What the Earth Knows

Understanding the concept of geologic time and some basic science can give a new perspective on climate change and the energy future

By Robert B. Laughlin

Any serious conversation about the planet's climate and our energy future must begin, paradoxically, with a backward look at geologic time. The reason for this is that the way forward is fogged by misunderstandings about the earth. Experts are little help in the constant struggle in this conversation to separate myth from reality, because they have the same difficulty, and routinely demonstrate it by talking past each other. Respected scientists warn of imminent energy shortages as geologic fuel supplies run out. Wall Street executives dismiss their predictions as myths and call for more drilling. Environmentalists describe the destruction to the earth from burning coal, oil, and natural gas. Economists ignore them and describe the danger to the earth of failing to burn coal, oil, and natural gas. Geology researchers report fresh findings about what the earth was like millions of years ago. Creationist researchers report fresh findings that the earth didn't exist millions of years ago. The only way not to get lost in this awful swamp is to review the basics and decide for yourself what you believe and what you don't.

Geologic time is such a vast concept that it's helpful to convert it to something more pedestrian just to get oriented. I like rainfall.

- The total precipitation that falls on the world in one year is about one meter of rain, the height of a golden retriever.
- The total amount of rain that has fallen on the world since the industrial revolution began is about 200 meters, the height of Hoover Dam.
- The amount of rain that has fallen on the world since the time of Moses is enough to fill up all the oceans.
- The amount of rain that has fallen on the world since the Ice Age ended is enough to fill up all the oceans four times.
- The amount of rain that has fallen on the world since the dinosaurs died is enough to fill up all the oceans 20,000 times—or the entire volume of the earth three times.
- The amount of rain that has fallen on the world since coal formed is enough to fill up the earth 15 times.
- The amount of rain that has fallen on the world since oxygen formed is enough to fill the earth 100 times.

Common sense tells us that damaging a thing this old is somewhat easier to imagine than it is to accomplish—like invading Russia. The earth has suffered mass volcanic explosions, floods, meteor impacts, mountain formation, and all manner of other abuses greater than anything people could inflict, and it's still here. It's a survivor. We don't know exactly how the earth recovered from these devastations, because the rocks don't say very much about that, but we do know that it did recover—the proof of it being that we are here.

Nonetheless, damaging the earth is precisely what's concerning a lot of responsible people at the moment. Carbon dioxide from the human burning of fossil fuel is building up in the atmosphere at a frightening pace, enough to double the present concentration in a century. This buildup has the potential to raise average temperatures on the earth several degrees centigrade, enough to modify the weather and accelerate melting of the polar ice sheets. Governments around the world have become so alarmed at this prospect that they've taken significant, although ineffective, steps to slow the warming. These actions include legislating carbon caps, funding carbon sequestration research, subsidizing alternate energy technologies, and initiating at least one serious international treaty process to balance the necessary economic sacrifices across borders.

Unfortunately, this concern isn't reciprocated. On the scales of time relevant to itself, the earth doesn't care about any of these governments or their legislation. It doesn't care whether you turn off your air conditioner, refrigerator, and television set. It doesn't notice when you turn down your thermostat and drive a hybrid car. These actions simply spread the pain over a few centuries, the bat of an eyelash as far as the earth is concerned, and leave the end result exactly the same: all the fossil fuel that used to be in the ground is now in the air, and none is left to burn. The earth plans to dissolve the bulk of this carbon dioxide into its oceans in about a millennium, leaving the concentration in the atmosphere slightly higher than today's. Over tens of millennia after that, or perhaps hundreds, it will then slowly transfer the excess carbon dioxide into its rocks, eventually returning levels in the sea and air to what they were before humans arrived on the scene. The process will take an eternity from the human perspective, but it will be only a brief instant of geologic time.

Some details of this particular carbon dioxide scenario are controversial, of course, since all forecasts are partly subjective, including those made by computer. You have to extrapolate from present-day facts and principles, and there are varying opinions about these. The time scale for man-made carbon dioxide to be absorbed by the ocean is set by the mixing rate of surface water with deep water in the sea, which is known only indirectly and might conceivably change during the thousand-year hot spell. The amount of carbon dioxide left in the atmosphere after equilibration varies from tolerable to alarming depending on how much industrial burning the model assumes. No one knows for sure how long it will take the excess carbon dioxide to turn into limestone and disappear into the rocks, or even the specific chemistry involved. The main reason for thinking it will disappear is that something, presumably a geologic regulatory process, fixed the world's carbon dioxide levels before humans arrived on the scene. Some people argue that carbon dioxide has been locked to these values for millions of years, the grounds of the argument being that the photosynthetic machinery of plants seems optimized to them. But the overall picture of a thousand-year carbon dioxide pulse followed by glacially slow decay back to the precivilization situation is common to most models, even very pessimistic ones.

Global warming forecasts have the further difficulty that you can't find much actual global warming in present-day weather observations. In principle, changes in climate should show up in rainfall statistics, hurricane frequency, temperature records, and so forth. As a practical matter they don't, because weather patterns are dominated by large multi-year events in the oceans, such as the El Niño Southern Oscillation and the North Pacific Gyre Oscillation, which have nothing to do with climate change. In order to test the predictions, you'd have to separate these big effects from subtle, inexorable changes on scales of centuries, and nobody knows how to do that yet.

Humans can unquestionably do damage persisting for geologic time if you count their contribution to biodiversity loss. A considerable amount of evidence shows that humans are causing what biologists call the "sixth mass extinction," an allusion to the five previous cases in the fossil record where huge numbers of species died out mysteriously in a flash of geologic time. A popular, and plausible, explanation for the last of these events, the one when the dinosaurs disappeared, is that an asteroid 10 kilometers in diameter, traveling 15 kilometers per second, struck the earth and exploded with the power of a million 100-megaton hydrogen warheads. The damage that human activity presently inflicts, many say, is comparable to this. Extinctions, unlike carbon dioxide excesses, are permanent. The earth didn't replace the dinosaurs after they died, notwithstanding the improved weather conditions and 20,000 ages of Moses to make repairs. It just moved on and became something different than it had been before.

However, carbon dioxide, per se, is not responsible for most of this extinction stress. There are a handful of counterexamples, notably corals, which may be especially sensitive to acidification of the ocean surface, and amphibians, which are declining noticeably for unknown reasons. But, except in these few isolated cases, keeping carbon-based fuels in the ground a while longer won't make much difference in mitigating the loss of biodiversity. The real problem is human population pressure generally—overharvesting, habitat destruction, pesticide abuse, species invasion, and so forth. Slowing man-made extinctions in a meaningful way would require drastically reducing the world's human population. That is unlikely to happen.

It's a mistake to suspend judgment on questions of population, climate, and carbon use just because they're sensitive. If you do, you'll become incapacitated by confusion. Earth scientists tend to be ultraconservative when it comes to the future, presumably because the scientific ethic forbids mixing speculation with fact, and go to extraordinary lengths to prove by means of measurement that the globe is warming now, the ocean is acidifying now, fossil fuel is being exhausted now, and so forth, even though these things are self-evident in geologic time. The unhappy result is more and more data but less and less understanding—a common problem in science but an especially acute problem in climatology. In such situations it's essential to weigh facts more strongly if they are simple, and use this practice to sweep away confusion whenever you can.

The sea's immense capacity to store carbon dioxide is one of the simple things with which you can reliably orient yourself. It's a junior-high-school science-fair project. Leave a glass of distilled water on the counter overnight, and by the next morning it will have become slightly acid, due to the absorption of carbon dioxide from the air. It hasn't absorbed much—about the amount stored in an equal volume of air—so this effect alone will not sequester much carbon. But drop a piece of limestone in the water, thereby emulating the presence of carbonate rocks at the bottom of the sea, and you will find the next morning that the water becomes slightly alkaline, and the amount of carbon dissolved in the water is now 60 times greater than it was before. After tinkering a bit to figure out where this carbon came from, you eventually discover that half came from the limestone and half came from the air. It all has to do with the marvelous (and elementary) chemistry of bicarbonate salts. You also find that the alkalinity of the water matches that of seawater, as does the carbon dioxide carrying capacity. Thus we learn that the oceans have dissolved in them, in the form of bicarbonate ion, 40 times more carbon than the atmosphere contains, a total of 30 trillion tons, or 30 times the world's coal reserves.

The experiments that assign specific numbers of years to geologic layers are almost as simple as this science-fair project, although not quite, and they are just as reliable. Not everyone agrees with this assessment, of course. Geologic time does contravene certain religious beliefs, a notorious difficulty with the subject that is very regrettable, since it doesn't contravene the religious beliefs that count. But it's probably more significant that the experiments, simple though they may be, involve obscure facts about rocks, a knowledge of physical law, and the assumption that this law was the same in the ancient past as it is now. None of this is obvious, much less interesting, to the average person. If you go to the supermarket and engage the checkout clerk in a conversation about the Paleozoic Era, radioactivity, or the disappearance of the megafauna, you'll be met with a smile, whereupon you'll probably be escorted from the building as a lunatic. However, the time scales do come from something concrete that can be explained simply.

You get a long way toward understanding geologic time by just disciplining yourself to use your common sense. A local beach a short drive from my home is backed by cliffs about 100 feet high that expose alternating layers of sandstone, mudstone, and aggregate, perhaps seven layers in all. You can tell without having attended a single geology class that these layers were formed by the action of water, the most likely candidate being the nearby ocean, especially in light of the fossilized clamshells entombed in some of the layers. Yet there they are high and dry, integrated into the rolling hills beyond, as though they were the sliced edge of a huge layer cake. The layers are also tilted, sometimes up and sometimes down, as though giants had sat down upon them in some places but not others. The tilt is large enough that some cliff-top planes continue downward to the beach and disappear into the ground. The cliffs are eroding. The rocks are noticeably crumbly in places, and you can see little landslides high up on the cliff face, and shelves and caves at the bottom where waves wash at high tide.

Once you begin noticing oddities in the rocks, you can't help but think about their implications. Layers of rocks with fossilized clams in them can only be above water now if the land rose, the sea sank, or both. Sea level has been quite constant throughout recorded history, say 5,000 years, and there are no documented cases of hundred-foot rises in the land either, except those resulting from volcanoes. So the cliffs are considerably older than recorded history. The tilting tells you that the land moved, regardless of what the sea did. The material forming the layers had to come from somewhere. Erosion from the cliffs themselves is really the only possibility, because there just isn't enough mud coming down local creeks and rivers to account for the sheer mass of rock, and anyway the layers are grainy and chunky, which the river mud isn't. But cliffs can't be made of erosion debris from themselves. The cliffs must therefore have eroded away completely and risen up again at least once, and more likely several times, judging from the layering complexity. The erosion rate of the cliffs thus sets the minimum age of the rocks. This rate appears to the eye of a regular visitor to be about one millimeter per year, perhaps less, for the rock here is relatively hard, so that it would take 100,000 years to erode a kilometer, or about a million years to erode away the shore entirely. That's sufficiently long so that you don't have to allow for the Ice Age. The age of the rocks is about a million years, or perhaps two million, just to be safe.

Such crude estimates of geologic time were the best anyone could do until the 1960s, when radiometric dating of rocks became commonplace. The relative newness of this technology accounts for some of geology's credibility problems, for geologic time itself was invented 100 years earlier and thus had plenty of time to develop a reputation for flakiness. While radiodating is technically difficult, indeed impossible without sophisticated equipment, it is straightforward conceptually. The method appropriate to this situation involves placing a piece of rock about the size of a golf ball in a vacuum chamber, melting the rock, collecting all the gases driven off, and measuring the total mass of the element argon that these gases contain. Then you dissolve the same rock in acid, do a bit of conventional wet chemistry with the solution, and measure the total mass of the element potassium that it contains. The ratio of these two masses, multiplied by a certain number, is the age of the rock. The physics underlying this procedure is that potassium, which is plentiful in nearly all rocks, is slightly radioactive and decays to argon, a chemically inert element. Argon likes to escape out of rocks when they are very hot, in particular when they are melted into volcanic lava, but is otherwise trapped. A conventional volcanic rock contains no argon right after it solidifies. The amount of argon it contains right now therefore counts the number of potassium atoms that decayed since it solidified, and thus the amount of time that elapsed.

Radiometric dating has to be used cautiously, however, because it's notoriously easy to do it wrong. The argon levels can be artificially high, for example, because of atmospheric contamination in air pockets and grain boundaries in the rock, or they can be artificially low because the rock got overheated sometime after it formed, or because the rock re-crystallized or acquired inclusions of younger rock through geologic processes underground. Sedimentary rock always gives nonsense readings because it doesn't get hot when it forms, and because weathering, aggregation, and metamorphism cause crystal structure changes, which corrupt the argon record.

The cliffs on my beach can be dated by a layer of volcanic ash that occurs fairly high up. The team that last surveyed the site chose not to date the ash directly, presumably because they didn't trust the argon levels, but instead identified it chemically with ash deposited hundreds of miles away and overlain by a layer of volcanic basalt. The basalt yielded a clean argon age of two and a half million years. Basaltic rocks higher up in the mountains behind this beach, which are older, yield an age of 20 million years. The rocks on the beach are thus somewhere between two million and 20 million years old. Cross-correlation of the fossils they contain narrows this date to about six million years, give or take a million. Thus, there were no human beings on the earth when the lowermost of these layers first sedimented out of the sea. Between then and now enough rain fell on the earth to fill up the oceans 2,000 times.

It would be very surprising if rocks conveniently near my home had especially large geologic ages, but naturally this isn't the case. When you go through the same kinds of analysis with rocks in other parts of the world, you typically get ages that are 10 to 100 times greater than these. A particularly famous example is in the first edition of *On the Origin of Species*, where Charles Darwin used erosion arguments to estimate the age of the Weald, a region southeast of London curiously deficient in chalk. He came up with 300 million years. It was impossible to refine this estimate radiometrically at the time, so it's probably not surprising that he reduced his estimate by half in the second edition and eliminated all mention of the subject in the third. But his reasoning was conceptually right, and the estimate itself was close to correct. The Weald is about 120 million years old, give or take 10 million. It's an interesting part of England, the place where the Battle of Hastings was fought, cricket was invented, and dinosaur fossils were first discovered.

The Weald is just the beginning, however, for Great Britain is extremely old. By a stroke of fortune, the entire country is a complete stack of the world's sedimentary layers tipped gently downward to the northwest and then planed level at the top. The plentiful fossils in the ground, which are different in different layers, thus form narrow tracks that run roughly parallel to the coast of France. When people first discovered these tracks, they had no way to date the rocks in question, so they just assigned names. The easternmost track became Cretaceous, after the Greek word *creta* for chalk. The next one became Jurassic, after the Jura mountains in Switzerland. The next one became Triassic after a characteristic three-level sedimentation pattern (the Tria) found commonly in Germany. The next one became Permian, after the region of Perm in Russia. And so on and so forth. But the subsequent invention of radiodating later enabled actual ages to be assigned to these names, albeit with the precision difficulties encountered on my beach. The white cliffs of Dover are 70 million years old. The clay under Oxford is 150 million years old. The rocks under Stratford-upon-Avon are 200 million years old. The coal under Stoke-on-Trent is 300 million years old. The Lake District is 400 million years old. The Isle of Man is 500 million years old. The Highlands of Scotland are 600 million years old—and more.

The oldest rocks in the world are not in Great Britain but in places exposed to extremes of Ice Age glaciation, such as Greenland, northern Canada, and northern Finland. Here the glaciers ground off all the upper sedimentary layers to expose the primordial rocks below. Radiometric ages of these rocks begin where the geological record in Britain ends and run back an additional four billion years. The oldest ages coincide with those of meteorites and moon rocks, implying that they date the birth of the earth. The age of the earth isn't important for energy discussions except in establishing that cosmic events, not value judgments, set the overall scale of geologic time.

The continents have moved up and down over the course of geologic time a greater distance than the sea is deep. We know this because the total thickness of sedimentary rock in some places exceeds four kilometers. After dating the Weald, Darwin also observed that the total thickness of all the sedimentary strata in England would total 22 kilometers if piled on top of one another. It wasn't clear at the time how literally to interpret this fact, because nobody had mined straight down through all the layers; nor did anyone know for sure how deep the ocean was. But now the oceans have been thoroughly surveyed, and oil technologies such as echo stratigraphy and deep drilling routinely find sedimentary rock layers 10 to 15 kilometers thick. The most sensational example of such thicknesses is the Grand

Canyon, which required a three-kilometer uplift from sea level to be cut by the Colorado River, and which forms, together with Utah's Escalante Staircase, a total sedimentary mass 10 kilometers thick. The Grand Canyon also demonstrates that uplift and subsidence alternated, since it contains plant fossil layers sandwiched between marine fossil layers. Less famous but no less relevant to the vastness of geologic time is the nearby Animas River canyon, which cuts through sedimentary rock five kilometers thick. Around the world, sedimentary deposits over one kilometer thick are commonplace.

Sea level has not, however, moved up and down over the course of geologic time an amount greater than the mountains are tall. We know this because marine sediments have accumulated continuously for the last 600 million years, which they would not have done if continental erosion had stopped or the seabed had emptied. Moreover, you can work backward from clues left in the rocks to reckon what the sea level was in the geologic past. This process has methodological uncertainties, because it involves judgments about how layer sequences in different parts of the world line up, what constitutes evidence for shorelines, and how the earth's crust yielded and rebounded as masses of rock came and went. However, it's accurate enough to tell you that the amount of water on the earth hasn't changed significantly over geologic time, and that the rise and fall of the oceans is adequately accounted for by the waxing and waning of the polar ice sheets and slow changes in ocean basin volumes. The sea level has had a complex and interesting history, but it has never deviated more than 200 meters from its present value.

The sea has risen and fallen particularly vigorously over the past million years as a result of Ice Age glaciation. We know this because oxygen isotope ratios in the ocean sediments vary violently with depth. These ratios indirectly measure the amount of water locked up in glacial ice sheets at the time of sedimentation. The sediments record nine major glacial episodes, each of which lowered the sea level by more than 50 meters and then returned it abruptly to its present value. At least four of these episodes lowered the sea by more than 100 meters. This includes the most recent one, which lowered it 120 meters. The amount of lowering is corroborated by uplifted coral reefs, which show growth in places that would otherwise have been impossible because they require shallow water. It's also consistent with estimates of the ice mass required to leave behind such industrial-strength mischief as Long Island, Nantucket, and the Great Lakes—about 50 million cubic kilometers in all, or five million billion tons.

The major glacial episodes are spectacular examples of the natural climate change that has occurred in geologic time. They took place at regular intervals of 100,000 years and always followed the same strange pattern of slow, steady cooling followed by abrupt warming back to conditions similar to today's. We know this because chemical records in polar ice, the patterns of which match those of the sediments, contain a signal that strongly tracks the earth's precessional wobble, the 24,000-year cyclic drift of the earth's spin axis caused by the gravitational tugging of the moon and sun. The precession is a clock-like astronomical quantity, so its appearance in the ice data enables a precise dating of the ice. That, in turn, enables a precise dating of the sediments. The last glacial melting, cross-dated at 15,000 years ago by the radiocarbon age of wood debris left by the glaciers as they retreated, occurred rapidly. The sea rose more than one centimeter per year for 10,000 years, then stopped. The extra heat required for this melting was 10 times the present energy consumption of civilization. The total meltwater flow was the equivalent of two Amazons, or half the discharge of all the rivers in all the world.

The great ice episodes were not the only cases of natural climate change, however. Six million years ago the Mediterranean Sea dried up. Ninety million years ago alligators and turtles cavorted in the Arctic. One hundred fifty million years ago the oceans flooded the middle of North America and preserved dinosaur bones. Three hundred million years ago, northern Europe burned to a desert and coal formed in Antarctica. The great ice episodes themselves were preceded by approximately 30 smaller ones between one and two million years ago, and perhaps twice that many before that.

Nobody knows why these dramatic climate changes occurred in the ancient past. Ideas that commonly surface include perturbations to the earth's orbit by other planets, disruptions of ocean currents, the rise and fall of greenhouse gases, heat reflection by snow, continental drift, comet impacts, Genesis floods, volcanoes, and slow changes in the irradiance of the sun. No scientifically solid support has been found for any of these suggestions. One thing we know for sure is that people weren't involved. There weren't enough people around during the ice episodes to matter, and there weren't any people around before the ice episodes.

The geologic record as we know it thus suggests that climate is a profoundly grander thing than energy. Energy procurement is a matter of engineering and keeping the lights on under circumstances that are likely to get more difficult as time progresses. Climate change, by contrast, is a matter of geologic time, something that the earth routinely does on its own without asking anyone's permission or explaining itself. The earth doesn't include the potentially catastrophic effects on civilization in its planning. Far from being responsible for damaging the earth's climate, civilization might not be able to forestall any of these terrible changes once the earth has decided to make them. Were the earth determined to freeze Canada again, for example, it's difficult to imagine doing anything except selling your real estate in Canada. If it decides to melt Greenland, it might be best to unload your property in Bangladesh. The geologic record suggests that climate ought not to concern us too much when we're gazing into the energy future, not because it's unimportant, but because it's beyond our power to control.