THE ANTHROPOCENE

THE HUMAN ERA AND HOW IT SHAPES OUR PLANET

CHRISTIAN SCHWÄGERL

Foreword by PAUL J. CRUTZEN

Translated from German by Lucy Renner Jones

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FOREWORD

This book is a striking manifestation of the power and potential in the idea of the Anthropocene. A skillful narrator with many years of journalistic experience, author Christian Schwägerl describes how a single species, our own, is irreversibly transforming the Earth's biological, geological and chemical processes, and thus affecting our very existence. Two hundred years of industrialization bear testimony to humanity's power of innovation and creativity but also prove our more perilous powers of degradation and destruction. For the first time in Earth's history, its future is being determined by both the conscious and unconscious actions of Homo sapiens. Schwägerl's book is a rallying cry for us to recognize our opportunity to build a long-lasting, viable, creative and freedom-loving human civilization. This book is like a navigation system for the new world of the Anthropocene that lies before us.

Paul J. Crutzen, PhD

Dr. Paul J. Crutzen, born 1933, is an atmospheric chemist who won the Nobel Prize for Chemistry (with Mario J. Molina and Frank Sherwood) in 1995, for his pioneering research into ozone layer depletion caused by chlorofluorocarbons (CFCs). From 1977 to 1980, Dr. Crutzen was the director of research at the National Center of Atmospheric Research (NCAR) in Boulder, Colorado and from 1980 to 2000, director of Atmospheric Chemistry at the Max Planck Institute for Chemistry in Mainz, Germany. He has undertaken research at numerous other institutions, such as the Scripps Institution of Oceanography and the Georgia Institute of Technology. Crutzen is a longstanding member of various scientific academies, including the National Academy of Sciences and the American Academy of Arts and Sciences.

PREFACE

I think I came across the word Anthropocene a few times without it making an impression. Then, one day, it really struck me. I was at a lunch with my friend Matthias Landwehr, in 2008, and he told me that this subject was something I should investigate. I agreed to do so. When I got back to my desk, I had an epiphany and my twenty-five years of reporting on environmental and science issues and forty years of love for everything natural suddenly appeared in a new light, as if I had been touched by a magician's wand.

One man, Paul J. Crutzen, had defined the relationship between humans and planet Earth, in such a powerful way, that it was hugely inspiring. Crutzen had melded humans and nature (two entities that I had previously thought of as separate, opposing forces), into a whole new science-driven idea. It described a connection that reaches back into the past and far into the future. After seeing, at first hand rainforests burning, land made toxic from mining, and species on the brink of extinction, this idea gave me hope that our ever evolving human consciousness might be about to enter a new phase.

So, this is how I came to write *Menschenzeit* (The Age of Humans), the German language precursor of what you hold in your hands. *Menschenzeit* was launched at the Berlin Museum for Natural History, in September 2010. Achim Steiner, the head of the United Nations Environment Programme, came to Berlin for the occasion and gave a wonderful speech about freedom and responsibility. The book launch also resulted in the beginning of a productive friendship with Reinhold Leinfelder, then director general of the Berlin Natural History Museum. Together, we approached the Haus der Kulturen der Welt, (House of World Cultures, abbreviated as HKW), a state-funded cultural center situated right next to the Federal Chancellery, Max Planck Research Society, and the Deutsches Museum in Munich, one of the world's leading technology museums, and proposed the idea of Anthropocene. We suggested this was a subject both institutions might want to pursue. What followed then was three years of productive collaboration and inspirational events at the HKW. "The Anthropocene Project" was funded directly by the German parliament. The first large-scale exhibition, "Welcome to the Anthropocene—The Earth in our Hands" is scheduled to be held at the Deutsches Museum, from December 2014 through January 2016.

I was able to convince Paul Crutzen to serve as an honorary patron of both projects and I'm very grateful that I have been able to discuss the Anthropocene idea with him so often in recent years.

When I was researching and writing the German edition of this book, the idea of the Anthropocene was rarely mentioned in the media. It might well have become an intellectual cul-de-sac. But, because of its inspirational quality and the efforts of many luminaries, including Jan Zalasiewicz, Reinhold Leinfelder, Andrew Revkin, Will Steffen, Libby Robins, Jürgen Renn, Klaus Töpfer, Bernd Scherer and Helmuth Trischler, the idea has now gained traction. It is now being discussed around the world as a new perspective on how humans and animals, plants and stones, the oceans and all other components of the earth interact. As an author, it is a gratifying experience to see that *Menschenzeit* really did focus attention on the Anthropocene idea.

My work on "The Anthropocene Project" and preparations for the "Welcome to the Anthropocene" exhibition have allowed me to keep thinking about the idea of a man-made geological epoch and to join in many debates, see artists working with the idea, and to meet very interesting people. This has helped me to further refine my personal perspectives on the many questions stimulated by the Anthropocene idea. The result of all this is an updated English language edition of *Menschenzeit*, published by Deborah Parrish Snyder and her wonderful team at Synergetic Press.

There are three changes in my own perspective that have occurred since the German edition was published that I would like to highlight.

Initially, I considered it strange that the Anthropocene idea was associated with geology as opposed to biology. I thought that in order for it to be meaningful, it had to have a connection with the living world. What I have come to understand is that geology offers that connection, on a grander scale. By being geological, the Anthropocene opens a doorway between supposedly dead matter and living matter. It tells us that humanity and the technosphere it has produced are now participating in the largest and most long-term of planetary cycles, with conscious thought thrown in! In the words of political scientist Jane Bennett: "If matter itself is lively, then not only is the difference between subjects and objects minimized, but the status of the shared materiality of all things is elevated." After so many decades of a consumerist materialism that "treats the planet like a zombie" (Giulio Tononi), we now have a chance to develop a "vital materialism" that honors life in all its forms, including those made of stone. Thus, the Anthropocene idea becomes the opposite of anthropocentrism. You will find far more references to this impression of the Anthropocene in the current edition than there were in the original German language one.

I also once thought that a flaw in the Anthropocene idea was that it did not immediately state what was good or what was bad. Stripped bare, it's a scientific hypothesis about the geophysical state of the planet and does not take into account ethical or moral or spiritual values nor discuss the suffering of humans or other species. Since then, I have experienced personally how contemplation of the Anthropocene idea triggers strong, ethics-driven reactions and a strong impulse of caring. Sustainability ideas come prepackaged with a set of imperatives. The Anthropocene idea works differently, but in a complementary way. It exposes us all and asks for responsibility. It invites commitment and responsible behavior instead of demanding it. There is a possibility that this idea might be abused in order to advocate human entitlement and insist upon simple techno-fixes. However, I'm confident that this line of thinking will not prevail.

Now I am speaking, even more directly, against misanthropy and "doomsday-ism." I disagree with those who say the words "good" and "Anthropocene" should probably not be used in the same sentence. Why not? Are our children and their descendants already doomed to live through millennia of ecological hardship? Even worse, are humans the problem and should they therefore vanish from the planet? No! I am the last person to downplay the severe problems created by our civilization, many of which you will read about in this book. But despising the human species and waiting for the end of the world, as we know it, is not the answer.

The Anthropocene is more than the sum of the parts of environmental havoc. It can be the arena in which humanity decides to wisely integrate into the planet's workings, enriching itself by its actions as a result. Smart cities, cultivated life-forms and landscapes with a human-induced biodiversity, are examples of how we can create a positive geological record. Human creativity, community spirit and conscious thought can lead to changes that might make our species look back at current behavior as sheer ecological barbarism. This is the journey I invite you to take with me in this book: going from today's crises to an enlightened planet with beautiful human imprints.

Christian Schwägerl, Berlin, 2014

PROLOGUE Writing in the Sky

On December 3, 1933, in Amsterdam, Anna Crutzen, a woman in her early twenties, gave birth to a son. She had moved from the Ruhr region in Germany to the capital of the Netherlands, five years earlier, to earn her living as a housekeeper. She had met Josef Crutzen, a young man from Vaals, a small Dutch town on the German border, who was working as a waiter. They fell in love, married in 1932 and soon started a family.

They named their first child Paul Jozef. Nothing at that time indicated that this young boy would literally be responsible for saving the planet from an existential threat and would introduce a groundbreaking idea that would redefine humanity's place on Earth. Paul did not enjoy a private education like Alexander von Humboldt, nor did he have a botanically minded uncle, as did Charles Darwin.

He grew up in harsh conditions. His mother, who made many sacrifices to care for the family, worked as a steward in a hospital kitchen. His father was regularly unemployed and the family was very poor. In addition, the darkest period of the twentieth century had just begun. Only months before Paul's birth, Adolf Hitler, the new German Chancellor, had seized power in neighboring Germany. In 1939, just before Paul's sixth birthday, the German dictator ordered his army to invade Poland, starting World War II. Crutzen's childhood took place in the midst of war. The boy saw German troops march into Amsterdam and commandeer his school. He lived through the *Hongerwinter* (the famine of 1944–45) in which thousands of Dutch citizens died, including some of his friends. The sight of the Allied bombers that flew from England, across the Netherlands to bomb German cities caused him much distress. His mother's family lived across the border in the Ruhr, the industrial heartland of Germany, an area laid waste by daily and nightly Allied bombing.

In spite of the wartime conditions, his parents noticed that their son had a special talent for observation and a keen thirst for knowledge. He quickly learned German, French and Flemish, and even memorized dictionaries, just for fun. One bitterly cold winter night, his parents found him sitting, shivering in his pajamas by an open window, gazing up at the sky. Upon seeing snow for the first time, he didn't feel the cold. Paul often came up with unusual observations. When he first glimpsed a half-moon, he said it was "broken," and when he saw a man swimming in an Amsterdam canal he insisted for a long time that it was a head without a body. As a teenager, he not only played football but also began reading everything he could find concerning natural science.

After the war, Paul did not want to be a burden to his parents and realized that further education in natural science was beyond his means. There was just enough money for him to attend engineering school. He learned how to build bridges across the many canals in the Netherlands. Then, at the beginning of the 1950s, a life-changing incident occurred. As a child, Paul had always longed to see mountains. Holland is not exactly famous for its high peaks so he often fantasized that the cumulus clouds at which he liked to gaze were mountains.

Now that the war was over, it was possible once again to travel. Using his modest savings, Crutzen managed to get to Switzerland. Had he reached the summit of Mount Pilatus—a well-known mountain near the city of Lucerne—either ten minutes earlier or ten minutes later, he might have continued life as a bridge-builder but, just as he reached the summit, a young woman from Finland was starting her descent. She was working as an au pair and was spending her day off learning about her host country. Terttu Soininen walked past the young Dutchman just as he was about to take a photograph of the view and the two of them started talking.

They married a few years later and moved to Sweden, to the small town of Gävle, to be nearer Terttu's family. Paul found a job as a construction engineer and began building houses instead of bridges. But his taste for knowledge, exploration and understanding had not diminished. The construction job only partly satisfied him. Thus, one day he glanced at a job ad in the newspaper: The Meteorological Institute at the University of Stockholm had an opening for a computer specialist. Admittedly, he hadn't the slightest experience in either meteorology or computer science, but something told him that he should apply.

The convoluted path leading Paul Crutzen to that café table in a provincial Swedish town, where a newspaper want ad lay before him, was to have momentous consequences—not only for himself but for all of humanity and for the course of Earth's history.[1]

Rare individuals sometimes change the course of human history on a large scale, in both positive and negative ways. We can think of examples as diverse as Alexander the Great, Jesus Christ, Julius Caesar, Christopher Columbus, and, more recently, Mikhail Gorbachev. But can ordinary human beings also alter the course of Earth's history?

Yes, they can! A few years before Paul Crutzen was born, an American mechanical engineer and chemist named Thomas Midgley had unknowingly done just that. Midgley worked for the General Motors Chemical Company and had the task of developing new coolants for use in refrigerators and recently-invented air conditioners. Refrigerators had already been through their first design cycle. For all their benefits in helping to preserve food, refrigerator coolants were also volatile, poisonous and combustible. Midgley went in search of alternatives. He and his team produced synthetic compounds that didn't occur naturally. The substances mixed together in Midgley's laboratory included carbon, hydrogen, chlorine and fluorine, which, in turn, produced new compounds. One of these substances—chlorofluorocarbon, or CFC—proved to be ideal: it was odorless, non-toxic, highly stable and perfectly suitable for refrigeration. CFCs quickly entered the market under the trade name Freon® and were successfully used all over the world.

In the economic boom of post-WWII, millions of people, especially Americans and Europeans, were suddenly able to afford cars and televi-

1. Source: extensive interview with Paul J. Crutzen, 2013 and: http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1995/crutzen-lecture.pdf.

sion sets, kitchen appliances, larger homes and long-distance travel. New supermarkets featured an abundance of foods as agriculture became more mechanized and productive. Chemical factories created new products that were designed to make life easier and more pleasant and that list included Freon. In the 1950s and 1960s, CFC use sharply increased because owning a refrigerator was now taken for granted. However, it wasn't long before discarded refrigerators dumped in landfills began leaking CFCs into the atmosphere. And because CFCs were odorless and colorless, no one noticed what was happening.

Unwittingly, Thomas Midgley's invention was causing immense damage to one of the systems most vital to protect life on Earth—a system that had taken hundreds of millions of years to evolve and that had made it possible for humanity to develop in the first place: the ozone layer. At a height of between six and thirty miles up in the Earth's atmosphere, the ozone layer intercepts most of the sun's harmful ultraviolet rays. Without the ozone layer, life on Earth, at least on land, would hardly be possible for higher diurnal life forms.

The environmental historian John McNeill later wrote that Midgley "had more impact on the atmosphere than any other single organism in Earth's history."[2] In the 1960s, no one knew about the dangers posed by chemicals mixing together, high above Earth's then three billion inhabitants. CFCs, nitrous-oxide, also known as "laughing gas," another ozone-depleting substance used in farming, and the burning of fossil fuels like coal and petroleum, were causing tremendous damage. Not even Paul Crutzen knew.

In 1958, our Dutch engineer applied for the position of computer specialist at the University of Stockholm's Meteorological Institute. He got the job because interviewers at the Institute believed that he would be a fast learner. This was the young man's entry into the world of scientific research, the career of his dreams. Not only was he a fast learner in the field of computer science, he also began to attend lectures in mathematics, statistics and meteorology. In 1963 he graduated and began a career as a scientist. Without deliberately planning it, he found himself in one of the hotspots of

2. John R. McNeill, *Something New under the Sun: An Environmental History of the Twentieth-Century World*. New York: Norton, 2001.

global environmental research. Among the young professors at Stockholm was Bert Bolin, who went on to co-found the Intergovernmental Panel on Climate Change (IPCC), which he then chaired, from 1988 to 1997.[3]

Crutzen picked an area of research that was relatively new: the chemical processes that take place in Earth's upper atmosphere. At first, he didn't realize how significant the gaps in then-current knowledge would prove to be. He was interested in the natural processes and how the protective layer of ozone in the atmosphere, constantly renews itself.

Then, his impact on Earth's future really began: he was one of the very first scientists to ask whether there are chemical processes that harm the ozone layer. Until then, this idea had seemed quite improbable. "The general feeling at the time was that 'nature is so big and mankind so small,'" says Crutzen today, in retrospect. "Nobody had thought that man-made substances could have a huge effect on stratospheric ozone."[4] Crutzen's initial research into how nitrous oxide, naturally released by soils, might damage the ozone layer, led him to a quite different discovery—that human activity was a threat to the ozone layer.[5]

Ever-increasing quantities of CFC molecules released into the atmosphere from landfills were not the only threat to the ozone layer. At around the same time, aviation engineers were developing large, high-tech nitrous oxide turbines. The United States, France, Great Britain and the Soviet Union had plans to build fleets of Supersonic Transport Aircraft (SSTs) to make it possible for civilians and the military to travel at supersonic speeds. Together with the American chemist Harold Johnston, Crutzen recognized the harm caused by nitrous oxide being released into the stratosphere so he used cool scientific logic to counter the dream that humans should be able to travel like gods to anywhere on Earth in a few hours. At the beginning of the 1970s he did some meticulous calculations to show that the additional nitrous oxide that would be emitted into the atmosphere from a fleet of 500 high-flying SSTs could cause "serious

3. I interviewed Bert Bolin in this function during the UN Climate Change Conference (COP1): Christian Schwägerl, "Umweltexperte: Kosten leider kein Thema in Berlin", *Süddeutsche Zeitung*, April 7, 1995.

4. From an extensive interview with Paul Crutzen in summer 2013.

5. Described in: Paul J. Crutzen, "Estimates of Possible Variations in Total Ozone Due to Natural Causes and Human Activities", *Ambio*, vol. 3, no. 6 (1974): 201–210.

decreases in the total atmospheric ozone layer and changes in the vertical distributions of ozone, at least in certain regions."[6]

The work of Paul Crutzen and his colleagues sent a new message to the world: humanity had become so powerful and dominant through science, technology and modern lifestyles that we could harm Earth's protective ozone layer.

Inspired by these warnings, other scientists began to look for additional chemicals that might be changing the ozone layer. Mario Molina and Sherwood Rowland made a discovery in 1974: they established that CFCs are particularly effective in destroying ozone molecules. When Crutzen heard about this groundbreaking work, he immediately contributed his research and calculations showing that the hypotheses of his American colleagues were correct and that in the foreseeable future, forty percent of the world's ozone layer might be depleted if the use of CFCs went unchecked. The consequences would be devastating; incidents of skin cancer and genetic mutation would multiply and some regions of the Earth might well become unfit for human life.

There were many objections to the researchers' theories, especially from the chemical industry that feared for its profits from the sale of CFCs and artificial fertilizers. The "hole" in the ozone layer could be a natural occurrence, critics argued. The harmfulness of CFCs was not proven. It would cause enormous damage to the economy to ban them, since there were no alternatives.

But in the mid-1980s, polar researchers led by Joe Farman returned from Antarctica with data showing that above a continent not populated by humans, the ozone layer was shrinking, especially during the southern hemisphere's spring and that hazardous ultraviolet rays were reaching the Earth's surface without hindrance. In 1985 Farman and his team published their results,[7] revealing why the thinning of the ozone layer was over Antarctica, of all places, and not over industrial areas: CFCs adhere particularly well to ice crystals.

6. Paul J. Crutzen, "My life with O_3, NO_x, and other YZO_xs". Stockholm: Almqvist & Wiksell International, 1995. See also: http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1995/crutzen-lecture.pdf.

7. Joe Farman et al: "Large losses of total ozone layer in Antarctica reveal seasonal ClO_x/NO_x interaction", *Nature*, vol. 315.

The Antarctic explorers' findings shocked public opinion even more than Rachel Carson's *Silent Spring*. Before this, millions of people had associated their refrigerators and freezers with the idea of cold beer and instant pizzas as well as other convenience foods. They sprayed underarm deodorant in the mornings to smell nice at work in the office where, on hot days, they were grateful for air conditioning. Now, all of a sudden, these symbols of modern prosperity were seen in a completely different light. What had been thoughtlessly emptied into the atmosphere was suddenly coming back to haunt, in the form of a "hole" in the ozone layer. The individual actions of millions were a major hazard that threatened human life on Earth, and risked damaging the conditions needed for any terrestrial life.

No matter how aggressively the chemical industry opposed demands made by environmentalists and scientists like Crutzen, Molina and Rowland to ban CFCs, the case was won in 1987. The United Nations drew up the Montreal Protocol, the single most effective international environmental treaty to date, which called for a gradual phase-out of harmful CFCs, used primarily as coolants. In 1997, the Kyoto Protocol was ratified, which aimed to drastically cut carbon dioxide emissions and nitrous oxide (N_2O) emissions.

Since then, a slow but constant regeneration of the ozone layer over Antarctica has taken place. In 2012 and 2013, scientists at NASA and the Alfred Wegener Institute in Germany reported that the Antarctic ozone "hole" had become noticeably smaller, for the first time.[8] There is now a chance that the Antarctic ozone "hole" will disappear by 2050––so long as climate change and the extreme durability of CFC molecules do not thwart this.[9]

Currently, researchers are optimistic that the ozone layer is regenerating globally and will be permanently restored. What would have happened if Paul Crutzen had not survived the "hunger winter" in Amsterdam and no one had undertaken research like his?

8. See: http://www.nasa.gov/content/goddard/antarctic-ozone-hole-slightly-smaller-than-average-this-year/.

9. If increasing amounts of carbon dioxide in the lower atmosphere prevent the sun's rays from reaching Earth's surface, it will become colder where the ozone layer is. Such an effect led to the first formation of a large ozone hole over the North Pole in 2011, to the surprise of explorers. See: Gloria L. Manney et al., "Unprecedented Arctic ozone loss in 2011", *Nature*, vol. 478, (2011): 469–475.

What if he and his colleagues had not had the academic freedom and sufficient funding to explore the chemistry of the ozone layer without any specific aim?

What if Thomas Midgley had put much more aggressive and faster-acting bromine instead of fluorine into refrigerators and aerosol sprays, right from the beginning, well before reliable instruments for measuring the chemistry of the atmosphere existed?

What if explorers like Farman hadn't spent long nights and bitterly cold days in the Antarctic to make measurements that, at the time, did not interest anyone?

Questions like these concern Paul Crutzen, who says that he has often asked himself since then: "What other surprises may await us?"

The repair of the ozone layer in the twentieth century was dependent on many coincidences. Models show that the ozone layer could have completely disappeared by 2050 had CFC emissions persisted. When Crutzen received the Nobel Prize for Chemistry in 1995, together with Molina and Rowland—or perhaps we should say the "Nobel Prize for Salvaging the Ozone Layer"—he conveyed how utterly humiliating it would have been for humanity to have destroyed the atmospheric layer that protects life on Earth, by the expedience of using aerosol sprays and refrigerators, unaware of the damage being caused. "I can only conclude that mankind has been extremely lucky."

So, in the twentieth century, individuals were indeed making human history but also global history. On the one hand there was Thomas Midgley, the inventor of a substance that was endangering the hundred-million-year-old life-protecting atmospheric layer, and on the other, there were Crutzen, Johnston, Molina, Roland and others who, having recognized what was happening, demanded action. Events high up in the sky, were being determined not just by the interaction of molecules, temperature and pressure, but also by the work of chemists synthesizing new substances, and by the scientists who were investigating the effects of these substances. Human work manifest in the form of notes, index cards, laboratory diaries and scientific papers led the way to a new global reality.

For the first time in Earth's history, the results of human activity could be read, as if written high up in the sky.

Paul Crutzen was possessed by his discoveries about the ozone layer.

So, back at his desk at the Max Planck Institute, he set about making a list of the ways in which humans were transforming the planet. His list was long—and it grew longer. The more aware Crutzen became of everything that humanity was doing to the Earth, the more a new idea began to form in his mind. He realized that the prevailing view that mankind is miniscule whereas nature is limitless, and that humans only scratch the surface of Earth's processes, is fundamentally wrong. In his Nobel Prize acceptance speech, he said: "The experiences of the early 1970s had made it utterly clear to me that human activities had grown so much that they could compete and interfere with natural processes."

This far-reaching notion grew in Crutzen's scientific mind until it burst onto the scene in early 2000. In February of that year our then sixty-seven-year-old scientist went to Cuernavaca, Mexico, to take part in an International Geosphere-Biosphere (IGBP) conference, a forum for Earth system research, hosted by the United Nations. The debate revolved around human impacts on the environment and, time and again, the term for the geological epoch in which we live came up: the Holocene. The Holocene is said to have started 11,700 years ago, as the last Ice Age came to an end. Crutzen remembers the moment thus: "The chairman mentioned the Holocene again and again as our current geological epoch. After hearing that term many times, I lost my temper, interrupted the speaker and remarked that we are no longer in the Holocene. I said that we were already in the Anthropocene. My remark had a major impact on the audience. First there was silence, then people started to discuss this."

The Australian climate researcher Will Steffen describes the scene like this: "Scientists from IGBP's paleo-environment project were reporting on their latest research, often referring to the Holocene, the most recent geological epoch of Earth history, to set the context for their work. Paul, a Vice-Chair of IGBP, was becoming visibly agitated at this usage, and after the term Holocene was mentioned again, he interrupted them. "Stop using the word Holocene. We're not in the Holocene any more. We're in the . . . the . . . the . . . (searching for the right word) . . . the Anthropocene![10]

10. Quoted from a commentary by Will Steffen on Paul J. Crutzen and Eugene F. Stoermer, "The 'Anthropocene' (2000)," in Libby Robin, Sverker Sörlin and Paul Warde (eds.): *The Future of Nature*, (2013): Yale University Press as well as personal communication with Will Steffen.

The word landed among the experts like a time-bomb. *Anthropos*: the Greek word for "humans," *cene*: from *kainos*, the Greek word for "new," *Anthropocene*: the new epoch of humans.

In the coffee break after the session, this new word was virtually the only topic of conversation. Crutzen had just redefined the context in which humanity exists on Earth. With it, he had portrayed everything humans do to and with Earth, normally measured in days, years and centuries, in a whole new way. Crutzen suggested a geological scale, of thousands and even millions of years. He had asserted that human activity has affected the Earth, on a geological scale.

The scientists in that conference room in Mexico were profoundly shaken because the Nobel Prize Laureate for Chemistry—one of the most often cited natural scientists in the world—was not only describing the *past* with this new term (something to which geologists are accustomed) but he was also redefining and connecting to the future of a world that is only just emerging: a new Earth sculpted by humans.

From the perspective of the Anthropocene, the ozone layer story will be just one of a hundred or a thousand ways in which humans are fundamentally altering this planet, 4.6 billion years after its formation. Until Crutzen's statement in Mexico, we had seen all this mainly from a narrowly short-term human perspective, and for the most part, we were unconscious of the consequences our actions had for the globe.

ONE Welcome to the Club of Revolutionaries

Whether you take a walk in the hills around your town or along the coast or by a river, you will encounter the results of geological forces that have been at work for millions of years. Magma that once was deep inside the earth has formed rocks and moved tectonic plates. Water has shaped shorelines and carved out deep valleys. Wind erosion has flattened mountains and created massive deposits of soil and sand.

The exact spot on the earth's surface that now lies beneath the city of Berlin, the German capital, where I live, was once near the earth's southern pole some 500 million years ago. Tectonic forces moved it north over that immense period of time.[11] Only tens of thousands of years ago, the area was covered with huge glaciers; the weight and the power of their melting water created today's landscape. Without much effort, one can also observe more recent changes due to geophysical forces. I only have to walk 500 yards from home to reach Heidelberger Platz, from where a wide boulevard runs toward the stores and cafés in the center of West Berlin. The difference in slope between one end of the street and the other is so slight that, in this otherwise flat city, most cyclists and motorists barely notice it. But there is a big story behind this slight slope. It was once the bank of a gigantic river that flowed here at the end of the last Ice Age, 12,500 years ago. This *Urstrom* (glacial river) was filled with icy water several hundred

11. Documentation for Berlin's geographical spot having traveled from the South polar region to its current location may be found in several sources: Stampfli, Gérard M., Jürgen F. von Raumer & Gilles D. Borel, "Paleozoic evolution of pre-Variscan terranes: From Gondwana to the Variscan collision," *Geological Society of America Special Paper* 364, 2002 and in Cocks, L.R.M. and T.H. Torsvik, "European geography in a global context from the Vendian to the end of the Palaeozoic," Geological Society, London, Special publications, 2006.

meters high, to the north of what is now Berlin, before the great thaws set in and the glaciers gradually melted away.

When I cycle down this slope, I hear cars thundering past. I try to imagine the thundering mass of water that used to rush past, which formed the landscape of sand and stone on which the city of Berlin arose in the thirteenth century. The opposite bank of this primeval river is almost six miles away in Prenzlauer Berg, one of Berlin's hip new districts. The river must have been gigantic and would make today's River Spree, which runs through the political and cultural center of Berlin, near the Brandenburg Gate, seem like a mere creek.

When you contemplate Earth's history—not just by rattling off things you learned at school but by touching stones or letting sand run through your hands or swimming in a river—even a brief encounter can turn into a fantastic adventure. For me, the excitement is even greater when I become aware of the workings of earlier life forms. Many inland hills found on continents are in fact the remains of ancient coral reefs. Many mountain ranges far from the sea are composed of the calcareous skeletons of earlier marine organisms. Thick deposits of coal and oil, which have provided the fuel for industrial prosperity, are the residues of earlier life forms. Here in Berlin, there is a lot of bog and marshland. When you go hiking where fauna and flora are scant, you sometimes feel as if you are in a Zen garden where lots of decaying moss is underfoot; if it were left undisturbed, these mosses would eventually form coal. In bogs like these you can witness geology at work. You can see how the stones here and the earth's crust are connected to life itself.

Earth's surface, as we know it today, has been transformed by a select group of organisms which I refer to as "The Club of Revolutionaries." These are the life forms that did not die out unceremoniously after a mere couple of million years. These are the species that did not just surrender their molecules to the great recycling process called evolution, to be absorbed by other life forms.

The Club of Revolutionaries is comprised of species that have caused lasting change and have created new structures, just as fire, water and wind have done. We still encounter them, eons after their biological demise, in the form of bizarre limestone sculptures, or as pitch-black coal seams, deep below the ocean.

The oldest—and from our point of view, most essential "revolutionary" is the one that has made possible today's earth, with all its trees and flowering plants, birds and mammals. This revolutionary is a tiny microorganism that has evolved over three billion years. It used to be called blue-green algae but this label was discarded once scientists realized they weren't dealing with algae at all but rather with bacteria. Since then, such life forms have been referred to as cyanobacteria. They paved the way for life to use the sun's energy and to spread from sea to land across the whole surface of the planet.

Before cyanobacteria entered the scene, a young earth, amassed from matter orbiting the sun, had already been through some dramatic changes. It had been hit by another celestial body, a space traveler roughly the size of Mars.[12] *Theia*, as it's now called, created such impact that the moon was ejected from the earth's mass. As a result, the planet's axis of rotation became tilted, leading to tides and seasons. The fiery interior of the earth still holds the heat from that impact—so, in a sense, we don't live on one planet, but actually two. After earth's and Theia's matter had merged, a core formed, composed mostly of iron, and a new magnetic field developed, shielding the planet's surface from harmful radiation from space. Next, a primordial atmosphere began to coalesce, consisting of toxic gases that would certainly be fatal to contemporary organisms. And then, approximately 3.7 to 4 billion years ago, a second "Big Bang" occurred, this one biological. Simple molecules morphed into cells that could replicate themselves. The earth now began to sustain life. In continuous cycles of mutation and replication, adaptation and extinction, these first life forms, now known as archaebacteria, evolved. But they were soon to be confronted with an early resource crisis. The chemical energy they needed for survival became increasingly scarce in their primeval world.

It was then that cyanobacteria entered the scene. Their altered metabolism proved to be superior in one essential respect: whereas archaebacteria were dependent on the earth's chemical energy, cyanobacteria were

12. Alex Halliday, "The Origin of the Moon," *Science*, vol. 338, no. 6110 (2012): 1040–1041; Matija Cuk and Sarah Stewart, "Making the Moon from a Fast-Spinning Earth: A Giant Impact Followed by Resonant Despinning," *Science,* vol. 338, no. 6110 (2012): 1047–1052.

able to tap into the sun's constant flow of energy. They developed molecular networks and metabolic pathways—the ability to convert energy from light and heat to enable small cell photosynthesis. Thus life's first resource crisis was solved to its advantage, yet if viewed from archaebacteria's perspective, it also created the first environmental disaster. Photosynthesis generated large quantities of oxygen. This element had already been present in the earth's atmosphere in its poisonous molecular form, O_2, but only in limited quantity as a trace element.

Now, cyanobacteria were pumping large amounts of O_2 into the atmosphere. Over the course of millions of years, the concentration of this gas grew, with far-reaching consequences. For archaebacteria, oxygen was poisonous, so they retreated to very remote locations, like deep-sea vents. Cyanobacteria, on the other hand, fared so well in this new oxygenated world that they multiplied, eventually spreading across the oceans and coastal regions, to form extensive mats and vast nodular colonies.

Thus, cyanobacteria became founders of "The Club of Revolutionaries," They released so much oxygen into the atmosphere that around 2.6 billion years ago, dissolved iron in the seas began to oxidize and settle to the bottom. Vast deposits of iron ore were formed, used today in the construction of buildings, complex machines and electronic equipment.

Once the oceans were saturated with oxygen, surplus gas escaped into the atmosphere, and the next revolution began. High up in the sky, ultraviolet radiation transformed some of this copious O_2 into O_3. (O_2, which contains two atoms of oxygen, is much more stable than O_3, with its three oxygen atoms.) This transformation created the ozone layer, which has intercepted the most aggressive radiations from the sun. (That is, until a life form called Thomas Midgley began tinkering with artificial chemical compounds). It was only due to this protective layer around the "sea of air"—as Alexander von Humboldt called the atmosphere—that new, more complex life forms could evolve. Approximately 420 million years ago life, in the form of plants, amphibians, reptiles and mammals, spread over the land.

Cyanobacteria not only provided these more complex life forms with the oxygen necessary to digest food effectively, they also passed on the molecular technology to produce it. According to a widely supported hypothesis, all multicellular plants came into existence by absorbing cyanobacteria and using them as interior "solar panels" to generate photosynthesis.[13] Cyanobacteria thus became a component of each of the quarter million plant species known today, from cacti and dandelions to Sequoia trees. They have even stored a ration of their own genetic material. For these partners, it was a win-win situation. Cyanobacteria's distant descendants are found everywhere plants grow, making the forest green. In addition, free-roaming cyanobacteria are still around. Two thousand contemporary species have been recorded to date. In the 1980s, American marine biologists Sallie W. Chisholm and Robert J. Olson, along with other collaborators, discovered a life form that had been previously overlooked. The organism was tiny but once it was detected, further research revealed that the cyanobacteria *Prochlorococcus marinus* was one of the most common organisms on earth and was probably one of the most widely spread types of picoplankton in the world.[14]

Most people today are unaware of cyanobacteria except in unpleasant circumstances. If they are present in large quantities, due to fertilizer run-off and warm weather, they can produce substances that irritate human skin. But in places like Australia, cyanobacteria can also be admired: For millions of years, they have formed large colonies where their excretions produce stone-like structures, called stromatolites.

No matter where you are and what you do, when you breathe to stay alive or enjoy time outside, when you eat vegetables or buy something made of iron or steel, you are inextricably linked to these revolutionaries.

This extraordinary feat surely merits having a memorial erected in every modern city, in honor of the founders of the Club of Revolutionaries: "To the creators of the oxygen atmosphere, our planet's protective shield, the plant world and iron deposits: In gratitude, humanity."

So far, that hasn't happened. But in the step-by-step process of science, humanity is at least starting to discover how deeply connected we are, not only to our primate ancestors but also to a whole set of life forms that

13. See seminal article of Lynn Sagan, "On the origin of mitoting cells," J*ournal of Theoretical Biology*, vol.14 no.3, March 1967.

14. Sallie W. Chisholm et al., "A novel free-living prochlorophyte abundant in the oceanic euphotic zone", *Nature*, 1988, vol. 334 (1988): 340–343 and F. Partensky *et al.* "*Prochlorococcus*, a marine photosynthetic prokaryote of global significance", *Microbiology and Molecular Biology Reviews* vol. 63 (1999): 106–27.

have made and continue to make earth livable. By doing research, humans have learned how bacteria, plants and animals have sustained life on earth and they have even begun doing experiments that attempt to recreate the conditions by which earth has stayed habitable.

One of the first to do this kind of research was Joseph Priestley, a British chemist, theologian, philosopher and physicist. In 1772, he founded the discipline of earth modeling. Today, earth modelers have the advantage of gleaning reams of data from satellites and supercomputers. Priestley, who was interested in oxygen and who is regarded as one of its discoverers, worked with simpler technology. He trapped mice under a bell jar and watched what happened. After disposing of the inevitably dead animals several times, he was surprised when he observed that mice survived if he included a green, living plant, thus creating a tiny, enclosed ecosystem.

Priestly wrote the first ever description of photosynthesis, describing how animals and plants interact, in his inimitable prose: "These proofs of a partial restoration of air by plants in a state of vegetation, though in a confined and unnatural situation, cannot but render it highly probable, that the injury which is continually done to the atmosphere by the respiration of such a number of animals, and the putrefaction of such masses by both vegetable and animal matter, is, in part at least, repaired by the vegetable creation."[15]

With his bell jar, Priestley inspired a whole new research discipline: ecology, and later biospherics, the study of artificial, enclosed ecosystems. In 1875, Austrian geologist Eduard Suess created the term "biosphere" to describe the space used by living organisms. A few decades later, the Russian geologist Vladimir Vernadsky expanded this concept when he realized that the biosphere is not only inhabited by living organisms but has also been shaped by them. Vernadsky demonstrated how humans are existentially a part of the biosphere.

When both the USA and the USSR were in a race to reach the moon and conquer the vastness of space, Russian scientist Yevgeny Shepelev confined himself in the smallest possible artificial ecosystem, assigning himself the role of Joseph Priestley's mice.

15. Joseph Priestley, "Observations on different Kinds of Air," Philosophical Transactions of the Royal Society, 62, (1772): 147–264, quoted from Malcolm Dick (ed.), *Joseph Priestley and Birmingham*, Brewin Books (2005).

In 1962, he climbed into a small, airtight metal container at the Institute of Biomedical Problems in Moscow. When he sealed the door behind him, he was not alone: he shared the cramped space with forty-five liters of green algae, of the genus *Chlorella*. His plan was for the algae to supply him with the oxygen he needed to survive. This forty-two-year-old Russian was the first person to make himself completely dependent on a bucket of plants.[16]

Shepelev grew up with eight siblings in impoverished circumstances. He discovered his love of science very early in life and managed to be accepted into the scientific youth club at the Moscow Zoological Gardens. He then studied medicine and devoted himself to a broader subject: how life could survive in outer space. He wanted his containers to show that cities of the future could be built and maintained, on other planets. Thus, the Soviet Union would colonize outer space before the capitalist West.

Shepelev's first experiment lasted a mere twenty-four hours. When a colleague opened the door of the container, he complained of being hit by a rotting smell. Its occupant was dazed and confused, his thought processes befuddled by his own exhaled gases. Yet, Shepelev had actually managed to live off the oxygen produced by his algae.[17]

In the Siberian city of Krasnoyarsk, other scientists were undertaking similar, strictly confidential research. In 1972 three scientists managed to survive for half a year in Bios-3, an artificial ecosystem, without external supplies of water and oxygen. By the end of the 1980s, Russian scientists succeeded in producing three quarters of the food they needed, in "closed" systems. Since a diet consisting entirely of algae made them feel bad tempered, they started growing cucumbers, tomatoes, potatoes, peas and other container plants, and even created a new type of soil that was dubbed "soil-similar substrate."

In time, the Russians became more daring. When the political climate in the Soviet Union began to change in the mid-1980s, they even started doing tests to measure environmental problems that, by definition, did not exist in

16. The biographical details were obtained from the Institute from Biomedical Problems in Moscow in a personal communication, April 2010.

17. Personal communication with Prof. A.G. Degermendzhi, Director of the Institute of Biophysics and Prof. A.A Tikhomirov, Director of the International Closed Ecosystems Center in Krasnoyarsk, April 2010.

a "socialist" society, even though everyday Soviet life was full of them. The scientists pumped pollutants into containers to investigate the effects. "The ability to buffer these kinds of substances and transform them is limited," stated a terse summary in one report. What was meant by this was clear: ecosystems can handle stress for a long time but under continual stress they will eventually collapse.[18]

While the Russian experiments were being carried out in secrecy, a group of scientists and idealists in the USA, meanwhile, were working on a significantly more complicated artificial ecosystem. In 1991, with great fanfare, Biosphere 2 was inaugurated by John P. Allen, a maverick with a background in mining and metallurgy, who had a strong personal vision that Biosphere 1, planet Earth, was in big trouble. Allen once held the rights to a coal seam worth a fortune, but according to him, the expected course of his life completely changed after a transformative experience with the psychotropic plant peyote which made directly aware of the biosphere.[19] Consequently, in the late 1980s, he formed an unlikely alliance between ecologically-minded friends and associates, American scientists and the Texan venture capitalist Edward Bass, in order to build the largest self-contained ecosystem in the world.

Between 1991 and 1994, two groups of "biospherians" lived in an enormous, sealed glass, cathedral-like structure, in the Arizona desert, which had taken four years to build. The first crew of eight spent two years inside, Biosphere 2 was a manifestation of research, environmental education and media hype. Like Yevgeny Shepelev, both John Allen and Edward Bass were interested in future settlements in space. Biosphere 2 may have looked like a study of how humans can live in an artificial environment but it turned out to be the complete opposite.[20]

The Biosphere 2 project generated a great deal of interest worldwide. For an admission fee, visitors were even allowed into Biosphere 2, itself. The grandiose white structure housed a man-made rain forest, an ocean,

18. Frank B. Salisbury et al., "Bios-3: Siberian Experiments in Bioregenerative Life Support," *BioScience*, vol. 47 (1997): 575–585.

19. John Allen has written an autobiography: John Allen, *Me and the Biospheres*, Synergetic Press, Santa Fe, NM, 2009.

20. John Allen et al., "The Legacy of Biosphere 2 for the study of Biospherics and closed ecological system," *Advances in Space Research*, vol. 31, no. 7 (2003):1629–1639.

a coral reef, a mangrove swamp, a desert and a savannah, all in miniature forms. Two and a half thousand square meters of agricultural land were set aside to produce food for the biospherians and a diverse selection of animals, ranging from bees for pollination to pygmy goats, were also included.

The first crew of eight biospherians moved into the enormous complex in 1991. Their aim was to live in the synthetic ecosystem for at least two years or for as long as possible, researching and observing how conditions for life changed over time. Serious problems arose, early on. The concentration of oxygen in the air dropped continuously during the first year and a half, from nearly 21 percent atmosphere, as in Biosphere 1, to 14.5 percent, similar to mountain air at four thousand meters above sea level. It took a while to ascertain the cause: Bacteria in the virgin soil, was consuming oxygen in the air while at the same time chemically active concrete walls were absorbing oxygen and producing calcium carbonate. Fatigue set in among the biospherians, so measured amounts of liquid oxygen were pumped in. The food supply was erratic, too. Pollinating insects died off while ants and cockroaches thrived. The harvest produced a smaller yield than expected, partly because of two consecutive years of the El Niño weather phenomenon, so reserve food stocks had to be used. The first mission ended after the prescribed two years setting world records (by far) for duration in enclosed human life support experiments. A second crew entered Biosphere 2 in March 1994 but the mission was terminated prematurely as a result of disputes between Allen and his design/management team, with his partner, Ed Bass and his team. After the partnership dissolved, the goals of the project shifted away from human enclosure experiments.[21]

While many in the media suggested it was a failure, Biosphere 2 had made an incredible contribution, not least with the many research and scientific papers it has produced and indeed is still producing.[22] It is because of the difficulties the project encountered that it became even more significant.

21. Personal communication with John Allen.

22. Most of the key published papers available at www.globalecotechnics.com. Elsevier special edition: *Biosphere 2 Research Past and Present*, eds.. B.D.V. Marino, H.T. Odum, Ecological Engineering Special Issue, Vol. 13, Nos. 1-4, Elsevier Science, 1999.

Each problem with living in an artificial ecosystem symbolizes the present situation of humanity. The scores of deriders who made fun of the bionauts in Russia and the biospherians in the Arizona desert must have forgotten how much harm people in the real world cause to the ozone layer, or to precious animal species that could become extinct before our very eyes. People forget what causes a shortage of food supplies for nearly a billion people or how we risk making the earth's climate very uncomfortable for ourselves.

The Russian and American projects yielded an essential insight: the earth is constantly providing us with a multitude of services and processes that have evolved over the course of hundreds of millions of years, thanks to the work of early earth "revolutionaries." If you want to re-create these services in the form of huge artificial ecosystems that can sustain hundreds of millions of people, the costs will clearly rocket into infinity. Even 150 million dollars was not sufficient for the Arizona experiment to sustain eight people in a 1.2–hectare artificial ecosystem. These biospheric projects therefore showed that nature sustains human civilization and the world economy.

Today, the University of Arizona owns and directs research at the Biosphere 2 facility. It would be good if there or elsewhere, bionauts or biospherians would again move inside enclosed systems to determine if humans can survive in strictly confined spaces.

It is telling how much people appreciate the oxygen created by cyanobacteria or simple plants or fruits when they are cut off from nature. In November 2013, Japanese astronaut Koichi Wakata tweeted an image from the International Space Station. It showed a tomato in a state of weightlessness, while the earth could be seen in the background. "One fresh tomato for dinner makes us happy in space. It came up with us on Soyuz TMA-11M, two weeks ago," read his text about the red marvel, seemingly appearing in front of the Blue Marble.[23]

In the Anthropocene, the earth itself becomes one giant biospheric experiment, but without any emergency exits or windows to let in additional fresh air. So, when you take your next walk outside, look closely, not only at the results at what wind, fire and water have carved out and

23. http://wordlesstech.com/2013/11/26/tomato-space/

what other organisms have left behind, but also examine the results of thousands of years of human activity. These cumulative actions stack up to look like a new geological epoch that puts us on a par with the cyanobacteria and other earth-transforming species: Welcome to "The Club of Revolutionaries."