of sediment core samples used in this study. Sample Information. Metadata includes: Yale Peabody Museum (YPM) Site Number, International Geo Sample Number (IGSN); when available, and details of the research cruise and core recovery: Research Vessel, Ship Abbreviation, Cruise ID, Leg, Station Number, Core Number, Latitude, Longitude, and Water Depth at the sea floor. Coring Device indicates the approach used to obtain the samples and includes: gravity core (GC), piston core (PC), pilot gravity core (PG), Knight Core (KC), Box Core (BC), and multicore (MC). Although all samples were targeted as core top samples (i.e., from the surface of the sea floor), the precise depth in the core from which the sample came is indicated as the Depth Interval. Source is the researcher and/or repository from which the sample came or was provided from. Samples from B.H. Bruce Corliss had age data that were published in Sun et al. (2006) and are provided here.

**AutoMorph** (automated morphometric post-processing)
Imaged slides were processed with the *AutoMorph* software package (http://github.com/HullLab), a bioinformatics pipeline designed to segment individual objects from light images and extract 2D and 3D shape information.\(^6,7\) There are four major routines in *AutoMorph*: `segment`, `focus`, `run2dmorph`, and `run3dmorph`. The first two routines (`segment` and `focus`) identify all the unique objects in a raw image (i.e., a scanned slide), extract and label all the objects from the raw images, and save the individual z-slices in unique directories, generating a single best 2D extended depth of focus (EDF) image for each object. Two different programs can be used to generate the best 2D EDF: the commercially

---

**Table 1. Metadata for collection and locality of sediment core samples used in this study. Sample Information.** Metadata includes: Yale Peabody Museum (YPM) Site Number, International Geo Sample Number (IGSN); when available, and details of the research cruise and core recovery: Research Vessel, Ship Abbreviation, Cruise ID, Leg, Station Number, Core Number, Latitude, Longitude, and Water Depth at the sea floor. Coring Device indicates the approach used to obtain the samples and includes: gravity core (GC), piston core (PC), pilot gravity core (PG), Knight Core (KC), Box Core (BC), and multicore (MC). Although all samples were targeted as core top samples (i.e., from the surface of the sea floor), the precise depth in the core from which the sample came is indicated as the Depth Interval. Source is the researcher and/or repository from which the sample came or was provided from. Samples from B.H. Bruce Corliss had age data that were published in Sun et al. (2006) and are provided here.

**AutoMorph** (automated morphometric post-processing)
Imaged slides were processed with the *AutoMorph* software package (http://github.com/HullLab), a bioinformatics pipeline designed to segment individual objects from light images and extract 2D and 3D shape information.\(^6,7\) There are four major routines in *AutoMorph*: `segment`, `focus`, `run2dmorph`, and `run3dmorph`. The first two routines (`segment` and `focus`) identify all the unique objects in a raw image (i.e., a scanned slide), extract and label all the objects from the raw images, and save the individual z-slices in unique directories, generating a single best 2D extended depth of focus (EDF) image for each object. Two different programs can be used to generate the best 2D EDF: the commercially
available Zerene Stacker (ver. 201404082055) and the open source ImageJ. We generated all 2D EDFs with Zerene Stacker because it consistently produced better EDF images. The second two routines (run2dmorph and run3dmorph) extract shape coordinates and basic measurements in 2D and 3D, respectively, along with images of the 2D and 3D shape extraction for quality control. This software package is freely available on GitHub (http://github.com/HullLab) and the methods are described in detail in two publications. Because we developed AutoMorph to generate this data set, code updates were made over the course of the project. Code versions and processing dates are listed in Table 2 (available online only) to track these revisions. AutoMorph is adapted to run on local computers and clusters, and this dataset was generated using both.

Once slide images were processed, all unique objects were identified by human observers (PMH and LEE) to one of 16 categories (Fig. 3) using classify (available at http://github.com/HullLab). classify is a custom-made application for viewing and assigning general object information to images (Supplementary Table 1). Supplementary Table 1 lists the classification (Object Type) of all objects (listed by Object ID) by slide (YPM Catalog Number), along with classification confidence (Certainty). In total, 124,230 unique objects from 155 slides were segmented and classified (Supplementary Table 1, and Table 3). In Supplementary Table 1, we provide information for 4/5ths of the sample set (99,384 objects). The remaining 1/5th of the sample set (i.e., 24,846 objects) is listed only as withheld so that these objects can be used to test machine learning algorithms trained on the dataset provided here. Table 3 indicates the number of objects in each object category by sample site.

Data Records

Metadata and images are provided for all 124,230 objects in the data set, with 2D and 3D shape information successfully extracted from 109,198 objects. Of the 61,849 complete and damaged planktonic foraminifera identified here with images and metadata, 57,304 also have accompanying 2D and 3D shape information and an additional 2,500 have 2D shape information only. The tables in this data report provide relevant metadata, summary statistics, and details on the technical validation of measurements. Sample identity, location, source, and handling information is provided in Table 1 and visualized in Fig. 1. Table 2 (available online only) provides relevant image processing information for the shape extraction pipeline in AutoMorph. The basic workflow is likewise shown in Fig. 2. The sixteen major categories used for classification are listed in Fig. 3 and the object classification results are provided in Supplementary Table 1 and summarized in Table 3. Because 2D and 3D shape and size information was extracted automatically, Table 4 provides technical validation for ten objects measured by stage micrometer, in ImageJ, and with all the various AutoMorph code versions used in this study. The data products of this research are all available on Zenodo (Data citation 1). The Zenodo data citation includes nine distinct data types uploaded as 13 distinct files and includes:

i) slide_images.tar.gz: 155 slide images with boxed objects identified by segment
ii) edf_images.tar.gz: 124,230 EDF images; i.e., one image for each object in the dataset
iii) obj_zstacks_part1.tar.gz and obj_zstacks_part2.tar.gz: combined, parts 1 & 2 contain 124,230 object specific subdirectories each with the original zstack images for the specific object
iv) 2d_outline_check.tar.gz: 113,847 EDF images of the objects successfully extracted for 2D outlines (included for quality control) and one text file (unextracted_objects_2D.txt) listing the 10,384 objects with failed extractions
v) 2d_coordinates.tar.gz: 155 CSV files containing all extracted outline coordinates for each of the 155 slides imaged, a text file of failed 2D extractions (unextracted_objects_2D.txt), and a summary CSV file including coordinates for all extracted objects (all_coordinates.csv)
vi) shape_measurements.csv: 2D and 3D measurements for all 124,230 objects
vii) metadata_tables.tar.gz: Tables 1–4 and Supplementary Table 1 from this contribution, detailing the sample set metadata (i.e., site, sample, object information, and summary statistics about the dataset)
viii) 3d_pdf5_part1.tar.gz and 3d_pdf5_part2.tar.gz: combined, parts 1 & 2 contain 109,207 3D PDFs of objects successfully extracted for 3D shape (included for quality control) and one text file (unextracted_objects_3D.txt) listing the 15,023 objects with failed extractions
ix) 3d_obj_files_part1.tar.gz, 3d_obj_files_part2.tar.gz, and 3d_obj_files_part3.tar.gz: combined, parts 1, 2, and 3 contain 109,207 3D shape coordinate files (.obj files) of objects successfully extracted for 3D shape and the text file of failed 3D extractions (unextracted_objects_3D.txt). The first data product, the slide images of boxed objects, is also available in a low resolution version on the Yale Peabody Museum’s collection portal (http://collections.peabody.yale.edu/search/), under the division of Invertebrate Paleontology, by searching with the YPM collection number listed in Table 2 (available online only).

**Technical Validation**
Technical validation occurred at a number of steps in the image processing pipeline, and included object selection, shape extraction, size measurements, and object classification.

**Object Selection**
The *AutoMorph* segment module saves a slide overview (a low resolution EDF) with each identified individual object boxed in red (Fig. 2; full sample set of boxed objects available in slide_images.tar.gz in...

| Category   | Definition                                           | Example |
|------------|------------------------------------------------------|---------|
| Agglutinated | Agglutinated foraminifera or frag.                  |         |
| Benthic    | Benthic foraminifera or fragment                     |         |
| Clipped    | Image clipped by segmentation                        |         |
| Complete   | Complete planktonic foraminifera                     |         |
| Damaged    | Damaged planktonic foraminifera                      |         |
| Diatom     | Diatom frustule                                      |         |
| Echinoid spine | Echinoid spine                                      |         |
| Fragment   | Planktonic foram. fragment                           |         |
| Unknown    | Unknown objects and junk images                      |         |
| Mollusk    | Mollusk shell or fragment                             |         |
| Ostracod   | Ostracod shell or fragment                            |         |
| Radiolarian | Radiolarian                                          |         |
| Rock       | Rock, mineral, or rock-like object                    |         |
| Spicule    | Spicule                                              |         |
| Tooth      | Ichthyolith (tooth, denticle, bone)                   |         |
| Touching   | Touching objects                                     |         |

*Figure 3. Illustrated classification categories with expanded definitions.*
Table 3. Summary statistics of object classifications summarized by YPM Site Number. Number of slides per site (# of YPM Catalog Numbers per Site), withhold object IDs per site (# Withheld per Site), categorized objects per site (# Categorized per Site (excluding Withheld)), and objects per site (# of Objects per Site (Categorized+Withheld)) listed in bold. Object classification counts summarized by object type at the bottom as ‘Column Totals’.

---

**Shape Extraction**

2D EDF images of individual objects were generated by the focus module and this output was checked by re-segmenting three slides twice and re-running the software. The number and identity of objects were then cross-checked with the number of objects outputted by all following modules (focus, run2dmorph, and run3dmorph) for each slide.
| Species            | Major Axis | Minor Axis | Major Axis | Minor Axis | Major Axis | Minor Axis | Major Axis | Minor Axis | Major Axis | Minor Axis | Major Axis | Minor Axis | Major Axis | Minor Axis | Major Axis | Minor Axis |
|-------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Orbulina universa | 1          | 700        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides ruber | 2          | 350        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Menardella menardii | 1          | 1100       | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides sacculifer | 1          | 870        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides ruber | 2          | 670        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides sacculifer | 1          | 360        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides ruber | 2          | 380        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides sacculifer | 3          | 380        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |
| Globigerinoides ruber | 4          | 420        | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     | 1369.8     | 2810.0     |

Table 4. Technical validation of automated 2D measurements. This table contains measurements of individual foraminifera from YPM Catalog Number IP.307866. Each individual foraminifer (identified by Species and Specimen) was measured along its minor and major axes with a stage micrometer on a Leica S8APO microscope, and in ImageJ using the scale bar added by the segment module of AutoMorph. Automated size measurements from run2dmorph are also provided as 'AutoMorph μm' for each foraminifer. In one instance, run2dmorph failed to extract the object outline as indicated by the n/a.

the quality and parameters of 3D shape extraction was checked visually using 3D PDFs of object meshes (see 3d_pdfs.tar.gz in data citation). Both run2dmorph and run3dmorph output lists of objects with failed outline (or mesh) extractions. These lists were examined for each slide to ensure that complete foraminifera were included and that specific species were not being disproportionately missed. When problematic (e.g., a large number of complete foraminifera failed to extract), the routines were re-run with different image extraction parameters to ensure the best possible 2D extraction. The same set of image extraction parameters yielded satisfactory results for 3D shape extractions of complete planktonic foraminifera from all samples.

Size Measurements
The accuracy and reproducibility of 2D and 3D size extraction was confirmed with direct measurements. For run2dmorph, a calibration slide (IP.307866), containing ten complete planktonic foraminifera from four species, was used to check 2D size extraction (Table 4). This slide can be viewed in the YPM collections digital database (http://collections.peabody.yale.edu/search/). In total, ten complete planktonic foraminifera from four species were measured along their minor and major axes using a stage micrometer on a Leica S8APO microscope. The calibration slide was also segmented with each of the three code versions of the segment module of AutoMorph, and then processed through run2dmorph to obtain automated measurements of the major and minor axis for each individual foraminifer. The same individuals’ major and minor axis lengths were also measured in ImageJ using each of the three segment outputs. To do this, the ImageJ scale was set using the automatic scale bar added to the image label by segment, and the major and minor axes were drawn by hand. The three measurement types (run2dmorph, ImageJ and stage micrometer) were then compared (Table 4 and Fig. 4). Fig. 4a and b illustrate the relative reproducibility of the fully automated measurements (Fig. 4a: AutoMorph, three segment code versions) versus traditional ImageJ measurements (Fig. 4b: ImageJ). In both panels, object measurements are normalized to the mean measurement to highlight the variation between repeated measurements and the relative reproducibility of both approaches. AutoMorph (Fig. 4a) clearly outperforms hand measurements (Fig. 4b: ImageJ) in reproducibility, although both approaches have no significant difference between batches (AutoMorph one way ANOVA F(2,57) = 0.0154, p = 0.985; ImageJ one way ANOVA F(2,57) = 0.00058; p = 0.999). The small amount of variation that does exist between repeated AutoMorph measurements is due to a switch between a MATLAB code base (the original modules, segment versions 9-3-2014b and 10_27_2015) and a Python code base (segment version 6_17_2016). MATLAB code versions gave identical results, and all Python output was within 0.49 microns of the MATLAB output (Table 4). Repeated hand measurements in ImageJ had as much as a 16 micron difference between measurements. Importantly, all three approaches (AutoMorph, ImageJ, and measurement with a stage micrometer) provide the same average 2D measurements for foraminifera (Fig. 4c). Averaged AutoMorph output and stage micrometer measurements by specimen, as well as averaged AutoMorph output and ImageJ measurements by specimen were not significantly different (ANCOVA F(6,131) = 0.036; p = 1). Together, these tests indicate that AutoMorph provides accurate and reproducible 2D measurements of foraminifera. The accuracy and precision of 3D size extraction was
where the small foraminifera were completely nested within the outline of the larger object. In cases similarly problematic. These combinations were assigned the classification of a sediment chunk should be: agglutinated, a category which includes rock-like objects, but sediment chunks occurred in 'agglutinated', 'touching', 'unknown', and 'rock'. Notably, as a category, 'rock' contained far more rock-like objects than actual lithic fragments. The occurrence of small foraminifera nested within complete, damaged and/or fragments of larger foraminiferal tests was similarly problematic. These combinations were assigned the classification of the larger object in cases where the small foraminifera were completely nested within the outline of the larger object. In cases where the small foraminifera obscured the outline of the larger object, the total image was classified as 'touching'.

Object classification

Extensive spot checks of final EDF image classifications found object classification by human observers to be 99.95% accurate with different types of errors characterizing each classification category. The errors are described briefly here (category listed in quotes followed by a list of object-types included in error), with each classification category described in more detail in Usage Notes. Noted classification errors include ‘agglutinated’: clipped and unknown; ‘benthic’: clipped; ‘clipped’: mollusk and unknown; ‘complete’: damaged, clipped, and touching; ‘damaged’; complete; ‘echinoid spine’: unknown; ‘mollusk”: clipped and touching; ‘fragment’: unknown, mollusk, touching, and radiolarian; and ‘radiolarian’: clipped; ‘rock’: agglutinated. Chunks of consolidated sediment were generally poorly classified. The proper classification of a sediment chunk should be ‘rock’, a category which includes rock-like objects, but sediment chunks occurred in ‘agglutinated’, ‘touching’, ‘unknown’, and ‘rock’. Notably, as a category, ‘rock’ contained far more rock-like objects than actual lithic fragments. The occurrence of small foraminifera nested within complete, damaged and/or fragments of larger foraminiferal tests was similarly problematic. These combinations were assigned the classification of the larger object in cases where the small foraminifera were completely nested within the outline of the larger object. In cases where the small foraminifera obscured the outline of the larger object, the total image was classified as ‘touching’.

Usage Notes

The splits of core top samples used in this study were, to our knowledge, unbiased by previous research efforts undertaken on the material, with exception to the benthic foraminifera. Many of the samples were picked for specific species of benthic foraminifera in the past, so all benthic foraminifera results should be considered as illustrative of some of the species present but not necessarily quantitative representations of their original abundance or full diversity in the samples. More generally, it is worth noting that most of the core top samples used here have a long collection history in other laboratories, so it is possible that selective sampling of some planktonic foraminifera or other species occurred in the past without our knowledge. Besides this effect, it is worth reiterating that the assemblage data provided here comes from death assemblages. In spite of visual evidence for good preservation in most of the core top samples included, selective dissolution of small-bodied and delicate species is known to begin even in the water column26,21, and the assemblages imaged are certainly time-averaged on the scale of hundreds to many thousands of years.

Objects that failed to properly extract for 2D and/or 3D shapes are listed in each of the appropriate data files (i.e., data citation files 2d_outline_check.tar.gz, 2d_coordinates.tar.gz, 3d_pdfs.tar.gz, and 3d_obj_files.tar.gz). Although we include all images extracted by AutoMorph in this dataset, do note that our initial sieve size was 150 microns. Although there are a number of objects smaller than 150 microns in this dataset, they are not representative of the abundance of this size category in the original sample. Rather, they are the rare objects that slipped through our size filter, and should be excluded for most
applications. At least one ancient fossil appears in the core top data set. We have left this ancient fossil in
as an indication of the level of cross-contamination in the lab (very low but potentially present). It is also
possible that this stratigraphically out of place foraminifera was reworked in the sediments or introduced
during handling in other labs. Regardless, users should remove this such outliers in species-specific
applications.

Samples from YPM Sites IPE.08282, IPE.08285 and IPE.08295 were sized fractioned when received
and different sized splits were taken from each size fraction. Here we described the post-processing that
we carried out to insure that images from these samples accurately reflect species and size distributions at
those sites. YPM Site IPE.08282 arrived in three sample jars containing, respectively, the 125–250 μm size
fraction, the 250–315 μm size fraction, and the greater than 315 μm size fraction. The 125–250 μm size
fraction was sieved over a 150 μm sieve and a 1/64th split was mounted on four slides (IP.308160, IP.308161, IP.308162, and IP.308163); a 1/32nd split of the 250–315 μm size fraction was mounted on two
slides (IP.307847 and IP.307848); and a 1/32nd split of the greater than 315 μm size fraction was mounted
on three slides (IP.307849, IP.307850 and IP.307851). This size-fractionated handling of these sites (Sites IPE.08282, IPE.08285 and IPE.08295) is problematic because it introduces a bias by over-
representing certain size classes in the imaged object output. In the case of YPM Site IPE.08282 the largest
two size fractions (the 250–315 μm and the greater than 315 μm size fractions) were over-represented by a
1/32nd split relative to the smallest size fraction (150–250 μm size fraction with a 1/64th split imaged).
To correct for this bias, it was necessary to subsample the object output from these slides to properly
represent the relative distributions of objects in the original sample.

More specifically, for IPE.08282 half the objects were randomly selected and discarded from the
combined object list of IP.307847 and IP.307848 (the 250–315 μm size fraction) and from the combined
object list of IP.307849, IP.307850 and IP.307851 (the greater than 315 μm size fraction), so that all size
fractions contained a ~1/64th split of objects from the original site sample. For YPM Site IPE.08285, the
largest two size fractions (the 250–315 μm and the greater than 315 μm size fractions) were over-
represented by a 1/2nd split relative to the smallest size fraction (150–250 μm size fraction with a 1/16th
split imaged). To obtain a 1/16th split across size fractions, one in every eight objects (12.5%) was
randomly selected from the combined object lists of IP.307857 and IP.307858 (the greater than 315
μm size fraction) and from the combined object lists of IP.307859 and IP.307860 (the 250–315 μm size
fraction). For YPM Site IPE.08295, the largest size fraction (the greater than 250 μm size fraction) was
over-represented by a 1/32nd split relative to the smallest size fraction (150–250 μm size fraction with a
1/256th split imaged). To obtain a 1/32nd split across size fractions, one in every eight objects (12.5%) was
randomly selected from the combined objects in IP.307853 and IP.307854 (the greater than 250 μm
size fraction). This data report includes objects after down-sampling and should be corrected for the bias
introduced during slide preparation.

Each object was classified by a human observer according to one of sixteen categories (Supplementary
Table 1), along with an indication of confidence in the classification: ‘very’, ‘somewhat’, and ‘not’. In a few
classification categories, the confidence categories were used to indicate other attributes; these exceptions
are explained below. Classification categories, listed in Fig. 3, were defined as follows. ‘Agglutinated’
indicates a complete agglutinated foraminiferal test, or some part thereof. Low confidence in this category
(i.e., ‘agglutinated’, ‘not’) typically occurred when the agglutinated fragment was so small as to make it
difficult to distinguish between an individual rock and individual foraminifera. ‘Benthic’ denotes any
clearly identifiable piece of a benthic foraminifer (i.e., complete, damaged or fragment of a benthic
foraminiferal test). Lower to low confidence (i.e., ‘somewhat’ or ‘not’) in the ‘benthic’ assignment arose
when test fragments were too small to confidently assign or when individuals were too small or
indeterminate to assign to either benthic and/or planktonic foraminifera categories. ‘Clipped’ indicates
any image with at least one edge of the object clipped, with the exception of objects in the category
‘spicule’ as described below. ‘Complete’ indicates complete tests of planktonic foraminifera: a category
that includes dirty tests (stained and/or visibly covered with some amount of sediment), but not tests that
are broken or fragmented. The three confidence categories for ‘complete’ planktonic foraminifera were
used in a non-standard way: i) ‘very’ indicates objects identified as complete planktonic foraminifera with
high confidence; ii) ‘somewhat’ indicates all small bodied and juvenile individuals, where confident
assignment to benthic or planktonic habitats was difficult; and iii) ‘not’ indicates planktonic species
Hirsutella scitula and Hirsutella theyeri and similar looking benthic foraminifera. Damaged tests of
planktonic foraminifera were classified as ‘damaged’ for all breaks, drill-holes, and damage assessed to
affect less than a third of the test. All cases of severe damage to planktonic foraminifera, including
small planktonic foraminiferal fragments, were classified as ‘fragment’. The ‘diatom’ category contains
diatom frustules, the ‘echinoid spine’ category contains echinoid spines, the ‘mollusk’ category contains
mollusks, the ‘ostracod’ category contains ostracods, and the ‘radiolarian’ category contains radiolarians.
In each of these (diatom, echinoid spine, mollusk, ostracod, and radiolarian), complete or large fragments
of organisms were typically identified with greater confidence than small or out-of-focus pieces. Echinoid
spines were confirmed as echinoid in nature by the match of the distinctive lattice structure in spine
images with those of an immature echinoid in the YPM Invertebrate Zoology collection (YPM
IZ.087653). The ‘unknown’ category contains non-target items, such as bits of background from the slide,
fibres, and other unknown objects. Small pebbles, minerals, and other rock-like objects were categorized
as ‘rock’. Sponge spicules, categorized as ‘spicule’, were almost always clipped by the automated image
segmenting routine. As a result, we included all clipped images of spicules in the category ‘spicule’ in spite of the incomplete nature of the image. All ichthyoliths (including fish teeth, shark dermal denticles, and other pieces of apatite) were categorized as ‘tooth’, with notably few actual teeth in this dataset. Small pieces of apatite and other ichthyoliths can be very difficult to identify, so many are likely categorized as ‘unknown’ or ‘rock’. Finally, when two or more objects touched, they were categorized as ‘touching’. Objects in direct or very near contact cannot be accurately extracted for 2D and 3D morphometrics.

References
1. Sutton, M. D. Tomographic techniques for the study of exceptionally preserved fossils. Proc. R. Soc. B 275, 1587–1593 (2008).
2. Cunningham, J. A., Rahman, I. A., Lautenschlager, S., Rayfield, E. J. & Donoghue, P. C. J. A virtual world of paleontology. Trend Ecol. Evolut. 29, 347–357 (2014).
3. Friis, E. M. et al. Phase-contrast x-ray microtomography links ctenaceous seeds with Gnetales and Bennettitales. Nature 450, 549–551 (2007).
4. Schmidt, D. N., Rayfield, E. J., Cocking, A. & Marone, F. Linking evolution and development: Synchrotron Radiation X-ray tomographic microscopy of planktic foraminifers. Palaeontology 56, 741–749 (2013).
5. Siveter, D. J. et al. Exceptionally Preserved 450-Million-Year-Old Ordovician Ostracods with Brood Care. Current Biology 24, 801–806 (2014).
6. Hsiang, A. Y. et al. AutoMorph: accelerating morphometrics with automated 2D and 3D image processing and shape extraction. Methods Ecol. Evol. doi:10.1111/2041-210X.12915 (2017).
7. Hsiang, A. Y., Elder, L. E. & Hull, P. M. Towards a morphological metric of assemblage dynamics in the fossil record: a test case using planktonic foraminifera. Phil. Trans. R. Soc. B 371, 20150227 (2016).
8. Hemleben, C., Spindler, M. & Anderson, O. R. Modern Planktonic Foraminifera (Springer-Verlag, 1989).
9. Darling, K. F. & Wade, C. A. The genetic diversity of planktic foraminifera and the global distribution of ribosomal RNA genotypes. Mar. Micropaleontol. 67, 216–238 (2008).
10. Beaufort, L. & Dolfus, D. Automatic recognition of coccoliths by dynamical neural networks. Mar. Micropaleontol. 51, 57–73 (2004).
11. Beaufort, L., Barbarin, N. & Gally, Y. Optical measurements to determine the thickness of calcite crystals and the mass of thin carbonate particles such as coccoliths. Nature Protocols 9, 633–642 (2014).
12. Bollmann, J. et al. in Image Analysis, Sediments, and Paleoenvironments (ed. P. Francus) Ch. 12, 229–252 (Kluwer Academic Publishers, 2004).
13. Schmidt, D. N., Thierstein, H. R., Bollmann, J. & Schiebel, R. Abiotic forcing of plankton evolution in the Cenozoic. Science 303, 207–210 (2004).
14. Rowe, T. & Frank, L. R. The Disappearing Third Dimension. Science 331, 712–714 (2011).
15. Bé, A. W. H. & Tolderlund, D. S. in Micropaleontology of Marine Bottom Sediments (eds B. M., Funnell & W. K., Riedel) Ch. 6, 105–149 (Cambridge University Press, 1971).
16. Schiebel, R. & Hemleben, C. Modern planktic foraminifera. Paläontologische Zeitschrift 79, 135–148 (2005).
17. de Vargas, C., Norris, R., Zaninetti, L., Gibb, S. W. & Pawlowski, J. Molecular evidence of cryptic speciation in planktonic foraminifera and their relation to oceanic provinces. Proc. Natl. Acad. Sci. USA 96, 2864–2868, (1999).
18. Archer, D. E. An atlas of the distribution of calcium carbonate in sediments of the deep sea. Global Biogeochem. Cy. 10, 159–174 (1996).
19. Ridgwell, A. & Hargreaves, J. C. Regulation of atmospheric CO2 by deep-sea sediments in an Earth system model. Global Biogeochem. Cy. 21, 1–14 (2007).
20. Berger, W. H. Foraminiferal ooze - solution at depths. Science 156, 383–385 (1967).
21. Berger, W. H. Planktonic Foraminifera - Selective Solution and Paleoclimatic Interpretation. Deep-Sea Res. Oceanogr. Abstr. 15, 31–43 (1968).
22. Polly, P. D. et al. History matters: ecometrics and integrative climate change biology. Proc. R. Soc. B 278, 1131–1140 (2011).
23. Sun, X. C., Corliss, B. H., Brown, C. W. & Showers, W. J. The effect of primary productivity and seasonality on the distribution of deep-sea benthic foraminifera in the North Atlantic. Deep-Sea Res Part I Oceanogr. Res. Pap. 53, 28–47 (2006).

Data Citations
1. Elder, L. E et al. Zenodo. https://doi.org/10.5281/zenodo.165514 (2017).

Acknowledgements
Support for LEE, AYH, and PMH was provided in part by the American Chemical Society Petroleum Research Fund to PMH (PRF no. 55837-DNI8). We would like to thank Joanne Zhenheng Li, Casey Culligan and Emma Tipton for assistance in arranging slides, Liana Epstein for assistance in testing the image classification app, and Gregory Meyer for contributing code on the classification app. We would like to thank Bruce Corliss, Richard Norris, and Michael Henehan for providing samples. We would also like to thank Jessica Utrup, Susan Butts and Larry Gall from the YPM for their help ensuring community data standards were followed and with workflows to integrate our dataset into KE EMu.

Author Contributions
P.M.H. conceived and coordinated the study. P.M.H. and L.E.E. selected the focal sites and drafted the manuscript. LEE performed all imaging and technical validations. L.E.E., A.Y.H., and S.S.K. carried out image processing, morphometric analyses, and database compilation. All objects were classified by P.M.H. and L.E.E. P.M.H. checked all data products for quality and completeness. Classification app was developed by A.Y.H., S.S.K., and P.M.H. and tested and improved by L.E.E. and L.C.S. A.Y.H., K.N., and P.M.H. developed AutoMorph software. A.Y.H., K.N., and P.M.H. optimized AutoMorph software with help from L.E.E.

Additional Information
Table 2 is available only in the online version of this paper.
Supplementary information accompanies this paper at http://www.nature.com/sdata

**Competing interests**: The authors declare no competing interests.

**How to cite this article**: Elder, L. E. *et al.* Sixty-one thousand recent planktonic foraminifera from the Atlantic Ocean. *Sci. Data* 5:180109 doi: 10.1038/sdata.2018.109 (2018).

**Publisher's note**: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

[Open Access] This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/

The Creative Commons Public Domain Dedication waiver http://creativecommons.org/publicdomain/zero/1.0/ applies to the metadata files made available in this article.

© The Author(s) 2018