Microscopy At The Ends Of The Earth

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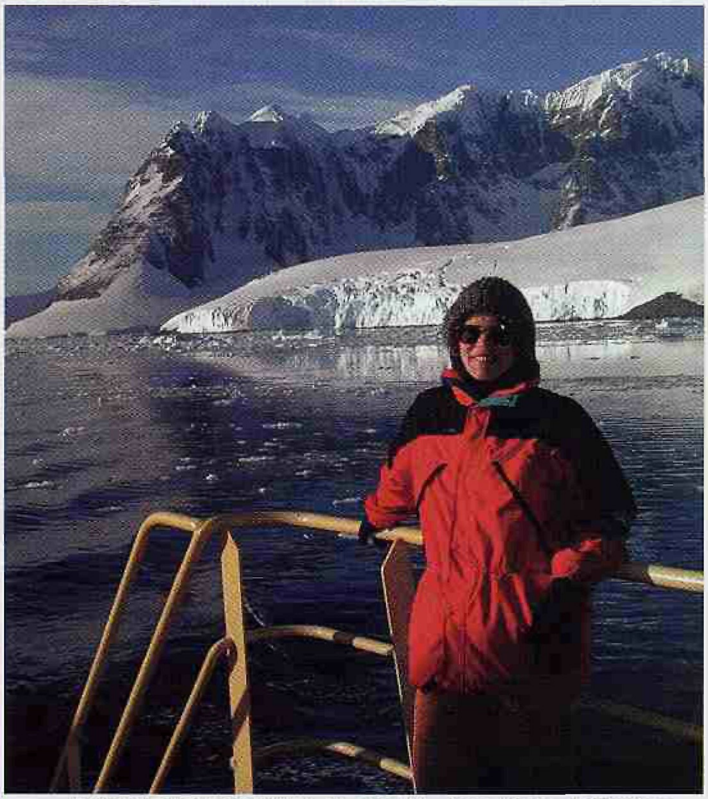
The first time you stand on the deck of a research icebreaker as it crunches its way through the Antarctic pack ice, you're surprised at how many colors there are. Ice covers the sea everywhere you look; perhaps here and there an occasional gargantuan iceberg rises majestically above the pack. Everything between you and all three hundred and sixty degrees of the horizon is gently undulating under brilliant sunshine in unison with the sea swell. It's a January midafternoon, the heart of the southern summer, and you're bundled up against the biting cold. You can't stop smiling.



Dee on deck of R/V L.M. Gould, *near Palmer Station, Antarctica. Photo © by Herb Baker*

The first time I experienced this was on an oceanographic expedition many years ago, and I've been back to the Antarctic a number of times since then. The joy, however, continues undiminished. It's exactly analogous to how I feel about the scanning electron microscope (SEM), which I've also been fortunate enough to enjoy during the same span of time. I never get tired of exploring the microworld, as I never tire of exploring Nature's glories at sea. Steaming towards Antarctica, for me the most heart-stopping moment happens some four or five days after we leave port. The ship has been chugging its way south through monotonous blue-gray water. Then one day I wake up, glance out of a porthole, and see ice: lots of ice, ice all over the place, pack ice, brash ice, "growlers", bergs. If it's a lucky day, the ice is dotted with penguins and seals. We have arrived at the last frontier and excitement pervades the ship.

Novices expect a black and white world, but I've been there before, so I know I'll see color. Besides extra suns and reverse rainbows, polar light does all sorts of peculiar things; look through a porthole at dawn and see blood-red icebergs against an inky sky. Put on your issued safety-red parka, take a cup of coffee out on deck and watch the morning colors change, reflected not only on the ice as the ship glides along, but mirrored on sheets of cloud hanging low overhead. One spectacular dawn in Marguerite Bay, a notch in the coast where the Antarctic Peninsula (actually a sheet of ice-covered islands) joins

Fig. 1, Chain-forming diatoms, 200X

the continent, I watched a smallish pale yellow iceberg slowly drift past a backdrop of deep pink mountains looming out of the dark blue sea and sky. Recesses sculptured by wind and water in sunlit traditional white icebergs are a glorious, luminous, turquoise. Have you ever seen bright metallic-gold water? Evening sunlight glinting in the cracks and open water between ice floes can do that. It's pretty astonishing. It looks like liquid pyrite.

One of the colors you see in Antarctic waters, though, is not very inspiring. In fact, to someone who would rather wax poetic, it mars the ethereal beauty of the scenery. It's a brownish stain that lines the undersides of the pack ice, and it literally turns up as the moving ship tears chunks out of the pack. The chunks of ice roll over as we pass through, and they just look dirty.

But it's very interesting dirt. Lower a water sampler over the rail – or better yet, have yourself lowered in a personnel basket onto the ice - and grab some. (Antarctic curiosity works both ways: penguins might just shoot out of the water onto your floe and waddle over to check you out.) Take your sample back to the ship's lab, melt the ice and filter the water. A month or two later take the yucky dried filter paper back to your home institute, cut out a couple of square centimeters and

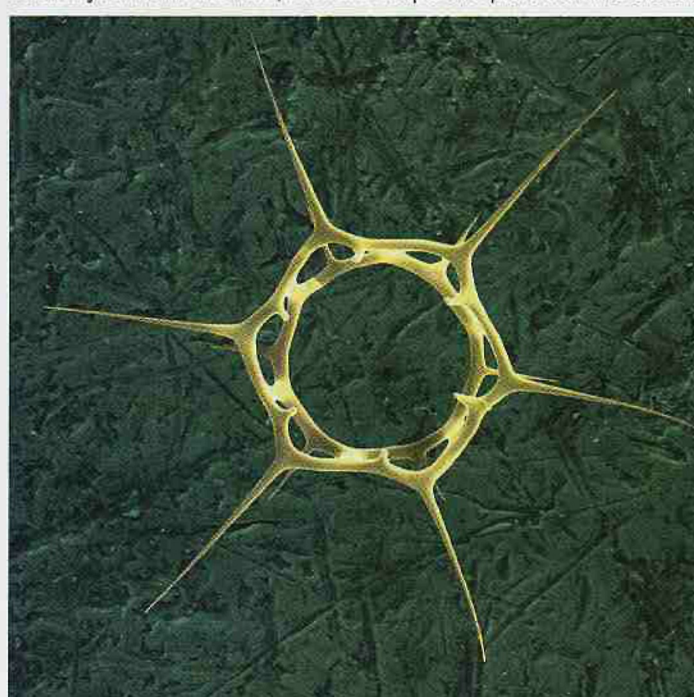


Fig. 2, Silicoflagellate, 1,300X

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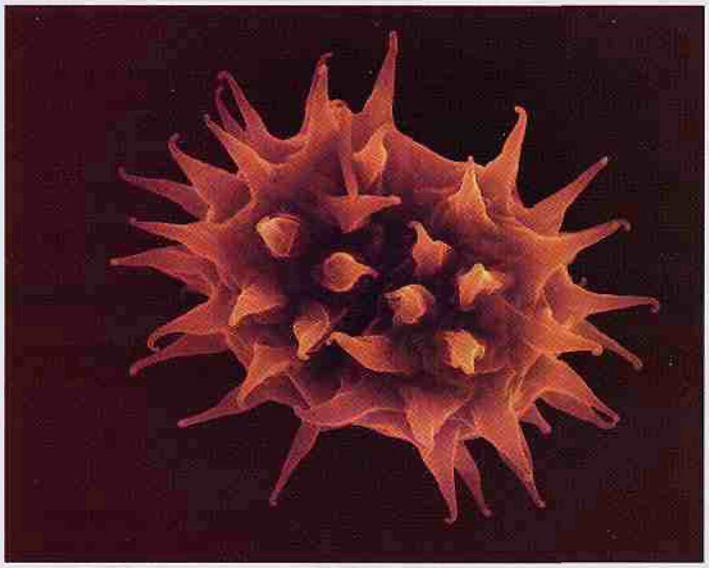

Fig. 3, Algal spore 1, 3,200X

look at it through the electromagnetic lenses of your scanning electron microscope. Wow! How can anything that started out on the grunge end of ordinary end up so beautiful?

Lots of things, as it turns out. But let's start with a few types of microplankton, the tiny plants and animals I call "invisible seashells" that live in surface seawater and are taken up into the undersides of polar sea ice. As we microscopists know, Mom Nature has designed some pretty amazing stuff with no particular regard to human curiosity, and until our powerful microscopes were developed we could never have predicted such unseen marvels. Magnify your brown smudge a few hundred times and you find an assemblage of surprisingly pretty ornaments. These are the siliceous shells of one-celled plants called diatoms (a term meaning "two parts"). You have to magnify each one about five hundred times - or maybe three thousand times, depending on the species, if you want to snap an individual's portrait. Zooming in, you can see that diatoms are made like little pill boxes, two halves tightly fitted together. Some species are fashioned like minuscule Oreo cookies and others resemble peanuts, or two overturned canoes snugged together. Most diatoms are dotted with pores and protrusions and all of them look a bit otherworldly. Victorians loved to make painstakingly intricate designs with them.

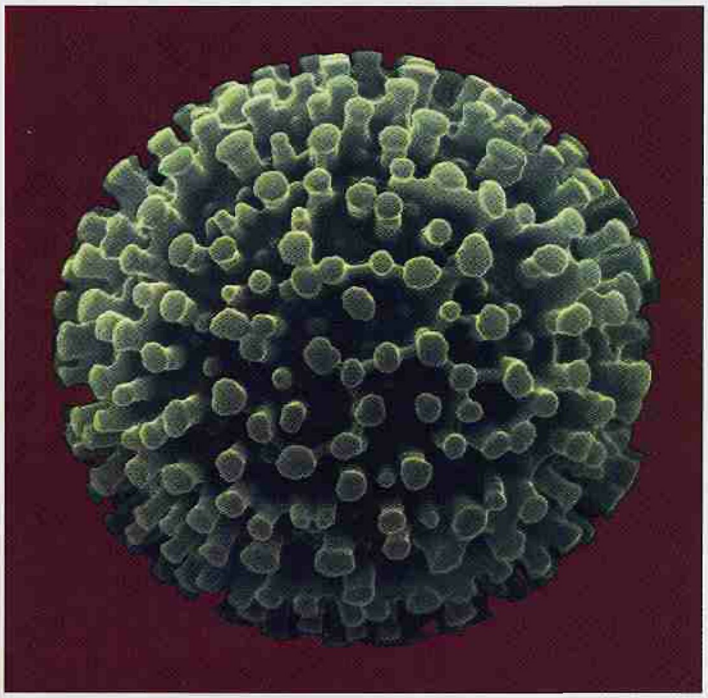

Fig. 4, Algal spore 2, 750X

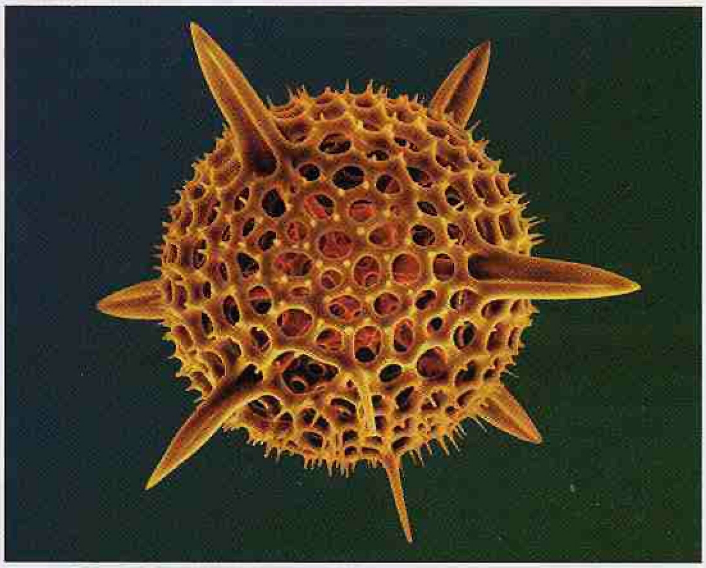

Fig. 5, Fossil radiolarian, 350X

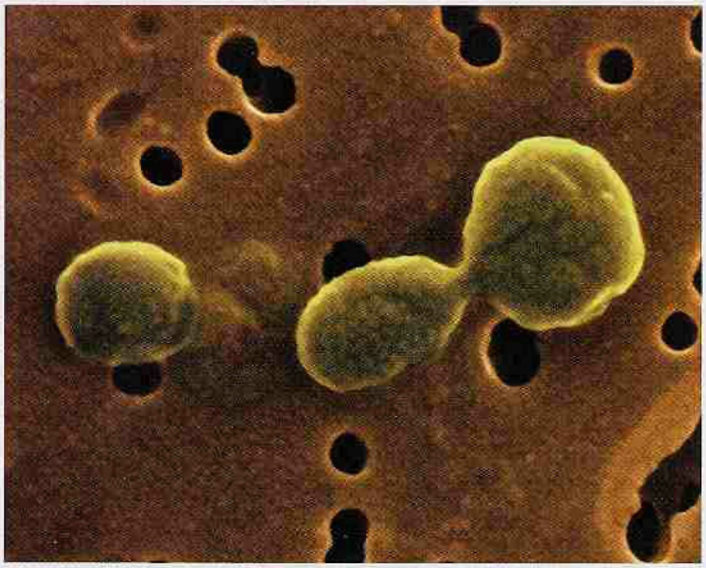

Fig. 6, Vostok bacteria, 32,600X

Because microplankton such as these are extremely sensitive to the environment, they have been studied to monitor changes in the chemical and physical properties of their worlds, and to compare living and fossil species in order to help reconstruct the climate history of the Earth. Two researchers interested in these matters are Lamont microbiologist Ray Sambrotto and his current graduate student Sara Green, and one of Ray's projects involves characterizing the microplankton population dominating the coastal Southern Ocean in a polynya (open water surrounded by ice) near the Mertz glacier. Sara filtered the critters from melted 'year-2000' sea ice during an expedition in the Mertz Polynya that year. Diatoms large and small, centric and pennate, were present, as well as a few other types of phytoplankton. Though it's hard to choose from among the many life forms found in his samples, four are illustrated here: a chain-forming centric diatom surrounded by diatoms of various other species (Fig. 1), a silicoflagellate - the silicious shell of another type of plant-like organism (Fig. 2), and two beauties that look like pollen but are probably algal spores (Figs. 3, 4).

As if diatoms aren't pretty enough, we have spectacular little one-celled protozoa called radiolaria, which are distant cousins of amoebae. As with other microplankton, stratified deposits of radiolarian shells form a fossil record of oceanic environmental changes over geologic time spans. Like diatom shells, radiolaria are also siliceous and they look very much like miniature Christmas tree ornaments. Most of them are constructed of sturdy ribs supporting a filigreed network

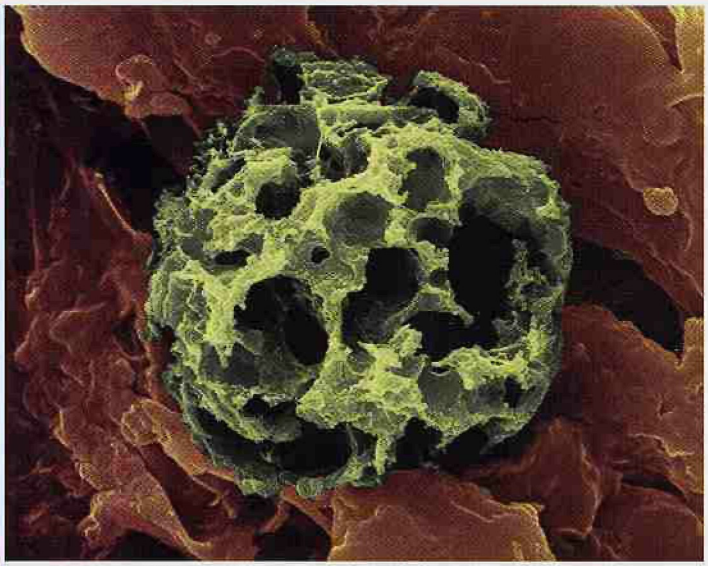

Fig. 7, Vostok ash, 4,700X

and they often sport spikes and spines. In the sea, the cell living inside each shell surrounds the shell with a cloud of protoplasm as it feeds on floating bits of even tinier things through the many windows in its glass house. The shells of some species look like a fine mesh, or like badminton shuttlecocks with long legs extending from the open end, while others are simply spherical. But, even these aren't quite as plain as your first glance would indicate. Figure 5 shows a fossil radiolarian shell discovered in a sediment core from the bottom of the Ross Sea. The SEM reveals that a second sphere lies suspended inside. (On occasion a third can be discerned even further in.) The image records the radiolarian's concentric globes being held together (and apart) by a forest of spikes radiating through the layers and into the outside world.

The SEM/EDX facility I manage is at Lamont-Doherty Earth Observatory, Columbia University's Earth Science Research Institute located on a bucolic country campus some ten miles north of New York City. Lamont scientists range far over the globe on both land and seagoing expeditions, and many of them bring back samples to study under the SEM. But here, we are mostly focusing (so to speak) on a representative sampling of projects that derive from the Antarctic - the highest, driest, windiest, and coldest place on Earth - with a token nod to the higher northern latitudes as well. I am a specialist in electron microscopy, who facilitates the SEM investigations of scientists and students plus the occasional intern or talented high schooler. I also participate in various capacities on expeditions of all kinds, though somehow I seem to keep being pulled back to the Antarctic in particular. Most of the SEM images that I create for public outreach and education are research-derived; some are from samples I collect myself along the way. Each of them, of course, has a story to tell. Since my lab is open to anyone who needs it, I am fortunate to have access to samples from diverse disciplines and institutes, which broadens the range of tales I can carry to the public. Happily, many of these are based in polar research.

Fig. 8, 12-million-year-old moss, 45X

I think a word is in order about how and why I work up my SEM images for public viewing from the original raw and monochromatic shots. First let's return to the subject of color. Electron-purists decry color as not being the truth. I agree. I join them in believing that a research image should be published unaltered except perhaps in contrast and brightness, and cropped for subject matter. But for the general public, color has become something of a necessity. The human eye has evolved to discriminate all the shades of the rainbow and most people are simply more comfortable in a colorful world. A second reason to colorize electron images for the public is to separate different structural elements for easier interpretation by viewers unfamiliar with the abstract nature of scientific imaging technologies. Finally, a little pizazz is productively eyecatching. All of these factors come into play when I colorize an SEM image. Sometimes I use a palette that evokes the sample's true colors, on other occasions I choose a more exotic effect for one reason or another, and sometimes an image goes off in an unintended direction the way authors describe their characters taking on lives of their own. I must also mention that I tend to clean up my images, taking out dust, fixing something broken here and there, changing some backgrounds to make the subject stand out better. When I publish or lecture, I make sure to tell my audiences that the images are enhanced.

Striking images are good teachers. They attract folks who are normally intimidated by Science – those who think it beyond their ability to grasp scientific concepts. It's gratifying to watch people soak up the stories behind the images, to enjoyably learn something they would otherwise have avoided, and to exclaim to their kids in delight.

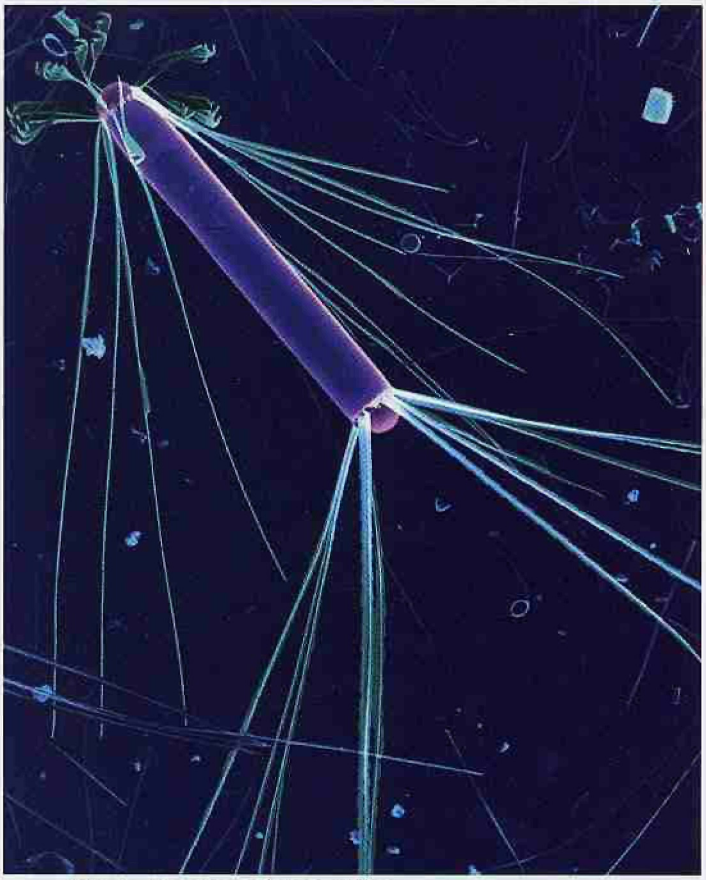

Fig. 9, Ross Sea diatom, 200X

Dee on ridge with pyrite underfoot, Arthur Harbor, Antarctica. Photo © by Tim Neuberger and Fig. 10, Palmer pyrite, 20X

(Bait and switch. It works!) I recorded these images on Cambridge 250 and LEO 1455 SEMs. Some were taken on Polaroid film followed by printing and scanning; others were recorded digitally. I cleaned and colorized all the images in Photoshop. Though creating and optimizing images for years, I have found Felice Frankel's new book "Envisioning Science: The Design and Craft of the Science Image (MIT Press, 2002) to be an extremely valuable resource, and urge anyone who creates scientific imagery to stock it for reference and revelation.

For those of you working with other types of microscopy and unfamiliar with the SEM, this instrument uses electrons to reveal objects smaller than can be imaged by the photons of visible light. The specimen resides in a vacuum chamber, where its image is formed by subatomic events triggered by the surface impact of an electron beam that is focused by electromagnetic lenses. Secondary electron images are formed from electrons ejected by the sample's surface and yield pictures with a crisp, three-dimensional appearance. Backscattered electron images are formed from beam (primary) electrons that have hit the sample and bounced back to a different specialized detector. The gray levels of a backscatter image correspond to differences in chemical composition and can be used as a map for X-ray microanalysis. This type of image tends to be flatter and softer, although sometimes I use it to illustrate a particular structure instead of a secondary image if conditions or a fortuitous aesthetic happen to appeal to me.

Returning to our journey, one of Ray's colleagues is Lloyd Burckle, another Lamont diatom expert working in Antarctica. The two research-

Fig. 11, Limpet worm tubes, 11X

ers have collaborated in a study of samples from Lake Vostok, the largest of about seventy ancient lakes buried nearly 4000m below the surface of the great Antarctic ice sheet. Hundreds of thousands of years old and about the size of Lake Huron (one of the U.S. Great Lakes), Vostok is a potentially sensational natural laboratory. Russian scientists have drilled through the ice to within 100m of the sealed lake, stopping short to preserve the pristine nature of the waters while an international group is currently working on a protocol to sample the lake without contaminating it in the process. Meanwhile, I can show you two samples from the Vostok ice core: Fig. 6 shows what are believed to be 430,000-year-old bacteria. Three seperate labs have reported viable bacteria and fungi from the same material. Fig. 7 is a tortured glassy sphere that is probably ash from an ancient volcanic eruption of yet-unknown origin. In a separate collaboration with Dave Marchant of Boston University, Lloyd is also looking at mossy vegetation from an ancient Antarctic pond (Fig. 8). There is little vegetation in its icy clutches now, but Antarctica was warmer 12 million years ago.

An image from a pioneer study done some years ago by the late John Martin of Moss Landing Marine Laboratories in Monterey Bay, California, can also illustrate current work by Lamont geochemist Bob Anderson. This elegant diatom (Fig. 9) participated in a seagoing experiment in which Martin conducted an iron fertilization experiment in the Ross Sea to see if a diatom bloom would result (it did). Since

Fig. 12, Penguin feather, 45X

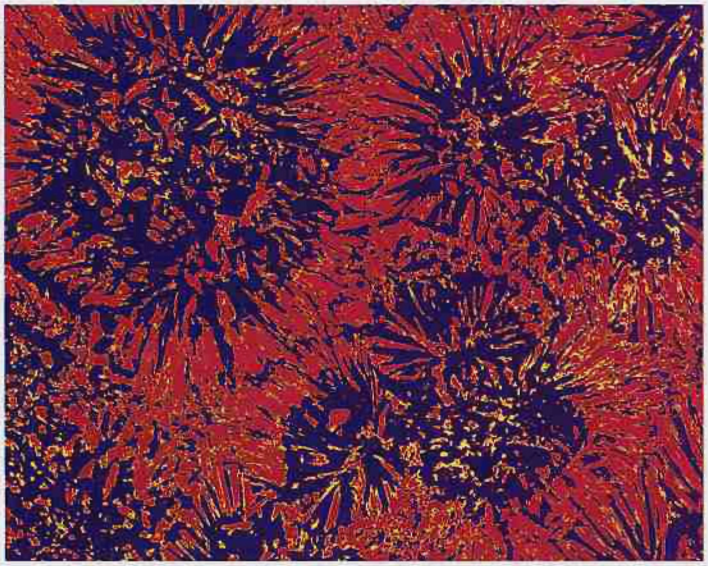

Fig. 13, Mixed minerals, 1,300X

diatoms help fix atmospheric CO_2, the study was an intriguing look at a potential antidote to global warming. At Lamont, Bob is using this and other diatom species to study the Southern Ocean's unique combination of both a high rate of nutrient supply to the surface waters and low efficiency of biological utilization. The Southern Ocean is suspected to have played a role in regulating glacial-interglacial changes in atmospheric gas concentrations; its present-day effect on atmospheric carbon dioxide levels may become important as the planet warms.

The last time I went to Antarctica was just a few months ago. Trekking the "back yard" of Palmer Station, a remote, brave cluster of buildings on Anvers Island along the Palmer Peninsula, I picked up a few samples of my own. One of my favorite spots in the world is where the vast Marr ice piedmont meets the sea in Arthur Harbor just behind the station. Half an hour's walk over an ankle-busting rocky terrain – unless it's snowed, making it even more treacherous – you can meditate by a stupendous view, listen to the leading edge of the glacier talk (and possibly catch it calving), admire whatever wildlife is in residence, and chuckle at gulls briefly hurling backwards when surprised by some of the infamous Antarctic gusts. Scrambling atop a rocky ridge, my shipmates and I noticed the sparkle of pyrite running through our perch: the Antarctic peninsula is an extension of the Andes mountains, continued in north America as the Sierra Nevadas. Composed of igneous rocks, Palmer Peninsula is an upthrust feature of a subduction zone, in this case, where the Pacific plate is being pushed – or pulled, (the jury's still out) down into the Earth's mantle by massive tectonic forces. Volcanic and hydrothermal activity creates suites of minerals such as pyrite under these conditions. Fig. 10 is a backscatter microscape from the vein of pyrite under my boots, its tiny form echoing the surrounding mountains.

Kelp gulls swallow their limpet meals whole at Arthur Bay, eventually regurgitating the neat stacks of empty shells that dot the terrain. I found one of these shells sporting a tiny necklace of individual marine worm tubes around its scalloped edge, each a miniature curl (Fig. 11, a shot taken uncoated in backscatter mode at 1.5 kV). I didn't attempt to get a sample from any of the local enormous (and as stinky as reputed) elephant seals. For one thing, we're not allowed to get close. For another, though they may look like sleepy wads of melted wax, they can rouse nasty and move fast. But any discussion of the Antarctic would be remiss without penguins, and I did pick up some penguin feathers to explore (Figure 12). As one might expect from a bird that flies in near-frozen waters, penguin feathers are remarkable, very small and stiff, tightly packed (up to seventy in each few square centimeters) and overlapping in insulating layers. Not to disturb Antarctic penguins, I collected mine from a Magellanic penguin burrow in Patagonia just before setting sail for the Southern Ocean on the *L.M. Gould*, one of the two U.S. National Science Foundation vessels dedicated to Antarctic service. The other is the *N.B. Palmer* and both are superb 24/7 scientific workhorses. (I've also sailed on ships from several other nations, variously departing from and ending at what a shipmate of mine once called the dangly-bits at the bottom of the globe: Australia, New Zealand, and South Africa in addition to the Patagonian tip of South America. These trips are hard work, but the science is terrific and the travel can't be beat!)

I don't have any samples from the high Arctic at the moment, but can evoke the higher northern latitudes with two final images. In addition to the pyrite discussed above, the dynamic forces that continually restructure our planet form many kinds of minerals that can be studied on the microscopic scale. One exotic SEM sample brought to the lab by mineralogist and former Lamonter Anne LeHuray is of two minerals that formed together when the landmass that later became Norway and Greenland parted company. These minerals (celadonite, red, and calcite, blue) were co-formed by subareal volcanic processes about 55 million years ago in a manner called "intimately mixed", before they eventually settled to the sea floor when the Norwegian-Greenland Sea was created. Fig. 13 is a backscatter image of a flat, polished slab of this rare rock, called tholeiite.

Coccolithophoridae are a type of single-celled marine golden-brown algae with shells made of calcium carbonate. Important sources of food for marine animals and of atmospheric oxygen, coccospheres are much smaller than most diatoms, but can reveal an even more intricate architecture. Because they have undergone rapid evolutionary change over large geographical distances with attendant variations in shape and ornamentation, these little beauties have become useful as index fossils that can help determine the geologic ages of rocks and sediments. We will draw our polar journey to a close with another of Ray Sambrotto's samples (Fig. 14), this one a coccolithophorid filtered from the waters near Iceland. Composed of a series of interlocking or overlapping plates called coccoliths, ("circular stones"), these phytoplankters are vanishingly small. Yet, large fine-grained limestone deposits such as the White Cliffs of Dover are made of countless numbers of these and other types of "invisible seashells." While fossil coccoliths are normally found scattered individually in the sediments, intact coccospheres are preserved only in anoxic environments where nothing lives to disturb them after they fall to the sea floor. Seawater can then react with the organic cells inside. This is another method our dynamic planet uses to form pyrite, although this time it's on the ultramicroscopic scale. And so, as we are privileged to watch, the Earth's cycles continuously turn on big scales and small. ■

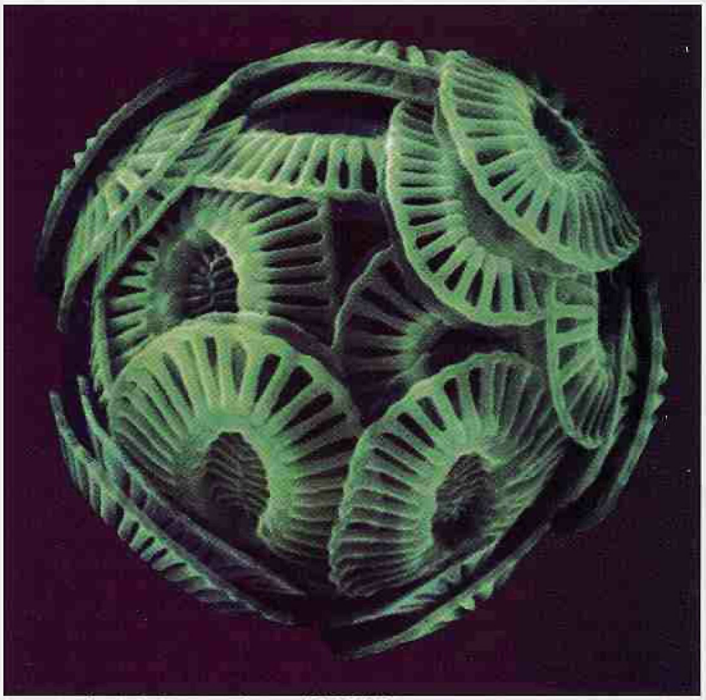

Fig. 14, Coccosphere, 10,875X