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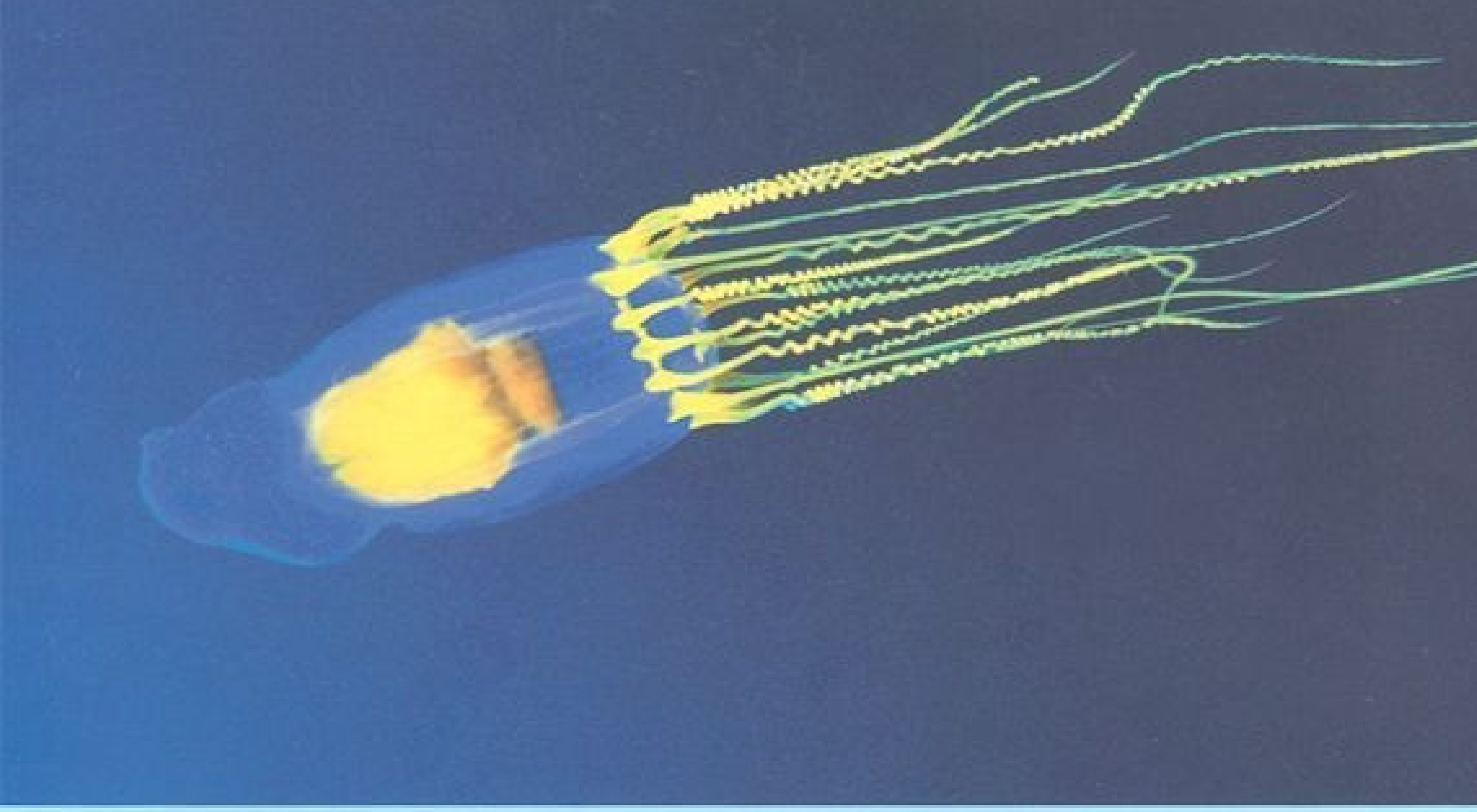

MAPPING THE DEEP

THE EXTRAORDINARY STORY OF OCEAN SCIENCE

ROBERT KUNZIG

"The best account of discovery in oceanography I've ever read."
—Laurence Madin, Woods Hole Oceanographic Institution

More praise for *Mapping the Deep*

“This recounting of recent advances in the ocean sciences presents a lot of fundamental Earth science in easily understood terms. . . . Most writing about the sea, even in the scientific literatur, addresses only coastal or continental shelf phenomena, and I value this book for its almost exclusive attention to the neglected deep oceans.”

—Alan Longhurst, *Nature*

“Fascinating. . . . On every page, another aspect of the ocean’s strangeness emerges. . . . Anyone who peers over the edge of a boat this summer, down into the green and fuzzy murk below, and feels that frisson of awe that the sea can suddenly evoke, will find plenty of interest in this book.”

—Philip Marsden, *Sunday Times* (London)

“Spirited and engaging. . . . A nimble, thorough introduction to the ocean in all its vast, untamable, and fearsome attraction. Kunzig’s flair should stir readers’ awe and allow them to share in his protective urge.”

—*Kirkus Reviews*

“With grace and humor and net cast widely for facts, [Kunzig] presents a compendium of what is known about the ocean and how the men and women we now call oceanographers have assembled that knowledge over the centuries. . . . A rich portrait.”

—*Scientific American*

To my mother and father

Mapping the Deep

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OF OCEAN SCIENCE

ROBERT KUNZIG

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PREFACE

Far from Shore

IMAGINE you looked out your window one morning and saw jellyfish. Not just the occasion songbird fluttering or hawk circling, soon to alight again, but a sky full of floating gelatinous animal jellyfish and ctenophores and salps sucking in microscopic plankton. Every now and then a shark or tuna glides through noiselessly; every now and then one of the jellies starts glowing like a gia firefly. A sky like that would be worth exploring, would it not?

Imagine that when you picked up your newspaper, the lead story concerned a mountain range new discovered in Switzerland. Its peaks, according to the paper, were higher than 10,000 feet; geographe were amazed. You would be amazed too, would you not?

Imagine, finally, that when you stepped out into your backyard, you discovered a new species plant. And reporting this to the proper authorities, you learned that this plant of yours, which no or had seen before, because no one had looked, was so fabulously abundant in everyone's backyard that seemed to be exerting a significant influence on the climate of the whole planet. Perhaps you ca imagine that; perhaps not.

The ocean is a sky like that, a landscape like that, a backyard like that. It is 320 million cubic mil of water covering 140 million square miles of seafloor covering seven-tenths of Earth. Gre discoveries remain to be made there, discoveries as big as mountains – or as *Architeuthis*, the gia squid. Giant squid are the world's largest invertebrate animals, as much as 60 feet long; we know th because from time to time their corpses wash ashore somewhere. But they have never been observ scientifically in their native habitat. In 1999 the Smithsonian Institution in Washington organized a expedition whose chief purpose was to find a giant squid in the waters off New Zealand, whe fishermen have hauled up the odd *Architeuthis* in their nets. The researchers stayed out for a mon with their television crew, diving daily in a submersible, reporting their observations of whales ar other creatures on the expedition Web site – but they never saw *Architeuthis*. Maybe by the time yo read this someone will have. But maybe not. The ocean is a place where giant squid, and much els can still hide.

The ocean remains largely unexplored – and yet oceanographic exploration in the past half centu has completely transformed our view of it: both statements are true, and they are the intertwine threads of this book. In 1950, when the famous naturalist Rachel Carson summed up the state marine science in her book *The Sea Around Us*, only two men, William Beebe and Otis Barton, ha ever penetrated deeper into the ocean than sunlight does; they had descended half a mile beneath th waves off Bermuda in a primitive steel sphere dangling from a ship. No one had ever been to the dee ocean floor. No one guessed the tremendous diversity of animals that lived there, or for that matter the water above. No one knew that a range of seafloor volcanoes, the mid-ocean ridge, ran rig around the planet, or that it was dotted with hot springs that teemed with an entirely new form of life a form no one, in 1951, could possibly imagine. No one had mapped the global web of current surface and deep ones, that, along with the microscopic floating plants, the phytoplankton, exert profound influence on our climate. The deep had not really been mapped at all.

The change since then is hard to sum up in a few sentences. It is like the change of view you get going from an overcast night sky to a clear one, or from a city night to a country one: what once w dull black is now full of stars. The ocean has become a lot more interesting in the last half centur ~~When Carson wrote her book, the seafloor was considered an ancient, unchanging place, a passi~~ receptacle for detritus washed off the continents; its mountains were far older than the ones on la and destined to outlive them. We now know the opposite is true. The seafloor is the youngest part Earth, because it is constantly being made anew by the volcanic outpouring of the mid-ocean ridg Something similar could be said of the ocean in general: it has in all ways come to seem more full motion and energy, life and change, than it used to.

We ourselves, it is now clear, can change the ocean. It may be too large for us to grasp easily, but is quite small enough for us to muck up. We have always caught as many fish as we could, alwa treated the ocean as a garbage can, but now there are more than twice as many of us as there were h a century ago, and our technology is more efficient and our garbage more durable. Day after day t newspapers confirm the trend. In the summer of 1999, the “dead zone” on the floor of the Gulf Mexico – a fishless region of oxygen-depleted water that has recurred every summer since the mi 1990s, and that is caused by pollutants washing down the Mississippi River – reached a record exte of more than 7,700 square miles, which is almost as big as Wales. In November 1997, when a 70-t finback whale washed ashore on a beach in northern Spain, an autopsy revealed that its digestive tra had been clogged by 40 pounds of plastic – shopping bags, trash bags, boat lines, yogurt containe Plastic, French researchers reported in 1999, accounted for more than 80 percent of the trash th found when they systematically surveyed the continental shelf around France and northern Euro They found half a billion bits of trash in all, one every few yards in some parts of the Mediterranean.

Through pollution and especially through overfishing, we have already changed the ocean; it is longer untouched wilderness. “The damage is so pervasive,” wrote Paul Dayton, a marine ecologist the Scripps Institution of Oceanography in California, commenting in early 1998 on the late overfishing report,

> that it may be impossible ever to know or reconstruct the ecosystem. In fact, each succeeding generation of biologists has markedly different expectations of what is natural, because they study increasingly altered systems that bear less and less resemblance to the former, preexploitation versions. This loss of perspective is accompanied by fewer direct human experiences (or even memories) of once undisturbed systems.

Dayton was writing from direct experience, 25 years of it, of diving in the kelp beds off San Dieg But man’s reach extends far beyond coastal waters now. According to one widely credited theor global warming caused by our burning of fossil fuels could one day realign the great ocean curren themselves – suddenly, and with effects that are not now foreseeable. Not many people are aware th we might have such power. To me it is astonishing.

Our newfound power to damage the ocean lends a special urgency to the work of oceanographe That work, rather than the environmental damage itself, is what this book is mostly about. I myself a not an oceanographer. My attraction to the sea is one that most of us share; you might almost call instinctual, though in my case it was nurtured by numerous Atlantic crossings as a child (back whe such voyages were still often done by ship). Later, as a science writer, my fascination took a intellectual route: I became absorbed by what science could tell us about the sea – especially its fa off hidden regions – and ended up devoting almost a decade’s supply of week-ends and vacatio looking into the matter.

This book, then, is about a long voyage among oceanographers, encountered sometimes on ship dock, but also in their laboratories and their literature. It is a book of ideas: a portrait of o understanding of the sea, of how we got it and how it is still only inchoate, even as we are changi the sea forever. There is not much written here about sharks or dolphins or whales or coral reefs; n much either of beaches, waves, or tides. Although all those things are important, they are relative familiar. ~~There is a lot instead about seafloor mountains and stormy deep currents and jellyfis~~ floating in the open sea, far from shore in blue water. My focus is on the distant and unfamiliar because there is so much that is unfamiliar, so much that is unexplored even now.

Ocean explorers these days have to struggle for support. The American government is the large supporter – but you could argue that even it, even in these times of economic boom, is stingy indee In 1999 the National Aeronautics and Space Administration (NASA) lost far more money, more tha $300 million, on two failed missions to Mars than the National Science Foundation spent on ocea science. To be sure, other agencies, such as the Navy, the National Oceanic and Atmospher Administration (NOAA), and even NASA itself, also spend money on oceanography. Most of i though, is devoted not to deep-sea exploration but to more practical work in coastal waters. And whe you throw things like the space shuttle onto the scale, or the manned space station that is now bein built, to uncertain purpose, at a cost of tens of billions of dollars, the conclusion is obvious: th American government thinks space is far, far more important than the ocean.

In 1996 a telephone survey commissioned by the Pew Charitable Trusts suggested that American disagree: 71 percent of them, the poll found, believe exploring the ocean is more important tha exploring space. Among science writers like me, however, and among readers of science magazine one is more likely to encounter a fascination with space exploration and an ignorance of the ocea The goals of space exploration are in a way easier to identify with; you can see them from yo backyard, just by looking up, with or without a telescope, and if they happen to be concealed by clou you can try again the next night. Seeing the deep is harder, which is why there are legions of backya astronomers but no amateur deep-sea explorers. The deep is always hidden by water.

Water is special stuff. Just how special was appreciated only in the twentieth century, as the structu of atoms and molecules was unravelled. The structure of the water molecule explains why we cann see the deep, but also (in the sense of being a necessary condition) why we and other organisms ca live on Earth at all.

Water exists because it solves a problem that oxygen has. An oxygen atom has six negativel charged electrons in its outer shell, orbiting the positively charged nucleus, but it has room for ar yearns to be filled by two more. Two hydrogen atoms donate the missing electrons and are thereb bound tightly to the oxygen. The result is a four-cornered molecule, a tetrahedron. Projecting fro two corners are the hydrogen nuclei, which are individual protons; the other two corners are occupi by electron pairs from the oxygen atom. The protons give one side of the water molecule a positi electric charge, while the electrons make the other side negative.

This electric polarization has profound consequences. The naked electron pairs and protons attra their opposite numbers in other water molecules, forming bonds known as hydrogen bonds. The intermolecular bonds are much weaker than the ones that join atoms in a single molecule of H_20. B as long as the forces of chaos – that is, heat – are not extreme, hydrogen bonds link water molecules a loose association. Each coupling is fleeting; it is like the passing touch exchanged by dancers in quadrille, as they constantly change partners. Water molecules change partners billions of times second.

Southeastern Pacific Ocean, southwest of Tierra del Fuego

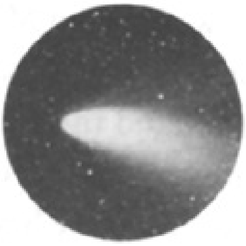
Southeastern Pacific Ocean, southwest of Tierra del Fuego.

Their dance is not quite as orderly as a quadrille, and its rules are only beginning to be understoo But its effects are clear enough. It allows water to exist as a liquid on Earth’s surface. (Witho hydrogen bonds, each molecule would go its own way, and water would exist only as a gas – lil hydrogen sulphide, say, which is a very similar molecule that does not happen to form hydrog bonds.) The liquid ocean, in turn, is Earth’s primary distributor of heat. Sunlight causes wat molecules to strain at their hydrogen bonds, pushing and pulling their neighbours, and the heat that stored in those vibrations can be transported great distances – by ocean currents that are driven by t heat, by variations in the amount of salt dissolved in the water (which affect its density), and b winds. The ocean soaks up heat in the tropics and transports it to higher latitudes, making the who planet more equable – and benefiting some countries in particular. England, for instance, would be grey and icy land were it not for hydrogen bonds, and for currents like the Gulf Stream.

The flip side of this wonderful property of water’s, however, is that the ocean is opaque. As sunlig penetrates into its upper layers, the red wavelengths are absorbed first; the blue light is scattere which is why the ocean often looks blue. At each successive layer, more and more of the light is eith absorbed or reflected. By a depth of 500 feet only around one percent of it is left. No sunlight at a penetrates below a depth of 3,000 feet. Below that depth everything is utterly dark, and utter invisible from the ocean surface. Divers without submarines must stop even higher to avo contracting the bends; the limit for ordinary scuba diving is just 200 feet or so. Exploring the deep s on your own is not practical.

Because of water, then, we live in a divided world. Thirty percent of it we can see; 70 percent of we cannot, because it is covered by water, and so we tend to ignore it. If we lived on Mars or Venu our world would contain no insurmountable frontiers. We could get in our sports utility vehicle ar drive around the planet on a continuous route, swerving only to avoid mountains and chasms. W could map all parts of it in equal detail – as indeed we have mapped Venus – instead of covering mo of it with great swatches of featureless blue. Our world would not end arbitrarily at coastlines, as does now, with vast underwater panoramas reduced in our minds to computer-generated images ar snapshots taken in the short beam of light from a submersible. We have the structure of the wate molecule to thank, and its propensity to form hydrogen bonds, for our existence on Earth – we cou not, in fact, live on Mars or Venus – but also for our monumental ignorance of most of the planet.

The ignorance begins with what sounds like a child’s question, but ought to be everyone’s fir question when standing on the beach: all this water, a million trillion tons of it, this stuff that mak our planet what it is and makes us who we are – where did it come from? And how did it come here To tell that story, it turns out, one must begin in space, and a long time ago.



CHAPTER 1

Space and the Ocean

THREE hundred thousand years after the Big Bang, when the primordial fireball had cooled to a me 5,000 degrees or so, electrons fell into orbit around protons. The change was sudden, as if a spell ha been cast. One instant the electrons were running amok, like children in a schoolyard; the next instan the universe had expanded and cooled and the negatively charged electrons had slowed just enough succumb to the positive pull of the protons. The particles lined up two-by-two. Astronomers speak this as the moment when the fog cleared, and light could at last course through the univer unimpeded. But to someone interested in Earth's ocean and its origin the moment has a differe significance. A single electron orbiting a single proton is a hydrogen atom; and although individu particles would part and reunite countless times in the aeons that followed, it was in that early epo that the universe acquired its basic supply of hydrogen.

When light stopped being intercepted all the time by matter, matter stopped being pushed around b light. The primeval radiation had been like a wind from all directions, and like the wind it had combe things flat. Freed at last from this smoothing pressure, matter could pursue its own natural tendency clump. Hydrogen clumped into ever larger clouds, and soon those clouds collapsed, under the force their own gravitation, to form embryonic galaxies. Within the large clouds, fragments collapsed form stars. In the cores of stars, history was reversed. Temperatures rose again to what they had been few minutes after the Big Bang; pressures rose even higher. But now these extraordinary conditio were maintained, not for a transient moment, but for millions of years. There was time now f hydrogen to fuse into two-protoned helium, and for three helium nuclei to fuse into carbon. There w time as well for a carbon nucleus to collect another helium and become oxygen.

As stars evolved they assembled the elements one after another, on up the periodic table to iro When a star's core is solid iron, however, fusion stops. Without an internal heat source, the star can longer fight gravity. It collapses in on itself, compresses itself, rebounds off a 12-mile wide core incompressible denseness, and then – all this in milliseconds – blasts itself apart, leaving only th dense cinder behind. Layers of hot star-gas millions of miles thick and laced with millions of yea worth of fusion products shoot into space at millions of miles per hour. There they ram into clouds primeval hydrogen left over from the Big Bang. Thus do interstellar clouds become seeded wi heavier elements.

And thus, many billions of years ago, somewhere in our galaxy and probably in a billion oth galaxies too, did hydrogen first encounter oxygen.

A few days before Christmas in 1968, Albert Cheung saw water in space. Cheung was a gradua student in astronomy at the University of California at Berkeley. His adviser was a physicist name Charles Townes. Some years before, Townes had conceived the wild notion that molecules, includin water, might be plentiful in space.

The idea was wild to most astronomers, anyway. Space is vast, they reasoned, and atoms are smal In a typical cubic foot of our galaxy, there are only a couple of hundred hydrogen atoms, and eac atom is just a few billionths of an inch across. Two sparrows released on opposite sides of the Ear and flying randomly have a greater chance of colliding in midair than two atoms have of meeting form a molecule in most parts of interstellar space. What is more, space is bathed in ultraviol starlight – the radiation our atmospheric ozone layer protects us from – which knocks molecules apa Infrequent births and rapid deaths should result in a relatively small population of molecules betwe the stars, or so most astronomers figured. “Astronomers thought they understood interstellar spa better than they actually did,” Townes recalls. “They felt stable molecules couldn’t exist and there w no point in looking for them. So they never looked.”

Townes was not an astronomer by training; he was a physicist looking for a new challenge. In 195 he had invented the maser, the microwave forerunner of the laser. In that device, a bunch of ammon molecules were pumped to a high-energy state of rapid rotation; then they were all stimulated b microwave radiation to fall to a lower energy. In the process they emitted a coherent beam o microwaves that had the same frequency as the stimulus but was much more intense. Masers – th name stands for “microwave amplification by stimulated emission of radiation” – soon found wi application. Among other things, radio astronomers began using them to amplify the weak signa they were receiving from the heavens. By 1964, though, when Townes got the Nobel Prize, he w bored with masers and lasers. When he moved to Berkeley in 1967, he encountered some of the fe astronomers who were following his earlier suggestion and looking for molecules in space. Towne decided to get into the act himself, and to start by looking for his old friend, ammonia.

With Cheung and two other colleagues, David Rank and Jack Welch, Townes installed a receiver f the ammonia frequency on the University of California’s new radio dish, at Hat Creek in northe California. Pointing the dish toward the centre of our galaxy, they pulled in ammonia’s 23,87 megahertz signal, the same signal that had coursed through Townes’s first maser all those years ag right away. Next the researchers tuned their receiver to 22,235 megahertz. They detected that sign too – the signal that a water molecule makes, floating in space and rotating in its lopsided, rabbi eared way, with its electrons sliding back and forth like the electrons in a tiny radio antenna.

One evening in December of that same year, 1968, Cheung was back up at Hat Creek. He had th radio dish pointed at the Orion Nebula – the gorgeous glowing cloud, 1,600 light years away, that the naked eye appears as the middle “star” in the hunter Orion’s sword. Townes was at his home Berkeley, entertaining the rest of his students and staff at a Christmas party. Sometime during th evening the phone rang: it was Cheung, and he was excited. “It must be raining in Orion,” he reporte “There’s water everywhere!”

The signal from Orion was far more powerful than what Cheung and Townes had observed comi from the galactic centre. The water molecules in Orion were giving off as much energy at a sing frequency as the sun emits at all frequencies. It did not take Townes long to figure out what was goi on. He and Cheung were using a maser in their receiver to amplify the weak signals they we expecting, but in this case the incoming signal was amplified already. Cheung and Townes ha discovered a water maser in space.

~~By now it was becoming clear what the astronomers' mistake had been, in assuming all those~~ yea that molecules were too unlikely to form in interstellar space, and too fragile to withstand t ultraviolet onslaught. Those assumptions were true enough for most parts of our galaxy. But they we not true in scattered dark patches, patches where astronomers had been unable to find any signals at a at the frequencies favored by lone atoms. The dark patches had remained mysterious. There was patch like that in Orion. It loomed around the visible nebula and behind it, like the hidden depths of a iceberg.

Now it too turned out to be a cloud: a giant cloud of molecular gas, in which matter is packed million times more densely than it is in ordinary interstellar space. That is still only a hundre trillionth as dense as the air in our atmosphere. But it is dense enough to allow molecules to for readily; and it is dense enough, given that the cloud is a hundred or more light-years across, to preve ultraviolet light or any other light from penetrating to its interior. That is why the cloud appears dar It is also cool, around -400 degrees Fahrenheit. And as astronomers have come to realize in the pa three decades, the molecular cloud in Orion and others like it – there are many in our galaxy – a more than just oddities. They are the places where stars are born. Their density and coolness allov gravity to triumph over heat, which is the first requirement if a gas cloud is to collapse in on itself form a star.

Moreover, molecular clouds are lousy with water. In their protected depths, hydrogen and oxygen hydrogen made in the Big Bang; oxygen made in the interior of stars – are always uniting to form H_2 probably on the surface of frozen dust grains. The mass of the water in all the clouds in our galaxy about the mass of a million suns. In most cases, as in Orion, the water is acting as a maser. Hot your stars in a molecular cloud may create masers by shedding torrents of gas and radiation that compre and heat the surrounding cloud.

Four and a half billion years ago, when our own sun ignited and emerged from the black with i retinue of planets, it may have announced itself with a water maser. Certainly the solar nebula – tl molecular cloud fragment that gave birth to our solar system – would have been laced with water. Ar somehow a lot of it happened to end up in liquid form on just one of the nine planets, the third o from the sun – that is, on Earth.

In the past three decades or so, the scientific notion about how Earth formed, and in particular of ho it got an ocean, has changed completely. Until well into the 1960s, the process was thought to b relatively gentle, cool, and gradual. Earth, in this view, condensed from a giant gaseous protoplane Only gradually did it heat up, as uranium and other radioactive elements embedded in it decayed ar released heat; only gradually did the heat drive water vapour – which had attached itself to rock minerals in the solar nebula – out of Earth's interior. Erupting in great clouds from volcanoes, tl water vapour condensed and rained out of the atmosphere. Gradually, over hundreds of millions c years, the ocean was filled. Rachel Carson, writing in 1950, pictured that primordial rain falling in empty ocean basins that already had much the shape they have today.

The "volcanic outgassing" scenario of the origin of the ocean is still found in textbooks ar encyclopaedias. But it is probably false. The available evidence suggests that over Earth's entire 4. billion-year history there has not been enough volcanic activity to cough up an ocean. It also sugges that the formation of Earth, at least in its final stages, was anything but gentle and cool – that Ear and its ocean were born in violence.

~~The birth of the solar system began when a dusty cloud, a small fragment of a giant molecular~~ clou like the one in Orion, somehow became denser than its surroundings and somehow was pushed in collapse, perhaps by the explosion of a nearby star. As the central bulk of the cloud collapsed into sun, in a hundred thousand years or so, the rest of it began to rotate rapidly, preserving in its motic all the rotational momentum of the original cloud. The centrifugal force of the rotation saved th dust-spiked gas from being swallowed by the newborn star. Instead it drifted down and out, snowin softly into the plane of the sun's equator, where it formed a broad, flat disc. The dust in the dis consisted of grains of rock and ice, including water ice.

In the hot, dense region near the young sun, however, where the temperature may have been as hig as 2,200 degrees Fahrenheit, only rocky grains could endure. Ice might have survived inside suc grains, but not on their surface and not as pure grains of ice; those would have been vaporized. As result, the inner planets – Mercury, Venus, Earth, and Mars – are mostly rock. These days they are n longer thought to have condensed from giant gaseous protoplanets. Instead they were built brick b solid brick, starting with the tiniest ones.

As the dust grains snowed down into the solar disc, and even more once they were there, they bega to collide and stick together; this swirling rush of dust may have produced such static electricity that was sometimes rent by thunderclaps and lightning. Clumps formed, then bigger clumps, then te billion rocks the size of asteroids. Rocks on the same orbits began to attract one anoth gravitationally and gently to collide. Within a million years after the sun first coalesced, most of th dust in the inner solar system had settled onto 30 or so planet embryos, each roughly the size Mercury.

Now all gentleness faded; now it was survival of the fittest and luckiest embryo. The inner sol system, home today to four planets, was not big enough for 30 Mercuries orbiting on concentr circles. But the embryos did not stay on safe, concentric paths for long. The gravitational attractio among them soon forced the issue. The embryos' orbits became more elliptical, and their paths bega to cross – which means they began to collide, not gently, but at speeds of tens of thousands of mile per hour. Only the embryos which started out somewhat larger than the rest could survive suc impacts, and they proceeded to grow even larger by absorbing their victims. Within ten to a hundre million years, this planetary barroom brawl had produced two winners, Earth and Venus. Mars an Mercury, which are much smaller, survived only by cowering well out of the way of the bullies.

Once the embryonic Earth was the size of Mercury today, its gravity would have accelerated an incoming rock to such a terrific velocity that on impact the rock shattered and melted or eve vaporized. Besides releasing a great deal of heat, the explosion would have immediately set free an water trapped in the rock. If Earth formed from colliding planetoids, then, it formed not cold but ho hot as blazes. And assuming there was water trapped in the rock, it formed wet, right from th beginning.

When one stops to consider just how much heat and how much water might have been released b the torrent of planetoids that pelted the young Earth, one arrives at an astonishing possibility, fir pointed out in 1986 by Takafumi Matsui and Yutaka Abe of the University of Tokyo. The cloud o water vapour would have lain like a thick blanket over the planet, and it would have trapped heat – s much heat that the water would have become hot steam. As the steam got thicker and thicker wi each fresh impact, almost none of the heat released by the exploding projectiles would have been ab to escape into space. The temperature of the planet surface would have risen inexorably, until final something gave: until Earth's entire surface melted. Our planet's first ocean, in this scenario, was a ocean of magma, of liquid rock.

~~The magma ocean would have prevented the steam from thickening and the temperature from~~ risi indefinitely. As incoming rocks released steam, some of it dissolved in the magma. At a temperatur of 2,300 degrees Fahrenheit, according to Matsui and Abe, the two processes would have been balance: the same amount of steam was. being released into the atmosphere as was being drawn out it into magma. At that point the atmospheric pressure would have been 100 times what it is today. Th weight of the steam atmosphere would have been around a million trillion tons.

What would this primordial Hades have been like? Perhaps like a pair of Rothko's colour field painted large: a bright-red ocean, the colour of the lava that flows out of Kilauea, on Hawaii, under perpetual gray fog. A boundless ocean of churning, boiling rock, stirred from time to time by th splashdown of a minor planet, which would radiate tsunamis of magma in all directions; a thic viscous ocean with no land, no landmark at all to catch the eye, even if the eye had been able penetrate more than a few feet through, the dense, crushing fog. A boundless shimmering bright-re ocean of rock below; and above, like some giant inflatable dome, propped up precariously by the he of sporadically exploding projectiles, a whole scalding ocean of water. The situation could not las Eventually the rain of projectiles had to taper off, and the surface of Earth had to cool. Eventually th rain of water had to begin.

It would have been a cooling rain by the standards of the day, but its temperature would have bee 600 degrees, because that (and not 212 degrees) is the temperature at which water starts to condense a liquid under 100 atmospheres of pressure. The rain, once it began, would have been implacable. would not have been a rain as we know rain, an event that leaves no permanent mark on th atmosphere; it would have been the collapse of the atmosphere. It would have lasted much longer tha 40 days and nights – millennia, perhaps, during which time virtually all the water in the atmosphe fell to Earth. The amount of water a steam atmosphere can support, Matsui and Abe calculate, is ver close to the amount of water in the ocean today – 1.4 million trillion tons – which is an encouragin coincidence for their scenario. That first ocean of water would have been boiling hot.

It may or may not be the same ocean we have today. The projectiles striking Earth gave our plan water, but the largest ones also took it away, blasting it into space. In particular, it is widely believe today that the Earth was struck, very early in its history but at a time when it was almost full-grow by a planet embryo at least the size of Mars. That impact melted our planet right through and perhap vapourized part of it. The incoming embryo too was vapourized, and most of it, all but its heavy co of iron (which sank to the centre of Earth and merged with Earth's own core), rebounded back in space. There the fragments quickly reaccreted, in as little as a year, to form a solid body in orb around our planet: the body we know as the moon.

Such an impact would certainly have stripped the planet of whatever steam atmosphere or ocean had at the time. Thus the ocean we have today must, if this scenario is true, have been born after th moon. Perhaps Earth was still accreting enough rocks from space, and perhaps those rocks were w enough, to endow it with a second and more lasting ocean. But many researchers think our planet mu also have gotten a lot of water from somewhere else.

Most human beings who look at the ocean are impressed by the amount of water they see. Viewe from space, Earth is the Blue Planet, the Water Planet. James Pollack, a NASA scientist who died i 1994, looked at Earth and the amount of water on it, and he said: "It's just an incredible depletion. Th

Earth has nothing close to what it could have ended up with.” And he looked at the solar system as whole, ~~and saw a strange paradox: “On the one hand, the terrestrial planets and particularly the~~ Ear are located just in the right temperature zone, at the right distance from the sun, so you could hav oceans of water – water in the liquid phase rather than in the solid phase. But on the other hand, th region that is really just enormously rich in all volatiles, including water, is the outer part of the sol system, beginning somewhere in the outer asteroid belt and continuing all the way’out.”

Earth has a lot of water – but “nothing close to what it could have ended up with,” according to planetary scientist James Pollack.

To resolve this paradox, Pollack proposed a link between the two regions: comets. In 1986, when flotilla of European, Russian, and Japanese spacecraft flew by Halley’s Comet, they confirmed wh had long been suspected about its composition. A comet is primarily a mixture of rock and water ic in roughly equal proportion – a dirty snowball, or snowy dirtball, depending on your point of view The moons of the outer planets have about the same composition; the Pioneer and Voyager mission in which Pollack was a leading participant, showed that. The similarity cannot be a coincidenc Halley and most of the other long-period comets, which visit us now from their home in the Oc Cloud – a spherical shell that lies well beyond Pluto and surrounds the entire solar system – a thought to have coalesced originally around Uranus and Neptune.

The solid cores of those planets, and of Jupiter and Saturn, were built like the inner planets wer brick by brick – only in their case the bricks were icy ones fabricated in the frigid temperatures of th

outer solar nebula. The larger bricks must have resembled comets and outer-planet moons. As Pollac
~~saw it, the comets we observe are just left-over bricks from the construction of the outer planets~~. On
Uranus, say, had reached its present mass, nearly 15 times that of Earth, its relation to a comet wou
have been that of Hercules to a discus. A comet passing near Uranus, but not near enough to fall i
would be gripped by the planet's powerful gravity and flung onto a new orbit. It might streak o
toward the outer fringes of the solar system and take up residence in the Oort Cloud. Or it might b
hurled in the other direction, toward the inner solar system.

Jupiter and Saturn, more Herculean even than Uranus, would have been scattering their own lef
over snowballs at the same time. Many of these icy projectiles must have crashed in on the brawl
rock that was just then being decided in favour of Earth and its three sister planets. Halley's Com
may contain hundreds of billions of tons of water; a typical outer-planet moon contains thousands
times that amount. If just a small percentage of the icy bodies that originally condensed in the out
solar system had struck Earth, they could have endowed it with an ocean of water.

If most of them struck while the rocky part of Earth was still coalescing, the result would have bee
much as if the rocks themselves had spit out the water, as Matsui and Abe envisioned. The sam
massive steam atmosphere would have formed, and the same magma ocean, until the steam collaps
into an ocean of liquid water. It is also possible, though, that the rain of icy planetesimals was draw
out over hundreds of millions of years. The ages of craters on the moon, as inferred from rock
retrieved by the Apollo astronauts, indicate that the moon was being heavily bombarded by the flyi
debris of planet formation until 3.8 billion years ago. Earth, being so nearby, must have experience
the same prolonged bombardment. A lot of the bombs may have been comets. Instead of a sing
massive steam atmosphere, Earth may have had a series of thinner and more transient ones, as ea
exploding comet vapourized part of the ocean and added its own mushroom cloud of water to th
expanding pool.

Comets brought Earth some of its ocean. This is Hale-Bopp in 1997.

That does not mean, however, that the ocean we have today is pure comet water. Indeed, judgin ~~from measurements made on three comets – Halley, Hyakutake, and Hale-Bopp, the latter two~~ o which passed near Earth in 1996 and 1997 – comet H_20 is chemically distinct from seawater. contains twice as much deuterium, the heavy isotope of hydrogen. That suggests the ocean cannot b more than half comet water, which must have been diluted with “lighter” water from other source The rocks that formed the planet are one possible source, as in the Matsui-Abe scenario. Anoth possibility are carbonaceous chondrites, meteorites that are believed to hail from the outer half of th asteroid belt between Mars and Jupiter, and that are extremely wet as rocks go. Perhaps early in ou planet’s history Jupiter was firing volleys of those wet rocks at us along with the dirty snowballs.

No one knows yet. But the common thread in all this, and the great change from the view th prevailed just a few decades ago, is that the Earth received its water from large objects slamming in it at high speed – that is, from the same violent process that gave rise to the planet itself. At lea some of. those objects were comets, and that means at least some of the water molecules in our ocea are truly original: they were made before the Earth itself, even before the sun, in interstellar spac they were frozen into solid grains of ice in the cold outer reaches of the solar nebula; and finally the were brought to Earth by the strange solar-system travellers that much later, in the strange huma mind, would become symbols of such portent.

Nor is water the only relic of the mother cloud that comets brought us. The most exciting news fro Halley, Hyakutake, and Hale-Bopp was not that comets contain a lot of water, which no one doubte It was that comets also contain a great deal of organic matter – compounds of carbon and hydroge sometimes including nitrogen or oxygen as well. About a quarter of Halley’s mass was made up o organic compounds. Notable among them were formaldehyde (H_2CO) and hydrogen cyanide (HCN Both of these molecules have been seen in interstellar clouds. They also happen to be two of the mo important chemical precursors of the more complex molecules – proteins, nucleic acids such as DNA and lipids – that are the most important molecules of life.

Christopher Chyba of Stanford University has calculated that over the course of Earth histor comets have delivered an amount of organic matter to the planet that is nearly a million times i present biomass – the total mass of all living things. Comets as large as Halley still scatter organ matter on us all the time. Their long tails consist in part of microscopic dust particles that are rich organics. As Earth passes through one of those dust trails, some of the particles burn up in th atmosphere and are seen as meteor showers, but others float gently to the surface. By one rece estimate these particles supply Earth with 300 tons of organic carbon a year.

Far more organic matter, though, must have arrived during the heavy bombardment of Earth, befo 3.8 billion years ago, when the solar system was rife with comets. When large comets actual collided with Earth, their organic cargo would have been destroyed. But Chyba estimates that come that just missed Earth during that period may have delivered anywhere from one hundred thousand ten million tons a year of organic matter – streaking past the barren planet like crop-dusting aircra but scattering seed rather than poison.

The oldest fossils known on Earth are 3.5 billion years old. Found in the desert of northweste Australia by J. William Schopf of the University of California at Los Angeles, they consist o filaments of cells, a dozen or more in a chain, each no more than a few micrometres wide. Schopf h found at least 11 different types of cell, some resembling ordinary bacteria and others cyanobacteri or blue-green algae. Such diversity indicates that evolution was already well underway 3.5 billio ~~years ago, and that the origin of life lies even farther back in time. It probably does not lie too muc~~ farther back, though, because until the heavy bombardment ceased 3.8 billion years ago, the ocea surface was being boiled and sterilized again and again as each new planetesimal plunged into it. Th is one reason some researchers have given in recent years for arguing that life did not begin at th surface – in a tide pool, say, or in the "warm little pond" favoured by Charles Darwin – but at a h spring on the ocean floor.

Where and how life originated on Earth, and whether organic matter delivered by comets played a important role in that process, is still a matter of great speculation and debate. One thing is certai however: the process required water. Living organisms today are mostly water. By virtue of i electrically polarized design – positively charged hydrogen and negatively charged oxygen at opposi sides of the molecule, both ready and able to grab onto other things – water is the universal solven the stuff that brings atoms and molecules together and also tears them apart. Water carries nutrien into the living cell, and it removes wastes. All biochemical reactions, inside cells and outside, tak place in water. The chemical evolution that culminated in the first living, self-replicating organis had to take place in water as well.

In our solar system Earth is the only planet with liquid water on its surface (although one Jupiter's moons, Europa, may have an ice-covered ocean), and as far as we can tell, the only plan with life. With rock and ice flying every which way in the solar nebula, Venus, Earth, and Mars woul have had a common endowment of water. But only Earth managed to hold onto it in liquid form Why? In the case of Venus the answer is fairly simple: it is too close to the sun. Like the young Earth the young Venus may have had a thick atmosphere of carbon dioxide and water vapour, both of them effective at trapping solar heat. But the Venusian greenhouse, being less than three-quarters as fa from the sun as Earth, received nearly twice as much sunlight. So it stayed hotter. Instead o condensing into a permanent ocean, the water vapour rose into the upper atmosphere, where it w torn apart by solar radiation. The hydrogen then escaped into space, taking with it, forever, th planet's potential for water. Today the Venusian atmosphere is 96 percent carbon dioxide, and it is 9 times as thick as Earth's. The temperature on its surface averages around 850 degrees Fahrenheit.

Mars is an altogether different case. It is half as far again from the sun as Earth is, but that is sti close enough for liquid water to exist. The network of river valleys that cut through its ancie southern highlands prove that Mars did have liquid water early in its history. It may even have ha primitive life: in 1996 NASA scientists claimed to have found microscopic fossils in a meteorite th fell to Earth from Mars. That claim is controversial, but everyone agrees that now, anyway, Mars bone-dry and dead. The reason is not that Mars is too far from the sun, Pollack and his colleague James Kasting of Pennsylvania State University and Owen Toon of NASA, concluded some years ag It is that Mars is too small.

The early rains that filled the early Martian ocean, they proposed, swept carbon dioxide out of th atmosphere as well, locking it up in rock as calcium carbonate. For hundreds of millions or eve billions of years, the interior of Mars remained hot, and erupting volcanoes returned carbon dioxide the atmosphere. The greenhouse effect kept the surface warm enough for liquid water. But eventual the volcanoes were stilled. Having a diameter only half that of Earth, Mars absorbed much less he from the collisions that formed it. Having a volume less than one-sixth that of Earth, it generate proportionately less heat from the decay of radioactive elements embedded in the rock. As a resul Mars simply ran out of steam. The last carbon dioxide taken from its atmosphere never got returne The Martian atmosphere today is less than a hundredth as thick as Earth's, and the planet is froze solid. Whatever water it has retained is locked up in permafrost and in polar ice caps.

~~Earth has an ocean today because its interior is still hot. The heat drives volcanoes that~~ retu carbon dioxide to the atmosphere, thus keeping our greenhouse at a friendly temperature. All aroun the rim of the Pacific, volcanoes bubble with activity; all down the centre of the world ocean, hidd from view by miles of water, a continuous range of volcanoes erupts continually but sporadically, in syncopated firing line. The mechanism that orchestrates all this activity was scarcely dreamed of 5 years ago. Then people regarded the ocean basins as ancient features and as unchanging ones – tediou deserts, uncharted but hardly worth charting, vacant spaces disturbed only by endless rains sediment. If the ocean basins really were like that, it is now clear, we would not have oceans at al There are oceans today on Earth, and there is life today on Earth, because the ocean floor itself young and moving and constantly changing and, in that sense, alive.

CHAPTER 2

Sounding the Depths

IF ONLY there were no water! If only the ocean basins were drained, just for a month, or a week, o even a day. Then we could stand like Balboa atop a Panamanian peak, or better yet at the edge of th continental shelf, where the land really stops, and see a truly New World where the Spaniard saw onl blank Pacific. We could fly low over the route Columbus took, marvelling at all he passed over i ignorance. Retracing his route on foot, we could hike across some of Earth's flattest and mo expansive plains, up into its youngest and most rugged mountain ranges, and down into its deepe valleys. Looking down at our planet from space, we could at last see it whole.

We will never have that perspective, because we cannot see through even the clearest water fo more than a few hundred feet. Insofar as we are interested in the shape of the ocean floor, the water o the ocean – teeming as it is with life, sustaining as it does all life on land – is merely an obstacl Until this century the obstacle remained almost entirely impenetrable. If geologists have no penetrated it, and if they are now on the verge of constructing an image of the ocean floor that is f them the next best thing to a world without water, it is thanks above all to one fortunate fact: althoug water transmits light only poorly, it transmits sound exceedingly well.

Charles Bonneycastle's name does not appear in the *Dictionary of Scientific Biography*, or in th *Dictionary of American Biography*, although he was an American scientist, and a prescient one at tha Perhaps if the one experiment for which he is now remembered (and not by many) had been a succes things would have been different. In 1838 Bonneycastle, a professor at the University of Virgini became the first man to attempt to determine the depth of the open ocean by echo sounding. He w about 75 years ahead of his time.

Bonneycastle had been inspired by an experiment done a few years earlier in Lake Geneva. On clear night in November 1826, the Swiss mathematician Jean Daniel Colladon positioned an assista in a boat on one side of the lake. A 140-pound church bell hung from the boat, a few feet below th surface of the water. As the assistant struck the bell with a hammer and simultaneously lit a flar Colladon sat in a boat on the other side of the lake, eight and a half miles away. Seeing the flare, h listened for the sound of the bell with a 17-foot-long ear trumpet: a tin pipe, one end closed an submerged in the water, the other end open and conical and nestled over Colladon's ear. The sound o the bell came in clear but muted – like two knife blades banged together, Colladon said. From th delay ~~between seeing the flare and hearing the bell, Colladon calculated the speed of~~ sour underwater: it was nine-tenths of a mile per second, more than four times the speed of sound in ai But that number, although it was the purpose of the experiment, was not the only thing that impresse Colladon. “The hearing of such a dry and short tone coming from many miles away,” he wrot “leaves an impression similar to that which one gets when one sees far-off objects appear clearly f the first time through a telescope.”

Twelve years later, Bonneycastle was bobbing in the Gulf Stream, trying to see the ocean floor b means of sound. He was sitting in a boat detached from the U.S. Navy brig *Washington*, two days’ sa out of New York. He had a tin pipe similar to Colladon’s pressed to his ear, but this time the cone wa at the other end, underwater, and pointed toward the seafloor. A hundred and fifty yards away, th crew of the brig detonated a cast-iron petard at a depth of several fathoms. Bonneycastle heard th explosion – it sounded like knives struck together, he later said – and a third of a second later, h heard what might have been an echo from the bottom. A third of a second between explosion and ech translated, using Colladon’s sound speed, into a depth of about 160 fathoms, or 960 feet. But whe Bonneycastle sounded the depth with a line and lead, he found the depth was really closer to 54 fathoms.

The second sound Bonneycastle heard was probably a sort of aftershock, created by the implosio of a bubble of gas that expanded outward from the initial explosion. Why he did not hear an echo not entirely clear. Perhaps the explosion was not powerful enough, or the noise of the sea surface wa too great, or the surface area of his listening cone was too small to pick up the faint echo. A few yea later Colladon did another experiment in Lake Geneva, this time with an 1,100-pound church bel which he found he could hear from nearly 22 miles away. More interesting, a companion o Colladon’s, sitting in a boat a couple of miles from the ringing church bell, appears to have heard a echo off the lake bank behind the bell. It ought to have been possible, even in the mid-nineteen century, to have heard an echo off the ocean floor. But neither Bonneycastle nor Colladon seems t have pursued the matter. For the rest of the century, echo sounding was dead.

Sounding by the ancient method of line and sinker was very much alive, of course, and it w beginning to be pursued scientifically even as Bonneycastle was failing to start a revolution. Fro earliest times sailors had dropped lines over the side as their ship approached land, with a view towa not running aground. (The archetypal story is that of Saint Paul in the tempest, Acts 27:27–29: “. about midnight the shipmen deemed that they drew near to some country; / And sounded, and found twenty fathoms: and when they had gone a little further, they sounded again, and found it fiftee fathoms. / Then fearing lest we should have fallen on rocks, they cast four anchors out of the ster and wished for the day”) These efforts had nothing to do with science, and for obvious reasons the did not extend to the deep sea. It is said that in 1521, Ferdinand Magellan ran off 400 fathoms sounding line in the Pacific out of pure curiosity and, failing to touch bottom, concluded somewh illogically that he had found the deepest part of the ocean. But as an oceanographic milestone the sto seems to be a myth; Magellan and his starving crew were approaching one of the northeaste Tuamotu Islands at the time and apparently were just looking in vain for an anchorage. Until th nineteenth century there was no will to explore the deep-ocean floor for its own sake, and thus the was no way.

The technical obstacles were twofold. To sound the bottom, you have to know when you have foun the bottom, and in the open ocean the depths are so great that the weight of the line itself is enough keep pulling it out even after the sinker is resting in the mud. That can fool you into believing th depth is greater than it really is. The second problem also leads to overestimated depths: ships tend drift, ~~particularly if there is a strong current, and so the sounding line is never quite vertical~~. In th 1830s and 1840s, as British and American sea captains began to adopt random deep-water sounding an occasional pastime, the public was regaled with a series of reports of incredible depths in th Atlantic – of 50,000 feet of line run out, say, with no bottom found. The reports were all quite wrong.

In the nineteenth century the only way to reduce the error that resulted from current drift was to t to steer the ship into the current or to drop the sounding lead from a longboat whose oarsmen kept from drifting. And the way to know when you had hit bottom was to time intervals at which 10 fathom lengths of sounding line ran out, and to watch for a slowdown indicating that the sinker ha stopped sinking. Hanging a heavy weight from a thin line helped to make the change in spee recognizable. The prototypical sounding apparatus of the late nineteenth century was invented in 185 by the American naval midshipman John Mercer Brooke: it used thin twine as a sounding line, and i sinker was a 63-pound cannonball. The ingenious thing about it was a system of hooks and lines th released the cannonball on impact. That allowed the line to be reeled back in – otherwise it wou have snapped under the weight of the cannonball – and to bring with it a sample of the seafloor mu pressed into a depression at the end of the iron bar from which the cannonball had hung. With a bit mud in hand, you could be sure you had found bottom.

The U.S. Navy Depot of Charts and Instruments, under its director Matthew Fontaine Maury, use Brooke's sounding apparatus to complete the first organized survey of a large area of seafloor: th North Atlantic. From its ship the *Dolphin,* the depot made 200 soundings in the Atlantic between 5 degrees north and 10 degrees south. In 1854 Maury published the first chart of an entire ocean basin. showed contours at 1,000, 2,000, 3,000, and 4,000 fathoms. It showed correctly that the bottom fell o rapidly at the edge of the continental shelf and that it rose again near the centre of the ocean, to broad elevation that Maury dubbed the Dolphin Rise. "The wonders of the sea are as marvelous as th glories of the heavens," Maury concluded, "and they proclaim, in songs divine, that they too are th work of holy fingers. . . . Could the waters of the Atlantic be drawn off so as to expose to view th great sea-gash which separates continents, and extends from the Arctic to the Antarctic, it woul present a scene the most rugged, grand and imposing." Maury had a mystical bent.

As it turned out he was right about the ruggedness of the seafloor, but it was just a lucky gues Again, Maury was working with a mere 200 soundings. They were tens and even hundreds of mil apart, and each one—each depth and ounce or two of mud—had to stand for tens of thousands square miles of varied terrain. Nor were the soundings evenly spaced; a bunch were in the Caribbea another bunch along the shipping routes to Europe. With 200 data points, Maury attempted encapsulate an ocean larger by far than North America. Knowing the altitude of 200 points on Nor America, you might recognize that the Rockies are higher than the Great Plains; but you might als miss the Appalachians altogether. You certainly could not see ruggedness. You could only envision it as Maury did.

He also envisioned, on the basis of 30 of his soundings, a "Telegraphic Plateau" betwee Newfoundland and Ireland. "The bottom of the sea between the two places," Maury said, "is a platea which seems to have been placed there for the purpose of holding the wires of a submarine telegraph In 1858 the Atlantic Telegraph Company, led by an American entrepreneur named Cyrus Field, lai the first trans-oceanic cable along Maury's plateau. It failed within a month. (Field received the la successful transmission, asking him to let the U.S. government know that the cable was ready f business, at a banquet held in New York to toast his achievement.) The cause of failure was probabl the poor design of the cable, but it is also true that the Telegraphic Plateau did not exist. The fir