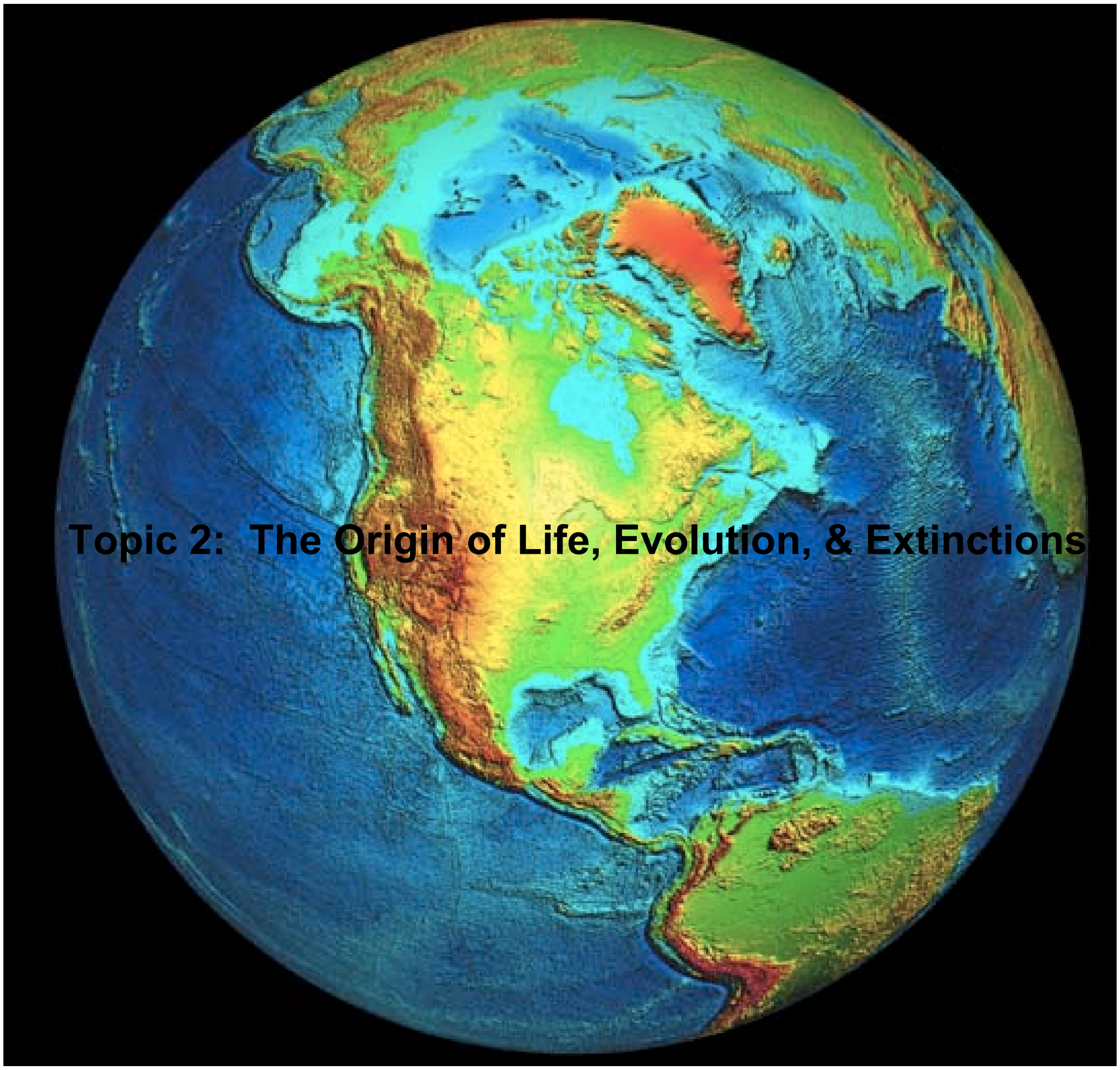
Planet Earth:
An Introduction to
Earth Sciences



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Planer Earth Topic 2: The Origin of Life, Evolution, & Extinctions

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Century after century, humans have looked to the stars questioning "Are we alone?" Does life exist elsewhere in the universe? Ancient mythologies , Hollywood, and science fiction have presented imaginative possibilities, but how does science approach this question? And how does this question relate to how life originated on our planet? Answers begin to emerge as we consider newly discovered facts.

Life on Planet Earth can thrive in environments previously thought too hostile and inhospitable, such as miles beneath the ocean in cracks and fractures in volcanic rock. Just 30 years ago, scientists discovered life thriving in the most extreme of terrestrial environments, more than two miles below the ocean surface at mid-ocean spreading centers. In perpetual darkness amidst scalding temperatures up to 400 degrees Centigrade and under intense pressures of thousands of pounds per square inch, oceanographers discovered hydrogen sulfide eating bacteria, giant tube worms, blood red clams, and blind crabs. These organisms live on chemosynthesis, not photosynthesis like the surface dwelling plants and animals of our common experience. Their life giving energy source is hydrogen sulfide rather than our glucose-based sugar diet. Apparently, conditions for life are more widely varied than previously believed possible on Planet Earth. What then of life on all those billions of other planets out there in the unimaginably infinite universe?

Yet we listen to space in hopes of finding the sounds of other intelligence, and so far, all we hear is static. It is likely that we are only just learning how to explore space, and that we are at the dawn of exploration. Our Milky Way galaxy contains countless planets yet to be discovered, and maybe explored. How many of them may harbor life?

Back Home – So We Know All There is to Know?

Scientists are not as likely to talk in wondrous superlatives as are say talking heads on cable television or used car salesmen, so imagine the surprise to read the following reports coming from the deep-diving submarine *Alvin* in 1977 – just 25 years ago. The *Alvin* was diving at the bottom of the ocean under 2 miles of water on the mid-ocean ridge spreading center of the East Pacific Rise just south of Baja California. The Mid-Ocean Ridge is the greatest mountain range on Earth, encircling the entire globe through all our oceans. Its crest is covered by active volcanoes belching out new sea floor at rates that vary from a few to a few tens of centimeters per year (much more on this later). Here are some of the quotes from the oceanographers who were there (from the *New York Times's* coverage of the events):

It was like Pittsburgh in 1925, *with all those blast-furnaces going full force!*

It was like seeing a 19th century steam locomotive, just pouring out smoke!

It was like a fire hose going full blast at the bottom of the ocean!

Headlines trumpeted:

Sea-floor geysers may be key to ore deposits!

Sea-floor oases of mineral-rich springs and amazing creatures exceed oceanographers' wildest dreams!

And perhaps the most startling of all:

May be the site of the origin of all life on the Earth!

An oceanographer wrote the following account of the *Alvin* dives that rank with the Apollo flights as the greatest expeditions of discovery in the 20th century:

It is difficult to convey the strange quality of the diving experience in Alvin. First one spends two hours or so in almost total darkness, dropping by gravity more than two and a half kilometers to the sea floor. Three people are huddled in the cold and cramped confines of the Alvin's pressurized, titanium diving sphere, which is only two meters in diameter. On approaching the bottom, the submersible's running lights are turned on, and the illuminated water takes on a dim, greenish glow. Minutes later, the sea floor is sighted. As soon as the Alvin has reached the bottom, the team reports its position to the control ship and is given a course to steer to a pre-determined bottom target. Edging ahead slowly (at about half a kilometer per hour) over the glistening volcanic rock, the investigators peer through portholes, seeing only 10 or 15 meters into the darkness. Heretofore, it was a monotonous, bleak and barren sea floor we always saw out the Alvin's porthole.

On the discovery dive, however, we were making gravity measurements in the volcanic zone of the mid-ocean spreading center's ridge axis when we came on the hydrothermal vents for the first time. The scene was like one out of an old horror movie. Belching black smoke, hot water rose from the tops of gigantic, metal-laden and golden shimmering chimneys growing upward from fissures in the black, basaltic lava along the volcanic sea floor (Figure 2-1).

Large white clams as much as 30 centimeters long nestled in the cracks between the black lava pillows; white crabs scampered blindly across the volcanic terrain. They had eye sockets, but seemed to be using them to scrape food from the giant stalks that populated the edges of the chimneys. These "Tube Worms" were the most unusual organisms I have ever seen in my life. Mounted around the chimneys were huge clusters of what turned out to be giant, bright RED, tube worms, some of them as much as three meters tall. You have to understand that color of any kind is rare on the sea floor. It is usually a bleak desert of grays and blacks. But these weird, brightly colored creatures swayed eerily in the hydrothermal vents, their bright red plumes extending well beyond their white protective tubes that we later found to be made of chitin, like your fingernails.

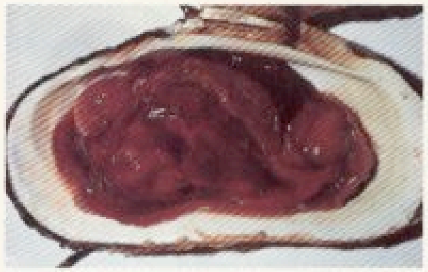
The red color of both the tube-worm plumes, and to our great surprise, of the tissue of the clams as well, turned out to result from the presence of hemoglobin in their blood! The clams look like they are filled with huge slabs of liver. One of my shipmates ventured a small taste, but I'm afraid the rest of us were not so brave.

On a subsequent Alvin dive, we were guided to another hydrothermal vent to the southwest of the first we visited. The sight there was even more dramatic: extremely hot water, blackened by sulfide precipitates, was blasting upward through even taller chimney-like vents as much as 10 meters tall and one meter wide. We named the vents "black smokers". The chimneys and inevitable tube-worm colonies protruded in clusters from mounds of sulfide precipitates that turned out to be mats of bacteria so thick that they looked like a white carpeting. We later found that they were metabolizing sulfur from the chimney water. They were chemosynthetic! And are probably the base of what has to be the most exotic food chain on Earth.

Our attempt to measure the temperature of the black smokers was an adventure unto itself. Until then the highest temperature ever record on the ocean floor was 21 degrees C., measured only two months earlier on a nearby spreading center. Our *thermometer was calibrated only to 32 degrees C. When I inserted it into the first chimney using the Alvin's mechanical arm, the temperature reading immediately sailed off- scale. Moreover, when the probe was withdrawn from the Black Smoke, the plastic rod on which it was mounted was melted! Back at the surface, we jury-rigged a calibration tank using the cooking oven in the galley, and went down to try again. Measurements were made that indicated astounding temperatures of at least 350 degrees C – as high as we could calibrate the thermometers at sea. And this was at the bottom of 2 1/2 kilometers of 2 degree C ocean water! If we didn't have it all on videotape, who would believe us?*

Figure 2-1. Deep-sea hydrothermal vents occur along the mid-ocean ridge spreading centers. More than a hundred different vent sites have been discovered since the first site was found in 1977 near the Galapagos Islands by oceanographers in the small research submersible *Alvin*. And scientists have explored only a small portion of the 50,000 kilometers of mid-ocean ridges on Planet Earth (Photo credit, American Museum of Natural History).

The remarkable process that provides the food for these organisms is called *hydrothermal circulation*. The new lava extruded from the volcanic magma chambers at the axis of the mid-ocean ridge spreading centers cools beneath 2 miles of near freezing seawater. The lava fractures from the quick quenching caused when 1200°C lava hits 2°C water. The water invades deep into the newly formed volcanic pile above the magma chamber, shattering the quickly cooling rock. Soon, the basalts, called pillows because they appear like rock squirted from a tube, is shot through with rubble zones and fractures. Water circulates right down to the top of the magma chamber, where fracturing must stop -- you cannot crack liquid magma. The result is virtually instantaneous cooling of the basaltic lava and superheating of the ocean water that has seeped down into the rock and near the magma chamber. The superheated water then explodes toward the sea floor at fire-hose velocities, extracting along the way precious metals and sulfur from the volcanic rock, creating sulfur bearing hot springs that feed the chemosynthetic organisms the oceanographer described above (see Figures 7-3,-4,-5,and -9 from Anderson, Marine Geology, 1986, reproduced below).



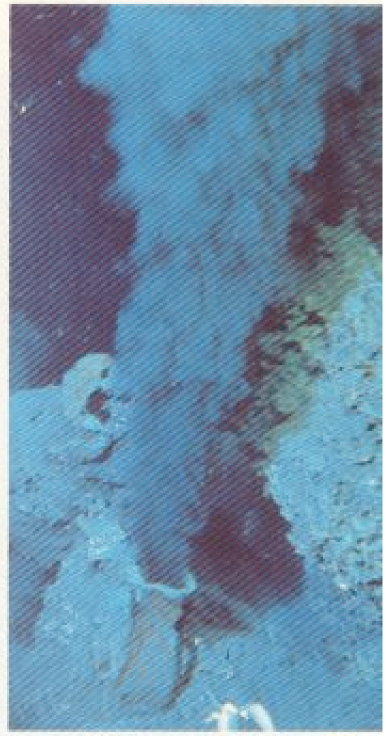


Figure 7–3 (above). The need for hemoglobin extends to the clams as well as the worms. The meat of the black-smoker clam is beefy red. High concentrations of heavy metals also present in the black smoke make it unadvisable to eat this clam. Also, note the huge size of the clam, again an indication of the plentiful supply of sulfur-rich food. (by Emory Kristof, © National Geographic Society)

Figure 7–4 (right). The black smokers exit the sea floor at "firehose velocities" as a clear liquid at up to 400°C. They immediately cool and begin precipitating their heavy metal contents. They are supersaturated in iron, copper, zinc, manganese, and most of the precious metals. (by Dudley B. Foster, Woods Hole Oceanographic Institution, © National Geographic Society, 1979).

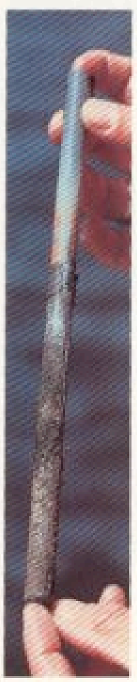


Figure 7–5. As evidence of the high temperatures present in the black smokers, consider this *Alvin* heat probe, which was inserted into the smoke to measure its temperature. The hottest waters ever encountered prior to the black smokers were 22°C, so not only did the temperature reading from this probe go off the scale, but the PVC plastic tubing melted. Melting temperature for PVC is 250°C. High-temperature platinum thermocouples were later used to measure temperatures up to 400°C in the black smokers (by Emory Kristof, © National Geographic Society).

Figure 7–9. If the rising, hot limb of the crustal convection cell mixes with downgoing cold water beneath the surface, the metals are precipitated beneath the sea floor and the smoke is colder and white as it exits into the water column. Such cases preserve massive amounts of metals, which are minable millions of years later if the deposits happen to be obducted onto land as ophiolites. Troodos on Cyprus was such a white-smoker case. Also, the metals shown here came from a hole drilled deep into the 6-million-year-old crust south of the Galapagos Spreading Center white smokers. The "golden" mineral is pyrite or "fools gold," but there are minable concentrations of copper and zinc present in this sample (from Deep Sea Drilling Project).

Chemosynthetic bacteria have been known for a hundred years, found living in hot springs, volcanoes and other hostile environments at the surface, but how they evolved on Planet Earth was previously unknown. Recent DNA fingerprinting has shown that they are a different branch of life from the surface plants and animals on the planet. All other life-forms ultimately depend upon a photosynthetic, sugar-based food chain. These chemosynthetic bacteria metabolize hydrogen sulfide acid!

The basaltic lava that makes up the sea floor at the mid-ocean ridge spreading centers is cooled very quickly by the 2 degree C ocean water at the bottom of the ocean. The vent fluids cannot heat above about 400°C though because of the remarkable buoyancy of hot water. Please don't ever try to prevent the steam from exiting a boiling teapot, for example, or leave the latch off a pressure cooker. As the water moves upward through the new basaltic lava, it changes chemically, giving up its sodium and magnesium and taking up calcium and potassium. But superheated water also extracts copper, zinc, iron, silver, gold, and other precious metals and concentrates them into a supersaturated fluid. The supersaturated fluid is cooled quickly as it escapes into the ocean at the sea floor, and it precipitates these metals into black, soot-like deposits that form ore bodies as they build the chimneys of the black smokers. These black smoker chimneys have been mined since antiquity. The Greeks got theirs from the island of Cyprus, where some of these ancient sea floor deposits ended up on land as Africa crashed into Europe (more on this later).

That the black smokers are periodic and directly related to volcanic eruptions can be seen from several facts. First, they are only found within a few hundred meters of the exact axis of the spreading center. They form a straight line delineating the axis of the magma chamber . Second, they remove far too much heat to be continuous features. One single 350 C black smoker removes 1 million years worth of heat from the ridge axis in 1 year. So they must be periodic, or they would quickly freeze the magma chamber into solid rock and kill the volcanoes that feed the spreading centers.

The most fascinating and beautiful by-product of the hot springs is the biological community that lives in the vents and is like no other on the surface of the Earth (Figure 2-2). Using the sulfur-eating bacteria as the basis of their food chain, the giant tube worms, huge clams, and blind crabs live, not off the Sun's energy as does virtually every other known ecosystem on the Earth, but instead, off the thermal energy of the Earth. This power source is unique for such a biological community, and it wasn't even discovered until 1977.

The hydrothermal vent organisms are oversized because of their plentiful food supply. Not unique to the vents, they live in smaller forms throughout the ocean. The tube worm, *pogonophoran* for example, is a larval, free-swimming worm that in other environments never attains enough size to be dissected except under a microscope. Yet in the vents, this worm grows a chitinous tube that is up to 10 m high and is attached to a rock. The worm itself is up to 18 inches long, has a bright, beautiful red color, and moves freely within its tube. Remarkably, it has no stomach, instead filtering the abundant food from the smoker fluids directly into its cell structure. Similarly, the clams are quahogs, eaten daily by many Cape Cod vacationers. Yet the vent clams are 12 to 18 inches long, their meat is like red liver, and they weigh up to a pound! You wouldn't want to eat too much of them though; they ingest lethal quantities of metals such as mercury from the black smokers. Both the tube worms and the clams use hemoglobin, just as we do, to extract oxygen from the bottom water. They need more oxygen than their shallow-water cohorts because they metabolize the hydrogen-sulfide-eating bacteria, which they use as food. So are they shallow water quahogs that have stumbled into the hydrothermal vents at the depths of the deep oceans, only to have magically turned on a genetic "hemoglobin switch" needed because oxygen at those depths is scarce? Or did they originate in these deep water vents and stumble to the oases of the shallow waters and no longer need hemoglobin in that oxygen-rich water? How they do any of this is still one of the great biological mysteries of these fascinating organisms.

Figure 2-2. Deep-sea hydrothermal vents support extraordinary *ecosystems* deep beneath the surface of the oceans. These ecosystems are the only communities on Earth whose immediate energy source is not sunlight. Life on Earth, and even possibly on other planets, may have formed in environments similar to these. Each of these tube structures is actually a worm. Tube worms vary in size depending on where they live. These particular tube worms are huge compared to their larvae-sized cousins known before the hydrothermal vents were discovered in 1977. (Photo credit, Woods Hole Oceanographic Institution, Deep Submergence Operations Group, Dan Fornari).

There are many more remarkable features of the vent organisms. The crabs have eye sockets like their shallow-water cousins, but since no light at all ever filters down to these great depths, they have no need for eyes in their sockets. Instead, they appear to use the sockets to scrape bacteria off the worm tubes for food. Did they lose the eyes when they stumbled into the ocean depths, or did they evolve sight in their eye stalks when they came upon the brightness of the shallow waters?

The clams grow about 10 times as fast as their shallow-water cousins. The shells have been age-dated using carbon isotopes, and none have ever been found that are older than 20 years. So the vents must be that age or less since a shallow-water clam lives much longer than that. Vast colonies of dead clams have been found just off the spreading axis, but since their calcium carbonate shells dissolve in seawater, the skeletons quickly disappear. They live and die with the hot-water source, and we have seen that the smokers can only last for a short time before they mine too much heat from the magma chamber.

How then could the animal colonies have survived through billions of years if their food source turns off after only 20 years in anyone spot? Clams, let alone tube worms, can hardly pick themselves up and walk over several miles of rocky terrain to the next vent site. They survive by sending their young off as free-swimming larvae in search of new vents. Turns out that larvae were found by oceanographers tens of years before their parents. We didn't know they were the young until 1977.

Where did our Life Originate? at Ancient Hydrothermal Vents?

Hypotheses for how these communities evolved have shaken the traditional "organic soup" theories for how life originated on Earth to their foundation. Remember those stromatolites that mark the oldest fossils on the planet – they turn out to be sulfur-eating bacterial mats! Some marine biologists have even suggested that life originated in the black smokers, and not in the primordial swamps on the surface in the first place. There has always been a problem with the organic soup hypothesis, that the soup needed lightening strikes to form DNA and RNA genetic material from amino acids (like all the Biology textbooks suggest).

Is it possible instead that the black smokers were to first locations where life originated on the planet? For one thing, they were at the bottom of the ocean, sheltered from the intensive bombardment from huge meteorites that pockmarked all the early planetary surfaces in their early days.

Clay minerals, when raised to just below kiln temperatures (remember the 400 degree temperatures required for dehydration), can combine to form amino acids. The problem with combining these into DNA and RNA is that they would immediately burn up in such temperatures. Thus, the fire-hose velocities of the exiting water would be needed to allow the organic compounds to survive and form the primordial bacteria as they spouted into the ocean from the chimneys to form the base of the chemosynthetic food chain at black smokers.

Enormous problems exist with this chemosynthetic origin for life as well, like how to convert from chemo- to photo-synthesis at the surface. The separate DNA fingerprints make it possible that there were even two different origins of life on Planet Earth. Look what that does to the odds that we are not alone in the Universe.

That the hydrothermal vents are sites for the origin of life is perhaps the most remarkable speculation to come from the finding of this, the first completely new ecosystem to be discovered by biologists in the last 100 years. Although not yet proven, this scenario for the origin of the earliest life on Earth. If the black smoker hypothesis is correct, an intriguing possibility is that new life is continually formed at black smokers, even today. If so, where is all that new life? Is it now being eaten for food by the life already existing around the black smokers? Marine biologists are now trying to find a way to scrape the inside walls of a black smoker chimney to return traces of newly forming life to the laboratory, but they have not yet been successful.

The Origin of Mass Extinctions and the Climate of Planet Earth

One of the most remarkable events to continually reappear in the fossil record other than the evolution of life is the repeated *extinctions* of vast numbers of organisms from the surface of the planet. The most robust and plentiful species die off as readily as the tiniest of microorganisms during these extinction events. Dinosaurs are the most famous example; they all died out 65 million years ago. But there are other extinctions as well. For example, trilobites dominated the ocean floor prior to their extinction 500 million years ago.

What killed off such prolific and well adapted organisms as the dinosaurs (Figure 2-3)? The mechanism for mass extinctions has been a controversial topic of geologic speculation for over 100 years. Disease, overspecialization, dramatic climate change, magnetic pole reversals, and extraterrestrial interference have all been extensively discussed. Recent dramatic improvements in analytical precision have allowed geochemists to measure the concentrations of rare elements on the atmosphere, water and rocks to accuracies of one part per billion. The measurement of significant quantities of one of these elements has sent lightning bolts through the community of scientists who study extinctions.

Figure 2-3. What killed such proficient and prolific animals as the dinosaurs was one of the great mysteries of 20th century science.

Geologists have been studying the trace element chemistry of outcropping exposures of 65 million year old rock at Gubbio, Italy, for over 10 years. There are no dinosaur fossils at Gubbio, but the limestones of Gubbio were deposited in a deep sea that existed 65 million years ago between Europe and Africa. With the subsequent closing of the Mediterranean Sea, the Gubbio limestones were accreted onto Italy (a fact deduced by Leonardo Da Vinci in the 14th century. The exposure of rock that records the age of the extinction of the dinosaurs is particularly well preserved at Gubbio. Within 5 cm of rock, the secret to the extinction of the dinosaurs has been unlocked. The content of rare earth elements in the Gubbio limestones is not normal. Instead of the usual 10 parts per billion of iridium, 10,000 parts of iridium per billion are recorded in this rock. At Gubbio, these high concentrations are found only exactly at the extinction boundary, and neither above nor below it. The only major source for such large concentrations of iridium is not the Earth, but space!

Meteorites, asteroids, and comets release iridium during collisions with the earth, whereas rocks on the Earth's surface do not have such appreciable concentrations. This excessive iridium anomaly has since been found in over 60 other locations of extinction boundaries worldwide. For example, near Trinidad, Colorado, the iridium anomaly is accompanied by dramatic changes in plant spores, which tell us how the dinosaurs actually died. Fern spores show a dramatic increase indicating that most other plants were killed off by the same event that produced so much iridium. Ferns can only compete successfully for space when more complex plants are not present. Throughout geological history, ferns disappear whenever higher forms of plants are abundant. The dinosaurs must have starved to death.

A large meteor impacting the earth was the most likely cause of the extinction of the dinosaurs. The meteor (10 km across) would have kicked so much dust into the atmosphere that the climate of the surface would have been changed for tens or hundreds of years (Figure 2-4).

Figure 2-4. As they grow or are deposited, tree rings, corals, rock layers, and ice all have the potential to record key climate indicators. Scientists study these records in order to learn how Earth's climate varies over time. This is a drilling site located deep in the interior of Greenland, where scientists have drilled through the nearly two kilometer-thick ice sheet. The Greenland ice core records Earth’s climate over the past 200,000 years, providing an invaluable record. The last ice age, the onset of the industrial revolution, and the Clean Air Act enacted by the United States Congress in 1974, are all visible in this rich data record. Such a climate record that goes back millions of years is more difficult though.

The extraterrestrial impact theory is not without controversy, however. Volcanoes also have high iridium contents in their erupted lavas. The deep mantle also has Iridium. And volcanic eruptions can put as much dust into the atmosphere as a meteorite impact. The largest volcanic eruption in recorded history, Krakatoa in Indonesia, darkened the sky for weeks, and changed the climate so that it is remembered as the year without a summer -- in New England!

Whatever the cause of the climate change, it has profound implications for our existence as a species. The biological implications of catastrophic extinctions are to free up niches that were once dominated by one species for exploitation by other species. Thus, mammals inherited the kingdom of the dinosaur.

The biological consequences of the disruption of the climate of the entire planet by dust entering the atmosphere and staying for years was the extinction of the most formidable animals ever to evolve on the planet, the dinosaurs. Sound familiar? The nuclear winter scenario for what might happen after a nuclear war is no far-fetched scientific guess; it has been caused repeatedly in the natural evolution of planet Earth by meteorite impacts. This is not an untested hypothesis. Dust in the atmosphere, whether from meteorite impacts or from volcanic eruptions, has killed more than 50 percent of all living things on the planet, not once but several times in the past history of the planet -- already.

In fact, mass extinctions appear to be regularly spaced in the past. Every 30 million years or so, an extinction event can be found in the fossil record, which corresponds to a periodicity in crater impacts on the Earth as well. This has led to a controversial speculation that our Sun has a companion star, called Nemesis. It is hypothesized that Nemesis travels through the Oort Cloud (a collection of comets and stellar debris), triggering a shower of comets and meteors that hits the Earth every 30 million years. No such Nemesis has yet been found by astronomers, however.

An alternative hypothesis is that our solar system travels periodically through the galactic plane, itself perturbing the Oort Cloud. It is harder to conceive of a periodicity in volcanic eruptions because they relate to plate-boundary interactions rather than to some orbital parameter. No periodicity to plate tectonics has yet been found.

Don't fret for our place in nature, however. The last extinction event on earth happened about 13 million years ago. If we do not bring extinction upon ourselves through a nuclear winter, we have another 13 million years to prepare for the next geological extinction.