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Impacts and the Origin of Life

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Figure 1. Orientale, the second largest impact crater on the Moon's surface (following Imbrium). The crater lies just beyond the western limb of the nearside and is 930 km in diameter. The innermost of the three observable rings is thought to have formed by thermal contraction; this permits an independent estimate of the energy required to form it (about 1.2 x 10^{26} J). The impactor that formed the crater was probably about 95 km in diameter.

As living creatures, all of us have some interest in the question of how life originated. To some, the question is more religious than scientific; nonetheless, a small but dedicated group of scientists spend their careers trying to answer it from a rational standpoint. Logically, the question can be broken down into the three standard divisions of any mystery: When did life originate? Where did it originate? And how did it originate? Of these three sub-questions the last is by far the most difficult and I will make no attempt to address it here. I will however take a personal look at the two easier parts of the problem. In particular, I will outline my current view of the physical environment of the early Earth, and I will try to show how observations of other solar system bodies, especially our own Moon (Figure 1), provide clues as to when and where life could have originated.

When Did Life Originate?

Radiometric dating of meteorites shows that the solar system as a whole formed approximately 4.6 billion years (b.y.) ago. The first step in the process was the formation of the Sun from gravitational collapse of the central regions of a large cloud of interstellar gas and dust. The Sun evolved rapidly at first as it picked up additional material from the surrounding nebula and shed much of its angular momentum by way of an intense 'T-Tauri' solar wind. It then reached the main sequence—that is, it became a 'normal' star—a few million years after the initial collapse. The planets formed later from accretion of solid particles that had condensed out of the remaining portion of the solar nebula. Earth and the three other terrestrial planets (Mercury, Mars, and Venus) reached their present sizes and orbital distances some 10^7 to 10^8 years after the formation of the Sun. By 4.5 b.y. ago the main era of planetary formation was essentially complete.

Life, as we now think, has been around during most of Earth's subsequent history. Before about 1950, our knowledge of early life was restricted to the last 550 million years, the Phanerozoic era, for which there is a relatively complete fossil record. But we now

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recognize that this period of multicellular, often shelly, life was preceded by a long evolution of single-celled microbial life during the Precambrian. Firm evidence for life, from microfossils and stromatolites (laminated structures in rocks that are thought to have been formed by microbial activity), goes back at least 3.1 b.y. and probably 3.5 b.y., the age of rocks from the Warrawoona Group of Western Australia (Schopf, 1983). Weaker evidence for life, specifically the presence of organic carbon in metamorphosed sediments from Isua, West Greenland, is found as early as 3.8 b.y. ago (Schopf, 1983). Thus if life did indeed originate on Earth, as opposed to being transported here from somewhere else in the cosmos—the 'panspermia' hypothesis—it probably did so during the 700-million-year 'window' between 4.5 and 3.8 billion years ago.

The Faint Young Sun Problem

What was the surface environment of the Earth like during this time interval? Were there suitable places on or near the surface where life could have originated? Two factors that ought to have been particularly relevant to these questions are the mean surface temperature of the early Earth and the oxidation state of its atmosphere. These factors are related because the surface temperature would have depended in part on the concentrations of various 'greenhouse' gases that could affect the planet's radiation budget.

One way to approach the problem is from a climatic standpoint. Stellar evolution theory predicts that all stars, including our Sun, slowly increase in luminosity during their main sequence lifetimes. The increase is a consequence of the conversion of hydrogen to helium by nuclear fusion. The helium increases the mean molecular weight of the star; this in turn requires an increase in pressure and temperature in the core to balance the higher gravitational attraction. Higher core temperatures cause the fusion reactions to speed up, so the star produces more energy. Our own Sun is thought to have increased in brightness by approximately 40 percent since it entered the main sequence. Its luminosity during the time period when life apparently originated, 4.5 to 3.8 b.y. ago, was only 70 to 75 percent of its present value.

If one creates a simple climate model of the Earth and then lowers the solar luminosity while holding atmospheric composition constant, it is easy to show that the oceans should have been frozen solid during the first half of Earth's history (Sagan and Mullen, 1972; see also Figure 2). This prediction though is in direct conflict with the geologic record: the fact that sediments were being formed at Isua indicates that liquid water was already present by 3.8 billion years ago. This apparent discrepancy has been termed the 'faint young sun paradox.' The paradox is easily resolved, however, if one allows for a substantially larger greenhouse effect in the past. The relevant question then becomes: What gas (or gases) was responsible for keeping the early Earth warm?

A Reducing Early Atmosphere?

The answer proposed originally by Sagan and Mullen was that the early atmosphere contained significant concentrations of ammonia (NH_3). Ammonia is indeed a good greenhouse gas; concentrations of 10 to 100 parts per million (ppm) would have been sufficient to compensate for the predicted deficit in solar luminosity. The presence of ammonia in the atmosphere also fit in well with some models for the origin of life. Laboratory experiments performed by Stanley Miller and Harold Urey in the early 1950s had shown that spark discharges (simulating lightning) in mixtures of ammonia, methane and hydrogen produce a wide variety of organic compounds, such as amino acids, that are the basic building blocks of living systems. Thus for a time the idea that the Earth's primitive atmosphere was a highly reducing mixture of NH_3, CH_4, and H_2 was widely accepted.

A problem arose, however, when photochemists studying the primitive atmosphere with theoretical computer models discovered that ammonia should have rapidly decomposed to N_2 and H_2 by solar ultraviolet radiation. Methane also should have been oxidized to carbon monoxide (CO) or to carbon dioxide (CO_2) even in the absence of photosynthetically-produced O_2. (Water vapor is used indirectly as the oxidant: the oxygen reacts with methane, while the hydrogen escapes to space.) Thus a highly reducing primitive atmosphere is now considered unlikely on photochemical grounds. Both the faint young sun problem and the problem of originating life seem to require a different solution.

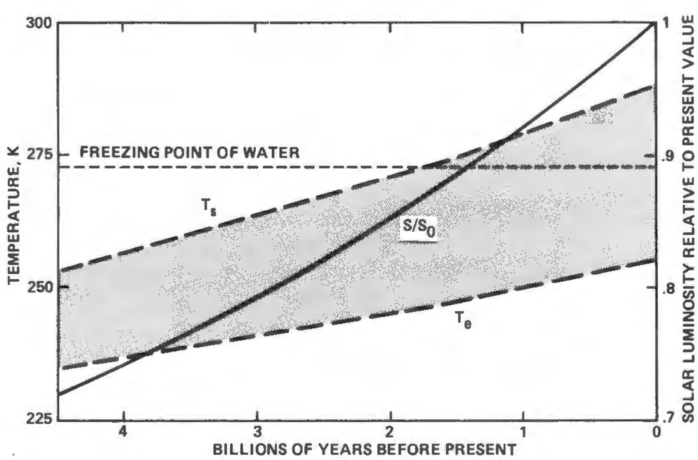

Figure 2. Schematic illustration of the faint young sun problem. The solid curve represents the solar flux normalized to today's value. The dashed curve labelled T_e is the effective radiating temperature of the Earth, which is what the surface temperature would by in the absence of an atmosphere. The dashed curve labelled T_s is the surface temperature of the Earth calculated with a one-dimensional climate model, assuming constant atmospheric composition and fixed relative humidity. The shaded area shows the magnitude of the greenhouse effect; this increases with time because of an increase in water vapor abundance. (From Kasting, 1989.)

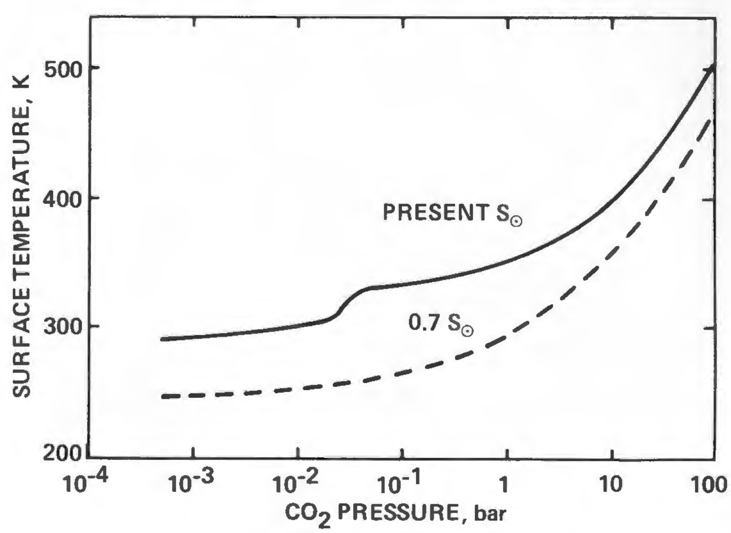

Figure 3. Surface temperature of the Earth as a function of CO_2 partial pressure according to the climate model of Kasting and Ackerman (1986). The solid curve is for the present solar luminosity; the dashed curve is for 30% reduced luminosity. The 'kink' in the solid curve is caused by a speculative relative humidity feedback which has been included so as to generate an upper limit on surface temperature.

Carbon-Dioxide-Rich Atmospheres and the Carbonate-Silicate Cycle

A more plausible way of solving the faint young sun problem is with carbon dioxide. Although the present atmospheric CO_2 concentration is only 350 ppm, the amount of CO_2 tied up in carbonate rocks is very large. If all of the CO_2 in carbonate rocks was present in the atmosphere, the atmospheric pressure would be ~60 bars, or sixty times its present value. This is almost as much carbon dioxide as is present on Venus, which has a CO_2-rich atmosphere with a surface pressure of about 90 bars. Carbon dioxide, of course, is itself a good greenhouse gas—that is why we are concerned about the fact that its concentration is increasing. A few tenths of a bar of CO_2 in the early atmosphere would have been sufficient to keep the oceans from freezing. This is roughly a thousand times the amount that is present in the atmosphere today, but is still only a small fraction of the carbon stored in sedimentary rocks.

A carbon dioxide-rich primitive atmosphere may actually be almost unavoidable. On long time scales, the CO_2 content of the atmosphere is controlled by interactions with carbonate and silicate rocks—the 'carbonate-silicate cycle.' Its long-term source is volcanic activity, which was probably several times more vigorous in the distant past than it is today. Its long-term sink is the weathering of silicate rocks, followed by the precipitation of carbonate sediments in the oceans. The weathering process requires liquid water (in the form of rainwater and groundwater) in order to proceed at an appreciable rate. This is the key to solving the faint young sun problem (Kasting et al., 1988). If the oceans had ever frozen completely as a result of reduced solar heating, silicate weathering would have ceased and CO_2 would have begun to accumulate in the atmosphere. Within a geologically short time period, enough CO_2 should have accumulated to melt the ice and restore relatively equable climatic conditions.

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Indeed it is possible that the atmospheric CO_2 partial pressure was large enough to over-compensate for the reduced solar flux and to make the early Earth considerably warmer than today. James Walker of the University of Michigan has suggested that in the absence of large continental platforms on which to store carbonate rocks, the atmospheric CO_2 pressure could have been as high as ten bars. My own climate model calculations (Figure 3) indicate that this would produce a mean surface temperature of about 85°C, or 70 degrees above the present value. This is certainly warm by our standards, but it is by no means incompatible with the existence of life. Norman Pace of Indiana University has isolated organisms living in 105°C water exiting from hydrothermal vents in the present seafloor. This water does not boil because the pressure at these vents is many times the atmospheric pressure. Similarly, early oceans with a temperature of 85°C would have been in no danger of boiling because the overlying atmospheric pressure would have been in excess of ten bars. The early Earth may have resembled a pressure cooker, but it should have been in no danger of going the way of Venus, which apparently lost its oceans because of a runaway greenhouse effect (Kasting et al., 1988).

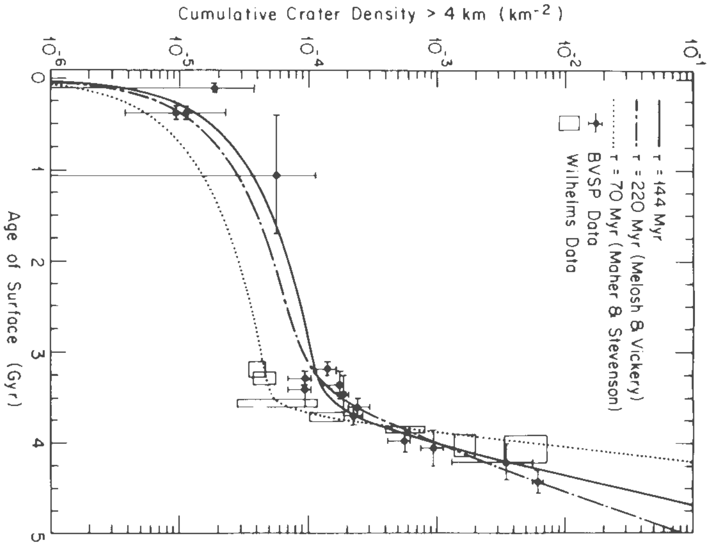

Figure 4. Cumulative crater density on the Moon as a function of surface age. The boxes and the crosses represent two independent datasets. The curves are analytical fits with exponential decay times of 70, 144, and 220 million years. (From Chyba, 1989.)

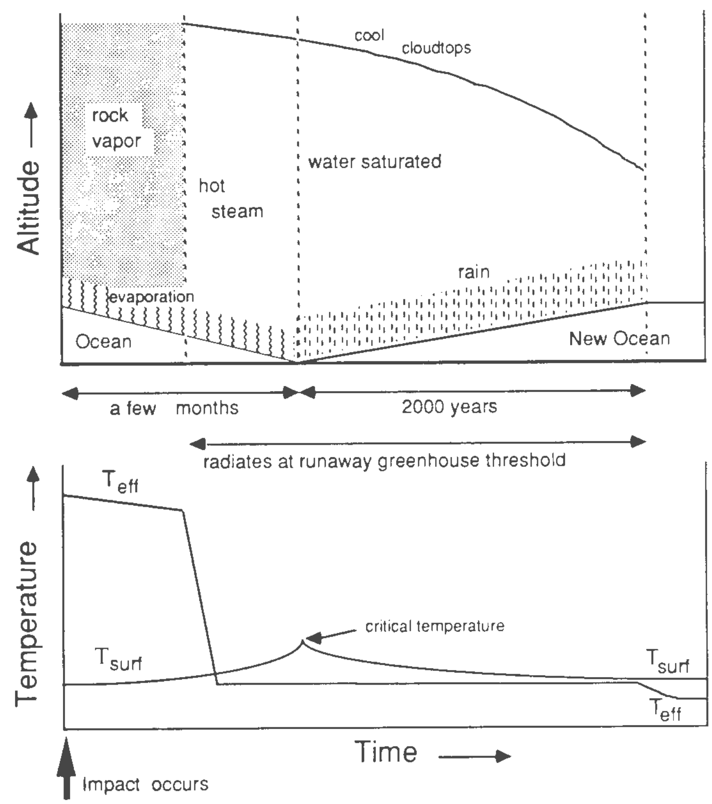

Figure 5. Cartoon depicting the sequence of events in a minimal, ocean-vaporizing impact. Hot rock vapor (upper panel) dominates the atmosphere for a period of about 4 months. This gives way to a dense steam atmosphere that lasts for approximately 1000 years. The rock vapor radiates energy both up and down at an effective temperature (T_{eff}) of ~2000 K; the steam atmosphere radiates to space at a temperature of ~300 K (lower panel). In this event, the steam atmosphere begins to condense and rain out just as the last drop of ocean water is evaporated. (Courtesy of N. Sleep and K. Zahnle.)

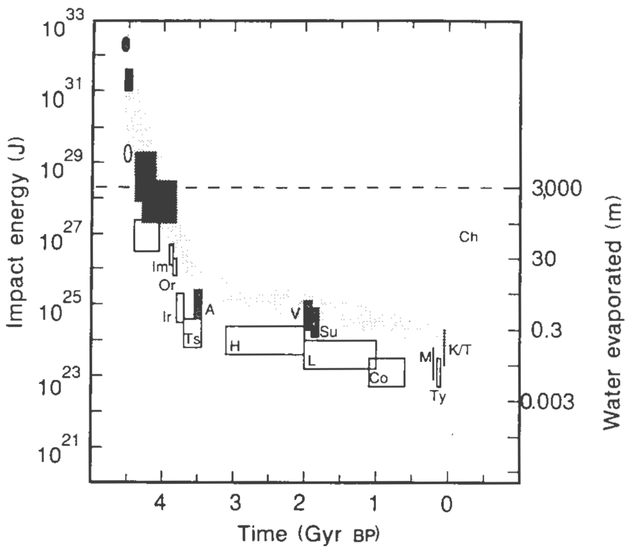

Figure 6. The largest impacts on the Earth and Moon. Open boxes are lunar, filled ones are terrestrial. Lunar craters are Tycho, Copernicus, Langrenus, Hausen, Tsiolkovski, Iridum, Orientale, and Imbrium. Terrestrial events are the K/T impact, Manicougan, Sudbury, Vredevort, and an impact energy corresponding to 3.5 b.y.-old Archean spherule beds. Ovals are self energies of formation; the early box refers to a possible Moon-forming impact. The stippled region represents the range of impact energies expected on the Earth, assuming a scale-invariant (power law) size distribution of impactors. The depth of ocean vaporized by the impacts is given on the right hand scale; the dashed line corresponds to an ocean-vaporizing impact. The 'Ch' represents Chiron, a large, modern-day comet in a Saturn-crossing orbit that could conceivably collide with the Earth sometime in the distant future. (From Sleep et al., 1989.)

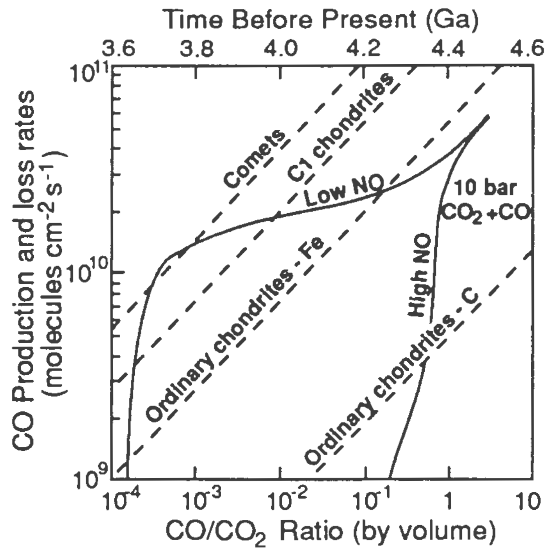

Figure 7. Diagram for estimating the effect of impacts on the CO/CO_2 ratio of the Earth's primitive atmosphere. The solid curves represent CO loss rates for different CO/CO_2 ratios calculated using a photochemical model. The assumed background atmosphere contains 10 bars of (CO_2 + CO) and 0.8 bar of N_2. The dashed lines represent estimated CO production rates from comets or chondritic asteroids at various times in the Earth's history (upper scale). The figure is read in the following manner: First, pick a time on the top axis. Then read down to the dashed line representing the type of impactor you think is hitting the planet. The left-hand scale gives the CO production rate. Now read over horizontally to the solid CO loss curve for either the 'high-NO' or 'low-NO' atmosphere; then read down to the bottom scale to determine the atmospheric CO/CO_2 ratio. CO/CO_2 ratios exceeding unity are possible prior to about 4 b.y. ago for carbon-rich impactors. For comparison, a typical model atmosphere with no impacts has a CO/CO_2 ratio between 10^{-4} and 10^{-3}. (From Kasting, 1990.)

Thermophilic Ancestors

I will return to the deep sea vents in a moment because this is a locale that may be relevant to the origin of life. But let me first introduce an observation from the field of molecular phylogeny—the classification of organisms on the basis of similarities in their genetic makeup, principally their ribosomal RNA. RNA sequencing indicates that the most 'primitive' organisms—that is, those organisms that appear to have diverged earliest in evolutionary history—are sulfur-metabolizing *thermophiles* (Pace et al., 1986; Lake, 1988). This implies that all modern organisms are descended from a single ancestor which lived in a high-temperature environment. If Walker's model is correct and the early Earth possessed a dense CO_2 atmosphere, then warm temperatures could have been found anywhere on its surface. But modern organisms could also have descended from bacteria living in hydrothermal vents or hot springs on an otherwise cold early Earth. Indeed the latter environments are somewhat favored because they both contain abundant elemental sulfur, which is what most primitive organisms like to eat. This does not clinch the argument, however, because elemental sulfur may have been produced globally from photolysis of volcanically-emitted SO_2 and H_2S (Kasting et al., 1989).

Obviously more information is needed to decide among the various alternatives. Fortunately an entirely different line of evidence is available from a rather unlikely source—our Moon. In what follows I will try to show that recent studies of the Moon provide an additional incentive for considering the deep sea vents as the abode for early life.

The Lunar Cratering Record

One motivation for studying the Moon is that it preserves an excellent record of the impact environment of the early solar system. As illustrated by Figure 1, the Moon has been bombarded throughout its lifetime by thousands upon thousands of bodies, ranging in size from microscopic interplanetary dust particles to asteroid-sized objects. Mercury, Mars, and even Venus, it now appears based on early returns from the Magellan spacecraft, also show evidence for extensive bombardment. Earth must evidently have experienced a similar impact history; however the geologic record of impacts is much poorer on Earth because of extensive resurfacing of the planet by plate tectonics and by weathering.

The lunar impact record contains two types of information that may be relevant to the origin of life on Earth. The first contains the magnitude of the impact flux as a function of time. American Apollo and Soviet Luna spacecraft brought back Moon rocks from landing sites near several large lunar craters. Radiometric dating of these rocks, in combination with photographic studies of how various craters overlie each other, allows one to estimate when the craters were formed (Figure 4). Such studies indicate that most of the craters, including all the really large ones, were formed between 4.44 billion years ago (the age of solidification of the bulk of the lunar crust) and 3.8 billion years ago. This time interval, which is the same as the interval during which life originated on Earth, is referred to as the period of 'heavy bombardment'. An earlier interpretation of the cratering record, which suggested an isolated episode of 'late heavy bombardment' around 3.8 b.y. ago, has given way to the view that the impact flux declined more or less exponentially with time throughout this interval. Many of the craters that formed during the early part of this period were presumably obliterated by later impacts.

The other type of information concerns the size distribution of the impacting bodies. Laboratory studies of small impacts can be used in combination with scaling relationships to estimate the amount of energy required to produce a crater of a given size. If one has some idea of the velocity and density of the impacting body, this energy can be converted to an estimate of impactor size. For rocky material hitting the Moon's surface at a velocity of about 13 km/s (Sleep et al., 1989), a rough rule-of-thumb is that the diameter of the impacting body is about one-tenth the diameter of the resulting crater. Thus the 930-km Orientale crater (Figure 1) was probably formed by the impact of a 90- to 100-km-diameter planetesimal. The largest clearly identifiable impact crater on the Moon, Imbrium, is 1200 km in diameter and would have required a slightly larger or higher-velocity impactor. Both Imbrium and Orientale are thought to be about 3.8 billion years old, indicating that stray 100-km diameter planetesimals were still present in the inner solar system at this relatively late date.

Impacts on the Early Earth

The planetesimals hitting the Earth during the pre-3.8-billion-year time period were probably even larger and more energetic. Earth's larger mass and higher gravity imply that typical impact velocities should have been at least 17 km/s (Sleep et al., 1989). Since the kinetic energy of a body is proportional to its velocity squared, this means that impactors of a given size would have released about 70 percent more energy on Earth than on the Moon. The Earth also has fifteen times the surface area of the Moon and about twenty-four times the effective collecting area when its higher gravity is taken into account. Thus if the planetesimal population included bodies significantly larger than 100 km in diameter, which seems likely, the chances are that most of these bodies should have hit the Earth rather than the Moon. Or to put it another way, the fact that the Moon was not hit by anything larger than 100 km across does not imply that the same was true for early Earth.

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What would have been the consequences of large terrestrial impacts for life and for the atmosphere? The most immediate consequence for life is the threat of direct thermal annihilation. Numerical studies of giant impacts using theoretical computer models indicate that about half the energy of the impact goes into vaporizing rock. The other half is deeply buried and goes into melting mantle material. An Imbrium-sized impact should produce enough rock vapor to increase the total atmospheric pressure by several bars. This rock vapor cools by radiating approximately half its energy to space and half to Earth's surface, both of which are much colder than the 2000 K rock vapor. Since the Earth's surface is 70 percent water-covered, and since there may have been even less land area in the past, most of the downward radiation goes into evaporating seawater. Thus, after the rock vapor had cooled and condensed out, the Earth should have been left with a dense steam atmosphere.

Larger impactors may have been capable of vaporizing the entire ocean (Figure 5). One can calculate thermodynamically that the energy required to accomplish this is about 5×10^{27} J. The impact itself must have released four times this much energy, since half the energy is buried and half is radiated away to space. For a 17-km/s rocky impactor, this requires a 440-km-diameter body—roughly four times the size of the object that formed Imbrium. Although nothing this big appears to have hit the Moon, there are two present-day asteroids, Vesta and Pallas, that are about this size and one, Ceres, that is more than twice as big. If the size distribution of modern asteroids is at all representative of that of the late-arriving planetesimals, it is conceivable—even likely—that the Earth was hit by one or more of these 'ocean-vaporizing' bodies between 4.5 and 3.8 billion years ago (Figure 6). It is even more likely that the Earth was hit by smaller 190-km diameter objects that were capable of evaporating the entire photic zone of the oceans (the uppermost 200 m). For reasonable planetesimal size distributions, photic-zone evaporating events should have been commonplace until about 3.8 billion years ago.

Implications for Early Life

The occurrence of large impacts has obvious implications for early life. Because of the production of hot rock vapor, even relatively small impacts would have been lethal to organisms living on land, if there were any such organisms that could survive the expected high solar ultraviolet flux. Benthic (bottom-dwelling) organisms living on continental shelves or on the slopes of volcanic islands would have experienced nearly the same risk. Any impact that evaporated the photic zone would have left them directly exposed to the radiative flux from the rock vapor. Planktonic organisms living in the surface ocean might have been somewhat better off, since they could in principle have continued to migrate down to lower levels in the ocean. However, any upwelling current that brought them to the surface would expose them to a layer of boiling water at the top. Since the rock vapor would have persisted for weeks to months, the steam atmosphere for tens to hundreds of years, it seems unlikely that any planktonic organisms would survive a photic-zone-evaporating impact.

It may be illuminating to compare such an impact to the one that is thought to have occurred at the end of the Cretaceous period, 65 million years ago. The K-T (Cretaceous-Tertiary) impactor was probably about 10 km in diameter, based on the amount of iridium it left behind, and should have been sufficiently energetic to evaporate about 20 cm of seawater (Figure 6). Even though this is miniscule by comparison with the events discussed above, the K-T impact apparently resulted in extinctions of phytoplankton and may have killed off the dinosaurs as well. A photic-zone evaporator would release 1000 times as much energy and could be expected to be proportionately more lethal.

Where could organisms have lived and evolved during these hazardous times? One obvious possibility is the midocean ridge hydrothermal vents. These vents today are covered by about 2.5 km of seawater; thus a near ocean-evaporizing impact would be needed to expose them. We don't know how deep the oceans were during the Earth's early history, but there is no good reason to suspect they were significantly shallower than today. A post-impact ocean, being heated from above, should be stable against convection; thus the thermal pulses caused by moderate-sized impacts, even photic-zone-evaporating ones, would not penetrate to the ridge crests. Unless an impacting bolide landed directly on top of it, a vent organism would have been aware of its arrival only because of a transient pressure increase caused by the passage of the initial shock wave.

Putting these observations together with the evidence cited above for the ubiquity of thermophilia and sulfur metabolism among primitive organisms leads to a rather remarkable hypothesis: modern organisms may all be descended from some bacterium that dwelt in the midocean ridge hydrothermal vents. This does not necessarily imply that life originated in the vents; indeed some prebiotic chemists would argue that it is difficult to assemble large complex organic molecules in this type of high-temperature environment. Life could, however, have evolved at the surface at temperatures ranging from rather warm to rather cold, depending on the atmospheric CO_2 level, and then colonized the midocean ridges at a later date. The next photic-zone evaporator annihilated all life at the surface, leaving only the thermophylic vent organisms to restart the evolutionary process. This scenario is by no means proven; however, it is consistent with the lessons that can be drawn from molecular phylogeny and from planetary physics.

Other Effects of Impacts

In addition to the destructive effects of their direct thermal pulses, impacts could have affected the origin and early evolution of life in a variety of other ways. One of the most fundamental is by bringing in additional water and carbon, which would have added to the existing inventories of these compounds in the oceans and atmosphere. This would have been particularly important if the late-impacting planetesimals were predominantly comets (icy bodies from the outer solar system) as opposed to rocky asteroids from farther in. Chris Chyba of Cornell University has calculated that such comets could have provided most or all of the water in Earth's present oceans if they made up a major fraction of the impact flux. Certain classes of meteorites, notably the carbonaceous chondrites, also contain significant amounts of water and carbon. Asteroid-sized bodies of similar composition could also have made significant contributions to Earth's volatile inventory.

Impacts may have influenced the origin of life in a more direct manner by bringing in complex organic molecules that were formed in outer space. I have already mentioned the difficulty in synthesizing complex organics in a relatively oxidizing CO_2-rich atmosphere. One alternative is to bring in preformed organic molecules

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along with the impactors. We know that carbonaceous chondrites contain a host of complex organic compounds, including amino acids, and we strongly suspect but have not yet proven that comets do as well. In large impact events, most of this material would undoubtedly have been pyrolized to carbon monoxide (CO) and water in the extremely hot impact plume. However many small dust particles survive atmospheric entry intact, as do the larger fragments of rocky material we refer to as meteorites. Substantially more incoming material might have survived entry to the early Earth because of the enhanced aerobraking provided by a dense CO_2 atmosphere (Chyba et al., 1990). So it is conceivable that an initially sterile Earth was alternately fertilized by small impacts and sterilized by larger ones, with the outcome fortunately being decided in favor of life's existence.

Finally, impacts may also have altered the composition of the Earth's atmosphere in such a way as to make it more conducive to the origin of life. As mentioned above, most of the organic carbon in large comets or carbonaceous asteroids should have been oxidized to carbon monoxide upon impact. My own photochemical models predict that this additional source of carbon monoxide could have significantly increased the atmospheric CO/CO_2 ratio, and may even have created a CO-dominated atmosphere (Kasting, 1990; see also Figure 7). Carbon monoxide could also have been generated by the reaction of hot metallic iron droplets with ambient atmospheric carbon dioxide. In addition, the shock waves generated by impacts would have created nitric oxide (NO) from the high-temperature reaction of carbon dioxide with N_2. For reasons that I will not attempt to explain here, high NO concentrations also tend to promote a high atmospheric CO/CO_2 ratio (Figure 7). This may have facilitated the origin of life, since CO is much preferred over CO_2 as a medium in which to synthesize complex organic compounds. (CH_4 is even better, but there is still no obvious way to achieve high concentrations of this gas in the early atrmosphere.) Thus, once again, impacts could have had a beneficial effect on the origin of life in addition to their destructive tendencies. Indeed, it may be that life could not have originated too early without being destroyed by large impacts, nor too late because the atmosphere became too oxidizing as the impact flux diminished. If so, then the time window for the origin of life may have been narrow indeed.

Conclusions

Obviously, the problem of life's origin is far from being solved. But we do have some good clues, and these clues are beginning to fit together into a self-consistent pattern. High temperatures are evidently associated with the early environment of life, if not with life's actual origin. The midocean ridges are a likely abode for early life because of their warmth, the availability of sulfur, and because they are shielded from impacts. The impacts themselves must have been a dominant feature of the early environment and should be factored into our physical models of the early atmosphere and oceans.

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The Geographic Information Systems Program

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In the past few years a new research and instruction program has been created in the Department of Geography that focuses specifically on the revolutionary developments underway in handling and using geographic information. The department has a long tradition of research dealing with the processing of spatial information by human mind and by mathematical, statistical, and cartographic means, and over the past few years, the addition of several faculty members with research and teaching specialties in geographic information systems, computer-related cartography, and remote sensing has created an excellent environment for the development of the Geographic Information Systems Program.

As a result of recent advances in remote sensing technology and high-speed digital computer systems., there has been a veritable explosion in the amount and types of geographic information available worldwide. The ready availability of this geographic information has in turn created an enormous demand for applications specifically designed to address a broad range of environmental and social problems. The principal tool for handling this spatial data is the geographic information system (GIS), which is designed to store, manipulate, analyze and display large volumes of data derived from maps, satellite imagery and other sources.

Penn State's GIS program has flourished as the demand for graduates with advanced GIS experience has increased. Recent geography graduates are currently working in GIS-related positions for such agencies and firms as the Environmental Systems Research Institute in Redlands, California; Aerial Data Reduction Associates in the Philadelphia area; the New York Department of Transportation; and the U.S. Geological Survey National Center.

Geography now offers fourteen separate courses in the general area of spatial representation. These include four specific GIS courses: *Geographic Data Systems*—an introduction to GIS principles and applications; *Digital Terrain Models*—techniques for digital investigation of geomorphic features; *Spatial Data Structures and Algorithms*—the internal design and construction of GIS; and *Geographic Information Systems Design and Evaluation*—design and evaluation of GIS and other integrated spatial data systems. These courses draw on the background provided by the department's computing skills course—*Computing for the Earth and Mineral Sciences*.

The GIS program received a major boost in fall 1990 with the installation of the Advanced GIS Laboratory (AGIS), a top quality facility that provides students with the opportunity to explore spatial analysis using the most advanced equipment and software available for instruction in geography and the earth sciences. The lab's eight SUN work stations have cartographic, image processing, and GIS software integrated in a multiprocessor local network with a specially configured operating system. The AGIS Laboratory was funded in part by the department, the College, and the University. However, the contributions of Geography majors and other EMS students through the tuition surcharge for instructional equipment were absolutely essential for realization of this project.

The AGIS Laboratory is already a busy center for fundamental GIS research and work on major investigations in the College, such as the Earth System Science Center's global water cycle project.

Research in the field began essentially in the 1960s. The first computer-based geographic information systems, developed in the mid-1960s, focused heavily on the handling of land use and natural resource data sets. The need for GIS theory and applications stemmed from two major forces—the emerging natural resource and environmental problems then causing increasing public concern, and the large volumes of geographically-referenced data being generated, much of it based on the increased use of remote sensing technology in map production. As these trends merged, it became possible and desirable to approach problems at regional, national, and even global scales—a task not previously possible.

It is clear that the utility of geographic information increases dramatically if, as part of problem solving, we can integrate data from various sources at various scales. We must develop system methods, not only for the application of digital computers in solving spatial problems, but also for organizing and accessing the base information to be used in that problem solving. We must go beyond simply enhancing our capability to quickly integrate large and varied collections of information about the Earth, and develop new approaches for representing, analyzing and just looking at data that are specifically attuned to the modern computing environment.

The Department of Geography and the College are now well-positioned in geographic information systems, a field where operational applications cover land and natural resources management, traffic planning, marketing, and military planning.

At the opening of the Advanced Geographic Information Systems Laboratory in the Department of Geography, visitors came from many parts of Campus to see the software demonstrations and assess the capabilities of the sophisticated new equipment.

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Peter M. Walsh
Dixie V. Wellmon
Anthony V. Williams
Ethel B. Williams
Shoko Yoshikawa
Martha Zerfoss

COLLEGE NEWS NOTES

Anthracite Institute Established at Penn State

A $108,900 grant from the Pennsylvania Energy Development Authority and matching funds from the anthracite industry have established a new Anthracite Institute at Penn State under the auspices of the Combustion Laboratory.

The Institute's goals are to create new markets for anthracite through the application of technical advances, to maintain a technical extension service to ease anthracite into new markets, and to help with existing markets.

The Institute will be directed by Peter L. Rozelle and have an advisory board consisting of representatives of industry, independent power producers, and state government. An extension office will be located at Penn State's Wilkes-Barre Campus to maintain a regular presence in the coalfields.

A number of research projects are underway and several others are under discussion. One such project, with the New York State Electric and Gas Company, focuses on developing optimal operating procedures for burning blends of anthracite and bituminous coal; another is testing the performance of limestone flux in anthracite-refuse-fired fluizided bed combustors. Most fluidized bed combustors in Pennsylvania are operated by independent power producers who sell electricity to the utilities and steam to processing plants.

A future project will be to introduce anthracite into the steel industry as a coke substitute. Rozelle points out that strict controls over the benzene emissions from coke ovens under the new Clean Air Act could cause substantial increases in the cost of coke, and that 'up to a certain percent' anthracite is an acceptable substitute that currently costs $20 per ton less than coke.

Another project would adapt steel fire-tube boilers to anthracite firing for space heating. It would focus on boilers with firing rates of two to 10 million BTUs per hour and attempt to lower the capital cost of equipment while increasing efficiency.

Anthracite, a high-carbon, low-volatile, low-sulfur coal, can also be used in the carbon industry to produce graphite and the activated carbon used in filters. The current market for anthracite is divided evenly among residential, industrial and commercial space heating; metallurgical uses; utilities and cogeneration and miscellaneous uses.

NABGG Meets at Penn State

John Leftwich, doctoral candidate in geosciences, served as chair of the 9th annual Conference of the National Association of Black Geologists and Geophysicists, held at Penn State in October.

The conference theme was "The Geoscientist's Role in Preserving the Environment: Education for the 21st Century," with technical sessions on a wide range of topics in geology and geophysics including sedimentology, shallow aquifer pollution and water resources, and the application of Earth Science information. The keynote address on the conference theme was given by Dr. Charles Brown, USGS hydrologist, who received his Ph.D. from Penn State in 1977.

In addition to its regular members, the conference was attended by about 40 high school students and their teachers from the Pittsburgh area. A specific goal of the Association is to inform students about careers in geology and geophysics and assist them with scholarships and summer employment opportunities.

College Establishes Ties with Turkish University

Leaders of Turkey's Middle East Technical University (METU) visited Penn State earlier this year to celebrate the signing of a memorandum to encourage exchanges and cooperative initiatives between the two institutions.

Since the initial focus of exchange will be with the College of Earth and Mineral Sciences, the distinguished visitors, METU President Dr. Omar Saatcioglu, Vice President Dr. Muharrem Timucin, Dean of Engineering Dr. Suha Sevuk, and Faculty Coordinator Dr. Erdal Unal, toured EMS and met with Dean John Dutton and members of the faculty.

Dr. Unal, an alumnus of the College, received his doctorate in mining engineering from Penn State in 1983, and is now associate professor of mining engineering at METU. During the visit, he and Dr. R.V.Ramani discussed plans for a joint research program between the METU and EMS Mineral Engineering Departments. In addition, a number of EMS professors plan to visit METU in June 1991.

The Middle Eastern Technical University was established in Ankara, Turkey, in 1957 and now has around 18,000 students. Both undergraduate and graduate programs are offered, with a strong emphasis on engineering disciplines. English is a common means of communication. Since 1962, a major reforestation program has been undertaken to beautify METU's large modern campus and its surroundings in the suburbs of Ankara.

CAM Attracts International Delegations

A delegation from the Royal Netherlands Embassy and several Dutch universities visited the College in October to discuss the industrial application of advanced materials research with researchers of the Center for Advanced Materials. Seminars on current research related to ceramics, diamond deposition, interfaces and composites, fibers, electroceramics and bioceramics were given by EMS researchers Karl E.Spear, David J. Green, Richard E.Tressler, Wayne Huebner, Carlo G.Pantano, John R.Hellman and Paul Brown, and others from the College of Engineering and the Materials Research Laboratory.

CAM recently sponsored a special seminar at Penn State by researchers from the Engineering Research Association for High Performance Ceramics-Japan. The ten-member Japanese team, led by Mamoru Nakamura, senior researcher at the Government Industrial Research Institute and Hiroshi Abe, director of ceramics at Asahi Glass, presented "An Overview and Specific Research Project Reports of Japan's Structural Ceramics Project."

In return, Richard Tressler, John Hellman, David Green and Wayne Huebner gave talks on recent CAM research. During an afternoon session, the delegation toured Penn State's Materials Research Laboratory.

Faculty Activities

Paul D. Simkins, professor of geography, received the Distinguished Teacher Award of the Pennsylvania Geographical Society at the society's annual meeting at Washington and Jefferson College, Washington, Pa.

Ronald Abler, professor of geography, and **Wilbur Zelinsky,** emeritus professor of geography, received the Distinguished Scholar Award of the Pennsylvania Geographical Society for their work as editors of the *Atlas of Pennsylvania*.

Robert E. Newnham, Alcoa professor of solid state science, delivered the Dow Lecture to Northwestern University's Material Science and Engineering Department; the plenary lecture at the 2nds International Ceramic Science and Technology Congress in Orlando, Florida, and the keynote address at the International Symposium on Fine Ceramics, held in Arita, Japan.

H.L.Barnes, distinguished professor of geochemistry, and **A.W.Rose**, professor of geochemistry, co-chaired a Workshop on the Geology and Geochemistry of Gold Deposits, sponsored by the National Science Foundation and the Brazilian National Research Council and held in Minas Gerais and Bahia, Brazil.

Ten leading researchers from each country examined the current understanding of the origins and exploration methods for gold deposits and discussed potential topics for joint research projects.

John J. Olivero, professor of meteorology, has been appointed to a committee to plan a supporting research and technology program for the Earth's mesosphere and lower thermosphere for NASA Headquarter's Space Physics Division.

L.G.Austin, emeritus professor of fuels and mineral engineering, presented a paper and served as session chair at the 2nd World Congress on Particle Technology, Kyoto, Japan, for which he was also a member of the organizing committee. Professor Austin is currently a Professional Fellow in Chemical Engineering at UMIST, U.K.

Student Awards

Charles William Bartges received the 1990 Xerox Research Award for "research accomplishment by a Ph.D. student." Dr. Bartges, a student of Professor Earle Ryba in Metals Science and Engineering, carried out his thesis research in the area of quasicrystals. His thesis title was, "An Investigation of the Structure of an Icosohedral Aluminum-Lithium-Copper Intermetallic Phase Using Modified Single Crystal X-Ray Diffraction Techniques."

C. Eric Ramberg won the 1990 Xerox Award in Materials Science for "Best Research by an Undergraduate" for his entry "Fabrication of Continuous Fiber Reinforced Al_2O_3 Composites via Infiltration with $Al(NO_3)_3 . 9H_2O$." His research advisor was John R. Hellman, Assistant Director of CAM.

Faculty Bookshelf

Peter R. Gould, Evan Pugh professor of geography, is author of *Fire in the Rain: the Democratic Consequences of Chernobyl*, published in the United States by Johns Hopkins University Press and in the U.K. by Polity Press and Basil Blackwell.

The book , which has received excellent reviews, illuminates the confused actions and statements of government agencies and media following the Chernobyl nuclear disaster of April 1986. Gould contrasts the approach of various democratic but bureaucratized European governments to the situation and poses fundamental questions of responsibility.

[Dr. Gould's brief summary of this book appeared in *Earth and Mineral Sciences*, V.57 No.4, 1988 under the title "Tracing Chernobyl's Fallout." A very few copies of this issue are still available.]

Benjamin F. Howell, Jr., emeritus professor of geophysics, is author of *Introduction to Seismological Research: History and Development*, published by Cambridge University Press. The book is divided into four periods: a mythological period previous to the Lisbon earthquake of 1755; an observational period from 1755 until the development of recording seismometers late in the nineteen century; an instrumental period during which the Earth's interior was explored by studies of recorded sismic waves; and a modern computational period that began with the development of the digital computer.

Professor Howell, associate dean emeritus of the Graduate School, was head of the Division of Geophysics and Geochemistry from 1949-54 and of the Department of Geosphysics and Geochemistry from 1954-63.

Derrill M. Kerrick, professor of petrology, is author of the book, "The Al_2SiO_5 Polymorphs," published as Volume 22 in the Mineralogical Society of America Series *Reviews in Mineralogy*, edited by Paul H. Ribbe. This is only the second monograph in the sixteen-year history of this geotechnical series. The volumes are frequently used in MSA short courses given at national meetings of the Geological Society of America and the American Geophysical Union.

Kerrick reviews the chronological development of research on aluminum silicates and uses this mineral group, comprising the minerals andalusite, sillimanite, and kyanite, to illustrate a range of experimental, theoretical and field problems in metamorphic petrology. Aluminum silicates are abundant in metamorphosed shales and widely used as geothermometers and geobarometers for metamorphic rocks. The book is based on a series of seminars presented by Dr. Kerrick at the University of Basel, Switzerland, in 1985 and as a subsequent graduate course in the Department of Geosciences.

Dr. Richard B. Alley, assistant professor of geosciences, was one of a team of U.S. scientists participating in the Greenland Ice Sheet Project 2 last summer. This is the second year for the ice boring project that aims to drill down approximately two miles through the ice sheet to bedrock and study ice cores for signs of climate and environmental change. So far they have bored about 1000 feet. Among other scientific investigations, they have taken temperatures from the top 700 feet, representing the past 500 years, and essentially confirmed evidence for the warm period of A.D. 1400 to 1650, the colder period from 1650 to 1900, and the warmer period of this century.

E. Willard Miller, emeritus professor of geography and associate dean of resident instruction emeritus, and Ruby M. Miller, associate map librarian and former map librarian, Pattee Library, are co-authors of *Environmental Hazards: Radioactive Materials and Wastes*, published by ABS/CLIO, Santa Barbara, CA.

A perspective presents a survey on the nature of radiation, natural and man-made sources of radiation, reactor plant accidents, emergency planning and health effects of ionizing radiation. Five chapters facilitate convenient access to chronological highlights, laws, regulations and treaties, directory of organizations, a bibliography of books, journal articles and government documents, and a list of films and videocassettes.

Robert F. Schmalz, professor of geology, E. Willard Miller, emeritus professor of geography, and S.K.Majumder of Lafayette College are co-editors of *Environmental Radon: Occurrence, Control and Health Hazards* published by the Pennsylvania Academy of Sciences.

This book of 30 chapters and 39 authors provides a comprehensive survey of environmental radon. The volume is divided into six parts: a historical perspective, geological aspects of radon, the detection and measurement of radon, health problems and the regulation and policies of radon control, legal aspects, and economic impacts.

Penn State chapter authors include geoscientists Arthur W. Rose, John W. Washington, and Daniel J. Greeman; nuclear engineers William A. Jester, Bonnie C. Ford, and James Livingston; and business lawyer Benjamin A. Henszey.

Allan Rodgers, emeritus professor of geography, is editor and contributor to *The Soviet Far East: Geographical Perspectives on Development*, published in London and New York by Routledge.

In chapters by eleven specialists, the book explores the geographical and economic complexity of the Soviet Union's largest economic region and considers the prospects for the successful development of its valuable natural resources. Remoteness, an inhospitable climate, primitive transportation networks, administrative inefficiency, and the inability to attract a suitable workforce are among the problems of this vast region that extends from Lake Baykal to the Arctic Ocean, the River Lena to the Pacific .

Barry Voight, professor of geology and geological sciences, is editor of *Snow Avalanche Hazards and Mitigation in the United States* , the Panel Report of the National Research Council, Committee on Ground Failure Hazard Mitigation.
The report examines the physical and social measures taken to combat a natural hazard that on average kills 17 and injures 65 in the United States each year, and reviews mitigation programs in other countries. The Panel deplores the lack of a national program or guidelines for avalanche prediction, land use planning, research or education since the U.S.Forest Service relinquished its limited responsibility in these areas in 1985 due to lack of funding. In contrast, other countries have both effective research programs and regulation of structures and activities in avalanche-prone areas. The Panel identifies the steps that should be taken to rectify the situation.

Message to EMS Alumni

Have We Missed You?

We want to be sure that the personal information in the new Alumni Directory is correct. All questionnaires should have been returned to Harris Company.
The verification phase of the project will now begin. A representative of Harris Publishing Company will telephone you to verify the directory information. Please give the representative who calls you a few moments of your time.

To place a reservation for a copy of the EMS Alumni Directory, please advise the Harris representative during the conversation, since this is the only opportunity to order the book. Scheduled for release in June/July 1991, the EMS Alumni Directory will be the reference to more than 12,000 graduates of the College. We hope you find it useful.

With deep regret we announce the death of Dr. Arnulf Muan, professor of geochemistry and materials science on December 17, 1990. An obituary will appear in the next issue of *Earth and Mineral Sciences.*

Mining Engineering Celebrates One Hundred Years at Penn State

Penn State's Mining Engineering Program celebrated its centennial in October with a number of special events for faculty, students and alumni, and the announcement of an endowed Centennial Professorship, established with funds given by alumni and friends. Dr. Stanley C. Suboleski, head of the Mining Engineering Section, was named the first Centennial Professor of Mining Engineering.

The three-day celebration was highlighted by a lively and informative seminar on *The Future of Mining Engineering Education* , presented by a distinguished panel of visitors: Dr. Thomas V. Falkie, president of Berwind Natural Resources, Inc. and former director of the U.S.Bureau of Mines; Dr. Howard L. Hartman, Drummond professor of mining engineering at the University of Alabama; E. Morgan Massey, chairman and CEO, A.T.Massey Coal Company; and Ivan H. Rahn, manager of manpower services, Consolidation Coal Company. Dr. Hartman headed Mining Engineering from 1957 to 1963, and Dr. Falkie from 1969 to 1974.

Alumni, faculty and students also attended the Penn State filming of a national TV debate on *Coal: the Challenge of Abundance,* sponsored by the Jefferson Energy Foundation. Speakers included Ambassador Richard Tallboys of the World Coal Institute, the Hon.Michael R. Deland, White House Council on Environmental Quality, and columnist Warren T. Brooks. The program was moderated by Hodding Carter. It will be seen nationwide on PBS-TV in the coming year.

Ambassador Tallboys was also the keynote guest at an alumni luncheon at Nittany Lion Inn, where he spoke of the image of coal mining and the worldwide importance of coal in the production of electricity.

Highlights of the Centennial Dinner, held at the Atherton Hilton Hotel, included remarks by Jesse Core, '37 , Distinguished Alumnus and former Vice President of U.S.Steel Corporation, who spoke about his memories of the College in the Depression years, and an entertaining address by Dr. Charles L. Hosler, former EMS dean and currently acting provost of the University.

The Department of Mining Engineering was established in 1890 by President Atherton in response to the urgent need for well-trained mining engineers in Pennsylvania's rapidly expanding bituminous and anthracite coal mine industry. Dr. Magnus Ihlseng was appointed as first department head in 1893. Three years later, he was named as the first Dean when the fledgling department was named a School of Mines—the forerunner of the College of Earth and Mineral Sciences.

In one hundred years, Penn State has granted 1,446 B.S. degrees in mining engineering, 168 M.S. and 11 M.Eng.. degrees, and 54 doctorates.

Panel speakers on "The Future of Mining Education": left to right, Dr. Howard L. Hartman, Dr. Thomas Falkie, Mr. Ivan H. Rahn, and Mr. E. Morgan Massey.

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