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General Results of Reexamination of Ehrenberg's Radiolarian Collections: with Instructions on Efficient Methods to Find Microfossils from the Collection

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Abstract The Ehrenberg Collection in Naturkunde für Museum, Berlin contains the type specimens of 486 radiolarian species. These species were described by Christian Gottfried Ehrenberg between 1839 and 1876, and many of these species are still important in determining geological ages and oceanographic environments. Using Ehrenberg's original taxonomic drawings and the index volumes prepared by his daughter Clara Ehrenberg, we digitally captured ca. 1150 radiolarian specimens from the Ehrenberg Collections. Location codes of the specimens examined by Ehrenberg from Ehrenberg's taxonomic drawings and trays were of considerable help to us in identifying ca. 800 specimens (from ca. 390 species) that were examined by Ehrenberg himself. Approximate 510 specimens were identified to the exact individuals. Ehrenberg's sketches were accurate representations of the actual specimens as preserved in the mica preparations (mica strips).

The Ehrenberg Collection includes not only radiolarians but also vast numbers of other organisms such as diatoms, and the source materials are very complexly structured. Both aspects complicate the procedure to find specimens. For thorough examination of the Ehrenberg Collection in a limited time, we prepared cross-reference lists from Ehrenberg's taxonomic drawings, Clara's Index Volumes, Micas (including mica strips, case labels and stored trays), and digital images of mica strips.

Key words: Classification, Ehrenberg, Legacy Collection, Radiolaria, Taxonomy.

Introduction

Christian Gottfried Ehrenberg is known as the founder of micropaleontology. He made some of the earliest recorded observations of fossil diatoms, radiolarians, silicoflagellates, ebridians, dinoflagellates, acritarchs, and he actively described many species of microfossils in his life (Siesser, 1981). He published 77 genera and 532 species names for fossil polycystine radiolarians, including 31 *nomen nudum* genera and species, from sea bottom sediments (Azores Islands, Bay of Biscay, east off California, Davis Strait in the North Atlantic, Gulf of Mexico, Philippine Sea, Zanguebar, Southern Ocean) and on-land samples (Aegina, Barbados, Bermuda, Caltanisetta, Camorta, Zante and Oran) (Fig. 1). Of these, an estimated 486 species are still taxonomically valid (Suzuki, 2009). His classic work, however, has sometimes been questioned by modern researchers in that some of his illustrated specimens looked simple, unusual or ambiguous, and

thus modern papers have often ignored such suspicious illustrations. Even more problematic are un-illustrated but valid species that were assigned as the type species of some well-known genera (i.e. *Pterocanium*, *Dictyophimus*) (Campbell, 1954). Ehrenberg's species were selected by previous authors such as Campbell (1954) as the type species of 134 genera (Suzuki, 2009). Such uncertainty has led to scientifically unfruitful disunity. Many of Ehrenberg's species (i.e. *Cycladophora davisiana*) have been used as oceanographic or age-diagnostic indices and thus it is important to create a stable, precise taxonomic usage for his species names, and to resolve these uncertainties, either by strict application of the International Code of Zoological Nomenclature (ICZN, 2000) or by explicitly conserving names in common use. The main reason until now for lack of progress has been the failure to re-examine the original type specimens (Lazarus, 2000; Lazarus and Suzuki, 2009). Although the desire to examine the Ehrenberg's specimens has increased since Cenozoic polycystine radiolarians were regularly reported in papers from the Deep Sea Drilling Project since the 1970's, such a study was effectively not possible until the late 1990's. The Ehrenberg Collection was stored in the Museum für Naturkunde, Berlin, in the former East Germany, and initial efforts to care for the collection by Museum staff began as early as the 1960's (Lazarus, 1998). However, the limited resources available to East German curators prevented all but the most basic protective measures, and with the exception of a very few diatom specialists from politically 'neutral' countries, no western workers visited and worked with the collection. In fact few specialists in the west were even aware of its continued existence. In consequence, many attempts to settle the taxonomic confusion caused by inadequately documented Ehrenberg (and Haeckel) names were carried out without examination of Ehrenberg's specimens. After the reunification of West and East Germany, the existence of the Ehrenberg Collection and the potential for reexamination was reported to the radiolarian community (e.g. Lazarus 2000). In the mid 1990's, the Ehrenberg Collection was still practically unusable due to more than a century of neglect, but gradually improved as basic curatorial work was completed (e.g. Lazarus and

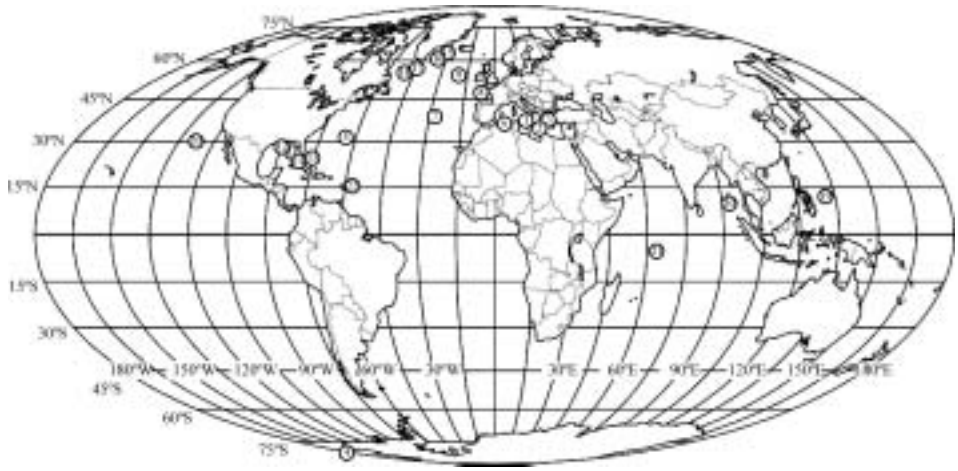

Fig. 1. Sample localities of Ehrenberg's radiolarians (1: Caltanisetta, 2: Zante, 3: Aegina, 4: Südpol I, 5: Bermuda, 6: Oran, 7: Meersgrund (Azores Island 6480'), 8: Meeresgrund II (Atlantic Ocean 10800' Bay of Biscay), 9: Meersgrund II (Nord Ocean 12000'), 10: Camorta, 11: Mexikanischer Golfstrom (Golfstrom 9066'), 12: Mexikanischer Golfstrom (Golfstrom 2556'), 13: Mexikanischer Golfstrom (Golfstrom 1158'), 14: Mexikanischer Golfstrom (Golfstrom 840'), 15: Davisstraße (6000 feet), 16: Davisstraße (9240 feet), 17: Davisstraße (10998 feet), 18: Davisstraße (11040 feet), 19: Philippinischer Ozean 19800', 20: Californischer Still Ozean 15600', 21: Zauguebarica 13200', 22: Barbados). Sampling locations except for lands are shown in the appendix figure in Ehrenberg (1873).

Jahn, 1998). Based on this restoration work, we were able to start the "Joint Haeckel and Ehrenberg Project" to reexamine the Ehrenberg and Haeckel siliceous microfossil collections in 2004 (Tanimura *et al.*, 2006, 2009; Lazarus and Suzuki, 2009).

As described in detail in Lazarus (1998) and Lazarus and Jahn (1998), the Ehrenberg Collection (leaving aside fresh-water materials) is mainly composed of Samples ("Proben"), Mica strip type microscope preparations ("Analyse"), and Drawings ("Zeichenblatt"). These three main components are indexed and partially cross-indexed in Clara Ehrenberg's handwritten Geographic (e.g. Sample) Index and Taxonomic Index. Some of Ehrenberg's publications, particularly the Mikrogeologie (1854) also provide useful, albeit only partial, indices to collection material. As the result of modern restoration and curation work, these resources are now supplemented by a digital database of the entire collection (http://onlinedb.naturkundemuseum-berlin.de/v1/default.asp), and digital images of all important documents, including the Drawings, Geographic and Taxonomic indices, as well as images of all the mica strips and their labels (http://download.naturkundemuseum-berlin.de/Ehrenberg). Using these resources it is generally possible to locate the specimens originally used by Ehrenberg on the mica strips. As pointed out by Lazarus and Jahn (1998) it is however not a simple task to identify the actual mica strips and samples that hold type material for any given species. Ehrenberg did not label any of his material as type as he worked before this concept developed, nor did he provide any global cross referencing to his various collection materials. Lastly, it is often a challenge simply to determine which publication of Ehrenberg's constitutes the first valid use of a new name. Thus, prior to beginning work in the collection, it is absolutely essential to study Ehrenberg's literature, and use the above resources to create a cross-reference between the various sources of information, so that the correct mica strips and samples can be identified for study. In practice, this is not a simple task, and each of the many users of the collection over the last several years has developed his or her own solution based on their scientific needs and personal working style. Most users of the collection have been interested in a limited range of taxa, and thus have used methods suited to the relatively modest scope of materials to be examined.

In this project we wished to find all the polycystine specimens which were recorded by Ehrenberg: we estimated ca. 1100 specimens of ca. 530 species. To insure that this tremendous number of specimens could be examined within the limited project period and the Japanese members short stay in the museum, we needed very thorough prior preparation for quick and efficient on-site selection of material. Our "wish list" worked very well for finding ca. 1000 specimens of ca. 520 species within ca. a total five-week examination between 2004 and 2007. Although our success is in part due to the large size of polycystines in comparison with diatom, dinoflagellate and nannofossils, we describe our methods below in the hope that it will be useful to other users of the Ehrenberg collection.

Source material for identification of type series specimens

Official source of the collection

Lazarus (1998) and Lazarus and Jahn (1998) introduced and explained in detail the main parts of the Ehrenberg Collection as noted above. Below we summarize important information from these two earlier papers and add additional details about the collection that assist in finding the specimens which were examined by Ehrenberg himself.

Drawings ("Zeichenblatt"): Ehrenberg's Drawings show sketches of his examined specimens and are labeled by him with taxonomic names and sample information (Fig. 2a). The drawings are essential source material to know what specimens were examined by Ehrenberg himself and find the examined specimens from the mica strip. These drawings include information on (1) taxonomic names (genus and species, in some cases with his working name), (2) sample names, (3)

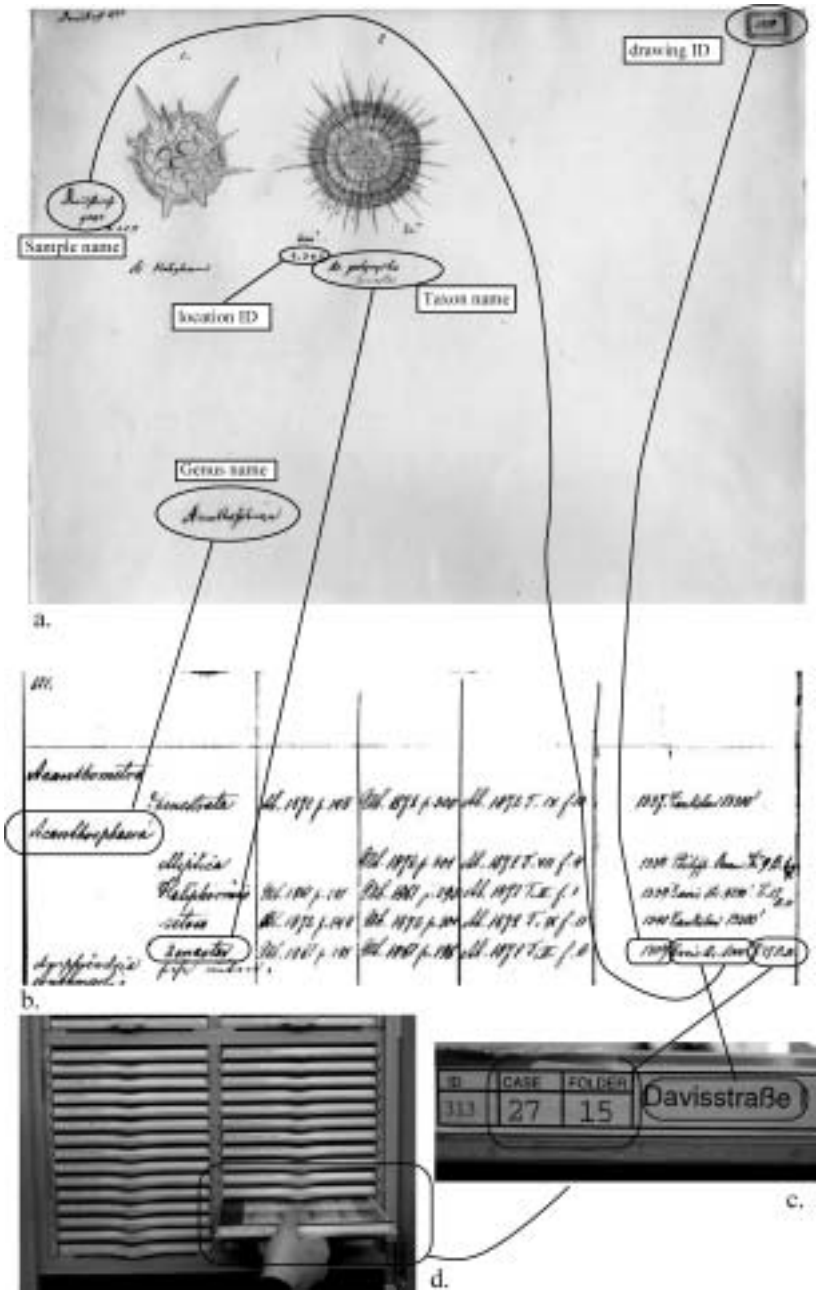

Fig. 2. Cross-reference among the Drawing, the Taxonomic Index and Micas in the case of *Acanthosphaera zonaster* (drawing ID: 1339, sample ID: 2.3.e.r). (a) Drawing, (b) part of the Taxonomic Index, (c) an enlarged image of a hold to connect with the Taxonomic Index, and (d) overall view of cabinet.

the location of his examined specimens on the mica strip (location ID, herein), and (4) drawing ID. The drawings were sorted by various criteria, both geographic and taxonomic. For our study the most important were those in the taxonomic section devoted to radiolaria, which are sorted by alphabetical genus order (drawing numbers 1337–1596).

Clara's Taxonomic Index: Lazarus (1998) and Lazarus and Jahn (1998) described the two cross-referencing indices created by Clara Ehrenberg, primarily indexing the geologic materials

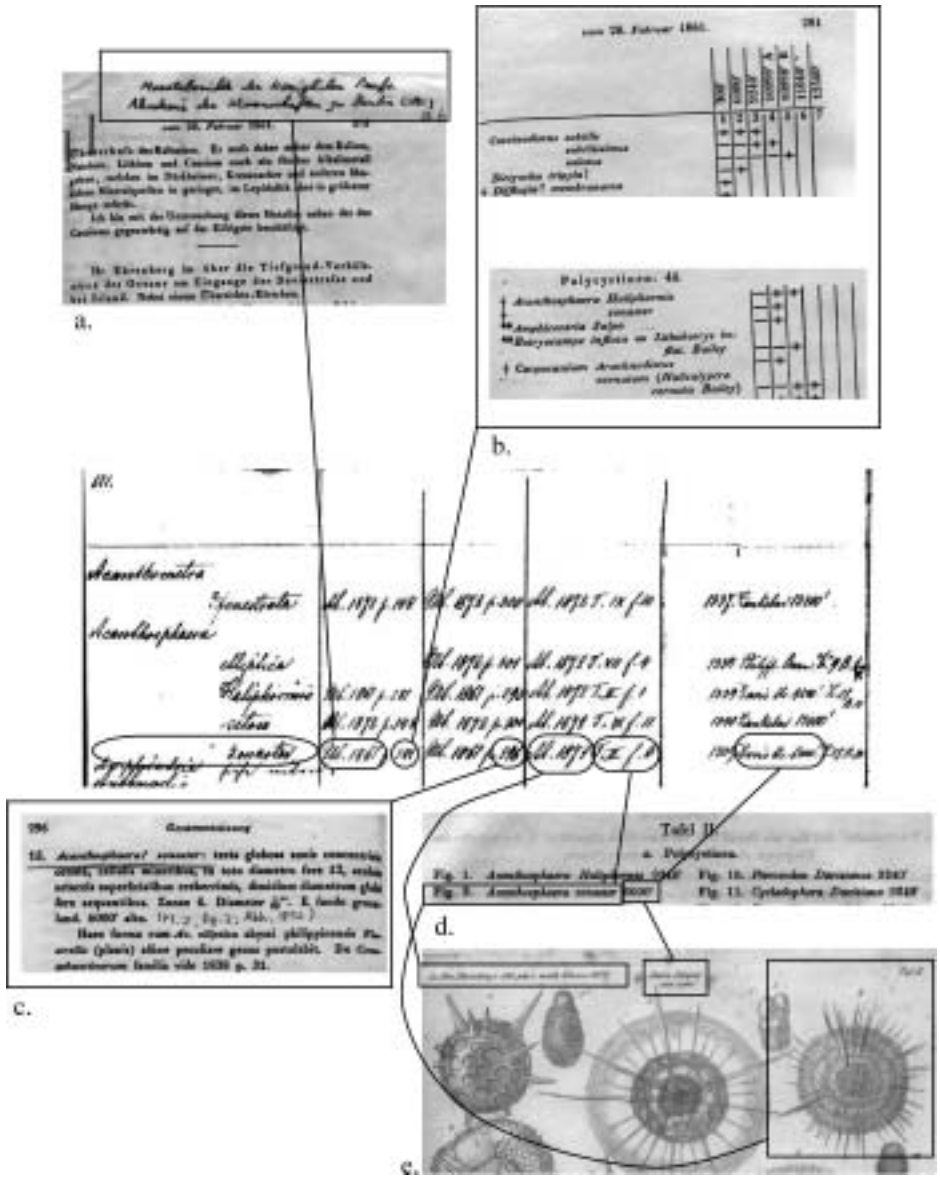

Fig. 3. Cross-reference among publications and the Taxonomic Index Volume in the case of *Acanthosphaera zonaster*. (a) part of the front page of Ehrenberg (1862), (b) the relevant page of the first published indication of the species, in regardless of nomen nudum, to the Taxonomic Index, (c) the relevant page of the first description of the species to the Taxonomic Index, (d) and (e) the relevant pages of the first illustrated publication of the species to the Taxonomic Index.

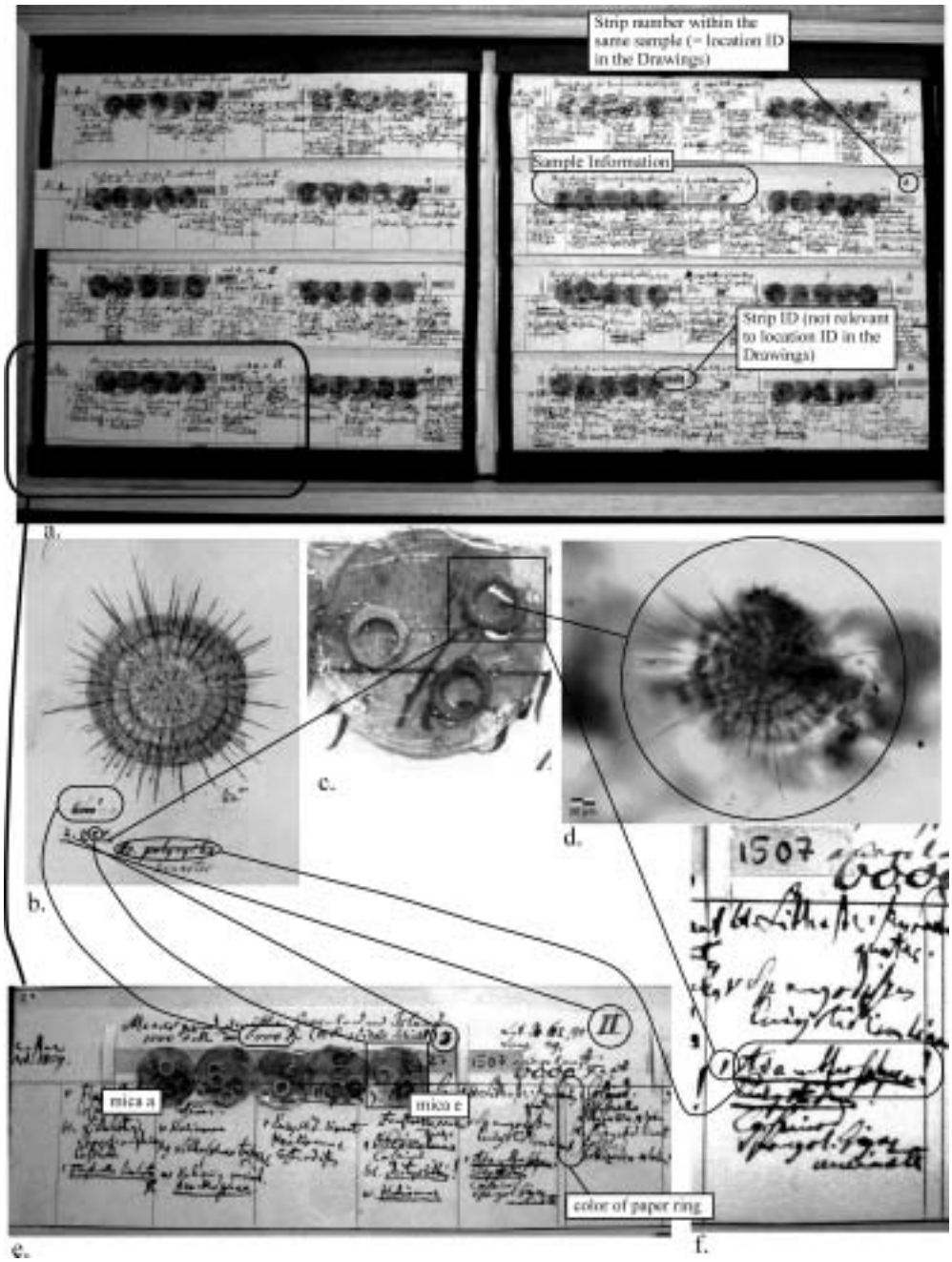

Fig. 4. Cross-reference among the mica strip, the location ID of the Drawing and the actual specimen in the case of *Acanthosphaera zonaster*. (a) the overall view of the folder (K27B15 or Case 27 Folder 15), (b) part of the Drawing, showing sample (6000' in this case), the location ID of the specimen (2.3.e.r in this case) ant species name. (c) the enlarged view of the mica "e" of the mica strip ID 271507, meaning the Folder 27, Case 15, the 7th mica strip on this folder. (d) the actual specimen search followed by the source materials, (e) the overall view of a mica strip, (f) the enlarge image of the taxon names (including his working names) for the mica "7.e.r", meaning "the strip 271507, mica e, and Rot (red in English).

summarized in Ehrenberg's Mikrogeologie (1854): the Geographic Index and the Taxonomic Index. Of these, the Taxonomic Index proved to be the most useful in our search for type series specimens of radiolarians. Fig. 2b shows a part of one Taxonomic Index page (pages 120–147 cover radiolarians, e.g. "Polycystinen"). The Taxonomic Index cross references taxonomic names to Drawings (Figs. 2a, 2b), Micas (Figs. 2c, 2d), the first published indication of the species (Figs. 3a, 3b), the first published description of the species (Fig. 3), and the first published illustration (Figs. 3d, 3e).

Clara's Geographic (Sample) Index: This index includes sample name, tray (originally, Case and Folder) ID and sample ID. The tray ID is also recorded in Clara's Taxonomic Index for each species.

Micas ("Analyse"): Mica strips (Fig. 4e) are currently stored in two large cabinets (Fig. 2d). Each strip has a hierarchic identification code based on the original storage structure used by Ehrenberg of Case, folder, strip. The cases are no longer actually used as they caused damage to the mica strips when accessing them but the folders are stored sequentially by case number in the cabinets (Fig. 2c). Each folder is stored in a glass covered tray, and the strips are arranged on both sides of the folder, normally 8 per side, or 16 per folder (Fig. 4a).

The detailed composition of a mica strip (Fig. 4e) is explained in Jahn (1995), Lazarus (1998), and Lazarus and Jahn (1998). The important thing is how to search for individual specimens. One mica strip consists of five mica discs (ca. 0.8 cm), and each mica disc is labeled, usually either "a" to "e" from left, or using the Greek alphabet from "α" to "ε" (Fig. 4e). Colored paper rings are attached to many of the micas (Fig. 4c), and these are referenced by the taxa names in the written labels on the associated strip of paper for the mica strip (Figs. 4e, f). The color references are typically abbreviated (Table 1).

Other sources of information for this project

Digital images of mica strips: All folders and their mica strips have been digitally imaged as part of normal curation work and are available online at the collection website. These images, however, were gray scale at that time. We need full-color image to detect the ring color, so that we used these images, as well as additional images of individual strips with their labels. Ehrenberg wrote his working taxonomic names, often abbreviated, in a very small handwriting on paper strips attached to the cardboard of the containing folder (Fig. 4a, 4e). The legibility of

Table 1. Abbreviation of color rings.

Abbreviation	German	English
bl	bluu	blue
br	braun	brown
g	gelb	yellow
gr	grün	green
o	orange	orange
r	rot	red
∫	schwartz	black
v	veilchen	violet
w	weiß	white

these labels varies. Some are, even for native speakers of German, undecipherable (Fig. 4f). The colors of the rings on the mica discs have often altered due to aging, and infiltration of now quite yellow-colored Canada balsam.

Alphabet list of handwriting: The Japanese members of our project are not familiar with 19th century German handwriting, so we made the example lists of handwriting from the Drawings (Figs. 5, 6). These lists were very helpful in the first two years of the project in Berlin.

How to find the target specimens

Different names for the same specimen: Although Ehrenberg's working taxon names on the mica strip labels mostly correspond to the taxon names of both the Clara's Taxonomic Index and Ehrenberg's Drawings, taxon names were often abbreviated and occasionally are different due presumably to Ehrenberg changing his opinion of the correct name while working on the material.

Independent numbering systems: There are several numbering systems used to identify objects in the collection, including the mica strips. This is normal for older museum collections, where collection objects may be labeled with as many as a half-dozen different numbers, but an unwary user can get confused if this is not kept in mind. For example, the current curatorial system and database entries use a uniform numbering system for all mica strips that is based on their physical storage location. This consists of the case and folder numbers, combined with the number of the strip in the folder. The strips are sequentially numbered from 1 to 16 from the left upper through the right lower in a folder, regardless of content (Fig. 4). Strip ID 160502 means, for instance, that the mica strip is the second strip in folder K16B05 (folder 5 from Case (Kasten) 16). Ehrenberg worked on a sample basis and made a highly variable number of mica strips from each sample, which were numbered sequentially within the sample. As these were put into folders, it was often the case that more than one sample might be held in a folder, or that one sample might extend across more than one folder. Thus the Strip ID cannot be read simply as the strip number as given in Clara's Taxonomic Index and on the Ehrenberg's Drawings. The original arrangement within sample numbers is noted in Ehrenberg's handwriting directly above the strips in the folder. Figs. 2–4 give an example using *Acanthosphaera zonaster* (working name originally "*Ac. polycyrta*"). This specimen is coded as "2.3.e.r" in the Drawing (drawing ID: 1339) (Figs 2a, 4b) whereas the Strip ID is "271507.e.r" (Figs. 4b, 4e). In another example, the folder "K16B04 Barbados 14 15" includes 16 mica strips from two samples, Barbados 14 and Barbados 15. They are sequentially arranged beginning with Barbados 14, and thus the first strip of Barbados 15 (Barbados 15 1 in the Clara's Index and Ehrenberg's drawing) is Strip 160505.

Preparation of cross reference lists

High resolution images of Ehrenberg's Drawings and Clara's Index Volumes are available and downloadable from the web site of Museum für Naturkunde, Berlin, and information about the drawings are searchable in the collection databases. However, the locations of the individual examined specimens on the mica strip, as recorded for some specimens on Ehrenberg's Drawings, have not been entered as digital data. Ehrenberg depicted as many as a thousand polycystine

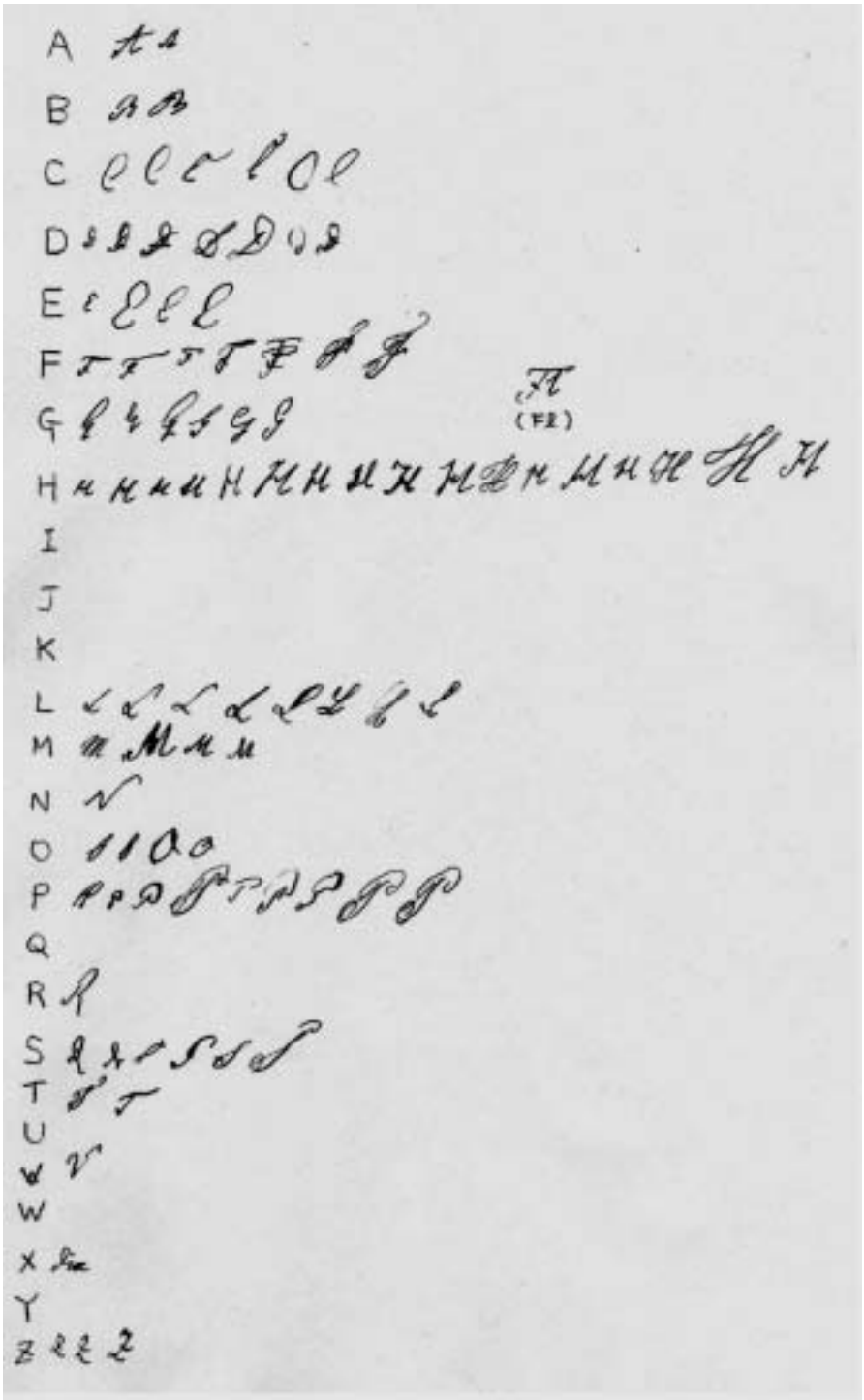

Fig. 5. Capital alphabet list from the Drawings.

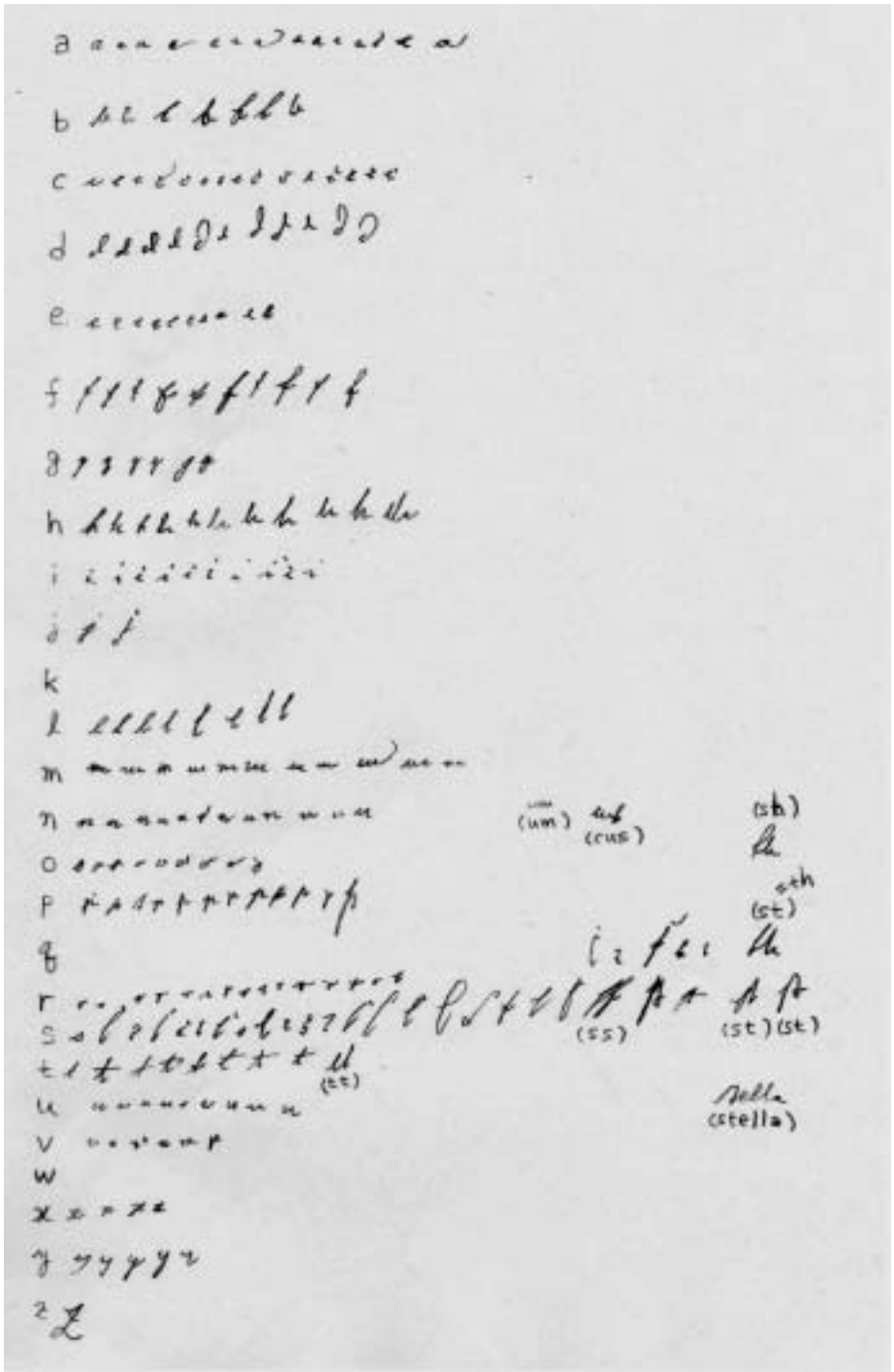

Fig. 6. Alphabet list of the small letters from the Drawings.

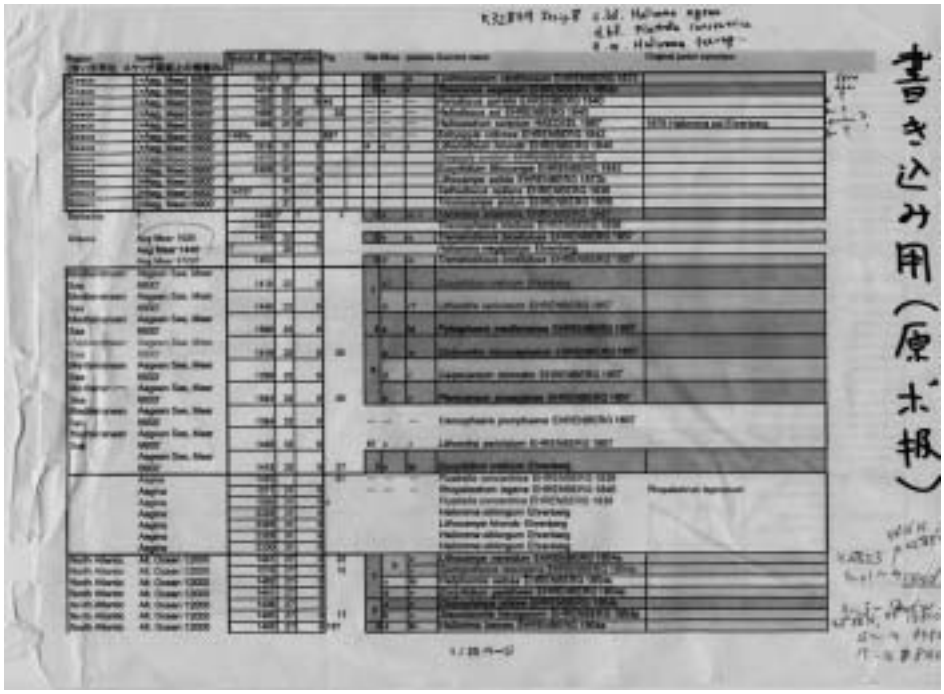

Fig. 7. One page of the working list that were actually used in our project.

specimens on his drawings, so that an efficient system to search for specimens was essential. For this purpose, our project first made a single composite cross reference list from all the separate sources (Fig. 7). This composite list unified information scattered across Drawings, Taxonomic Index, Micas and mica strips into a single list. Any single species needs a complex cross-referencing procedure as shown in figs. 2–4, so that, if as in our study, many specimens were likely to be found on a single strip, it would be useful if all the specimens that need to be located in each mica strip are known. This list was therefore sorted by sample information and folder ID. This sorted list was checked with digital images of mica strips to make more useful list.

Results

Total number of detected specimens and species

Our composite list includes approximately 1150 specimens which were examined by Ehrenberg based on his drawings. This number is approximate as there are a few specimens duplicated on illustrations, some of the information from the drawings is only fragmentary, and, as was common for Ehrenberg, some specimens not mentioned elsewhere (drawings, index volumes) were found based on the handwritten strip labels. After excluding the duplicated illustrations, a total of 590 polycystine individuals were illustrated on Ehrenberg's Drawings (drawing ID Ec dr 1337 to 1602, 1920, 2080, 2089, 2309, 2319, 2320, 2321, 2328, 2329, 2330, and 2393), and of these, 507 specimens (85.9 %) were identifiable on the mica strips as the exact individual that was illustrated (T-3 in CD). This number also includes a few species described by other authors (e.g. Bailey, 1856).

Ehrenberg published 528 “polycystine” species names, including four spherical sponge spicules (*Haliomma ovatum* Ehrenberg 1840, *H. radians* Ehrenberg 1841, *H. radiatum* Ehrenberg 1854 and *H. radicatum* Ehrenberg 1844), one silicoflagellate (*Halicalyptra virginica* Ehrenberg 1854), and 36 “nomen nudum”, and thus 486 species are considered as taxonomically available names. On the other hand, we found the original drawings for only 441 radiolarian species in the Ehrenberg Drawing Collection. Of these un-illustrated 45 species, we recognized 3 species (*Eucyrtidium hispidum* Ehrenberg 1862, *Halicalyptra hexathyris* Ehrenberg 1862 and *Rhopalodictyum truncatum* Ehrenberg 1862), and were unable to identify exact specimens for the remaining 42 species owing to absence of sufficient information. Although two ‘nomen nudum’ species were detected, we conclude that a total number of 396 of Ehrenberg’s species (81.5% of the total of 441 documented, taxonomically available species) were identified from Ehrenberg’s radiolarian collection in our project.

Since Ehrenberg provided information about his examined specimens on his drawings as well as on the mica strip labels, we were able to locate a total of 797 specimens for these 396 species during our project. In addition, we illustrate 84 specimens that were recorded by Ehrenberg under working names (including nomen nudum) and 268 specimens which were not specifically marked on the drawings or strip labels as having been examined by Ehrenberg (Suzuki *et al.*, 2009; Ogane *et al.*, 2009, this volume).

Condition of collection

Mica strips and specimens: Color rings on the mica strips have changed their colors after 140–170 years. White rings, for example, have sometimes turned black or brown, while other colors have taken on a yellowish cast from the Canada balsam. Green and blue rings have been the least affected. Digital images of the mica strips were useful in determining the original color from discolored paper rings because digital images can be adjusted in image management programs using color balance controls.

Specimens: Specimens on mica strips can be difficult to see clearly owing to the surface roughness of the embedded Canada balsam and to the large refractive index of mica itself. Light passing through the mica is more strongly refracted than in a modern glass slide. The rough surface of the mica further refracts light coming from the polycystine specimens. In a few cases these optical problems prevented from obtaining a good image for illustration regardless of our effort. A few specimens have rotated slightly within the embedding material in the 140–170 years since Ehrenberg sketched his specimens.

Cracks in the Canada balsam of the mica have occasionally passed through polycystine specimens and split them. Since some species described by Ehrenberg involve taxonomically problematic or poorly preserved specimens, we imaged supplemental specimens beyond those illustrated by Ehrenberg.

Inclination in his drawing Polycystina

Our reexamination of Ehrenberg’s specimens proved that Ehrenberg generally drew accurate representations of the forms. Some inclination of specimens can be seen in some of his drawings in which are also reflected in overall views, recognition of morphological characters, and misinterpretation of parts of the original images. He also drew inverted images (left to right). Knowing inclination is helpful when we encounter a specimen which looks different from Ehrenberg’s

drawings in the mica strip.

Overall views: Unlike the artificially perfect illustrations produced by some of his contemporary taxonomists (Müller, 1858; Haeckel, 1862; Harting, 1863), Ehrenberg faithfully replicated the individual, often imperfect morphology of observed specimens in his drawings, as did some other early workers (Bailey, 1856; Bury, 1862). The length, position and shape of radial spines, for example was drawn as they actually existed on each specimen. Distribution patterns and irregularity in the shape and size of pores also correctly reflect the actual specimens. Breakage of parts of the test has not been "repaired." Only on a few specimens (e.g. *Lychnocanium hirundo* Ehrenberg) were 'extension' added of the missing part via dotted lines, which are easily distinguished from the real part of the specimen. However, the width of nassellarian specimens tends in his drawings to be more slender than that of actual specimens. The curvature of tests is also slightly overstressed in his drawings.

Ehrenberg's drawings contain rough and therefore ambiguous illustrations for some species. These are frequently due to poor image quality in the original specimens, owing to very rough surfaces on the mica strips. The validity of such drawings was confirmed by our own careful observation with a variety of focus depths and magnifications.

Ehrenberg sometimes drew images reversed between left and right when compared to images of the modern microscopes used in our study. It is curious that only some of his drawings are mirror images.

Recognition of morphological characters: The shaded patterns used in Ehrenberg's drawings to show vertical depth in our opinion do not produce a strong three-dimensional appearance to spumellarian specimens. The differences in the height of specimens between spherical and discoidal Polycystina seems not to have been precisely recognized on the basis of his classification at the species level. For example, he recorded many "*Flustrella concentrica*" in his mica tray labels, but the specimens of this species are found to be a mixture of spherical and flattened forms. The illustration of *Haliomma oculatum* does not make clear whether this species is spherical or flattened, but the actual specimen was a spherical form, for another example. It was impossible for *Haliomma octacantha* to be linked to a modern species using only Ehrenberg's drawing, but this species was easily identified as a member of the genus *Heliodiscus* by examination of the actual specimen. Correct recognition of spherical or flatten shape for these Polycystina was needed during our reexamination. The shallow conical shape of *Lamprodiscus* was also confused with the convex shape of *Spongodiscus*.

In a few specimens, triradiate radial spines were drawn as cylindrical ones, for example in the case of *Cenosphaera magnaporus*.

Misinterpreted parts of drawings: The internal structures of spherical and discoidal Polycystina are not shown in Ehrenberg's drawings for most species. The internal spherical shell(s) of *Cenosphaera plutonis* (the type species of the genus *Cenosphaera*) and *Acanthosphaera haliphormis* (the type species of the genus *Acanthosphaera*) were missing in his drawings, for example, which complicates the traditional meaning of both genera. *Stylosphaera coronata* did not figure the internal spherical shell in his drawing.

The longitudinal costae of nassellarians are generally not shown in Ehrenberg's drawings. The actual specimen of *Podocyrtis papalis* has significant longitudinal costae between the rows of pores on the thorax that are aligned vertically. We noticed a small aperture on the proximal

part of the stout apical horn in the genera *Podocyrtis* and *Theocorys*, but it has not been shown in Ehrenberg's drawings.

Matching the specimen illustrations of Ehrenberg to actual specimens mostly relied on correlation of information on the location as given on Ehrenberg's drawings, the taxon name given in the labels for micas in the mica trays, observation of the actual specimens and comparison to the illustrations.

Discussion

Reliability of Ehrenberg's drawings

Despite the problems noted above, almost all the specimens other than a few exceptions, were correctly illustrated by Ehrenberg in his drawings. Implausible sketches were detected for *Haliomma triplex* (drawing ID: 2080. Pl. 31, figs. 4a–e in Suzuki *et al.*, 2009, this volume), *Lithocampe hirundo* (drawing ID: 1516. Pl. 26, figs. 3a–3c in Suzuki *et al.*, 2009), and *Lithocampe radicula* in Ehrenberg (1839) (drawing ID: 1496. Pl. 12, figs. 7a–7c in Suzuki *et al.*, 2009). The direction of curvature for one of the polar radial spines of *Stylosphaera flexuosa* (drawing ID: 1591. Pl. 11, figs. 4a–4f in Ogane *et al.*, 2009, this volume) is inverted from the actual specimen. Two radial spines of *Haliomma triactis* (drawing ID: 1475. Pl. 11, figs. 3a–3c in Ogane *et al.*, 2009) were not recognized in the actual specimen. This specimen is clearly the one drawn because the location of the specimen in both Ehrenberg's drawing and working taxon names on trays shows the same position, only one spherical polycystine specimen is found within this paper ring, and other probable specimens were not encountered on overall scan of all the mica discs of this mica strip (Strip ID 160316).

Several of Ehrenberg's drawings seemed at first to be inaccurate sketches, but we instead confirmed that he drew these specimens correctly. Four spinules ("fronte 4 spinulis coronata" in the original description in Ehrenberg 1874) on the cephalis of *Eucyrtidium coronatum* (drawing ID: 1419. Pl. 19, figs. 4a–4e in Ogane *et al.*, 2009) were correctly recognized in the actual specimen. One of the few significant oversights in Ehrenberg's drawings is not to have drawn the saturnalid ring of *Stylosphaera holosphaera* (drawing ID: 1592. Pl. 53, figs. 2a–2c in Suzuki *et al.*, 2009), but this kind of mistake is exceptional.

A probable incorrect indication of the mica used for a sketched specimen on Ehrenberg's drawings was found for *Eucyrtidium trachelius* (drawing ID: 1436. Pl. 55, figs. 4a–4c in Suzuki *et al.*, 2009). Ehrenberg's drawing indicated that the specimen was located on "6.c.w" of Strip ID 090606, Philippinischer Ozean 19800', but this specimen differs in the shape of cephalis and thorax and the length of abdominal tube from the drawing. The presence of this species is also recorded at the location "2.e.g." of Strip ID 250702, California Ocean 15600' (pl. 65, figs. 8a–8d in Suzuki *et al.*, 2009). This specimen is morphologically identical with that of the drawing, suggesting that it is the correct specimen.

Ehrenberg's drawings are generally accurate, but some specimens from Barbados were too simplified in comparison with the actual specimens (See Ogane *et al.*, 2009). These species meanings were first clear only since Ogane *et al.* (2009) re–imaged the actual specimens.

Conclusions

Thanks to well-organized curation by Clara Ehrenberg, subsequent curation by the curators

of the Museum für Naturkunde, Berlin and the presence of many original materials, approximately 800 original specimens of the ca. 390 species which were formally described by Christian Gottfried Ehrenberg were found from the Ehrenberg Collection. Except for a few cases, all the drawings were confirmed to be accurate representations of the specimens. We cannot directly identify the type specimens of Ehrenberg's species because he did not designate types, and did not explicitly give detailed information about the samples that served as the source for each illustrated specimen in published papers, but his source materials helped us to identify these samples and his examined polycystine radiolarian specimens. These can in most cases be subsequently used for typification in future papers. Our Joint Haeckel and Ehrenberg Project has thus contributed to the revision and stabilization of Ehrenberg's species.

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References

Bailey, J. W., 1856. Notice of microscopic forms found in the soundings of the Sea of Kamchatka-with a plate. *Am. Jour. Sci. Arts Ser.* 2, **22**(64): 1–6.

Bury, P. S., 1862. Polycystins, Figures of Remarkable Forms & c., in the Barbados Chalk Deposit, (Chiefly Collected by Dr. Davy, and Notice in a Lecture to the Agricultural Society of Barbados, in July, 1846). W. Weldon, London, 25 plates.

Campbell, A. S., 1954. Radiolaria. *In* R. C. Moore (ed.) Treatise on Invertebrate Paleontology, Part D Protista 3. Protozoa (Chiefly Radiolaria and Tintinnina), Geological Society of America and University of Kansas Press, Kansas, p. D1-D163.

Ehrenberg, C. G., 1839. Über die Bildung der Kreidefelsen und des Kreidemergels durch unsichtbare Organismen. *Abh. Königl. Akad. Wiss. Berlin*, **1838**: 59–147.

Ehrenberg, C. G., 1840. Hierauf 274 Blätter von ihm selbst ausgeführter Zeichnungen von eben so vielen Arten in dem 1838 erschienenen grösseren Infusorienwerke noch nicht abgebildeter Infusorien. *Ber. Verh. König. Preuß. Akad. Wiss. Berlin*, **1840**: 197–219.

Ehrenberg, C. G., 1844. Über 2 neue Lager von Gebirgsmassen aus Infusorien als Meeres-Absatz in Nord-Amerika und eine Vergleichung derselben mit den organischen Kreide-Gebilden in Europa und Afrika. *Ber. Königl. Preuß. Akad. Wiss. Berlin*, **1844**: 57–97.

Ehrenberg, C. G., 1854. Mikrogeologie. Voss, Leipzig, 374 pp.

Ehrenberg, C. G., 1862. Über die Tiefgrund-Verhältnisse des Oceans am Eingange der Davisstrasse und bei Island. *Monat. Königl. Preuß. Akad. Wiss. Berlin*, **1861**: 275–315.

Ehrenberg, C. G., 1873. Mikrogeologische Studien über das kleinste Leben der Meeres-Tiefgründe aller Zonen und dessen geologischen Einfluss. *Abh. Königl. Akad. Wiss. Berlin*, **1872**: 131–399.

Ehrenberg, C. G., 1874. Grössere Felsproben des Polycystinen-Mergels von Barbados mit weiteren Erläuterungen. *Monat. Königl. Akad. Wiss. Berlin*, **1873**: 213–263.

Haeckel, E., 1862. Die Radiolarien (Rhizopoda Radiolaria). Eine Monographie. Tafel 1, Reimer, Berlin, 572 pp.

Harting, P., 1863. Bijdrage tot de kennis der mikroskopische fauna en flore van de Banda-*Zee. Verh. Konin. Akad. Weten.*, **10**: 1–34.

ICZN, 2000. International Code of Zoological Nomenclature. Fourth Edition, The International Trust for Zoological Nomen Clature, London, 306 pp.

Jahn, R., 1995. Ehrenberg's marked species on five mica. *Iconographica Diatomologica* **1**: 101–107.

Lazarus, D. B., 1998. The Ehrenberg Collection and its curation. *In* D. M. Williams & R. Huxley (eds.) Christian Got-

tfried Ehrenberg (1795–1876), The Man and His Legacy, Special Publication of the Linnean Society, Academic Press, p. 14–29.

Lazarus, D. B., 2000. Ehrenberg, Haeckel and the problem of types: status report. *In* Ninth Meeting International Association of Radiolarian Paleontologists, E. S. Carter, P. Whalen, P. J. Noble & A. E. J. Crafford (eds.) Department of Geological Sciences, University of Nevada, p. 46.

Lazarus, D. B. & R. Jahn, 1998, Using the Ehrenberg Collection. *Diatom Res.*, **13**: 273–291.

Lazarus, D. & N. Suzuki, 2009. Introduction to the reexamination of the Haeckel and Ehrenberg radiolarian collections. *In* Y. Tanimura & Y. Aita (eds.), Joint Haeckel and Ehrenberg Project, Reexamination of the Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy, National Museum of Nature and Science Monographs, **40**: 23–34.

Müller, J., 1858. Über die Thalassicollen, Polycystinen und Acanthometren des Mittelmeeres. *Abh. Königl. Akad. Wiss. Berlin*, **1858**: 1–62.

Ogane, K., N. Suzuki, Y. Aita, T. Sakai & D. Lazarus, 2009. Ehrenberg's radiolarian collections from Barbados. *In* Y. Tanimura & Y. Aita (eds.), Joint Haeckel and Ehrenberg Project, Reexamination of the Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy, National Museum of Nature and Science Monographs, **40**: 97–106.

Siesser, W. G., 1981. Christian Gottfried Ehrenberg: Founder of Micropaleontology. *Centaurus*, **25**: 166–188.

Suzuki, N., 2009. Radiolarian studies by Christian Gottfried Ehrenberg (1795–1876) and value of his species as type species of genera. *In* Y. Tanimura & Y. Aita (eds.), Joint Haeckel and Ehrenberg Project, Reexamination of the Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy, National Museum of Nature and Science Monographs, **40**: 55–69.

Suzuki, N., K. Ogane, Y. Aita, T. Sakai & D. Lazarus, 2009. Reexamination of Ehrenberg's Neogene radiolarian collections and its impact on taxonomic stability. *In* Y. Tanimura & Y. Aita (eds.), Joint Haeckel and Ehrenberg Project, Reexamination of the Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy, National Museum of Nature and Science Monographs, **40**: 87–96.

Tanimura, Y., A. Tuji, T. Sakai, Y. Aita, N. Suzuki, K. Ogane, J. Young, D. M. Williams, D. Lazarus, O. Breidebach & T. Bach, 2006. Joint Haeckel and Ehrenberg Project. A Taxonomic Reexamination of the Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy. Research Report of the Museum Director General's Support Program in 2004–2006, The National Science Museum, Tokyo, 23 pp.

Tanimura, Y., A. Tuji, Y. Aita, N. Suzuki, K. Ogane & T. Sakai, 2009. Joint Haeckel and Ehrenberg Project "Reexamination of Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy": a summary. *In* Y. Tanimura & Y. Aita (eds.), Joint Haeckel and Ehrenberg Project, Reexamination of the Haeckel and Ehrenberg Microfossil Collections as a Historical and Scientific Legacy, National Museum of Nature and Science Monographs, **40**: 1–5.

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