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The Origin and Evolution of Earth: From the Big Bang to the Future of Human Existence

Course Guidebook

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Professor Robert M. Hazen is the Clarence J. Robinson Professor of Earth Sciences at George Mason University and a Senior Staff Scientist at the Carnegie Institution's Geophysical Laboratory. He received his B.S. and S.M. in Geology at the Massachusetts Institute of Technology and his Ph.D. at Harvard University in Earth Science. He was also a NATO Postdoctoral Fellow at Cambridge University.

Professor Hazen is the author of more than 380 articles and 25 books on science, history, and music. His most recent book is the critically acclaimed *The Story of Earth: The First 4.5 Billion Years, from Stardust to Living Planet*—a nominee for the 2013 Royal Society Winton Prize for Science Books. A Fellow of the American Association for the Advancement of Science, Professor Hazen has received the Mineralogical Society of America (MSA) Award and the MSA Distinguished Public Service Medal, the American Chemical Society Ipatieff Prize, the ASCAP Deems Taylor Award, and the Educational Press Association Award. In addition, he was the 2012 recipient of the Outstanding Faculty Award given by the State Council of Higher Education for Virginia. Professor Hazen has presented numerous named lectures and was a Distinguished Lecturer for Sigma Xi. He also has served as a Distinguished Lecturer and President for the MSA. His recent research focuses on roles of minerals in life's origins, including mineral-catalyzed organic synthesis and selective adsorption of organic molecules on mineral surfaces. Professor Hazen also has developed a new approach to mineralogy, called mineral evolution, which explores the coevolution of the geo- and biospheres. The biomineral "hazenite" was named in his honor.

At George Mason University, Professor Hazen developed curricula on scientific literacy with Professor James Trefil. Their books include the best-selling *Science Matters: Achieving Scientific Literacy* and *The Sciences: An Integrated Approach*, now in its seventh edition. Professor Hazen teaches courses on symmetry in art and science, images of the scientist in popular culture, and scientific ethics, and he frequently appears on radio and television programs about science.

Professor Hazen was named Principal Investigator in 2008 and Executive Director in 2011 of the Deep Carbon Observatory (DCO), a 10-year effort to achieve fundamental advances in understanding the chemical and biological roles of carbon in Earth (http://deepcarbon.net). With significant funding from the Alfred P. Sloan Foundation, the decadal aspiration of the DCO is to become an international community of more than 2,000 collaborators from 60 countries with anticipated total funding from governmental, corporate, and private sources approaching $1 billion.

In October 2010, Professor Hazen retired from a 40-year career as a professional trumpeter. He performed with numerous ensembles, including the Metropolitan, Boston, and Washington operas; the Royal, Bolshoi, and Kirov ballets; the Boston and National symphonies; and the Orchestre de Paris. Prior to his retirement, he was a member and soloist with the Washington Chamber Symphony, the National Philharmonic, the Washington Bach Consort, and the National Gallery Orchestra.

Professor Hazen's other Great Courses are *The Joy of Science* and *Origins of Life*. ■

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The Origin and Evolution of Earth:
From the Big Bang to the Future of Human Existence

Scope:

Earth is an astonishing planet—an evolving world of dynamic, constant change. The epic story of Earth's evolution and development is a journey that begins almost 14 billion years ago, with the formation of atoms and molecules shortly after the big bang. Those raw materials became the building blocks of stars, which in turn produced all of the chemical elements that would form Earth and other rocky planets.

This course follows the origin of the solar system, with its central Sun and eight major planets, from a swirling nebula of dust and gas 4.567 billion years ago. The course also explores how and why other planets differ from Earth and considers a gradual diversification of the mineral kingdom as heat and water refined the raw materials into an expanding repertoire of rocks and minerals. Early Earth grew and separated into great layers—crust, mantle, and core—only to be disrupted by the catastrophic Moon-forming impact of a competing planet.

As Earth cooled, it became enveloped in a globe-spanning blue ocean, punctuated by violently erupting volcanic islands. Only gradually did dry land accumulate to form continent-sized masses of gray granite. With the advent of plate tectonics, and its reprocessing of vast volumes of crust and mantle, the mineral realm continued to diversify. A supercontinent cycle ensued, in which major landmasses repeatedly collided to form a supercontinent, only to break up again: Kenorland over 2.5 billion years ago; then Columbia (also known as Nena, Nuna, or Hudsonland) until 1.5 billion years ago; then Rodinia over 1 billion years ago; and, most recently, Pangaea, which began breaking up 200 million years ago.

Through more than 4.5 billion years, our home has progressed through 10 dramatic stages of change, each marked by intriguing novelties in the near-surface environment. In the process, Earth has morphed from a blackened basalt sphere with incandescent orange streaks of lava to shades of blue, gray, red, white, and green. And, in a discovery of profound implications, we find that life and rocks have coevolved for most of that storied past. We are only just beginning to understand the remarkable feedbacks by which life alters and diversifies rocks and minerals, which in turn alter and diversify life.

This course makes use of a new approach to earth sciences called mineral evolution. In this original framing of the earth sciences, introduced by Robert Hazen and colleagues in 2008, minerals at or near Earth's surface have undergone a sequence of evolutionary transitions associated with chemical, physical, and biological changes. Each stage resculpted our planet's surface, each introduced new planetary processes and phenomena, and each inexorably paved the way for the next. This hitherto untold grand and intertwined tale of Earth's living and nonliving spheres is utterly amazing, and it must be explored, because we *are* Earth. Everything that gives us shelter and sustenance, all of the objects that we possess—indeed, every atom and molecule of our flesh-bound shells—comes from Earth and will return to Earth. To know our home, then, is to know a part of ourselves.

This course's journey follows Earth through three overall phases, or eras, of Earth's mineral evolution, which are further divided into 10 partly overlapping stages—each of which saw dramatic changes in our planet's mineralogy and each of which arose from physical, chemical, and biological influences. The first phase was the time of planetary accretion and is represented by stage 1, with approximately 60 minerals found in the most primitive chondrite meteorites that condensed from the solar nebula; and stage 2, with a much more diverse suite of 250 different minerals found in the striking variety of achondrites and other meteorites.

The second overall phase of Earth's history was the time of crust and mantle reworking, with three further stages of mineral evolution. Stage 3 is the earliest part of the Hadean Eon following Earth's differentiation into crust, mantle, and core at about 4.5 billion years ago—a time characterized by the formation and alteration of a black basalt veneer as well as the first shallow ocean. Stage 4 commenced with the production of the first granites and associated pegmatites with their host of gemstones and other rare minerals. Stage 5 saw the beginning of large-scale plate tectonic processes and fluid-rock interactions associated with subduction—processes that led to major metal ore deposits and other mineral-forming events.

Thereafter, the geological realm would have stagnated without the single most important factor in Earth's unique geological evolution: the origin of life. Accordingly, the third broad phase of Earth's mineral evolution focuses on the coevolution of the geosphere and biosphere. Stage 6 was prior to about 2.5 billion years, a time when microbial activity altered Earth's surface in an anoxic environment. Stage 7 centered on the great oxidation event (approximately 2.4 to 2.2 billion years ago), which triggered Earth's greatest episode of mineral diversification. Stage 8 is the subsequent billion-year interval, an intriguing time known as the "intermediate ocean"—or, more whimsically, the "boring billion"—which saw the formation and breakup of two supercontinents in succession without any obviously new modes of mineral formation. Snowball Earth episodes of global glaciation 700 million years ago were key to stage 9 and served as preludes for increased atmospheric oxidation. Stage 10 encompasses the past 543 million years—the modern period of biomineralization, which includes the rise of plants and the terrestrial biosphere.

From a planetary perspective, the concept of mineral evolution allows each terrestrial body in the solar system to be placed in a broader mineralogical and comparative context. Mineral evolution also provides an intellectual framework for identifying mineralogical targets in the search for extraterrestrial life. From the perspective of complex evolving systems, which have often become a lightning rod for debates over biological evolution, mineral evolution provides an excellent example of a nonliving system that diversifies over time through well-known physiochemical mechanisms. Finally, mineralogy can now be understood as central to the overall story of Earth, intimately intertwined with the drama of planet formation, plate tectonics, and the origin and evolution of life.

For the past 4 billion years, life and minerals have coevolved in astonishing ways. This course tours the epic, intertwined sweep of life and rocks, with such dramatic innovations as the rise of algae that produce oxygen by photosynthesis, the evolution of complex cells with nuclei, the near extinction of life during episodes of extreme cold, the emergence of multicellular animals and plants, the gradual transformation of the land to an emerald planet, and ultimately to the modern world that is being shaped in part by human activities. ■

Mineralogy and a New View of Earth

Lecture 1

The story of planet Earth is one of remarkable, repeated change; 4.5 billion years in the making, our world is a unique product of a dynamic cosmos. Located a favorable distance from the Sun, Earth has liquid water, active tectonic plates, a protective atmosphere, and a large Moon that protects us from asteroids. And Earth is the one planet that plays host and mother to trillions of living, breathing organisms. But how did Earth begin? The rich history of our planet is preserved in its minerals and rocks.

Mineralogy

- Mineralogy is the scientific study of all aspects of minerals, which are defined as naturally occurring, crystalline compounds that have a well-defined chemical composition. Minerals are the fundamental building blocks for all kinds of rocks, and they're also critical components in the evolution of life.

- In spite of the fact that minerals are clearly part of Earth's geological history—indeed, minerals are fundamental to understanding Earth history—mineralogy itself is a field that has long been taught in a manner rather divorced from the grand story of Earth. In many highly respected mineralogy courses around the world, minerals are treated as idealized crystals.

- For more than two centuries, mineralogical research has focused on the static physical and chemical properties of crystals. Investigations of hardness and color, chemical elements and isotopes, optical properties, crystal structures, and external form have dominated the literature of traditional mineralogy.

- A benefit of this seeming lack of historical curiosity among professional mineralogists is that it has allowed for an impressive body of knowledge to form. Mineralogy has long allied itself with the so-called hard sciences of physics and chemistry, as opposed to the more historical sciences of geology and biology. Mineralogists know a great deal about chemical composition; crystal structure (that is, how the atoms are arranged); and physical properties, such as hardness, fracture strength, density, and color.

- Mineralogists have learned a great deal about magnetic properties and electrical properties; they have also measured compressibility (the reduction in volume when a crystal is subjected to high pressure) and thermal expansion (the change in volume at high temperature).

- The Mohs hardness scale is named after the 19th-century German mineralogist Friedrich Mohs, who became a leader in what was then a new approach—adding physical properties as a means to identify and describe minerals. He introduced a scale from 1 to 10 as a means to characterize minerals based on their relative hardness.

- Hardness, like many other diagnostic chemical and physical properties, is a useful way to distinguish different minerals, but it tells you nothing about the history of your calcite or feldspar specimen, for example.

- The reason for this curious bias has to do with an old prejudice that physics and chemistry are somehow more rigorous—more "scientific"—than the historical sciences of geology and biology. There's a sense that physics and chemistry are based on real, measureable aspects of nature—density, hardness, structure, composition—whereas much of geology relies on a kind of guesswork and storytelling that can never be so absolutely rigorous.

- As a result, rather than tell stories about their crystal specimens—rather than speculate on how and when those crystals formed—mineralogists have long stuck to what they can measure with great precision and accuracy.

- But even physicists learned to appreciate the unavoidable role of time, once the big bang theory came to be accepted within cosmology. That's the kind of change that has been taking place more recently within the Earth sciences: Experts in scientific approaches that used to be separate are now talking to each other much more.

Geology

- A second scientific tradition, geology, has been oddly separated from mineralogy. Geology focuses on the history of Earth by dividing Earth's history into distinct eons, eras, periods, and epochs—with each subdivision smaller than the one that came before.

- The study of geological time is critical to describing the story of changes on our planet over immense intervals of time, with four eons used to mark the largest divisions in Earth's history: the Hadean, lasting 550 million years; the Archean, lasting almost 1.5 billion years; the Proterozoic, stretching from 2.5 billion years ago to about half a billion years ago; and the Phanerozoic, which is the most recent 542 million years. The Archean Eon is the time, starting about 4 billion years ago, that probably marks the origins of life.

In his *Systema Naturae* ("The System of Nature"), Carl Linnaeus outlined his classification of the various kingdoms of species on Earth.

Mineral Evolution

- Ever since 1735, when the famous Swedish taxonomist Carl Linnaeus included the mineral kingdom in his great classification scheme, *Systema Naturae* ("The System of Nature"), Earth's mineralogy has been treated as a fixed and static aspect of nature. Linneaus described the animal kingdom, the plant kingdom, and the mineral kingdom, all using the familiar binomial nomenclature of genus and species—for example, *Tyrannosaurus rex* or *Homo sapiens*.

- In the 19th century, mineralogists began classifying minerals in terms of their underlying chemical properties, but they continued to refer to "mineral species." For more than two centuries, students of mineralogy have learned about each mineral species by memorizing names, chemical compositions, crystal forms, and such distinctive and immutable physical properties as color, hardness, transparency, and magnetism.

- Through all this, the dimension of time was never considered. No one, it seems, bothered to ask if Earth's past mineralogy differed from that of today. But Earth's mineralogy must have evolved in striking ways over the vast expanse of geological time, as even a cursory glance at geological history reveals.

- Mineral evolution is a whole new framework for the science of mineralogy that brings mineralogy together with the rest of geology. This approach also became a way of bringing the earth sciences as a whole together with the life sciences—thus bringing together, in a new way, the old Linnaean kingdoms of animal, vegetable, and mineral. The three kingdoms are no longer viewed as static and can no longer be studied in isolation from one another.

- Mineral diversity comes from chemistry—from the richness of the periodic table of the elements. More than 80 different elements help to form the mineral kingdom, but some elements are far more common than others.

- Mineral evolution was preceded by element evolution. The cosmos began with almost nothing but the lightest, star-forming elements: hydrogen and helium. Gradually, stars manufactured the rest of the periodic table, first by the gradual processes of nuclear fusion to make the most common Earth-bound elements: oxygen, magnesium, silicon, and iron. Then, in great paroxysms, the rest of the periodic table emerged in supernovas—violent explosions of stars that seeded our Milky Way galaxy with planet-forming dust.

- It took several million years for the first minerals to appear in the cooling, expanding environments of exploding stars. As near as we can tell, about a dozen different mineral species formed early on—what we call the "ur-minerals," which are locked into the microscopic dust grains that are the ultimate building materials of planets like Earth.

- It took millions more years for the first rocky planets to appear, as stars and planets began a cycle of formation and destruction that eventually led to our own solar system more than 4.5 billion years ago. Most of this course focuses on the subsequent assembly and evolution of Earth.

- First, Earth differentiated into its great layers: the core, mantle, and crust; the oceans and atmosphere; and the geosphere and biosphere. Second, there were violent transformative events, including the origin of the Moon and the extinction of the dinosaurs. Third, there have been more gradual changes of ocean chemistry, supercontinents, climate, and life's origins and evolution.

- This 4.5-billion-year history spans up to the present day, when humans are playing such a significant role in changing our planet. The story of Earth and its evolution is a story of mineral evolution as well. Everything we know of Earth and its history comes from studies of the rocks and minerals.

- Earth's mineral history had at least 10 distinct stages, but we can combine those stages into just three broad eras, each of which saw the appearance of new minerals at or near Earth's surface.
    - The first era of mineral evolution (stages 1 and 2) was in the early solar system, which includes the ancient period more than 4.5 billion years ago when planets formed from dust and

gas. The first era is preserved in the varied meteorites that still fall to Earth.

- ○ The second broad era is Earth's own mineral evolution before the arrival of life (stages 3 through 5), beginning with the formation of the planet from thousands of planetesimals. This second era involves chemical and physical processes that separate and concentrate elements—processes that lead to more than 1,000 new mineral species.

- ○ The third broad era of Earth's mineral evolution is linked to life (stages 6 through 10). This third era focuses on the origins of life and subsequent interactions between the geosphere and biosphere. More than two-thirds of all known minerals are now thought to be the indirect consequence of life.

Suggested Reading

Deer, Howie, and Zussman, *An Introduction to the Rock-Forming Minerals*.

Hazen, "The Evolution of Minerals."

———, *The Story of Earth*, Introduction, pp. 1–6.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapters 1, 18–21.

Wenk and Buklah, *Minerals*.

Questions to Consider

1. What is mineral evolution, and why does it represent a new way to frame the very old science of mineralogy?

2. What are the three eras of Earth's mineral evolution, and how do they differ from each other?

Origin and Evolution of the Early Universe

Lecture 2

Earth and the solar system are more than 4.5 billion years old, yet they are relatively young compared to the universe. The discovery of the age of the cosmos and its remarkable origins in the so-called big bang began with the telescopic measurements of American astronomer Edwin Hubble. To understand Earth's origin, you must first understand where all the matter—all the atoms—that make Earth came from, and that is a story that begins with the big bang. Following the big bang, the moment of creation, the universe transformed again and again as it expanded.

Hubble's Discoveries

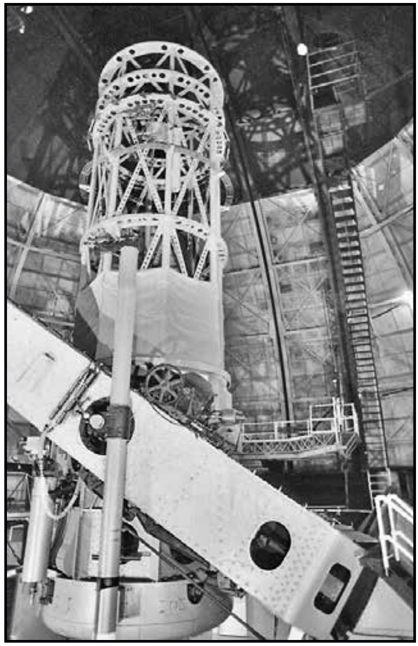
- The central questions of cosmology are how the universe arose, and what its fate will be. Before about 1920, the question of the origin of the universe was outside the realm of science, because no reproducible measurements informed the question. Edwin Hubble used the new 100-inch Mount Wilson telescope to image individual stars in distant galaxies for the first time.

- Hubble's measurements found that the universe is composed of distant galaxies that are actually enormous collections of stars, just like the Milky Way, which is now thought to have hundreds of billions of stars.

- Hubble's studies led to the first clear observational evidence for the age and origin of the universe. Hubble and other astronomers measured the relative velocities of galaxies by what's known as their red shifts.

- The red shift is an apparent change in the wavelengths of light coming from a distant object, such as a star or galaxy. If the object moves toward you, then waves pile up more closely together, and there's a shift of apparent wavelength to the higher-frequency blue part of the spectrum—called a blue shift. If the object moves away from you, then waves spread out, and there's a shift of apparent wavelength to the lower-frequency red part of the spectrum—called a red shift.

- Hubble discovered that more distant galaxies are moving away from us more quickly. Hubble measured the red shifts of about 20 galaxies and realized that there's a simple relationship between distance and velocity. But this result leads to an amazing conclusion: The universe is expanding. And, if you play the cosmic tape backward, everything converges to a point in both space and time.



Edwin Hubble used this telescope to measure galaxy red shifts and discover the expansion of the universe.

- Hubble's great discovery of the expanding universe has startling implications regarding the origin of the universe. In fact, it now appears that the universe began at an instant of time approximately 14 billion years ago, and it has been expanding ever since. This theory—that the universe came into existence at one moment in time and subsequently has undergone rapid expansion—is called the big bang.

The Big Bang: Three Lines of Evidence

- Three lines of observational evidence support the big bang theory: the universal expansion; the discovery of a pervasive background of microwave radiation in the cosmos; and the ratios of the light elements hydrogen, helium, and lithium.

- First and foremost was Hubble's discovery in the 1920s of the expanding universe, which has now been amplified by thousands of observations. Time and again, astronomers have confirmed that all but the closest galaxies are speeding away from us and that the farther the galaxy, the faster it's receding.

- A second compelling piece of evidence for the big bang, discovered quite by accident in the 1960s, is a pervasive background of microwaves that seems to flood every corner of the universe. This "cosmic microwave background radiation" was discovered by two researchers at the American Telephone and Telegraph Company's Bell Laboratory in New Jersey. Arno Penzias and Robert Wilson were studying microwave communications, and they had developed a new high-sensitivity, cone-shaped microwave antenna that they were testing. But they experienced a high level of noise, or static, and they tried everything to eliminate the noise, but nothing worked.

- At the same time, Phillip James Peebles, a theoretical astrophysicist working just a short distance away at Princeton, had been thinking about the consequences of the big bang, and he realized that what Penzias and Wilson had discovered was exactly what theoretical astrophysicists had predicted: The microwave static was actually primordial electromagnetic radiation left over from the big bang.

- At the instant of the big bang, the universe was flooded with all the matter and energy that would ever be. Unimaginable amounts of energy were converted into highly energetic electromagnetic radiation with unimaginably short wavelengths (which translate into high energies). Then, as the universe expanded after the big bang, and as the universe began to cool, the wavelengths of that electromagnetic radiation were stretched out to lower and lower energy along with the expansion.

- The background microwave radiation we see today represents the remnants of that initial intense radiation, which has been stretched out to microwave wavelengths—which are wavelengths on the order of a foot long.

- The third line of evidence for the big bang is based on the ratios of the lightest elements—hydrogen, helium, and lithium, respectively—that we measure today. These three elements of the periodic table condensed directly out of the big bang. While most of this matter was in the form of hydrogen atoms, about a tenth was helium plus a very small amount of lithium.

- Measurements of the relative amounts of these light elements provide strong evidence for the big bang. Especially important in this regard is the ratio of two variants of the hydrogen atom—normal hydrogen and the heavier version, an isotope called deuterium. The observed ratios of light elements in the universe closely match the predictions of a big bang origin, as opposed to the steady state theory.

- In spite of its name, the big bang was not an explosion in which matter expanded into an existing space. Existence itself expanded, and not into anything—there was no inside and no outside. Instead, it was what physicists call a singularity—a transformation from nothing to something. We know of no way to make any measurement that provides any insight about what came before the big bang.

Seven Cosmic Freezings

- Scientists who study the big bang see the universe today as a place where not only different particles of matter, but also all forces like gravity, have frozen out of an earlier, uniform, and perfectly symmetric time—a time 13.7 billion years ago when all the particles and all the forces were indistinguishable.

- Think backward in time, to that instant of creation, when all the matter and energy of the universe appeared at a point. As that hot, compressed universe cooled, a dramatic series of seven cosmic "freezings" took place. Think of freezing as a phase transition that happens when a very hot object gets colder.

- The earliest three freezings occurred in a fraction of the first second, as the four known forces in nature separated from their initially homogeneous state. The first of these freezings, according to theoretical calculations, occurred when the universe was only 10^{-43} seconds old—that's a ten millionth of a trillionth of a trillionth of a trillionth of a second—a very short time, indeed.

- At that point in the early history of the universe, gravity forever split off from the other forces, and the universal expansion was opposed by gravity for the first time. Before that time is referred to as the inflationary period—a time when the universe expanded extra fast, perhaps all the way up from a point to the size of a grapefruit.

- There's no known way to reproduce the incredible concentrated energy of that earliest cosmic event—nor of the second freezing, which occurred at about 10^{-35} seconds, when what is called the strong force froze out. The strong force holds nuclear particles like the proton and neutron together, so this was an important step in the invention of atoms.

- At 10^{-10} seconds, when the universe was one ten-billionth of a second old, the two remaining forces separated. One of these, the weak force, is manifest today in radioactivity—it's the force that causes dangerous particles to fly away from a radioactive atom.

- The other force, the so-called electromagnetic force, is manifest in such everyday phenomena as static cling and refrigerator magnets. The electromagnetic force holds atoms together and is ultimately responsible for all the matter that makes up our planet.

- Hints of this third cosmic freezing can be gleaned from experiments at the world's largest particle accelerators, which can reproduce the energies associated with the unified electroweak force.

- Subsequent freezings led to all the matter that we see today. Prior to 10^{-5} seconds—which is ten millionths of a second—all matter existed as electrons and other isolated particles called quarks and leptons.

- At 10^{-5} seconds, the quarks combined to form all sorts of additional particles, including protons and neutrons. Protons are massive, positively charged atomic particles while neutrons are similar to protons in mass but have no electrical charge. Both of those particles play a major role in the atomic nucleus, and each is formed by a combination of three quarks.

- So, when the universe was still less than a second old, all four forces had frozen out, as had the basic building blocks of atoms—electrons, protons, and neutrons. It took about three minutes more for the first atomic nuclei of protons and neutrons to fuse together and form deuterium—an atomic nucleus that contains one proton and one neutron.

- These hydrogen and deuterium nuclei were surrounded by a sea of hot, speeding electrons, forming one immense plasma, which is the state of matter that forms stars. Plasma is extremely hot and is like a gas, but the atoms are broken apart—into positive nuclei and negative electrons.

- Things were still ridiculously hot in that early universe, and they remained so for about half a million years. Gradually, as the universe continued to expand, the cosmos cooled to a few thousand degrees, and that was sufficiently cold for electrons to latch onto nuclei and form the first atoms.

- The overwhelming majority of those first atoms were hydrogen—more than 90 percent of all atoms, with a few percent helium and a trace of lithium thrown in. That mix of elements is what would form the first stars.

Suggested Reading

Hawking, *A Brief History of Time*.

Hazen, *The Story of Earth*, Chapter 1, pp. 7–10.

Singh, *Big Bang*.

Trefil, *The Moment of Creation*.

Questions to Consider

1. What is the central question of cosmology?

2. What observational evidence supports the big bang theory?

Origins of the Elements—Nucleosynthesis
Lecture 3

If the big bang contributed mostly hydrogen, where did all the other elements come from? The next dramatic steps leading to the birth of Earth took place over the next several millions of years, as the first elements formed stars and the first stars began to give birth to the entire periodic table of the elements. That process is called nucleosynthesis. In this lecture, you will learn about the remarkable evolution of energetic stars and the processes by which they first generated the chemical richness that we now take for granted.

The Basics of the Periodic Table

- An atom is any object with a positively charged nucleus with one or more protons and usually neutrons, surrounded by one or more negatively charged electrons.

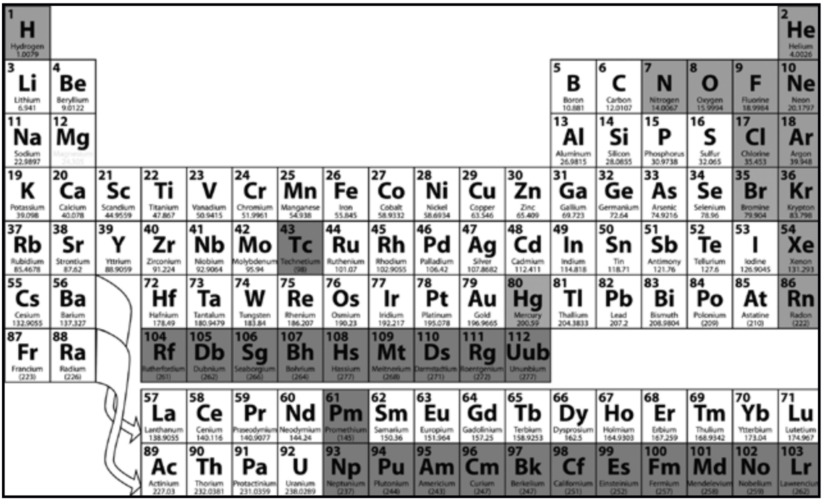
- An element is an atom for which the exact number of protons is known. The number of protons, or atomic number, also defines an element's position in the periodic table.

- Hydrogen is element 1, with one proton in the nucleus, so it's found in the upper left-hand corner of the periodic table. Helium is element 2, carbon is element 6, and gold is element 79—so they have 2, 6, and 79 protons in the nucleus, respectively.

- An ion is any atom that has a net electrical charge—that is, the number of positive protons in the nucleus is different from the number of negative electrons surrounding the nucleus.

- An isotope is any element for which you know both the number of protons and the number of neutrons in the nucleus. The number of protons defines the element, but every element comes in a variety of isotopes, which turn out to be fundamentally important in our understanding of Earth history.

The Periodic Table of the Elements



- In the chart of isotopes, the number of protons is on the vertical axis while the number of neutrons is on the horizontal axis. That means that the chart of isotopes has lots of squares, each corresponding to a unique combination of protons and neutrons. In fact, we know of more than 2,000 different isotopes, meaning 2,000 different combinations of protons and neutrons.

- For any number of protons—for any given element—there are several isotopes. As you get to higher and higher atomic numbers—that is, elements with more and more protons—you notice two important trends. The first is that heavier elements have many more isotopes.

- The other trend is that as the atomic number rises, the average number of neutrons greatly exceeds the number of protons. This effect can be explained in part by the electrostatic repulsion that occurs between two positively charged protons. Like electrical charges repel each other, positive repels positive, and when you try to cram dozens of positive protons into the same nucleus, the neutrons can act like tiny spacers.

Cosmic Evolution and Nucleosynthesis

- Almost 14 billion years ago, at the beginning of all things, the big bang paved the way for cosmic evolution. A sequence of freezings led first to the four forces and then to the principal subatomic particles—leptons and quarks. Eventually, when the universe was only a few hundred thousand years old, the first atoms emerged—the first chemical elements—hydrogen, helium, and lithium.

- None of the richness of the periodic table of the elements had yet appeared. The raw materials of earthlike rocky planets, and of the minerals that form them, did not yet exist. Simple atoms of hydrogen and helium made stars, and stars manufactured all the rest of the periodic table of the elements. This remarkable stellar mechanism of making chemical elements is a process called nucleosynthesis.

- All of the chemical elements form in the extreme pressure cookers called stars. First, hydrogen fuses to make helium; then, helium fuses to make carbon. The entire periodic table of the chemical elements formed in a sequence of four processes, collectively called nucleosynthesis. Each of these four steps diversified the chemistry of the cosmos.

- Stars begin their lives as giant balls of hydrogen, the first element, which formed shortly after the big bang. Every star balances the forces of gravity pulling hydrogen inward and nuclear reactions pushing outward.

- In stars, immense inner pressures and temperatures drive nuclear fusion reactions. In the first series of fusion reactions, hydrogen forms helium, helium forms carbon, and so on—up to the element iron, which is the endpoint of fusion. No more energy can be extracted from an iron nucleus, either by fusion or by fission.

- When the star forms an iron core, the entire star collapses and then rebounds like a trampoline, causing an intense flux of neutrons that generates all the elements and hurls them into space in a supernova explosion. We now have observational evidence for supernovas from as long ago as the first five percent of cosmic history, so the creation of elements probably first occurred even earlier, within the first few million years.

- Many generations of stars come and go, each with more heavy elements than the last. Earth's atoms represent the remains of many previous star cycles. Endowed with all the chemical elements, Earth was poised to do amazing chemistry.

Stars and Supernovas

- Stars have many millions or even billions of years of hydrogen fusion. Then, they have helium fusion for a tenth of that time span. Successive stages of fusion lead to faster and faster generation of shells of fusion: hydrogen, helium, carbon, neon, oxygen, silicon. The last stage—silicon fusion to elements all the way up to zinc, with back reactions to make a lot of iron-56—occurs in just one day.

- When the core converts to iron-56, the nuclear reactions stop. All of the forces pushing outward, countering the immense gravitational forces pulling inward, stop cold. Then, the star simply collapses. The star may have burned for a billion years, but in a process that lasts only a few seconds, the star is destroyed.

- Gravity is the culprit. Until that point, the star survived by balancing its two great inner forces: gravity pulling mass toward the center and nuclear reactions pushing mass outward from the center. For many millions of years, a stable equilibrium between opposing forces persisted.

- However, when the core filled with iron, the outward push just stopped, and gravity took over in an instant of unimaginable violence. The entire star collapsed inward with such swiftness that it rebounded off itself and exploded in the first supernova. The star was ripped apart, blasting most of its mass into deep, dark space.

- Such a cataclysm might seem a completely random, chaotic event, hardly amenable to systematic description. Yet recent research reveals how the entire periodic table, indeed the entire chart of the isotopes with more than 2,000 entries, can be formed from supernovas.

- The key is neutrons. The supernova collapse and subsequent explosion is accompanied by an unimaginable flood of neutrons, which are the electrically neutral particles in the atom's nucleus that define which isotope you have.

- Huge fluxes of energetic neutrons have a tendency to stick to any atomic nucleus that they find, so for a brief time—perhaps only a second—a significant fraction of all the existing nuclei in one of those exploding stars becomes crammed full of extra neutrons. These neutron-saturated isotopes then undergo another radioactive process called beta decay.

- An excess neutron inside the nucleus transforms into a positively charged proton, while a negatively charged electron goes flying off. The result is a new element with the element number—the number of protons—increased by one. On the chart of isotopes, this is a diagonal move one space up and one space to the left.

- The new element can capture more neutrons and undergo more beta decays, so step by step, the heavy elements are formed—in a kind of zigzag march up the chart, eventually all the way up to uranium (element 92), which is the heaviest naturally occurring element on Earth.

- The periodic table now features artificial elements beyond uranium, all the way up to element 118. Many of those artificial elements are made just like in stars, by bombarding uranium and other heavy elements with neutrons, and then watching for beta decay to elements with more protons—higher up the periodic table.

- It now turns out that there are two variants of this process of neutron capture, both of which contribute to the rich storehouse of elements that make planets. In supernovas, the neutron capture occurs quite quickly, so it's called the rapid process, or r-process.

- In the instant following a supernova collapse, the entire periodic table of the elements can be formed in this amazing way. This was the only way that the heaviest elements were manufactured in the first generation of stars following the big bang. When those stars exploded, they seeded the universe with all the heavy elements, iron and beyond, to form the next generation of stars. So the second generation of stars in the universe formed with a small fraction of elements other than hydrogen and helium.

- In addition, astrophysicists now recognize a slower neutron capture mechanism, the s-process, which occurs in the most energetic red giant stars, where helium-burning nuclear reactions can produce lots of excess neutrons that are then captured on iron nuclei from previous generations of stars.

- Stars that begin their lives with some iron and other heavy elements can make a good portion of the periodic table, even without exploding, sometimes creating elements as heavy as lead. And because those big red giant stars have very intense solar winds that can blast off as much as 30 percent of their total mass, some of those heavy elements can even make it out into space without the entire star exploding. Still, the only source of the heaviest elements like uranium and thorium is supernovas.

Suggested Reading

Hazen and Trefil, *Science Matters*.

Kwok, *Stardust*.

Pagel, *Nucleosynthesis and Chemical Evolution of the Galaxies*.

Schatz, "The Evolution of Elements and Isotopes."

Questions to Consider

1. How do stars make the elements of the periodic table?

2. Why is a star's mass important in determining what elements arise by nucleosynthesis?

Ur-Minerals, First Crystals in the Cosmos

Lecture 4

In this lecture, you will learn that the earliest beginnings of mineralogy in the cosmos started with about a dozen ur-minerals—microscopic grains that crystallized in the cooling carbon-rich envelopes of energetic supernovas and in the solar winds of red giant stars. Diamond and graphite were first, followed by a modest suite of high-temperature carbides, nitrides, oxides, and silicate minerals. Those crystals survive to this day in the form of presolar grains, the oldest objects we can study in the lab.

The Formation of Minerals

- A number of different definitions of "mineral" have been proposed, but they all involve three key characteristics: A mineral is a (1) naturally occurring, (2) crystalline solid with a (3) more or less well-defined chemical composition. Each of the more than 4,700 known mineral species fits this definition.

- The story of Earth's mineralogical richness began many billions of years ago, in the black void of space, long before the origin of our solar system. There were certainly no minerals right after the big bang. In those early times of an unimaginably hot and dense cosmos, there weren't even atoms.

- Even after a few hundreds of thousands of years, when the first hydrogen and helium atoms formed, with a sprinkling of the element lithium thrown in, there were no crystals. It was simply too hot.

- In addition, hydrogen and helium are gases. Minerals form primarily from the heavier elements, and heavier elements form in stars by the processes of nucleosynthesis. That means that the first mineral must have formed *after* the first stars made heavier elements—carbon and above.

- That first population of stars was composed almost entirely of hydrogen and helium, but large hydrogen-rich stars go through a series of fusion reactions: Hydrogen fuses to make more helium and releases a lot of energy. That's why stars shine; they radiate some of that nuclear energy. Then, helium fuses to make carbon and releases more energy, and carbon fuses in a succession of other energetic nuclear reactions that produce oxygen, nitrogen, magnesium, aluminum, silicon, titanium—all the way up to element 26, which is iron.

- In the final stages of a big star's evolution, the star is layered like an onion, with hydrogen and helium on the outside and then layers rich in carbon, oxygen, magnesium, and silicon. Those are all common elements that can form minerals, but they were initially locked into stars, and stars are made of superhot plasma—much too hot to form crystals. No minerals can exist in the incandescent vapors of stars.

- But the largest stars have at least two mineral-forming tricks up their sleeves. The most dramatic mineral-forming event in the cosmos is the supernova. When a big star fuses all the way to iron, the fusion reactions just stop. Up to that point, the star played a balancing act between two epic forces: gravity pulled all of the star's mass inward, while nuclear reactions pushed outward. But iron is the ultimate nuclear ash. There's no way to get energy by fusing iron to anything, so the outward force just stops, and gravity takes over.

- It's difficult to imagine what the sudden collapse of a star is like, but gravity is so strong that the outer layers of a collapsing star reach relativistic velocities—a significant fraction of the speed of light. And when all that mass collapses down to the star's core, it rebounds in an epic explosion—a supernova—that blasts all of those chemical elements out into space.

The Earliest Minerals

- Prior to the first exploding star, perhaps at a time when the universe was a few million years old, there had never been a place that was both dense enough with mineral-forming elements and also cool enough to condense crystals. But when a dying star explodes into a supernova, the star's element-rich gaseous envelope expands, and as it expands, it rapidly cools, with the outer layers cooling first.

- That's why we speculate that the very first mineral in the history of the cosmos was diamond, which is pure carbon that crystallized in the outer reaches of the first supernova explosion. The concentration of carbon was high enough—and the temperature "cool" enough (4,000 degrees above absolute zero)—that diamond crystals could grow.

- Diamond was first by virtue of two facts: There was a lot of carbon, and diamond crystals form at exceptionally high temperature—much higher than almost any other known substance.

- Shortly after diamond appeared, the other common form of pure carbon, called graphite, with a slightly lower but still extremely high crystallization temperature (around 3,500 degrees above absolute zero), also formed.

- It's difficult to imagine two minerals that are more different from each other. Diamond is transparent and sparkly, while graphite is dull and black—it's the material in pencil "lead." Diamond is the hardest known substance and is used as an abrasive, while graphite is one of the softest solids and is used as a lubricant. Diamond is one of the most valuable gems, while graphite is common and cheap.

Graphite, which is one of the softest solids, is a form of pure carbon.

- So how could pure carbon form two such contrasting materials? The answer is found in their very different crystal structures. In diamond, every carbon atom is linked in a little pyramid to four others—an arrangement that makes for an incredibly strong lattice of atoms. Graphite, by contrast, features carbon atoms linked in a plane to only three others. So graphite has very strong sheets of atoms, but the sheets are only weakly linked to each other.

- Diamond and graphite were the first of what we now call the "ur-minerals." The reference to "Ur" recalls the most ancient roots of human civilization in the 5,000-year-old Mesopotamian city of Ur, located in what is now Iraq. The prefix "ur" has been applied in various contexts to the original version of something.

- The term "ur-minerals" refers to the earliest crystals in the cosmos—the starting point of perhaps a dozen different mineral species in all. These minerals include cohenite and moissanite (carbides); nierite and osbornite (nitrides); calcium-aluminum oxide hibonite, spinel, aluminum oxide corundum, and rutile (oxides); and olivine forsterite and pyroxene enstatite (magnesium silicates).

- A supernova explosion may not be the only way for stars to make tiny mineral crystals. Red giant stars are old stars that have spent most of their lives in the hydrogen-burning phase, but most of the hydrogen in the core has been used up.

- Red giant stars have entered their dynamic helium-burning stage, so they produce a lot of carbon, which is the principal byproduct of the fusion of helium atoms. Red giant stars are so energetic that they don't easily settle down. They go through amazing cycles of expansion and contraction, and they can generate very intense carbon-rich solar winds.

- The star in this mode makes immense quantities of carbon, and some of that carbon is blasted outward into the cooler surrounding space. So, as in a supernova explosion, if the density of carbon atoms is great enough and the temperature cool enough, diamond and graphite will form.

- The first of these ur-minerals, including carbon-rich diamond and graphite crystals along with about 10 other species, formed very early in the history of the universe—probably within the first few million years of the big bang—and all have been present continuously throughout the subsequent history of creation.

- In the chemical elements involved in these earliest crystals, the dozen ur-minerals, there are only 9 elements: carbon, nitrogen, and oxygen (elements 6 to 8); magnesium, aluminum, and silicon (elements 12 to 14); calcium (element 20); titanium (element 22); and iron (element 26). All of these elements continue to play key roles on Earth today.

- It's equally revealing to consider the chemical elements that did not form, including the most abundant elements, hydrogen and helium. In addition, we don't see elements 3 to 5: lithium, beryllium, and boron. Sodium and chlorine, the common elements of table salt, are also missing, as are the essential biological elements sulfur and phosphorus.

- Three reasons contribute to which minerals appear and which minerals don't, and these three reasons hold lessons that will recur over and over again in our consideration of mineral evolution. First is abundance. Some elements are just too rare to have found each other and formed a crystal in the chaotic environment of a stellar envelope.

- Second is chemistry. Some abundant elements, such as helium, neon, and argon—which form the last column of the periodic table—simply don't form minerals. They remain in the gaseous state in virtually every cosmic environment.

- The third reason that some elements don't form ur-minerals is temperature. All of the ur-minerals crystallize at extremely high temperatures because their elements combine with extremely strong bonds. The elements sodium, chlorine, and sulfur, by contrast, bond rather weakly, so they form crystals at relatively low temperatures. Minerals containing hydrogen typically break down at even lower temperatures. So there's no chance that they would appear in the list of ur-minerals.

Evidence for Ur-Minerals

- There is real, solid evidence for ur-minerals in the form of microscopic dust grains that constantly rain down from space and are by far the oldest objects we know. These are the presolar grains, the rare remnants of the original building blocks of our solar system.

- When stars and planets form in a nebula of dust and gas, most of the nebula is hydrogen and helium: roughly 90 percent hydrogen and 9 percent helium, with the balance dust.

- As the solar system formed, 99.9 percent of those raw materials wound up in the Sun, while almost all of the remaining 0.1 percent wound up in the planets, moons, asteroids, and comets. But a tiny, tiny fraction of a percent of the original dust was never captured by gravity, or it just sort of stuck on the surface of a meteorite and has been sequestered there for the better part of 5 billion years.

- Presolar grains are found concentrated in two principal places. Some grains have been collected very high in the atmosphere by NASA's fleet of specially modified U-2 spy planes that have a kind of sticky paper attached to their wings. Early studies of presolar grains relied on these stratospheric samples.

- In modern times, most presolar grains come not from the upper atmosphere, but from meteorites. It turns out that primitive meteorites concentrate and preserve some of the original, unaltered bits of our nebula. With care, it's possible to identify and isolate such ancient bits of cosmic matter.

Suggested Reading

Hazen, “The Evolution of Minerals.”

———, *The Story of Earth*, Chapter 1, pp. 10–13.

Kwok, *Stardust*.

Wenk and Buklah, *Minerals*.

Questions to Consider

1. What is a mineral?

2. Why was diamond the first mineral in the cosmos?

Presolar Dust Grains—Chemistry Begins

Lecture 5

The search for the first minerals in the cosmos now focuses on presolar grains, which preserve the tiny crystals that began to seed the universe with dust, the raw materials of all earthlike planets. In this lecture, you will learn about what is now one of the hottest topics in cosmochemistry: the quest to find those amazing presolar grains and to identify the ur-minerals they hold—minerals that are older than our solar system.

Chemical Reactions

- Chemistry happens when everyday atoms bump into each other. Every atom has a central nucleus with positive electric charge, surrounded by a cloudlike distribution of one or more negatively charged electrons. Isolated atomic nuclei almost never interact, except in the ultimate pressure-cooker environments of stellar interiors, where nuclear fusion reactions occur.

- Electrons from one atom are constantly bumping into the electrons of adjacent atoms. Chemical reactions occur when two or more atoms meet, and their electrons interact and rearrange. Such shuffling and sharing of electrons occurs because certain combinations of electrons, notably collections of 2 or 10 or 18 electrons, are particularly stable.

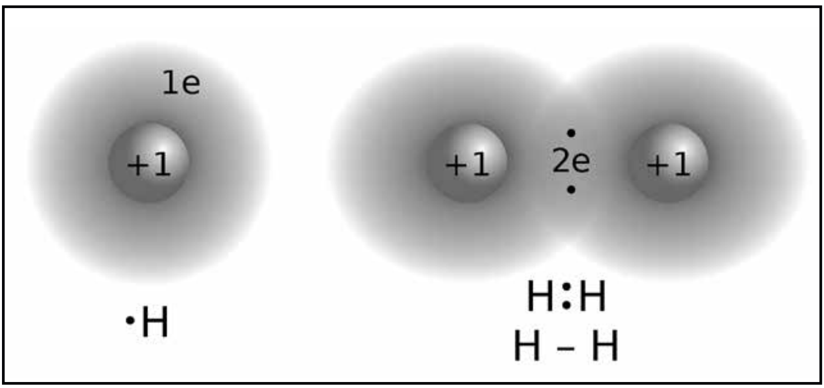
- On the periodic table of the elements, elements 2, 10, and 18 are found in the right-most column; they are helium, neon, and argon. These elements are found in the hot envelopes of exploding stars, but they never form minerals. That's because they have a full complement of electrons. Their electron shells are complete, so they remain as isolated atoms and typically remain in the gas state unless temperatures drop close to absolute zero, when they can freeze into crystals.

- Other elements don't naturally have these magic numbers of electrons, so they go through all sorts of changes to gain or lose electrons to achieve 2 or 10 or 18. That need to achieve a magic number is what drives chemical reactions and forges chemical bonds.

- The first chemical reactions following the big bang produced molecules, which are small clusters of a few atoms tightly bound into a single unit. Hydrogen molecules (H_2), each with two hydrogen atoms locked together, came first. Each hydrogen atom carries only one electron, which is a rather unstable situation in a universe where two electrons is a magic number.

- When two hydrogen atoms meet, they pool their resources to form a molecule with that magic number of two shared electrons. This sharing of electrons is called covalent bonding, which is the most important type of bonding in all living things—because it's the way the element carbon typically bonds to other elements.

- Given the abundance of hydrogen following the big bang, hydrogen molecules surely predated the first stars, and they have been a



H_2 is formed with a covalent bond, where two hydrogen atoms share two electrons.

perpetual feature of our cosmos since atoms first appeared about 13.7 billion years ago.

- However, lacking any other molecule-forming elements, hydrogen must have been all that was there before the first stars. There may have been a tiny amount of the lithium-hydrogen compound, lithium hydride, which would have been a gas.

- Following the first supernova, as space was seeded with a variety of other elements, many interesting molecules could form. Water (H_2O), with two hydrogen atoms bonded to an oxygen atom, is one early example. Chances are that nitrogen (N_2, with two nitrogen atoms bonded together), ammonia (NH_3), methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2) molecules also enriched the space around supernovas.

- All of these molecular species are formed from covalent bonds, and all would come to play key roles in the formation of planets and in the origins of life. But none of them is a mineral unless it freezes into an ice at temperatures much colder than those found in the vicinity of an exploding star.

- Two other types of chemical bonding enrich the cosmos. Ionic bonding occurs when two atoms exchange one or more electrons. Metallic bonding occurs when lots of atoms have too many electrons.

Modern Research on Isotopes

- Each chemical element of the periodic table is defined by its fixed number of protons, but the number of neutrons is not fixed. For example, in carbon, which has 6 protons, the number of neutrons in common isotopes can vary from 5 to 8. In nature, carbon-12 (with 6 protons plus 6 neutrons) is the most common. Less common is carbon-13, which has 6 protons and 7 neutrons. A relatively rare radioactive isotope of carbon is carbon-14, which has 6 protons and 8 neutrons and is used in carbon-14 age dating.

- Isotopes have provided the key to discovering the dozen or so ur-minerals, which are found in presolar grains. Somehow, those grains have to be distinguished from the vastly more common dust particles that surround us.

- The chemical composition of mineral dust is similar to that of presolar grains, but the isotopic compositions of presolar dust grains are often radically different from anything on Earth.

- For example, on Earth, the average composition of hydrogen is about 150 parts per million deuterium, which represents a kind of average of all the presolar material that made up the planets in our solar system—all the varied dust and gas that made the original solar nebula.

- By contrast, the individual presolar dust grains that made up the solar system had ratios of hydrogen to deuterium from just a few parts per million to thousands of parts per million. That's because different presolar dust grains come from different kinds of stars, and different kinds of stars vary widely in how they process and make isotopes.

- Presolar grains are distinguished from ordinary specks of dust by their isotopic anomalies—that is, ratios of isotopes wildly different from those of the well-mixed average we see on Earth today. The challenge is to identify and isolate microscopic presolar dust grains from everything else.

- The ion microprobe, which came into common use in the 1990s, is an amazing multimillion-dollar piece of scientific hardware that can measure the isotopic composition of individual dust grains and, thus, pick out the anomalous presolar bits.

- Once a precious presolar grain is identified by its isotopic anomalies, it can be studied by other techniques to tease out what minerals make up the dust. Much of every grain is noncrystalline; the atoms haven't organized themselves into a regular structure with a well-defined composition. This so-called amorphous state speaks of atoms clustering randomly in a chaotic, hot environment. But embedded in most presolar grains are also regions of crystalline order—tiny crystals of ur-minerals.

Mineral Evolution

- Mineral evolution represents an alternative approach to systematizing—and to teaching—the subject of mineralogy. The mineral diversity of terrestrial planets evolves as a consequence of the dynamic histories of planets. The roles of epic physical, chemical, and biological processes create gradients in temperature, pressure, and composition. These gradients selectively process elements and lead to new equilibrium mineral species.

- In this approach, the chronological stage of planetary evolution and the associated rock-forming processes that lead to distinctive suites of minerals—rather than the equilibrium structure, composition, and properties of the minerals themselves—is the underlying organizing principle. Geologic time becomes a central parameter of mineralogy.

- First in traditional mineralogy comes chemical bonding, which is a core concept in understanding how minerals form. The ur-minerals incorporate a wide range of bond types: covalent bonds in diamond, ionic bonds in oxides and silicates, van der Waals forces between the carbon layers of graphite, and even metallic bonds in the tiny specks of iron metal alloys.

- Mineralogy professors demand that any serious mineralogy course must introduce the key atomic structural motifs that appear over and over again in minerals. In particular, in oxides and silicates, the same patterns recur again and again: calcium surrounded by eight oxygen atoms, magnesium surrounded by six oxygen atoms, and aluminum and silicon surrounded by four oxygen atoms. These "polyhedra," which are common to many rock-forming minerals, all occur in the ur-minerals.

- The dozen ur-mineral species also illustrate such key mineralogical concepts as solid solution (which is how two or more different elements can substitute for each other in the same crystal), as exemplified in the olivines, and polymorphism, as shown by the two very different crystal forms of carbon—diamond and graphite.

- Traditional mineralogy courses also emphasize phase diagrams, which are graphical representations of how minerals form in different domains of pressure, temperature, and composition. In fact, the ur-minerals are ideal for introducing basic phase diagrams.

- These characteristics of ur-minerals provide a rich context by which to introduce the chemical and physical principles that are fundamental to all mineralogy. However, unlike traditional mineralogy curricula, these principles are introduced as part of a larger evolutionary story.

- Mineral evolution complements more traditional approaches to teaching mineralogy by providing a historical narrative for each mineral phase. The 4.5-billion-year story integrates the principal themes of planetary science: geodynamics, petrology, geochemistry, thermodynamics, and geobiology. As such, mineralogy becomes key to unlocking our planet's history and, thus, assumes a central role in the earth sciences.

Suggested Reading

Hazen, "The Evolution of Minerals."

———, *The Story of Earth*, Chapter 1, pp. 10–13.

Keller, Messenger, Stadermann, Walker, and Zinner, "Samples of Stars beyond the Solar System."

Kwok, *Stardust*.

Wenk and Buklah, *Minerals*.

Questions to Consider

1. What is an ur-mineral?

2. What kind of samples do scientists use to find and study ur-minerals?

Coming to Grips with Deep Time
Lecture 6

Perhaps the biggest stumbling block in understanding the evolution of Earth, as well as the diversification of its rich biosphere, is the immense span of time required: 4.5 billion years since our planet's origins. This concept of "deep time" represents one of the most important scientific discoveries. Numerous lines of observational evidence—drawn from physics, chemistry, geology, and biology—support the antiquity of our planet. These complementary and independent approaches all produce similar ages for Earth.

Evidence for Deep Time

- The cosmic timescale stretches from the big bang at 13.7 billion years ago to Earth's origin 4.5 billion years ago to today. There's simply no easy way to comprehend "deep time" because numbers like millions and billions are extremely difficult to understand. Nevertheless, earth scientists have developed numerous independent yet consistent lines of evidence that point to an incredibly old Earth.

- Rocks and minerals provide earth scientists with their most reliable clocks. For example, annual layerings can give very accurate age measurements up to perhaps a million years. Estimates of much longer time spans are based on the rates of ongoing geologic processes. The most accurate and reliable method for determining the timing of events all the way back to 4.5 billion years is isotopic age determinations, or radiometric dating. When properly applied, all three of these approaches yield identical estimates of geologic events.

- The most straightforward and unambiguous geologic timekeepers are rock formations with annual layers. Annual tree rings provide a familiar analog. Each year of a tree's life is marked by a distinctive ring with lighter and darker zones. These color changes result as growth increases in spring and slows the following winter. Based on counting tree rings, the oldest trees on Earth are a few thousand years old, but tree ring dating (or dendrochronology) has been pushed back 26,000 years by comparing living trees with buried logs of increasing age.

- Sedimentary rocks, too, can display annual layerings, or varves, that result from seasonal differences in sediment deposition. The most dramatic varve deposits, such as a meticulously documented 13,527-year sequence in glacial lakes in Sweden, occur as thin alternating light and dark layers, representing coarser-grained spring sediments and finer winter sediments, respectively.

- Ancient varved deposits sometimes preserve much longer time spans: The finely laminated Green River shale in Wyoming features continuous vertical sections half a mile in thickness, with 6 million such layers. That implies that deposition continued for 6 million years in the shallow lakes that hosted the Green River sediments.

- Some of the oldest continuous annual layerings are extracted from ice cores, whose laminae arise from seasonal variations in snowfall. One 2,000-meter-long ice core from East Antarctica reveals 160,000 annual layers of accumulation, year by year, snow layer by snow layer. And those annual layers rest atop another 2,000 meters of ice, which sit on vastly older rocks. Similar ages of ice cores comprise Greenland's thick glacial deposits.

- At least a million years is needed to account for many surficial deposits of sediment and ice. Earth must be much older than that, but how old? Slow, inexorable changes of Earth's dynamic surface provide a vivid, if approximate, measure of deep time.

- Great geological processes like growing volcanoes, opening oceans, and eroding mountains can take up to several hundred million years. Nevertheless, a few hundred million years is but a small fraction of a few billion years. How can we possibly say that Earth is 4.56 billion years old?

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The Grand Canyon, which dates from 3.8 billion to 540 million years ago, provides evidence of an incredibly old Earth.

Radiometric Dating

- The physical process of radioactive decay has provided Earth scientists with their most important method for determining the absolute age of rocks and minerals. This remarkable technique, which depends on measurements of the distinctive properties of radioactive materials, is called radioisotope geochronology, or radiometric dating.

- Trace amounts of isotopes of radioactive elements, including carbon-14, uranium-238, and dozens of others, are all around us—in rocks, in water, and in the air. These isotopes are unstable, so they gradually break apart, or decay. Radiometric dating works because radioactive elements decay in predictable fashion, like the regular ticking of a clock.

- If you have a collection of 1 million atoms of a radioactive isotope, half of them will decay over a span of time called the half-life. Uranium-238, for example, has a half-life of 4.468 billion years, so if you start with 1 million atoms and come back in 4.468 billion years, you'll find only about 500,000 atoms of uranium-238 remaining. The rest of the uranium will have decayed to 500,000 atoms of other elements, ultimately to stable (nonradioactive) atoms of lead-206. Wait another 4.468 billion years and only about 250,000 atoms of uranium will remain.

- Radioactive isotopes come with a wide range of half-lives, from a fraction of a second to many billions of years. Isotopes with very short half-lives aren't very useful in dating rocks. The best-known radiometric dating method involves the isotope carbon-14, with a half-life of 5,730 years.

- Every living organism takes in carbon during its lifetime. Most of this carbon (about 99 percent) is in the form of stable (nonradioactive) carbon-12, while perhaps 1 percent is the slightly heavier and stable carbon-13. But a certain small percentage of the carbon in your body and every other living thing—no more than one carbon atom in every trillion—is in the form of radioactive carbon-14.

- Carbon-14 is constantly being produced high in the atmosphere when cosmic rays interact with common nitrogen-14. Those nuclear interactions convert a tiny fraction of nitrogen-14 to carbon-14, which then starts to decay back to nitrogen-14.

- As long as an organism is alive, the carbon-14 in its tissues is constantly renewed in the same small part-per-trillion proportion that is found in the general environment. All of the isotopes of carbon behave the same way chemically, so the proportions of carbon isotopes in the living tissue will be nearly the same everywhere, for all living things.

- When an organism dies, however, it stops taking in carbon of any form. From the time of death, therefore, the carbon-14 in the tissues is no longer replenished. Like a ticking clock, carbon-14 atoms transmute by radioactive decay to nitrogen-14, atom by atom, to form an ever-smaller percentage of the total carbon.

- Scientists can thus determine the approximate age of a piece of wood, hair, bone, or other object by carefully measuring the fraction of carbon-14 that remains and comparing it to the amount of carbon-14 that can be assumed was in that material when it was alive.

- Scientists have conducted meticulous year-by-year comparisons of carbon-14 dates with those of tree ring chronologies, and the result is that the two independent techniques yield exactly the same dates for ancient fossil wood.

- Carbon-14 dating has been instrumental in mapping human history over the last several tens of thousands of years. When an object is more than about 50,000 years old, however, the amount of carbon-14 left in it is so small that this dating method cannot be used.

- To date rocks and minerals that are millions of years old, scientists must rely on similar techniques that use radioactive isotopes of much greater half-life, including potassium-40 (half-life of 1.248 billion years), uranium-238 (half-life of 4.468 billion years), and rubidium-87 (half-life of 48 billion years). In these cases, geologists measure the total number of atoms of the radioactive parent and stable daughter elements to determine how many radioactive nuclei were present at the beginning.

- Much older events in the history of life, some stretching back billions of years, are often based on potassium-40 dating. This technique works well because fossils are almost always preserved in layers of sediments, which also record periodic volcanic ash falls as thin horizons of tiny glass shards and other distinctive particles. Volcanic ash is rich in potassium-bearing minerals, so each ash fall provides a unique time marker in a sedimentary sequence.

- The rise of humans about 2.5 million years ago, the extinction of the dinosaurs 65.5 million years ago, the appearance of animals with hard shells starting about 540 million years ago, and other key transitions in life on Earth are usually dated in this way.

- The oldest known rocks, including basalt and other igneous formations, solidified from incandescent red-hot melts. These durable samples from the Moon and meteorites are typically poor in potassium, but fortunately they incorporate small amounts of uranium-238 and other radioactive isotopes. As soon as these molten rocks cool and harden, their radioactive elements are locked into place and begin to decay.

- The most ancient of these samples are several types of meteorites, in which slightly more than half of the original uranium has decayed to lead. These primordial space rocks, the leftovers from the formation of Earth and other planets, yield a maximum age of about 4.567 billion years for the nascent solar system. The oldest known Moon rocks, at about 4.46 billion years, also record these earliest formative events. Earth must have formed at about the same time, but our restless planet's original surface has now eroded away. Only a few uranium-rich, sand-sized grains of the hardy mineral zircon, some as old as 4.4 billion years, survive. Nevertheless, uranium-bearing rocks on every continent provide a detailed chronology of the early Earth.

- The oldest Earth rocks, at about 4 billion years, point to the early origins of continents. Rocks from almost 3.5 billion years ago host the oldest unambiguous fossils: primitive microbes and dome-like structures called stromatolites, which formed their rocky homes. Distinctive uranium-rich sedimentary formations and layered deposits of iron oxides from about 2.5 to 2.0 billion years ago document the gradual rise of atmospheric oxygen through photosynthesis.

Suggested Reading

Gee, *In Search of Deep Time.*

Gould, *Time's Arrow, Time's Cycle*.

Grotzinger, Jordan, Press, and Siever, *Understanding Earth*.

Hazen, *The Story of Earth*, Chapter 1, pp. 25–30.

McPhee, *Annals of the Former World*.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. How might you explain the concept of a billion to a child?

2. What are some of the lines of evidence that geologists use to demonstrate that Earth is more than 4.5 billion years old?

The Birth of the Solar System

Lecture 7

To understand Earth, we must place our planet in the context of the solar system, which consists of the myriad objects that are gravitationally bound to the Sun. Astronomers who study these objects have discovered several clues to solar system origins. The solar system formed from a giant, swirling cloud of dust and gas more than 4.5 billion years ago. The nebular hypothesis traces the history of the solar system through several evolutionary stages that ultimately led to the formation of the Sun, Earth, and other planets.

The Formation of Galaxies

- In terms of our surrounding real estate, at the largest scale, we are one small part of what is known as the Local Supercluster, or Virgo cluster, of galaxies. A galaxy is an immense collection of tens to hundreds of billions of stars. Galaxies can appear as fuzzy elliptical shapes, can have big spiral arms—which is probably the most familiar kind—or can adopt a more chaotic shape. The key is that all of the stars are gravitationally bound to the galaxy.

- The vast region of space called the Local Supercluster is more than 100 million light-years across, and it contains many thousands of galaxies. And our Local Supercluster is just one of thousands of known superclusters. Within the Local Supercluster, we are in the Local Group, which includes more than 50 galaxies spanning a diameter of about 10 million light-years.

- All of the Local Group galaxies are bound by gravity to a common center, which lies somewhere between our own big Milky Way spiral galaxy and our twin, the somewhat larger Andromeda galaxy, which is about 2 million light-years distant. Our Local Group is just one of perhaps 100 groups in the Local Supercluster.

The Milky Way's galactic center can be viewed from the Paranal Observatory in Chile.

- Our galactic home is the Milky Way galaxy, which is a large spiral galaxy with perhaps 400 billion stars. The age of the Milky Way, based on the ages of its oldest stars, is about 13.2 billion years—which is almost as old as the universe and suggests that stars and galaxies formed rather quickly after the big bang.

- Galaxies don't just form from stars; they are the engines of new-star formation. As one generation of stars explodes or sheds its outer layers, it seeds space with the dust and gas that will become the next generation of stars.

- Scattered debris of old exploded stars are constantly subjected to the organizing force of gravity. Thus, remnants of former stellar generations inexorably seed new populations of stars by forming new nebulas—each a vast interstellar cloud of gas and dust that represents the wreckage of many prior stars. Each new nebula is more iron-rich than the last, and each is a little poorer in hydrogen than the previous population.

- For billions of years, this cycle has continued, as old stars produced new stars and slowly altered the composition of the cosmos. Countless billions of stars emerged in countless billions of galaxies. Nebulas abounded in our neighborhood of the Milky Way galaxy and became the breeding grounds for still more stars.

The Dawn of Our Solar System

- The nebular hypothesis was first outlined by the French mathematician and physicist Pierre-Simon Laplace, who described his theory in the bestselling book titled *The System of the World*, which was first published in French in 1796. Any theory of the origins of the solar system had to take into account the distinctive distribution of planets, plutoids, asteroids, and so forth.

- The key characteristics of the solar system that inform the nebular hypothesis are as follows.
    - The distribution of mass: 99.9 percent of the mass is concentrated in the Sun, with only about 0.1 percent in everything else—the planets, moons, asteroids, comets, and so forth.

    - The distribution of elements: The inner solar system is dominated by rocky planets with silicate minerals while the outer solar system is dominated by hydrogen, helium, and other volatile elements and compounds.

    - The distribution of angular momentum: Virtually all of the solar system's angular momentum is in the orbiting planets, mostly in Jupiter.

    - The orientation of planetary orbits and rotations: All orbits are in a plane with the same direction of orbiting, and the Sun and most planets rotate on their axes close to the same plane and in the same direction.

- According to Laplace's nebular hypothesis, a solar system begins as a nebula—a giant cloud of dust and gas—as a consequence of the competing phenomena of gravity, which pulls mass inward, and angular momentum, which keeps matter in orbit around a central mass.

- In the case of our nebula, the cloud was likely gigantic, perhaps a light-year across. The composition of our nebula was unremarkable—roughly 90 percent hydrogen, with various other elements. Later generations of stars have more of the heavier elements; our solar system may have been preceded by half a dozen or more cycles of exploding stars.

- Gravity gradually attracted the nebular dust and gas into an ever-denser, more compact cloud. This process of compaction, once started, accelerated as the mass became more concentrated, and the centralized force of gravity increased.

- Ever so slowly, the immense swirling mass of presolar gas and dust was drawn inward. Like a twirling ice skater, the big cloud rotated faster and faster as gravity pulled its wispy arms to the center. As it collapsed and spun faster, the cloud became denser and flattened into a disk with a growing central bulge—what was to become the Sun.

- Larger and larger grew that greedy, hydrogen-rich central ball. As it grew larger, its gravitational pull increased, so it became even more efficient at gobbling up the mass of the nebula. Ultimately, the Sun swallowed 99.9 percent of the giant cloud's mass, but most of the angular momentum remained in the outer reaches of the nebula.

- As the Sun grew, internal pressures and temperatures rose to the fusion point, triggering hydrogen fusion to make new helium nuclei, igniting the Sun. Every star is a balancing act between two competing forces: Gravity pulls inward, which causes the temperature and pressure to rise higher and higher, and then fusion reactions begin, adding more temperature and pressure and pushing outward.

- The ignition of the Sun marked the beginning of the solar system—an event now confidently dated at approximately 4.567 billion years ago. The Sun defines the solar system, which is simply the region of space containing everything: planets, moons, asteroids, comets, dust, gas, and any other debris that is gravitationally bound to the Sun.

- It took some tens of thousands of years for that nuclear energy to work its way outward to the Sun's surface, but when it did, a strong solar wind began to push outward from the Sun through the rest of the solar system.

- The heat and wind from the Sun stripped the inner planets of most of their hydrogen, helium, and other volatiles. That process left behind the four rocky terrestrial planets. Much farther out, it was cool enough for hydrogen and helium to condense into the four Jovian planets.

- The shared orbital direction and plane, as well as the similarity of the axial rotations of the Sun and most planets, is a relic of the original swirling nebula. Angular momentum is conserved, so the net rotation of the nebula is preserved to this day as the orbits and rotations of the planets.

Are There Other Solar Systems Like Ours?

- The nebular hypothesis of Pierre-Simon Laplace was embraced because it is simple, elegant, and it explains the major features that we observe today in our own solar system. Support for the nebular hypothesis comes from varied sources.

- First, one can use computer models that keep track of the evolution of a dust cloud under gravity. Surprisingly, under most conditions, you don't get one star. In most computer simulations, two stars end up forming a binary star system. This surprising result is a consequence of the amount of initial angular momentum. Faster-rotating clouds tend to spread out the mass into two lumps. This theory is borne out by observations as well.

- When only one star dominates a system, some calculations suggest that a pattern of planets like our own is quite probable. But computations must be tested by real-world observations. We are fortunate to be living in a time of unprecedented planetary discovery, thanks to the ongoing search for extrasolar planets, or exoplanets.

- Some of the first critical data came from the Hubble Space Telescope, which has produced dramatic images of what are believed to be dynamic star-forming regions in nearby space. Some Hubble photos show immense dust concentrations, with dramatic fingers of matter—as seen, for example, in the now-famous views of the Eagle Nebula.

- The Hubble Space Telescope has also captured photos of what appear to be stars surrounded by flattened disks of dust. These objects may be solar systems in their first million years of formation—when the star has ignited, when planetesimals are forming and colliding to make protoplanets.

- Another hot area of planetary research is the search for extrasolar planets. Powerful telescopes, both on land and in orbit, are providing amazing opportunities to detect the presence of planets orbiting relatively nearby stars in the Milky Way. It’s not yet possible to see most exoplanets directly in a telescope, but various telescope techniques reveal their presence.

- The technique that was used first to identify hundreds of planets beyond our Sun involves looking for a slight periodic wobble that’s caused when a star and one of its larger planets orbit around a common center. Among the most intriguing findings of this kind of exoplanet research is that many planetary systems are quite different from our own solar system.

Suggested Reading

Boss, *The Crowded Universe*.

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What astronomical evidence did Laplace use to develop the nebular hypothesis?

2. What modern telescopic evidence supports the nebular hypothesis?

The Early Solar System—Terrestrial Planets

Lecture 8

The search for extrasolar planets, or exoplanets, and the complementary efforts to model the origins of planetary systems have come a long way. Measurements of subtle wobbles in distant stars point to hundreds of extrasolar planets, including some that are quite unlike anything in our system—hot gas giants orbiting perilously close to their stars or planets in extremely elliptical orbits, for example. But these discoveries are being quickly eclipsed by the most ambitious and successful planet-finding effort in history: NASA's *Kepler* space telescope mission.

The *Kepler* Space Telescope

- *Kepler* is a 1.4-meter-diameter telescope which was launched in March of 2009. The first data were collected from a stable orbit around the Sun on May 12, 2009. The heart and soul of the *Kepler* mission is an array of 42 state-of-the-art electronic detectors, each of which has over 2.2 million pixels with amazing sensitivity—they're not unlike the kind of detector you might find in the best digital cameras.

- *Kepler*'s mission is conceptually beautiful and simple. The telescope always points in exactly the same direction, at a significant area of the night sky in the constellation Cygnus, about 11 degrees by 11 degrees square. The telescope has been accumulating data on this region by taking exposures for 30 minutes at a time: 48 images every day, day after day, week after week, for years.

- In the process, astronomers have collected extremely accurate data on the brightness of more than 100,000 different stars. Those data are a gold mine for understanding how stars operate and behave—their variability over time, for example, and the statistical distribution of different kinds of stars: big and small, young and old. There's never been anything like the *Kepler* mission's database.

NASA's *Kepler* telescope was specifically designed to detect extrasolar planets.

- Thanks to *Kepler*, we are learning details about planets many light-years away that we didn't even know about—planets in our own solar system—until relatively recently. *Kepler* is discovering thousands and thousands of planets. There are so many planets that we can do statistical analyses and get a sense of the entire sweep of what's out there. In addition, there are hundreds of planetary systems emerging from *Kepler* data as well—many systems with two, three, or more planets.

- The preliminary statistics from the thousands of planets already discovered suggest that perhaps 1 in 10 stars will host a planet the size of Earth or larger in orbits closer to their star than Earth is to the Sun. This extrapolation has to take into account the fact that most planetary systems appear to be planar, like our solar system, and that most of those planes will have orientations that are not edge-on to us. So *Kepler* will only detect a small fraction of all the planetary systems in its field of view.

- The implication of *Kepler*'s historic mission of discovery is that planets are a pervasive characteristic of the cosmos. As many as half of all sunlike stars may have planets, and our Milky Way galaxy alone may hold more than 100 billion planets. A significant proportion of those planets may be in the habitable zones, like Earth—with liquid water, the elements of life, and a rich storehouse of rocks and minerals. The story of Earth is unique to us, but it may be a story that has been repeated many times elsewhere in the cosmos.

- *Kepler* is not the final word in the search for extrasolar planets. Ultimately, we'd like to be able to take pictures of these distant worlds—to see if they have oceans and continents; clouds; or possible signs of life, such as an atmosphere rich in oxygen. A new generation of space-based and ground-based telescopes, now in the planning stage, is being designed specifically to achieve that dream: to image individual planets orbiting nearby stars.

Mercury, Venus, Earth, and Mars

- There are eight planets that we can study in much greater detail—the planets that make our solar system. Each planet is different, with its own distinctive characteristics and its own mysteries. But there are also important common themes that reveal critical aspects of Earth's history.

- The four planets closest to the Sun—Mercury, Venus, Earth, and Mars—are all relatively small, rocky worlds. The elements silicon, oxygen, magnesium, and iron, with significant amounts of calcium and aluminum, characterize their compositions. Those elements all appear in the ur-minerals, and they are among the most abundant elements produced by fusion reactions in big stars.

- The prevailing idea is that when the Sun ignited with nuclear fusion reactions, it began to blast a solar wind out past the planets. The regions closer to the Sun were naturally a lot hotter, and most of the hydrogen and other gases were stripped off and blown out to colder regions of space. What were left behind were four rocky terrestrial planets.

- The innermost planet, Mercury, is the smallest of the eight major planets and the one that is most desolate and forbidding. Its small size and its proximity to the Sun have made Mercury extremely difficult to observe with Earth-based telescopes, but we're now getting an amazing close-up view with NASA's spacecraft *Messenger*, which is in orbit around the planet.

- Mercury turns out to be distinctive in a few ways. For one thing, its short orbit of 88 days is quite elliptical; it gets as close as 46 million kilometers to the Sun and as far away as 70 million kilometers. In spite of the very short year—less than three Earth months—the Mercurian day is very long: 176 days, or exactly twice the year on Mercury. One aspect of Earth that makes it habitable is the length of day, which is neither too long (as in the case of Mercury) nor too short (as in the case of Jupiter).

- Dramatic photographs from *Messenger* reveal a surface that is heavily cratered but also with possible regions of relatively recent volcanic activity. There's virtually no atmosphere on Mercury, so there's no erosion to speak of; old landforms persist for a long time. Mercury is very hot and very dry, with the exception of the polar regions. It is perhaps the most inhospitable world in the solar system for a living being.

- Venus is Earth's closest planetary neighbor, both in its distance and in its size. The nearly circular orbit of Venus has an average distance of about 108 million kilometers from the Sun. It orbits the Sun every 225 Earth days, so a year on Venus is about two-thirds of Earth's year.

- Venus has a very slow retrograde rotation about its axis—that is, it rotates the "wrong" way compared to the Sun and most other planets. On Venus, the Sun rises in the west, sets in the east, and rises again once every 243 days. Venus is even more extreme than Mercury. The Venusian day lasts almost eight Earth months.

- The most important aspect of Venus in the context of comparisons with Earth is its thick atmosphere composed primarily of clouds of carbon dioxide and nitrogen. The surface pressure on Venus is about 95 times that of Earth. In addition, all the carbon dioxide has produced what might be called a runaway greenhouse effect. Carbon dioxide efficiently traps the Sun's radiant energy, so temperatures build up unmercifully. Daytime temperatures on Venus reach about 490 degrees.

- The surface of Venus is effectively hidden from view by the thick cloud cover, but the *Pioneer Venus* spacecraft was able to map the surface in detail using radar. Scientists discovered a surface with big mountain ranges, cratered plains, and volcanoes. So Venus must still be a very active planet—which is another point that reflects on Earth and its evolution: Bigger planets hold more internal heat, and internal heat can drive a lot of interesting geology.

- Mars is by far the most intensively studied planetary neighbor for one simple reason: Of all the planets, Mars boasts the strong possibility that it once had abundant surface water, and if it had water, then it might possibly have had, or might still have, life.

- Mars is half the diameter of Earth, and it has just over a tenth of Earth's mass. It has an elliptical orbit that averages about 1.5 times the Earth-Sun distance. Depending on the relative positions in their orbits, Earth and Mars can be as close as 60 million kilometers and as far away as 400 million kilometers.

- A year on Mars lasts almost two Earth years because it's farther from the Sun, but the day on Mars is, quite coincidentally, close to the length of an Earth day—about 25 hours. Mars has an intriguing similarity to Earth in that its axis is tilted about 25 degrees to the plane of orbit around the Sun—as compared to Earth's 23.5-degree tilt—so Mars has seasons just like Earth.

- Unlike Mercury and Venus, Mars has two small, irregularly shaped moons, just tens of kilometers across. These moons, called Phobos and Deimos, look a lot like they could be captured asteroids. Unlike Earth with its one big moon, Mars has nothing to keep the planet from wobbling on its axis. That means that over many hundreds of thousands of years, Mars goes from rotating almost perpendicular to its orbit (just like Mercury) to being tilted more than 40 degrees. That extreme variation, coupled with Mars's relatively elliptical orbit, results in much greater climate fluctuations than on Earth.

- Mars has prominent surface features that are clearly visible from Earth. Most obvious are the polar ice caps, which wax and wane with the 686-day Martian year. The planet also shows brighter and darker reddish areas, with what appeared to some 19th-century astronomers as linear features.

- Thanks to a host of orbiting spacecraft, from *Mariner* in the 1960s to orbiters that are operating today, we have detailed photos of almost the entire Martian surface. The landscape is amazing, with water-carved valleys and ravines, cratered plains, and huge volcanoes—the largest known volcanoes anywhere in the solar system. These observations suggest that Mars once had lots of water, possibly even a large ocean, and perhaps a thicker atmosphere as well.

- Certainly, Mars is the first planet we would consider for human expedition. Venus is much too hot and hostile. Mars has water and sunlight and the prospect of setting up a sustainable base camp.

Suggested Reading

Boss, *The Crowded Universe*.

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

Lemonick, "The Dawn of Distant Skies."

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What are exoplanets, and how are they discovered?

2. What are the four terrestrial planets of our solar system, and what features do they have in common?

Hints from the Gas Giants and Their Moons

Lecture 9

The solar system is an incredibly rich and varied place, with innumerable objects that provide hints about the origins and evolution of individual planets and moons as well as systems of gravitationally linked bodies. The inner solar system is dominated by the relatively dense planets—Mercury, Venus, Earth, and Mars—with surfaces of silicate rocks and minerals. By contrast, the outer four planets—Jupiter, Saturn, Uranus, and Neptune—are gas giants made primarily of hydrogen and helium, but with a lot of other interesting molecules thrown in. The diverse inventory of moons provides even more perspective on common themes in the behavior of terrestrial worlds and on what makes Earth so special.

The Jovian Planets

- The accepted idea is that 4.567 billion years ago, when the Sun ignited and swept solar winds out past the planets, hydrogen, helium, and other gases were stripped off and blown outward, far out into colder regions of space where the gases could condense into liquids or ice. As a consequence, the character of the solar system changes radically out beyond the asteroid belt—farther out than about 750 million kilometers from the Sun. This is the colder, darker domain of the gas giant, or Jovian, planets.

- Jupiter is by far the largest of the Jovian planets. Like all of the gas giants, it's basically a ball of hydrogen and helium, probably with an unseen rocky core that may be about the same mass as one of the inner terrestrial planets. Even so, that rocky center represents at most only a few percent of the total mass. Jupiter is about 2.5 times as massive as all the other planets combined. Because it's so massive and so far from the Sun, Jupiter holds a significant fraction of the angular momentum of the solar system.

- One way to think of a gas giant planet like Jupiter is a failed attempt to make a star. The interior of Jupiter and other gas giants is hot and compressed, and a lot of gravitational potential energy is converted to heat as the planet forms, but there's not nearly enough temperature and pressure to make fusion reactions go.

- Jupiter, at five times the Earth-Sun distance, orbits the Sun every 12 Earth years. Even so, the Jupiter day is short—only about 10 hours—because Jupiter rotates on its axis really quickly. That rapid rotation causes the planet to bulge about its middle—a phenomenon readily visible in photographs of the planet—and it causes extreme weather as well.

- The fast rotation breaks Jupiter's thick atmosphere into fast-moving bands and swirls, which are easily seen as a sequence of lighter and darker stripes parallel to the equator. Jupiter experiences extreme wind shearing that creates immense vortices—cyclones many times the diameter of Earth that can last for many years and with sustained winds of hundreds of kilometers per hour.

- Exploration of gas giant planets faces challenges that don't apply to the closer terrestrial planets, including the fact that NASA can't land on Jupiter because there's no real surface. In spite of the difficulties in any close approach to Jupiter, we have had some spectacular space probes visit the big planet—notably the *Voyager*, *Galileo*, and *Ulysses* missions that have returned gorgeous photos and reams of data on Jupiter and its vicinity.

- One of the most amazing aspects of Jupiter, and one that has importance for understanding Earth's origins and evolution, is the wealth of moons. In fact, astronomers have identified at least 64 moons orbiting Jupiter, ranging in size from big rocks only a kilometer or two in diameter; to irregular asteroid objects up to 200 kilometers in diameter; to several round worlds ranging in size up to the planetlike Ganymede, which is more than 5,200 kilometers in diameter—significantly bigger than the planet Mercury.

- The smaller "irregular" moons (that is, moons not spherical in shape) account for most of this big number—56 in all, and the number keeps growing as more little ones are found. The orbits of these small moons tend to be quite elliptical in many cases and in a hodgepodge of directions. By contrast, Jupiter's eight "regular" (spherical) moons have almost circular orbits, they all lie in a single orbital plane that matches Jupiter's rotation plane, and the directions of orbit are the same as Jupiter's rotation.

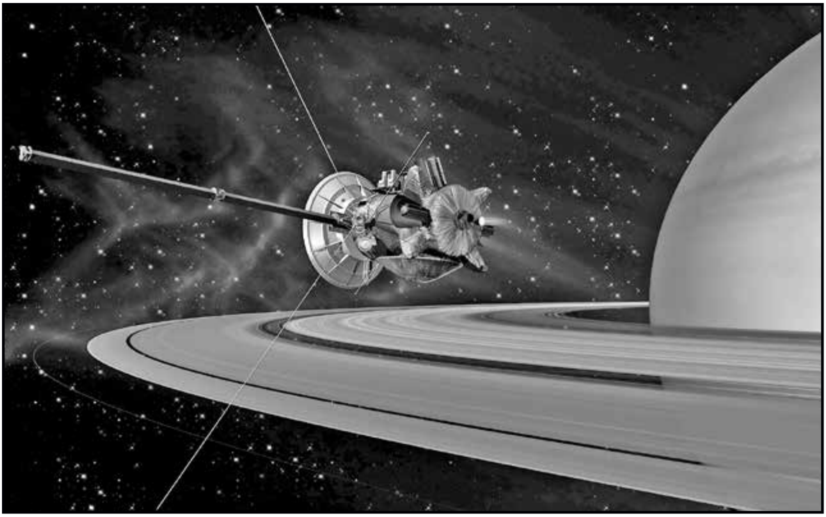
- The four largest moons of Jupiter, called the Galilean moons because Galileo first saw them in his telescope early in the 17th century, are arguably the most interesting. Io, Europa, Ganymede, and Callisto are large enough to see with a good pair of binoculars. Each moon has been studied by space probes in close-approach flybys, so we have a lot of data, including close-up photographs and lots of physical and chemical information as well.

Saturn, Uranus, and Neptune

- Saturn, the ringed planet, is a majestic and beautiful sight. It's only about a third the mass of Jupiter, but it's quite similar in composition and character. Like Jupiter, Saturn is made primarily of hydrogen and helium. And, like Jupiter, it also has violent weather and has lots of moons.

- Saturn is far away, almost 10 times farther from the Sun than Earth, and it takes almost 30 years to complete one orbit. So unlike the other planets we've met, each of which tends to move significantly in the night sky from year to year, if not month to month, Saturn wanders the sky at a leisurely pace. Like Jupiter, Saturn's 10-hour day causes an equatorial bulge and severe weather, with the same extreme atmospheric shearing and intense cyclonic storms.

- Saturn's most distinctive feature, visible in even a modest telescope, is the magnificent complex of rings. What appears at first to be a continuous broad ring is actually a complex system of ringlets with a very dynamic set of shepherding moons and other complex gravitational interactions. The bright rings are composed primarily of tiny ice crystals in a surprisingly thin, flat sheet.



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The *Cassini-Huygens* space probe was the result of a joint U.S.-European desire to explore Saturn.

- Astronomers have identified more than 60 Saturnian moons larger than 1 kilometer in diameter. Most of these are irregular, asteroid-like bodies, but 24 have been classified as "regular" satellites—that is, they have near-circular orbits in Saturn's plane of rotation.

- By far the most interesting moon, indeed one of the most interesting places in the solar system, is the largest moon, Titan. This planet-sized world has a thick atmosphere—the only moon with that feature—and its own uniquely dynamic surface. It's the only body other than Earth with lakes and rivers at its surface. Titan is bigger than Mercury, though only half as massive, because it's about half ice, so much less dense than silicate rock.

- The *Cassini-Huygens* space probe landed on Titan and took amazing photographs during its descent of a complex system of lakes and rivers, probably filled with liquid hydrocarbons, because the temperatures at the surface are far below the freezing point of water. *Cassini-Huygens* confirmed that Titan has a substantial nitrogen atmosphere, with a surface pressure estimated to be about 1.5 atmospheres.

- Titan's atmosphere also features fascinating orange smog that seems to be made of carbon-based compounds—which is the kind of chemistry that must have preceded life's origin on Earth. So Titan is another place where planetary scientists want to visit in their search for life on other worlds.

- The outer two major planets, Uranus and Neptune, are not visible without the aid of a good telescope. Uranus was discovered in 1781 by the celebrated English astronomer William Herschel. He and other astronomers suspected the existence of this seventh planet because of orbital irregularities in Saturn. As Isaac Newton stated, no object in the solar system can change its path without a force, so the deviation of Saturn from its predicted orbit implied some other big, as-yet-unseen source of gravity.

- Uranus turns out to be at about 19 times the Earth-Sun distance, with an orbital period of 84 years. The planet is more than 4 times the diameter of Earth and 15 times more massive.

- *Voyager 2* revealed that the Uranian day is about 17 hours long and that the rotation axis of Uranus is on its side relative to the other planets. Uranus actually sort of rolls along in its orbit, so unlike other planets, each pole of Uranus receives direct sunlight for 42 years at a time.

- Like the other gas giants, Uranus is composed mainly of light elements, but it has a lot more ices, including methane and ammonia, as well. Uranus has five major moons, all of which appear frozen and inactive, as well as more than 20 smaller moons and a complex system of rings.

- The discovery of Neptune, the most distant planet, was a great triumph of Isaac Newton's model of gravitation and forces. Uranus was discovered because the orbit of Saturn appeared to be perturbed slightly, and astronomers had noticed that the orbit of Uranus was itself perturbed slightly, so the existence and approximate location of the eighth planet was deduced independently by astronomers in England and France. Then, in 1846, the planet was observed by French and German astronomers.

- Neptune is very far away—30 times the Earth-Sun distance, so it takes light about four hours to travel from the Sun to Neptune. It orbits the Sun once every 165 Earth years. Neptune is difficult to study in Earth-based telescopes because it's so faint and far away, but we got a pretty good view in 1989 from the *Voyager 2* flyby. That's when we got the best photographs of the beautiful blue planet.

- Neptune's atmosphere, consisting of hydrogen and helium laced with methane and ammonia, is a frigid 60 degrees above absolute zero. The planet rotates quickly—once every 16 hours—which drives dynamic weather patterns. It has big, long-lasting cyclonic storms like those seen on Jupiter and Saturn.

- Like all the other gas giant planets, Neptune has lots of moons—13 moons at last count—and a ring complex as well. The largest and most interesting moon is Triton, 2,700 kilometers in diameter with its own methane-rich atmosphere.

- Triton is a real anomaly: It has an ice-plus-rock composition that is quite different from Neptune, and it's also orbiting around Neptune in a retrograde orbit (the "wrong" way). These characteristics suggest that Triton is a captured plutoid; it's just slightly larger than Pluto, and it doesn't appear to be a moon formed in place like Jupiter's Galilean moons. That's a very tricky scenario—for a planet to capture a big moon.

Suggested Reading

Boss, *The Crowded Universe*.

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What are the four gas giant planets of our solar system, and what do they have in common?

2. What are the Galilean moons, and what are their distinctive characteristics?

Meteorites—The Oldest Objects You Can Hold

Lecture 10

Meteorites, remarkably diverse rocks that fall from space, hold the most important clues to the earliest stages of Earth's formation and history. A century ago, collections were dominated by iron metal meteorites, which are very different from ordinary rocks. New finds in Antarctica and North Africa are providing a much better picture of the range of meteorites, as well as their origins. The most primitive meteorites, called chondrites, point to a time when the Sun was just beginning to emit strong pulses of radiation.

Our Planet: Earth

- Earth is, in many respects, a lot like the other planets of the solar system. For one thing, Earth orbits in the same plane and in the same direction as the other planets. We also know from radiometric dating of various rocks and minerals that Earth must have formed at very close to the same time as the other planets. Earth is made of the same chemical elements—and, for the most part, the same isotopes—as most of the other objects in the solar system. Of course, Earth obeys the same physical laws that hold sway throughout the cosmos.

- But Earth is also unique in important ways. As far as we can tell, Earth is the only body with extensive deposits of liquid water on its surface. Virtually all theories of life's origin point to the central chemical role that water must have played. Water may be the universal medium for all life—at least life as we know it—so in that key aspect, Earth is a pretty special place.

- The Earth-Sun distance is about 150 million kilometers, which is close enough to maintain liquid water over most of the surface most of the time, but it's not so close as to boil water away. So that's a pretty critical distance.

- The 24-hour rotation period is also important. That length of day is short enough to prevent extreme temperature contrasts between night and day—like the contrasts that occur on Mercury or Venus—but it's slow enough to prevent extremely violent weather patterns of the kind that exist on Jupiter and Saturn.

- Earth has a diameter of almost 13,000 kilometers, which is large and massive enough to have a strong gravitational field, and that field prevents fast-moving water vapor molecules from escaping the planet. If Earth had been as small as Mars or the Moon, Earth would be a dry world. Instead, Earth has held onto most of its water throughout its 4.5-billion-year history.

The Discovery and Study of Meteorites

- Details of the dramatic events that formed Earth from the solar nebula are revealed by studies of the amazingly diverse varieties of meteorites, which are rocks that have fallen from space. The concept that pieces of rock bombard us from space was not taken seriously by the scientific establishment until rather recently. Until about two centuries ago, there was little in the way of serious observation or reproducible scientific evidence that could be used to confirm the reality of meteorites, much less explain where they come from.

- Two centuries and countless thousands of meteorite finds later, that point of view is no longer tenable. As meteorite experts examine more ground, and as the voracious meteorite-collector community vies for the rarest varieties, both public and private collections across the globe have swelled.

- The history of those collections is quite revealing about the varied ways that meteorites have been found, described, and valued. For a long time, meteorite collections were biased in their holdings of distinctive iron-nickel metal meteorites. These dense objects often feature black crusts and weirdly sculpted shapes that cause them to stand out in a field or streambed. In addition, iron meteorites are magnetic, so it's fairly easy to identify and separate them from ordinary stones.

- That bias was largely corrected by the 1969 discovery by Japanese scientists of thousands of untouched meteorites lying on pristine Antarctic ice fields. The Antarctic continent features vast, flat plains surfaced by ancient blue ice. These are ice deserts—places where it never snows and the where hard, frozen surface slowly sublimes away for many thousands of years. When a rock falls from space, it just lays there, and because the surface is white, any dark object is obvious.

- Fortunately, there are rigorous international treaties that ban any commercial exploitation of Antarctica. Those restrictions, plus the fact that access to the remote ice fields is extremely dangerous and limited, ensure that these irreplaceable extraterrestrial treasures are going to be preserved for scientific study.

- Almost as rich in meteorites, though much less amenable to systematic recovery and sterile preservation, are the great sandy deserts of Earth, including those in Australia; the American Southwest; the Arabian Peninsula; and, most productively, the vast, sandy Sahara desert. Meteorites can be worth a lot of money, so word has spread widely among the desert-crossing nomads.

- Sadly, unlike the frozen meteorites from Antarctica, most of the desert specimens will never make it into public research collections. Two reasons conspire against Saharan finds. First and foremost is the intense and growing competition from the passionate community of amateur collectors. That collecting community is dominated by a few very wealthy aficionados, and it's being fueled by the readily available Saharan finds. In addition, most specimens collected in the desert are essentially undocumented and poorly handled.

- In spite of those limitations, the sand deserts of the Sahara and the ice deserts of Antarctica benefit the study of meteorites in a critical way that goes beyond just finding lots of new specimens. These virgin landscapes are essentially unbiased. They reveal the natural distribution of all kinds of meteorites that fall from space and, thus, provide unrivaled clues to the nature of the matter that formed the early solar system, including the rocks and minerals that formed our own planet.

- In the old days, iron meteorites dominated collections because they were the only meteorites that stood out on the ground. Today, we have a very different perspective of the solar system's raw materials.

© NASA.

Iron-nickel metal meteorites were the most common type of meteorite collected for a long time.

The Earliest Solar System

- The great majority of meteorite finds are ordinary chondrites, which represent almost 9 out of every 10 finds. By contrast, only about 1 in 20 is an iron meteorite. Most of the other meteorite finds encompass a diverse and, therefore, most revealing group of achondrites. These are rocky remnants of a turbulent coalescing nebula that speak of a time when chondrites clumped together into larger and larger bodies. Those so-called planetesimals experienced a sequence of dramatic changes on the way to becoming planets.

- Meteorites offer hints to the Sun's origin in the form of those most common and ancient meteorites, the 4.56-billion-year-old chondrites—which date from a time before there were any planets or moons, to a time when the Sun's nuclear fusion reactor was just starting to turn on. That earliest period of the solar system is called the T Tauri phase, after a young star system in the constellation Taurus where a similar process is now underway.

- For almost all of its 4.5-billion-year existence, the Sun has been a main sequence star, which is a star that is steadily consuming hydrogen in its core, steadily producing helium in a sequence of nuclear fusion reactions. That's the normal state for most stars most of the time, and astronomical observations reveal that the great majority of stars in the night sky are of this type. The Sun will remain in this state for billions of years to come.

- Main sequence stars don't all look exactly the same, because their temperatures can vary so much. Hydrogen-burning stars much smaller than the Sun appear reddish or even reddish-brown—the so-called red dwarf and brown dwarf stars, respectively. Hydrogen-burning stars much larger than the Sun are white hot, or even blue-white, with surface temperatures much higher than the Sun. But all of these stars share the characteristic of hydrostatic equilibrium—that is, the force of gravity pulling inward is balanced by the force of hot hydrogen undergoing nuclear reactions pushing outward.

- Before the Sun achieved its present stable state, it had to go through a violent birth—that's the T Tauri phase. Fascinating, young T Tauri stars triggered the first stages of planetary origins. There is a sequence of events leading to every sunlike star.

- As the protostar that became the Sun collapsed, it emitted huge amounts of radiation, including a big range of the electromagnetic spectrum—radio waves, microwaves, infrared, visible light, ultraviolet radiation, all the way up to X-rays. At this stage, the young star developed a powerful magnetic field, a result of the swirling charged particles deep inside the contracting sphere.

- There were also extremely powerful solar winds of charged particles. Those winds blasted hot plasma radially outward into the disk of gas and dust surrounding the evolving Sun. The solar wind also had an important effect on angular momentum—by blasting a significant amount of mass outward, it slowed the rotation of the central star and transferred most of the system's angular momentum to the region where planets would form.

- This picture of the earliest solar system is based in part on astrophysical theory. The physics of gravity, atomic and nuclear interactions, electromagnetic phenomena, and fluid dynamics in a turbulent cloud are all well understood, so it's possible to make very accurate calculations of what happens in dynamic star-forming systems. But our understanding of the birth and early lives of sunlike stars is also informed by lots of direct telescopic observations. The idea that the Sun has to go through a sequence of stages before achieving stability is well established, both theoretically and observationally.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

McCoy, "Mineralogical Evolution of Meteorites."

Papike, *Planetary Materials*.

Weisberg, McCoy, and Krot, "Systematics and Evolution of Meteorite Classification."

Questions to Consider

1. What is a meteorite, and where does it come from?

2. Why is Antarctica a good place to find meteorites?

Mineral Evolution, Go! Chondrite Meteorites

Lecture 11

Chondrite meteorites are the most primitive objects from our solar system. Their distinctive structure and modest mineralogical diversity of only about 60 different mineral species tells of a time when the Sun first ignited and bathed the nebula with pulses of intense heat and radiation. The resulting frozen droplets of rock—the chondrules—are their most distinctive characteristic. In this lecture, you will learn how the rich mineralogy of meteorites reveals the first stages of mineral evolution beyond the dozen or so ur-minerals.

The Classification of Meteorites

- The classification of meteorites is a topic that has generated a lot of discussion and controversy, and there's no single, universally accepted system. For most of the last two centuries, meteorite classification was rather ad hoc and was based on three broad groups: stony meteorites that look more or less like ordinary rocks; iron meteorites that are made primarily of iron metal, usually with some nickel thrown into the mix; and stony-iron meteorites, with obvious mixtures of iron metal and silicate minerals.

- Those categories still prove useful as a first-cut grouping, but the terms "stony meteorite" or "iron meteorite" aren't very helpful in a generic sense. They don't indicate where or when or how a meteorite formed. So a rather complicated subgroup classification of meteorites focuses on more subtle details of bulk chemical composition, mineralogy, and texture.

- Stony meteorites are commonly divided into two big subgroups. First come the chondrites, which are distinguished by their numerous droplet-like chondrules. Detailed studies of these distinctive space rocks reveal that many chondrules were heated more than once—some were even melted multiple times—as repeated pulses of radiation transformed the regions closest to the

Sun. Countless chondrules clumped together, cemented by finer-grained presolar dust and mineral fragments. Taken together, these ancient chondrite meteorites provide our best view of the brief window in time when the Sun had just been born, but planets had yet to form.

- A second varied class of stony meteorites, collectively dubbed "achondrites," lacks the droplet-like chondrules of the oldest meteorites and, thus, represents a time when the earliest materials of the solar system had been extensively reworked: melted, smashed, altered by hot water, and otherwise transformed. The diversity of the achondritic meteorites—some with nuggets of shiny metal, some like chunks of blackened rock, some as fine-grained as glass, and others with lustrous crystals an inch across—is astonishing, and important discoveries of new varieties are still being made in some of Earth's most remote regions.

- As for the two other main groups, the iron meteorites have long been divided into subgroups based on the structure and composition of the metal—for example, the amount of nickel. Hexahedrites, octahedrites, and ataxites are three important types of iron meteorites in order of increasing nickel content. Stony iron meteorites, the rarest of the three main groups, are further subdivided into pallasites and mesosiderites, which differ in the textures of the metal-silicate mixture.

- Irons, stony irons, and achondrites are all remnants of small bodies called planetesimals, or miniature planets, that formed in the early solar system. They grew large enough to have a metal core, and then they were blasted apart in subsequent collisions.

- Chondrites are both the most primitive and by far the most common meteorites. The classification of chondrites alone can become overwhelming, as there are about 20 main types and many subtypes, each of which is distinguished by its bulk composition, mineralogy, and texture.

- The two biggest groups of chondrites are the abundant ordinary chondrites, which account for about 87 percent of all meteorites, and the carbon-rich carbonaceous chondrites, which represent slightly less than 5 percent of meteorites. The uncommon, but highly significant, enstatite chondrites account for less than 2 percent of all meteorites.

The Anatomy of Chondrites

- Chondrites incorporate four principal components. First and foremost are the tiny frozen droplets called chondrules. Depending on the meteorite type, these objects can range from a couple of hundredths of a millimeter to about 10 millimeters in diameter. The word "chondrule" comes from the ancient Greek word for "grain," and many chondrules are round and about the size of a grain of barley.

- There's also a huge range in abundance: Many ordinary chondrites approach 80 volume percent chondrules, whereas one important type of carbon-rich chondrite, the CI chondrites, have been so altered by water that they don't have any chondrules at all.

- The mineralogy of chondrules is very revealing. The very first step in the reworking of the presolar dust occurred when the Sun's T Tauri phase began. Intense heat with temperatures approaching 2000 degrees melted grains of dust, which became sticky and began to collect into larger and larger droplets, not unlike the way that raindrops form from lots of water molecules. These droplets of molten minerals are what are preserved today as the chondrules.

- Several of the dominant chemical elements in presolar dust grains—oxygen, magnesium, silicon, calcium, and aluminum—are also predominant in chondrules. But these elements are refined, concentrated, and reworked at somewhat lower temperatures to give a somewhat different assemblage of minerals.

- The most common chondrule phases are two magnesium silicates: forsterite (an olivine group mineral) and enstatite (one of the pyroxene group). Both of those silicates were among the original dozen ur-minerals. But there are new, lower-temperature minerals as well. The calcium aluminum silicate called anorthite ($CaAl_2Si_2O_8$) appears for the first time. Anorthite is a member of the feldspar group, which collectively are the most abundant minerals in Earth's crust, so this is an important development.

- The iron sulfide troilite (FeS), the earliest mineral to form with sulfur, also appears. And the first phosphorus and chromium minerals occur in chondrules. These elements are present in presolar grains, but their concentrations were too low, and the temperatures too high, to crystallize separate sulfur, phosphorus, or chromium minerals in the envelopes of stars. In fact, about two dozen different minerals have been identified in chondrules, most of which occur as extremely tiny crystals only a hundredth or a thousandth of a millimeter across.

- The mineralogy and textures of chondrules point to episodes of very rapid heating, perhaps within a minute or less, to temperatures between 1500 and 1900 degrees Celsius. Then, cooling of the droplets occurred in no more than a few hours. These time and temperature relationships follow from the size and complex intergrowths of crystals, primarily olivine and/or pyroxene crystals, in the chondrules. There's also abundant evidence that some chondrules have been reheated, some several times.

- Chondrules are old, but they aren't the oldest components of chondrites. The calcium-aluminum-rich inclusions (CAIs) are rounded objects ranging in size from less than a millimeter to about a centimeter. It's easy to see CAIs in some meteorites, because they're relatively light colored compared to chondrules.

- Like chondrules, CAIs also represent cooled droplets of silicate minerals, but these formed earlier and at temperatures even greater than the chondrules. Radiometric dating places their age at 4.567 billion years. As the very first new materials processed and refined by the solar nebula, the CAIs define the date of the solar system's birth.

- These inclusions from the birth of our solar system contain several of the ur-minerals—for example, the calcium aluminum oxide hibonite, the magnesium aluminum oxide spinel, and the magnesium silicates forsterite and enstatite (both of which are common in the chondrules as well). Anorthite is also a common constituent, here as in chondrules, but there is also another calcium aluminum silicate called melilite, and there's a calcium titanium mineral called perovskite.

The Murchison meteorite is the most intensively studied CM chondrite.

- In addition, there are 20 or more minor phases that form microcrystals, some too small to see in a light microscope. These are all relatively high-temperature minerals, with freezing points above 1500 degrees Celsius. The mineralogy of the solar system was beginning to diversify beyond the initial dozen kinds of crystals.

- In addition to chondrules and CAIs, chondrite meteorites also typically have a host of mineral phases that are opaque to visible light. These opaque minerals are significant and are considered separately because one of the standard ways to study meteorites is to cut and polish a very thin section, no more than a few hundredths of an inch thick, and look at it with transmitted light. Most of the minerals—almost all of the oxides and silicates, for example—are partially transparent to light, so you can see grain sizes and textures easily.

- The rounded chondrules and CAIs really stand out, but you can't see through the opaque phases. You have to identify those phases using reflected light techniques. Various naturally alloys of iron-nickel metal are most abundant, along with a variety of metal sulfide minerals, iron oxides, and some exotic phases as well—about 20 opaque minerals altogether.

- Chondrites typically have a very fine-grained matrix made of interlocking crystals that are barely visible even in a powerful light microscope. Many of the same minerals found in the chondrules are also found in this fine-grained matrix—oxides, silicates, sulfides, and metal particles are all common.

- Meteorite experts have tallied 60 different mineral species in all the different kinds of chondrite meteorites. These 60 minerals, which include all of the dozen ur-minerals, define the first stage of Earth's mineral evolution.

Suggested Reading

Brearley and Jones, "Chondritic Meteorites."

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

McCoy, "Mineralogical Evolution of Meteorites."

Weisberg, McCoy, and Krot, "Systematics and Evolution of Meteorite Classification."

Questions to Consider

1. What is a chondrite meteorite? What is a chondrule?

2. What is the evidence that chondrite meteorites formed very early in the history of the solar system?

Meteorite Types and Planetesimals

Lecture 12

The central question of mineral evolution is how the original dozen ur-minerals were processed and reworked to begin yielding the many thousands of minerals found on Earth today. The answer lies in processes that selected and concentrated different chemical elements and situated those elements in different regimes of temperature and pressure. In this lecture, you will take a significant step in that path of mineral evolution—the second stage of mineral evolution, as revealed in the amazingly diverse meteorites known as achondrites. It's in the transition from chondrites to achondrites that mineral diversity begins to take off.

Achondrite Meteorites

- Chondrules and other material, clumped together by gravity, formed the chondrite meteorites, and chondrites in turn formed larger and larger bodies called planetesimals. As planetesimals grew to hundreds of kilometers in diameter, the primary chondrite minerals were subjected to repeated cycles of alteration by water, heating, melting, and impacts with other bodies—processes that eventually led to the second class of meteorites, the achondrites. These varied objects hold more than 250 different minerals, which represent the starting point for any planet or moon in our solar system.

- The origins of all the chemical richness of Earth were locked into those meteorites, but most elements were impossibly dilute—a few atoms per billion, or less. Barring some remarkably efficient concentration mechanisms, the chances of most chemical elements clumping together to form separate, distinct minerals are vanishingly small. The mineral evolution story, therefore, is a 4.5-billion-year narrative of successive stages of element selection and concentration through diverse physical, chemical, and biological processes. That story begins with the achondrites.

- Planets form by the clumping together of matter into larger and larger objects—a phenomenon called accretion. Accretion in the solar nebula took place by two very different physical processes.

- At first, clumpiness arose from the surface properties of small particles—the kind of electrostatic attraction that causes dust bunnies. This kind of accumulation, called coagulation, dominates for nebular objects up to sizes of several centimeters in diameter. Chondrules and CAIs thus mixed with smaller dust grains in those early coagulates in masses that must have been sort of fluffy, loosely consolidated, and irregularly shaped.

- Electrostatic attraction is ineffective for objects larger than a meter or so, so another mechanism of accretion had to take over. Astronomers assume that gravity is the culprit, but models suggest that gravity doesn't take over in a big way until objects are about a kilometer across.

- One hypothesis for how accretion works for those meter-sized masses is that turbulence leads to local concentrations of coagulates and gravitational collapse—which is not unlike the way that the entire solar system was triggered by a gravitational instability in a giant molecular cloud. There's still work to be done to understand how lots of objects the size of a basketball turned into fewer objects the size of a small town.

- Once kilometer-sized objects had accreted, the story becomes much clearer. At some point in the early solar system, perhaps over the span of its first few millions of years, billions of these kilometer-scale planetesimals had formed. With a large population of large bodies, gravity could take over in what is known as runaway accretion. Larger and larger the planetesimals grew, up to perhaps 1,000 kilometers in diameter. Within 100,000 years, gravity had clumped most of those smaller planetesimals into protoplanets, which are objects large enough that they pull themselves into a spherical shape by gravity.

- As millions of planetesimals merged together through this chaotic process of accretion, they experienced new ways to diversify. As they grew to 100 kilometers or more in diameter, two complementary and more or less comparable sources of heat—the gravitational potential energy of many small objects smashing together, plus the nuclear energy of fast-decaying radioactive elements that were abundant in the early solar system—thermally altered minerals and eventually melted the planetesimal interiors.

- The next critical phase in the distillation of the solar system is called differentiation, which is the separation of a protoplanet into layers. Once a miniature planet was molten inside, density became a powerful driver of element separation. Dense iron and nickel metal separated from magnesium silicates to form, for the very first time, concentrically layered structures—metal cores and silicate mantles as well as a thin crust of even less dense material. New minerals invariably followed from this selection and concentration of elements.

- Pervasive internal heat and ubiquitous water further expanded the mineralogical repertoire inside these growing protoplanets. Heat led to the first molten rocks enriched in silicon, while water-rock interactions produced the first clay minerals. Mineralogical diversity was also enhanced through catastrophic hypersonic collisions between planetesimals, which added a suite of distinctively shocked and deformed minerals that can only form in the violent fractions of a second when impacts cause temperatures and pressures to soar. All of these new minerals would have remained inaccessible, locked inside the growing planetesimals and protoplanets, were it not for those increasingly violent impacts.

- The usual scenario was that smaller objects impacted bigger ones and were simply swallowed whole in a kind of cosmic rich-get-richer drama. Sometimes, however, when two big bodies of similar mass smashed together with sufficient force, the objects were blasted to smithereens—which is why there is such a diversity of non-chondritic meteorites.

- Most of the varied achondrite meteorites that are found on Earth today represent different parts of these destroyed miniature planets—core, mantle, and crust. Studying achondrites is thus something akin to a messy anatomy lesson from a cadaver that has exploded. It has taken meteorite experts a lot of time and patience and a growing inventory of planetary bits and pieces, but we're beginning to get a pretty clear picture of the original body.

- The dense metallic cores of planetesimals, which wound up as the distinctive class of iron metal meteorites, are the easiest to interpret. Because the irons are so durable and look so different from the surrounding rocks, they were once thought to be the most common type in existence. However, the unbiased sample of meteorites from Antarctic ice reveals that irons represent a modest five percent of everything on Earth that lands from space. Planetesimal cores must have been correspondingly small relative to their stony mantles.

Lunar and Martian Meteorites

- Lunar meteorites have been collected for more than a century, but they weren't recognized as such until 1982, when Smithsonian expert Brian Mason was handed a strange sample collected in the Allan Hills region of Antarctica the previous year. The meteorite's name is Allan Hills 81005.

- This type of meteorite had been overlooked because most lunar rocks look very much like other common types of meteorites—basalt, breccia, and the like. The lunar origins have to be confirmed by comparisons with the distinctive compositions of *Apollo* Moon rocks.

- Lunar meteorites are not only rare, but they're also typically small. In contrast to irons that can weigh many tons, the 150 or so confirmed lunar meteorites collectively weigh about 100 pounds. These rocks reach Earth following asteroid impacts on the Moon.

- Moon rocks don't stay in space for too long; measurements of space weathering ages suggest that most lunar meteorites were blasted into space less than 100,000 years ago. So far, these Moon rocks haven't dramatically changed the view of the Moon provided by the *Apollo* missions.

- Perhaps the most precious meteorites of all are the Martian meteorites. These rare objects, representing only about 1 in every 500 meteorites, are our only known samples from another planet.

- Experts had long recognized that some falls were different from most other meteorites, but the identification of the Martian origins had to await data from the *Viking* lander mission in the 1970s, which first determined the distinctive chemical and isotopic composition of the Mars atmosphere. In 1983, scientists analyzed small gas bubbles encased in minerals and found a similar chemical and isotopic signature.

- Almost all Martian meteorites are divided into three groups: shergotites, nakhlites, and chassignites. In fact, Martian meteorites are often collectively called "SNC" types. Shergotites are by far the most abundant—more than 80 percent of all Martian meteorites—and they are igneous rocks typical of terrestrial planets. Much rarer are the nakhlites, with about a dozen examples. Only two chassignites have been confirmed. These latter two groups are also igneous rocks with different mineralogies.

The Allan Hills 84001 meteorite is unlike any of the other Martian meteorites.

- The Allan Hills 84001, the first find of the 1984 season in the Allan Hills region of Antarctica, is unique—unlike any of the SNCs. It also is unique in that it holds a variety of microstructures and trace amounts of carbon that some scientists have interpreted as signs of life on Mars. The great majority of scientists have not accepted this notion, and the story of Allan Hills 84001 has faded from prominence. Nevertheless, the Allan Hills 84001 meteorite remains the single best sample from the early time when water may have been present on the surface of Mars.

- Remarkably, the most revealing meteorites for Earth history may eventually come from Earth itself. We have never found a convincing piece of rock from Earth's earliest history, when the planet was just beginning to form, but such rocks must exist. Most Earth meteorites would have just fallen back to the surface, and they've long since disappeared. But some early Earth fragments must have landed on the nearby Moon, where weathering is not as big of an issue.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

McCoy, "Mineralogical Evolution of Meteorites."

Mittlefehldt, McCoy, Goodrich, and Kracher, "Non-Chondritic Meteorites from Asteroidal Bodies."

Weisberg, McCoy, and Krot, "Systematics and Evolution of Meteorite Classification."

Questions to Consider

1. What is an achondrite meteorite, and how might it be distinguished from a chondrite meteorite?

2. Why are there so many different kinds of achondrite meteorites?

Achondrites and Geochemical Affinities

Lecture 13

At 4.56 billion years, the Sun had formed and ignited, while thousands of planetesimals competed for space in the young solar system. As you will learn in this lecture, three processes—heating that produced thermal metamorphism and melting, fluid-rock interactions that produced aqueous alteration, and impacts—diversified the mineralogy of the solar system. Victor Goldschmidt's classification of the chemical elements helps to explain why some elements are rare or did not form separate minerals at this early stage.

Sources of Mineralogical Innovation

- As gravity clumped the early chondrites together, and as crushing pressure, scalding temperature, corrosive water, and violent impacts reworked the growing planetesimals, more and more new minerals emerged. Altogether, more than 250 different minerals have been found in all the varieties of meteorites—a 20-fold increase over the dozen presolar ur-minerals. These varied solids became the starting point for Earth and all the other planets.

- As planetesimals gravitationally attracted more and more mass, and grew bigger and bigger in the process, three primary mechanisms altered the 60 or so chondritic minerals: heat, water, and impacts. Together, these three agents of change ushered in the second stage of mineral evolution.

- Three sources of heat transformed the evolving solar nebula. The first was the Sun, with solar winds like a blast furnace that baked the innermost regions, stripped gases and other volatiles from the extended zone inside the orbit of Jupiter, and provided the first significant episode of distillation in the solar system.

- The Sun caused the dramatic contrast between the inner rocky planets and gas giant outer planets. The Sun was the likely culprit in the production of the odd oxygen-poor enstatite chondrites as well. The 60 or so stage 1 minerals, all contained in primitive chondrite meteorites, arose as a consequence of the Sun's refining power.

- As the Sun settled down into a more stable hydrogen-burning phase, two additional sources of heat energy took over. The first was gravity, or more specifically, the transformation of gravitational potential energy into heat as planetesimals got larger. Each new collision added more heat; the bigger the planetesimal, the more amplified that effect. Lastly, the accretion of mass also trapped large amounts of highly radioactive isotopes that decayed and thus released more heat energy.

- Water represents the second powerful source of mineralogical innovation in planetesimals. Water is unparalleled as an agent of change because it is both chemically reactive and mobile. The ocean's saltwater speaks of water's ability to break down and dissolve minerals. When saltwater evaporates, tiny crystals of the mineral halite form. Sodium chloride—common table salt—is produced by water's ability to first dissolve and then transport other chemicals.

- As a result, achondrite meteorites hold a variety of similar evaporite minerals. Halite forms some beautiful purple crystals—the color comes from the extreme age of crystals that have suffered billions of years of radiation damage. And there are other water-deposited minerals, including the appearances of both the important sulfate mineral gypsum as well as the carbonates—minerals that today form coral reefs and shells.

- The third powerful source of mineralogical innovation is the dramatic, mineral-forming effects of impacts. When a smaller asteroid hits a growing planetesimal, a brief period of extremely high temperatures and pressures follows. The effects of this shock include the production of a variety of minerals that can only be produced at very extreme conditions—those typically found deep inside planets.

Stage 2 of Mineral Evolution

- The second stage of mineral evolution included the first fine-grained clays, sheetlike mica, and semiprecious zircon, all of which became building blocks of planets. But that's not the entire story of stage 2 of mineral evolution. It's also important to consider what minerals didn't form—and why.

- It's easy to focus on the 250 or so minerals that had appeared by the time of the achondrites: it's an increase from about 1 percent to about 5 percent of Earth's future mineral inventory. But perhaps equally important are the myriad minerals—almost 95 percent of all known species—that had not formed by 4.5 billion years ago.

- Even in the most processed achondrite meteorites, most elements (including uranium, boron, beryllium, and dozens of others) did not form their own minerals—or if they did, they are so rare and the crystals are so tiny that they haven't been found yet.

- An important unanswered query is where those rare elements reside, and there are a number of competing ideas. Some elements could be randomly distributed as foreign atoms in other minerals. With a solid solution, one element substitutes for another element of similar size and bonding character.

- One common example is iron substituting for magnesium in olivine. And the element hafnium always substitutes for zirconium, most commonly in the mineral zircon. Hafnium is right below zirconium in the periodic table. It's likely that other rare elements substitute in the same way for more common elements from the same group in the periodic table: gallium for aluminum, lithium for sodium, or selenium for sulfur, for example.

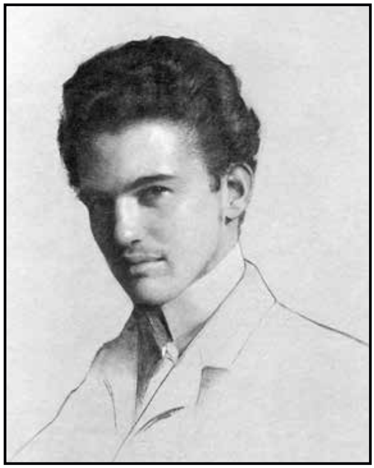
- Another hypothesis is that trace amounts of rare elements concentrate at grain boundaries, perhaps in tiny volumes that don't have regular crystalline structures. Or perhaps some of the elements are present in nanophases, but we just haven't found them yet.

The Goldschmidt Classification

- By the end of stage 2, only about 250 minerals of the over 4,700 known today had appeared. One way to understand all those missing minerals is to look at the geochemical classification of the elements, first introduced in the 1920s by the Swiss mineralogist and geochemist Victor Goldschmidt.

- Goldschmidt made many contributions to mineralogy, including revealing field studies where he grew to realize that new minerals form in environments where key elements have been concentrated by various means, including water and heat.

- His observations led to his most famous and influential publications. The title of these lasting contributions can be roughly translated from the original German as "The Geochemical Laws of the Distribution of the Elements." Today, they are best known as the Goldschmidt classification of the chemical elements.



Mineralogist Victor Goldschmidt (1888–1947) is recognized as the founder of modern geochemistry.

- Goldschmidt's elegant idea is that different chemical elements have different geochemical affinities—that is, they can be separated and concentrated in a few broad types of natural environments, in much the same way as the early solar nebula separated gases like hydrogen and helium from the silicate-rich rocks.

- The original classification scheme focused on the 86 most common elements that are found in Earth and divided the periodic table into four major groups: lithophile, siderophile, chalcophile, and atmophile elements. Elements within each of these groups share chemical features that lead to distinctive mineralogies.

- Lithophile ("rock-loving") elements concentrate in crustal rocks.

- Siderophile ("iron-loving") elements concentrate in the metallic core.

- Chalcophile ("ore-loving") elements bond to sulfur.

- Atmophile ("atmosphere-loving") elements tend to remain in a gaseous state.

- The Goldschmidt classification has many subtleties that enrich the field of geochemistry. For one thing, quite a few elements have mixed character. So iron, which is the defining siderophile element, also commonly occurs with sulfur—for example, in the lustrous golden mineral pyrite, or fool's gold. Iron is also one of the most common elements in the crust in oxides and silicates—for example, in the important magnetic mineral magnetite, an iron oxide that is one of the principal iron ores.

- Indeed, most of the siderophile elements, including manganese, nickel, and cobalt, can take on lithophile characteristics if there's a lot of oxygen around, while many of the lithophile elements can bond to sulfur and become chalcophile under low-oxygen conditions. The unusual enstatite chondrite meteorites incorporate sulfides of calcium and magnesium, which are normally lithophile elements.

- Temperature and pressure also play important roles. As many lab experiments have shown, it turns out that virtually every chemical element takes on metallic properties at high enough pressure. As atoms are forced closer and closer, some electrons inevitably become too confined and break free, to move freely about the substance. That's the definition of a metal. High-pressure experiments have demonstrated the metallization at high pressure of all sorts of elements, from iodine to sulfur to oxygen.

- One of the great challenges in experimental materials science is to achieve the extremely high pressure necessary to turn hydrogen gas into a metal. Some researchers have gotten close. Hydrogen crystallizes to a colorless solid at about 50,000 atmospheres, which is easy to achieve. The crystals consist of regular rows of little H_2 molecules, like dumbbells. At those lower pressures, the dumbbells rotate every which way.

- Then, as you get to higher pressures, as the volume decreases and space gets tight, the dumbbells get locked into one orientation; they don't have room to rotate freely. Above 1 million atmospheres, the little H_2 molecules begin to break apart—the two hydrogen atoms within a molecule actually get farther apart, while spaces between the molecules get much shorter.

- Then, at some really high pressure—maybe 5 million atmospheres—the atoms should become evenly spaced and form a metal. That's a huge experimental challenge, but theoretical calculations make it pretty certain that hydrogen metal will be the stable phase and that the metallic state of hydrogen must occur inside the gas giant planets.

- In fact, some astrophysicists suggest that metallic hydrogen inside big planets is the most common mineral by volume in the universe. Regardless, the hydrogen story reveals the nuances and flexibility of the Goldschmidt classification of elements.

- Naturally, as the decades have passed and the Goldschmidt classification scheme has been adopted by more and more specialists, new subclassifications have arisen. One of the most interesting is the category of pegmatophile ("pegmatite-loving") elements, which are extremely water-rich igneous rocks that tend to concentrate some of the rarest lithophile elements.

- Goldschmidt's geochemical classification of the elements is just another way to catalog elements—but these are not just lists. The classification scheme, and its subsequent elaborations, helps us understand the many ways that elements can be selected, concentrated, transported, and crystallized into Earth's rich mineralogical heritage.

- Siderophiles are densest and most likely to be found toward the core; chalcophiles are not quite as dense; lithophiles are even less dense; and atmophiles are the least dense of all, common in the atmosphere or lost to space.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 1, pp. 13–25.

McCoy, "Mineralogical Evolution of Meteorites."

Mittlefehldt, D. W., T. J. McCoy, C. A. Goodrich, and A. Kracher. "Non-Chondritic Meteorites from Asteroidal Bodies." In *Planetary Materials*, edited by J. J. Papike, 4-001–4-196. Chantilly, VA: Mineralogical Society of America, 1998.

Weisberg, McCoy, and Krot, "Systematics and Evolution of Meteorite Classification."

Questions to Consider

1. What processes lead to new minerals in the achondrite minerals?

2. What is the Goldschmidt classification of the chemical elements, and why is it useful?

The Accretion and Differentiation of Earth

Lecture 14

Earth's formation in the solar nebula took place in two overlapping stages: accretion and differentiation. Earth assembled from kilometer-sized planetesimals through runaway accretion—a process that may have lasted about 100,000 years. Planet-scale melting led to the differentiation of Earth into three major layers: core, mantle, and crust, each of which is further subdivided into layers of different composition and density. Details of Earth's inner structure come primarily from two kinds of geophysical measurements: moment of inertia and seismology.

The Process of Accretion

- The stage has been set for the formation of Earth. The solar nebula had been processed, first by heat and radiation from the T Tauri Sun. That initial solar wind formed the chondrules and CAIs and separated most of the volatile, "atmosphere-loving" components from the inner rocky regions of the solar system. Isotope data from the most primitive meteorites date those initial events at 4.567 billion years ago. This first stage of mineral evolution saw the production of perhaps 60 different minerals, many of which occurred only in microscopic crystals.

- Electrostatic forces caused the chondrules and dust to stick together to form lumps the size of basketballs, and then automobiles, and maybe even houses. As the clumps got larger over an extended period of perhaps 10 or 20 million years, gravity increasingly took over, eventually forming billions of irregular objects up to a kilometer across.

- This process of accretion accelerated as the planetesimals grew and their gravitational attraction increased. Isaac Newton's law of gravitation explains why. The force of gravity is equal to a constant (G) times the mass of the first object, times the mass of the second object, all divided by the distance squared: $F = G(m_1m_2)/R^2$. That is, a gravitational force is experienced by any two objects that are separated by a distance.

- The implication of this equation is that mass really matters. In a swirling nebula, objects are constantly moving and brushing by each other, so the distance term is pretty much the same for smaller or larger objects, at least while there are lots of objects in orbit around the Sun. However, if masses are small—just a few ounces or a few pounds—gravity is extremely weak and can't have much influence. That situation changed, as planetesimals grew larger and larger to masses of thousands or millions of tons. That's the point when gravity took over.

- The same scenario was being played out at all distances from the Sun between what is now inside the orbit of Mercury to beyond the asteroid belt—that is, from perhaps 10 million to 700 million kilometers from the Sun. This region had been largely stripped of its hydrogen, helium, and other volatiles. What remained 4.55 billion years ago were innumerable big rocks that would eventually become the four terrestrial planets.

- The final stages of Earth's formation must have been typical of all the inner rocky planets; indeed, computer models show that for a time all of their fates were linked by random violent events. This ultimate stage of planet formation is called runaway accretion—an interval perhaps lasting 100,000 years when gravity was fully in control.

- We begin that stage with billions of objects in a variety of sizes, but with a significant population a kilometer across or more. When two such objects get close, the force of gravity pulls them together and they merge: The larger and more massive the bodies, the more violent the impact.

- Computer models reveal the inevitable progression of such a scenario. Statistics show that a few objects inevitably get larger faster, which means they have much stronger gravitational pull, and they grow faster still.

- Perhaps thousands of planetesimals grow to sizes of 50 to 100 kilometers or more. They sweep up the smaller bits, and some of those planetesimals grow even faster than others, leading to perhaps dozens of protoplanets reaching 500 kilometers in diameter. This is a solar system of perhaps 50 to 100 good-sized protoplanets.

- At this point, each impact releases huge amounts of energy. Some planetesimals are blasted to bits—that's where many of the asteroids and meteorites come from. More typically, a smaller planetesimal will smash into a larger one and be completely swallowed up.

- Computer models show that the orbits of these larger protoplanets are easily altered by the late-stage collisions, so if you have a dozen really large objects in orbit in the range from 10 to 700 million kilometers from the Sun, any one of them could ultimately wind up in almost any orbit. What is not entirely random is the final orbital distribution of the stable planets. No two planets can persist for long at the same orbital distance; the bigger planet always consumes the smaller.

- The protoplanet that would become Earth was the largest object to survive in our section of solar system real estate, roughly 150 million kilometers from the Sun. At the time of its final stages of formation, Earth was a lonely, moonless world that had almost achieved its present size of 12,740 kilometers in diameter and its mass of 6 billion billion kilograms.

- Its orbit then, as it is now, was nearly circular, and the length of the year was close to the modern value of 365 current days, though the length of Earth's day was much shorter than the 24-hour cycle we experience today.

- Astronomers conclude that the newly accreted Earth bore some similarities to our modern planet, but its appearance was radically different from the marbled blue planet we know. There were no oceans or continents. There wasn't even an atmosphere at first. During Earth's turbulent earliest days, it was a hot, blackened sphere of dense igneous rocks.

- Earth could not remain airless for long. The rocky planets are volatile-poor relative to the more distant gas giants, but they are not volatile-free. The magma beneath the thickening black crust contained enough water, nitrogen, and carbon to lower the melting points of rock significantly and to decrease its viscosity from that of a thick paste to running water.

- This magma, less dense than its surroundings, exploited cracks and fissures to force its way to the surface. The magma exploded with tremendous force as it breached the surface, releasing vast amounts of steam and other gases—what would eventually become the oceans and atmosphere. Earth, then, was as alien and hostile as any world we can imagine.

The Process of Differentiation

- The timing of the final accretionary events that formed Earth is still a matter of scientific debate, but there are a couple of lines of evidence. Most important are the radiometric ages of the most processed meteorites—the irons, stony irons, and stony achondrites. These ages are relatively consistent and point to the existence of fully differentiated protoplanets by about 4.55 billion years. That's roughly 15 to 20 million years after the first space droplets formed—those calcium-aluminum-rich inclusions that are found in chondrites.

- Astronomers also get a sense for timing from the number of young stars that still have protoplanetary discs of gas and dust. We can't watch as those discs turn into planets; the process takes too long. But the mere fact that so many young stars are surrounded by discs of small objects indicates that planet formation requires extended timescales.

- The best guess for the duration of the entire process—from the first solar flare up to a solar system with a dozen or so planets and protoplanets—is certainly no less than 10 million years, but probably no more than 20 or 30 million.

- We know from the variety of meteorites that a lot was going on deep inside protoplanets and, by extension, inside Earth as well. In our planet, as in all other big rocky objects, gravity had clumped the primitive chondrites together as heat altered the mix. Crushing pressures, searing temperatures, chemically reactive water, and violent impacts reworked the growing planetesimals.

- In the process, more and more new minerals emerged—together more than 250 different minerals collectively found in all the varieties of meteorites—a 4-fold increase over stage 1 and a 20-fold increase over the dozen presolar ur-minerals. These richly varied mineral species, the building blocks of Earth and other rocky planets, reveal the deeply buried flip side of accretion: the process of differentiation.

- Differentiation—which ultimately led to the separation of elements in iron meteorites, versus stony iron meteorites, versus the varied achondritic stony meteorites—was driven by heat from two sources. Radioactive isotopes, particularly the short-lived radionuclides such as aluminum-26 and xenon-129, were one major source, representing more than half of the total heat energy in the earliest planetesimals. Added to this radiogenic heat was the transformation of gravitational potential energy to heat as planetesimals added mass and as denser material accumulated in the deep cores of these objects.

- These same processes occurred in Earth, but at an even grander scale. Planetary differentiation of the kind experienced by Earth arises principally from two complementary mechanisms: chemical differentiation and physical differentiation. According to current thinking, both chemical and physical processes contribute to the kind of concentric layering seen in all of the terrestrial planets, as well as all of the larger rocky moons and protoplanets.

Probing Earth's Interior: Moment of Inertia and Seismology

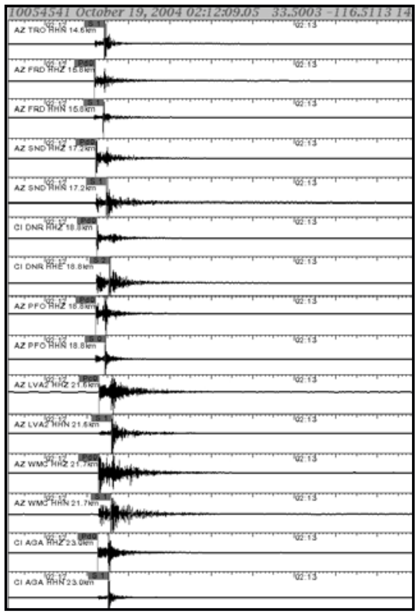
- The diversity of meteorites provides strong evidence for a layered Earth, with an iron core and silicate mantle. Two primary geophysical techniques reveal the distribution of mass inside Earth. The first and older technique involves measuring Earth's moment of inertia, which is defined as an object's resistance to any change in rotation.

- If you can measure the force needed to slow Earth's rotation, then you have direct evidence for the distribution of mass inside. Earth's moment of inertia has been measured in variety of ways, including modern satellite measurements. Studies of the effect of tides in gradually slowing Earth's rotation and increasing the Earth-Moon distance provide one important classical method.

- Earth's moment of inertia is significantly less than that of a uniform sphere of the same size and mass, which means that significantly more mass is concentrated in a dense core compared to a uniform sphere. If you assume that Earth has two dominant regions, the core and mantle, then it's possible to predict with good accuracy the 2,900-kilometer depth of the core-mantle boundary.

- Our most detailed picture of Earth's interior comes from the branch of geophysics called seismology, which is the study of how sound waves travel through Earth. Seismic waves are the kind of waves generated by earthquakes.

- The key to seismology is that sound waves travel through different kinds of materials at different speeds, typically several kilometers per second. These speeds, or seismic velocities, are generally faster for denser materials and slower for hotter materials, especially if they're partially melted.



Seismographs are used to measure seismic waves. Seismograms are generated when the pendulum of a seismograph moves.

Suggested Reading

Grotzinger, Jordan, Press, and Siever, *Understanding Earth*.

Hazen, *The Story of Earth*, Chapter 3, pp. 60–76.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What are Earth's major layers, and how do they differ?

2. What evidence is used to determine Earth's interior structure?

How Did the Moon Form?

Lecture 15

The Moon provides an important example of how Earth evolves by repeated cycles of element selection and concentration. The Moon's formation is thus another of the critical steps in Earth's evolution. Humans have speculated about the Moon's formation for centuries. Three competing theories—the fission theory, the capture theory, and the coaccretion theory—were all in contention prior to 1969, but the treasure trove of *Apollo* Moon rocks provided the answer: None of the pre-1969 theories worked.

The Moon's Origins

- The story of Earth's origins seems to be neat and tidy—except for one striking detail: the Moon. For much of the past two centuries, the presence of the Moon has proven exceedingly difficult to explain.

- Small moons are pretty easy to understand. Mars has two small moons called Phobos and Deimos. These two irregular objects are just a few miles across, and they appear to be nothing more than captured asteroids. It's now thought that the largest of the moons that orbit the outer planets formed from the unclaimed remnants of planet formations. So they were formed from lots of smaller bits, just like miniature solar systems.

- Earth's Moon, by contrast, is relatively huge compared to the planet it orbits. Our Moon is more than a quarter of Earth's diameter and about $1/80^{th}$ of its mass. That's uniquely large for a moon in our solar system.

- A century and a half ago, long before the historic *Apollo* Moon landings beginning in 1969, long before the recovery of pristine Moon rocks, and long before we had access to any careful geophysical measurements of the Moon's interior, all we could do was look at the Moon. We could use telescopes to study the lunar surface and measure the Moon's orbit and its variations over time. That's not a lot of data.

- The first widely accepted scientific hypothesis about the origins of the Moon was the fission theory, proposed in 1878 by George Howard Darwin—son of Charles Darwin, who proposed the theory of evolution by the process of natural selection.

- George Darwin's scenario imagines how the primordial molten Earth must have spun on its axis so rapidly that it stretched out and became elongated. Eventually, a big glob of magma was flung off the surface into orbit (with a little help from the Sun's gravitational pull). The Moon in this model is like an Earth bud that's broken free. He also went on to calculate how the Moon must have been much closer to Earth in the distant past, and he estimated the rate at which they are continuing to move apart.

- In one variant of this dramatic tale, the Pacific Ocean basin remains as a telltale mark—sort of like Mother Earth's birthing scar. On first hearing, this idea seems plausible enough. When soft, elongated objects like pizza dough or water droplets spin too fast, they split apart in two. The fission theory imagines a pretty violent and dramatic event.

- A second competing idea is called the capture theory. In this reasonable model, the Moon is thought to have formed separately as one of the numerous smaller planetesimals that occupied more or less the same distance from the Sun in the emerging solar system. At some point, as the story goes, the two orbiting bodies passed close enough to each other so that the larger Earth captured the smaller Moon.

- We're now pretty sure that such a gravitational mechanism worked well enough for the smaller rocky moons of Mars, so why not for Earth's Moon? Unlike George Darwin's fission theory, there doesn't seem to have been any one inventor of this capture theory; a number of astronomers just accepted it as a good possibility.

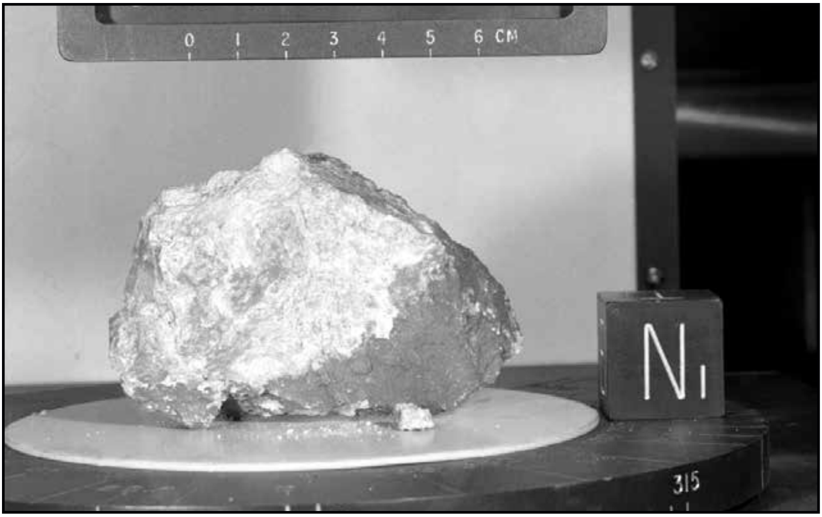
- The third, and perhaps the least dramatic, hypothesis is called the coaccretion theory, which suggests that the Moon formed more or less in its present location and at about the same time as Earth. In this view, planets form around the Sun from its leftovers—including all the chondrite and achondrite meteorites—and then moons form around planets in exactly the same way from their leftovers. It's almost certain that the big moons of Jupiter and Saturn formed this way. It's a common theme, seen over and over again in the solar system: Smaller objects accrete from clouds of dust, gas, and rocks around larger objects.

- There are times in science when there's just not enough data to decide among the multiple working hypotheses. One group of scientists will promote one favorite idea, and others will promote another; the debates can be lively—sometimes even angry and bitter. But without more data, there's no real chance for a resolution that satisfies everyone.

The *Apollo* Missions

- Answers to the mystery of the Moon's origins had to await data from the Moon rocks. The six *Apollo* landings between July of 1969 and December of 1972 featured Moon walks by 12 NASA astronauts, starting with Neil Armstrong and Buzz Aldrin. These missions resulted in a phenomenal collection of more than 840 pounds of Moon rocks and soil samples from six different sites. There were also many other key lunar measurements, such as gravity readings and seismic surveys.

- The *Apollo* Moon missions transformed planetary science in so many ways. Sure, they were an unrivaled showcase for American technological prowess and bravado. Undoubtedly, they provided a tremendous boost to the military-industrial complex. And the countless *Apollo*-inspired innovations, from minicomputers to polymers to Tang, provided an economic driver that may well have



The Genesis Rock is a sample of Moon rock that was returned by NASA's *Apollo 15* mission.

paid for the 20-billion-dollar missions many times over. It's not surprising that national pride and the race for the "high ground," not just lunar science, were primary drivers for those costly and dangerous early Moon missions.

- Even so, it would be difficult to overstate the impact of the *Apollo* missions and their treasure trove of Moon rocks on earth scientists. For all of human history, the Moon was tantalizingly close, less than a quarter of a million miles away. On a clear summer's evening, as the full Moon rises, you feel like you could just reach out and touch it. But we had no samples—nothing to tell us for sure of what the Moon is made. We had no real way of knowing how the Moon was formed.

- All of that changed with the first batch of returned lunar samples. For the first time, we had ground truth for the three competing theories. We could, for the first time in human history, touch the

Moon. In fact, now everyone can touch a piece of the Moon as a visitor to the Smithsonian Institution.

- When the subject of lunar samples comes up, most people immediately think of Moon rocks, perhaps something chunky that you can hold in your hand. But a significant fraction of the *Apollo* material was lunar soil, what is known as regolith. The finest-grained fraction of regolith is pulverized rock in fragments so small you can't resolve them in a microscope. It's the cumulative consequence of billions of years of bombardment by a battery of cosmic insults—from mighty asteroids, to meteorites, to the incessant solar wind.

- You can get a sense of regolith by thinking about powders. This material is much, much finer than sand or granular sugar or salt. It's even finer than flour; maybe a bit more like talcum powder or black Xerox toner. This ultrafine lunar powder has really strange properties. Most notably, the dust sticks to itself and to just about everything else it touches.

- The last *Apollo* Moon mission was in December 1972, with *Apollo 17* and the return of 275 pounds of samples from the Taurus-Littrow Valley, which is a region of suspected lunar volcanoes. No one has gone back to the Moon in more than four decades.

- Nevertheless, the Moon rocks have been meticulously curated in sterile vaults at the Lunar Sample Laboratory Facility at NASA's Johnson Space Center in Houston, Texas. And there's also a secure backup of representative lunar samples in White Sands, New Mexico. These specimens continue to provide an amazing wealth of opportunities for researchers.

- Research on samples from the Moon has shown that the Moon's minerals, while very similar in major elements to those on Earth, are rather different in detail from what we find at Earth's surface. They have a lot more titanium; the chromium is different, too.

- Remarkably, the results of the *Apollo* samples cast doubt on all three of the competing Moon-forming hypotheses: the fission theory, the capture theory, and the coaccretion theory. None of the three prevailing theories of Moon formation in 1969 fit the data of the Moon rocks. There must be another explanation.

Suggested Reading

Canup and Righter, eds. *Origin of the Earth and Moon*.

Comins, *What If the Moon Didn't Exist?*

Hazen, *The Story of Earth*, Chapter 2, pp. 31–52.

Mackenzie, *The Big Splat, or How Our Moon Came to Be*.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What aspects of Earth's Moon are unique, compared to other moons in our solar system?

2. What three theories of the Moon's origins vied for acceptance prior to the *Apollo* Moon landings?

The Big Thwack!

Lecture 16

The Moon is now thought to have formed as the result of an epic impact with a Mars-sized planet that was competing for the same solar system real estate as Earth. Earth was bigger and won, but the Moon was formed from the debris of the impact. Just after its formation, the Moon was much closer and exerted much greater forces on Earth. Complex gravitational interactions have caused the Earth-Moon distance to increase—and it's still increasing today. The Moon is thus an integral part of Earth's evolution, and it carries a unique record of that evolution.

New Evidence from *Apollo* Moon Rocks

- Close scrutiny of the Moon rocks and soils brought back by the *Apollo* missions proved that all three of the pre-1969 theories were simply wrong. Three new clues from *Apollo* rocks placed severe constraints on ideas regarding how the Moon came to be.

- First, it turns out that the Moon differs dramatically from Earth in that it does not have a big, dense iron metal core. Earth's core holds almost a third of its mass, but the Moon's tiny core is less than three percent of its mass. This is not a trivial difference, as the Moon's average density is only about two-thirds that of Earth.

- Second, Moon rocks contain almost no traces of the most volatile elements—notably nitrogen, carbon, sulfur, and hydrogen—which are so common at Earth's surface. Unlike Earth, which is covered in liquid water and whose soils contain abundant water-rich minerals such as clays and micas, no water-bearing minerals of any kind have been found in the *Apollo* Moon rocks. Something must have blasted or baked the Moon to remove most of those volatiles, because the Moon is now an extremely dry place.

- The third key finding of the *Apollo* missions is based on the element oxygen—or, more specifically, the distribution of its isotopes.

The key finding is that the oxygen isotope composition of the Moon is indistinguishable from that of Earth. So the two bodies appear to have formed from the same stuff.

- This evidence proved that the fission theory, the capture theory, and the coaccretion theory were all wrong. It didn't take very long for a new idea to emerge.

The Big Splash/Big Thwack Model

- The "big splash" or "big thwack" model arose in the mid-1970s in response to the urgent need for something new. What began as a series of related but poorly constrained hypotheses coalesced into conventional wisdom at a pivotal 1984 conference in Hawaii, where planetary formation experts gathered to weigh all of their options. In such a heady environment, Ockham's razor—which is the demand that the simplest solution to a problem consistent with the facts is likely to be correct—prevails. The big thwack model fit the bill.

- More than 4.5 billion years, the planets had just formed from all of those smaller competing planetesimals. As Earth grew close to its present diameter of more than 12,700 kilometers, it swallowed up almost all of the remaining bodies in a succession of huge impacts. Those penultimate collisions with objects many hundreds of miles across would have been spectacular, but had little effect on Earth, which was the much more massive protoplanet.

- But not all impacts are equal. In Earth history, one single event stands out. About 4.53 billion years ago, when the solar system was perhaps 30 million years old, Earth was not alone. Two planet-sized objects—the black proto-Earth and a slightly smaller planet-sized competitor—jockeyed for the same narrow ring of solar system real estate. The smaller would-be planet, dubbed "Theia" after the Titan goddess who gave birth to the Moon, was worthy of planetary status—probably larger than Mars and roughly a third of Earth's mass.

- A rule of astrophysics is that no two planets can share the same orbit. Eventually, they will collide, and the larger planet always wins. So it was with Earth and Theia. The principal way that scientists attempt to understand what might have happened is through increasingly vivid computer simulations. A few models are surprisingly successful and produce an Earth-Moon system rather like the one we see today.

- In one oft-described version, the impact occurred as a solid sideswipe, big Theia smashing the bigger Earth slightly off center. Seen from space, the event would have played out in slow motion. At the moment of contact, the two worlds seemed at first to gently kiss. Then, over the next four or five minutes, Theia was smashed without much effect on Earth. Ten minutes later, Theia was pretty much squashed, while Earth began to deform. Half an hour into the collision, Theia was simply obliterated, while injured Earth was no longer a symmetrical sphere. Superhot rock had been vaporized, blasting out in luminous streams from the gaping wound and obscuring the disrupted worlds.

- Another widely cited solution, first proposed in the 1970s and refined over the next two decades, was developed by Canadian-born theorist Alastair Cameron. In his intriguing scenario, Theia was roughly 40 percent the mass of the proto-Earth. Again, he theorized that there was an off-center impact, but this time, Theia more or less bumped against Earth—kind of bounced off as an elongated blob—and then was pulled back in for a second thwack, in which Theia disappeared forever.

- In either case, the catastrophe obliterated Theia, which simply vaporized into an immense incandescent cloud, tens of thousands of degrees hot, surrounding Earth. Theia did its damage as well. A significant chunk of Earth's crust and mantle also vaporized and blasted outward to mix with Theia's scattered remnants. Some material escaped to deep space, but most of the savaged remains were retained in orbit by Earth's unyielding gravitational grip.

- From this roiling cloud, the dense metal from the cores of both worlds comingled and sank to form a new, larger core for Earth. Mantle materials also mixed and vaporized, forming a hellishly hot globe-encircling cloud of vaporized rock. For a violent time of days or weeks, Earth experienced an incessant rain of orange-hot silicate droplets, which merged with a shoreless, red-glowing magma ocean. Ultimately, Earth seized much of what had been Theia and, thus, emerged a more massive planet

- Not all of Theia was captured. Higher up in space Earth became encircled by a vast accumulation of rocky collisional debris, mostly an intimate mixture of the two planetary mantles. Cooling rocky droplets stuck together, with bigger chunks sweeping up the smaller. In a sort of instant replay of the gravitational clumping that originally formed the planets, the Moon coalesced rapidly and may have achieved more or less its present size in a few years.

- The physics of planet formation dictate where the Moon could have formed. Every massive object has an invisible surrounding sphere, called the Roche limit, inside of which gravitational forces are too great for a satellite to form. Earth's Roche limit is about 11,000 miles, or roughly 7,000 miles up from the surface.

- Accordingly, models of Moon formation locate the new satellite at a distance of about 15,000 miles up, where it could grow in an orderly fashion by sweeping up most of the scattered bits and pieces from the big thwack. So, roughly 4.53 billion years ago, the Moon was born. Earth found itself with a companion, formed in part from pieces of itself.

- Scientists quickly embraced the big thwack theory because it explains all of the major clues better than any other model. The Moon lacks an iron core because most of Theia's iron wound up inside of Earth. The Moon lacks volatiles because Theia's volatiles were blasted away during the impact. One side of the Moon always faces Earth because the angular momentum of Earth and Theia were coupled into one spinning system.

The collision between two planetary bodies—the Earth and a Mars-sized object—likely formed the Moon.

- The big thwack also helps to explain Earth's anomalous axial tilt of about 23 degrees—a factor not well handled by any of the previous scenarios. The impact tipped Earth onto its side. Indeed, the realization that a late, giant impact formed the Moon has led to speculation about other planetary anomalies in our solar system.

- Perhaps late big thwack events of one kind or another are common—even necessary. Perhaps that explains why Venus rotates the "wrong" way on its axis and why it lost so much of its water. Perhaps a late, giant impact caused Uranus to rotate on its side.

The Early Moon

- The Moon's formation was a pivotal event in Earth history, with far-reaching consequences that are utterly amazing and only just now coming into focus. The Moon of 4.5 billion years ago was not the romantic, silvery disk we see today. Long ago, it was a far more looming, dominant, and unimaginably destructive influence on Earth's near-surface environment.

- The Moon formed only 15,000 miles from Earth's surface. Today, by contrast, the Moon is 239,000 miles away. At first blush, it seems utterly implausible that a giant Moon could just drift away from Earth like that, but measurements don't lie.

- About 4.5 billion years ago, the Moon filled the sky, dominating the view of the cosmos, and it orbited Earth every few days. In addition, Earth rotated on its axis much faster than today: A day lasted only 5 hours, and there were more than 1,500 days per year.

- Gravitational interactions between Earth and Moon caused epic tides on land as well as in the water. Those tides pulled on the Moon, making it orbit faster and faster—and, thus, farther and farther away—while Earth's rotation slowed down. These interactions are still occurring today.

- The Moon remains a luminous reminder that the cosmos is a place of intertwined creation and destruction. Our nearest cosmic neighbor offers mute testimony: While change is usually gradual and benign, there can be really bad days. We are loathe to imagine ourselves back to that violent, frenzied time—magma oceans, incandescent silicate rain, and epic land tides on a world utterly lacking in life-sustaining atmosphere or cooling water.

Suggested Reading

Canup and Righter, eds., *Origin of the Earth and Moon.*

Hazen, *The Story of Earth*, Chapter 2, pp. 31–52.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What did the Moon look like shortly after its formation?

2. How do the orbital behaviors of Venus and Uranus provide support for the big thwack model of the Moon's formation?

The "Big Six" Elements of Early Earth

Lecture 17

The earliest period of Earth's history, the aptly named Hadean Eon, was a hellish time of incessant meteorite bombardment and explosive volcanism. Earth was covered with red-hot lava flows that hardened to black basalt, which is the starting point for the surfaces of all of the inner planets. As you will learn in this lecture, six dominant elements—the electron acceptor oxygen and the electron donors silicon, aluminum, magnesium, calcium, and iron—played pivotal roles.

The Six Dominant Elements

- Earth's inevitable chemical differentiation was a direct consequence of two complementary chemical processes. First was making elements, the cosmochemical process of nucleosynthesis. Big stars make all the elements of the periodic table heavier than hydrogen and helium. The second chemical process is making the rocks, or petrology.

- It may be hardwired into our universe that about a half of a dozen of the more than 100 known chemical elements were destined to become dominant in rocky planets—we still have a lot to learn about rocky planets—but if we focus on Earth, there are six dominant elements, and their atomic numbers are (8) oxygen, (12) magnesium, (13) aluminum, (14) silicon, (20) calcium, and (26) iron.

- If we ignore hydrogen, helium, and neon, the six dominant elements on Earth account for about three of every four atoms in the solar system. Moreover, much of the rest is—in proportions even greater than for Earth itself—carbon, nitrogen, and sulfur, each of which are critical for life.

- If we focus on just the inner terrestrial planets, where most of the volatiles have been stripped off, the "big six" elements have an even more important role: They make up a whopping 97 percent of

Earth's mass, just as they do for the mass of Mercury, Venus, and Mars, and Earth's big Moon.

- For Earth, the big six ranked by their contribution to the mass of the planet are as follows: iron and oxygen, 30 percent each; silicon and magnesium, 15 percent each; and a little less than 2 percent each for aluminum, calcium, and nickel (though a lot of the nickel is in the Earth's core).

- We can also count by the number of atoms each element contributes. Looked at in terms of number of atoms, oxygen is really the king, accounting for almost half the atoms of Earth. Magnesium, silicon, and iron follow with roughly 15 percent each. Aluminum accounts for only 1.5 percent, and calcium is roughly 1 percent.

- Each of these elements has played key roles throughout Earth's history, and each has an important chemical story. Chemical bonding lies at the heart of these stories. The key to chemical bonding is that an exchange of electrons must occur—some atoms give away electrons, and other atoms accept electrons.

Oxygen

- Oxygen is by far the most abundant element in Earth's crust and mantle. On the periodic table, oxygen lies in the eighth position, just two places to the left of the inert gas neon. Oxygen wants two more electrons; in fact, it plays the role of Earth's most voracious electron acceptor. That's because every oxygen atom holds 8 protons in its nucleus—that's the definition of "oxygen." Those 8 protons have 8 positive charges, which are usually balanced by 8 negative electrons, but 10 is the nearest magic number, and that means that oxygen is constantly on the lookout for 2 extra electrons.

- Given our dependence on oxygen, it's odd that the eighth element is one of the most chemically reactive and corrosive gases in nature. Oxygen reacts violently with many carbon-rich chemicals. It also turns shiny iron metal into a pile of rust, and it quickly breaks down many minerals.

- Most of us naturally think of oxygen's primary role as an essential, life-giving part of the atmosphere, but oxygen in the atmosphere is a relatively recent development. For more than half of Earth's history, the atmosphere had virtually no persistent oxygen, and even today, with a lot of oxygen now in the atmosphere, 99.9999 percent of Earth's oxygen is locked into the minerals and rocks of the crust and mantle.

Silicon

- Oxygen couldn't play such a critical chemical role as an electron acceptor in Earth's outer layers were it not for several kinds of atoms that are equally eager to give away or share their electrons. In fact, the other five elements of the big six are all electron donors. The most enthusiastic of these electron donors is silicon, which accounts for about one in every four atoms in Earth's crust and mantle.

- On the periodic table, silicon is in the 14^{th} spot, just below carbon. That means that silicon has 14 protons in its nucleus, which can be balanced by 14 negative electrons. But 14 is not a magic number; 10 or 18, equally distant from 14, are magic numbers. As a result, silicon has to form chemical bonds.

- Silicon-oxygen bonds have a significant amount of electron sharing. As a consequence, the silicon-oxygen bond always has a component of covalency as well as ionicity. Resilient silicon-oxygen bonds are found in almost every crustal and mantle rock and in the majority of minerals.

- Minerals with silicon-oxygen bonds are Earth's most common materials, both in total volume and in the sheer number of different species—more than 1,300, and counting, because more are discovered almost every month. These minerals, collectively known as silicates, are also richly varied in their atomic architectures and in their physical and chemical properties. That's because the silicon-oxygen bond is so versatile in the way it can connect to other atoms.

Aluminum, Magnesium, Calcium, and Iron

- Aluminum is found to silicon's immediate left in the periodic table. At position 13, aluminum has three more electrons than ideal, so it serves the role as another important electron donor in Earth's crust and mantle.

- Aluminum is a lot less abundant than oxygen or silicon; only about one in 20 atoms of the average mantle and crust are aluminum. In spite of that relative scarcity, aluminum plays unique structural roles in many of the most common minerals: in the pyroxene chain silicate group, in the mica and clay layer silicate groups, and in feldspar and other framework silicates.

- Magnesium, which is located to the left of aluminum one space and is element 12, accounts for approximately one in every six atoms of the crust and mantle. Every magnesium atom wants to get rid of two electrons, so it easily bonds in a one-to-one ratio with oxygen.

Calcium is the fifth most abundant element in Earth's crust.

- However, it turns out that the pure magnesium oxide, MgO, is quite rare in nature. That’s because magnesium tends to join with silicon and other elements to form many of the most common silicates in both the crust and mantle. Indeed, magnesium silicates are estimated to form about half of Earth’s volume, mostly in the most abundant mantle minerals: the olivine forsterite; the pyroxene enstatite; the garnet pyrope; and their varied dense, high-pressure equivalents deep within Earth.

- The fifth of the big six elements is calcium, which represents about six percent of atoms in the crust and mantle. Calcium appears at position 20 in the periodic table, so it lies immediately below magnesium. That means that calcium is somewhat larger than magnesium, but in other respects, it’s magnesium’s chemical twin.

- Elements that lie in the same vertical column usually have similar chemical properties. So calcium, like magnesium, is two electrons away from a magic number—in calcium’s case, 18. Calcium wants to get rid of 2 electrons, so (like magnesium) it bonds to oxygen in a one-to-one ratio to make CaO, the mineral lime. Also like magnesium, it’s rare to find pure calcium oxide in nature. Calcium almost always combines with silicon and other elements, often as a substitute for magnesium in minerals like olivine, pyroxene, mica, or garnet.

- Iron is by far the most versatile of the big six elements. That’s because each of the other five elements—oxygen, silicon, aluminum, magnesium, and calcium—plays one and only one dominant role in the chemistry of rocks and minerals. They are all quintessential lithophile elements that adopt ionic bonds and concentrate in the crust and mantle. Oxygen almost always plays the role of an electron acceptor, while the others are almost always electron donors. Iron, by contrast, embraces three very different chemical responsibilities.

- Unlike silicon, aluminum, magnesium, or calcium, iron commonly bonds to other electron acceptors, especially sulfur (fool’s gold is just one example). Iron also readily forms the dense metal that sinks to the center of planets and forms their massive cores. In short, iron is one of the few elements that commonly acts as a lithophile, siderophile, *and* chalcophile element.

Suggested Reading

Deer, Howie, and Zussman, *An Introduction to the Rock-Forming Minerals*.

Hazen *The Story of Earth*, Chapter 3, pp. 53–63.

Philpotts and Ague, *Principles of Igneous and Metamorphic Petrology*.

Wenk and Buklah, *Minerals*.

Questions to Consider

1. What are Earth's big six elements? Which are electron acceptors, and which are electron donors?

2. What characteristics of iron set it apart from the other big six elements?

The Black Earth—Peridotite to Basalt

Lecture 18

By looking back at the earliest history of Earth, you can see how both astrophysical chance and geological necessity played crucial roles. Even a slight difference in the orbit of Earth or Theia could have changed the character of the Earth-Moon system, but once the big thwack happened, the histories of Earth and the Moon were ordained. Peridotite inevitably crystallized from Earth's cooling magma oceans. And, just as inevitably, dense peridotite sank and was partially remelted to form basalt, the most abundant rock on Earth.

Earth's First Rocks: Peridotite

- The stories of Earth's first rocks come from more than a century of research by experimental petrologists, who devise novel techniques and build laboratories to heat and pressurize rocks in an effort to replicate conditions of Earth's deep interior. Experimental petrologists face two technical challenges in their quest to discover the origins of rocks.

- First, they need to produce and control the incredibly high temperatures of rock formation—thousands of degrees in some cases. To attain such lofty temperatures, scientists have to craft costly platinum wire into meticulously spaced coils and then control extremely high electrical currents that are required to achieve and stabilize such temperature extremes.

- Second, what makes this effort far more challenging is that heating has to be done while samples are subjected to crushing pressures that are tens or hundreds of thousands of times that of the atmosphere. Researchers enlist massive hydraulic rams to reach and sustain such immense pressures.

- Experimental petrologists find that a melt rich in the big six elements, with element ratios similar to what we find in rocks like the black igneous rock basalt, will typically begin to solidify by forming crystals of the magnesium silicate olivine forsterite at temperatures below 1900 degrees Celsius.

- In rocks of the type found on Earth—on the Moon and in many achondrite meteorites—we find that beautiful tiny green crystals begin to grow in the magma as microscopic seeds. These small crystals grow larger and larger as the temperature cools, first to the size of a BB, then a pea, and then a grape.

Olivines are any member of a group of common magnesium, iron silicate minerals.

- Then, a really interesting phenomenon kicks in that changes the game. Olivine is typically slightly denser than the liquid in which it crystallizes, so those first forsterite crystals began to sink, and they settled faster and faster as the crystals grew larger and larger. Eventually, huge, deep masses of nearly pure olivine crystals accumulated at the bottom of a magma chamber to form a stunning green rock called dunite.

- On Earth today, this rock is relatively uncommon. It appears in large bodies at the surface only when rocks cooled and settled fairly near the surface or when mountain-building activities of uplift and erosion exposed what was once a deeply buried horizon of this distinctive, deep olivine cumulate.

- During the continuous removal of olivine crystals, the crystals of Mg_2, Si, and O_4 in the melt have a different composition than the bulk melt, so their removal depletes the melt in magnesium and silicon and thus increases the proportions of calcium, aluminum, and iron. When the magma ocean began to cool on the Moon more than 4 billion years ago, anorthite began to form.

- This second mineral, the calcium aluminum silicate member of the common feldspar family of framework minerals, formed blocky, pale-colored crystals. However, unlike olivine, anorthite was significantly less dense than its host liquid, so anorthite crystals tended to float.

- Great volumes of anorthite popped to the surface of the Moon's magma ocean to form a thick crust made almost entirely of floating feldspar crystals—a rock known as anorthosite. In spite of hundreds of millions of years of subsequent basalt volcanism, which form the splotchy dark "seas" on the Moon's surface, the prominent whitish-gray anorthosite accumulations still dominate 65 percent of the Moon's reflective silvery face.

- Earth is wetter in composition to the Moon, and it has deeper magma oceans and correspondingly greater internal temperatures and pressures. A small amount of anorthite probably crystallized early in Earth history in some near-surface, low-pressure environments, but anorthosite was a rather minor rock type on Earth.

- Instead, the second silicate mineral to crystallize on Earth was the magnesium-rich pyroxene enstatite, the most common of the chain silicate minerals. Enstatite comingled with olivine in a thick crystal slush that formed magma chambers tens of kilometers beneath the surface and gradually cooled to the earliest major rock type on Earth—a hard, greenish-black rock called peridotite.

- Several varieties of peridotite began to crystallize throughout Earth's outer 80 kilometers, different varieties at different depths. Peridotite production probably commenced more than 4.5 billion years ago, and it continued as a dominant igneous process for many hundreds of millions of years.

- In spite of this prominence early in Earth's history, peridotite is relatively rare at the surface today. It's likely that rafts of peridotite did harden and cool to form Earth's very first rigid, black surface, but that crust was unstable and therefore transient. That instability arises because cooling peridotite is significantly denser than the hot magma ocean on which it tried to float.

- Consequently, the thin peridotite surface layer cracked and buckled, and big chunks sank back into the mantle. As masses of peridotite plunged downward, they displaced more magma that cooled to form more olivine-pyroxene peridotite.

- In this way, a kind of peridotite conveyor belt operated in Earth's outer 80 kilometers, perhaps over a span of hundreds of millions of years. By this process, the crust and uppermost mantle slowly solidified. Throughout this process, the ratio of dense solid peridotite to liquid silicate magma increased, until the upper mantle was mostly solid olivine-pyroxene rock.

- A similar scenario of cooling and crystallization must have played out deeper in the mantle, albeit more slowly. Experimental petrologists are still uncertain of all the details, but more difficult experiments at higher pressures and temperatures reveal that separation of crystals from melts by both sinking and floating were probably instrumental in deeper domains, just as they were in nearer surface environments.

- Much of what we know of the composition and structure of the upper mantle comes from detailed seismological studies. Exacting measurements of seismic wave velocities are consistent with a peridotite-dominated upper mantle that extends down to approximately 400 kilometers. That's the depth at which pressure transforms olivine into the denser wadsleyite structure, which is the dominant mineral in the transition zone.

- This transition from olivine to wadsleyite—and, hence, from peridotite to denser rocks—is relatively sharp. The exact depth of the transition zone varies by 15 or 20 kilometers from place to place; it's generally deeper beneath the continents than the oceans, for example.

Earth's First Rocks: Basalt

- The grand story of Earth's mineral evolution is framed by a preordained succession of igneous rock types, each type followed inexorably from the previous one. Peridotite was Earth's first crust-forming solid. That was a critical but rather brief juvenile phase that arose directly from the crystallization of olivine and pyroxene from the well-mixed primordial magma ocean.

- That peridotite surface, once cooled and hardened, was much too dense to remain at the surface; it quickly sank back into Earth's depths. For a crust to survive billions of years, it had to be tough, but it also had to be a lot less dense than peridotite. The igneous rock known as basalt fit the bill.

- Basalt dominates the crust of every terrestrial planet, and the Moon's dark "mares"—which means "seas"—are frozen, flat plains that were once black basaltic lakes. Earth is no different. About 70 percent of the surface—primarily all of the crust underlying the entire ocean—is a layer of basalt several kilometers thick.

- Basalt comes in several important varieties, but all kinds of basalt are dominated by two silicate minerals. The first key mineral is a feldspar called plagioclase—anorthite is the calcium end-member of the plagioclase series, but plagioclase feldspar in basalt often contains a significant amount of the sodium end-member as well. Because of its importance in basalt and other common rock types, feldspar is by far the most important aluminum-bearing mineral in terrestrial planets and moons, and it is Earth's most common crustal mineral.

- The second essential basalt mineral is pyroxene, the same common chain silicate group that is found in peridotite. The pyroxene in peridotite was enstatite, close to the simple end-member composition $MgSiO_3$. However, the pyroxene structure is extremely adaptable, and it can accommodate many other elements as well.

- In fact, pyroxene is one of a handful of common minerals that commonly incorporates all of the big six elements. In basalt, the pyroxene (or pyroxenes, because sometimes there are two different kinds) displays much of the complex chemical character of the magma from which it forms.

- Peridotite begins to melt at about 1100 degrees Celsius, though the exact temperature is quite sensitive to the volatile content of water and carbon dioxide. The chemical composition of the first droplets of melt differs significantly from that of the bulk peridotite. A key difference is that the liquid of peridotite's first melt is much less dense than peridotite itself.

- Consequently, even a small amount of partial melting—as little as five percent—can produce a melt that concentrates along mineral grain boundaries, accumulates in fissures and pockets, and rather easily rises toward the surface. That magma, nothing more than partially melted peridotite, will become basalt. The production of basalt by partially melting peridotite has occurred continuously for most of Earth's history, generating hundreds of millions of cubic kilometers of basalt in the process.

Suggested Reading

Bowen, *The Evolution of the Igneous Rocks*.

Hazen, *The Story of Earth*, Chapter 3, 63-67.

Philpotts and Ague, *Principles of Igneous and Metamorphic Petrology*.

Rollinson, *Early Earth Systems*.

Yoder, Jr., *Generation of Basaltic Magma*.

Questions to Consider

1. What are the three major types of rock, and how do they form?

2. What is meant by the "rock cycle"? What cycles?

Origins of the Oceans

Lecture 19

Water is an amazing substance that has transformed Earth's surface in many ways: erosion, weathering, transport, and ultimately life. On Earth, volatiles deep in the mantle were brought to the surface through intense explosive volcanism—events that ultimately produced the oceans and atmosphere. Water is a polar molecule, which accounts for many of its distinctive properties, including its relatively high melting temperature, its ability to form raindrops, and capillary action in plants. In fact, Earth is not alone in the universe as a wet place; studies of other bodies, from our neighboring planets to distant galaxies, reveal a wet universe.

Earth's Oceans

- In all of the earliest stages of Earth evolution, heat was the principal agent of change. Heat caused the entire planet to melt and thus divided the denser iron core from the less dense silicate mantle and crust. Volcanism, also driven by heat, separated the volatiles that would eventually become oceans and atmosphere from the rocks.

- Earth's earliest history is marked by a succession of heat-driven element separations. It was because of heat that Earth spent a brief part of its infancy as a blackened, basalt-covered world. But that phase couldn't last long on a volatile-rich planet. The globe was about to be enveloped by a new volcano-born layer of brilliant blue.

- We can deduce a general picture of Earth's initial cooling and the subsequent release of volatiles to form the atmosphere and oceans, but much of what we deduce boils down to informed speculation based on lab experiments and computer models. Hardly any rocks are known to have survived from the Hadean Eon.

- One thing is very clear: With active volcanism and abundant volatiles, Earth could not remain black and dry for long. Thundering volcanic vents blasted hot nitrogen, carbon dioxide, and water vapor into the thickening atmosphere at rates of many millions of tons per day.

- The volatile atmophile elements and compounds—the atoms and molecules that are gases in our atmosphere—were the same atoms and molecules that formed all the different ices of the former solar nebula. In fact, they are the same atoms that contribute to all the tissues of your body. And those volatiles have played many roles throughout Earth history, including in the rapidly evolving Hadean Earth.

- Hot water played several crucial roles in the evolution of rocks and minerals. Water and carbon dioxide mixed with magma, which lowered the melting temperatures of the rocks significantly and turned the liquid rock into a superheated soup that more quickly ascended to the surface.

- Once that water-saturated magma came close enough to the surface, all the dissolved gases transformed rapidly and violently from liquid to expanding gas. The resultant massive volcanic explosions were like mountain-scale replicas of a shaken warm soda can. Rocks and magma and ash were blasted across the countryside.

- Water-rich fluids associated with magmas played another key role: They dissolved and concentrated all sorts of rare elements that don't find a ready home in the common rock-forming silicates. The light elements lithium, beryllium, and boron were concentrated in the hot liquid water phase.

- Many of the elements that form common saltlike minerals also entered the aqueous phase: sodium and chlorine, as well as fluorine, sulfur, and potassium. So did rare metal elements like silver, gold, and uranium, and many more that would eventually become concentrated in the world's great ore bodies.

- As bodies of water accumulated in larger and larger volumes, water began to shape the surface in ways that volcanoes and meteorites never could. Roaring rivers cut deep valleys while crashing waves ate away at shorelines. Water thus became the principal agent of rock erosion, which produced Earth's first sandy beaches along with ever-thicker accumulations of near-shore sediment wedges. Water quickly became the chief architect of Earth's surface.

- This focus on water—on oceans and atmosphere—can appear to reflect a rather anthropocentric view. Water is volumetrically a trivial fraction of the whole planet. All the oceans today represent only about two hundredths of a percent of Earth's total mass. The atmosphere is much less than that—about one part in a million of its bulk. But the oceans and atmosphere have always exerted, and they continue to exert, disproportionately great influences on our planet. H_2O, as much as any chemical, makes Earth what it is today.

The Properties of Water

- Water's many roles in Earth history are a consequence of the distinctive chemical and physical properties of H_2O, the oxide of hydrogen. Hydrogen is the first element of the periodic table, while oxygen is the eighth. Neither element has a magic number of electrons, so two hydrogen atoms share their electrons with one oxygen atom. The result is the V-shaped H_2O molecule, with a larger oxygen atom flanked by two smaller hydrogen bumps—an arrangement not unlike Mickey Mouse's ears.

- Given oxygen's propensity as an electron acceptor, it borrows the two electrons from the two hydrogen atoms and thus develops a slightly negative charge. The two hydrogen atoms develop a corresponding slight positive charge. An important consequence is that water molecules are polar—meaning that they have positive and negative electrically charged ends. That polarity accounts for many of water's distinctive properties and behaviors.

- Water is an excellent solvent because the positive and negative ends can exert strong electrostatic forces that tend to pull apart other molecules. That's why table salt, sugar, and many other chemicals dissolve so rapidly in water. It's also why the oceans are salty. Rocks can take a long time to partially dissolve, but over accumulated millions of years, ocean water has become enriched in virtually the entire periodic table of the elements.

- The amazing ability of water to dissolve and transport other chemical compounds is what makes it such an ideal medium for the origins and evolution of life. All known life on Earth—and some researchers argue, all possible life in the cosmos—is dependent on water.

- The polarity of water molecules dramatically affects the properties of both liquid water and ice. Water molecules bond strongly to each other, as the positive side of one water molecule attracts the negative sides of other molecules. As a result, ice is unusually strong for a molecular solid.

- Ice also has an unusually high melting temperature for a small molecule: Ice won't melt until 32 degrees Fahrenheit, compared to –108 degrees for solid ammonia (NH_3); –109 degrees for solid carbon dioxide, or dry ice; and –297 degrees Fahrenheit for methane, or natural gas (CH_4).

- Another consequence of water's unusually strong intermolecular forces is its high surface tension, which is a fascinating property that allows small insects to walk on water. Surface tension also facilitates capillary action, which is the ability of water to rise up against the force of gravity through the stems of vascular plants.

- Another phenomenon related to surface tension is rounded raindrops, which are drawn into their shapes by the strong mutual attraction of water molecules. Raindrops are absolutely vital to maintaining Earth's unusually rapid water cycle. It turns out that nonpolar molecules like methane and carbon dioxide can't form droplets easily, so they would just float in the atmosphere as a fine, pervasive mist. Rain might be unlikely on a planet without a polar atmospheric molecule, so the cycling of volatiles would probably be much slower and certainly different in character.

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Raindrops are rounded in shape because of the strong mutual attraction of water molecules.

- Strong bonding between water molecules leads to another of water's curious and critical properties. It turns out that liquid water is 10 percent denser than solid ice—which is odd. In almost every other known chemical compound, the solid state is denser, so crystals sink in their liquid. That situation is intuitively logical, because a repeated packing of the same molecules in a crystal contrasts with the more random distribution in a liquid.

- However, the V-shaped H_2O molecules actually pack more efficiently in their random liquid state than in orderly ice crystals, and important consequences follow: The ice floats. Were it not for this curious trait, rather than forming a relatively thin surface layer of ice, many bodies of water would freeze solid, bottom to top. Aquatic life would be severely challenged in cold regions of such a frozen world, and the vital water cycle would certainly come to a screeching halt once everything was solid.

- Another really interesting characteristic of water, even so-called pure water, is that it isn't ever pure H_2O. No matter how carefully you might filter or distill water, it's never made entirely of H_2O

molecules. Inevitably, a very small fraction of those three-atom units break apart into two smaller units. There are positively charged hydrogen ions, or hydrons—H+ ions, which are nothing more than individual protons without any electrons attached. There are also negatively charged hydroxyl groups, or OH–molecules.

- Because hydrons have positive charges, the hydrons quickly latch onto the more negative oxygen end of water molecules to produce H3O+, or hydronium ions. So "pure water" at room temperature and pressure has negative hydroxyls and positive hydroniums. And these components have to occur in equal concentrations to maintain the totally neutral electrical charge—a requirement of any liquid.

- It turns out that the concentration of positive hydronium and negative hydroxyl groups is about one part in 10 million. In chemical terms, that's 10^{-7} of a mole of hydroxyl and hydronium per liter of water. This arcane concentration measurement is usually reported as a power of hydrogen, or pH, of 7. The definition of pH is as follows: the negative logarithm of the hydrogen ion concentration, expressed in moles of H+ per liter of solution.

- When describing any body of water, and Earth's oceans are a prime example, a major focus is the bulk composition—both the pH and the salt content. It turns out that these two chemical properties are closely related. The changing pH and salinity of Earth's ancient oceans remain topics of debate.

- Studies of many objects in space, from distant and ancient galaxies to nearby planets, reveal that water is an abundant molecule throughout the universe. Mercury and Venus are much drier than Earth, but Mars has significant near-surface water. However, the study of the nature and extent of those resources on Mars had to wait until a variety of space probes reached the Martian surface.

Suggested Reading

Brutsaert, *Hydrology*.

Hazen, *The Story of Earth*, Chapter 4, pp. 77–101.

Hazen and Trefil, *Science Matters*.

Valley, "A Cool Early Earth?"

Questions to Consider

1. What are some of the distinctive physical and chemical characteristics of water?

2. How widely distributed is water in the solar system?

Blue Earth and the Water Cycle

Lecture 20

Recent studies by planetary probes and of samples from Mars and the Moon reveal that water is commonplace in our neighboring worlds. On Earth, water cycles rapidly in the near-surface environment among several major repositories: The oceans dominate, while ice caps and glaciers, groundwater, lakes and rivers, and the atmosphere also play key roles in the water cycle. Water is even more abundant on Earth than once thought: Recent studies of high-pressure minerals suggest that deep hydrogen reservoirs may hold the equivalent of 80 times all the oceans.

Water on Mars

- One of the most important discoveries about Mars—a finding that has only come into focus in the early 21st century—is that Mars has a lot of water, most of which occurs as subsurface permafrost and maybe some groundwater in deeper zones where it's warm. These hidden repositories are potentially huge, and they are for the most part isolated from the dry outermost layer.

- The first substantive hints of the true extent of subsurface water came in 2002 from the *Mars Odyssey* spacecraft. In 2007, NASA's *Mars Reconnaissance Orbiter* offered a much higher-resolution picture of the buried water by employing ground-penetrating radar. These pioneering measurements pointed to vast glacier-scale underground accumulations of water ice in the mid-southern latitudes.

- More recent similar measurements by the European Space Agency's *Mars Express* orbiter point to deep ice across much of the planet. There are places near the south polar ice cap, for example, with ice-rich zones more than 1,500 feet thick. It now appears that Mars has enough near-subsurface frozen water to form a globe-spanning ocean hundreds of feet deep.

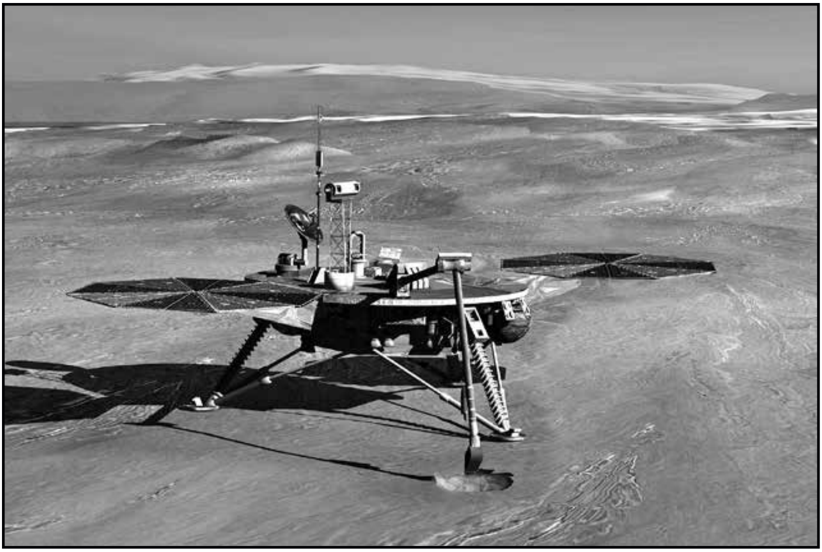
- Distinctive rocks and minerals on Mars also point to the presence of abundant water on the Red Planet. NASA's *Phoenix* lander—and its amazing two rovers, *Spirit* and *Opportunity*—fed scientists wonderful data for years beyond their projected lifetimes, and they detected a variety of such mineral evidence.

- Then, NASA's *Curiosity* rover began doing the same. Water-rich clay minerals, which suggest rock weathering in the presence of water, turn out to be rather common in the near-surface environment of Mars. Much of the near-surface hydrogen-rich material observed by *Mars Odyssey* were probably clay minerals.

- Equally compelling are so-called evaporite minerals, which are characteristic of dried up lakes or oceans. A variety of these minerals, notably flat deposits of distinctive sulfates, point to dried up bodies of water. Opal—which is a poorly crystallized variety of quartz that typically forms in wet sediments, commonly on the ocean floor—is also found on Mars.

- There's much more evidence for water at the local and planetary scales, evidence that water once flowed freely across the sculpted Martian surface. The highest-resolution photographs of the Martian surface—for example, those obtained by telescopic cameras on NASA's *Mars Global Surveyor* and *Mars Reconnaissance Orbiter*—reveal clear signs of rivers: ancient boulder-strewn, branching valleys and systems of gullies; teardrop-shaped islands in ancient riverbeds; water-induced, slumping features on steep hillsides; and even complex, braided stream channels. All of these landforms are diagnostic of flowing water.

- In addition, many of those features cut through layers of sediment reminiscent of Earth deposits laid down in shallow lakes or seas. There's even a suggestion of a global high-water mark, where such a body of water may have left ancient beach-like terraces. These characteristic landforms girdle the northern hemisphere of Mars, which happens to be topographically quite a bit lower than the southern hemisphere.



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NASA's *Phoenix* lander—with its two rovers, *Spirit* and *Opportunity*—explored the polar region of Mars.

- Some planetary scientists conclude that one continuous ocean covered most of the northern latitudes—more than a third of the Martian surface—to an average depth of 1,800 feet. If that's true, then it's quite possible that Mars may have been a blue, ocean-covered, life-giving planet many millions of years before Earth.

- Whatever water Mars has left, it's a lot less than the way it started. Gravity—or, rather, the lack thereof—is the culprit. Mars is too small to hold onto its hydrogen. Water molecules evaporate, but they're a bit too massive to just fly off into space. The trouble is that cosmic rays split the water in two—into one OH molecule and one H atom. That isolated hydrogen atom can fly off into space.

- Over a span of billions of years, Mars has lost a lot of hydrogen, and that translates directly into losing a lot of water. Only the water locked deep beneath the surface is immune from this kind of loss.

Water on Earth's Moon

- Mars may have a lot of water, and it may have once had a lot more, but the Moon appears to have always been a dry place. Several lines of evidence support this contention of a dry Moon. First, Earth-based telescopes find no characteristic infrared absorption. Even more convincing, the *Apollo* Moon rocks had no traces of water, at least according to the analytical capabilities of the 1970s. The fact that iron metal persists on the lunar surface for 4 billion years is yet another indication that there's not even a trace of corrosive water.

- However, two new findings provide convincing evidence that the Moon is not as dry as we once thought. Spacecraft observations of the Moon's surface provide one line of evidence that's not too surprising. We know that comets must slam into the Moon from time to time, and when they do, some water must be added to the surface. A lot of that water must gradually escape back into space, but if a comet strikes near one of the Moon's poles, then some ice could concentrate in a perpetually dark crater floor—the coldest places on the Moon's surface. Temperatures never get close to the melting point of water, so ice could persist.

- The first hints of such crater floor ice came from a single flyby of the *Clementine* mission in 1994. Radar measurements were consistent with deposits of water ice, but many planetary scientists were unconvinced.

- The *Lunar Prospector* spacecraft, employing neutron spectroscopy four years later, detected significant concentrations of hydrogen atoms—a sign of either water ice or hydrous minerals near the poles. That result also raised objections. After all, there must be a significant accumulation of hydrogen ions implanted in the lunar soil by billions of years of the Sun's solar wind. That could be a more likely source of the signal.

- A decade later, some NASA scientists had the neat idea of smashing the big upper stage of an *Atlas* rocket—a 30-foot-long, 2-ton chunk of metal—into one of those craters near the pole and then looking at the impact debris for signs of water.

- The consequent mission, the *Lunar Crater Observation and Sensing Satellite* (*LCROSS*), targeted a shadowed south polar crater called Cabeus. The impact took place on October 9, 2009, and it produced a fair-sized plume of dust and debris visible in Earth-based telescopes. There was a small but significant amount of water.

- All of this renewed interest in lunar water led to yet another discovery, this time in old data. Roger Clark of the United States Geological Survey reexamined data collected during a lunar flyby on August 19, 1999, by the *Cassini-Huygens* mission, which was on a five-year journey to study Saturn. It turns out that *Cassini-Huygens*'s infrared camera had picked up clear evidence of lunar water.

- The discoveries by *LCROSS* and *Cassini-Huygens* were further reinforced by another mission—the Indian *Chandrayaan-1* spacecraft, which conducted its own infrared observations of the lunar surface.

- Then, there were findings that the *Apollo* Moon rocks contained previously undetected water, which suggested that the Moon's total water might be even greater. Most of the original water has been lost: A great deal of water certainly boiled off during earlier volcanism, and a lot more water has gradually evaporated to space over billions of subsequent years of lunar history.

- Based on the water that remains, researchers have calculated that the magma's original water content may have been as high as 750 parts per million. This is comparable to the water content of many volcanic rocks on Earth, and it's more than enough water to drive explosive volcanism. In addition, if that much water drove explosive volcanism on the Moon billions of years ago, then a lot of water must still be stored somewhere deep inside the Moon today.

Earth's Water Cycle

- Two ongoing processes—subduction, by which old crust is swallowed up by the mantle, and volcanism, by which mantle material generates new crust—have tremendous effects on the water cycle.

- Earth's water cycle involves ongoing exchanges of water molecules among several major reservoirs.
  - The oceans are the largest water reservoirs, holding more than 96 percent of available water.

  - Ice caps and glaciers now hold more than 3 percent of Earth's near-surface water; that amount can increase to as much as 6 percent during ice ages.

  - Most of the non-salty water available for consumption is in groundwater.

  - Lakes, rivers, streams, and the atmosphere account for only about 0.01 percent of all near-surface water.

  - Life holds a very small fraction of all water, but it plays a significant role in the water cycle.

- High-pressure experiments employing big presses and small diamond-anvil cells reveal that many common minerals incorporate hydrogen atoms—the chemical equivalent of water—at mantle and core conditions.

Suggested Reading

Brutsaert, *Hydrology*.

Hazen, *The Story of Earth*, Chapter 4, pp. 77–101.

Trefil and Hazen, *The Sciences*.

Questions to Consider

1. What evidence from space missions suggests that water is present on Mars and the Moon?

2. What are the major reservoirs of water on Earth, and how does water move among them?

Earth and Mars versus Mercury and the Moon

Lecture 21

At 4.4 billion years, Earth was a water world, almost completely covered in ocean. That water dramatically altered the course of mineral evolution. As the first rains fell, Earth's surface cooled, and low-lying basins filled to form the first lakes, then seas, and ultimately a globe-spanning ocean that submerged almost everything except for a few tall volcanic peaks. In this lecture, you will learn about how minerals—particularly the difference in near-surface mineralogy of Earth and the Moon—provide important clues about what happened to all the water.

Where Is Earth's Missing Water?

- The oceans hold a lot of water, but they represent only a miniscule fraction of what would be found in a similar mass of volatile-rich CI chondrites—the most primitive carbon-rich type. Recent findings suggest that lots of water might be stored at depth—perhaps 80 times the water found in all the oceans. But even that prodigious amount of water pales beside the multiples more of water that meteorites suggest must have once been there.

- From the earliest days on Earth, volatiles were released in huge quantities from the deep interior as mega-volcanoes pumped water, carbon dioxide, nitrogen, and other gases into a rapidly thickening atmosphere. Water would have rained down onto the cooling surface, possibly forming wide, shallow seas near the poles within a few tens of millions of years.

- Then, the big thwack blasted all the atmosphere and incipient oceans away. Almost every molecule of water and air that had found its way to the surface was lost to space, with remnants initially sequestered in ways we are only beginning to detect on the Moon. For Earth, the impact of Theia was like a giant reset button—back to a globe-encircling magma ocean and absolutely no atmosphere or oceans.

- For another half of a billion years, hundreds of smaller-scale impacts of objects from 10 to 100 kilometers in diameter caused disruptions. Each of those events vaporized more of the oceans and may have ejected significant quantities of volatiles into space.

- Following the Moon-forming event, but still within Earth's first 100 million years—about 4.45 billion years ago—water vapor had become a significant part of the atmosphere. Somewhat like Jupiter today, Earth's rapid rotation produced severe wind shears and violent weather. Thickening, turbulent dark clouds were accompanied by howling winds, shattering lightning, and unceasing torrential rain.

- As the surface of this storm-lashed land gradually cooled and hardened, low-lying basins gradually filled with water. What would become the oceans slowly formed. Volcanoes were everywhere, and magma poured out onto the surface. For a time, the expanding ponds and lakes must have caused a global sauna.

- Surface waters penetrated cracks and fissures, where they contacted the hot rocks below and returned to the surface as gargantuan geysers of roaring steam and superheated water. One important consequence of these intense water-rock interactions was to speed up crustal cooling, which led to the accumulation of even deeper lakes, then seas, and ultimately oceans.

- Rocks older than 3 billion years are rare on Earth, and we don't know the exact timing of the first ocean's formation, but provocative evidence is now emerging in the form of Earth's oldest crystals. For example, zircon crystals survive billions of years, endure many cycles of erosion and deposition, and can preserve details of the age, temperature, and water content of their original environment.

- Most experts agree that relatively shortly after Earth's formation, probably no more than 100 to 200 million years after the Moon's formation, Earth had become a water world with an almost continuous, kilometer-deep, encircling ocean.

Earth's First Ocean

- Earth's first ocean was probably a lot hotter than today's ocean, given the global magma ocean beneath. In addition, it was probably salty. Salt is the most distinctive property of ocean water today, but it might seem logical that Earth's first ocean started out with few dissolved chemicals—as freshwater. In fact, recent evidence suggests that the salinity of the first ocean may have been twice that of the modern world.

- Atmospheric carbon dioxide, coupled with salinity, controls the ocean's pH. Most experts agree that the CO_2 content of the early atmosphere was at least hundreds, if not thousands, of times higher than today. Much more CO_2 in Hadean air also meant much more CO_2 in the water.

- As a result, this water was probably acidity, perhaps having a pH as low as 5.5. Such acidic conditions have a chain of consequences: For example, acids accelerate the weathering of basalt and other rocks, which adds even more salts to an already salty ocean.

- According to a growing body of astronomical observations and astrophysical calculations, a star like our Sun undergoes a very slow brightening over its 10-billion-year lifetime. By current estimates, the young Sun 4.4 billion years ago was only about 70 percent of its current brightness—a state that persisted for at least another 1.5 billion years.

- If the Sun were suddenly to dim today by that extreme amount—20 percent or more—then Earth would rapidly go into a disastrous ice age, perhaps freezing solid from the poles almost to the equator. So did Earth freeze over?

- Evidence for abundant surface water at least as far back as 3.5 billion years is unambiguous. Geologists find substantial layers of water-deposited sediments from both shallow-water and deepwater environments. In addition, fossil evidence reveals that life began and thrived at that time. But did the ocean remain liquid?

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The Dead Sea, the lowest body of water on Earth's surface, is one of the world's saltiest bodies of water.

- A much hotter Earth must have helped. It took a long time for the primordial magma ocean to cool, and there was a lot of hot molten rock and other volcanic activity to keep the surface warm. But that wasn't enough to keep things unfrozen for half a billion years.

- The leading hypothesis to explain the faint Sun paradox is an exaggerated greenhouse warming effect caused by the extremely high atmospheric concentrations of carbon dioxide. A second clever idea is that Earth—in its early black, then blue, phases—must have absorbed much more of the Sun's energy than the surface does today. Yet another hypothesis suggests that the early atmosphere had a significant concentration of methane, CH_4, which could affect global climate in a few different ways.

Stage 3 of Earth's Mineral Evolution

- Stage 3 of Earth's mineral evolution begins with the formation of Earth's black crust and the birth by volcano of the global ocean and atmosphere. Up to this point, minerals have formed before the planet as a whole: first, a dozen ur-minerals in the cooling envelopes of big stars; then, stage 1, with 60 or so minerals that condensed in primitive chondrites; and stage 2, with about 250 different mineral species from planetesimals that experienced differentiation and alteration by heat, water, and impacts.

- All of those minerals still fall to Earth and the other planets and moons of our inner solar system. All of those 250 species have been present continuously at or near the surface of Earth since the crust first hardened.

- The third stage of mineral evolution requires a planet-sized body. This makes possible the crystallization of peridotite, the partial melting of peridotite to form basalt, and the production of residual melts and other fluids concentrated in rare elements that had not previously played much of a role in mineral evolution.

- All terrestrial planets (as well as Earth's big Moon) participated, at least part of the way, in this next stage. In all of these rocky bodies, magmas produced new kinds of silicates, including the chain silicate group called amphiboles. Silicate minerals in the familiar garnet group are a good example, because they are found in minor quantities across many kinds of rocks.

- New minerals of the elements titanium, manganese, sulfur, and chlorine also are likely to have formed. Altogether, igneous processes may have resulted in another 100 species, for a grand total of perhaps 350 minerals.

- That's it for Mercury—and probably the Moon as well. The Moon might differ in some way because of its early collision with Earth, but we haven't found any other mineral-forming processes that would have diversified those relatively small, dry worlds on their own. There simply wasn't enough internal heat or water to drive the cycles of melting and freezing that are so critical to separating and concentrating elements.

- It is estimated that all the mineral diversity that would ever be on the Moon and Mercury was achieved more than 4 billion years ago.

The story for Earth and Mars is quite different. Those planets are a lot wetter than Mercury or the Moon—or Venus. This difference caused a divergence in their mineral evolution.

- Water enhances mineral formation in at least three ways. First, water dissolves a variety of elements and thus holds the potential to transport those elements from one place to another. In addition, water greatly lowers the melting point of rocks, which means that a planet's inner heat can accomplish more in the way of partial melting and fractionating rocks. Finally, a huge number of mineral species on Earth incorporate water—almost 60 percent of all known mineral species are hydrous—so a wet planet can make a much greater diversity of mineral species than a dry one.

- Fluids are the real key to mineral evolution of stage 3, and even stages 4 and 5. New minerals arise when dozens of different elements that initially are extremely rare become concentrated in one fluid or another, including molten magma, a hot-water-rich liquid, or something more exotic enriched in sulfur or carbon. It just needs to be a fluid that separates from the magma or the solid rock.

- A part per million of uranium or beryllium, or a part per billion of mercury or cesium, simply cannot form a separate mineral. But if you repeatedly concentrate those elements into a fluid—hot, salty brine, for example—then you can achieve concentration factors of a billion times or more. That's exactly what happened on Earth and, to a lesser extent, on Mars.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 4, pp. 77–101.

Philpotts and Ague, *Principles of Igneous and Metamorphic Petrology*.

Rollinson, *Early Earth Systems*.

Yoder, Jr., *Generation of Basaltic Magma*.

Questions to Consider

1. Why are there fewer kinds of minerals on the Moon and Mercury than on Earth or Mars?

2. What is the relationship between granite and basalt?

Gray Earth—Clays and the Rise of Granite

Lecture 22

Heat and water drove the mineral evolution of Earth's outer layers. As rocks are heated from below, they partially melt. The key to rock and mineral evolution is that the composition of the partial melt is very different from the original rock, and the resulting minerals are much less dense. Thus, black basalt partially melts to produce hard, gray granite—the bedrock of continents. At 4.4 billion years, Earth was a water world, almost completely covered in ocean. But granite formation led to the first significant landmasses, as less dense granite bodies floated on basalt. Such granite landmasses became the cores of protocontinents.

Stage 4 of Mineral Evolution

- Clay materials are perhaps the most distinctive water-bearing minerals at the surface of any wet planet. They are a rather broad class of minerals that don't have a precise definition, but the familiar look and feel of clay are explained by two key formal criteria for identifying clay minerals.

- First, at a minimum, all clay minerals are extremely fine grained, with typical particle sizes of about one micron. The second essential characteristic is that all valid clay minerals have to have a layered atomic structure with silicate tetrahedra linked in flat sheets. In other words, clays are members of the layer silicate structural group. These layers are what allow clays to be so slippery.

- One of the exciting discoveries of recent Mars missions is that the surface of Mars is covered with clay minerals. Satellites in orbit around the planet measure the way light is reflected off the surface—the way that certain wavelengths are reflected and other wavelengths are absorbed. This is known as a reflectance spectrum, and clay minerals have distinctive reflectance spectra. In fact, each major group of clay minerals has a slightly different spectrum, so planetary scientists have now mapped large areas of the Martian surface according to the dominant kind of clay.

- By adding up all the hydrous minerals that might have formed on Mars—the hydrated evaporite minerals like sulfates, hydroxides, and clay minerals—there might be an additional 150 minerals that couldn't have formed on dry Mercury or the Moon. In total, there are a dozen ur-minerals, 60 chondrite minerals in stage 1, 250 minerals in stage 2, and 350 minerals on Mercury or the Moon. Add 150 water-rich minerals, and we're up to 500 stage 3 minerals on Mars and Earth.

- But that's where Earth and Mars part ways, because Earth is a much larger planet, and it has a lot more internal heat. Earth's extra heat added to the water equals more mineral diversity; Earth was about to double in mineral diversity, which leads to stage 4 of mineral evolution: the formation of granite and the origins of the continents.

- About a third of Earth's surface is taken up by the continents—but that hasn't always been true. Very early in Earth's history there were no continents, and it must have taken a long time to build them up.

- The growth of continents was a huge step in the episodic differentiation of Earth into zones of distinct composition and character. Differentiation was a sequence of chemical and physical processes that began long before Earth formed. Over and over, the chemical elements that once formed our solar nebula have been separated and concentrated into new zones.

- At the biggest scale of the solar system, the inner rocky planets—Mercury, Venus, Earth, and Mars—became concentrated in such elements as magnesium, iron, silicon, and oxygen as intense solar winds swept gaseous hydrogen and helium away from the heavier elements. Those lighter elements became concentrated in the distant domain of the gas giant planets—Jupiter, Saturn, Uranus,

Clay materials, which are water-bearing minerals, are often used in construction.

and Neptune. So the rock-forming elements were separated from the lightest gases.

- Then, on Earth, the dense metallic elements iron and nickel separated by gravity to the core, while Earth's mantle became correspondingly enriched in magnesium silicates. The main rock type in the mantle is peridotite—named for the magnesium silicate olivine, or peridot in its gemstone form. The chemical formula of olivine is Mg_2SiO_4, so the bulk mantle composition is about two-to-one magnesium oxide to silicon oxide, with smaller amounts of calcium and aluminum. That means the mantle is on average about one-third silicon oxide.

- The next big stage of element separation occurred when peridotite was partially melted in the mantle to produce basalt. The resulting basaltic magma is relatively enriched in calcium, aluminum, and silicon.

- The dominant minerals in basalt are pyroxene and feldspar; these minerals have about a one-to-one ratio of silicon oxide to magnesium oxide plus calcium and aluminum, so basalt is about 50 percent silicon oxide—compared to about 33 percent silicon oxide for peridotite. Basalt is also about 10 percent less dense than peridotite, so basalt magma rose to the surface to make the first crust.

- Another episode of element separation occurred when basalt erupted explosively onto Earth's surface. Water and other volatiles quickly separated from the basaltic magma as superheated steam and other gases. These gases cooled to form the first oceans and the atmosphere. So Earth became even more layered—solids, liquid, and gases—and each layer had its own chemical composition.

Granite and Continent Formation

- The story of continent formation, which is also the story of granite, repeated the fruitful history of element separation and concentration through heating. As the outermost crust of black basalt cooled and hardened, it created a lid-like cover that trapped Earth's inner heat. Inevitably, as the basalt crust thickened and was heated more and more, it began to partially melt, just as peridotite had partially melted before.

- This wet crustal basalt, as it was reheated from below, started to melt at relatively low temperatures. As with peridotite, basalt didn't melt all at once. As heat built up, the percent of basalt melting gradually increased. In an echo of the way peridotite melts, the resulting magma was quite different in composition from the basalt that was melting.

- Most strikingly, this new melt was much, much richer in the element silicon. This partial melt also concentrated the alkali elements sodium and potassium. Those elements, located in the first column of the periodic table, are enthusiastic electron-donating elements. This new silicon-rich magma was at least 10 percent less dense than the basalt from which it was produced, so the magma inevitably pushed its way toward the surface, forming an entirely new kind of crustal rock called granite.

- A key characteristic of the magma that formed granites is its ability to incorporate water in a hot fluid that also selectively concentrates dozens of rare trace elements—beryllium, lithium, uranium, zircon, tantalum, boron, cesium, rubidium, and many more. The presence of all these rarer elements in concentrated form often leads to scattered, tiny grains of new, relatively rare minerals.

- Up until the formation of granite, Earth was pretty much like its planetary neighbors—Mercury, Venus, and Mars. All those bodies must have started with something like an iron core and a peridotite mantle, and all produced copious amounts of basalt that formed their black crusts. But with the partial melting of basalt and the formation of lots of granite, we see the first really significant divergence of Earth from those other inner planets.

- Granite formation not only requires a lot of basalt near the surface, but it also requires a lot of internal heat to remelt the basalt. Mars and Mercury are simply too small; they don't have enough heat. It's likely that relatively small volumes of granite have been produced on Mars and Mercury, but nothing like the deeply rooted granite continents of Earth.

- Venus is a lot larger and has correspondingly more inner heat than Mars or Mercury. But Venus also appears to be a lot drier than Earth. That means it's harder to melt basalt and harder to produce much granite. So Earth really does seem to be a mineralogically unique world in our solar system.

- The rise of granite on Earth caused a number of profound changes, not the least of which was the landscape. Black basalt, which formed Earth's primordial crust, was constantly softened by heat from below. With its average density about three times that of water, it never could support much topography. A few of the most actively growing volcanoes might have built mountains that rose a mile or more above the ocean, but there were probably no great mountain ranges—nor were there any extremely deep ocean basins—before the rise of continents.

- Granite has a significantly lower average density of about 2.7 times the density of water. That means granite floats on basalt and on peridotite. It can pile up in great mounds, rising miles above the surface like an iceberg floating on water.

- Granite is typically about 10 percent less dense than the basalt on which it rests. So as fresh granite piles up on top of the partially melted basalt crust, the granite forms mountains. These mountains are simply iceberg-like protrusions. Over time, as more granite accumulates to thicknesses of many miles, big mountain ranges miles high can form simply by this kind of buoyancy.

The Rise of Mountains

- A mountain is typically several cubic miles of rock rising way above the surrounding landscape, so there needs to be a really big force to counter gravity. Geologists see two basic ways to do this. The one that is more often invoked today is lateral tectonics. If two great masses of rock are pushed together from the sides, then they come together and form a mountain chain. That's one of the key ideas of the theory of plate tectonics.

- Early in Earth's history, it wasn't obvious how big lateral forces would have been generated. The crust was simply too thin, hot, and plastic—at least according to a lot of current thinking. Before the theory of plate tectonics, geologists believed in a different kind of mountain building called vertical tectonics, which is mountain building by buoyancy.

- The idea was that the power of buoyancy drives all kinds of geological change. Geologists called this buoyancy of some less dense rocks on top of other more dense rocks isostasy; the way a granite mountain rose up was called isostatic readjustment. It was a compelling explanation, but it was only partly true.

- Pretty early in Earth's history, perhaps within the first 100 million years, some modest-sized landmasses that were rooted by buoyant masses of gray granite must have begun to form. Earth's surface gradually became more interesting, with both black volcanic cones and gray granite islands. At this early time, with predominantly vertical mountain building, no obvious mechanism could have caused isolated granite masses to coalesce into expanses of dry land the size of today's continents.

Suggested Reading

Hazen, "The Evolution of Minerals."

———, *The Story of Earth*, Chapter 5, pp. 102–126.

Rollinson, *Early Earth Systems*.

Wenk and Buklah, *Minerals*.

Questions to Consider

1. How are new rocks and minerals formed by temperature from previous rocks and minerals?

2. Why is granite thought to be the foundation stone of Earth's early continents?

Earth's Mineralogy Takes Off—Pegmatites

Lecture 23

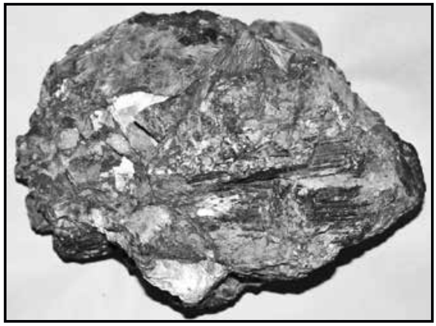
The central theme of this course is the story of Earth, but it's also the story of Earth materials—from rocks and minerals to the oceans and atmosphere. A recurrent theme in the evolution of Earth is the selective selection and concentration of the chemical elements. The most dramatic example of this process is the fascinating rock type called pegmatite. Many rare incompatible elements concentrate in the very last water-rich fluids to crystallize from a granite melt. These elements, including uranium, beryllium, lithium, tantalum, and many more, form hundreds of rare minerals in pegmatite.

Mineral Diversity

- One of the keys to all of the material diversity of our modern society is refining, which is the process of separating and concentrating useful chemicals from complex mixtures like petroleum, which contains tens of thousands of different kinds of organic chemicals all mixed together. The most common method of refining involves a tall distillation column that's hotter at the bottom and cooler at the top.

- Human activities today mimic what Earth has been doing for more than 4.5 billion years. Earth is like a giant still that is hotter in the center and cooler on the outside. That temperature gradient distills all the elements of the periodic table. The sequence of rock types that we've seen so far—first peridotite, then peridotite partially melting to form basalt, and then basalt partially melting to form granite—illustrates this point.

- Early in the history of the universe, there were only about a dozen different ur-minerals. Then came about 60 primary minerals in the chondrite meteorites, and more than 250 minerals as chondrites clumped together and were subjected to differentiation and alteration by water, heat, and impacts. And even after Earth formed and the surface cooled, there probably weren't more than about 500 different kinds of minerals. So the number of different materials on early Earth was rather limited.



Pegmatites containing lepidolite, tourmaline, and quartz can be found in the Black Hills of South Dakota.

- Pegmatites represent an extreme case of distillation. The definition of pegmatite is somewhat fuzzy, but basically, a pegmatite is an igneous rock with a mass of large crystals that formed near the end of the cooling process—usually the cooling of granite. Whereas the grains in granite are visible but small, in pegmatites, the grains are by definition at least half an inch in size and often as large as your fist.

- Because pegmatites represent the very last stages of crystallization, when sufficient water is present, they tend to concentrate all of the strange and rare chemical elements that don't easily fit elsewhere. And that means that pegmatites can form hundreds of rare minerals that simply don't occur anywhere else. In fact, with the advent of pegmatites, the mineral richness of Earth may have doubled from 500 to about 1,000 different mineral species.

- The key to understanding pegmatites is to see where elements fit comfortably into crystal structures. There are many elements that don't form minerals in peridotite, or in basalt, or in granite. And as you go from one of these rock types to the next, those so-called incompatible elements just keep getting more concentrated in the residual fluid—the part that doesn't solidify.

- The key is seeing which elements don't fit easily anywhere else—which ones are left over at the very end of the cooling process. As the residual liquid cools in a pocket, usually inside a larger body of granite, beautiful crystals of exotic minerals can grow to immense sizes. Topaz, tourmaline, aquamarine, and other gems are found in these pegmatite deposits. Hundreds of new mineral species formed in these rocks.

Rare Pegmatite Minerals

- It took more than a billion years of processing of crustal materials to sufficiently concentrate beryllium, element 4 of the periodic table, into fluids that could produce beryl and other beryllium minerals. It takes time, and it takes a lot of fluid-rock interactions.

- Such processes simply cannot occur on a relatively dry planet like Mercury or on the Moon, and they can't occur on a small planet like Mars that doesn't have enough internal heat to generate lots of granite. In fact, with the possible exception of Venus, Earth is probably the only planet in our solar system with all the conditions necessary to make beryllium minerals, as well as hundreds of other rare pegmatite minerals of other exotic elements.

- The next rare elements to form minerals after beryllium in many pegmatites are the twin elements niobium and tantalum. These two elements—numbers 41 and 73 in the periodic table, respectively—are both scarce, at concentrations of much less than a part per million in the crust, but they do have a few specialized commercial uses, notably as an alloying agent in corrosion-resistant steels. There are dozens of unusual niobium-tantalum minerals found in complex pegmatites, and these minerals constitute the principal ores.

- Like beryllium, lithium, which is element number 3 of the periodic table, is much rarer in nature than you might expect from its prominent position in the periodic table. Lithium is present in the crust at only about 20 parts per million, and it must be concentrated in late-stage fluids more than one-hundred-fold before it can begin to form its own distinctive minerals. That's because lithium is the only common element with a +1 charge that is comfortable in six-coordination with oxygen—called octahedral coordination, because the six oxygen atoms form a tiny eight-sided octahedron.

- There are a few other unusual elements that can become concentrated in pegmatite. One of the most important in terms of sheer mineral diversity is phosphorus, element 15 in the periodic table. Phosphorus is an extremely important element in nature, the 11th most abundant of all the crustal elements at about a tenth of a percent. Phosphorus is also a key element in life. When phosphorus becomes concentrated in a pegmatite along with many other more exotic elements, you suddenly get hundreds of new kinds of phosphate minerals that simply don't occur anywhere else on Earth—and probably don't occur anywhere else in our solar system.

- Many of these minerals are extremely rare, forming tiny crystals that only the most experienced mineral collectors can identify on sight. Some of these minerals form as colorful microscopic crystals in tiny open pockets, which reveal that at the very last stages of a cooling pegmatite, some of the minerals form from a hot vapor and probably not as a liquid.

- Boron, element 5, is yet another distinctive and relatively rare mineral-forming element. At only a twentieth of one percent of Earth's crust, boron is not a major rock former, but it does tend to concentrate into one of the most fascinating minerals in nature—or, rather, the group of minerals called tourmaline.

- Like lithium and beryllium, boron is unique in terms of its crystal chemistry. It is the only element that has a +3 charge and typically occurs in three-coordination with oxygen. Tiny BO_3 triangular clusters of atoms lead to numerous unique minerals, but the tourmaline group dominates in pegmatites and many other kinds of rocks as well. The complex tourmaline crystal structure has all sorts of atom sites—room for alkali metals, divalent atoms in six-coordination, silicon and aluminum, and more.

- In fact, more than 50 different chemical elements can find some kind of home in the accommodating tourmaline structure. That's why there are almost 20 different categories of tourmaline minerals, plus thousands of compositional variants.

- Tourmaline's individual crystals can also grow and change composition at the same time—a phenomenon called zoning. And those zones can be different colors. Tourmaline crystals, which usually are prisms with a roughly triangular cross-section, can be absolutely gorgeous. Some of the most amazing and beautiful crystals in nature are zoned tourmalines.

- The most amazing example of a pegmatite mineral is cesium, element 55, which is one of the rarest elements in nature to form its own mineral. Cesium is in the first column of the periodic table, like the much more common elements lithium, sodium, and potassium. Cesium represents only about two atoms per million in Earth's crust, but in certain complex pegmatites, you can find crystals of the mineral pollucite—cesium aluminum silicate, $CsAlSi_2O_6$.

- In order to form a pollucite crystal, the fluid concentration has to rise from two parts per million to at least 40,000 parts per million—which means that four percent cesium is needed. That's because at lower concentrations, cesium follows other alkali elements as a minor element in feldspar and mica. So there needs to be a concentration mechanism by a factor of at least 20,000.

- What is most amazing is that in some pegmatites, there are individual masses of pollucite crystals more than 30 feet across. It has been estimated that those pollucite crystals represent the concentration of cesium by fluid-rock interactions of a volume of crust approaching 10,000 cubic miles. What is so special about pegmatites is how pegmatites and their unique mineralogy may distinguish Earth from all other planets.

- Earth is an engine of mineral diversification. It may have taken a billion years or more to distill our planet to the point where beryl, tourmaline, and pollucite can form, but now those treasures lie in wait for the keen-eyed collector.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 5, pp. 102–126.

London, *Pegmatites*.

Wenk and Buklah, *Minerals*.

Questions to Consider

1. What are incompatible elements, and why do they concentrate in pegmatites?

2. What are some of the gemstones formed in pegmatites?

Moving Continents and the Rock Cycle

Lecture 24

Great scientific discoveries often require decades, if not centuries, of painstaking observations and data collection. It's rare that a big new idea springs forth from only one mind or that a new point of view takes root quickly. So it was with the discovery of plate tectonics, which is now recognized as Earth's dominant geological process. Indeed, the establishment of plate tectonics is in many ways a scientific story that spans most of modern science. In this lecture, you will learn about the work leading up to plate tectonics—which was anticipated by at least four centuries of research.

Continental Drift

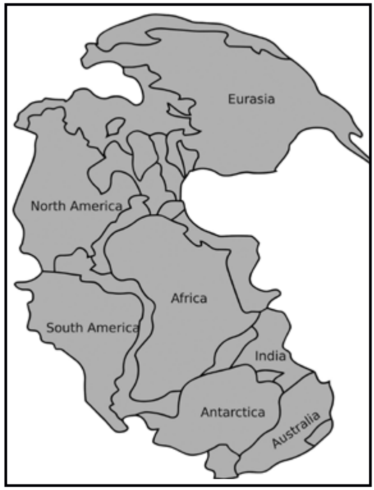
- For centuries, mapmakers have noted the similar contours of the west coasts of Africa and Europe and the east coasts of the Americas. Geologists of the 19th and 20th centuries also found numerous suggestively matching similarities in geological features of the two coastlines, including distinctive fossil and mineral deposits.

- Even after the field of geology got its name in the 18th century and began to be pursued as a science, most geologists weren't thinking about correlating features across oceans. Nevertheless, the very first detailed transatlantic geological comparisons were made by a meteorologist: the German scientist Alfred Wegener, whose most memorable and lasting work by far related to what has been called continental drift, which is a pioneering and much-maligned contribution to lateral tectonics.

- Like many scholars who came before him, Wegener was struck by the evident fit of the Americas with Europe and Africa across the Atlantic Ocean. Some had simply dismissed the fit as coincidence, but Wegener cast a wider field of view and realized that similar continental matches could be seen in the coastlines of East Africa, Antarctica, India, and Australia. In fact, it turns out that all of Earth's continents can be rather easily clustered together to make one supercontinent, which he dubbed "Pangaea."

- Wegener also realized that one could test the hypothesis that the continents were all once joined together by looking for identical marginal features. He and others cataloged evidence from recently published geological surveys of coastal regions of Europe, Africa, and the Americas. These treatises, published in many languages by many independent authors, point to numerous intriguing correlations across the wide Atlantic Ocean.

Pangaea



- Among the most obvious correlations are great mining districts, such as the extensive stream-hosted alluvial diamond fields of Brazil and Africa. These economically important zones form a single large deposit when the continents are juxtaposed. There are also many examples of similar distinctive fossils on both sides of the Atlantic. Wegener detailed these observations and argued that such geological and paleontological correlations can't be simple coincidence.

- The continental drift hypothesis first appeared in print in 1915, and Wegener kept expanding and elaborating on the idea. As more data came in, so did some support for the idea that continents were once joined together and later drifted apart.

- In spite of the growing evidence that the two sides of the Atlantic somehow match up, most members of the earth science community were not persuaded. And there was a good reason for this skepticism. Newton's first law of motion tells us that nothing happens without a force, so if continents were somehow drifting apart, then there must be a huge force at work. Wegener simply had no answer for that objection; in fact, his default suggestion was merely that continents somehow cut a path through the even harder underlying rock of Earth's crust.

- Without a reasonable mechanism for continental drift, most geologists were openly contemptuous of this idea. Until an epic, global-scale force could be clearly established, continental drift was doomed to be just another crackpot idea by a geological amateur. Not everyone was dismissive, but the ideas of some of Wegener's supporters were sufficiently wacky to generate more negative than positive feedback. The key was to come up with novel mechanisms for continental shifts.

- One amusing school of thought posited that Earth is shrinking, perhaps because it's slowly cooling and thus contracting—or maybe by the collapse of gas-filled chambers in Earth's deep interior. But this model simply doesn't work. Another group of Earth scientists proposed the exact opposite hypothesis: that Earth has been expanding and continues expanding to this day. This hypothesis has never been a mainstream idea, but it does have real staying power. Most scientists gladly abandoned any notion of a shrinking or expanding Earth as soon as a compelling new idea took its place: plate tectonics.

The Testimony of the Rocks

- Everything we know about Earth ultimately comes from the testimony of the rocks and minerals. All across the globe are three basic kinds of rocks—igneous, sedimentary, and metamorphic—that collectively make up Earth's great cycle of rock formation.

- The first solid rocks at Earth's surface were examples of igneous rocks—rocks that form from the hot, molten state. Basalt is an igneous rock, as is granite. Igneous rocks come in two principal types. Volcanic rocks, or extrusive rocks, form quickly at Earth's surface as magma solidifies in air. The second major type of igneous rocks hardens underground, typically form larger grains, and are called intrusive rocks.

- Earth's first crust was composed almost entirely of igneous rocks, but sedimentary rocks—the second of the three major groups—account for two-thirds of all rocks exposed on Earth's surface today. They form wherever fragments of other rocks accumulate into layers.

- On early Earth, when the first rains began to fall on the first igneous rocks, the process of weathering began; small mineral grains were washed off from those recently hardened volcanic rocks, basalt and granite. Lots of grains flowed down through streams and rivers and were laid down into layers in shallow lakes and on the ocean floor.

- Weathering also occurred by chemically dissolving rocks and by the mechanical action of water freezing in cracks. Over time, thick layers of sediment accumulated, especially in big fanlike deltas at the mouths of rivers. These sediment layers can reach incredible thicknesses; in many places on Earth, sediments are miles deep.

- Sediments start as loosely consolidated grains, just like sand at the beach. But when sediments are buried deep, the temperature and pressure increases and hot water flows through the sand and silt layers, dissolving and redepositing glue-like chemicals. All that pressure, heat, and the effects of mineral-laden water welded the bits of sediment together into new layered rocks.

- Many sedimentary rocks form from tiny particles, or sediments, but many also form directly by chemical precipitation from water. One familiar example is salt deposits from a dried-up salty lake. There are places where immense layers of salt have accumulated; some of those have been mined for centuries for table salt. In addition, many other chemicals can form rocks by precipitation. The most common of these is limestone, which forms from calcium carbonate.

- The rich variety of metamorphic rocks encompasses the third great group of rocks on Earth. As igneous or sedimentary rocks are slowly buried deep, they're subjected to intense heat and pressure, and they can transform into new kinds of rock.

- Igneous, sedimentary, and metamorphic rocks all participate in the rock cycle. Igneous rocks, once formed, can be weathered to form sedimentary rocks, or they can undergo metamorphism. Layers of sedimentary rocks also can be transformed into metamorphic rocks. All three kinds of rocks can be partially melted and reformed as new igneous rocks. In this way, the rock cycle never ceases. All of Earth's atoms are recycled: The atoms are always shifting around, but it's always the same matter recycling over and over.

- Time is another crucial aspect to understanding the rock cycle. It often takes immense spans of time—hundreds of millions of years—to make new rocks or transform them. This discovery of so-called deep time was made more than 200 years ago by the Scottish geologist James Hutton, who is often referred to as the "founder of modern geology."

- James Hutton reached his great insight near the town of Jedburgh, where spectacular sea cliffs reveal vertical layers of rock overlain by horizontal layers. How could such a sequence have occurred? Hutton studied these remarkable cliffs and realized that he was seeing the end product of a long chain of events.

- Hutton realized that the processes of sedimentation, burial, uplift, tectonic forces, and more were acting in the present, albeit very slowly. He concluded that the same geological forces must have been operating for an almost unimaginably long time. Each step of the formation process must have taken tens to hundreds of millions of years. In order for a formation like the one at Jedburgh to exist, Earth had to exist not for thousands of years or even hundreds of thousands of years, but for many hundreds of millions of years.

- Thanks to Hutton and his successors, we now know that Earth's age is more than 4.5 billion years, and the existence of structures like the one at Jedburgh becomes comprehensible. Hutton had captured a crucial feature of what we call the rock cycle, where surface rocks are ceaselessly broken down and become the raw materials for the creation of new rocks.

Suggested Reading

Grotzinger, Jordan, Press, and Siever, *Understanding Earth*.

Hazen, *The Story of Earth*, Chapter 1, pp. 102–126.

Hazen and Trefil, *Science Matters*.

McPhee, *Annals of the Former World*.

Oreskes, *Plate Tectonics*.

Wood, *The Dark Side of the Earth.*

Questions to Consider

1. What evidence did Wegener use to propose his hypothesis of continental drift?

2. What is meant by geologists when they talk about the "testimony of the rock"?

Plate Tectonics Changes Everything

Lecture 25

The theory of plate tectonics provides a compelling view of a dynamic, evolving planet. The centerpiece of the theory is mantle convection, which drives plate motions. Three kinds of plate boundaries—divergent, convergent, and transform—explain the distributions of volcanoes, earthquakes, and many other phenomena at Earth's surface. Plate tectonics unifies earth science as never before. Our planet is now seen as a world where geological phenomena are not local but, rather, follow a logical global pattern. Among the many consequences are the predictable distributions of many kinds of valuable ore rocks and minerals, formations that would not occur on a world lacking plate tectonics.

The Birth of Plate Tectonics

- Sonar is a sounding technique that was refined during World War II to find submarines, but it was applied after the war to mapping ocean depths. Sonar revealed an immense mountain range—the Mid-Atlantic Ridge—on the floor of the Atlantic Ocean.

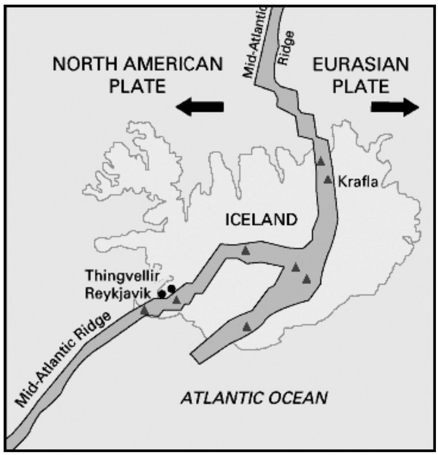
- Similarly, magnetometers were developed during the war to detect metal submarines, but they were applied after the war to measure magnetic properties of basalt on the ocean floor. Scientists found compelling evidence that the Atlantic Ocean is getting wider.

- By the late 1960s, it was clear that there are important connections among trenches, earthquakes, and volcanoes. The shallowest quakes occur exactly at deep-sea trenches, which are the deepest places on Earth's surface. And earthquake depths increase away from the trenches.

- This pattern of deeper and deeper quakes reveals that huge slabs of ocean crust are moving down into the mantle along what are known as subduction zones. Old basalt crust is colder and denser than the hot mantle, so subducting slabs are swallowed up. This rigid subducting basalt buckles the adjacent crust downward to form trenches. It's a simple equation: Every square mile of new crust made at ocean ridges is balanced by a square mile of old crust lost at a subduction zone.

- The realization that oceans open and close over geological time led quickly to a transformative idea—the theory of plate tectonics. This theory, which says that Earth's surface is broken into about a dozen shifting continent-sized thin slabs, unifies our view of Earth's evolution.

- And so it was that plate tectonics, the new paradigm of the earth sciences, was born. Earth's surface is formed from a dozen shifting plates, each a cold and brittle slab of crust and upper mantle, each only a few tens of miles thick but hundreds to thousands of miles wide. Plate boundaries are defined by ocean ridges and subduction zones. These thin, rigid plates easily slide across hotter, softer mantle rocks. That's how continents can "drift."



The Mid-Atlantic Ridge splits Iceland, separating the North American and Eurasian plates.

- Ocean ridges make new basalt while subduction zones swallow up old crust. But there's a problem because Earth is a sphere. On a sphere, some moving plates have to scrape against each other at long scar-like features called transform faults. For example, the San Andreas Fault causes many of the big California earthquakes. Every day, more stress builds up along this transform fault, because the North American Plate moves to the southeast relative to the Pacific Plate.

Conduction, Convection, and Radiation

- What epic forces drive plate motions? The answer can be found in Earth's inner heat. The second law of thermodynamics demands that heat must flow from hotter to cooler objects by one of three mechanisms: conduction, convection, or radiation. Rock and magma don't conduct heat very well over large distances—nor do they allow much heat transfer by radiation.

- But long-range convection is possible, because at high temperatures, rocks become soft and plastic; over millions of years, rocks deform, ooze, and flow. Hot, buoyant rocks gradually rise toward the surface, even as cooler, dense rocks sink. These motions set up great convection cells thousands of miles across—motions that drive plate tectonics.

- After all, even the biggest continent is a tiny thing compared to Earth's mantle. Shifting continents are like scum on the surface of a pot of boiling soup. The rate of convection is vast—it may take 100 million years or more for a single turn of the convection cell, which is exactly the timescale for opening and closing oceans.

- At Earth's earliest time, 4 billion years ago, we imagine that mantle convection must have been a chaotic, swirling hodgepodge. There were dozens of hot mantle plumes rising like a lava lamp, carrying hot melts of low density in disorganized pulses and plumes to the surface. And isolated dense chunks of colder crust must have sunk into the interior. But lateral tectonics—plate tectonics—wasn't yet a global, organized cycle.

- Over the next billion years, mantle convection became more orderly. Many smaller convection cells consolidated into a handful of majestic cycles, each thousands of miles across. Where these convection cells rose to the surface, new seafloor ridges rose up. Where convection cells cycled back into Earth, subduction zones formed. Earth in cross-section might have looked like a collection of sideways whirlpools, with each swirling rotation taking 100 million years.

- Thanks to plate tectonics, Earth's surface evolved, and the topography became more extreme. Giant mountain ridges of basalt grew at the diverging boundaries of ocean ridges. Deep gash-like trenches formed where old crust plunged downward at subduction zones. Subduction also accelerated the production of granite and the growth of continents. That's because the wet, subducted basalt began to heat up and melt—not completely, but perhaps 20 or 30 percent—and this partial melt rose back to the surface as granite.

- The key to making continents is that granite floats. Granitic melt slowly, inevitably rises to form near-surface rock masses. Countless granite islands have formed by this continuous process. And plate tectonics not only produces granite island chains, but it also assembles them into continents.

- That's because low-density granite won't subduct. Basalt easily sinks into the mantle, but granite is like a floating scum. Imagine a subducting plate of basalt crust that has unsinkable granite islands. As the basalt subducts, the islands remain at the surface to form a strip of land immediately above the subduction zone. After tens of millions of years, lots of granite islands pile up to form a wider and wider strip, while new volumes of granitic melt rise above the subducting slab. In this way, a continent forms from lots of smaller granite islands.

Earth's Mineral Evolution

- Plate tectonics transformed the earth sciences. In the dark ages of vertical tectonics, every geological discipline was more or less separate. Paleontologists had no need to talk to oceanographers; research on volcanoes seemed unrelated to ore geology; and geophysicists were unconcerned with life's origins and evolution. Now, plate tectonics has unified everything about Earth. Earth is an amazingly complex, integrated system where every component affects—and, in turn, is affected by—every other.

- Nowhere is this interconnectedness more obvious than in Earth's mineral evolution, because plate tectonics is a great driver of mineral diversity on Earth. The most notable mineralogical effects were associated with extensive hydrothermal processing of the upper mantle and crust.

- In particular, subduction zones are sites of lots of mineral action. As cold, wet slabs subduct, they partially melt and release lots of water in the process. That hot water rises toward the surface, in the process interacting with vast volumes of Earth's upper mantle and crust. Hot water strips out all sorts of rare and widely dispersed elements.

- These hydrothermal processes at subduction zones reworked millions of cubic miles of Earth's outer layers and concentrated immense quantities of metals in the first episodes of massive sulfide ore bodies.

- Massive sulfide deposits, and their associated precious metal concentrations, are truly awe-inspiring. The largest mines can hold as much as 10 million metric tons of copper. Hot water concentrates copper, lead, zinc, nickel, gold, silver, and many other metals along with sulfur. When the fluids near the surface cool, all of these metals precipitate out as new minerals—primarily groups of metal ore minerals called sulfides and sulfosalts.

- Only about a dozen different minerals form the major ore reserves, but hundreds of other minerals occur as accessories, and many of these are found only in this kind of rich, massive sulfide deposit. The oldest such massive sulfide deposits are found in 3.5-billion-year-old formations in Australia, and they speak to a time when plate tectonics was just getting started. North America is especially rich in younger sulfide ore bodies, with major mining operations in several Western states.

- Plate tectonics led to lots of other mineralizing events. The new kinds of volcanoes above subduction zones involve magmas that can interact with the surrounding rock—what geologists call the country rock—in complex ways. So you can get magmas enriched in alkalis like sodium and potassium, or calcium, or carbon. Each can, in turn, lead to some fascinating new minerals.

- One whole series of minerals that is relatively high in sodium and potassium but low in silicon produces new suites of minerals, such as sodalite and lazurite, which sometimes occurs in a beautiful blue form known as lapis lazuli. We can't tell for sure, but it's likely that the first sodalite and all sorts of related minerals low in silicon first appeared around this time.

- Another mineralogical consequence of plate tectonics was the uplift and subsequent exposure of rocks that had experienced very high-pressure metamorphism. In some places of very rapid subduction, a wedge of buoyant crustal rocks can be driven down deep, as much as 50 miles down, only to pop back up to the surface—a process that takes a few million years. The high pressures and temperatures can produce distinct new minerals through extreme metamorphism.

- Quartz, for example, is observed to transform, not just to quartzite, but also to an even denser form called coesite. In addition, feldspar can transform to the lustrous, hard mineral jadeite, which is one of several prized minerals that is used in Asia as jade. In fact, there are perhaps 20 distinctive high-pressure minerals that only reach Earth's surface through subduction-related processes.

- Plate tectonics is the fifth stage of 10 in Earth's mineral evolution, adding perhaps 500 minerals for a grand total of about 1500 on Earth by roughly 3 billion years ago. During this period, our planet also provided a home for the origins of life—something that would eventually take over and drive mineral and planetary evolution for the rest of Earth's history.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 1, pp. 102–126.

Hazen and Trefil, *Science Matters*.

Oreskes, *Plate Tectonics*.

Rollinson, *Early Earth Systems*.

Wood, *The Dark Side of the Earth.*

Questions to Consider

1. How were World War II submarine-hunting technologies applied to the discovery of plate tectonics?

2. What are three types of plate boundaries, and how are they related to earthquakes and volcanoes?

Geochemistry to Biochemistry—Raw Materials
Lecture 26

The story of Earth is the story of incessant change. Our planetary home has been an engine of change for more than 4.5 billion years. The origin of life is a chemical process, albeit one that is incompletely understood today. Building on the assumption that life arose from Earth's raw materials—rocks, oceans, and air—and that the first life form used carbon-based chemistry just like today, life is imagined as emerging in steps.

The Chemistry of Life

- All living things are basically organized molecular systems; they undergo all sorts of chemical reactions, many of remarkable complexity and coordination. The most basic unit of every known life form is the cell—an intricate assemblage of molecules that is separated by a flexible cell membrane from the environment.

- Cells are remarkably well adapted assemblages of chemicals that have evolved two codependent means of self-preservation: metabolism, by which cells take in energy and raw materials to grow and reproduce, and genetics, by which cells store and pass on all the information required to make more cells. Together, metabolism and genetics would seem to distinguish living organisms from the nonliving environment.

- As difficult as it may be to define life, metabolism and genetics must together play roles in any successful definition. In spite of centuries of study by millions of life scientists, biologists have simply not been able to come up with one universally accepted definition of life.

- Most origins-of-life researchers adhere to the idea that the emergence of life was an inevitable geochemical process. It's clear that Earth had all of the essential raw materials, including lots of water in the oceans, key chemicals in the atmosphere, and vast supplies of rocks and minerals that were rich in all the elements of life—that is, carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus.

- Earth was also rich in sources of energy. There was the Sun's radiation, though that was not the most likely source early on. More significant was Earth's inner heat. The thermal energy provided a ubiquitous reliable source, though it's certainly plausible that lightning, radioactivity, meteor impacts, and many other forms of energy contributed as well. That's one reason why there are at least as many different theories of the origins of life as there are different sources of elements and energy.

- Carbon typically forms up to four bonds at once, which can be arranged into long chains of atoms, interlocked rings, complex branching arrangements, or almost any other imaginable shape. That's how carbon helps to form the backbones of all sorts of biological molecules, including proteins, carbohydrates, fats and oils, and DNA and RNA. No other element has the potential to fulfill the twin defining characteristics of life: the ability to make copies and the ability to evolve.

- Carbon's unique chemical character explains why it's the central element of life, and it has become the dominant element of modern chemical technology. As important as carbon was in the story of life's origins, it was by no means the only factor. The transition from geochemistry to biochemistry also must have relied on water, heat energy, and very likely the chemical energy of rocks. This was a chemical process that also required lots of time—perhaps many millions of years.

- Science is not yet able to say exactly how or when life emerged, but we are able to point to some basic principles. The origins of life must have occurred as a sequence of steps. Each step added chemical complexity to the evolving biological world.

- First, you have to synthesize the small carbon-based molecules from which all organisms are formed. Those are the most basic building blocks of life. But these small carbon molecules are much less dense than the minerals we've been exposed to so far, with values clustered around the density of water. The lightest of these small carbon-based molecules would have floated on the water's surface, or even into the atmosphere, but larger carbon molecules would sink and settle to wherever rocks and water meet.

- Then, you must concentrate and organize those small molecules into life's essential structures—the membranes, polymers, and other functional components of a cell. Ultimately, at some point, the molecules had to start making copies of themselves, and they also had to devise a means to pass genetic information from one generation to the next. And once molecules could self-replicate and mutate, then evolution by Darwinian natural selection took over. That's how life must have emerged.

- By far the best understood step in the origins of life was the synthesis of life's small molecular building blocks, including sugars, amino acids, lipids, and more. All of these essential chemicals are based on carbon, and all of them are known to form just about anywhere that a source of energy interacts with simple gas molecules like carbon dioxide and water.

- Life's raw materials must have formed in all sorts of environments—where lightning pierced the atmosphere, for example, or where volcanic heat boiled the deep ocean, or even where ultraviolet radiation bathed molecular clouds in deep space. It's likely that Earth's first ocean more than 4 billion years ago became increasingly concentrated in the molecules of life. After all, biomolecules must have rained from the skies in the form of carbon-rich meteorites, and they rose from deep volcanic zones.

The Miller-Urey Experiment

- Scientists began to get a handle on these processes in the early 1950s, with what surely remains to this day as the single most famous experiment in biogenesis. The two lead characters in this drama—Nobel Prize–winning chemist Harold Urey and his graduate student Stanley Miller—designed a rather simple and quite elegant tabletop experiment.

- It consisted of a pair of glass bulbs a few inches in diameter connected to each other by a loop of tubing. In one bulb was a small pool of heated water; in the other was a mixture of gases exposed to little electric sparks. The idea was to simulate early Earth, with the hot water representing oceans and the gas mixture representing the atmosphere laced by lightning.

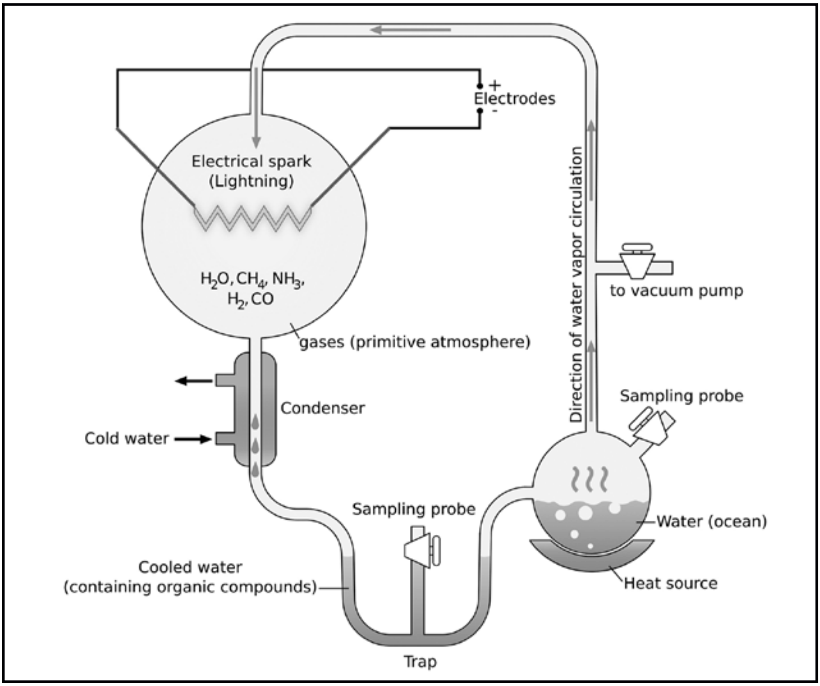
- It only took a few days for the confined, colorless water to become first pink, then brown, with a complex mix of organic molecules. As the experiment progressed, the transparent glass around the electrodes became smeared with a sticky black organic sludge.

- What Miller found after analyzing the colorful mixture was an abundance of amino acids, lipids, carbohydrates, and other building blocks of life. He made headlines around the world with his 1953 paper in the journal *Science* that announced the key findings. Dozens of other chemists soon flocked to the study of origin-of-life chemistry, and thousands of subsequent experimental variations on the Miller-Urey theme have established beyond any doubt that early Earth must have been an engine of organic synthesis.

- Miller's experiment was masterful, and it placed origin-of-life research solidly in the domain of the organic chemists. Miller and Urey established the leading paradigm that life emerged from a prebiotic soup of organic molecules formed by lightning. However, few experimentalists during the 1950s had considered the absolutely staggering complexities of geochemical environments.

- In nature, there are daily cycles of night and day, hot and cold, wet and dry, and more. All of these cycles are key to natural environments. Real geochemical environments also display a range of natural gradients—in temperature and salinity, for example. And

The Miller-Urey Experiment



geochemical environments also have rocks and minerals; none of Miller's experiments incorporated rocks and minerals. Miller and coworkers simply assumed that Earth's sunlit surface was all that was needed for life's origins, so they spent decades ignoring what early Earth was really like.

- Miller's influence was immense, and for almost 30 years, he and his growing number of followers had the dominant influence on the origins-of-life community. It wasn't until 1987 and the discovery of deep-sea communities of organisms at so-called black smoker ecosystems that an alternative to the Miller origins paradigm emerged to challenge the primordial soup model.

- The idea was that in those deep zones of total darkness, mineral-rich fluids react with hot volcanic crust. Ocean-floor geysers jet scalding water into the frigid ocean. A constant rain of microscopic minerals creates a kind of black "smoke" of reactive particles. An amazing quantity of life abounds in those remarkable places, and that life is not fueled by the Sun or lightning but, rather, by chemical energy at the interface between crust and ocean.

- Miller and his followers hated the idea that these deep, dark, volcanic environments might have fostered life, and they did whatever they could to squelch the hypothesis. The discovery of black smokers underscored a growing awareness that microbial life thrives in all sorts of extreme environments, in many places where previous generations of scientists wouldn't have dreamed of looking.

- These amazing organisms, which are collectively known as extremophiles, have radiated into all sorts of astonishing environments. Microbes have been discovered in extremely acidic streams that flow from old mine waste dumps, and they have been discovered in boiling pools above volcanic zones. Microbes have been found living inside frozen Antarctic ice and rocks, and they persist on stratospheric dust particles miles above Earth's surface, where they are blasted by ultraviolet radiation. In addition, there are really amazing deep microbial ecosystems that extend many miles beneath Earth's surface. This deep cellular life lives in narrow cracks and fissures underground; they subsist on a meager diet of chemical energy associated with minerals.

- If life can survive in such extremes, especially in deep environments that were protected from impacts from asteroids and comets, then life could have originated in deep, hot zones. And if life originated in deep environments on Earth, then it could have originated in the deep environments of other worlds as well.

- The possibility of life arising deep in our planet has led NASA into planning new missions to many other bodies in our solar system.

The intriguing prospect that life might have come from the deep, hot vents remains one of the most exciting frontiers in origins research, and it epitomizes how much we have to learn about the story of Earth.

Suggested Reading

Deamer, *First Life*.

Hazen, *Genesis*.

———, *The Story of Earth*, Chapter 6, pp. 127–153.

Lahav, *Biogenesis*.

Questions to Consider

1. What were the raw materials that led to the origins of life?

2. What was the first key step in life's origins, and how might minerals have played a role?

Biomolecules—Select, Concentrate, Assemble

Lecture 27

The origins of life required that simple molecules assemble into the essential macromolecules of biology, including cell membranes, proteins, and the nucleic acids DNA and RNA. Two complementary assembly mechanisms are self-assembly and synthesis. Some molecules clump together by self-assembly; these molecules spontaneously form chains or layers. Some molecules may have been selected, concentrated, and assembled on the crystal surfaces of common rock-forming minerals. Ultimately, for life to get started, collections of molecules must learn to self-replicate.

Self-Assembly and Synthesis

- The first step in life's origins, the synthesis of the fundamental biomolecules, is for the most part solved. It's easy to make amino acids, lipids, and sugars. Indeed, the problem is making too many different kinds. A fundamental attribute of life is chemical parsimony. Only a relatively few small molecules are used by life, but nature manufactures millions.

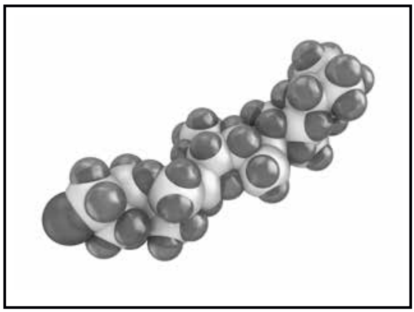
- That's why the second emergent stage in the origins of life seems to have been the selection, concentration, and assembly of molecules from the complex but dilute prebiotic soup into life's macromolecules. Those macromolecules include structures that enclose the cell and promote its chemical reactions and carry genetic information. We suspect that two complementary processes likely played a role: first self-assembly, and then template-directed synthesis.

- Often, elongated molecules with a skinny backbone of carbon atoms clump together spontaneously. These chemicals, including molecules that form the encapsulating membranes of cells, are called lipids. They self-assemble into tiny cell-sized spheres because one molecular end is attracted to water, and the other is repelled by water.

- If you place huge numbers of these molecules into water, they find each other and form a remarkable double layer with water-hating ends pointing inward (away from the water) and water-loving ends pointing outward (in contact with water). Every known plausible source of biomolecules form lipid molecules that self-assemble in water. Experiments that demonstrate this behavior have led most origins scientists to agree that lipid self-assembly must have played a key role in life's origins.

- But self-assembly can't possibly be the whole story, because most of the familiar biological molecules don't self-organize. Sugars and amino acids, for example, tend to dissolve in water and remain there in solution. But there is a simple and effective way out. These molecules can become concentrated and neatly arrayed on the protective, orderly surfaces of different mineral crystals.

- These days, the principal experimental program for many researchers is studying how life's molecular building blocks adsorb onto the surfaces of virtually every natural mineral, including all of the common rock-forming minerals in the major rock types like basalt and granite. In every case, amino acids and sugars are selectively pulled out of the solution and array themselves on the mineral surfaces.



Cholesterol, a lipid that is essential to life, is present in all animal tissues.

- These experiments show that wherever the diverse molecules in the prebiotic soup contacted minerals, the result was highly concentrated arrangements of life's molecules—sugars, amino acids, lipids, and the building blocks of DNA. So that's an effective mechanism for achieving those critical steps of selecting and concentrating, and maybe even templating, more complex structures from the formless broth.

- No one yet knows—and we may never know—exactly what combination of molecules and mineral surfaces led to the first lifelike assemblage of chemicals, but we're now learning the guiding principles of molecular selection and organization. It's now certain that biomolecules were synthesized in abundance. It's equally certain that some of those molecules formed larger and larger clusters.

- One principle that has emerged from experiments is that electric charge played a big role. Some molecules carry a slightly positive electric charge, while others have a slightly negative charge. And quite a few interesting molecules, including water, are polar—that is, they have both slightly positive and negative ends to the same molecule. In a similar fashion, minerals have charged surfaces.

- Some mineral surfaces are slightly positive, some are slightly negative, and sometimes a mineral will have both positive and negative regions on its surface. The result of all these charged regions of molecules and surfaces is that they can organize spontaneously, as positive electric charge attracts negative electric charge. The details of this kind of prebiotic self-organization are still very much a frontier of origins research, but it's clear that self-assembly has to have occurred on early Earth in virtually every wet, chemically diverse environment.

Self-Replication

- The first two steps in life's origins are pretty well understood, at least in principle. Biomolecules like amino acids, sugars, and lipids were manufactured abundantly in all sorts of prebiotic environments. Earth's surface had all the raw materials it needed, and those raw materials could be assembled in complementary ways—through self-assembly and by selection on mineral surfaces and by intricate combinations of those processes.

- But arrays of molecules, no matter how intricately they might be patterned, can't be said to be alive unless they can make copies of themselves. The biggest hurdle to understanding the origins of life is how a collection of lifeless molecules became organized in such a way that it could make copies of itself. What was the first self-replicating system of molecules?

- Life's most distinctive characteristic is self-replication: One collection of molecules becomes two, two become four, doubling again and again in geometric expansion. In some cases, we can work backward by mimicking what life does so well. Scientists have devised clever experiments that replicate portions of plausible reproductive cycles, but no one has been able to create a lab system that takes in small "food" molecules and makes copies of much bigger molecules.

- This is a big challenge. We know that at some point in Earth history, at some specific time and location, probably in a volume smaller than a dust grain, an organized collection of molecules began to copy itself, while using other molecules in the environment as food.

- Earth had hundreds of millions of years during which it could conduct chemical experiments in all kinds of geochemical environments, with varying temperature, pressure, salinity, and acidity. Only an infinitesimally small fraction of the molecular experiments on mineral surfaces did anything useful by producing some kind of organized structure with some kind of enhanced function—maybe stronger surface attachment, a way to attract more molecules to the local community, or the tendency to destroy competing molecular species.

- At some time and place, a collection of surface-bound molecules discovered the ability to make copies of itself. Once self-replicating molecules took hold, they could rapidly take over, infesting every habitable crack and fissure on the globe.

- Evolution seems to be a universal feature of the cosmos. We see complex evolving systems all around us—in the emergence of the varied elements and isotopes formed in stars, in the evolution of minerals, in the evolution of biomolecules, and in the origins and evolution of life. In all of these cases and many more, the twin evolutionary pillars are variation and selection.

- First, all of these systems evolve because they display vast numbers of different possible configurations. The nuclear particles, protons and neutrons, can come together in millions of different arrangements, of which a few are the stable elements and isotopes. Natural systems display tremendous potential variation because they are made of lots of smaller components that can be arranged in vast numbers of different configurations.

- The second, and equally essential, attribute of all evolving systems is selection. If all possible configurations were equally probable, then evolution couldn't happen—you'd just have a mess. But in these systems, it turns out that some configurations are much more likely to survive than others.

- In the case of protons and neutrons, only a few arrangements are stable—that is, they aren't radioactive and spontaneously disintegrate. The same thing is true for organic molecules; most atomic arrangements spontaneously break apart. And that's also true for collections of molecules. That's selection: What survives the first cut is what is stable.

- But collections of molecules have the potential for even more powerful selection. For a collection of molecules to be stable, it has to first survive. Not all molecules are equally suited for survival. Some molecules are relatively unstable, so they decompose. Any unstable molecule is quickly eliminated from the competition.

- Other molecules probably clumped together into useless tar-like masses, which floated away or sank to the ocean floor. Those molecules could play no further role. But some small fraction of molecules must have proved to be especially stable, and that stability was surely enhanced when they bound themselves to others of their kind or to a stable mineral surface.

- All sorts of molecular interactions further refined the prebiotic mix. Some groups of molecules cooperated with each other to attach to various mineral surfaces in ways that individual molecules could not, thus enhancing survival of the group.

- Other small molecules must have acted as catalysts that enhanced survival in two ways: Some chemical species promoted stability by catalyzing the formation of new chemical bonds, while others accelerated the destruction of molecular species by breaking their bonds. In this way, the molecular soup was inexorably refined.

- For a time, perhaps for hundreds of millions of years, the prebiotic soup was refined in these varied ways. But being the most stable molecule is not always the best way to ensure survival. Ultimately, security in the prebiotic soup was to be found not by eliminating the competition or just surviving. The ultimate guarantee of survival went to that precocious collection of molecules that learned to self-replicate.

- Self-replication increases the concentration of the winners while gradually consuming—that is, eating—the competition. In the natural world, self-replication isn't perfect every time, so mutant versions of the self-replicating molecules pop up from time to time. While most of those mutants at best have no effect on the system and at worst will slow down or halt reproduction, once in a while, a lucky mutant will be better at the self-replication trick. A self-replicating system has the potential to evolve into new systems that do the tasks of life even better.

Suggested Reading

Deamer, *First Life*.

Hazen, *Genesis*.

———, *The Story of Earth*, Chapter 6, pp. 127–153.

———, "Life's Rocky Start." *Scientific American* 284 (2001): 76–85.

Kwok, *Stardust*.

Lahav, *Biogenesis*.

Questions to Consider

1. What are life's key macromolecules, and what are their small molecular building blocks?

2. By what mechanisms might the molecules of life have been selected and concentrated?

Why Reproduction? World Enough and Time

Lecture 28

The key step in the transition to a living world was the ability of an organized collection of molecules to make copies of itself. At least three competing models describe the first possible self-replicating system: the reverse citric acid cycle, autocatalytic networks, and self-replicating RNA. Whatever the first self-replicating system might have been, once life began, it radiated into many different environments, and it evolved as selection and competition winnowed all but the most successful forms.

The First Self-Replicating System: Three Models

- Reproduction is the hallmark of life. Every proposed definition of life has to include self-replication, and that's why so much emphasis is placed on figuring out what was the first collection of molecules that could make copies of itself. Three rather different models are in competition to describe that first self-replicating system: the reverse citric acid cycle, autocatalytic networks, and self-replicating RNA.

- By far the simplest of these three models, and consequently the scenario that many researchers prefer, is based on a very well-known cycle of a few small molecules called the citric acid cycle, which is sometimes called the Krebs cycle or the tricarboxylic acid (TCA) cycle. The idea is to build up bigger molecules from smaller pieces.

- Start with acetic acid, which has only two carbon atoms, and react the acetic acid with carbon dioxide, or CO_2, to form pyruvic acid with three carbon atoms. Then, pyruvic acid undergoes a second reaction with CO_2 to make oxaloacetic acid with a backbone of four carbon atoms. These initial reactions are followed by other simple chemical reactions that produce progressively larger molecules up to citric acid, which has six carbon atoms.

- This cycle becomes self-replicating because the citric acid molecule splits into two pieces—two smaller molecules, acetic acid and oxaloacetic acid. But those two smaller molecules are both part of the original cycle. So now you have two cycles going, one starting with acetic acid and the other with oxaloacetic acid. In that way, one cycle of molecules becomes two, and two cycles become four, and so on.

- It turns out that it's easy to synthesize many of life's essential building blocks, including amino acids and sugars, by simple chemical reactions with the core molecules of the citric acid cycle.

- One of the most convincing arguments in favor of the TCA cycle as the first self-replicating system is that it's obviously very ancient. Just about every known living cell on Earth has the citric acid cycle buried deep inside, so some people suspect that it's a primordial characteristic that may have descended from the very first life form.

- The citric acid cycle, with just a dozen key molecules forming a self-replicating loop, is the simplest model of molecular reproduction in play right now. At the opposite extreme of chemical complexity is a competing model celled the self-replicating autocatalytic network. This model is a self-organizing model of life's origins that was championed by Stuart Kauffman, a pioneer in studies of complex systems.

- It's likely that the prebiotic soup grew richer and richer in its variety of organic molecules. It may have eventually incorporated hundreds of thousands of different kinds of small, carbon-based molecules from different sources, including meteorites, Miller-Urey processes, hydrothermal vents, and more.

- At some point, when organic molecules became concentrated—for example, in a drying tidal pool—some of those carbon-based chemicals would have triggered more reactions that made new kinds of molecules. At the same time, other reactions would have accelerated the breakdown of less stable molecular species. The result is that concentrations of some molecules increase while others decrease.

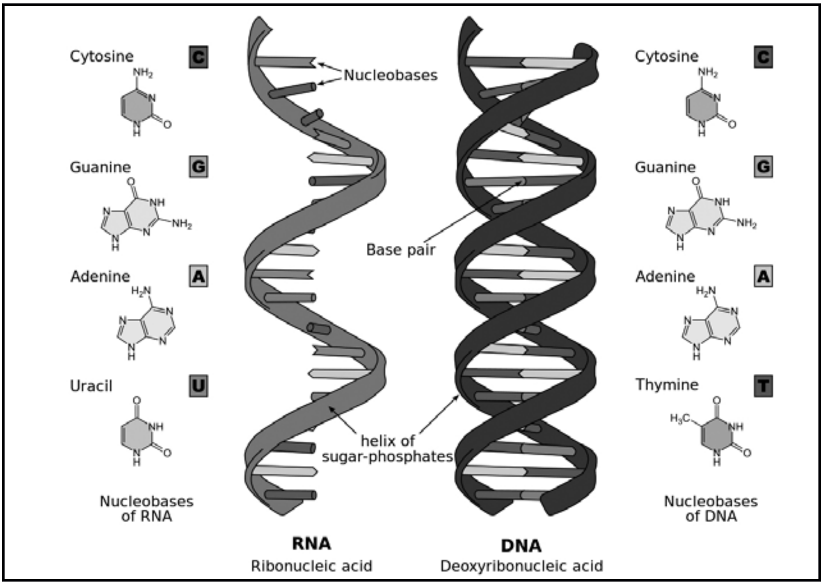
- Kauffman's idea of an autocatalytic network takes this idea to an extreme. He suggests that there would develop a collection of molecules—maybe 1,000 or even 10,000 different species working in concert—that favor the synthesis and stability of themselves, while they accelerate the destruction of any molecule that isn't in that network. It would be difficult to claim that such a molecular network is alive, but the network does make copies of itself, uses its surroundings to gain energy and "food," grows, and is far more complex in its chemical activities than most nonliving chemical systems. A principal objection to this idea is that it's really untestable.

- A third origin-of-life scenario, called the RNA world, is clearly the front-runner. It's the one idea probably favored by most biologically trained origins researchers. The RNA world model is based on a molecule that is, at least for now, hypothetical. It's a molecule of the genetic chemical RNA that has learned to make copies of itself.

- The two most critical functions of life are metabolism, which means making and assembling life's molecules into cells, and genetics, which is transferring information on how to make life's molecules from one generation to the next. In modern cells, it's the complexly folded proteins that run metabolism, but the ladderlike molecule DNA stores and copies the information needed to make more proteins. It's a chicken-versus-egg problem, because protein molecules assemble the DNA, but DNA is necessary to make proteins.

- It turns out that RNA may be able to do both jobs at once. RNA is an elegant polymer. It's a long strand made from numerous individual molecules called nucleotides, which come in four different types—A, C, G, and U—that line up like beads on a string. You can

The Comparison of RNA and DNA



construct any imaginable sequence from RNA letters. It turns out that these RNA letters hold genetic information in the same way as DNA, so RNA can fulfill the role of DNA.

- At the same time, RNA has the ability to fold up into complex shapes that have the ability to catalyze some biological reactions, and that's just what proteins do. In fact, it's now known that RNA molecules play key roles in assembling all proteins. RNA is a molecule that does both key tasks: carrying genetic information and catalyzing protein formation. Of all life's diverse molecules, RNA is the only one that seems to do it all.

- The RNA world has attracted many supporters, but there are problems with this model. First, no one seems to be able to come up with any chemical mechanism to produce RNA nucleotides, much less to produce the vast numbers of different strands of

RNA required to generate at random some kind of self-replicated RNA molecule.

- The central, and as yet unproven, assumption of the RNA world hypothesis is that one of the vast number of prebiotic RNA strands learned the useful trick of how to make copies of itself: It became a self-replicating molecule. This idea is unproven, but it may not be so far-fetched. After all, strands of RNA are a lot like strands of DNA, which we know is able to make copies of itself. And RNA, like DNA, can incorporate mistakes and, thus, is easily mutated.

- Even if the first self-replicating RNA molecule was inefficient or sloppy, it would have quickly found itself competing against all sorts of slight variants of itself. And some of those mutants inevitably would have been a little more efficient at making copies. An RNA molecule that could make copies of itself while evolving would seem to fulfill all of the minimum requirements for life.

- Regardless of the model, it's likely to have taken a long time—maybe hundreds of millions of years—for that first crudely self-replicating molecular system to emerge. But Earth had vast amounts of time and surface area with which to try out different chemical combinations, so it's plausible that versions of all three models would have been given a chance. And all it took was for one of those inconceivably immense numbers of molecular combinations, someplace, sometime, to make copies of itself. That was the moment of life's origins.

The Steps of Life's Origins

- Recall that making the small biomolecules like amino acids and sugars was the first step in life's origins. Next was the selection and assembly of those molecules into larger structures. Ultimately, a collection of molecules became self-replicating. But how exactly can a collection of molecules evolve? What is the natural process that would drive such a phenomenon?

- The answer lies in selection—the driving force behind all evolving systems. We live in a world that rewards certain essential functions related to survival. In such a world, the molecules that are most functional will always be the ones most likely to survive. And molecules that don't make the grade are doomed to be eliminated.

- The power of natural selection, whether for molecules or living creatures, is not just idle conjecture. Experiments now being conducted in the laboratory of Harvard biologist Jack Szostak have demonstrated over and over again the power of selection in molecular evolution.

- Evolution by natural selection is the fastest and most demonstrably reliable path to attaining function; by contrast, intelligent design of biochemical structures from scratch is immensely more complicated—engineering is unlikely to be either fast or even functional. In addition, contrary to some criticisms, there's nothing random about selection. Selection always picks the configuration that works.

- We certainly don't yet know all the details, but at some place and time in Earth's first billion years, a collection of molecules learned to self-replicate. It's clear that any collection of molecules with even the slightest useful function had an advantage in the prebiotic soup. But no function was more valuable than the advantage conferred upon groups of molecules that could make copies of themselves. Such a self-replicating system insured its own survival by producing more-or-less identical offspring.

- The molecular copying process must have been messy, so some of those molecular copies were mutants. Most mutations were lethal or conferred no significant advantage, but a few fortuitous alterations allowed offspring to outshine their parents. The system evolved through chance copying errors. The first self-replicating molecules were without competition, so it's likely that they engulfed all of Earth's nutrient-rich zones in a geological instant.

- How long ago did life arise? The answer depends as much on philosophy as science, but it seems logical that life began in an interval from about 4 billion years ago, when the most intensive asteroid bombardment slowed down, to 3.8 billion years ago, when we start to see some pretty convincing isotopic evidence that life was influencing the surface environment.

Suggested Reading

Deamer, *First Life*.

Hazen, *Genesis*.

———, *The Story of Earth*, Chapter 6, pp. 127–153.

Lahav, *Biogenesis*.

Questions to Consider

1. What is life?

2. What is the relationship between molecular self-replication and life?

Eons, Eras, and Strategies of Early Life

Lecture 29

Life originated on Earth when the first living cell began to replicate, sometime before 3.5 billion years ago. For the next billion years, single-celled life radiated and diversified but appears to have had little effect on Earth's near-surface environment, including its rocks and minerals. The geological timescale systematizes more than 4.5 billion years of planetary history. Earth's history is divided into four major eons: the Hadean, the Archean, the Proterozoic, and the Phanerozoic. These divisions are based somewhat arbitrarily on changes in the rock and fossil record and only partially match up with the 10 stages of Earth's mineral evolution.

The Emergence of Life

- Life emerged on Earth over 3.5 billion years ago, at a time when oceans still covered most of the world, where basalt volcanoes and protocontinents of granite represented the only land. A simple, single-cell form of life now inhabited our world, and it radiated and diversified in that form for the next billion years. Life's great trick throughout this time was to mimic the existing chemistry of rocks.

- Life has irrevocably transformed every facet of Earth's near-surface environment. The most obvious changes have occurred in the oceans and atmosphere, but life has radically altered the rocks and minerals as well. Those big changes took a lot of time.

- For a billion years or more after the innovation of that first living microbe, Earth's surface hadn't changed in any significant way. It is true that new varieties of microbes probably formed brownish or purplish scums along some coastlines. It's even possible that there were patches of greenish slime that populated shallow ponds and bays as a few pioneering cells began to experiment with ways to capture the Sun's energy. But 3.5 billion years ago, the continents were still totally barren. No plants decorated the rocky landscape, and there certainly weren't any animals of any sort.

- Earth at age 1 billion years, or roughly 3.5 billion years ago, was at a major transition point in our planet's history. A lot has happened to set Earth on its path to the modern world we know. The oceans and atmosphere had formed, though they were very different from the oceans and atmosphere of today. Plate tectonics was just getting started, and the first continents were being assembled, though they were much smaller in total landmass compared to our time. And the first life had emerged, though it consisted entirely of microscopic cells. In many senses, Earth was well on its path to what it would become.

- In terms of earth science, something special set Earth at 3.5 billion years apart from earlier times. At about 3.5 billion years ago, we begin to see a significant rock record. For the first time in Earth's long history, large-scale deposits of rock survive. These revealing fragments of the early crust are called cratons, which are very old, very stable, buoyant pieces of continents that represent ancient large islands and minicontinents. Cratons are generally more than 2 billion years old, and some may be closer to 4 billion years old. A handful of cratons in North America, Africa, and Australia form the very hearts of continents, and they preserve the oldest rocks on Earth.

The Geological Timescale

- The timescale that geologists use to pinpoint different episodes in Earth's history is a constant work in progress. The geological timescale divides Earth history into major transitions as that imperfect history is known at a given time. However, we keep learning more, and it turns out that many of Earth's most transformative events probably don't correspond exactly to any boundary in the current time line, so the names and dates might change sometime in the future.

- Earth history is first divided into four major eons. The earliest, and consequently the least understood, is the Hadean Eon—the hellish time—extending from Earth's formation through about 4.03 billion years ago. By convention, the Hadean Eon is defined as the time from which no rock formations are known. A few years ago, that number was 3.85 billion years, but as of today, the Hadean Eon ends at 4.03 billion years, because that's now the oldest known rock formation on Earth.

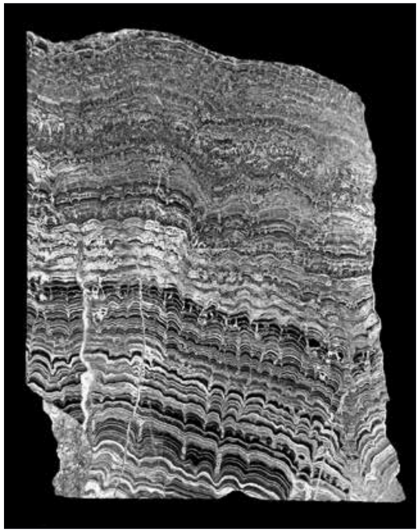
- Next comes the Archean Eon, which spans the period from 4.03 to 2.5 billion years—almost a third of Earth history. The Archean Eon is further divided into four eras, which seem to be arbitrary.

- The Eoarchean Era spans from 4.03 to 3.6 billion years. There are only a very few small outcrops from that interval; these oldest Eoarchean rocks are all pretty altered by heat and pressure. They've been metamorphosed in such a way as to mask what the original rocks might have been. It's not even clear in most cases whether the rocks were sediments or from volcanoes.

- One exception, and an incredibly important discovery, is the oldest of the so-called banded iron formations (BIFs). These iron-rich rocks must have formed on the ocean floor where iron-rich minerals were deposited in layers. The rocks have alternating bands of red hematite and black magnetite, which are both iron oxide minerals. It's possible that microbes played an important role in the formation of the BIFs by pulling the iron out of solution and forming those uniform layers, so it's entirely possible that these rocks represent some of the earliest signs of life—as old as 3.85 billion years.

- The Paleoarchean Era comes next. It rather arbitrarily spans 400 million years, from 3.6 to 3.2 billion years. Neither of those endpoints is associated with any obvious major events in Earth history. However, this is the time span when the first major pieces of crust—the first real surviving cratons—date from. The oldest known unambiguous fossil structures come from this time.

- Then comes the Mesoarchean Era, another 400-million-year chunk, from 3.2 to 2.8 billion. In this interval, we find increasing volumes of preserved rocks in more cratons, so it's clear that continents were being assembled. This is also the interval for which there's growing evidence that modern plate tectonics probably took over in a global-scale, organized way from the vertical, plume-driven tectonics of before, forming the first large continent by around 3.1 billion years ago. And later, with global-scale plate tectonics, came what may have been the first instance of all the continents coming together to form a single supercontinent.



Stromatolites were common more than 542 million years ago, which includes the Proterozoic Eon.

- The fourth and final segment of the Archean Eon is the Neoarchean Era, the 300-million-year interval between 2.8 and 2.5 billion years ago, a time when the rock record becomes more complete and nuanced. A fair amount of Neoarchean mineralization, including some huge ore deposits in Australia, Africa, Canada, and Europe, is associated with rocks of this age. Importantly, 2.5 billion years ago is about the time when the most important atmospheric change in history took place—the rise of oxygen through the invention of oxygen-producing photosynthesis.

- The third of Earth's four grand eons is the Proterozoic Eon, which embraces more than 40 percent of history, from 2.5 billion to 542 million years ago. In fact, 542 million years is not an arbitrary cutoff date; it represents a significant innovation in life—when the first big pulse of mineralized shells occurs in the fossil record.

- The Proterozoic Eon is divided into three eras, a division that seems arbitrary, even unfortunate, because there are big transitions that are simply not represented by this timescale. The Paleoproterozoic Era spans from 2.5 to 1.6 billion years—a 900-million-year interval during which a lot happened, including atmospheric oxygenation, the oldest unambiguous fossils of microbes, two huge pulses of banded iron formations, and the beginning of a long period during which much of Earth didn't seem to do much of anything new.

- The Mesoproterozoic Era is the 600-million-year period from 1.6 to 1 billion years. During this time, there was at least one new supercontinent formed and broken up, and there were huge pulses of new minerals and major ore deposits as well. However, other than being a nice round number, there's nothing special about 1 billion years ago.

- The Neoproterozoic Era is the period from 1 billion to 542 million years ago, although a better starting point might be 850 million years ago. Regardless, a huge amount happened during that roughly 450-million-year interval. There were astonishing changes in climate and equally dramatic biological innovations, including the first multicellular animals. In addition, another supercontinent formed and dispersed.

- The last of the four grand eons is the Phanerozoic Eon—the time that saw the emergence of the modern living world over the last 542 million years. Naturally, being closer to modern times, and with a profusion of animals and plants that left clear fossils, we have a much more detailed picture of this last half billion years or so.

- The relatively short Phanerozoic Eon is divided into three eras, which are further divided into a dozen or so periods, which are subdivided into smaller and smaller time intervals based primarily on important innovations in life as well as a series of mass extinction events. The closer we get to the present, the more richly woven is the tapestry of Earth's story.

Suggested Reading

Banfield and Nealson, *Geomicrobiology*.

Hazen, *The Story of Earth*, Chapter 6, pp. 150–153.

Knoll, *Life on a Young Planet*.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology.*

Questions to Consider

1. What are the four eons of Earth history, and what events delineate those eons?

2. Why did the earliest life forms on Earth have little effect on the near-surface environment?

Red Earth—The Great Oxidation Event

Lecture 30

Energy is an essential requirement of all life, and the Sun provides an especially convenient and reliable source. Early in Earth's history, microbes employed sunlight in a variety of photosynthetic oxidation-reduction reactions. The earliest photosynthesis reactions did not produce oxygen; some microbes today retain this ancient process. The evolution of modern oxygen-producing photosynthesis appears to have occurred when two independent photosynthetic pathways were combined into one. This process now is the primary producer of biological energy on Earth.

The Great Oxidation Event

- Oxygen is the most abundant element in Earth's crust and mantle. Almost two of every three atoms are oxygen. But it took life, and the emergence of the amazing process of photosynthesis, to isolate oxygen into the molecule that we breathe. As a direct consequence of photosynthesis more than 2 billion years ago, Earth's solid surface changed from dull gray to brick red in a geological afternoon.

- We are learning about this critical transformation in Earth and in life from fossils of many kinds—impressions in rock, molecular remains, and isotopes. Oxygen-producing photosynthesis points to the growing influence of new kinds of algae and the consequent rapid rise of an oxygen-rich atmosphere. Many details of this epic transition, called the great oxidation event, are uncertain and intensely debated.

- Our best guesses regarding the timing of the great oxidation event come from subtle changes in the rock record, which reveal a rise in atmospheric oxygen shortly after Earth's two-billionth birthday, perhaps 2.45 billion years ago. By 2.2 billion years, atmospheric oxygen had for the first time risen to more than one percent of its modern level. Today, oxygen makes up about one in five molecules of the air we breathe—about 20 percent. So, 2.2 billion years ago, there was perhaps two-tenths of a percent of oxygen, and that was enough to forever change Earth's surface.

- This fascinating story of how Earth became a planet with an oxygen-rich atmosphere has only recently come into focus, and there's still a lot we don't know. But there is a scientific consensus about many important aspects as more and more new lines of evidence have emerged and new research directions have been tackled.

- All the evidence for the great oxidation event is locked in old rocks and minerals from around the globe. Most critically, there's a growing catalog of observations that span a vast interval of Earth's history from about 3.5 to 2 billion years ago. We find that many rocks older than 2.5 billion years contain distinctive minerals that rapidly weather away in the modern environment because of the corrosive effects of oxygen. Findings point to an atmosphere completely lacking in oxygen.

- Rocks deposited at or near Earth's surface after about 2.5 billion years ago show a very different chemical pattern that appears to point unambiguously to oxygen. Most notable are the massive layered deposits of iron minerals called banded iron formations (BIFs) from between about 2.5 and 1.8 billion years ago. There are also immense deposits of manganese oxides at about that same time. Many hundreds of other new minerals also appeared for the first time after the atmosphere became oxygen rich.

- Colorful minerals of copper, nickel, molybdenum, cobalt, mercury, uranium, and many other elements also appear for the very first time in Earth history after the great oxidation event. That diversification of the mineral kingdom was just one more manifestation of the great oxidation event.

- The rock record is incomplete, and it can become altered in ways that are confusing and misleading. Nevertheless, new evidence kept building for a major transition in Earth's atmosphere more than 2 billion years ago. The smoking gun for the great oxidation event came early this century from isotopes. In fact, it was an unexpected

Photosynthesis is the process by which plants transform light energy into chemical energy.

source that is deeply buried in data on the isotopes of the very common element sulfur that established the beginning of the great oxidation event at about 2.4 billion years.

Photosynthesis

- There's now ample evidence that Earth's atmosphere contained a small but significant amount of molecular oxygen by 2.4 billion years ago, but where exactly did that oxygen come from? It's now common knowledge that plants and other organisms make oxygen by the remarkable process of photosynthesis.

- Photosynthetic cells combine water, carbon dioxide, and sunlight to make the energy-rich molecule glucose, which serves both to form plant tissues and to power other biochemical processes. This chemical reaction is as follows.

$$6CO_2 + 6H_2O + \text{energy} \Rightarrow C_6H_{12}O_6 + 6O_2$$

- One consequence of this reaction is the production of oxygen as a byproduct. So familiar is this chemical reaction that we now just take it for granted that plants play a central role in making our world a habitable place. But photosynthesis is not an obvious process, and the discovery of how photosynthesis works was one of the greatest advances in the history of science.

- In its bare-bones form, the chemical reaction of photosynthesis is very straightforward: Carbon dioxide plus water combine to make sugar. Yet the details of photosynthesis turn out to be extremely complex, and some of the steps are still being studied.

- Many scientists study the nature and origins of photosynthesis. Historical details are murky, but biochemist Robert Blankenship's best estimate is that the most ancient and primitive light-collecting chemical reactions probably date back more than 3.5 billion years. Those earliest forms of photosynthesis didn't produce oxygen at all. Some ancestors of those early kinds of cells still survive today, and they reveal that these most deeply rooted photosynthetic microbes lived without oxygen. Indeed, most of these primitive microbes don't even tolerate oxygen.

- Perhaps the most important discovery is the tendency of microbes to shuffle and swap their light-collecting genes. For microbes, this form of lateral, or horizontal, gene transfer turns out to be an important mechanism of adaptation and evolution. In the distant past, some single-celled organisms borrowed photosynthetic pathways from other cells in this way.

- Today, the oxygen-producing kind of photosynthesis that's used by almost all plants appears to be a coupling of two primitive chemical reaction pathways identified in the early 1960s called photosystem I and photosystem II. The two systems differ in many details, but each houses a few dozen chlorophyll molecules bound to proteins in a core complex, plus pigments in a so-called reaction complex. In most plants, the combination of these two pathways provides an extra energy boost. That's how today's plants exploit sunlight far more efficiently than did those earlier forms of photosynthesis.

- Even before photosynthesis, and even if photosynthesis had never gotten started on our planet, there were still nonbiological ways by which Earth's surface would have inevitably produced a very modest amount of atmospheric oxygen. And it's very likely that life itself contributed a small amount of oxygen, even before the evolution of photosynthesis.

- It turns out that living cells have learned at least four different ways to make oxygen from their surroundings in addition to photosynthesis. Of course, oxygenic photosynthesis is the huge process today, and it dwarfs all other ways to make oxygen. But these other biochemical pathways may very well have resulted in oxygen production for the past 3 or more billion years.

- It's a recurrent theme in biology. Life is remarkable in its ability to scavenge energy from its environment any way it can. Life uses heat energy from volcanoes, chemical energy of rocks, sunlight, and radioactivity in some special deep subsurface ecosystems.

- By far, the easiest way to obtain energy while liberating oxygen is to start with a reactive molecule that's already oxygen rich. So microbes have learned to exploit hydrogen peroxide, H_2O_2, which is produced in small quantities high in the atmosphere.

- It's certainly true that there wouldn't have been very much hydrogen peroxide before the rise of atmospheric oxygen. It's a trace chemical in any conceivable Earth scenario, and consequently, non-photosynthetic microbes can't have played any significant role in modifying Earth's early environment.

- There are other chemical approaches to making oxygen as well. A team of Dutch microbiologists recently reported what was perhaps a more significant oxygen-producing scenario through most of Earth history. They reported on some microbes that obtain energy by decomposing the oxides of nitrogen, which can be produced by lightning and by burning fossil fuels with small amounts of nitrogen. Early in Earth's history these so-called NOx chemicals were produced in small amounts through reactions of nitrogen gas with minerals.

- Today, even more NOx compounds are generated because of the widespread use of nitrogen-rich fertilizers that run off into lakes, rivers, and estuaries. Large microbial blooms include contributions from cells that are able to decompose nitrogen oxides into nitrogen plus oxygen. Then, those clever cells use the newly formed oxygen in reactions with methane, which is also available in the environment. And those oxidation reactions provide life's energy source.

- Of course, all of these investigations of modern living cells and their biochemical processes must be supplemented by studies of ancient fossil organisms, including fossils of the earliest oxygen-producing life. And those studies represent some of the most revealing, and at times dangerous, research in our quest to understand the story of Earth.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 7, pp. 154–180.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*.

Sagan and Chyba, "The Early Faint Sun Paradox."

Questions to Consider

1. What are the principal reactants and products of the photosynthesis reaction?

2. What is the early faint Sun hypothesis, and why didn't Earth freeze over?

Earliest Microbial and Molecular Fossils?
Lecture 31

Of the several ways that Earth has learned to make atmospheric oxygen, photosynthesis is without question the champion. The question of how photosynthesis began is in large part the domain of paleontologists, who study what turn out to be extremely fragmentary remains of the ancient microbial world. Archean paleontology involves the search for signs of life in rocks older than 2.5 billion years, which is where we find the earliest evidence for any kind of photosynthesis and see hints of the initial transition to an oxygen-bearing atmosphere. In their search for earliest traces of photosynthesis, fossil hunters concentrate on Earth's oldest rocks.

Archean Paleontology

- There are precious few fossil remains of the first photosynthetic single cells. Microbes have no hard parts, like bones or shells, so they don't generally remain intact after they die. After billions of years of burial, heating, squeezing, and chemical alteration, almost nothing in the way of microbial fossils has been preserved, much less documented.

- What little has survived is typically baked and crushed. Colonies of presumed fossil microbes at best look like a smear of small black smudges. It takes a creative imagination, and more, to make any sort of biological interpretation—at least one that will convince other scientists—so it's not too surprising that every new announcement of microbial fossils more than 2 billion years old is met with a lot of skepticism.

- Try to imagine what would happen to a colony of microbes when they die. Almost invariably, the microscopic collection of chemicals that was a living cell is going to fall apart. Larger biomolecules like proteins and cell membranes will break down into smaller and smaller molecular pieces, ultimately into water and carbon dioxide. Many microbes will be eaten or scavenged, and almost nothing will remain after a few months or years, much less millions or billions of years.

- Time is not kind to dead cells. There may be rare exceptions, but it takes extraordinary circumstances. Cells must be buried quickly in fine-grained sediments with absolutely no corrosive oxygen in the environment. The host rock can't get too hot, nor can the rock be too deformed by pressure. Even so, only the hardiest carbon-based molecules can survive any length of time, and those molecules survive in an altered form.

- What's most likely to persist is the sturdy carbon backbone of molecules, perhaps up to about 20 carbon atoms total. Sometimes the backbone is a simple, long chain with a few carbon atoms branching off to the sides, and sometimes it will be a hopanoid group of interlocking rings.

- The diagnostic molecular fragments are like ultrasmall skeletons. They're all that's left of much larger collections of functioning biomolecules that have been depolymerized, degraded, and otherwise altered down to a resilient core.

- This is a new and different game in paleontology. We're talking about searching for the actual molecular pieces of once-living cells. These are the atoms and molecules that were once alive. It's really challenging, but if you can find such a molecular skeleton in old sedimentary rocks, and if you can convince yourself and others that it's not simply contamination from younger rock formations or from all the living microbes in our environment, then you might be able to claim discovery of a chemical fossil—the original atoms of a once-living microbe.

- The contrasting lifestyles of this new breed of molecular paleontologists are fascinating. On the one hand, the women and men who enter this field have to endure the rigors of field geology in some of Earth's most forbidding places—remote locations in

Africa, Australia, and northern Canada. It requires hiking miles across arduous terrain, excavating hard rocks by hand, and carrying hundreds of pounds of promising specimens back to base camp.

- Other geologists work for months at drilling rigs, because fresh drill cores are less likely to be weathered and contaminated by surface microbes and vegetation. These scientists face months of hardship, danger, and deprivation.

- Then, it's back to the laboratory for more months of clean-room tedium. Once you have the rock in hand, a single thumbprint, even the slightest breath, can contaminate a precious three-billion-year-old rock sample and lead to false results. It not only takes time and patience—and exquisite care in handling specimens—but you also need an arsenal of specialized microanalytical apparatuses to extract individual molecules from a rock.

- One of the pioneers in this kind of 21st-century paleontology is Roger Summons, whose laboratory looks for molecular fossils in some of Earth's oldest rocks. It will probably take many years, more samples, refined separation methods, and new analytical techniques before the challenges facing this kind of research are fully resolved.

The Fossil Record and Photosynthesis

- The fossil record holds many clues related to the history of photosynthesis. In addition to fossils of primitive cells and algae, mound-shaped stromatolites, and even possible molecular fossils, there are microbial mats, which may be at once the most obvious and the most overlooked fossils of ancient photosynthetic life. Today, you can find microbial mats just about anywhere around the world, wherever shallow coastal waters or banks and slopes of slow-moving rivers and streams provide a foothold for algae.

- Given the chance, algae will form thick, tangled carpet-like layers of intertwined filaments. These resilient coatings provide a kind of anchoring to loose, sandy sediments and ensure that the algae are stabilized in a wet, sunlit environment—a protection from the erosion of floods and waves. The paleontological community all but overlooked these fossil microbial mats before the discoveries of Nora Noffke, the world's leading authority on ancient microbial mats.

- Microbial mat fossils are important because they have to be associated with some kind of photosynthesis. That's not necessarily true of microbes that left fragmentary remains in black cherts or black shales. Those fossils could have come from deep, dark zones—far from the surface and sunlight.

- A strong case can be made that shallow-water stromatolites were formed by microbes that were photosynthetic, because the microbes are held in place right at the surface, though it's also possible that this kind of mineralized mound could simply represent a protective home in an otherwise harsh, wave-swept environment.

Shallow-water stromatolites can be found off the coast of Australia.

- But it seems logical that microbial mats must have been made by photosynthetic organisms. After all, why would a colony of microbes use all that energy to stabilize itself in a rough, shallow tidal zone if it wasn't trying to collect the sunlight?

- Scientists have been looking at ancient microbial fossils for about half a century. For much of that time, paleontologists focused on only three kinds of rock formations. First are the black cherts, which are silica-rich rocks like the controversial 3.5-billion-year-old apex chert that Bill Schopf studied.

- In fact, old fossiliferous black cherts first made the news in the early 1960s, when Harvard's paleobotanist Elso Barghoorn recognized ancient microbial fossils in the 1.9-billion-year-old gunflint chert from northern Minnesota and western Ontario. When Barghoorn examined thin, transparent sections of the gunflint, he realized that he was seeing ancient single cells preserved in exquisite detail. It turns out that these fossils are still the oldest absolutely unambiguous fossils of photosynthetic cells on Earth. There are older claims, but none that everyone accepts.

- Then there are carbon-rich black shales, which is the rock type studied by Roger Summons and colleagues. Black shales are very fine-grained rocks that often come from deeply buried sediments, so they are perhaps the best source of ancient molecular fossils. Black shale typically represents a deepwater accumulation of mud and carbon-rich debris. They must have entombed ancient microbes.

- A third intensively studied group of microbial fossils are the dome-like structures called stromatolites. It might have been difficult to interpret these distinctive mound- or cone-shaped structures, which are commonly preserved in limestone, but modern living stromatolites still form reefs in a few shallow coastal areas, most famously at Shark Bay in Western Australia.

- These odd layered structures form when a thin surface coating of photosynthetic microbes causes layer upon layer of minerals to precipitate. There are countless fossil stromatolite localities in older rocks all around the world, some in rocks about 3.5 billion years old.

- By about 1990, black chert, black shale, and limestone stromatolites were all well-established rock types in which to find evidence of ancient microbes. To this very limited list of Earth's oldest fossiliferous formations Nora Noffke has now convincingly added a fourth rock type: sandstone.

- It's easy to understand why sandstone wasn't embraced earlier. Microbial fossils are most easily preserved in fine-grained rocks like chert or shale, or in limestone reefs, where the grain size is smaller than the microbes. That explains the focus on black chert, black shale, and stromatolites. Sand, by contrast, is relatively coarse, and the mineral grains are very much larger than most microbes. That makes it hard to preserve small fossils.

- In addition, sand accumulates in the turbulent tidal zones of beaches, where sand patterns and most signs of life are quickly erased. Fossils in sand are likely eroded away and dispersed. Nevertheless, Nora Noffke has spent more than two decades studying modern tidal flats and their rich ecosystems of tough, fibrous microbial mats. One of the neatest things about these microbial mat structures is that you don't need a microscope to see them.

- Noffke found that microbial mats impose all sorts of distinctive structures along shallow, sandy shorelines. For one thing, they imprint a crinkly texture to the sand surface. Mats also bind and trap sediment grains in a thick, resilient mass of algal strands, and they alter the pattern of ripple marks in the sand. Mats rip apart and fragment in storms by tearing into distinctive geometric chunks and rolling up. All of those features can be seen in the field, if you know what to look for.

- Most sandstone outcroppings have none of these attributes suggestive of photosynthesizing life. They appear monotonously smooth or perhaps gently rippled, but they lack anything that's obviously biological. Nora Noffke has an amazingly sharp eye, and she learned to spot the distinctive wrinkled and cracked surfaces characteristic of fossilized microbial mats in ancient rocks.

Suggested Reading

Hazen, "The Evolution of Minerals."

———, *The Story of Earth*, Chapter 7, pp. 154–180.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapters 7, 19, and 20.

Questions to Consider

1. What evidence suggests that oxygen became significant after 2.5 billion years ago?

2. How did oxygen change the character of Earth's near-surface environment?

Microbial Mats and Which Minerals Can Form

Lecture 32

Important evidence for Earth's early oxygenation comes from fossils of primitive organisms that used sunlight for their energy source. Fossil microbial mats provide some of the most compelling evidence for early photosynthesis. Oxygen is a remarkably corrosive element, and the rise of oxygen quickly caused Earth's land surface to become rusty red, a consequence of oxidation reactions involving common iron compounds. A review of geochemical data shows why it appears that there was not a trace of oxygen on Earth before 2.5 billion years ago. A wealth of geochemical data reinforces this conclusion.

Microbial Mats

- It's not at all surprising that microbes would have colonized coastal areas with sturdy mats *after* the great oxidation event. We know that filament-like algae are a major source of oxygen, produce a lot of the oxygen in our atmosphere, and form mats today.

- But 3 billion years ago is a time long—at least 600 million years—before the presumed great oxidation event. There was simply no reason to believe that oxygenic photosynthesis started much before 2.4 billion years ago. So no one expected—indeed, many paleontologists were probably highly skeptical—of claims for an ecosystem that relied so heavily on sunlight so long ago.

- Black chert and black shale represent deep subsurface ecosystems, where any microbes relied on the chemical energy of rocks to survive. Such microbes should have been around since the dawn of life more than 3.5 billion years ago. But there was really no reason to expect photosynthetic surface life until about 2.5 billion years ago.

- Stromatolites are certainly surface deposits formed by layers of microbes, but the protection provided by these rocky mounds

Microbial mats have a texture that is similar to that of elephant skin.

appears to be explanation enough. Stromatolites didn't have to be photosynthetic, though now it seems likely they were.

- Microbial mats are different. It takes a lot of metabolic energy to build up mat structures and bind all that sand. The only logical reason to do so is to anchor yourself in a sunny environment. Therefore, most paleontologists agree that if you find a microbial mat fossil, you are finding incontrovertible evidence for photosynthesis. The trick is to find the oldest microbial mat fossils—an exceptionally difficult task.

- Microbial mat features are subtle. They involve slight irregularities in the surface topology of a sandstone outcrop. The outcrop has to be weathered to expose one ancient flat surface. And you can imagine how challenging it is to spot such features in the overhead glare of the midday sun of the South African or Australian deserts.

- Microbial mats are the new evidence to watch. After all, there's no question that microbial mats were a common feature of shorelines on Earth more than 3 billion years ago, and it's certain that those microbes used sunlight as their energy source. But a key question remains: Did the mat-forming microbes produce oxygen, or did they use sunlight for simpler photochemistry?

- Modern microbial communities reveal the evolutionary history of a variety of sunlight-harvesting strategies, and many of those mechanisms don't produce oxygen. In fact, it's likely that the very first microbes using photochemistry to harvest the Sun's energy did not give off oxygen as a by-product.

- That's why the details of how those 3-billion-year-old mat-forming microbes used the Sun's energy will remain a hot topic for some time to come. What we can say for sure is that these fossils date not only the earliest appearance of photochemistry, but also some of the earliest appearances of life itself.

Earth's Gradual Oxygenation

- Whatever new fossils are discovered, the big picture of Earth's gradual oxygenation is widely accepted by geologists. The history is divided roughly into three parts. During Earth's first 2 billion years, prior to about 2.4 billion years ago, Earth's atmosphere was basically lacking in O_2. There are numerous lines of evidence that early Earth's atmosphere was devoid of molecular oxygen.

- There is mineral evidence, such as the occurrence of unweathered pebbles of pyrite and uraninite, and there is chemical evidence in the anomalies of such elements as cerium and iron in ancient soil deposits. In addition, there is sulfur isotope data—sulfur isotope fractionation, based not on mass but on ultraviolet radiation, that could only have occurred before the rise of oxygen and a protective ozone layer. Just about everyone agrees with this scenario.

- Then, we see a rather sudden change in these characteristics at 2.4 billion years ago, which has been interpreted as the time when oxygen rather quickly rose to a few percent of modern levels.

- Rocks younger than 2.4 billion years lack the mass-independent fractionation of sulfur isotopes. And that change parallels the rise of photosynthetic microbes, which caused the dramatic cumulative changes that are thought to have occurred between about 2.4 and 2.2 billion years ago. That was a key change, and—so far, at least—it was an irreversible change that transformed Earth's near-surface environment and paved the way for even more dramatic changes in Earth's geology and biology.

- The next 1.5 billion years or so—the interval lasting to perhaps 700 million years ago that includes almost the entire Proterozoic Eon—is generally presented in graphs and tables as a time when the level of atmospheric oxygen stayed more or less constant at a couple of percent modern levels.

- However, this is not a universally held idea, and many researchers think that oxygen contents must have gradually risen during that time, with smaller fluctuations up and down. After all, it's almost never a good bet that Earth just did exactly the same thing for 1.5 billion years.

- The period between 700 and 600 million years ago, and again between 300 and 200 million years ago, are thought to be intervals when atmospheric oxygen spiked in concentration, largely as a result of feedbacks with the biosphere.

Aqueous Geochemistry

- In 1965, geochemists Robert Garrels of Northwestern University and Charles Christ of the U.S. Geological Survey published a now-classic book called *Solutions, Minerals, and Equilibria*, in which they showed how to calculate what minerals can form under what near-surface conditions. Their central idea is that each kind of mineral can only form under a limited set of chemical conditions.

- Some of these parameters are obvious. You can't form minerals of copper or uranium unless there's a significant amount of copper or uranium in the environment. You can't form carbonate minerals unless there's a supply of the carbonate CO_3 ion in the environment. What is probably not so obvious is that any element that occurs in more than one oxidation-reduction state is extremely sensitive to the amount of oxygen in the environment.

- The amount of oxygen in the environment can be measured in many ways, but perhaps the most intuitive way is with the fraction of total air pressure contributed by oxygen—what's known as the partial pressure of oxygen. Today, the partial pressure is about two-tenths of an atmosphere, which is just another way of saying that oxygen is roughly 20 percent of the atmosphere.

- Everyone agrees that the amount of oxygen early in Earth's history was much, much lower than our current two-tenths of an atmosphere. It has been argued that the partial pressure of oxygen before the great oxidation event was pegged at about 10^{-72}, which is 72 orders of magnitude less oxygen than today. At first, the idea sounds crazy, but the graphs of Garrels and Christ support this idea.

- There is other important mineralogical evidence that points to an anoxic early environment—evidence based on some of the minerals that *did* form at the surface. One notable example is the iron carbonate mineral siderite, $FeCO_3$, a mineral that commonly occurred early in Earth's history but rarely forms today. Siderite is the carbonate of plus-two iron, and it can only form under extremely low partial pressures of oxygen—even lower than 10^{-72}.

- A useful graph in *Solutions, Minerals, and Equilibria* outlines this point by showing the range of conditions under which siderite forms, given varying amounts of carbonate and oxygen. And it's very restrictive: Only a small area in the plot, where carbonate is enriched and oxygen is lacking, covers the conditions under which siderite can form.

- The graph shows that whenever we find iron carbonate in rocks—and we find it commonly in rocks older than 2.5 billion years—the atmosphere contains essentially no oxygen. And the same kind of evidence can be extracted from many other minerals—from unweathered pyrite, unweathered uraninite, oceans rich in sulfide, the presence of cerium in soils, and many other signs if you know what to look for.

- This important textbook, published in 1965 and studied by a generation of mineralogists, clearly describes the conditions under which various minerals are possible and impossible. That information, together with ever more precise data from paleochemists about conditions on Earth before and after the great oxidation event, allows us to identify which minerals could exist before that event and which could not.

- The reasons for the limited mineralogical repertoire before the great oxidation event are not difficult to understand. It turns out that thousands of mineral species formed in the shallow crust by interactions of oxygen-rich waters with preexisting minerals. These waters resulted from the exchange of oxygen between air and water, but oxygen-rich waters simply could not have occurred before 2.4 billion years ago.

Suggested Reading

Hazen, "The Evolution of Minerals."

———, *The Story of Earth*, Chapter 7, pp. 154–180.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapters 7, 19, and 20.

Questions to Consider

1. What is oxidation, and what role does oxygen play in oxidation reactions?

2. What evidence suggests that there was no atmospheric oxygen before 2.5 billion years ago?

Earth's Greatest Mineral Explosion

Lecture 33

This lecture more closely examines the rise of mineral diversity in the Proterozoic Eon. A few years ago, this lecture would have been based almost entirely on speculation, but thanks to recent and exhaustive research, we're gaining a remarkable picture of exactly when and where mineral diversification took place, with two important conclusions: First, it took a long time—a billion years or more—for the mineral diversification to follow the great oxidation event. Second, new minerals appeared—not steadily, but during short episodes of intense activity associated with the formation of supercontinents.

Stage 7 of Mineral Evolution

- The first comprehensive mineral evolution survey of any chemical element was undertaken by Ed Grew, the world's leading authority on the minerals of the rare element beryllium. Beryllium is element 4 in the periodic table, is surprisingly rare, and is the first of the so-called alkaline earth elements, right above the more abundant magnesium and calcium.

- Like magnesium and calcium, beryllium readily gives up two electrons to become a plus-two ion in crystals. But beryllium is very small and thus doesn't easily fit into the larger crystal sites with six or eight surrounding oxygen atoms. Beryllium always wants to be at the center of only four oxygen atoms, and that means it needs its own distinctive crystal structures.

- In this respect, beryllium is what is called an incompatible element—it simply doesn't fit into ordinary rock-forming minerals, so it becomes concentrated in the leftover fluids. And those are the fluids that form pegmatites during the gray Earth of stage 4 mineral evolution.

- What Grew did for our understanding of stage 7 mineral evolution after the great oxidation event was remarkable. First, he catalogued every known beryllium mineral; it turns out that there are 106 approved species. Then, he tracked down all the localities where each of those 106 minerals have been reported. Then, he dove into the obscure geological literature in a dozen different languages to find out how old each mineral locality might be.

- Grew was able to produce a landmark graph on which he plotted age extending back 3.5 billion years on the horizontal scale and the cumulative number of beryllium minerals that had appeared on Earth on the vertical scale. Instead of a gradual and rather continuous rise in the diversity of beryllium minerals through Earth history, Grew observed very distinctive pulses of mineral-forming events.

- The oldest known beryllium mineral, found in rocks 3 billion years old, is beryl, which is an aluminum-silicate that occurs in many pegmatites and is the principal beryllium ore. A few more beryllium minerals appear before a small pulse between 2.8 and 2.6 billion years. Then, a much bigger pulse occurred—a tripling of the number of beryllium minerals—at about 1.8 billion years. Following that, there are additional episodes at about 1 billion years and then a big increase during the last 500 million years. These intervals turn out to be very significant.

- Grew followed his beryllium study with an even more ambitious project on all the minerals of boron—element number 5. There are well over 200 boron minerals, so it was a huge challenge to compile all that data. Like beryllium, boron does not easily fit into any common rock-forming mineral. It adopts a plus-three charge like aluminum, but it's too small to fit comfortably into the crystal sites of most aluminum minerals.

- One family of boron minerals, the colorful tourmaline, stands out as the oldest mineral containing boron. We suspect that tourmaline was first because it can form at relatively low concentrations of boron, but it's also a tough mineral that can persist as sand grains when most other minerals weather away. The oldest dated boron mineral is tourmaline, which appears in rocks more than 3.5 billion years old. All other boron minerals are more recent than tourmaline.

- Just like beryllium minerals, we see pulses of boron mineral formation at about 2.8 and at 1.8 billion years ago as well as at 1 billion years ago. Then, in the last 500 million years, boron minerals display a rapid diversification. And that effect may be a reflection of the fact that many boron minerals weather away quickly. Many boron minerals just couldn't survive very long and appear only in relatively young rock formations.

The Assembly of Supercontinents

- These episodes of mineral formation at 2.8 billion years, 1.8 billion years, and 1 billion years are all times during which it's now thought that supercontinents were being assembled. Perhaps the most astonishing conclusion of the theory of plate tectonics is that entire continents shuffle about the surface of Earth, moving from one hemisphere to another and from poles to equator over times of hundreds of millions of years. And an inevitable consequence of such continental motions is that, from time to time, continents collide.

- Details of those collisions are preserved in many lines of evidence. Paleomagnetic studies of once-molten rocks reveal the latitude and orientation of continents at the time when those rocks cooled. So we find that continents that are now widely separated appear to have been joined at earlier times. Fossils tell us the locations and ages of coastal beaches, coral reefs, and deepwater environments.

- In addition, certain distinctive fossil species like dinosaurs and land plants of a specific age are found on continents now widely separated but that must have once been joined. And continental collisions themselves have profound geological consequences that can be mapped and dated, not the least of which are pulses of mineralization.

- What these varied studies reveal is that on perhaps five separate occasions in Earth history, most of Earth's continental material converged in a series of collisions into a single supercontinent, surrounded by an even larger superocean. The details of the exact position and shape of those supercontinents becomes increasingly uncertain the farther back in time we go.

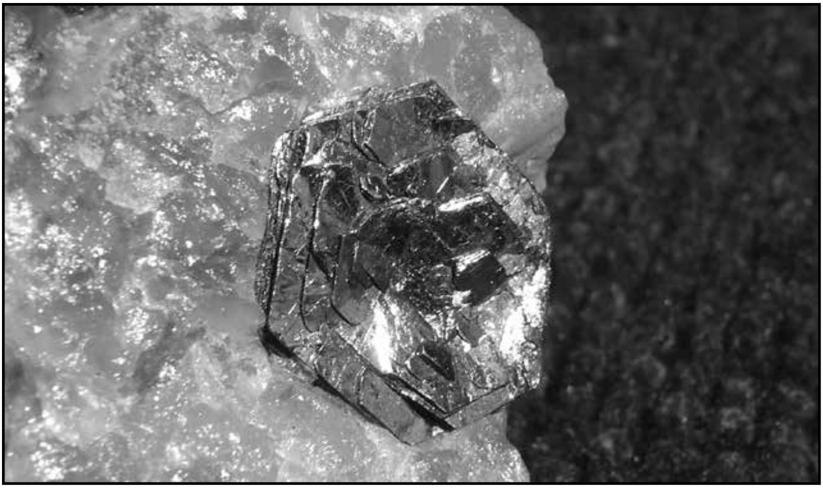
- Continental collisions produce minerals because collisions induce melting, and melting mobilizes mineral-rich fluids. Many of the most important ore deposits arise at these times and places of supercontinent assembly. Abundant granites and their associated pegmatites lie along these continental suture zones as well. Indeed, the larger and as yet unanswered question might be why we don't find more mineralized zones during the long intervening periods of supercontinent stability and breakup.

- What are these episodes that appear in Ed Grew's diagrams of beryllium and boron mineralization? The earliest well-documented supercontinent formed from about 2.8 to 2.5 billion years ago, when most, if not all, the continents clumped together to form the one gigantic supercontinent called Kenorland.

- Details are difficult to sort out because rocks of that age are sparse and generally quite altered by heat, pressure, and time. But mineral deposits, especially in Australia, South Africa, and Canada, paint a fuzzy picture of Kenorland. The supercontinent may have been stable for only about 100 million years, from 2.5 to 2.4 billion years ago—just before the great oxidation event.

- Then, the Kenorland breakup correlates with the great oxidation event. Indeed, it seems likely that increased coastline created by splitting Kenorland, and the increased flow of nutrients from the newly exposed coastlines, caused the immense algal blooms that caused the oxidation.

- Next came the supercontinent of Columbia, also known as Nuna, which began to assemble about 2 billion years ago. It's thought to have been a stable supercontinent for about 200 million years,



Molybdenite is the most important mineral source of molybdenum.

from 1.8 to 1.6 billion years ago; then, it broke up and had separate continents—not unlike today's globe—for perhaps 400 million years.

- Roughly 1.2 billion years ago, the supercontinent of Rodinia began to form. By 1 billion years ago, Rodinia was stable and lasted for a quarter of a billion years. Another period of breakup and isolated continents followed, starting about 750 million years ago. All this suggests that the supercontinent cycle is clearly implicated as a key factor in the diversification of Earth's near-surface mineralogy.

- Nevertheless, life and the rise of oxygen in the atmosphere is without any doubt the top cause of mineral richness on Earth. Most known oxide and hydroxide minerals simply cannot form without the abundant oxygen that has been produced by life.

Molybdenum and Rhenium

- Not everyone agrees that the great oxidation event marked a clear beginning of oxygen in Earth's atmosphere, but everyone agrees that molybdenum and rhenium data tell us something about erosion 2.5 billion years ago.

- Molybdenite is the most common mineral of molybdenum, and it often incorporates rhenium as well. Molybdenite is an exceptionally soft and easily abraded mineral, similar to graphite, only 1 on the Mohs hardness scale.

- There is solid evidence that there wasn't any atmospheric oxygen before 2.4 billion years. Even with significant atmospheric oxygen, as occurred after 2.4 billion years, that's simply not sufficient to increase mineral diversity right away. That's because *subsurface* waters, not air, are necessary to dissolve, transport, chemically alter, and otherwise modify the upper few thousand feet of rock.

- New minerals aren't formed primarily right at the surface, though there are certainly some new types that occurred as older rocks were weathered in air. But most of the numerous new minerals that arose for the first time after global oxidation formed underground, in the upper mile or so of the crust.

- More than 200 uranium minerals, almost 400 copper minerals, and hundreds more minerals of iron, manganese, nickel, mercury, molybdenum, and many other elements arise in this way. Many of these minerals form when oxygen-rich waters circulate through metal-rich ore bodies.

- Prior to the rise of oxygen, such mineral-forming reactions simply could not have occurred. But even long after the atmosphere had oxygen, the subsurface waters were highly reducing, and no new minerals occurred. Until recently, that statement was more of a conjecture than anything that could be proven, but new data—that comes from molybdenum and rhenium—make a convincing case for how very long it takes the subsurface to become oxidized and thus generate new minerals.

Suggested Reading

Anbar and Knoll, "Proterozoic Ocean Chemistry and Evolution."

Hazen, "The Evolution of Minerals."

———, *The Story of Earth*, Chapter 8, pp. 181–205.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 18.

Questions to Consider

1. What is mineral evolution, and how does it differ from previous approaches to mineralogy?

2. Why did the number of mineral species increase sharply after the great oxidation event?

The Boring Billion? Cratons and Continents

Lecture 34

The first 2.5 billion years of Earth history were characterized by incessant, often dramatic change. But the enigmatic billion-year span that followed at first glance appears to be an extended time of stasis—no major changes in climate, no glaciations, no major changes in near-surface mineralogy, and no major changes in atmosphere or ocean chemistry are thought to have occurred. How could a planet as dynamic as Earth be stable for such a long span?

The Boring Billion

- By most accounts, during the billion-year time in Earth history from roughly 1.85 billion to 850 million years ago—the middle of the Proterozoic Eon—our planet seems to have changed very slowly and in ways that are both subtle and as yet not fully understood.

- This vast interval has been dubbed the "intermediate ocean" by more conservative writers, but many prefer the more whimsical title, the "boring billion." It's a period that is often skipped over, but there are important changes in mineralogy, the oceans, the continents, and perhaps the structure of life—changes that together make this a very pivotal stretch of time.

- The Mesoproterozoic Era spans the interval from 1.6 to 1.0 billion years ago, so it encompasses only the middle 600 million years of the much longer boring billion. Before and after, things already look more interesting.

- The immediately preceding period, from 1.85 to 1.6 billion years, constitutes the tail end of the Paleoproterozoic Era, which includes the much more dynamic time of gradual global oxidation from 2.5 to 1.85 billion years ago. In fact, oxidation most likely continued underground until 1.5 billion years ago.

- After the Mesoproterozoic is the earliest bit of the Neoproterozoic Era, the interval from 1.0 billion to 850 million years ago. The end of the Neoproterozoic Era lasted until 542 million years ago and saw some of Earth's most dramatic changes, including at least two episodes of global glaciation and other dramatic changes in the near-surface environment, along with corresponding changes in biological evolution.

- The eras of the Proterozoic Eon can cause some confusion because the timings of its three big subdivisions—the Paleoproterozoic, the Mesoproterozoic, and the Neoproterozoic eras—were defined before some key events in Earth history were discovered. In other words, the timings don't quite match our present understanding of Earth history.

- In any case, with the boring billion we have a vast chunk of Earth's history—almost a quarter of the story—and there are essentially no headlines. No big thwack, no formation of first continents, no inception of plate tectonics, no origin of life.

- At first blush, the rock record of the boring billion interval reveals no epic, game-changing impacts or sudden climate changes. There are no obvious signs of glaciations or of mass extinctions.

- About the only thing going on was that the important interface between the ocean's more oxidized near-surface layer and the anoxic ocean depths may have gradually gotten deeper and deeper—on average, maybe a meter deeper every hundred thousand years or so, thus dropping 10,000 meters over the billion-year period.

- However, no fundamentally new life forms are known to have emerged from that ocean, nor is it generally thought that many new rock types or mineral species arose. At least that's the conventional wisdom. Many researchers believe that some hints of dramatic transformations must lie hidden in rocks of the boring billion, and those stories are so far largely unread.

- Some of Earth's most valuable ore reserves—immense deposits of lead and zinc and silver from Zambia and Botswana in Africa, from Nevada and British Columbia in North America, and from the Czech Republic and southern Australia—are found in rocks of ages smack in the middle of that billion-year interval. Many other important rock and mineral localities that formed at that time are rich in exotic minerals of beryllium, boron, and uranium.

- The tectonic story is equally interesting—and perhaps related to the valuable ores and exotic minerals from this time. Growing evidence suggests that Earth's continents clumped together into one gigantic supercontinent during the boring billion, then broke apart, and clumped together again in Earth's most majestic surface cycle.

- Biologically, this long period may not be boring at all. Throughout that billion-year interval are abundant, beautifully preserved fossils of microorganisms that reveal how life, though perhaps under great stress, still crowded coastal shallows and offshore environments. Though lacking confirmation from other lines of evidence, research using so-called molecular clocks has suggested that this period marks the first genetic divergence of precursor cells for fungi, modern plants, and animals.

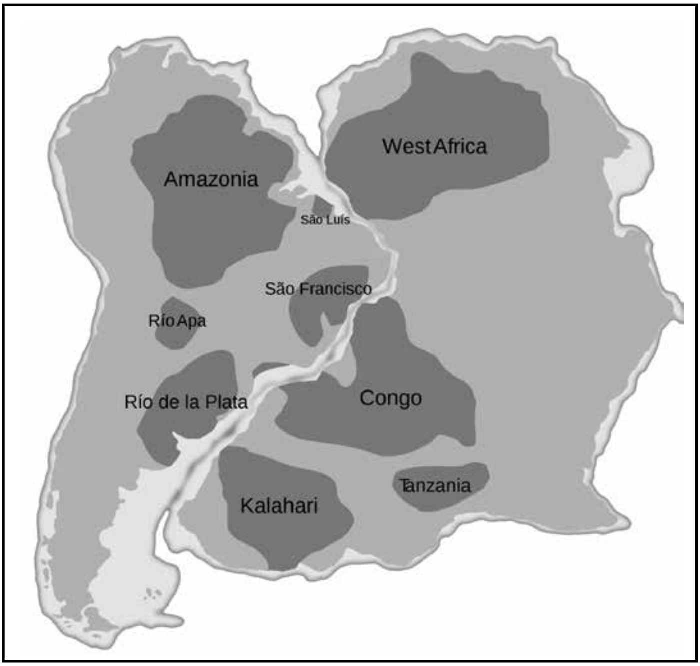
- All of these organisms depend on eukaryote cells—that is, their cells have a nucleus and specialized organelles—but the earliest differentiation into distinct types may have occurred at this time, along with the development of sexual reproduction and the first steps toward multicellularity.

Plate Tectonics and Cratons

- Perhaps the most significant change during the boring billion was associated with plate tectonics. Geological evidence from every continent on Earth reveals that the Mesoproterozoic Era was a time of inexorable shifts in the positions of continents.

- Probably the single most important geological discovery of the last half century is that Earth's familiar geography of oceans

Mesoproterozoic Cratons in South America and Africa



and continents is ephemeral. Our globe's land and water have transformed in position and relative extent over and over again.

- Plate tectonics not only acts to assemble all of the continents, but it also rearranges them by shuttling them across the globe, causing them to collide and split apart. Plate tectonics is the engine of Earth's constant extreme makeovers.

- The job of reassembling early Earth falls to a mix of geoscience disciplines, which collectively produce remarkable, though admittedly approximate, maps of past and future Earth. Fortunately, Earth has preserved numerous clues to help in the reconstructions.

- A key starting point is knowledge of how the continents are moving today—how fast they're traveling and in what directions. Year by year, scientists have employed satellites to measure the distance across the Atlantic Ocean. Thus, we have direct measurements of an increase of roughly two inches every year.

- We also see that Africa is splitting in two, and we can document how India smashes into China, which crumples the impact zone into the jagged Himalayan mountains, which are rising an inch or two every year. With changes occurring at a steady rate of an inch or two a year for 100 or 200 million years, these small increments add up to monumental changes.

- If we try to look back much farther than 100 or 200 million years, then we need to invoke other kinds of geological clues. Longitude ceases to be something we can extrapolate backward with any precision, but important data about latitude come from fossil magnetism that has been locked into volcanic rocks. Those paleomagnetic data have the potential to reveal the orientation of Earth's magnetic field long ago.

- Moreover, the dip of the field can also reveal the latitude of the continents at the time when those rocks solidified. Such subtle evidence frozen into solid rocks shows that rocks now at the equator were once at the poles, and vice versa. And that information is complemented by evidence from fossils and sediments that points to former tropical lagoons in what is now Antarctica or frozen tundra in what is now equatorial Africa.

- The sedimentary rock record adds vital data because different kinds of sediments accumulate in different environments. Sand accumulates in shallow seas while black mud forms continental shelves. The steady laying down and compression of layers in a swamp differs from the windswept sediments of a rocky alpine tundra, and both differ from the daily cycles of tidal lagoons, the annual and multiyear cycles of glacial lakes, and the very long-term sediment patterns caused by the advance and retreat of glaciers, or the cycles of sea level rise and fall.

- The complex picture of shifting continents is clarified over the past half billion years by the rich fossil record of animals and plants. Certain species are indicators of climatic zones, while the distributions of distinctive flora and fauna can point to widely separated continents that followed divergent evolutionary pathways.

- Experts in paleogeography have managed to bring many lines of evidence together to produce a coherent view of Earth back to at least 1.6 billion years ago, which is well into the boring billion. And there are now well-informed speculations about continental positions that have been pushed back much farther, all the way to 3 billion years ago.

- According to the most accepted models, Earth has repeatedly experienced times when all of the continents were clumped together into one or two supercontinents, and these supercontinents have repeatedly broken apart and dispersed.

- The view that is supported by many (though not all) geologists who study early Earth is that it took a long time to make the first continent. Plate tectonics was the prime driver, both promoting the production of granitic crust and assembling bits of granite crust into larger and larger landmasses.

- The focal point of these continent-forming activities is the subduction zone. At the point where a subducting slab plunges down into the mantle depths, all of the unsinkable granite bits and pieces pile up, one after the next, to make larger and larger stable, long-lasting landmasses.

- At the same time, the subducting slab partially melts to make even more granite above the subduction zone. That's how the most ancient protocontinents form. Those earliest pieces of continents are the cratons, and because cratons are made of tough igneous and metamorphic rocks, once a craton forms, it lasts a very long time and preserves a record of its history.

- Geologists have identified perhaps three dozen more or less intact cratons on six continents. Some are as old as 3.8 billion years, and they range in size from 100 to more than a 1,000 miles across.

- Examples of cratons include the Slave and Superior cratons in North America, the Kaapvaal and Zimbabwean cratons in Africa, and the Pilbara and Yilgarn cratons in Australia. Each of these cratons has experienced billions of years of motion across the globe. They've been jumbled together and ripped apart over and over again, along with many smaller ancient fragments. If we are ever to gain a picture of early Earth, it's the cratons that will provide the evidence, because cratons survive as the foundation stones of the continents.

Suggested Reading

Anbar and Knoll, "Proterozoic Ocean Chemistry and Evolution."

Hazen, *The Story of Earth*, Chapter 8, pp. 181–205.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 20.

Questions to Consider

1. What was the boring billion, and why is it called that?

2. What are cratons, and why are they the key to understanding Earth's geological past?

The Supercontinent Cycle

Lecture 35

Despite the name "boring billion," new research on rocks and minerals deposited between 1 and 2 billion years ago points to several ways that Earth may have transformed during that long interval. Perhaps most significantly, all of Earth's continents came together into one supercontinent—and then broke up again. According to the latest compelling interpretations, for at least the last 3 billion years, Earth has experienced a repeated cycle of at least five supercontinent assemblies, periods of stability, and then fragmentation. It appears that if we are to understand Earth, that great supercontinent cycle lies at the heart of the story.

Columbia

- Paleomagnetic data and a number of mountain belts suggest that between about 2.0 and 1.8 billion years ago, varied lands collided at convergent plate boundaries. The resulting supercontinent has been variously named Columbia, Nena, Nuna, or Hudsonland. This vast, barren land—roughly estimated to have been 8,000 miles long from north to south and 3,000 miles wide from east to west—incorporated almost all of Earth's cratons.

- The problem of arranging 30-plus cratonic fragments into one extinct supercontinent is daunting. In effect, each craton has traveled a distance equivalent to two-and-a-half times around the globe, and each craton has taken a different erratic path. That's why it's not at all surprising that multiple models compete for acceptance.

- What most experts agree on was that by 1.85 billion years ago, with the assembly of Columbia, the stage was set for the boring billion. Whatever the exact details of the Columbian supercontinent, we are fairly confident that the interior of the landmass was a hot and dry terrain with a great expanse of rusty red desert.

- There was no vegetation and certainly no animals; multicellular life hadn't yet appeared. From space, Earth may have appeared as a strangely lopsided world, with its one great reddish-colored landmass surrounded by an even more expansive, as yet unnamed, blue "superocean."

- With all the continents concentrated together near the equator, it's likely that the poles held only modest amounts of ice. With minimal ice caps, the ocean levels would have been correspondingly high, maybe even high enough to invade some coastal regions with shallow inland seas.

- The boring billion began with the Columbian supercontinent as a lone and relatively long-lived supercontinent that persisted more or less intact from 1.8 to 1.5 billion years ago. However, just because there was a single large landmass doesn't mean that plate tectonics had stopped.

- One notable feature of supercontinents is that they continue to grow slowly around their edges, because ocean plates subduct under their margins, and new volcanoes rise just inland near the coasts.

- Today, a good example of this coastal expansion can be seen along the Pacific Northwest coast, where such majestic and potentially dangerous volcanoes as Mount Rainier, Mount Hood, Mount Adams, and Mount Saint Helens are still active. It's certain that some portions of the Columbia coastline were similarly active.

- It's also certain that even more continental crust was added to Columbia as it experienced episodic rifting and ultimately breakup into smaller continents and islands. A big landmass like Columbia traps mantle heat and must eventually crack and fragment.

- About 1.6 billion years ago, the continent of Ur began to split off from Laurentia and the rest of Columbia, moving to the west. The newly formed ocean basin between Ur and Laurentia saw the deposition of a massive sedimentary sequence with layers of sand and mud that reached amazing thicknesses of more than 10 miles.

- The rifting of the Columbian supercontinent into two diverging continents had other consequences as well. Laurentia and Ur were still more or less at the equator, and that means there were still no continents at the poles, which in turn means that there probably wasn't any significant ice buildup at the poles. We have to conclude that ocean levels were still relatively high.

- Indeed, based on sediments formed at that time, we know that much of Laurentia's newly exposed west coast was flooded by shallow seas. Unlike today, when about 30 percent of the globe is land, it's likely that less than a quarter of Earth's surface was dry. And that state persisted for perhaps 200 million years as thick sediment formations accumulated in shallow waters around the globe.

- No ice also means no glaciers, so the interval from 1.6 to 1.4 billion years ago lacks in such characteristic glacial remains as piles of ice-rounded cobbles and boulders and layers of rock powder that are found in most other geological ages. So it's evident that as Columbia broke apart, the supposedly dull Mesoproterozoic saw a great deal of change, even if those changes were geologically familiar.

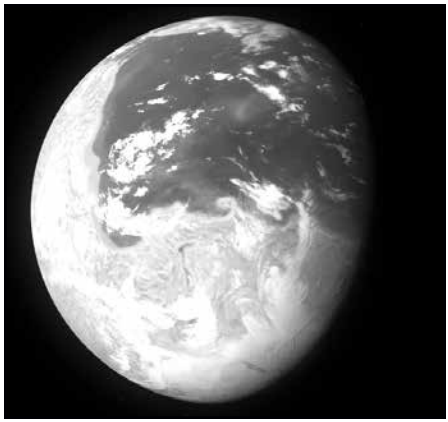
- But that's not the end of the supercontinent cycle during the boring billion. The fragments of Columbia scattered across the globe for perhaps 200 million years, but a collection of continents can only diverge for so long before they start to converge once again.

Rodinia

- About 1.3 billion years ago, Ur, Laurentia, and other Mesoproterozoic continents began to reassemble into a new supercontinent called Rodinia, named for the Russian word for "motherland" or "birthplace." The evidence is strong: There's a worldwide pulse of mountain-building events preserved in rocks formed between 1.3 and 1.1 billion years ago in Europe, Asia, and

North America. Each of those mountain ranges represents a suture where two converging continents collided and crumpled.

- The exact geography of Rodinia is still a matter of some debate, but there are many constraints on any model, including geological and paleomagnetic data and the arrangement of cratons on today's globe. One area of agreement is that the Rodinian supercontinent was located near the equator, with Laurentia—what is now most of North America—at the center and significant fragments of what are now other continents accreted to the north, south, east, and west.



The evidence for a supercontinent known as Rodinia is strong.

- One widely cited model has Baltica and portions of what are now Brazil and West Africa to the southeast, with additional fragments of what is now South America to the south and portions of Africa to the southwest. However, at this stage, the relative positions of much of what is now Australia, Antarctica, Siberia, and China are uncertain.

- Rodinia seems to be distinctive in one important respect. All earlier supercontinents were probably incomplete; that is, there may have been one or more large isolated islands, something like a smaller version of Australia or Antarctica. The evidence comes from minor sediments that represent coastal sedimentary deposits that formed during the period of Columbia's presumed stability, about 1.6 billion years ago.

- However, a curious lack of similar sedimentary evidence suggests that once Rodinia was completely assembled about 1.1 billion years ago, virtually all of Earth's land was clustered tightly together. This circumstance results in a 250-million-year interval, between about 1.1 billion and 850 million years ago, unlike any other in Earth's history—at least going back more than 2 billion years.

- Basically, there are no sedimentary rocks from that age range. That lack points to the fact that there were probably no shallow seas between continents of the type that saw the deposition of the 1.6-billion-year-old Belt-Purcell Supergroup. That's why geologists have concluded that all of the continents must have fit neatly together and that there weren't any large inland seas.

- From a plate tectonics point of view, the boring billion was pretty intense: Between 1.85 billion and 850 million years ago, two supercontinents—Columbia and then Rodinia—were assembled, each producing a dozen mountain ranges by continental collisions. And in between those two great gatherings of lands, when the Columbian supercontinent rifted apart, we find some of Earth's most impressive sedimentary rock deposits.

- Whatever the exact geometry of the continents, every expert is in agreement that the supercontinent of Rodinia must have been completely surrounded by a much, much larger superocean. This ancient globe-encircling body has been named Mirovia, after the Russian word for "global." If, in fact, the Mesoproterozoic Era was boring, then Mirovia is the principal reason why.

- In the previous half-billion years, the great oxidation event was a pivotal geological transition, but it was primarily a time of changes in atmospheric chemistry. Earth's atmosphere went from having essentially no oxygen to maybe a percent or two. That's an epic chemical change as far as the surface environment goes, but to Earth's vast oceans, such a change in the composition of the atmosphere was insignificant, because the oceans contain more than 250 times the mass of the atmosphere.

- A small change in the composition of the atmosphere, even a one-percent increase in oxygen, can't have an immediate effect on ocean chemistry. It takes a very long time for oceans to change—in this case, about a billion years.

Rocks and Minerals of the Oceans

- It's not possible to measure directly the composition of the ancient oceans. So geochemists who want to understand ocean history study rocks and minerals that formed in those oceans. They measure a host of chemical elements and their isotopes because the oceans hold at least minor quantities of almost every element in the periodic table.

- Five key elements—oxygen, sulfur, and nitrogen (all of which are found in the atmosphere and play key roles in life) as well as the metals iron and molybdenum—each tell us something about how oceans changed through time.

- The bad news for life was its absolute reliance on the element nitrogen. The only readily available source of nitrogen on Earth is nitrogen gas (N_2) in the atmosphere—about 80 percent of the atmosphere today and an even higher percentage 1.5 billion years ago. The problem is that life can't use nitrogen gas; instead, cells require nitrogen in its chemically reduced form, called ammonia (NH_3).

- Out of necessity, life has evolved a clever protein, an enzyme called nitrogenase, which converts nitrogen gas into biologically useful ammonia. This process requires a metal atom to shuffle electrons. Before the great oxidation event, the metal was iron; after the boring billion, the metal is most commonly molybdenum. But during the boring billion, neither metal was widely available, which may have greatly limited life and its evolution.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 8, pp. 181–205.

Nance, Worsley, and Moody, “The Supercontinent Cycle.”

Nield, *Supercontinent*.

Questions to Consider

1. What is the supercontinent cycle?

2. What is the nitrogenase enzyme, and why was it limited during the boring billion?

Feedback Loops and Tipping Points

Lecture 36

Complex systems, including Earth's oceans, atmosphere, and ecosystems, follow the law of unintended consequences—you can't change one part of a system without changing other parts. Many of these changes result from positive and negative feedback loops, by which changes in one part of a system trigger changes in other parts of the system. Natural systems, including those responsible for many aspects of Earth's near-surface environment, may have many complex and interrelated feedback loops, both positive and negative. Feedback systems can reach tipping points and thus move away from one equilibrium state and move quickly to another state.

Complex Systems and the Law of Unintended Consequences

- The Proterozoic Eon, which encompassed most of the second half of Earth's history—nearly 2 billion years, from 2.5 billion to 542 million years ago—was a long time interval of sharp contrasts. Its first half billion years or so was perhaps the most newsworthy, because it witnessed the great flourishing of photosynthetic algae and the consequent rise of atmospheric oxygen.

- Oceans transformed from their ancient iron-rich state as the immense banded iron formations were deposited on the ocean floors. The living world of cells also transformed with the innovation of complex cells with nuclei—the precursors of all plants and animals.

- The middle billion years of the Proterozoic Eon was much less eventful, though far from downright dull. Then, the final frenetic 300 million years, which constitutes the tail end of the Neoproterozoic Era, was perhaps the most dynamic time interval of all the Proterozoic—with continental breakup and assembly, repeated radical climate swings, epic shifts in ocean and atmospheric chemistry, and the rise of animal life.

- You might wonder how such radical changes could have all taken place in a few hundred million years, when the previous billion years were so uneventful. It turns out that feedback loops hold the key to understanding such surprising changes.

- Earth systems of water, rock, atmosphere, and life are complexly interconnected. Air, water, and land may appear to us superficially as separate spheres, which change over very different scales of time. After all, the weather report varies daily, ocean shorelines change over millennia, rocks cycle over millions of years, and supercontinents take hundreds of millions of years to assemble and break apart—yet every Earth system affects every other in ways both obvious and hidden from view.

- This realization brings us to what ecologists call the law of unintended consequences. Namely, when you're dealing with a complex system, you can't change one characteristic without changing other aspects, and often in ways that are difficult to predict.

- Three examples of complex systems and the law of unintended consequences—the Peter's Mountain mallow, the Aral Sea, and Lake Victoria—were all set in motion by human actions, and that clearly didn't happen to our planet hundreds of millions of years ago. But more generally, in each instance, a complex system was disrupted by changing just one thing, and that one change—something as small as introducing one new species or diverting part of a river—led to a cascade of consequences.

Feedback Loops and Tipping Points

- In addition to analyzing complex systems and the law of unintended consequences, it's possible to analyze system change in terms of positive and negative feedback loops, as well as tipping points.

- A house serves as a useful, though not exact, metaphor for our home planet. Like Earth, a house is a complex system with many interconnected parts. When you buy a house, you should find out many things—when it was built, for example, as well as the age and configuration of any additions or major renovations. You'll want to obtain details about the materials used in the construction of your house as well as information about their installation, from the foundation to the roof.

- Of course, it's essential to learn about the plumbing system and its source of water as well as the air-handling system—the furnace and air conditioner and their sources of energy. If you're a smart homebuyer, you'll also find out about all kinds of potential risks, including fire and carbon monoxide, termites and carpenter ants, radon and asbestos, and leaks and mold.

- This homeowner checklist is a good metaphor for the way geologists think about Earth. We want to understand Earth's origins and major transitions, the nature of rocks and minerals, the movement of water and air, the sources of energy, and the risk from geological hazards.

- Your house also displays many of the same complex behaviors that we see at the scale of Earth, because different systems are interconnected in sometimes surprising and unexpected ways through negative and positive feedback loops.

- Consider the familiar example of a cold winter day. As inside temperature drops below your comfort level, the thermostat responds by turning on the furnace, and the temperature rises for a time. Once the house warms up, the thermostat senses that change, and the furnace shuts off.

- By the same token, on hot summer days, the air conditioner trips on if the inside temperature rises too high and then shuts off when things have cooled down. These are negative feedback loops, where changes in your house's temperature are linked to processes that mitigate the changes. So in a negative feedback loop, change is met and cancelled out by the negative of the initial change.

- In a similar way, Earth operates through the operation of many negative feedback loops that help the planet maintain climate at a

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Lake Victoria, the largest lake in Africa, used to be a prime tourist destination, but its ecosystem was radically altered by the introduction of a single new species: the Nile perch.

more or less narrow range of conditions of temperature, humidity, and composition at and near the surface.

- For example, warming oceans result in more clouds, which reflect sunlight back into space and cool the oceans. Likewise, rising concentrations of atmospheric carbon dioxide cause global warming, and warming accelerates rock weathering—but rock weathering gradually consumes excess carbon dioxide and leads in turn to cooling.

- On the other hand, houses also occasionally display self-reinforcing—or positive—feedback, when the increase or decrease in some environmental condition is amplified; ironically, these so-called positive feedbacks often have bad or unpleasant consequences.

- Perhaps the most familiar example is a fire that starts to burn out of control. As long as a fire is confined in a fireplace, it behaves in a more or less stable and predictable way. However, if uncontrolled, the growing heat of a raging fire causes the fire to spread even more rapidly.

- A similar effect can occur with cold. If your heating system fails on a cold winter day, the water pipes can freeze and burst, which causes cold water to flood your home, making the house even colder and less livable. Many of the greatest uncertainties regarding Earth's changing climate today focus on these kinds of potential positive feedback loops, where one change might trigger even bigger cascading effects.

- Eventually, such a complex system out of balance can reach a so-called tipping point, where a set of reinforcing changes push the entire system into a new state. For example, rising sea levels will lead to coastal flooding, which might result in more evaporation and more rainfall, which in turn might cause even more coastal flooding. A warming ocean is likely to cause the widespread melting of methane-rich ice at and beneath the ocean floor, which could add the greenhouse gas methane to the atmosphere and cause even more warming, which could release even more methane.

- It's difficult to predict when and how extensive such a climate tipping point might be, but we have only to look at the runaway greenhouse effect of our neighboring planet Venus, with its thick carbon dioxide atmosphere and 900-degree Fahrenheit surface temperatures, to see the potentially catastrophic effects of positive feedback. Venus likely reached its methane tipping point very early in its history, perhaps within the first 100 million years, and it has never recovered.

- Like a house, Earth can enjoy long periods of relative stability and gradual drift, or it can experience sudden and dramatic change that may disrupt ecosystems worldwide. The boring billion, to the extent that it really was boring, must have been a consequence of many negative feedbacks that more or less moderated the near-surface environment and held major changes in check.

- Naturally, change did happen. Nothing at Earth's surface could stop plate tectonics, which is driven by the second law of thermodynamics and the imperative that heat must find a way to move from Earth's hot core to the cool surface.

- Nevertheless, in spite of ongoing plate tectonics activity, including the great slow-motion migrations of landmasses and the assembly and breakup of supercontinents, Earth's climate during the interval that encompassed the Mesoproterozoic Era seems to have been fairly stable. There's no evidence for great ice ages, and it appears that the chemistry of the oceans remained both anoxic and sulfur-rich.

- The paleontological record, similarly, shows nothing that would suggest that life evolved any new characteristics with planetary consequences comparable to photosynthesis. Scientists who specialize in studying rocks of this age conclude that there weren't any major tipping points to alter the atmosphere, continents, or oceans between 1.85 billion and 850 million years ago.

- That age of stability was about to change with the breakup of Rodinia about 850 million years ago. Earth was about to reach its first tipping point in a long time, as the next few hundred million years experienced some of the most remarkably rapid and extreme near-surface fluctuations in our planet's history.

Suggested Reading

Donnadieu, et al, "A 'Snowball Earth' Climate Triggered by Continental Break-Up through Changes in Runoff."

Hazen, *The Story of Earth*, Chapter 9, pp. 206–231.

Hoffman and Schrag, "Snowball Earth."

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 20.

Macdougall, *Frozen Earth*.

Questions to Consider

1. What are positive and negative feedback loops, and what are everyday examples of each?

2. What is a tipping point, and how does it relate to climate change?

Snowball Earth and Hothouse Earth

Lecture 37

A billion years ago, new changes drove the Earth to some of its most remarkable transformations. Most continents were positioned near the equator, resulting in higher rates of weathering and reduction in carbon dioxide. Highly reflective ice at the poles reflected more sunlight into space, thus cooling Earth more. In a rapid, positive feedback loop, ice eventually covered virtually the entire globe. By contrast, the end of each snowball Earth episode produced some of the most rapid and extreme changes in Earth's history. With almost all surface rocks insulated by ice, carbon dioxide from volcanoes built up to extremely high levels in the atmosphere. At a tipping point of carbon dioxide concentration, a runaway greenhouse effect caused rapid heating and melting of equatorial ice, which raised temperatures further as more solar radiation was absorbed.

The Snowball Earth Hypothesis

- For most of the Proterozoic Eon, Earth's near-surface environment shifted only gradually, with no obvious periods of extreme global warming or cooling. However, for a combination of reasons that are still being revealed, 750 million years ago, around the middle of the Neoproterozoic Era, Earth entered a period of extreme climate instability the likes of which had never been seen before. This unsettled interval began with a brutal ice age.

- Geologists deduce the timing and intensity of these changes because glaciers leave an unambiguous suite of sedimentary features. First and foremost of these glacial leftovers are thick, irregular layers of diagnostic rocks called tillites, which preserve chaotically jumbled piles of sediments that are carved out and concentrated by the action of ice flowing over rock. That includes sand and gravel as well as angular rock fragments and fine rock flour.

- Glaciers also alter the landscape in very diagnostic ways. They leave behind characteristic rounded and elongated outcrops of bedrock that have been shaped by what might be called "rivers of ice." That ice also carries along rocks and boulders, which scratch and polish outcrops of bedrock in very distinctive ways.

- Other geologic clues to glaciers are thick deposits of finely layered varved sediments. Paper-thin alternating light and dark layers represent seasonal runoff deposits into glacial lakes—coarser in the spring and finer in the fall.

- Added to these sedimentary features are erratic boulders and mound-like accumulations of gravel called moraines. It's this diverse combination of features that points to regions of ancient glaciation.

- Field geologists around the world have discovered that these glacial features occur abundantly in rocks of ages between 580 and 740 million years old, just about everywhere they look around the world. These data have piled up for more than half a century.

- Evidence for extensive glaciation is found on every continent, and at latitudes from the equator to the poles, at more than 50 localities, and the list keeps growing. As a result, the geological community has come to realize that an ice age far worse than anything we had imagined once gripped the entire globe, beginning roughly 740 million years ago.

- For almost 3 billion years, Earth had existed without any such global ice event. So why was the time 740 million years ago different? The model that has emerged relies on a sequence of nested feedback loops, each of which drove Earth to a colder and colder state.

- One feedback depended on continental weathering, which was accelerated in hot and humid tropical zones. Rocks simply weather faster in warm and wet zones, and that pulls more and more carbon dioxide from the air.

- Another feedback was triggered by the massive blooms of photosynthetic algae, which scavenged even more CO_2 out of the

Glaciers leave a suite of sedimentary features that allow geologists to deduce the timing and intensity of changes to early Earth's near-surface environment.

air. The drop in carbon dioxide weakened the greenhouse effect, and as Earth's atmospheric greenhouse weakened, its climate cooled. That means that ice caps began to form and grow larger at the poles. This fresh white ice and snow effectively reflected much more sunlight into space, so solar energy was also lost, creating a positive feedback that cooled Earth even more rapidly than before.

- So we have an unstable situation in which ice sheets were spreading to lower and lower latitudes from both poles, while the still-warm equatorial continent and the profligate algal growth continued to remove more and more CO_2 from the skies, further weakening the greenhouse effect.

- The net result was that Earth's climate was at least temporarily skewed out of balance, so it reached one of those unpredictable tipping points. Earth cooled quickly, more and more sunlight was reflected into space, more ice formed, the global greenhouse weakened, and ultimately white ice converged from both poles toward the equator.

- Eventually, in the most extreme version of this story, ice may have completely encircled the globe. In this scenario, promoted by Paul Hoffman and his colleagues, estimates are that average Earth temperatures plunged to 50 degrees Celsius below zero while a mantle of ice up to a mile thick surrounded the entire globe.

The Hothouse Earth Hypothesis

- Once the snowball Earth events reached the tipping point, things settled into a very long time of cold. How could Earth possibly have recovered from that seemingly static icy state? It's pretty easy to find an answer in the inexorable power of plate tectonics. Indeed, so many aspects of Earth's changeable surface are rooted in our planet's much deeper, ceaseless churnings. Nothing occurring at the surface of our planet, and certainly not the white veneer of ice and snow, could stop plate tectonics.

- The key link between the deep interior and the surface is the global network of volcanoes. Constant volcanism, along with the constant emission of volcanic gases like water vapor and carbon dioxide from hundreds of black cones that must have poked through the ice, slowly tipped the balance.

- Carbon dioxide and water vapor are the dominant volcanic gases, so CO_2 once again began to build up in the atmosphere. With the land entirely jacketed in ice, there was no way to remove that CO_2 by rock weathering. And with the microbial ecosystem all but shut down and photosynthesis all but ceased, the carbon dioxide wasn't removed by life either.

- That means that carbon dioxide concentrations must have gradually risen—and probably to levels not seen in more than 2 billion years. It's likely that CO_2 concentration increased eventually to perhaps several hundreds of times modern levels, and that rise in greenhouse gases must have triggered a new positive feedback: a runaway greenhouse effect.

- This is the snowball scenario in reverse. Sunlight still scattered off the white landscape, but carbon dioxide in the atmosphere bounced that radiant energy right back to the surface, inexorably warming the planet.

- As the atmosphere warmed, small patches of equatorial ice melted, perhaps for the first time in many millions of years. As the darker land became exposed, more and more sunlight was absorbed by rocks and soils, and the warming accelerated. The oceans, too, began to clear of their white covering as positive feedbacks between the Sun and the surface caused Earth to become warmer and warmer.

Other Great Glaciations

- The snowball Earth episodes were by no means the first periods of glaciation on Earth, nor would they be the last, but the Neoproterozoic snowball intervals stand out in history. To the best of our knowledge, never before and never since have such extreme cold spells occurred on Earth. Why should that be?

- Almost every aspect of Earth history repeats itself. Furthermore, the preceding billion-year interval was a time of exceptional global stability. So how can one relatively brief period of Earth history have been so different from any other?

- The contrast is made starker by looking at the two earlier periods of glaciation, which were evidently a lot less severe. The earliest known ice advance was a relatively brief event revealed by tillite deposits on ancient South African cratons. That advance occurred about 2.9 billion years ago, in the middle of the Archean Eon.

- That it should have taken so long for Earth's ice caps to expand from the poles toward the equator is something of a mystery. Astrophysicists tell us that earlier in Earth history, the Sun was much fainter than it is today—or than it was in the Proterozoic Eon. Why no snowball Earth episodes back then?

- With so much less energy coming from the Sun, there must have been other warming mechanisms at play. Many scientists suggest that much higher levels of greenhouse gases—including carbon dioxide, methane, and perhaps an orange hydrocarbon haze—were critical moderating influences that held off cooling, glacier-forming events. It's also certain that early Earth experienced much higher heat flows from the turbulent deep interior, so greater volcanic outputs must have played a role.

- Ironically, Earth's first glacial episode 2.9 billion years ago may have been the result of too much greenhouse gas. If the atmosphere's methane content rose to high enough levels, as it may well have done before the rise of oxygen, then chemical reactions high in the stratosphere would have produced more and more of the big hydrocarbon molecules that may have given early Earth a hazy orange sky.

- But if that haze became just a little bit too thick, then some of the Sun's energy, which was formerly trapped by the greenhouse effect, would have been blocked in the upper atmosphere, and Earth's surface would have cooled somewhat.

Suggested Reading

Donnadieu, et al, "A 'Snowball Earth' Climate Triggered by Continental Break-Up through Changes in Runoff."

Hazen, *The Story of Earth*, Chapter 9, pp. 206–231.

Hoffman and Schrag, "Snowball Earth."

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 20.

Macdougall, *Frozen Earth*.

Questions to Consider

1. What factors led to the Neoproterozoic snowball Earth episodes?

2. What factors led to the rapid transitions between snowball Earth and hothouse Earth episodes?

The Second Great Oxidation Event

Lecture 38

The snowball Earth was not without its consequences. Each episode of global glaciation was followed not only by a period of rapid temperature rise, but also by an increase in atmospheric oxygen. Over a relatively short period of 200 million years, Earth's air increased from less than a percent of oxygen to close to the 20 percent of the modern world. The unprecedented rise in atmospheric oxygen paved the way for the first animals and plants and the colonization of the seas and continents.

Extreme Global Changes

- The Neoproterozoic Era featured a time of snowball episodes, followed by hothouse episodes—at least three times between 740 and 580 million years ago, and together, these episodes raised the level of oxygen close to modern levels.

- The living world had to be dramatically affected by such extreme global changes. During the global winters lasting millions of years, the lands were covered by thick ice, so very little erosion could occur. Without erosion, essential mineral nutrients couldn't flow into lakes and oceans, so microbial life was greatly limited in extent. It's very likely that life was restricted to those few places where mineral-rich hot waters spewed out of volcanic zones.

- By contrast, after each glaciation, the melting ice and exposed continental shores must have contributed pulses of essential mineral nutrients to every coastal ecosystem. The element manganese, which is required for photosynthesis, was one such vital mineral supplement.

- Molybdenum, which is used by many cells for processing nitrogen, was available in much greater quantities. There were also new pulses of iron, nickel, copper, and vanadium, all of which are employed in varied metabolic roles. Like iron, these are metals that form not only metallic bonds, but also covalent bonds or ionic bonds capable of joining organic molecules.

- But of all the many chemical elements that were available in only limited supplies during global glaciation events, phosphorus may have been the most important in those freshly exposed Neoproterozoic seas. Phosphorus is the 11th most abundant element in Earth's crust, where it is concentrated by pegmatites. It is also the sixth most abundant element in the human body and is absolutely essential for all life.

- Phosphate—the five-atom group of one phosphorus surrounded by four oxygens that gave rise to hundreds of new minerals inside pegmatites—also helps to form the backbone of the genetic molecules DNA, the double helix, and RNA. In addition, phosphorus helps to stabilize many kinds of cell membranes as part of phospholipids. And phosphorus bound to oxygen atoms plays a key role in storing and transferring chemical energy in small molecules called adenosine triphosphate (ATP). Those small, energy-rich molecules are found in every cell in your body.

The Clay Mineral Factory Hypothesis

- Geochemist Martin Kennedy and four coauthors devised a particularly novel, albeit speculative, scenario for the codependence of rocks and life. The title of their article included the phrase "the clay mineral factory," and it appeared in the March 10, 2006, issue of *Science*.

- The hypothesis is that life greatly accelerated the production of clay minerals, and the clay minerals in turn had important feedbacks to life. Specifically, the rise of atmospheric oxygen from a few percent to its present level was accelerated by positive feedbacks between microbes and clay minerals.

- "Clay" is a generic term for a large group of dozens of different minerals that consist primarily of ultra-fine-grained microscopic mineral bits that soak up water and form sticky, gooey masses.

Clays appear during stage 4 of Earth's mineral evolution, at a time when the first granite protocontinents were just beginning to appear.

- The principal mode of clay mineral formation on land is weathering, especially weathering by chemical alteration under the wet, acidic conditions of the kind that predominated during the late Neoproterozoic Era. CO_2 was still abundant, so rain of carbonic acid would have been, too. That's why Kennedy and coworkers suggest that the rapid post-glacial weathering of continents between about 700 and 580 million years ago produced an order of magnitude more clay minerals than before.

- Added to chemical weathering were biological processes. There's a lot of growing evidence from the fossil record that microbial colonies began to colonize the coastal landscape at about this time, and it turns out that microbes can be especially efficient at turning hard rock into soft clay.

- It's not entirely clear how they do this trick, but scientists have shown that all sorts of common rock-forming minerals, especially feldspars and micas, break down as much as 10 times faster when they're attacked by microbes. And the minerals that are most commonly produced are clays. So 600 million years ago, huge quantities of clay minerals were being generated both by chemical weathering and by microbes.

- Among the most important characteristics of many clay minerals is their ability to form strong chemical bonds to organic biomolecules. Clay minerals often develop a slight electrostatic charge on their surfaces, which complements the polarity of many organic molecules. Those molecules, like water, have positive and negative ends, so the molecules stick to clays.

- The greatly increased production of clay minerals, coupled with the extensive blooming of algae, would have sequestered huge amounts of carbon-rich biomass. As large volumes of clay minerals washed into the oceans, they would have sequestered those biomolecules in thick piles of fine-grained carbon-rich sediments.

- Burial of organic carbon is equivalent to releasing oxygen into the atmosphere; it's just like photosynthesis, which takes carbon dioxide and turns it into biomass while releasing oxygen. According to the Kennedy clay mineral factory scenario, burial of carbon tied to clay minerals led to the rise of oxygen, which further accelerated weathering and the chemical production of clay minerals on land, which led to even more carbon burial.

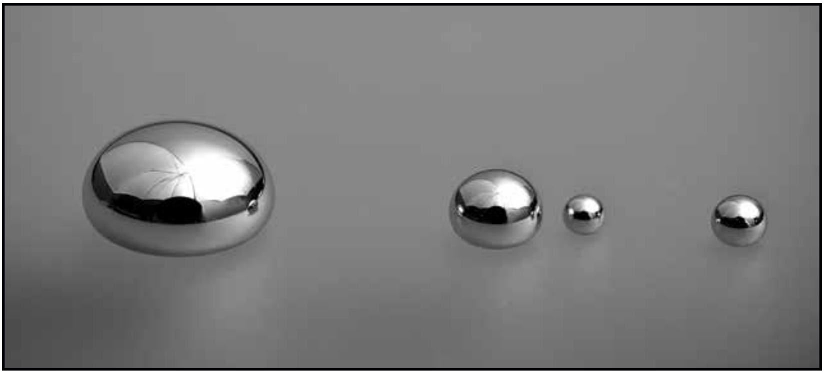
- This explains how complex feedbacks among weathering, microbes, clay minerals, and the atmosphere may have contributed directly to the rise of atmospheric oxygen and the evolution of the modern living world.

Earth's Mercury Cycle

- The element mercury is a rare and toxic chemical. Living cells, whether in algae or in people, simply cannot tolerate much mercury. The mercury binds strongly to key biomolecules and disrupts their functions.

- Sometime in the history of Earth, probably after the initial great oxidation event, microbes developed a very clever and sophisticated method of eliminating mercury by binding it to a methyl (CH_3) group. The resulting chemical compound, called methyl mercury, is very soluble in water and is easily passed through the microbial cell membrane and thus voided from the cell. Today, numerous kinds of primitive microbes are able to tolerate mercury-rich environments by producing and excreting methyl mercury.

- It was recently discovered that Earth's mercury cycle appears to have completely changed about 1.8 billion years ago, right about the beginning of the boring billion. Prior to that time, there were quite a few mercury mineral deposits around the world. But rather suddenly, at 1.8 billion years ago, mercury mineralization just seems to stop. In fact, for another 1.2 billion



Living cells cannot tolerate much of the rare and toxic chemical element mercury.

years, there are simply no known mercury mineral deposits, right up until the last of the snowball events.

- That's a really strange thing, because mercury should have been continuously recycled by plate tectonics and concentrated in hydrothermal fluids and released as mercury ore deposits when those hydrothermal solutions cooled near the surface.

- It may be that the microbial invention of mercury methylation suddenly changed the mercury cycle. If microbes started pumping lots of methyl mercury into the oceans, then very slowly, the ocean's mercury concentration would have risen, while this new reservoir essentially took up any excess mercury that previously went into mercury mineralization.

From the First to the Second Great Oxidation Event

- Oxidation below Earth's surface probably lagged, for hundreds of millions of years, later than the appearance of increased oxygen in atmosphere. The evidence for this conclusion involves studying the kind of subtle change in the mineral record that would probably never have been recognized before the rise of the new geobiological paradigm. Two rather scarce metal elements that are very sensitive to the oxidation state of their surroundings were key: molybdenum and rhenium.

- Molybdenum, element 42 of the periodic table, is a member of the column that includes the somewhat more familiar elements chromium and tungsten. Like chromium and tungsten, molybdenum finds important uses in the steel industry for making specialty alloys of great strength and hardness. In addition, molybdenum is an important element for creating the enzyme that allows plants to take nitrogen from the air.

- The other element in this story is rhenium, number 75 of the periodic table. This extremely scarce metal element is present at only about a part per billion in Earth's crust. Its principal uses are in high-temperature alloys, such as those employed in thermocouples for measuring extreme temperatures where other metals melt. Rhenium's geochemical behavior is remarkably similar to that of molybdenum.

- It took a very long time—at least hundreds of millions of years—for low levels of atmospheric oxygen to penetrate down into the subsurface zone where molybdenum and other ores form. A systematic trace element survey that also incorporates depth information might point to a gradual increase in the depth of the subsurface oxidation that increased rhenium contents in molybdenite, which in turn might hold the key to the timing of Earth's mineralogical diversification from the first great oxidation event to the second.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 9, pp. 206–231.

Hoffman and Schrag, "Snowball Earth."

Kennedy, et al, "Late Precambrian Oxygenation."

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 20.

Questions to Consider

1. In what ways did the second great oxygenation event differ from the first great oxidation event? In what ways were they similar?

2. What is the clay mineral factory, and how does it illustrate the coevolution of the geosphere and biosphere?

Deep Carbon—Deep Life, Fuels, and Methane

Lecture 39

Our uncertainties over the sudden release of methane point to how critical it is to understand the element carbon—the key element of energy, climate, environment, and life. The mission of the recently organized Deep Carbon Observatory is to achieve transformational understanding of carbon's chemical and biological roles in Earth. One of the key questions we hope to answer is the origin and behavior of deep methane. To this end, we are designing and building a new analytical machine to measure methane isotopologues, which are variants of the methane molecule that may reveal its temperature of formation. Cold methane is biological whereas hot methane comes from the mantle.

Learning about Earth's Carbon

- The Deep Carbon Observatory was initiated by the Alfred P. Sloan Foundation. Alfred P. Sloan was president and then chairman of General Motors during the time it became the largest car company in the world. He established the Sloan Foundation in 1934.

- The Deep Carbon Observatory launched in the summer of 2009 and now has about 1,000 researchers in 40 countries taking an active role. The Carnegie Institution's Geophysical Laboratory is the headquarters of this ambitious 10-year program to understand carbon in our planet. Our resolve is to achieve a new level of understanding of carbon in Earth's deep interior.

- There are so many things we want to learn about Earth's carbon. Most basically, we want to know how much carbon our planet holds; at this point, we don't know Earth's total carbon budget to a factor of 10 or 20. That's because we don't know if there's much carbon in the lower mantle or the core, where even a few parts per million of carbon would add up to much more than all the known carbon in the crust.

- The mantle might hold even more carbon, some of it in the form of diamond and carbonates, but maybe as a trace element in much more abundant deep silicate and oxide minerals as well. So many of us now think that Earth's total carbon budget is at least 1 percent of the planet's total mass.

- One of the most amazing hidden repositories of carbon is deep microbial life. It turns out that just about anywhere you dig or drill into Earth's crust, whether on land or at sea, there are microbes living in the subsurface. Microbes have been found in drill cores as deep as three miles, and they seem to thrive in deep sediments and in solid rocks—anywhere there is subsurface water—as long as the temperature is below about 130 degrees Celsius.

- This deep life is sparse, typically with no more than about a million individual cells per cubic centimeter. However, by some estimates, the biomass of living cells beneath the surface may be as much as 30 percent of all the life we see at the surface. Deep microbes, though largely hidden forever from our view, may thus represent a significant fraction of all life on the planet. All of that subsurface life—indeed all of life—is only the tiniest fraction of all carbon on Earth, but it's a really fascinating fraction.

- There's now a lot of evidence pouring in that the subsurface also holds a vast amount of viruses that "live" beneath the surface. (There is debate over the extent to which viruses are actually living.) Viruses on Earth are so numerous that their total length, placed end to end, has been estimated to equal the length of the Milky Way galaxy times 100.

- Deep viruses play a few key roles that are only just now coming into focus. For one thing, deep viruses have a significant effect on carbon turnover—that is, the rate at which carbon atoms are reworked from one reservoir to another. When viruses kill cells, their carbon atoms get reprocessed by other cells. The deep turnover rate is thus many times greater than previously thought.

- In addition, deep viruses play a key role in evolution by shuffling and swapping genetic material among microbes. So microbes are constantly evolving by this lateral transfer of genes, and that's because of the way viruses manipulate DNA. Viruses introduce new genes, alter the structure of microbes, and break them down completely into molecular fragments—and they have a cosmically stunning amount of genetic material to work with.

Deep Methane

- Methane is the lightest of all hydrocarbons. The gas methane, CH_4, is a powerful greenhouse gas that may have played an important role in the history of Earth's variable climate. Methane gas—the smallest hydrocarbon molecule, with a central carbon atom surrounded by four hydrogen atoms—is molecule for molecule about seven times more effective a greenhouse gas than carbon dioxide (CO_2). A sudden release of methane, therefore, would be expected to have a much more pronounced effect on climate than a comparable amount of carbon dioxide.

- Part of the concern is the potential positive feedback caused by any methane release. Much of the methane stored near the ocean floor is trapped in a fascinating compound called methane clathrate, which is an icelike crystalline mixture of water and gas that forms under moderate pressure and cold temperatures. This freezing cold methane ice actually burns.

- Methane clathrate outcrops on the continental slopes and forms large deposits beneath the ocean floor. Vast quantities of methane—by some estimates, several times all other known methane reserves combined—are locked into these methane ices. The methane in the methane ices must have formed as gas rising from below, either from deeper microbes or from the mantle, reacted with cold ocean water.

- There's also a lot of methane locked in methane clathrates in Arctic permafrost. Soils in parts of Siberia, northern Canada, and other

Methane, which is burned off at oil refineries, is a much more effective greenhouse gas than carbon dioxide.

polar regions that have been frozen for centuries are now thawing and releasing methane at an increasing rate.

- An extreme positive climate feedback might occur when ocean waters or tundra warm even slightly, which causes the shallowest clathrate deposits to melt and release copious amounts of methane gas. This methane adds significantly to the greenhouse effect, which causes the oceans to warm even more. Some scientists now point to a possible catastrophic Neoproterozoic release of ocean-floor methane as a way to accelerate global warming, perhaps flipping Earth from cold to hot in a matter of decades.

- For billions of years, methane has accumulated in ocean-floor sediments, and the growing evidence now suggests that the methane is coming from two contrasting sources. Some methane deposits result from methanogenic microbes that release methane as part of their normal metabolic cycle. These methanogens thrive in oxygen-poor ocean sediments that are found near many known methane reserves. Some very large and shallow natural gas deposits are thought to have formed by the sustained action of these microorganisms.

- In addition, when biomass is deeply buried and subjected to temperature and pressure, methane is often produced as a byproduct. This so-called thermogenic methane is very commonly associated with both petroleum and coal deposits.

- Experiments show that methane can form and accumulate in Earth's crust both through biological and nonbiological mechanisms. These experiments have relevance to Neoproterozoic global warming, because deep methane may have contributed to a particularly strong positive feedback. This Neoproterozoic warming scenario depends strongly on the sources of methane.

Measuring Isotopologs

- How can we tell if a methane deposit on the ocean floor was produced by a rock or by a microbe? Theoretical calculations point to a subtle effect in the distribution of isotopes that might be the key, but not with any ordinary measurement of heavy versus light isotopes. Geochemist Ed Young and coworkers want to measure isotopologs, which are molecules that are chemically identical but that differ in the arrangement of their isotopes.

- For example, methane has 1 carbon atom and 4 hydrogen atoms, so it comes in several different isotopologs: 99.8 percent of all carbon atoms are the less massive carbon-12 while one in every 500 carbon atoms is the more massive carbon-13.

- Hydrogen also comes in a less massive version—technically hydrogen-1 but always just called hydrogen—and the more massive hydrogen-2, which is always called deuterium. The typical hydrogen-to-deuterium ratio on Earth is about 1,000 to 1. About 1 in every 500 methane molecules incorporates carbon-13 while about 4 in every 1,000 methane molecules holds a deuterium.

- Measuring trace amounts of either of these two heavy isotopes is difficult enough, but Ed Young and colleagues want to measure the doubly substituted methane isotopologs—that is, the roughly one in a million molecules of methane that holds both a carbon-13 and one deuterium ($^{13}CH_3D$), or else two deuteriums ($^{12}CH_2D_2$).

- According to their calculations, the ratio of those two rare isotopologs in any given sample of methane depends on the temperature at which it formed. If a methane deposit formed at temperatures below 200 degrees, then it must be microbial; if it formed at temperatures above 1,000 degrees, then it is most likely abiotic.

- One of the first actions of the Deep Carbon Observatory was to help fund a $2 million prototype instrument in England specifically to measure the isotopolog ratios of methane. It will take years to complete this spectrometer and find out if it works, but many scientists think the time and effort is worth the risk. In addition, if—as some scientists suspect—a significant fraction of Earth's deep methane does come from the mantle, then that might just help explain why the Neoproterozoic climate shifted so far and so fast.

Suggested Reading

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Hazen, *The Story of Earth*, Chapter 9, pp. 206–231.

Hazen, Jones and Baross, *Carbon in Earth*.

Wigley and Schimel, *The Carbon Cycle*.

Questions to Consider

1. What are the key questions being addressed by the Deep Carbon Observatory?

2. What is an isotopolog? How might methane isotopologs reveal the source of methane deposits?

Biominerals and Early Animals

Lecture 40

Following the snowball Earth episodes, a dramatic rise in atmospheric oxygen promoted the rapid evolution of life, notably with the appearance of multicellular animals. The fossil record documents several stages of this evolution, most notably with the so-called Cambrian explosion at about 530 million years ago, when numerous animals with hard, mineralized shells first appeared. Rocks and their fossil ecosystems have a great deal to teach us, and the recent sedimentary record is unambiguous on this point: The land never stays the same.

A New Kind of Cellular Life

- The fossil evidence from just before the beginning of the boring billion is sparse for microbial life, but some of the rare fossils that are preserved point to the rise of a completely new kind of cellular life at perhaps 2 billion years ago. Before that time, which is in the Paleoproterozoic Era, all organisms appear to have been single-celled life forms consisting entirely of cells without internal structures such as the nucleus.

- Before 2 billion years ago, cells were simpler in their architecture, and the DNA was not isolated into a separate compartment. In many modern cells, by contrast, a central nucleus holds the critical genetic information package in the form of strands of DNA.

- The difference this innovation makes is that replication of the genetic material (in the nucleus) is separated from translating the genetic material into proteins (outside of the nucleus). This separation allows cells to share the same DNA (in the nucleus) but to express that shared genetic material in an increasingly wide variety of new proteins, such as collagen for animals and pectin for plants.

- How did the cell nucleus arise roughly 2 billion years ago? According to an originally controversial but now widely accepted idea first expounded by biologist Lynn Margulis, one cell swallowed a second cell whole. Normally, the bigger cell would simply digest the smaller, but in this case, the bigger cell incorporated the smaller one in a symbiotic relationship, perhaps in order to provide more protection to the vital DNA. This rise of a new kind of cell, called a eukaryote, or "true nucleus," forever transformed life on Earth.

- By the Neoproterozoic Era, complex eukaryotic cells with nuclei were well established. They had experimented for a billion years with microbial mats and other multicellular colonies, and they were about to begin a new era in cooperative biology. More than 600 million years ago, single-celled organisms learned how to grow and move as a single entity. In short, they learned to become animals.

- The earliest unambiguous fossil evidence for an ecosystem that was dominated by animals, as opposed to microbes and algae, comes from the so-called Ediacaran Period, a time interval that began about 635 million years ago, which was shortly after the second of the three great Neoproterozoic snowball Earth events.

- The first of these rather distinctive symmetrical fossils to be recognized came from a terrain of 580-million-year-old rocks from the Ediacara region in Southern Australia, where the Ediacaran fauna got its name. These fossils represent an array of soft-bodied animals, some of which are easy to imagine as distant relatives of jellyfish and worms. Closely related fossils have now been found in many places around the world in rocks from a 65-million-year span, between about 610 and 545 million years old.

- The most remarkable Ediacaran site is probably the 633-million-year-old phosphate-rich Doushantuo formation of southern China. This amazing deposit holds fossilized clumps of microscopic cells that are interpreted as animal eggs and embryos. Individual clusters look just like the early stages of animal development today, with 8 or 16 or 32 or even 64 cells arranged in a little ball. These structures, which grew in shallow seas just after the second of the big Neoproterozoic global glaciations, appear identical in every respect to modern animal embryos.

- In this way, the severe snowball-hothouse climate cycle ultimately played a central role in the evolution of the living world as we know it today. In fact, it would be accurate to claim that the modern biosphere owes its very existence to that interval starting 800 million years ago when Earth reached a climatic tipping point. And the coevolution of the geosphere and biosphere has only increased in complexity and consequences in the time since.

- What is perhaps surprising is how long it took for life to venture onto land. New chemical evidence obtained from shallow-water sediments deposited about 575 million years ago suggests that the great algal blooms of that post-glacial time period may have begun the transition. Those are the earliest rocks that show evidence for green photosynthetic algae that had the ability to survive on swampy land.

- That suggests that for the first time in Earth's history, there were patches of green, slimy algae above ocean level along some shorelines. With these new stable populations of photosynthetic life, atmospheric oxygen levels would have continued to rise along with an increasingly protective stratospheric layer of ozone layer.

- That radiation barrier effectively shielded Earth's solid surface from harmful ultraviolet solar radiation. That protection was an essential prelude to the emergence of the terrestrial biosphere of plants and animals. Nevertheless, even after the establishment of that ozone layer, it took life another 100 million years to crawl onto land.

- Indeed, for many millions of years, the most significant biological innovations took place in the shallow waters of sunlit coastal seas. Based on the Ediacaran fauna, jellyfish and worms and microbially precipitated reefs appear to have dominated the post-glacial oceans for perhaps 40 million years. The many varieties of soft-bodied animals appear to have fed on seafloor detritus, in what seems to have been a kind of ecological status quo for tens of millions of years.

The Cambrian Explosion

- That period of stability didn't last. It was dramatically altered by about 530 million years ago, when numerous groups of animals learned how to construct their own protective shells out of hard minerals. It's quite a mystery how this evolutionary development came to be.

- Of course, microbial life had been depositing mineral layers for billions of years in the form of reef-like stromatolites, but stromatolites are more like a simple layered platform on which the microbes grow and attach. That's a real advantage in a rough tidal zone, but stromatolites aren't shells. Animal shells are different because they provide a protective armoring with an elaborate mineral architecture.

- Following the Gaskiers glaciations, the last of the Neoproterozoic ice ages 580 million years ago, an unknown animal evolved the ability to grow its own protective hard parts out of commonplace minerals—most often calcium carbonate or silica. Calcium was available in essentially unlimited quantities in the ocean, so marine life had an advantage over freshwater life.

- This innovation provided a tremendous advantage in the struggle for survival. Predators aren't going to waste the energy to break a tough shell when they can eat a soft-bodied worm. The realm of ocean life was transformed, as the rule quickly became to make your own shell or die.

- The consequences for the fossil record are astounding. The resulting layers of sediment are for the first time packed with amazingly diverse life forms—corals, brachiopods, bryozoan, mollusks, and trilobites. The sudden transition from soft-bodied to shelly fauna constitutes such a dramatic change in sediments that the time has been called the Cambrian explosion.

Caves like Carlsbad Caverns in New Mexico are formed by the dissolution of limestone over many millions of years.

- The Cambrian explosion is another stage within mineral evolution, with a new propagation of minerals such as calcite, aragonite, and dolomite—all carbonate minerals—as well as the phosphate hydroxylapatite and opal. It took many millions of years of what might be thought of as experimentation in "biomineralization" to catch on.

- The initial 50-million-year rise of biomineralization was very gradual, but 530 million years ago, life with hard parts suddenly seemed to be everywhere. In sedimentary rock sequences from Montana to Morocco, it's possible to zero in on the exact layer when these fossils appear. Notable examples in North America occur in northwestern Vermont and in the mountains of Nevada.

- Each kind of rock tells a specific story of a time and a place, so you can imagine how a thick sequence of varied sediments reveals changes in a place through time. The most dramatic sequences of layered rock types often occur in association with coal deposits, which formed abundantly in swampy coastal zones 300 million years ago—so that's just inland of the sandstone, limestone, and black shale sequence.

- It's common to find coal sandwiched between layers of sandstone, which are in turn sandwiched between limestone and shale. Such a cyclical sequence (with shale, limestone, sandstone, coal, sandstone, limestone, shale repeated over and over again) reveals quite dramatic repeated shifts in sea level—lower, then higher, then lower again, likely in response to cyclical advances and retreats of polar ice and glaciers. These rocks, and the hard-shelled fossils they contain, tell an inescapable story of constantly changing sea levels, with periodic variations of hundreds of feet.

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Dove, P. M. "The Rise of Skeletal Biomineralization." *Elements* 6, no. 1 (2010): 37–42.

Hazen, *The Story of Earth*, Chapter 9, pp. 227–231; Chapter 10, pp. 232–239.

Knoll, *Life on a Young Planet*.

Knoll, "Biomineralization and Evolutionary History."

Questions to Consider

1. What changes in Earth's near-surface environment facilitated the rise of multicellular life on Earth?

2. What was the Cambrian explosion, and how is it manifest in geologic record?

Between Rodinia and Pangaea—Plants on Land

Lecture 41

The early Paleozoic Era, from about 540 to 350 million years ago, was a time of remarkably rapid biological evolution. A rich fossil record reveals this evolutionary story. Among the most important innovations was the appearance of the first primitive fishes, which came to dominate the seas. For most of the history of life, all cells lived in a water environment. Biological innovations in cell structure, coupled with the rise of a thicker protective ozone layer, allowed life to radiate onto land. The earliest fragile land plants quickly evolved into more robust forms as deep, clay-rich soils formed for the first time.

A Pattern of Evolution

- The Cambrian explosion, when all sorts of animals learned to make their own protective mineral shells, marked a turning point in Earth history. Just before that time, our planet experienced intense cycles of extreme cold and extreme heat, in part because of the equatorial position of the sprawling Rodinian supercontinent. But the inexorable motions of the tectonic plates caused Rodinia to fragment, and as landmasses moved toward the poles, Earth's climate achieved a degree of moderation.

- Abundant new photosynthetic algal life bloomed along nutrient-rich continental margins and helped to buffer the extreme fluctuations of carbon dioxide, while raising oxygen concentrations close to modern levels. Earth may never again have to endure such excesses of global temperature.

- The rise of atmospheric oxygen that promoted the evolution of the first animals of the Ediacaran interval resulted in another crucial benefit that promoted life's increasingly rapid evolution and diversification. The Sun's intense ultraviolet radiation has the ability to destroy essential biomolecules, so it kills most cells.

That's the simple explanation for why the dry surface has been a deadly, uninhabitable wasteland for almost all of Earth's history.

- It took at least half a billion years for life to emerge, and then it took at least another 3 billion years for life to produce enough oxygen in the atmosphere to generate the ultraviolet protective ozone layer. But once that ozone layer was established, and life learned a few essential biochemical tricks, it quickly took over every possible niche on land, at sea, and in the air.

- Throughout Earth history, this kind of event chain has occurred. Each stage in Earth's biological evolution—and chemical evolution, and mineral evolution—depended on the stage that came before. Evolution can only build from one state of affairs to the next.

- In this surprising way, the severe snowball-hothouse cycle ultimately played a central role in the evolution of the modern living world. With such biological innovations as crawling animals and hard shells, evolving Earth soon became infested with novelties—swimming creatures, burrowing creatures, and crawling and flying creatures boasting ever more extreme habitats and behaviors.

- That pattern of evolution, with the changes in near-surface environment experienced in one period leading directly to changes in the next, has continued at an accelerated rate for the last half-billion years. Indeed, at least five kinds of complexly interconnected factors have influenced Earth's surface during the vibrant Phanerozoic Eon—the eon of "visible life"—which encompasses the last 542 million years.

- Plate tectonics is the first of these factors. Continents have continued to shift their relative positions across the globe, first closing one ocean to form yet another great supercontinent, and then breaking up to form the still-widening Atlantic Ocean.

- The second factor is climate: Partly in response to continental geography—the positions of mountain ranges, seas, and interior plains—the climate has fluctuated from hot to cold and back again many times, though never to the snowball-hothouse extremes of the Neoproterozoic Era.

- The oxygen content of the atmosphere is a third important and interconnected changing factor. The Phanerozoic Eon enjoyed a third great oxygen enrichment event, only to see atmospheric concentrations drop almost in half and then rebound again to modern levels.

- A fourth intertwined factor that had a profound effect on Earth's surface is sea level, which has risen and fallen countless times over the last half-billion years. Variations in the extent of polar ice have caused cyclical variations, often by hundreds of feet. In the process, Earth's coastlines have been constantly reshaped in ways that are difficult for us to imagine.

- By far, the most spectacular agent of change at Earth's surface is life, which has evolved radically and irreversibly over and over and over again.

The Phanerozoic Eon

- Earth has always been a planet of repeated radical change, but the story of the Phanerozoic Eon is much more sharply in focus than the Hadean, Archean, or Proterozoic eons. The Phanerozoic rock record is much more complete, for one thing, and much less altered. And the abundance of intricate fossils that reveal evolution in every successive rock layer provides a narrative that is correspondingly more elaborate and nuanced in its variations.

- Indeed, the key to this rich story is the astonishing wealth of exquisitely preserved fossils, which are the consequence of life's newfound ability to make teeth, shells, bones, wood, and other durable hard parts. Unlike microbes, which can persist in their simple forms for billions of years, animals and plants turn out to be particularly sensitive to changes in Earth's near-surface environment.

- Animal and plant fossils thus record episode after episode of adaptation. Microbes could survive almost any kind of change. That resilience, coupled with their simple shapes and rarity in the fossil record, means that it's impossible to recognize a mass extinction in the eons before the Phanerozoic. But life during the Phanerozoic Eon provides an altogether different story.

- Thanks to the extensive rock and fossil record from the last 542 million years, we see Earth in rich detail as a planet of incessant change. And this is not a planet that changes leisurely over tens or hundreds of millions of years—much less a boring billion—but a giddy, changeable world.

- In the Phanerozoic Eon, every 100,000 years is different from what came before and what came next. Of course, part of this insight is the detailed record preserved in rocks. There must have been significant changes on short timescales prior to half a billion years ago as well.

- But it's also built into the very nature of multicellular life. Animals and plants, especially those life forms that colonized the lands, are exceptionally sensitive to any environmental changes. Terrestrial life responds to Earth's cycles quickly—these plants and animals evolve fast, old species die out, and new species take their places.

- On Earth today, 1.2 million plant and animal species have been catalogued, versus fewer than 5,000 mineral species; while those numbers are not directly comparable, they do convey a sense of how much more complicated the story of life's evolution is. That's why the Phanerozoic Eon, certainly more than any other time in Earth history, reveals the kind of changes that will inevitably influence our modern world as well.

The Rise of Land Plants

- The single most important transformation of Earth's continental surface is the rise of land plants. For billions of years, dry land was barren and windswept. Bare rock dominated, with thin layers of chemically weathered soil. Nothing lived on that surface for 90 percent of Earth history.

- And then a great green revolution occurred. Plants were an innovation that is first recorded in the fossil record as distinctive, rugged microscopic spores in some sedimentary rocks as old as 475 million years.

- We haven't yet found fossils of the earliest delicate, easily decayed vegetation, but based on the distinctive shapes of the spores, it's likely that those first true plants were similar to modern liverworts, which are rootless, ground-hugging descendants of green algae. Liverworts can only survive in low, wet places, where ponding water contacts the plant tissues. These earliest plants would have provided a green fringe to the low-lying swampy areas of the continents starting about 475 million years ago.

- But dead plants quickly rot in swamps. Consequently, for more than 40 million years, the only surviving evidence for these earliest land

Liverworts are distributed worldwide, but they are most commonly found in the tropics.

plants are the microscopic decay-resistant spores. At first, before the terrestrial ecosystem really got going, evolution of these hardy green pioneers seems to have been remarkably slow.

- Then, roughly 432 million years ago, fossils of plant spores suddenly shift in character, pointing to a new distribution of land plants. Over the next 30 million years, the liverwort-like spores become much less abundant, while spores that appear similar to those of modern mosses and the simplest vascular plants—that is, plants with an internal plumbing system of roots and stems—become dominant.

- This new pattern holds for rocks of this age from around the world—from Scotland, Bolivia, China, and Australia. And these rocks also preserve the oldest known unambiguous fossils of the plants themselves. Though fragmentary, the remains are clearly related to modern clubmosses and other primitive relatives of modern vascular plants.

- These ancient plants lack extensive root systems, and they were probably restricted to low-lying, wet areas. But they didn't have to grow in swamps, so periodic floods and influxes of sediments led to conditions that occasionally favored preservation of the plant tissues.

- As we move forward in time, the plants become more widespread and robust, and the fossil record continues to improve. By 400 million years ago, which is a long 75 million years since the first land plants evolved, the primitive vascular plants had begun to colonize the barren, dry land.

- The first diminutive plants had shallow roots, which produced shallow soils. These soils facilitated deeper roots and taller plants, which formed even deeper soils. Thus, the evolutionary history of soils and plants are intertwined—a textbook example of the coevolution of the geosphere and biosphere.

- Some of the most famous of all the fossil plants are the remarkably preserved fossils from the 400-millio-year-old Rhynie chert of Aberdeenshire, Scotland. In a very unusual set of circumstances, those plants were saved from rotting when hot springs in the vicinity flooded the plants with mineral-rich waters. The plants were in effect hermetically sealed and partially replaced with tough, fine-grained silica. It was just by chance that a century ago, geologists discovered boulders of the chert in a stone fence near the small village of Rhynie.

- Research by Kevin Boyce on Rhynie chert specimens has reinforced the conclusions of the paleobotany community: For the first time in Earth's history, the landscape 400 million years ago was green. This was the Devonian Period. But the plant and fungal life of that ancient world was utterly alien. Plants were little more than bare green branches, while the land was dominated by towering treelike fungi. That strange ecosystem featured only a few small insects and spiderlike animals. But all of that was soon to change.

Suggested Reading

Beerling, *The Emerald Planet*.

Hazen, *The Story of Earth*, Chapter 10, pp. 232–256.

Knoll, "Biomineralization and Evolutionary History."

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapters 11 and 21.

Questions to Consider

1. What factors facilitated the rise of life on land? What were the first organisms to populate dry land?

2. What fossil evidence reveals the nature of the earliest land plants?

Life Speeds Up—Oxygen and Climate Swings
Lecture 42

With the rise of life on land, and the greening of the planet, remarkable new feedback loops linked geology and biology. Oceans, atmosphere, and the land changed and were changed by each other. About 300 million years ago, Earth's climate was warm, vast forests of fern trees flourished, and huge quantities of dead plant material were buried—what we now mine as coal. These biological changes resulted in a large spike of oxygen, to perhaps 35 percent of the atmosphere, a rise that had amazing biological consequences.

The Animal Kingdom

- In the early Devonian Period, prior to 400 million years ago, the distribution and diversity of land animals were nothing like they are today. On the one hand, the early Paleozoic seas were rich with animal life. The reefs of the Cambrian Era—now preserved in rocks from Wales, to British Columbia, to Morocco, to Siberia—were thriving places, with all manner of invertebrates, many like trilobites, brachiopods, bryozoa, and corals with hard mineral shells of carbonate or phosphate.

- By 450 million years ago, marine vertebrates were well established, as a variety of armored and bony fish, including some large predators with massive teeth and jaws, quickly came to dominate the oceans. In that regard, the coastal reefs would have borne some resemblance to reefs of today, yet terrestrial vertebrates had yet to make a pervasive appearance.

- This transition from fish to land-dwelling amphibians is being clarified, specimen by specimen, by a wealth of recent fossil finds. In addition, animals experienced profound evolutionary advances as edible plants emerged from the oceans and expanded across the landscape.

- A host of invertebrates, including insects, spiders, worms, and other small creatures, were the first land animals. Their fossils are rare, but they occur in well-preserved deposits rich in the earliest land plants, including the Rhynie chert of Scotland. Some of these fossils—notably beetles and spiders—are remarkably modern in appearance.

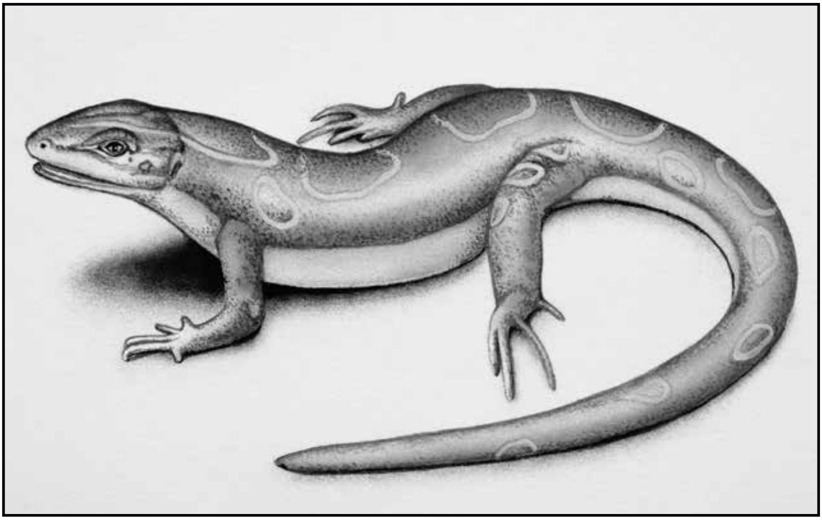
- Vertebrates took much longer to colonize dry land. The oldest vertebrates are primitive jawless fish that appeared in the fossil record about 500 million years ago and underwent more than 100 million years of gradual evolution in the oceans.

- Roughly 420 million years ago, the jawless fish were joined by armored fish with bony-plated heads and jaws. Some of those fish were monsters, exceeding 25 feet in length. And cartilaginous sharks and ancestors of the modern bony fish also appeared about that time and diversified over the next 20 million years. So by 400 million years ago, the diversity of fish had greatly increased.

- At some point, a fishlike animal must have ventured onto land. The recent discovery of a 395-million-year-old fossil fish from China, *Kenichthys campbelli*, is for now the leading contender for the oldest land vertebrate. This modest fossil species, represented by skull fragments only a fraction of an inch long, provides the earliest signs of the evolutionary transition to four-footed land animals, or tetrapods.

- The oldest known fossil bones of what was clearly a four-legged animal that could walk on land are found in rocks about 375 million years old. Even so, these creatures, such as *Tiktaalik* found on Ellesmere Island in northeastern Canada, look like a two-foot-long walking fish with finlike feet.

- Then, by 365 million years ago, the distinctive vertebrate *Acanthostega*, though fishlike in its elongated hydrodynamic body and long finned tail, had four distinct limbs with small toes. So *Acanthostega* may be interpreted as the oldest known amphibian. It



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The earliest known true reptile fossils are from the foot-long lizard-like insectivore *Hylonomus*, from rocks deposited about 315 million years ago.

was an animal that was suited as well for life on land as it was for life in water.

- As with most aspects of the history of life, fossils provide the unequivocal evidence for this gradual transition from fish to amphibian. These numerous new fossil finds point to a 30-million-year interval of intermediate forms, each progressively more suited to land but still retaining distinctively fishlike anatomical features.

The Carboniferous Period

- By 340 million years ago, in the middle of the so-called Carboniferous Period, when immense swampy forests were thriving in low-lying areas around the world, amphibians were the biggest, most dominant animals on land. For the next 40 million years, amphibians would be kings.

- Amphibians enjoyed a relatively brief interval of dominance, which was soon challenged by the emergence of reptiles about 320 million years ago. Reptiles differ from the amphibians in two key ways. Unlike the thin-skinned amphibians, reptiles have a protective scaly exterior. And reptiles lay eggs with hard, mineralized shells—as opposed to the amphibians, which typically must return to water to lay their soft eggs. Reptiles could thus spend almost all of their time on dry land and expand their habits to places where amphibians could not easily go. Gradually, the reptiles assumed dominance.

- In addition to the growing diversity of amphibians and reptiles, by the end of the Carboniferous Period about 300 million years ago, Earth's continents had, for the first time, evolved to a strikingly modern appearance. They had dense green jungles of tall fernlike trees; extensive swamps; and meadows that were populated with a rich variety of insects and spiders, tetrapods, and other creatures. Hand in hand with life on land, Earth's near-surface rocks and minerals also evolved, and they achieved something close to the modern state of diversity and distribution.

- In spite of these evolutionary developments, Earth had not achieved anything close to stasis. Just as before, the climate got hotter, then colder, and then hotter again. Earth experienced what we might describe as uncomfortable extremes, with droughts and floods, not to mention asteroid impacts and supervolcano eruptions. But it's clear from the fossil record that Earth and life have proven unfailingly resilient to such changes. Individual species go extinct, but life has always found a way to adapt and radiate into every available niche.

- Life also can trigger great changes in Earth's environment. The Carboniferous Period, which saw that explosive radiation of land plants, fundamentally changed erosion patterns and the environments of coastal regions. For the first time in Earth's history, stream banks were stabilized, and rivers were more confined to their paths for more of the time. Plant roots led to deeper soils and more clay minerals, which supported rich ecosystems both above and below ground. Patterns of coastline erosion were also altered, as vegetation slowed the flow of nutrient runoff to coastal waters while moderating erosion at the interface between land and sea.

- But the biggest effect on the near-surface environment involved the intertwined cycles of carbon and oxygen. For the first time in Earth's history, ferns and other land vegetation grew at a rapid rate. At the same time, fungi and the symbiosis of termites with bacteria had not yet evolved to process the dead plant matter, so biomass was buried in prodigious quantities never before or since matched in Earth history.

- Deeper and deeper these deposits of dead plant material became. They accumulated in layers that were sequestered under more and more sand and silt, until pressure and temperature transformed vast volumes of former trunks, roots, branches, and leaves into carbon-rich layers of coal. In fact, the Carboniferous Period gets its name from these great deposits of coal. A significant fraction of the world's fossil fuel reserves is still buried in the vast Carboniferous coal measures that are found around the world.

- This large-scale removal of organic carbon from the near-surface environment had a remarkable consequence. The composition of Earth's atmosphere reflects a number of interrelated cycles, with both positive and negative feedbacks. Important feedback loops connected the oxygen cycle with the carbon cycle so that there's always a balance in Earth's crust among these three chemicals: carbon, oxygen, and carbon dioxide.

- When vast amounts of carbon are locked away rather quickly in the crust in the form of coal and other dead plant and animal matter, that carbon is no longer bound to oxygen, so the oxygen is effectively liberated. The more carbon that's buried, the more oxygen is liberated into the atmosphere.

- As a consequence, in the Carboniferous Period, the oxygen content of the atmosphere appears to have soared. The oxygen content of the atmosphere more than doubled in less than 100 million years. Of course, extremely high oxygen levels can have one obvious down side. Forest fires triggered by lightning would have burned with much greater ferocity in 35 percent oxygen—a natural negative feedback for oxygen levels.

- As is evident by the air we breathe today, with about 21 percent oxygen, those extremely high oxygen levels didn't last. In fact, there was what amounted to a drastic and rapid drop by more than half in atmospheric oxygen, from over 30 percent to just 15 percent, between 270 and 250 million years ago. That time span represents about the last third of the Permian Period, which was one of the most dynamic and devastating intervals in Earth history.

- The transition to a desertlike climate had a big influence on terrestrial animals. Reptiles, with their tough, scaly hides and hard-shelled eggs, are more suited to the desert climate than amphibians, so the Permian Period is marked by a significant radiation of reptiles. The ancestors of turtles, crocodiles, dinosaurs, and many lizard-like groups first appeared during this interval. And some of those groups represent the ancestral vertebrate forms that would give rise to the mammals.

- It would be easy to assume that during the entire 150-million-year-interval between the early Devonian Period and the rise of land animals, the Carboniferous Period rise of oxygen, and the subsequent collapse of atmospheric oxygen during the Permian Period, there was a long interval of relative warmth, perhaps even tropical climates because of all the ferns. But it's not so. The Paleozoic Era was marked by many long ice ages, and each one had a big effect on the biosphere.

Suggested Reading

Beerling, *The Emerald Planet*.

Berner, *The Phanerozoic Carbon Cycle*.

Hazen, *The Story of Earth*, Chapter 10, pp. 232–256.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 21.

Questions to Consider

1. What was the nature of the earliest terrestrial vertebrates? From what animals did they evolve?

2. How and when did coal form? What is the relationship between coal and atmospheric oxygen?

From the "Great Dying" to Dinosaurs
Lecture 43

About 250 million years ago, Earth suffered the "great dying"—the largest mass extinction of life in its history. More than 90 percent of all species disappeared, including all the trilobites and many other groups of animals. Following the great dying, the last 250 million years have seen first the rise of great reptiles, including the dinosaurs. Reptiles thrived for more than 185 million years, but then another mass extinction wiped out all the dinosaurs (except for one small lineage, the birds). That extinction opened up new opportunities, which led to the rise of mammals.

The Great Dying

- There were many extinction events within the Paleozoic Era, including three in the Cambrian Period, a big one at the end of the Ordovician Period, and six more during the Devonian and Carboniferous periods. Each of these intervals of increased species loss appears to be associated with a positive shift in carbon and oxygen isotopes and, thus, ice ages.

- But of all the many periods of biological stress, one event stands out. The end of the Paleozoic Era, 251 million years ago, saw the extinction of an estimated 70 percent of land species and a whopping 96 percent of marine species—an unprecedented global event called the Permo–Triassic extinction, or the "great dying." Never before or since in Earth history have so many land or sea creatures, including all the trilobites, disappeared forever.

- The great dying was one of the most dramatic and enigmatic events in Earth history, and scientists aren't yet agreed on what caused it. Unlike some of the earlier, smaller extinctions, it doesn't appear to have been caused by just one factor like an ice age.

- In addition, growing evidence suggests that this was not a quick episode, either. In fact, it may have been spread out over several million years, or, as several groups are now claiming, there may have been two closely spaced and in some ways related extinction events.

- The Permian Period was ushered in as a time of environmental stress. A great ice age, almost 50 million years in duration, lasted until about 275 million years ago. Then, the single Pangaean supercontinent was dominated by desert conditions. Those climates led to a decline in plant life and a corresponding precipitous reduction in atmospheric oxygen to less than half of the Carboniferous maximum.

- That relatively low 15-percent oxygen content of the atmosphere was a source of stress for animals, which began to show a sharp uptick in extinction rates as early as 265 million years ago—about 15 million years *before* the great dying. Then, at about 260 million years ago, a clear extinction event caused the loss of entire groups of marine animals, including small, shelled creatures called fusulinids and ancient relatives of the chambered nautilus called ammonoids.

- But the biggest extinction interval appears to have been between about 252 and 251 million years ago, when fully 96 percent of all marine life forms went extinct, along with perhaps 70 percent of land animals and plants. So one can point to that last time as the height of a much more protracted period of species loss. And the whole Permo–Triassic extinction represents an interval of both gradual and relatively sudden declines in diversity.

- What could have caused this unique crisis in the history of Earth's biosphere? Without a doubt, there were multiple reinforcing stress factors that may have come into play. A protracted ice age, decline in atmospheric oxygen, and desertification set the stage for a stressful environment that greatly reduced the extent of conifer forests and killed off the jungles of fern trees.

- Scientists have not been at a loss to suggest a host of additional factors in the great dying, all of which seem to pile on one another. For one thing, the decline of oxygen may have reduced the extent of the protective ozone layer so that harmful ultraviolet radiation may have increased. Mutant fossil spores from end-Paleozoic rocks around the world, from Antarctica to Greenland, provide intriguing evidence, if not a smoking gun, for this ozone crisis. There's also evidence that the deep ocean in some places became anoxic and thus limited in its ability to support animals.

- In addition, reduced oxygen led to chemical changes that increased the ocean's acidity and made it much more difficult for organisms to form their carbonate shells. We thus observe very high rates of extinction among those creatures, including most kinds of brachiopods and crinoids and all the trilobites.

- There were also other environmental stresses. The end of the Paleozoic Era saw a modest ice age, with thick ice covering the south polar portions of Pangaea. That return to cold climates from 260 to perhaps 252 million years is another possible factor in extinction, because severe cold always places stresses on ecosystems.

- And a consequent large drop in ocean levels would have provided additional stresses by exposing most of the world's continental shelves to air. The loss of a large fraction of those productive, shallow-water zones would have restricted the growth of coral reefs, lagoons, shoals, and other diverse shallow-water ecosystems. In a cascading effect, those lost habitats would have constricted the entire ocean food web.

- Two additional factors, both of which came right at the end of the Permian Period, seem to have combined to make this time very different. The first, and arguably the most important of all, was large-scale volcanism that commenced near the end of the Paleozoic Era and almost exactly coincides with the mass extinction 251 million years ago.

- Much of the volcanic rock erupted through thick coal deposits, and the burning of that coal caused vastly more CO_2 to be pumped into the atmosphere, along with the possible release of toxic coal ash.

Such a vast release of potentially harmful gases must have severely compromised Earth's environment.

- Volcanic CO_2 is implicated in a swift and devastating shift in climate that almost exactly correlates with the end of the Permian and maximum extinction rate. A sudden rise in average global temperatures by as much as 15 degrees Fahrenheit led to a global drought and widespread loss of terrestrial plants and animals. This rapid climate change may have been worsened by the global-scale melting of methane hydrates and release of immense quantities of that potent greenhouse gas into the atmosphere—a positive feedback loop that worries some scientists today.

- There's also some evidence to support one more global catastrophe near the end of the Permian Period: There may have been a giant impact of an asteroid or comet as well. The evidence comes from reports of shocked mineral grains and layers of meteorite fragments in ancient layers of Antarctic ice of the correct age, roughly 250 million years old. No large impact site has been found of that age, but given the rapid turnover of ocean crust—70 percent of Earth's surface every 200 million years or so—that's not too surprising.

The Mesozoic Era

- Whatever the causes, the great dying left a staggering gap in Earth's biodiversity, and it was unusually slow to recover. It was several million years before reef ecosystems again appear in the fossil record, and it took 30 million years for anything approaching full recovery. But recover it did, and in a theme repeated after every extinction event, loss led to opportunity.

- It was a new era, the Mesozoic Era, and it saw new fauna and flora evolve to fill the vacant niches. We have entered the age of dinosaurs, and this is indeed the time span, from 251 to 65.5 million years ago, during which dinosaurs were the dominant vertebrates. It's also the interval when the Pangaean supercontinent began to split apart and what we recognize as today's continents and oceans began to take form.

- The Mesozoic Era is conveniently divided into three periods, each of which saw the appearance of distinctive new life forms, and each of which is bounded by a mass extinction event. The Triassic Period came first—that's the 50-million-year interval from about 250 to 200 million years ago. Life got off to a slow start, but soon, new organisms had evolved to fill the oceans and populate the lands.

- During the Triassic Period, two large groups of reptiles competed on land: the therapsids, including ancestors of mammals, and the archosaurs, which were ancestral to the dinosaurs and birds. Branching evolution was rapid among these terrestrial vertebrates.

- The first true dinosaurs appeared in the late Triassic, about 225 million years ago, and they quickly split into the two familiar dinosaur groups, which are distinguished by their very different pelvic anatomy. The saurischian, or "lizard-hipped," dinosaurs

The classic giant dinosaurs, including *Tyrannosaurus rex*, thrived in the Cretaceous Period.

display more reptilian characteristics, while the ornithischians, or "bird-hipped," dinosaurs have a distinctly avian pelvic girdle.

- We tend to think of dinosaurs as great lumbering beasts, and it's true that by the end of the Mesozoic Era dinosaurs had become the largest land animals in Earth history. But those first dinosaurs of the Triassic Period were rather modest creatures, short in stature and looking rather like a generic two-legged dinosaur.

- The Triassic Period ended about 200 million years ago quite abruptly with a major mass extinction, perhaps the fifth or sixth largest in the Phanerozoic Eon. This event was so obvious in the fossil record that it's used to mark the boundary between the Triassic and Jurassic Periods.

- Approximately half of all species on Earth became extinct in a very short time interval—no more than 10,000 years and possibly much more rapidly than that. As with the Permo–Triassic extinction, an episode of mega-volcanism correlates with the loss of species.

- This end-Triassic mass extinction is a case where loss of old species opened the door for new species, most notably the rapid radiation of large reptiles into the seas—the ichthyosaurs and plesiosaurs—and into the air, most notably the pterosaurs, but also the first known diminutive ancestral birds (which were related to dinosaurs).

- The end of the Jurassic Period, dated to 145.5 million years ago, merges seamlessly into the Cretaceous—the final period of the Mesozoic Era. There was no great extinction event, nor were there radical changes in life forms at that boundary.

- Instead, the Jurassic-Cretaceous divide simply reflects the ages of certain distinctive rock formations in Europe, where geologists first established the geological time line. The Cretaceous Period lasted for 80 million years—the longest period of the Phanerozoic Eon—yet conditions seem to have been much more stable than in most previous times.

Suggested Reading

Erwin, *Extinction*.

Hazen, *The Story of Earth*, Chapter 10, pp. 232–256.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 21.

Questions to Consider

1. What was the great dying, and what might have caused it?

2. How did the great dying change life on land and in the sea?

Impact! From Dinosaurs to Mammals

Lecture 44

The Cenozoic Era, often called the "age of mammals," spans the last 65.5 million years of Earth history. The extinction of the dinosaurs and ammonites 65.5 million years ago opened up the world's ecosystems to new biological opportunities, which led not only to the rise of mammals, but also to an explosion of flowering plants. In these epic events, we see replays of earlier episodes in Earth history. Shifting continents, ice ages, climate change, variations in ocean and atmospheric chemistry, the evolution and radiation of life, and mass extinctions have been a part of Earth's story for billions of years and will continue to play interconnected roles in Earth's evolution.

The Cenozoic Era

- The stage was set for Earth's most recent geological era, the Cenozoic Era—also known as the "age of mammals"—with the most famous mass extinction of all time—the event at the end of the Cretaceous Period that killed the dinosaurs and many other groups of plants and animals. In spite of its fame, the terminal Cretaceous extinction event was, according to the fossil record, only perhaps the fifth-worst incident in terms of species loss.

- However, the mass extinction 65.5 million years ago was unmatched in the number of large animals that disappeared, because this time saw the loss of all the dinosaurs as well as the big swimming reptiles and the flying reptiles. Many distinctive kinds of Mesozoic plants also vanished, as did entire groups of insects and other terrestrial invertebrates. Marine shell fossils suffered, and the last of the ammonites also vanished completely.

- For many years, this episode was known as the Cretaceous–Tertiary (K–T) extinction, and the geological periods immediately following the Cretaceous were called the Tertiary and Quaternary—meaning "third" and "fourth," respectively—periods of Earth history. These names provided an evocative reminder of a much older and simpler four-part geological timescale that was proposed by European geologists almost two centuries ago.

- In that archaic system, the Primary and Secondary rocks represented the older layers of Precambrian, Paleozoic, and Mesozoic ages. The names "Primary" and "Secondary" were dropped long ago, but for some reason, "Tertiary" and "Quaternary" survived into the early 21st century. But in 2004, the International Commission on Stratigraphy changed the officially approved division of the Cenozoic Era into three periods: Paleogene, Neogene, and Quaternary.

- The Paleogene Period is by far the longest of the three, stretching from 65.5 to 23 million years ago. The Neogene Period, which is about half as long, goes from 23 to 2.59 million years, and the Quaternary Period spans only the last 2,590,000 years. The name "Tertiary" is now completely abandoned, and "Quaternary" is reserved for the most recent period—the last 2.6 million years or so.

- As a consequence of these changes in nomenclature, the old K–T boundary and associated mass extinction is now officially designated as the Cretaceous–Paleogene extinction, or K–Pg boundary, though most scientists in the field still talk informally about the K–T boundary.

- Unlike any other mass extinctions before or since, the K–T event is marked by a distinctive worldwide geological marker—a specific thin layer of fine-grained sediments, only a few millimeters thick at many sites, that serves as a sharply defined time line.

- Below this seemingly innocuous layer are the last Mesozoic Era rocks—the very tail end of the Cretaceous Period, when the greatest variety and sizes of dinosaurs prevailed. And above the K–T marker layer are the first rocks of the Cenozoic Era and the Paleogene Period, which are utterly devoid of any dinosaur remains, except for the birds. As insignificant as that unassuming thin layer might seem, it tells a story of catastrophic global change.

- The loss of all the dinosaurs is a pretty obvious worldwide change in the fossil record—one that geologists recognized more than a century ago. However, for most of the last century, the relevant data were severely limited to rather qualitative measurements, and the exact position and significance of the K–T boundary layer hadn't yet been recognized.

Foraminifera are the smallest common shells in Cretaceous and Paleogene sediments.

- First and foremost in describing the extinction event were the distributions of fossils just above and below the presumed transition from Mesozoic to Cenozoic eras. Big fossil shells that you can hold in your hand are useful because they yield immediate and obvious markers in the field for extinction, but microscopic organisms are much more likely to reveal details of how a mass extinction event occurred.

- The smallest common shells in Cretaceous and Paleogene sediments are called foraminifera, or "forams" for short. They are beautiful, highly sculpted objects, usually less than a tenth of an inch long. Their shapes are typically tightly coiled spirals, sometimes with beautiful ornamentation not unlike larger gastropods, such as snails or whelks. They occur in abundance in many marine sediments, and they evolved so rapidly and come in so many distinctive forms that it's possible to do very detailed stratigraphy based entirely on meticulous separation of these microfossils layer by layer.

- When paleontologists undertook these vitally important and very tedious studies, they found an astonishing and somewhat puzzling trend in the distribution of foram species. Prior to the mass extinction, distinctive Cretaceous forams flourished. In one study of marine sediments from a 20-foot-thick section of marine sediments in Tunisia, paleontologists found almost 50 different foraminifera species in the lower few feet of rocks, right up to what is now recognized as the K–T boundary.

- Then, at one specific horizon—one layer of sediment a fraction of an inch thick—more than half of the species disappear all at once and forever. And many of the surviving Cretaceous forams go extinct in the next few inches of sediment. Remarkably, within another few inches, five new, distinctly Paleogene forams appear for the first time, with a half dozen more appearing in the next two or three feet of sediments.

- That pattern is very characteristic of mass extinctions: Many species go extinct at more or less one time, and many new species arise shortly thereafter. However, detailed studies of the foraminifera reveal an interesting wrinkle. Perhaps a dozen of the Cretaceous forms went extinct a few inches *below* the K–T boundary—before the big mass extinction.

- This pattern is also reflected in the chronological distribution of ammonite species, all but a handful of which disappeared in the million years before the mass extinction. That premonitory loss of species suggests some kind of significant environmental stress many thousands of years before the actual mass extinction.

- So the question becomes, based on these paleontological data, what caused the Cretaceous–Paleogene mass extinction? Few topics in the history of life have been subject to so much debate. Countless scientific papers and conferences have appeared on the subject, with competing theories falling into and then out of favor.

- There is a vast amount of supporting evidence that there was a huge impact event at 65.5 million years ago, and the patterns of extinction are fully consistent with the consequences we might expect from such an event. What remains unsettled is the extent to which other factors may have contributed as well.

Life after the Extinction Event

- Whatever the cause or causes of the Cretaceous–Paleogene extinction event, it left the world devoid of organisms in many key ecological niches for both plants and animals. Repopulating those niches took millions of years, but flowering plants on land and mammals on both land and at sea ultimately made the most of the opportunity. Within a few million years, flowering plants, or angiosperms, had replaced the gymnosperms that had dominated in the Cretaceous.

- The rise of mammals (including humans) was similarly gradual at first, with most mammals remaining small and rodent-like, though there were remarkable exceptions. Within 15 million years, such diverse forms as ancestral whales, bats, horses, and elephants had appeared to occupy the niches left vacant by the reptiles. The first primate ancestors also appeared during this time.

- Climate change may have played a role in mammal diversification. Around 55 million years ago, Earth experienced a relatively rapid thermal maximum lasting about 100,000 years, with temperatures and carbon dioxide levels far above what we have today. Some researchers suggest that increased CO_2 levels would have promoted smaller animal species and may have stimulated greater diversity of mammal species at this time.

- Then, a major cooling event followed at about 49 million years, perhaps promoting the evolution of somewhat larger animals, and this is when early precursors for several familiar mammals such as whales, horses, bats, and elephants seem to have first appeared.

- There were many additional cyclical changes in average global temperatures, ice distribution, and sea levels throughout the Cenozoic Era. Those variations are not unlike changes associated with the temperate conditions of more recent times. With each change, there were biological winners and losers, and the world's ecosystems evolved.

- The plate tectonic story is also much more clearly in focus than in earlier times. All the continents continued to shift into their modern locations. One big change during the age of mammals is how landmasses that had been separated into north and south for 150 million years now began to regroup and come together in new ways. The northern supercontinent containing both Europe and North America began to separate, widening the Atlantic Ocean an inch or two a year while shrinking the Pacific Ocean by a similar amount.

- The southern supercontinent broke apart sooner. And, over the past 50 million years, Africa has pushed toward Europe to produce the Alps, while India has collided with Asia to raise the Himalayan mountains. Peaks in both of these high mountain ranges are rather new, only about 10 million years old. North and South America marked a third joining of north and south with a land bridge at Panama forming just about 3 million years ago.

- Australia, by contrast, has gone its own way, rifting away from Antarctica about 50 million years ago and sheltering marsupial forms of mammal life, such as kangaroos, that were outcompeted and went extinct on the larger continents.

- More important, having the large, isolated continent of Antarctica over the South Pole allowed a circumpolar current to form over the last 10 million years that has blocked the approach of warm water and warm air and thereby facilitated the formation of a long-term ice cap that now holds more than two percent of Earth's near-surface water.

- Meanwhile, the Arctic Sea at the North Pole was increasingly surrounded by continents, so it was also cut off from warmer currents, and thus, it does not behave like a large ocean. Together, the enclosed Arctic Sea and continent of Antarctica have made Earth cooler than it otherwise would have been.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 10, pp. 232–256.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 21.

Prothero, *After the Dinosaurs*.

Questions to Consider

1. What killed the dinosaurs 65.5 million years ago?

2. What major changes in terrestrial life have occurred over the past 65 million years? How do these changes illustrate the coevolution of geosphere and biosphere?

Humans and the Anthropocene Epoch

Lecture 45

The last several thousand years have seen a significant change in the character and pace of change at and near Earth's surface. Scholars have proposed that we have entered a new geological period called the Anthropocene Epoch, the starting point for which is yet to be firmly established. The industrial revolution of the past two centuries has accelerated human influence on the geosphere and the biosphere, by triggering changes in atmospheric composition that may cause significant changes in climate while initiating a significant decline in species diversity.

The Anthropocene Epoch

- In 2000, as scientific evidence kept building that humans have imposed significant and increasing impacts on Earth's geosphere and biosphere for many tens of thousands of years, the Nobel Prize–winning chemist Paul Crutzen brought attention to the name "Anthropocene"—the time of humans—for the most recent geological era.

- Although Crutzen was by no means the first scholar to come up with this kind of name (in fact, American biologist Eugene Stoermer had coined "anthropocene" in the late 1980s), Crutzen was perhaps the first to use the geological time line to focus widespread attention on the extreme consequences of the industrial revolution for global-scale processes.

- Crutzen proposed the year 1784 and James Watt's invention of the steam engine as the beginning date of the Anthropocene Epoch. While others have countered with different definitions, the fact that we are in a very different time from prior geological periods is now widely accepted.

- *Homo sapiens*, our species, appeared approximately 200,000 years ago, though many other hominid species populated northern Africa for at least 6 million years, and a number of earlier species of *Homo* have walked Earth over the past 2.5 million years.

- In the past several million years, many different beings could be classed as “humanlike,” and several different genera and many species of the hominid family have walked on Earth. Today, for perhaps a variety of reasons, only we have survived (perhaps with a little genetic help from those that didn’t survive). The processes of natural selection and extinction have extensively pruned the branch of the family tree leading to human beings, just as they have for virtually all other life forms.

Human-Induced Changes

- The first hints of human-induced changes in Earth’s near-surface environment come from the vertebrate fossil record of the past 50,000 years. During that interval, a significant fraction of large vertebrates became extinct. Plants, insects, small mammals, and ocean life show no obvious global declines over this timescale, but numerous big vertebrates—including mammoths, mastodons, wooly rhinoceros, and a host of grazing animals, not to mention many types of birds, reptiles, and amphibians—have disappeared.

- In some cases, the link to humans may be only coincidental. More than 90 percent of large mammals on the Australian continent became extinct at about the same time that human colonization began, roughly 50,000 years ago. Debates still rage regarding whether these extinctions are attributable directly to human hunting, indirectly to human causes such as wildfires (which could also be used for hunting), introduction of new diseases brought over by humans, or environmental changes unrelated to human habitation.

- Similar debates surround the rise of human populations and the concurrent loss of large mammalian species in North America shortly after the last ice advance, roughly 13,000 years ago. On the one hand, some of the most recent mastodon and mammoth fossil remains on the continent are associated with projectile points that indicate organized human hunting parties. On the other hand, those now-extinct animals may represent the last individuals from stressed populations that would have died out anyway.

- Several early human technologies—including agriculture and irrigation, mining, and urbanization—had the potential to alter the near-surface environments, at least locally. But whatever the collective impacts of these early human technologies, they pale in comparison to the potential effects of industrialization. Today, human agriculture occupies 40 percent of the planet's land surface, and that's because of industrial technologies.

- Global climate and sea level, not to mention the diversity and distributions of animal and plant species, are intimately tied to a host of factors. Some of those factors are surely beyond our technological control. The relative positions of continents, including their latitudes near the poles or the equator and the degree to which they are clumped together into supercontinents, would seem to be utterly beyond any conceivable human technology to alter.

- Similarly, the variable intensity of volcanic activity at mid-ocean ridge systems and the periodic disruptions of the surface environment by large-scale volcanic eruptions reflect the ongoing process of convection in Earth's deep interior. There's nothing we can do to alter those factors in Earth's climate.

- On the other hand, human contributions to Earth's greenhouse gases now dwarf by perhaps a factor of 100 or more the amount contributed by volcanoes. This is the sort of change that leads scientists to note that we are living in a new geological epoch. We may not be able to change the volcanoes, but we now affect the atmosphere more than they do.

- It used to be thought that oceans were too vast to be altered in any fundamental way by humans. But increased CO_2 in the atmosphere has already been absorbed by the ocean, which increased in acidity

The Gulf Stream evolves to the west of Ireland, continuing as the North Atlantic Current.

by 0.1 on the pH scale from 1750 to 2010. That may not sound like much, but pH is in powers of 10, so acidity has actually increased by 30 percent.

- Large-scale regional weather patterns are also controlled in significant measure by the position of mountain ranges and the location of major ocean currents. Across the globe, the windward side of tall mountains feature wet climates as water-laden air rises, cools, and forms rain clouds. At the same time, the leeward sides of those mountains are often arid, as cool, dry air flows down into the desiccated lowlands. Many of Earth's most forbidding deserts, from the Sahara to the Gobi, form downwind, in the lee of mountain ranges.

- Another major factor in the local climate of many coastal regions is the distribution of surface ocean currents. The Gulf Stream, which takes warm equatorial waters from the Caribbean north and east toward the British Isles and northern Europe, has become the poster child of such climate-altering currents. In spite of their high northern latitudes, these regions are temperate, at least compared to portions of Canada and Siberia at the same latitudes.

- One of the potential paradoxes from global warming is the potential triggering of local cooling. If polar waters warm much faster than the equator, then the Gulf Stream could stall. And it's not just that the temperature contrast between poles and equator decreases. An additional important factor could be that melting freshwater from large icebergs breaking off Greenland could reduce the density of the surface water and thus halt the sinking of cool surface waters at high latitudes, which is essential to driving the Gulf Stream convection cycle.

- Although the idea of us imposing any kind of geo-engineered change at a global scale might seem like pure science fiction, we humans have been engaged in just such a massive project for the last two centuries. We have taken reduced carbon that was locked away in the crust for hundreds of millions of years and converted hundreds of billions of tons of that carbon into carbon dioxide, much of which has been added to the atmosphere. This is a significant global change in atmospheric chemistry.

- Records preserved as air bubbles in ancient ice cores from the past 650,000 years reveal by direct measurements that levels of atmospheric carbon dioxide have been relatively stable between values of 180 parts per million during maximum glaciation and 300 parts per million when, as today, the glaciers have retreated.

- Furthermore, indirect measurements based on carbon isotopes and other methods suggest that the atmospheric concentration of CO_2 has not exceeded 300 parts per million at any time over at least the last 20 million years. However, atmospheric carbon dioxide reached 400 parts per million by 2012, and the rate of increase was accelerating.

- The last time carbon dioxide reached anything like these levels was tens of millions of years ago in the Paleogene Period. An extended period of dramatic global warming ensued, with a corresponding rise in sea level and significant shifts in global ecosystems. And we can expect the same kind of change today.

- While the extent of warming is a matter of considerable debate, average global temperature is already increasing, suggesting that more severe weather systems will occur and that sea levels will rise.

- Computer models provide hints as to the consequences of this CO_2 buildup, and some degree of warming seems inevitable. But what we cannot yet model are possible tipping points—for example, those associated with the accelerated release of methane from thawing permafrost and methane ices.

The Concern for Global Warming

- As the scientific community comes to accept the reality of climate change and the inevitability of global warming, melting ice caps, sea level rise, and shifting ecosystems, it's interesting to see a gradual change in the rhetoric at science conferences and in publications. There are, of course, ongoing expressions of concern, pleas for moderation and conservation, and frequent dire predictions of coming mass extinction and societal collapse, even extending to the extinction of our own species. And these concerns are not to be taken lightly, because we have seen similar dramatic changes over and over again in the history of our planet.

- But there are also intelligent and constructive discussions of global-scale mitigation strategies. Humans have now demonstrated that they have the capacity to alter environments on a planetary scale, and we can potentially use that knowledge to engineer the planet. We might, for example, place large reflecting shields in orbit around Earth to decrease solar inputs.

- Concurrently, thousands of earth scientists are working on strategies to sequester carbon dioxide deep underground—perhaps pumping

CO_2 back into old oil wells, for example. And chemists are feverishly developing industrial processes of artificial photosynthesis. They are attempting to mimic plants by using the Sun's energy to turn carbon dioxide into a host of useful materials, including food and fuel.

- Thus, even as human populations grow and impose more stress on the global environment, our expanding understanding of Earth's story may play a key role in our continued survival. And that enhanced understanding, as well as how humans adapt, may become the true legacy of the Anthropocene Epoch.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 10, pp. 232–256.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 22.

Seielstad, *Dawn of the Anthropocene*.

Questions to Consider

1. What are arguments for and against defining a new geologic period called the Anthropocene?

2. What are significant geologic changes caused by humans, and when did these changes begin to occur?

The Next 5 Billion Years

Lecture 46

Our view of Earth's evolution would not be complete without taking a look ahead to a few deterministic aspects of our planet's future. Astrophysicists tell us that any sunlike star must come to a dramatic end as a red giant. The Sun will become gradually hotter over most of the next 5 billion years and will eventually expand to beyond Earth's present orbit. Long before that time, Earth will experience many other transformative events.

Peering into the Future: 5 Billion Years

- About 5 billion years from now, the Sun will enter its old age, and Earth will be a very different place. Astrophysicists tell us with confidence that the Sun is now almost halfway through its roughly 10-billion-year lifetime.

- For 4.5 billion years, our solar system's central star has shone steadily, while getting slightly brighter through time as it consumes its vast store of hydrogen fuel. This stable state results from the steady process of hydrogen "burning," by which hydrogen atoms, subjected to tremendous temperature and pressure, fuse to make helium plus energy. For perhaps another 4 or 5 billion years—a doubling of the age of the solar system—the Sun will continue to generate nuclear energy by this stable process.

- Hydrogen burning can't go on forever; eventually, the hydrogen fuel has to run out. Some stars smaller than the Sun just sort of peter out when they reach this stage and never do anything very dramatic. They eventually cool and shrink in size, while emitting much less energy than before.

- Had the Sun been such a relatively cool "red dwarf" star, Earth's ultimate fate would probably be to slowly get colder, eventually freezing solid. Life on such a world could most likely survive for a long time, maybe tens of billions of years, but it would be limited to a few hardy microbes deep underground, where liquid water could persist.

- That's not the fate in store for Earth, because the Sun won't die in that gradual way. It turns out that the Sun is large enough to have a nuclear backup plan. The Sun is now in the midst of its reliable hydrogen-burning phase, so it has a stable diameter of about 870,000 miles. That size has persisted, and will continue to persist, for a total span close to 10 billion years.

- The Sun is large enough so that when the hydrogen-burning phase ends, a new, much more rapid and energetic helium-burning phase will begin. Helium, which was formed as the byproduct of hydrogen fusion reactions, can itself be a nuclear fuel. Helium fuses to other helium atoms to make the element carbon. These reactions will keep the Sun going for another few hundreds of millions of years, but with rather startling consequences for the inner planets.

- As it enters the helium-burning phase, the Sun will swell, larger and larger, like a superheated balloon. This solar expansion results from the outward push of nuclear reactions overcoming the gravitational inward pull. The resulting red giant star will pulsate, getting larger, then smaller, then larger again.

- The Sun will swell by tens of millions of miles, expanding past the orbit of little Mercury and thus engulfing the innermost planet. Then, the Sun will swell some more, past what is the orbit of our neighbor Venus, probably swallowing that sister world as well. In fact, by the best estimates of astrophysicists, the Sun will swell to 200 times its present diameter. That's even past the orbit of Earth.

- These events will be hard on planet Earth, though exact details of what will happen are somewhat murky, and they depend on the details of the Sun's endgame. According to some scenarios, the red giant Sun will simply expand to overwhelm and swallow Earth, which will then vaporize in the solar atmosphere and be no more.

- Other astrophysical models have the Sun shedding more than a third of its present mass in solar winds of unimaginable ferocity. If that happens, then as the Sun becomes less massive and its gravitational pull gets weaker, Earth's orbit will become correspondingly larger. Earth will then become the innermost planet.

- Of course, if Earth isn't swallowed by the expanding Sun, then its surface will be scorched, and most near-surface water will escape into space. It's very likely that a sparse subsurface microbial ecosystem could persevere for another billion years, but being the planet closest to the Sun, Earth would be very different.

Peering into the Future: 2 Billion Years

- Ever so slowly, even in its present calm hydrogen-burning state, the Sun is getting hotter. It's estimated that 4.5 billion years ago, the Sun shone with only 70 percent of its present light. More than 2 billion years later, the great oxidation event 2.4 billion years ago found a Sun shining with perhaps 85 percent of today's intensity. Today, the Sun is significantly brighter than that, and a billion years from now, the Sun will be brighter still.

- Perhaps for many hundreds of millions of years, Earth's negative feedbacks will likely moderate the changing solar output and may keep Earth habitable for a long time to come. Of course, if the Sun gets too hot for Earth's gravity, then there will come a tipping point.

- Our smaller planetary neighbor Mars, with its much weaker gravity, appears to have experienced this scenario billions of years ago, when almost all of its near-surface water was lost to space, even though Mars is farther from the Sun and the Sun was dimmer at the time.

Peering into the Future: 1 Billion Years

- About 1 billion years from now, the increased heat from the Sun may cause Earth's oceans to evaporate at an increasing rate, perhaps turning the atmosphere into a perpetual sauna. If that happens, then ice caps and glaciers will melt, as even the poles will become tropical zones. Life will most likely thrive, at least for a time, in such a hothouse environment.

- More life may live below the surface. And if human descendants learn a few geo-engineering tricks, it's very possible that a warming Sun will act as an evermore bountiful energy source.

- Nevertheless, as the Sun continues to emit more and more radiation, and more water vapor enters the atmosphere, it's likely that the greenhouse effect will intensify. Hydrogen may be lost to space at ever-increasing rates, and that could gradually dry out the planet, but there are eons of time to adapt.

Peering into the Future: 250 Million Years

- Projections into the less-remote future paint a benign picture of a dynamic yet relatively safe planet. Looking forward a few hundred million years, the past is indeed the key to understanding the future.

- At the global scale, plate tectonics will continue to play the central role in changing Earth's geography. Today, we live in a time when the continents are pretty much scattered across the globe, from poles to equator and in both hemispheres. But all of that is temporary. These landmasses are constantly in motion at rates of roughly an inch or two per year, and that adds up to 1,000 miles of motion every 60 million years.

- Looking at the details of ocean-floor basalts—their positions and their ages—we can establish rather precise vectors for every landmass. Basalt near the mid-ocean ridges is quite young, just a few million years at most, while basalt at continental margins and subduction zones may be more than 200 million years old.

- It's a fairly simple matter to take all of these ocean-floor ages and play the plate tectonics tape backward in time. And from that information, it's also possible to project current plate motions many millions of years into the future.

Gradually, the Sun is getting hotter, and if the Sun gets too hot for Earth's gravity, then there will come a tipping point.

- When geologists undertake this exercise, they find that all the continents are headed for another collision. In roughly a quarter of a billion years from now, most of Earth's land may once again form one giant supercontinent. This imagined landmass already has a name: Novopangaea. While the exact arrangement of that future supercontinent is still a matter of much debate, everyone agrees that Earth's map 250 million years from now will feature a new supercontinent.

Peering into the Future: 50 Million Years

- We can be pretty confident that 50 million years from now, Earth will still be a vibrant, living world. Our planet will still have blue oceans and green continents. Continents and oceans will have shifted, of course, but still will be recognizable.

- Nevertheless, we can be absolutely certain that another big asteroid impact of the dinosaur-killing variety is coming someday—somewhere. Given the best estimates of what's happened in the past, we can be almost certain that in the next 50 million years, Earth will suffer at least one really big hit. It's simply a matter of time and probabilities.

- The fate of our human species is uncertain. Fifty million years is 20 times longer than the time from the first *Homo* species to now, so it's certainly possible that in 50 million years, all descendants of *Homo sapiens* will be extinct.

- If we don't evolve into another species, then 50 million years is more than sufficient time to erase almost every trace of our residence on the planet. Every city will have eroded away. Every highway and every monument will have been buried or weathered to nothing millions of years earlier. An alien archeologist or paleontologist would have to search for a long time to find the fossilized traces of our vanished species.

- Of course, it's also possible that humans will survive and evolve. If we move outward to colonize neighboring planets, and perhaps eventually planets orbiting neighboring stars, then new species of *Homo* will appear.

- If our descendants make it into space, and if they preserve a record of the deep past of human origins, then Earth most surely will be treasured as never before. Earth might become a natural preserve, a global museum, and a shrine and place of pilgrimage.

- Perhaps by moving far beyond, out into space to other worlds—even in the imagined journey of a thought experiment—humans will learn to cherish our beautiful, fascinating home as never before.

Suggested Reading

Appell, “The Sun Will Eventually Engulf Earth—Maybe.”

Hazen, *The Story of Earth*, Chapter 11, pp. 257–280.

Nield, *Supercontinent*.

Seielstad, *Dawn of the Anthropocene.*

Questions to Consider

1. How is the Sun predicted to change over the next 5 billion years, and how might those changes affect Earth?

2. What might Earth’s next supercontinent look like, when is it likely to form, and how do we know?

The Nearer Future

Lecture 47

Over the course of the last 46 lectures, you have learned about the full sweep of cosmic evolution that led to our planetary home. Earth has displayed its own complex evolution—a history of repeated and incessant change. The past is the key to understanding Earth's future. Changes in the next million years will reflect the kinds of variations in climate and coastline that have characterized the entire history of our planet. The history of Earth is a story of repeated, dramatic changes. No matter what humans do, or do not do, Earth will continue to be a planet of change.

The Next 50,000 Years

- The next million years of Earth's geological story will simply mimic what's been happening for hundreds of millions of years. The next 50,000 years of Earth's story is in rather sharper focus. Geologists are now scrutinizing the recent rock record to see what's in store, and they conclude that the most significant changes to Earth's geography by far will come not from shifting continents, but from rises and drops in sea level. Surprising new research suggests that these changes are inevitable and that they can approach 10 feet per century.

- On historical timescales of a few hundred to 1,000 years, the depth of the oceans is tied primarily to the total volume of Earth's ice, and that includes the polar ice caps, glaciers, and continental ice sheets. The equation is simple: The greater the volume of water tied up in ice on land, the lower the sea level.

- If we're going to say with any confidence what will happen in the future, we have to have a method of determining the depth of historic oceans. We now have a very accurate measure in the form of satellite observations of ocean levels, but those measurements are restricted to the past two decades. There's a somewhat longer record, perhaps a century and a half in some places, of tide gauge measurements, but those values are intrinsically less accurate and are subject to local idiosyncrasies.

- Going back into the recent geological record, we can resort to mapping a variety of ancient shoreline markers. In some places, there are clear raised beach terraces, which can be dated by fossil shells. Those features can be found in sediments dating back tens of thousands of years. The problem is that those kinds of elevated features can only reveal periods when the water level was higher.

- A similar kind of data can be obtained from the positions of fossil corals, which have to grow in the ocean's relatively shallow photic zone. One complication is that those older rock formations often have experienced episodes of uplift, subsidence, or tilting, so the actual sea level change is obscured.

- To tease out sea level changes, many scientists are now focusing on what might not seem to be an obvious indicator of sea level: the ratio of oxygen isotopes in tiny seashells. Oxygen isotopes may be the best key to unlocking the volume of Earth's ice in the past, and if we know the volume of ancient ice, we can make a pretty good guess about sea level changes.

- The evidence is clear that sea levels have repeatedly risen by as much as 300 feet higher than today. A 300-foot rise in sea level would submerge hundreds of thousands of square miles of coastal areas around the globe. And these changes haven't occurred just once or twice. In the last million years alone, sea levels have risen by more than 100 feet and fallen by a similar amount at least a dozen times.

- Details certainly vary from cycle to cycle, but these events are clearly periodic and are probably related to the so-called Milankovitch cycles. About a century ago, Serbian astrophysicist Milutin Milankovitch discovered that three well-known variations in Earth's orbit—elliptical orbit, tilt of the axis, and a slight wobble in its rotation axis—result in cycles of climate change with intervals of roughly 20,000, 41,000, and 100,000 years. Solar energy exerts a profound effect on global climate, and these variations collectively affect the amount of sunlight hitting Earth. Currently, all three are moderating the amount of sunlight.

- Unless the human race comes up with some pretty extraordinary global engineering plans, we can be confident that over the next 50,000 years, the sunlight Earth absorbs will go through cycles, and sea levels will continue to vary dramatically. At times, probably over the next 20,000 years, icecaps will grow, glaciers will advance, and sea level will decrease by 200 feet or more.

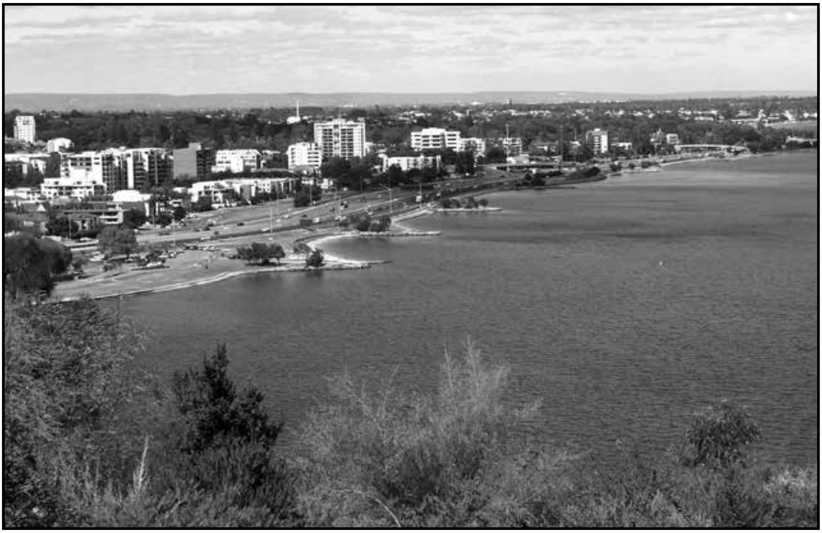
- The biggest change will be to coastlines. A 200-foot drop in sea level means the east coast of the United States will shift dozens of miles to the east, as more of the shallow continental slope is exposed. All east coast harbors, from Boston to Miami, will be high and dry inland cities. New ice and land bridges will connect Alaska to Russia and the British Isles to mainland Europe.

The Next 1,000 Years

- In the case of sea level, what goes down must also go up. It's very possible that over the next 1,000 years, sea level will increase by more than 100 feet. That's not a huge rise by geological standards, but it will dramatically alter the map of the United States.

- A 100-foot rise in sea level would submerge almost all of the coastal plain of the east coast. Shorelines would shift up to 100 miles westward while every major East Coast city would be completely submerged. Only a few skyscrapers will poke above the waves. Los Angeles, San Francisco, San Diego, and Seattle would also drown. Indeed, almost all of Florida except for what would become an island on the panhandle would be gone. The distinctive peninsula would be completely submerged in a shallow sea. Almost all of Delaware and Louisiana would be under water, too.

- It's hard to imagine the consequences of a 100-foot rise in sea level in other parts of the world. Entire countries—Holland, Bangladesh,



Over the next 20,000 years, it is likely that sea level will decrease by 200 feet or more, causing great shifts to coastlines.

the Maldives—would be no more. In addition, because coastal areas are so heavily populated, billions of people would lose their homes.

- There can be no doubt about these coming changes. The geological record is unambiguous. And if, as most experts predict, global climate change is accelerating, then waters will rise soon, perhaps as much as a foot per decade—a whopping 10 feet in the next century. Such changes will pose severe challenges to human society, but they will have little effect on planet Earth.

The Next 100 Years

- Barring an unforeseen cataclysm like an asteroid impact, Earth next year or next decade is going to seem pretty much like it does today. By and large, the differences from one year to the next will probably be too small to notice. It's certainly true that we may experience big wildfires or a spate of unusually severe weather, but those changes are incremental and not out of the range of past experience.

- We can be absolutely certain that Earth will continue to change. Earth always changes—hotter or colder, wetter or drier, higher sea level or lower sea level. Present indicators point to a coming episode of significant global warming and melting glaciers, and these changes are very likely accelerating because of human activities. These changes could have pretty significant consequences for human civilization.

- Changing climates may not be kind to some animal and plant species. Loss of north polar ice is reducing the habitat of polar bears and adding significant challenges to that shrinking population. Rapidly shifting climate zones will also stress many threatened species, most notably birds, which are susceptible to alterations in migratory nesting and feeding areas. There can be little doubt that we're entering a time of accelerated extinction.

- So if climate change is a constant aspect of Earth's behavior, should we be concerned? It turns out that rates of change, not changes per se, are the biggest concern. Most of Earth's changes—including sedimentation, erosion, opening oceans, or rising mountains—are extremely slow compared to a human life span. These phenomena take hundreds of millions of years. It's easy to adapt, so we simply don't need to worry about those changes.

- Other geological events are all but instantaneous: great earthquakes, volcanic eruptions, or an asteroid impact. Humans are not as well prepared for the once-in-a-century storm or earthquake, much less the truly catastrophic once-in-a-thousand-year disaster like a megavolcano. Nevertheless, it's clear from Earth's story that such events are an integral part of our planet's past and future. And humans have always learned to adapt and, at least as a species, survive such natural disasters.

- In between those very slow and very fast events are a variety of cyclical geological processes that would usually occur over hundreds or thousands of years. That includes shifts in climates, sea level, and ecosystems. Such changes are usually noticeable only over several generations, and it turns out that these are the kinds of fluctuations for which we have the most uncertainty.

- Climate, sea level, and ecosystems all are subject to feedback loops, and all of them can reach tipping points. If the climate is pushed too far and positive feedback loops kick in, then it's possible that a switch in climate that normally takes 1,000 years could happen much faster, maybe even in a decade or two.

Suggested Reading

Appell, "The Sun Will Eventually Engulf Earth—Maybe."

Hazen, *The Story of Earth*, Chapter 11, pp. 257–280.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*, Chapter 22.

Seielstad, *Dawn of the Anthropocene*.

Questions to Consider

1. Based on the geologic record of the past million years, what kinds of change is Earth likely to experience over the next 50,000 years?

2. How might such changes affect human populations?

Coevolution of Geosphere and Biosphere

Lecture 48

The journey of our evolving Earth is far from over. If 4.567 billion years has taught us one thing, it is that there is much more to come. Earth's lessons, once deciphered, give us a new appreciation of who we are and how far our planetary home has come. And we can appreciate our amazing world as a place where rocks and life continue to coevolve, where new wonders continue to emerge.

The Story of Earth: Profound Truths

- The story of Earth is an immense and complex tale, filled with details and nuances that can at times be breathtaking and more than a little overwhelming. But step back from the sweeping transformations and subtle complexities, and we find three profound truths that underlie any consideration of our amazing planetary home.

- First, for its entire 4.567-billion-year history, Earth has been, and continues to be, a planet of incessant, remarkable change—sometimes sudden, sometimes gradual, but always change. Nothing you see of our planet today is the way it *always* was or the way it *always* will be.

- Many of the grandest mountains, such as Mount McKinley or Mount Everest, began forming only about 50 million years ago. And surface features can be far more recent still: San Francisco Bay on the west coast of North America and Chesapeake Bay on the east coast both date from just 10,000 years ago.

- All plants and animals are newer than we realize, too, having appeared on Earth only after more than 85 percent of Earth's history had already passed, some 600 million years ago. Very early mammals and flowering plants only began to take over some 60 million years ago, while the split between monkeys and humans from a common genetic pool was 30 million years ago. The first dandelions, so ubiquitous today, appear in the fossil record only 5 million years ago, and that was long before modern humans came on the scene.

- A second profound insight is that such changes have been occurring through billions of years of history. As revealed by a site like the Grand Canyon, whose layers stretch back to over 2 billion years ago, getting to know our world means coming to terms with the power of deep time to alter every aspect of the planet.

- Third, more than any other factor, life has profoundly affected our planet in ways that are unparalleled in any other known place in the cosmos. Just look at the immense limestone reefs that form the highest peaks of the Canadian Rockies or the vast coal deposits of Pennsylvania.

- It's only in the context of these three truths—incessant change, deep time, and life—that we can come to know our home. As we look at the planet today with a new sense of that dynamic history,

Limestone reefs form the highest peaks of the Canadian Rockies.

and with more informed eyes, we can appreciate our amazing home as a place where rocks and life continue to coevolve in remarkable ways. The planet changes, but we can learn to see those changes in what remains today.

Mineral Evolution and Earth's History

- The story of minerals parallels, and even provides a foundation for, many other aspects of the story of Earth. In the beginning, in the first millions of years following the big bang, there were no minerals and no planets anywhere in the cosmos. Only after the first generation of giant stars exploded were all the planet-forming chemical elements produced and ejected into space. And only then could the first dozen or so ur-minerals crystallize in the expanding and cooling gas envelopes of those stars.

- In those ancient times, most chemical elements were much too scarce and widely dispersed to form minerals. On the other hand, the abundant element carbon formed microscopic crystals of diamond, which became the very first mineral. And diamond was soon joined by a dozen or so other hardy microcrystals, with the common elements silicon, aluminum, magnesium, iron, calcium, and oxygen.

- Diamond is so pure and simple, and it lasts virtually forever to reveal the earliest times of our universe. And it was carbon, and a handful of companion elements, widely dispersed in a succession of supernova explosions, that became the great engines of mineral formation and seeded the first generation of earthlike planets.

- At each stage of Earth's mineral evolution, new mechanisms selected and concentrated combinations of elements that altered and enriched the mineralogy, as well as the life-forming molecules, of our planet's surface.

- Most of Earth's thousands of varied mineral species owe their existence to the origin and evolution of life on the planet. It's so easy to think of all the nonliving world as a fixed stage on which life plays out its evolutionary drama, but we now know that this perspective is incorrect.

- In this drama, the actors—the microbes, plants, and animals of Earth's rich biosphere—are constantly renovating their theater along the way. This observation also has profound implications for our ongoing quest to find signs of life on other worlds. As a consequence of this coevolution, the sturdy minerals, rather than fragile organic remains, may provide the most robust and lasting signs of a living world.

Dynamic, Changeable Earth

- The concept of mineral evolution points to some exciting opportunities for future research. For example, we see that different planets achieve markedly different stages of mineral evolution. Small, dry worlds like Mercury and the Moon possess relatively undifferentiated surfaces of low mineral diversity. These bodies essentially froze billions of years ago and are now geologically dead.

- Small, wet Mars fared a little better: Billions of years ago, it was a wet, active planet that saw the formation of diverse hydroxides, evaporites, clay minerals, and ices. Mars is now much less active, but life might have begun at some point in the distant past. Bigger planets like Earth and Venus, with their greater stores of volatiles and inner heat, progressed further, perhaps through the formation of granitoids and the initiation of plate tectonics.

- But the origin of life, and the subsequent coevolution of biology and minerals, sets Earth apart. Consequently, minerals may be as valuable as organic remains for identifying the signature of life on other worlds. Only those planets with photosynthetic life would likely be extensively oxidized, for instance. So we must watch for these traits to help us identify exoplanets most like Earth.

- Keep in mind that Jupiter's moon Europa and Saturn's moon Enceladus are both believed to harbor liquid oceans of water below their surfaces. These moons are thus prime sites for possible extraterrestrial life.

- Perhaps the most profound consequence of viewing minerals in an evolutionary context may be that Earth exemplifies a more general theme of evolving systems throughout the cosmos. Evolution occurs when simple components combine into increasingly complicated states.

- We observe this phenomenon in the evolution of all the chemical elements from neutrons and protons in the nuclear furnace of stars. We see it in mineral evolution through the assembly of the chemical elements in planets. We see a molecular evolution of building blocks for life in meteorites and all over the solar system, and on Earth, we see molecular evolution lead to the origin of life, followed by biological evolution through Darwinian natural selection.

- We live in a universe apparently primed for complexification: Hydrogen atoms form stars, stars form the elements of the periodic table, and those elements form planets, which in turn form minerals abundantly. Minerals catalyze the formation of biomolecules, which on Earth led to life, biomineralization, complex multicellular organisms—a sweeping series of steps in the evolution of a cosmos that is learning to know itself.

- Earth's mineralogical diversity reveals how unique and special our planetary home is. Given this new, integrated perspective on the natural world, we see Earth with a new understanding of the intertwined coevolution of the geosphere and the biosphere. Remarkable transformations are occurring before our eyes.

- Minerals provide the essential environment for plants, while plants create the essential environment for the formation of mineral-rich waters. Those waters nurture a new generation of microbes, which in turn form a new generation of minerals. We live on a seemingly magical world, where life and minerals coevolve.

- Throughout Earth's 4.567-billion-year history, the air, the seas, the land, and ultimately life have been shaped by Earth's transformative powers: the energy of sunlight together with Earth's inner heat; the ability of water to select, concentrate, and redistribute elements; the chemical reactivity of carbon, oxygen, and iron; the ceaseless convection of the deep interior and consequent formation of continents; and the disruptions of the crust through earthquakes, volcanoes, and the incessant shifting of continental plates.

- Through these diverse mechanisms, Earth has evolved from black, to blue, through gray, and red, and icy white, and ultimately to the green living world we know today. It has been an amazing journey, and it's nowhere near its end.

- Every day, if we are attuned to these dynamic processes of our planetary home, we can observe—and benefit from our understanding of—these intertwined, creative forces that make Earth possible. And we can then truly come to know how dynamic and changeable our beautiful home can be.

Suggested Reading

Hazen, *The Story of Earth*, Chapter 11, pp. 257–280; Epilogue, pp. 281–283.

Knoll, Canfield, and Konhauser, eds., *Fundamentals of Geobiology*.

Seielstad, *Dawn of the Anthropocene*.

Questions to Consider

1. What do you think are the most important unanswered questions related to Earth history and the coevolution of the geosphere and biosphere?

2. How might answers to those questions change our view of the human role in the present and future of our planet?

Timeline

13.78 bya ....The big bang

4.567–4 bya ....**HADEAN EON**
4.55 bya ....Earth's accretion and differentiated meteorites
4.53–4.51 bya ....Theia collision with Earth, formation of Moon

4–2.5 bya ....**ARCHEAN EON**
~3.8 bya ....Evidence of life
~3.5 bya ....Photosynthesis
~3.1 bya ....Possible formation of continent "Ur"
~2.7 bya ....Formation of supercontinent Kenorland

2.5 bya–600 mya ....**PROTEROZOIC EON**

2.5–1.6 bya ....**Paleoproterozoic Era**
~2.4 bya ....First great oxidation event
~2.0–1.8 bya ....Formation of supercontinent Columbia/Nuna

1.6–1.0 bya ....**Mesoproterozoic Era**
~1100 mya ....Formation of supercontinent Rodinia

1.0 bya–600 mya ....**Neoproterozoic Era**
775–635 mya ....Snowball Earth intervals

542 mya–present ....**PHANEROZOIC EON**

542–251 mya ....**Paleozoic Era**

541–485 mya ....Cambrian Period

485–443 mya ....Ordovician Period

443–419 mya ....Silurian Period

419–359 mya ....Devonian Period

359–299 mya ....Carboniferous Period

~300 mya ....Formation of supercontinent Pangaea

299–252 mya ....Permian Period

251–65 mya ....**Mesozoic Era**

252–201 mya ....Triassic Period

201–152 mya ....Jurassic Period

~175 mya ....Break up of Pangaea into Laurasia and Gondwana

152–65 mya ....Cretaceous Period

~175 mya ....Break up of Gondwana into Africa, India,

....South America, Australia

65.5 mya–present ....**Cenozoic Era**

~60–55 mya ....North America separated from Eurasia

2.6 mya–present...................Quaternary Period

1.8 mya–11,700 ya ....Pleistocene Epoch

11,700 ya–present ....Holocene Epoch

250 ya–present ....Anthropocene Epoch

Eras and Stages of Mineral Evolution

Era/Stage	Age (Ga)	~ Cumulative # Species
Pre-Nebular "Ur-Minerals"	> 4.6	12
Era of Planetary Accretion (> 4.55 Ga)		
1. Primary chondrite minerals	> 4.56 Ga	60
2 Achondrite and planetesimal alteration	> 4.56 to 4.55 Ga	250
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)		
3. Igneous rock evolution	4.55 to 4.0 Ga	350 to 500*
4. Granite and pegmatite formation	4.0 to 3.5 Ga	1,000
5. Plate tectonics	> 3.0 Ga	1,500
Era of Biologically Mediated Mineralogy (> 2.5 Ga to Present)		
6. Anoxic biological world	3.9 to 2.5 Ga	1,500
7. Great oxidation event	2.5 to 1.9 Ga	> 4,000
8. Intermediate ocean	1.9 to 1.0 Ga	> 4,000
9. Snowball Earth events	1.0 to 0.542 Ga	> 4,000
10. Phanerozoic era of biomineralization	0.542 Ga to present	> 4,800

* Depending on the volatile content of the planet or moon. On Earth … On the Moon …

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