Antoine-Laurent Lavoisier’s Scientific Contributions

The Proof of Lavoisier's Plates

Stephen Jay Gould

Writing in the Margins

Part I.

Stephen Jay Gould

I once had a teacher with an idiosyncratic habit that distressed me forty years ago but now and finally, oh sweet revenge—can work for me to symbolize the general process of human creativity. I never knew a stingier woman, and though she taught history in a New York City junior high school, she might well have been the frugal New England farmer with the box marked "pieces of string not worth saving."

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* Stephen Jay Gould (1998). "Writing in the margins." *Natural History* 107 (November): 16-20.
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Readers who attended New York City public schools in the early 1950s will remember those small yellow slips of paper, three by six inches at most, that served all purposes, from spot quizzes to "canvases" for art class. Well, Mrs. Z. would give us one sheet—only one—for any classroom exam, no matter how elaborate the required answers. She would always reply to any plea for advice about containment or, God forbid, an additional yellow sheet (comparable in her system of values to Oliver Twist's request for more soup) with a firm refusal followed by a cheery instruction expressed in her oddly lilting voice: "And if you run out of room, just write in the margins!"

Margins play an interesting role in the history of scholarship, primarily for their schizophrenic housing of the two most contradictory forms of intellectual activity. Secondary commentaries upon printed texts (often followed by several layers of commentaries upon the commentaries) received their official designation as "marginalia" to note their necessary position at the edges. The usual status of such discourse as derivative and trivial, stating more and more about less and less at each iteration, leads to the dictionary definition of marginalia as "nonessential items" (*Webster's Third New International Dictionary)* and inevitably recalls the famous lines of Jonathan Swift:

So, naturalists observe, a flea
Hath smaller fleas that on him prey;
And these have smaller still to bite 'em;
And so proceed ad infinitum.
Thus every poet, in Iris kind,
Is bit by him that comes behind.

But margins also serve the diametrically opposite purpose of receiving the first fruits and inklings of novel insights and radical revisions. When received wisdom has hogged all the central locations, where else can creative change begin? The curmudgeon and cynic in me regards Thoreau's *Walden* as the most overquoted (and underwhelming) American classic, but I happily succumb, for the first time, to cite his one-liner for a vibrant existence: “I love a broad margin to my life.”

Literal margins, however, must usually be narrow—and some of the greatest insights in the history of human thought necessarily began in such ferociously cramped quarters. The famous story of Fermat's last theorem, no matter how familiar, cannot be resisted in this context: When the great mathematician Pierre Fermat died in 1665, his executors found the following comment in his copy of Diophantus' *Arithmetica*, next to a discussion of the claim that no natural numbers x, y, and z exist such that $x^n + y^n = z^n$, where n is a natural number greater than 2: "I have discovered a truly remarkable proof but this margin is too small to contain it." Mathematicians finally proved Fermat's last theorem just a few years ago, to great subsequent fanfare and an outpouring of popular books. But we shall never know if Fermat truly beat the best of the latest by 350 years or if (as my own betting money says, admittedly with no good evidence) he had a promising idea but never saw its disabling flaw in the midst of his excitement.

I devote this essay to the happier and opposite story of a great insight that a cramped margin did manage (just barely) to contain and nurture, but which then grew to such originality and fruitfulness that I need a two-part essay to do the subject justice. Part I appears here, and Part 2 will be published in next month's issue. But this tale, for reasons that I do not fully understand, remains virtually unknown (and marginal in this frustrating sense) both to scientists and to historians alike, although the protagonist ranks as one of the half-dozen greatest scientists in Western history, and the subject stood at the forefront of innovation in his time. In any case, the movement of this insight from marginality in 1760 to centrality by 1810 marks the birth of modern geology and gives us a rare and precious opportunity to eavesdrop on a preeminent thinker operating in the most exciting and instructive of all times: at the labile beginning of the codification of a major piece of natural knowledge—a unique moment featuring a landscape crossed by a hundred roads, each running in the right general direction toward a genuine truth. Each road, however, reaches a slightly different Rome and our eventual reading of nature depends crucially upon the initial accidents and contingencies specifying the path actually taken.

In 1700, all major Western scholars believed that the earth had been created just a few thousand years earlier. By 1800, nearly all scientists accepted a great antiquity of unknown duration and a sequential history expressed in the strata of the earth's crust. These strata, roughly speaking, form a vertical pile, with the oldest layers on the bottom and the youngest on top. By mapping patterns of the exposure of these layers on the earth's surface, this sequential history can be inferred. By 1820, detailed geological maps had been published for parts of England and France, and general patterns had been established for the entirety of both nations. This discovery of "deep time," and the subsequent resolution of historical sequences by geological mapping, must be ranked among the sweetest triumphs of human understanding.

Few readers will recognize the name of Jean-Etienne Guettard (1715–86), a leading botanist and geologist of his time and the instigator of the first "official" attempt to produce geological maps of an entire nation. In 1746, Guettard presented a preliminary "mineralogical map" of France to the Academic des Sciences. In subsequent years, he published similar maps of other regions, including parts of North America. As a result, in 1766, the secretary of state in charge of mining commissioned Guettard to conduct a geological survey and to publish maps for all of France. The projected atlas would have included 230 maps, but everyone understood, I suspect, that such a task must be compared to the building of a medieval cathedral and that no single career or lifetime could have completed the job. In 1770, Guettard published the first 16 maps. The project then became engulfed by political intrigue and, finally, by a revolution, which (to say the least) tended to focus attention elsewhere. Only 45 of the 230 projected maps ever saw the published light of day, and control of the survey had passed to Guettard's opponents by this time.

Guettard's productions do not qualify as geological maps in the modern sense, for he made no effort to depict strata or to interpret them as layers deposited in a temporal sequence—the revolutionary concepts that validated deep time and established the order of history. Rather, as his major cartographic device, Guettard established symbols for distinctive mineral deposits, rock types, and fossils—and then merely placed these symbols over appropriate locations on his map. We cannot even be sure that Guettard understood the principle of superposition; the key concept that time lies revealed in a vertical layering of strata, with younger layers above (superposed upon) older beds. Guettard did develop a concept of *bandes*, or roughly concentric zones of similar rocks, and he probably understood that a vertical sequence of strata might be expressed as such horizonal zones on a standard geographical map. But, in any case, he purposely omitted these *bandes* on his maps, arguing that he only wished to depict facts and avoid theories.

This focus on each factual tree, combined with his studious avoidance of any theoretical forest of generality or explanation, marked Guettard's limited philosophy of science, and also (however unfairly) restricted his future reputation, for no one could associate his name with any advance in general understanding. Rhoda Rappoport, a distinguished historian of science at Vassar College and the world's expert on late-eighteenth-century French geology, writes of Guettard (within a context of general admiration, not denigration): "The talent he most conspicuously lacked was that of generalization, or seeing the implications of his own observations. . . . Most of his work reveals . . . that he tried hard to avoid thinking of the earth as having a history."

But if Guettard lacked this kind of intellectual flair, he certainly showed optimal judgment in choosing a younger partner and collaborator for his geological mapping, for Guettard fully shared this great enterprise with Antoine-Laurent Lavoisier (1743–94), a mere fledgling of promise at the outset of their work in 1766 and the greatest chemist in human history when the guillotine cut short his career in 1794.

Guettard and Lavoisier made several field trips together, including a four-month journey in 1767 through eastern France and part of Switzerland. After the first sixteen maps were completed in 1770, Lavoisier's interest shifted away from geology toward the sources of his enduring fame—a change made all the more irrevocable in 1777, when control of the geological survey passed to Antoine Monnet, inspector general of mines and Lavoisier's enemy. (Later editions of the maps ignore Lavoisier's contributions and often don't even mention his name.)

Nonetheless, Lavoisier's geological interests persisted, buttressed from time to time by a transient hope that he might regain control of the survey. In 1789, with his nation on the verge of revolution, Lavoisier published his only major geological paper—a stunning and remarkable work that shall occupy the second installment of this essay. Amid his new duties as *régisseur des poudres* (director of gunpowder) and leading light of the commission that invented the meter as a new standard of measurement—and despite the increasing troubles that would lead to his arrest and execution (for his former role as a farmer general, or commissioned tax collector)—Lavoisier continued to write notes about his intention to pursue further geological studies and to publish his old results. But the most irrevocable of all changes fractured these plans on May 8, 1794, less than three months before the fall of Robespierre and the end of the Terror. The great mathematician Joseph-Louis Lagrange lamented the tragic fate of his dear friend by invoking the primary geological theme of contrasting time scales: "It took them only an instant to cut off his head, but France may not produce another like it in a century."

All the usual contrasts apply to the team of Guettard and Lavoisier: established conservative and radical beginner; mature professional and youthful enthusiast; meticulous tabulator and brilliant theorist; counter of trees and architect of forests. Lavoisier realized that geological maps could depict far more than the mere location of ores and quarries. He sensed the ferment accompanying the birth of a new science, and he understood that the earth had a long history, potentially revealed in the rocks on his maps. In 1749, Georges Buffon, the greatest of French naturalists, had begun his monumental treatise—*Histoire naturelle*—which would eventually run to forty-four volumes, with a long discourse on the history and theory of the earth.

As Lavoisier groped for a way to understand this history from the evidence of his field trips, and as he struggled to join the insights published by others with his own original observations, Lavoisier recognized that the principle of superposition could yield the required key: the vertical sequence of layered strata must record both time and the order of history. But vertical sequences differed in all conceivable ways from place to place—in thickness, in rock types, in the order of the layers. How could one take this confusing welter and infer a coherent history for a large region? Lavoisier appreciated the wisdom of his older colleague enough to know that he must first find a way to record and compile the facts of this variation before he could hope to present any general theory to organize his data.

A geological map by Guettard and Lavoisier, with Lavoisier's temporal sequence of strata in the right margin.

Lavoisier therefore suggested that a drawing of the vertical sequence of sediments be included alongside the conventional maps festooned with Guettard's symbols. But where could the vertical sections be placed? In the margins, of course—for no other space existed in the completed and conventional design. Each sheet of Guettard and Lavoisier's atlas therefore features a large map in the center with a marginal column on either side: a tabular key for Guettard's symbols in the left margin and Lavoisier's vertical sections in the right margin. If I wished to epitomize the birth of modern geology in a single phrase (admittedly oversimplified, as all such efforts must be), I would honor the passage—both conceptual and geometric—of Lavoisier's view of history, as revealed in sequences of strata, from a crowded margin to the central stage.

Many fundamental items in our shared conceptual world seem, obvious and incontrovertible only because we learned them in our cradle (so to speak) and have never even considered that alternatives might exist. We often regard such notions—including the antiquity of the earth, the rise of mountains, and the deposition of sediments—as simple facts of observation, so plain to anyone with eyes to see that any other reading could arise only from the province of knaves or fools. But many of these "obvious" foundations emerge as difficult and initially paradoxical conclusions born of long struggles to think and see in new ways.

If we can recapture the excitement of such innovation by temporarily suppressing our legitimate current certainties and reentering the confusing transitional world of our intellectual forebears, then we can understand why all fundamental scientific innovation must marry new ways of thinking with better styles of seeing. Neither abstract theorizing nor meticulous observation can provoke a change of such magnitude all by itself. And when—as in this story of Lavoisier and the birth of geological mapping—we can link one of the greatest conceptual changes in the history of science with one of the most brilliant men who ever graced the profession, then we can only rejoice in the enlarged insight promised by such a rare, conjunction.

Most of us, with minimal training, can easily learn to read the geological history of a region by studying the distribution of rock layers on an ordinary geographical map and then coordinating this information with vertical sections (as drawn in Lavoisier's margins) representing the sequence of strata that would be exposed by digging a deep hole in any one spot. But consider, for a moment, the intellectual stretching thus required, and the difficulty that such an effort would entail, if we didn't already understand that mountains rise and erode and that seas move in and out over any given region of our ancient earth.

A map is a two-dimensional representation of a surface; a vertical section is a one-dimensional listing along a line drawn perpendicular to this surface and into the earth. To understand the history of a region, we must mentally integrate these two schemes into a three-dimensional understanding of time (expressed as vertical sequences of strata) across space (expressed as horizontal exposures of the same strata on the earth's surface). Such increases in dimensionality rank among the most difficult of intellectual problems—as anyone will grasp by reading the most instructive work of science fiction ever published, Edwin A. Abbott's *Flatland* (1884, and still in print), a "romance" (his description) about the difficulties experienced by creatures who live in a two-dimensional world when a sphere enters the plane of their entire existence and forces them to confront the third dimension.

As for the second component of our linkage, I can offer only a personal testimony. My knowledge of chemistry is rudimentary at best, and I can therefore claim no deep understanding of Lavoisier's greatest technical achievements. But I have read several of his works and have never failed to experience one of the rarest emotions in my own arsenal: sheer awe accompanied by spinal shivers. A kind of eerie, pellucid clarity pervades Lavoisier's writing (and simply makes me ashamed of the peregrinations in these essays).

Perhaps, indeed almost certainly, a few other scientists have combined equal brilliance with comparable achievement, but no one can touch Lavoisier in shining the light of logic into the most twisted corners of old conceptual prisons and onto the most tangled masses of confusing observations, and extracting new truths expressed as linear arguments accessible to anyone. As an example of the experimental method in science (including the fundamental principle of doubleblind testing), no one has ever bettered the document that Lavoisier wrote in 1784 as head of a royal commission (including Benjamin Franklin, then resident in Paris, and, ironically, Dr. Guillotin, whose "humane" invention would end Lavoisier's life) to investigate (and, as results proved, to refute) the claims of Franz Mesmer about the role of "animal magnetism" in the cure of disease by entrancement (mesmerization).

Lavoisier did not publish his single geological paper (analyzed in next month's column) until 1789, but Rhoda Rappoport has shown that he based this work upon conclusions reached during his mapping days with Guettard. Lavoisier did not invent the concept of vertical sections, nor did he originate the idea that sequences of strata record the history of regions on an earth of considerable antiquity. Instead, he resolved an issue that may seem small by comparison but couldn't be more fundamental to any hope for a workable science of geology (as opposed to the simpler pleasures of speculating about the history of the earth from an armchair): he showed how the geological history of a region can be read from variations in strata from place to place—in other words, how a set of one-dimensional lists of layered strata at single places could be integrated by that greatest of all scientific machines, the human mind, into a three-dimensional understanding of the history of geological changes across an entire region.

(I doubt that Lavoisier's work had much actual influence, for he published only this one paper on the subject and did not live to realize his more extensive projects. Other investigators soon reached similar conclusions, for the nascent science of geology was the hottest intellectual property in late-eighteenth—century science. Lavoisier's paper has therefore been forgotten, despite several efforts by isolated historians of science through the years—with this two-part essay as the latest attempt—to show the singularity of Lavoisier's vision and accomplishment.)

From my excellent sample of voluminous correspondence from lay readers during a quarter century of writing these essays, I have learned the irony of the most fundamental misunderstanding about science among those who love the enterprise (I am not discussing the different errors made by opponents of science). Supporters assume that the greatness and importance of a work correlates directly with its stated breadth of achievement: minor papers solve local issues, while great works claim to fathom the general and universal nature of things. But all practicing scientists know in their bones that successful studies require strict limitations. One must specify a particular problem with an accessible solution, and then find a sufficiently simple situation where attainable facts might point to a clear conclusion. Potential greatness then arises from cascading implications toward testable generalities. You don't reach the generality by direct assault without proper tools. One might as well dream about climbing Mount Everest wearing a T-shirt and tennis shoes and carrying a backpack containing only an apple and a bottle of water.

I shall, in next month's essay, show how Lavoisier's only geological paper rests upon such a simple and testable theme—the claim that sea level rises and falls in cycles and that distinctive differences m type of sediment mark the lowstands and highstands. The argument of this remarkable work then cascades in two directions from this firm starting point: first, toward a great statement about the methodology of science and, subsequently, toward a framework for the full panoply of concepts that would elevate the diffuse and tentative efforts of naturalists into an expansive and cohesive science of geology.

Capturing the Center

Part II.

Stephen Jay Gould

Antoine-Laurent Lavoisier began his geological work with Jean-Etienne Guettard in 1766, he accepted a scenario, then conventional, for the history of the earth as revealed by the record of rocks: a simple directional scheme that envisaged a submergence of ancient landmasses (represented today by the crystalline rocks of mountains) under an ocean, with all later sediments formed in a single era of deposition from this stationary sea (on this topic, see Rhoda Rappoport's important article "Lavoisier's theory of the earth," *British Journal for the History of Science*, 1973)

* Stephen Jay Gould (1998) "Capturing the center." *Natural History* 107 (December): 14-25.
This is the second part of a two-part essay. Part 1, "Writing in the Margins," on the great chemist Lavoisier's contributions to the nascent science of geology, appeared in last month's issue.

Since geologists then lacked techniques for unraveling the contorted masses of older crystalline rocks, they devoted their research to the later stratified deposits and tried to read history as an uncomplicated tale of linear development. (No fossils had been found yet in the older crystalline rocks, so these early geologists also assumed that the stratified deposits contained the entire history of life.)

Lavoisier's key insight led him to reject this linear view (one period of deposition from a stationary sea) and to advocate the opposite idea, that sea level had oscillated through time and that oceans had therefore advanced and retreated through several cycles in any particular region—a notion now so commonplace that any geologist can intone the mantra of earth history, "The seas go in and the seas go out." Lavoisier reached this radical conclusion by combining the developing ideas of such writers as Georges Buffon and Benoit de Maillet with his own observations on cyclical patterns of sedimentation in vertical sections.

Lavoisier christened his 1789 paper with a generous title fully characteristic of a time that did not separate literature and science: *Observations générales sur les couches modernes horizontales qui ont été déposées par la mer, et sur les conséquences qu'on peut firer de leurs dispositions relativement à l'ancienneté du globe terrestre* (General observations on the recent horizontal beds that have been deposited by the sea, and on the consequences that one can infer from their arrangement about the antiquity of the earth). The title may have been grand, general, and expansive, but the content remained precise, local, and particular—at first. Lavoisier begins his treatise by distinguishing the properties of sediments deposited in open oceans from those formed along shorelines—a device to establish data for his central argument that seas advance and retreat in a cyclical pattern over any given region.

After two short introductory paragraphs, Lavoisier plunges right in by expressing puzzlement that two such contradictory kinds of rock can be found in alternating cycles of a single vertical section. The nature of the fossils and sediments indicate calm and gentle deposition for one kind: "Here one finds masses of shells, mostly thin and fragile, and most showing no sign of wear or abrasion. . . . All the features [of the rocks] that surround these shells indicate a completely tranquil environment." (I am responsible for these translations from Lavoisier's 1789 paper.) But rocks deposited just above testify to completely different circumstances of formation:

A few feet above the place where I made these observations, I noted an entirely opposite situation. One now sees no trace of living creatures; instead, one finds rounded pebbles whose angles have been abraded by rapid and long-continued tumbling. This is the picture of an agitated sea, breaking against the shore and violently churning a large quantity of pebbles.

Lavoisier then poses his key question, already made rhetorical by his observations:

> How can we reconcile such opposite observations? How can such different effects arise from the same cause? How can movements that have abraded quartz, rock crystal and the hardest stones into rounded pebbles also have preserved light and fragile shells?

The simple answer to this specific question may then lead to important generalities for the science of geology and also to criteria for unraveling the particular history of the earth:

> At first glance, this contrast of tranquillity and movement, of organization and disorder, of separation and mixture seemed inexplicable to me; nevertheless, after seeing the same

> phenomena again and again, at different times and in different places, and by combining these facts and observations, it seemed to me that one could explain these striking observations in a simple and natural manner that could then reveal the principal laws followed by nature in the generation of horizontal strata.

Lavoisier then presents his idealized model of a two-stage cycle as an evident solution to this conundrum: "Two kinds of very distinct beds must exist in the mineral kingdom: one kind formed in the open sea . . . which I shall call pelagic beds, and the other formed at the coast, which I shall call littoral beds." Pelagic beds arise by construction as "shells and other marine bodies accumulate slowly and peacefully during an immense span of years and centuries." But littoral beds, by contrast, arise by "destruction and tumult . . . as parasitic deposits formed at the expense of coastlines."

In a brilliant ploy of rhetoric and argument, Lavoisier then builds his entire treatise as a set of consequences from this simple model of two types of alternating sediments representing the cycle of a rising and falling sea. This single key, Lavoisier claims, unlocks the great conceptual problem of moving from one-dimensional observations of vertical sequences in several localities to a three-dimensional reconstruction of history (I call the solution three-dimensional for a literal reason: the two horizontal dimensions record geographical variation over the earth's surface, while the vertical dimension marks time in a sequence of strata):

> This distinction between two kinds of beds . . . suddenly dispersed the chaos that I experienced when If first observed terranes made of horizontal beds. This same distinction then led me to a series of consequences that I shall try to convey, in sequence, to the reader.

The remainder of Lavoisier's treatise presents a brilliant fusion of general methodology and specific conclusions, making the work a wonderful exemplar of scientific procedure at its best. The methodological passages emphasize two themes: the nature of proof in natural history and the proper interaction of theory and observation. Lavoisier roots the first theme in a paradox discussed at the end of last month's installment of this two-part essay: the need to simplify at first in order to generalize later. Science demands repetition for proper testing of observations—for how else could we learn that the same circumstances reliably generate the same results? But the conventional geologies of Lavoisier's time stymied such a goal—for the concept of one directional period of deposition from a single stationary sea offered no opportunity for testing by repetition. By contrast, Lavoisier's model of alternating pelagic and littoral beds provided a natural experiment in replication at each cycle.

But complex nature defies the needs of laboratory science for simple and well-controlled situations, where events can be replicated under identical conditions set by few variables. Lavoisier argues that we must therefore try to impose similar constraints upon the outside world by seeking "natural experiments," where simple models of our own construction might work adequately in natural conditions chosen for their unusual clarity and minimal number of controlling factors.

Consider three different principles, each exploited by Lavoisier in this paper, for finding or imposing a requisite simplicity upon nature's truly mind-boggling complexity.

1. Devise a straightforward and testable model. Lavoisier constructed the simplest possible model of seas moving in and out and depositing only two basic (and strongly contrasting) types of sediment. He knew perfectly well that real strata do not arrange themselves in neat piles of exactly repeating pairs, and he emphasized

two major reasons for nature's much greater actual complexity: first, seas don't rise and fall smoothly, but rather wiggle and jiggle in small oscillations superposed upon any general trend; second, the nature of any particular littoral deposit depends crucially upon the type of rock being eroded at any given coastline. But Lavoisier knew that he must first validate the possibility of a general enterprise three-dimensional reconstruction of geological history—by devising a model that could be tested by replication. The pleasure of revealing unique details would have to come later. He wrote:

> Beds formed along the coast by a rising sea will have unique characteristics in every different circumstance. Only by examining each case separately, and by discussing and explaining them in comparison with each other, will it be possible to grasp the full range of phenomena . . . I will therefore treat [these details] in a separate memoir.

2. Choose a simple and informative circumstance. Nature's inherent complexity of irreducible uniqueness for each object must be kept within workable scientific bounds by intelligent choice of data with unusual and repeated simplicity. Here Lavoisier lucked out. He had noted the problem of confusing variation in littoral deposits based on erosion of differing rocks at varying coasts. Fortunately, in the areas he studied near Paris, the ancient cliffs that served as sources for littoral sediments might almost have been "made to order" for such a study. The cliffs had been formed in a widespread deposit of Cretaceous age called *La Craie*, the Chalk—the same strata that build England's white cliffs of Dover. The Chalk consists primarily of fine white particles, swiftly washed out to sea as the cliffs erode. But the Chalk also includes interspersed beds of hard flint nodules, varying in size in most cases from golf halls to baseballs. These nodules provide an almost perfect experimental material (in uniform composition and

limited range of size) for testing the effects of shoreline erosion. Lavoisier noted in particular (see the accompanying figures) that the size and rounding of nodules should indicate distance of deposition from the shoreline for pebbles should be large and angular when buried at the coast (before suffering much wear and erosion) but should then become smaller and rounder as they tumble farther away from the coastline in extensive erosion before deposition.

3. Ask a simple and resolvable question. You needn't (and can't) discover the deep nature of all reality in every (or any) particular study. Better to pose smaller but clearly answerable questions, with implications that then cascade outward toward a larger goal. Lavoisier devised a simple and potentially highly fruitful model of oscillating sea levels in order to solve a fundamental question about the inference of a region's geological history from variation in vertical sections from place to place—the sections that he had placed in the right-hand margins of the maps he made with Guettard (see last month's essay). But such a model could scarcely fail to raise, particularly for a man of Lavoisier's curiosity and brilliance, the more fundamental question—a key, perhaps, to even larger issues in physics and astronomy—of why oceans should rise and fall in repeated cycles. Lavoisier noted the challenge and wisely declined, recognizing that he was busy frying some tasty and sizable fish already and couldn't, just at the moment, abandon such a bounty in pursuit of Moby Dick. So he praised his work–in–progress and then politely left the astronomical question to others (although he couldn't resist the temptation to drop a little hint that might help his colleagues in their forthcoming labors):

> It would be difficult, after such perfect agreement between theory and observation—an agreement supported at each step by proofs obtained from strata deposited by the sea—to claim that the rise and fall of the sea [through time] is only a hypothesis and not an

> established fact derived as a direct consequence of observation. It is up to the geometers, who have shown such wisdom and genius in different areas of physical astronomy, to enlighten us about the cause of these oscillations [of the sea] and to teach us if they are still occurring, or if it is possible that the earth has now reached a state of equilibrium after such a long sequence of centuries. Even a small change in the position of the earth's axis of rotation, and a consequent shift in the position of the equator, would suffice to explain all these phenomena. But this great question belongs to the domain of physical astronomy and is not my concern.

For the second methodoligical theme of interaction between theory and observation in science, Lavoisier remembered the negative lesson that he had learned from the failures of his mentor Guettard. A major and harmful myth of science—engendered by a false interpretation of the eminently worthy principle of objectivity—holds that a researcher should just gather facts in the first phase of study and rigorously decline to speculate or theorize. Proper explanations will eventually emerge from the data in any case. In this way, the myth proclaims, we can avoid the pitfalls of succumbing to hope or expectation and departing from the path of rigorous objectivity by "seeing" only what our cherished theory proclaims as righteous.

I do appreciate the sentiments behind such a recommendation, but the ideal of neutrally pure observation must be judged as not only impossible but actually harmful to science in at least two major ways. First. one cannot possibly make observations without questions in mind and suspicions about forthcoming results. Nature presents an infinity of potential observations; how can you possibly know what might be useful or important unless you are seeking answers to particular puzzles? You can hardly fail to waste a frightful amount of time when you don't have the foggiest idea about the potential outcomes of your search.

Second, the mind's curiosity cannot be suppressed. (Why would anyone ever want to approach a problem without this best and most distinctive tool of human uniqueness?) Therefore, you will have suspicions and preferences whether you acknowledge them or not. If you truly believe that you are making utterly objective observations, then you will really tumble into trouble, for you will probably not recognize your own inevitable prejudices. But if you acknowledge a context by posing explicit questions to test (and, yes, by inevitably rooting for a favored outcome), then you will be able to specify—and diligently seek, however much you may hope to fail—the observations that can refute your preferences. Objectivity cannot be equated with mental blankness; rather, objectivity resides in recognizing your preferences and then subjecting them to especially harsh scrutiny—and also in a willingness to revise or abandon your theories when the tests fail (as they usually do).

Lavoisier had spent years watching Guettard fritter away time with an inchoate gathering of disparate hits of information, without any cohesive theory to guide and coordinate his efforts. As a result, Lavoisier pledged to proceed in an opposite manner, while acknowledging that the myth of objectivity had made his procedure both suspect and unpopular. Nonetheless, he would devise a simple and definite model and then gather field observations in a focused effort to test his scheme. (Of course, theory and observation interact in subtle and mutually supporting ways. Lavoisier used his preliminary observations to build his model and then went back to the field for extensive and systematic testing.) In an incisive contrast between naive empiricism and hypothesis testing as modes of science, Lavoisier epitomized his preference for the second method:

> There are two ways to present the objects and subject matter of science. The first consists in making observations and tracing them

> to the causes that have produced them. The second consists in hypothesizing a cause and then seeing if the observed phenomena can validate the hypothesis. This second method is rarely used in the search for new truths, hut it is often useful for teaching, for it spares students from difficulties and boredom. It is also the method that I have chosen to adopt for the sequence of geological memoirs that I shall present to the Academy of Sciences.

Lavoisier therefore approached the terranes of France with a definite model to test: seas move in and out over geographical regions in cycles of advancing and retreating waters. These oscillations produce two kinds of strata: pelagic deposits in deeper waters and littoral deposits fashioned from eroded coasts near the shoreline. Type of sediment should indicate both environment of deposition and geographical position with respect to the shoreline at that time: Pelagic deposits always imply a distant shore. For littoral deposits, relative distance from shore can be inferred from the nature of any particular stratum; for littoral beds made mainly of flint nodules eroded from the Chalk, the trigger and more angular the nodules, the closer the shoreline.

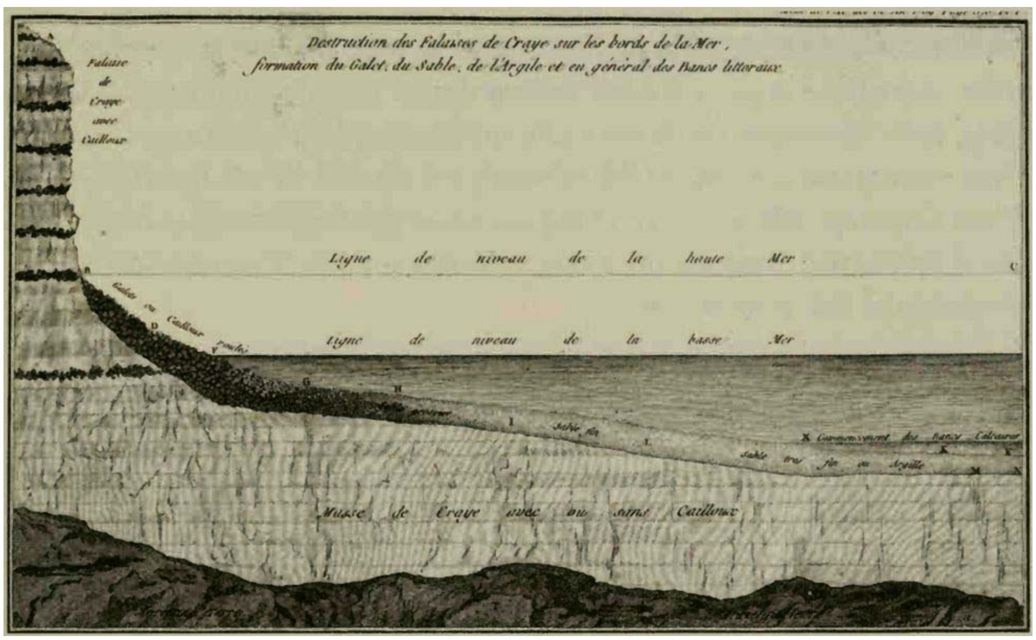
From these simple patterns, all derived as consequences of an oscillating sea, we should be able to reconstruct the three-dimensional geological history of an entire region from variation in vertical sequences of sediments from place to place. (For example, if a continuous bed representing the same age contains large and angular flint nodules at point A and smaller and more rounded nodules at point B, then A lay closer to the shoreline at the time of deposition.)

Lavoisier devotes most of his paper, including all seven of his beautifully drafted plates, to testing this model, but I can summarize the bulk of his treatise in three pictures and a few pages of text because the model makes such clear and definite predictions—and nature must either affirm or deny. Lavoisier's first six plates—in many ways, the most strikingly innovative feature of his entire work—show the expected geographical distribution of sediments under his model. The first plate, for example, shows the predictable geographical variation in a littoral bed formed by a rising sea. The sea will mount from a beginning position, marked *ligne de niveau de la basse mer*, "line of low sea level" and indicated by the top of the illustrated waters, to a high stand, marked *ligne de niveau de la haute mer*, "line of high sea level." The rising sea beats against a cliff, shown at the far left and marked *falaise de Craye avec cailloux*, "Chalk cliff with pebbles." Note that, as discussed previously, this deposit contains several beds of flint nodules, drawn as thin horizontal hands made up of dark pebbles.

The rising sea erodes this cliff and deposits a layer of littoral beds underneath the waters and on top of the eroded chalk. Lavoisier marks this layer with a sequence of letters (BDFGHILMN) and shows how the character of the sediment varies systematically with distance from the shoreline. At B, D, and F, near the shore, large and angular pebbles, formed from the eroded flint nodules, build the stratum (marked *cailloux roulés*, "rolled pebbles"). The size of particles then decreases progressively away from shore as the pebbles break up and erode (going from *sable grossier*, "coarse sand," to *sable fin*, "fine sand," to *sable très fin ou argille*, "very fine sand or clay"). Meanwhile, far from shore, marked KK at the right of the figure, a pelagic bed begins to form, marked *commencement des bancs calcaires*, "beginning of calcareous beds."

From this model, Lavoisier must then predict that a vertical section at G, for example, would first show (as the uppermost stratum) a littoral bed made of large and angular pebbles, while a vertical section at M would show a pelagic bed on top of a littoral bed, with the littoral bed now made of fine sand or clay. The two littoral beds at G and M would represent the same age, but their differences in composition would mark their varying distances from the shore. This simple principle of relating differences in beds of the same age to varying environments of deposition may seem straightforward, but geologists did not really develop a usable and consistent theory of such facies, as we call these variations, until this century. Lavoisier's clear vision of 1789, grossly simplified though it may be, seems all the more remarkable in this context.

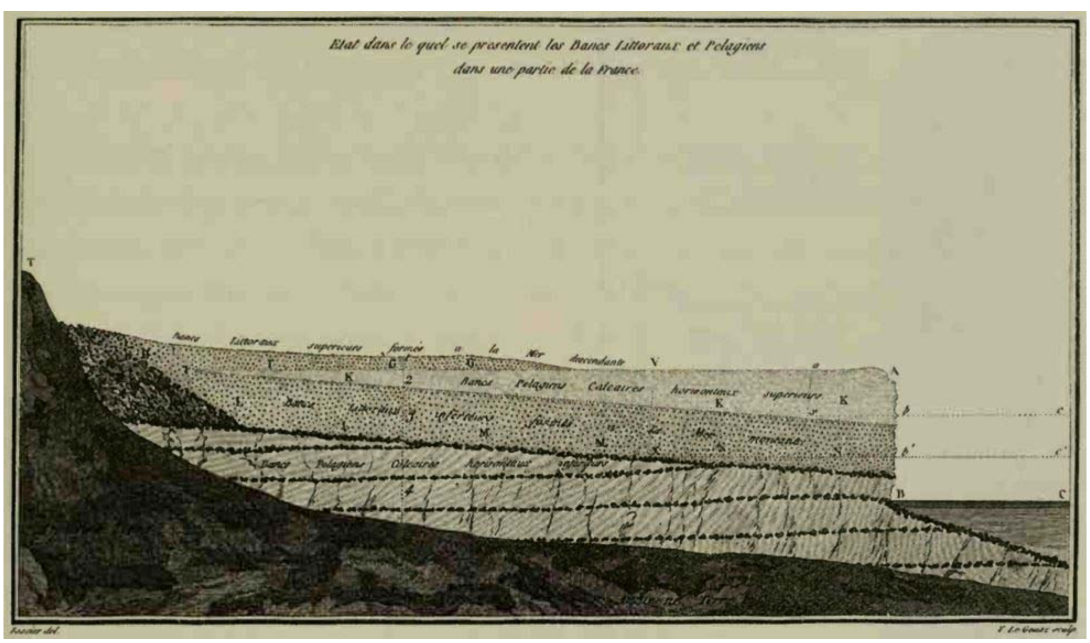
Lavoisier's first plate, showing spatial variation in sediments deposited in a rising sea.



Lavoisier then presents a series of similar diagrams of growing complexity, culminating in Plate 6, also reproduced here. This plate shows the results of a full cycle—the sea, having advanced to its full height, has already retreated hack to its starting point. The chalk cliff has been entirely eroded away and now remains only as a bottom layer. (Note the distinctive bands of flint nodules for identification. I will discuss later the lowermost layer, marked *ancienne terre*, "ancient earth.") Above the eroded chalk lies a lower littoral layer, marked HLIMN and *bancs littoraux inférieurs foremés à la mer montante*, "lower littoral beds formed by the rising sea." Just above this layer lies a pelagic bed, marked KKK (don't blame Lavoisier for a later and accidental American anachronism!) and labeled *bancs pelagiens calcaires horizontaux supérieurs*, "upper calcareous horizontal pelagic beds." Note how the pelagic bed pinches out toward shore because sediments of this type can be deposited only in deep water. This pelagic bed forms when sea level reaches its highest point. Then, as the sea begins to fall, another littoral bed—marked HIGG and *bancs littoraux supérieurs formés à la mer déscendante,* "upper littoral beds formed by the falling sea"—will be deposited in progressively shallower water atop the pelagic bed.

Again, Lavoisier's insights are subtle and detailed—and several specific predictions can be made from his model. For example, the upper and lower littoral beds will be confluent near the coast because the intervening pelagic bed didn't reach this far inland. Thus, a vertical section drawn here should show a single thick littoral bed made of large and angular pebbles. But, farther away from shore, a vertical section should include a full array of alternating beds, illustrating the entire cycle and moving (top to bottom as shown in the vertical line, located just left of center and marked 12345) from the upper littoral bed of the falling sea (1) to the intervening pelagic bed (2), the lower littoral bed of the rising sea (3), the underlying chalk (4), and finally the foundation of the *ancienne terre* (5).

Thus, Lavoisier's model makes highly specific predictions about the sediments deposited in full cycles of rising and falling seas, as expressed in the vertical sections that adorned the right-hand margins of the maps he made with Guettard, and that represented his signal and original contribution to the developing science of geology. Moreover, the model specified predictions not only for the vertical sequences of single places but also for geographical variation in those sequences from place to place. Therefore, in a last figure, Lavoisier presents some actual vertical sections measured in the field. The example presented here corresponds exactly to his prediction for section 12345 in the idealized model. Note the perfect correspondence between Lavoisier's *Coupe des Montagnes des Environ de Saint Gohain*, "section through the mountains in the neighborhood of St. Gobain," and his model (except that the actual section doesn't extend below the chalk into the ancient basement). The measured section shows four layers, labeled upper littoral, pelagic beds, lower littoral, and chalk (note the layers of flint nodules in the lowermost chalk). Lavoisier had intended to write several more geological papers filled with similar empirical details to test his model. Thus, this pilot study presents only a few actual sections, but with impressive promise for validation. Lavoisier had achieved a scientific innovation of the finest and most indubitable form: he had added a dimension (literally) to our knowledge of natural history.

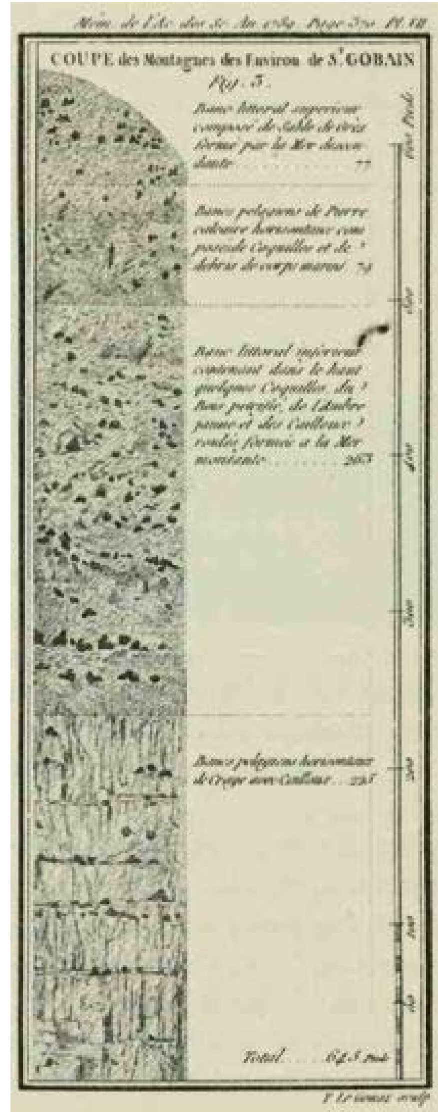


Lavoisier's final plate, showing the spatial and temporal complexity of sediment deposited in a full cycle of a rising and falling sea.

As if he had not done enough already, Lavoisier then ended his treatise with two pages of admittedly hypothetical reasoning on the second great general theme in the study of time and history. His model of oscillating seas lies fully within the Newtonian tradition of complete and a historical generality. Lavoisier's ocean cycles operate through time, but they do not express history because no events of distinctive directionality ever occur; no result ever denotes a unique moment. The cycles obey a timeless law of nature and proceed in the same way, no matter when they run; cycle 100 will yield the same results as cycle 1, and the record of rocks can never tell you where you stand in the flow of history. All variation reflects either general environment (high or low sea) or local circumstance (type of rock in the cliff being eroded), and not any distinctive imprint of history.

Lavoisier, in other words, had worked brilliantly with the necessary concept of time's cycle, so vital for any scientific account of the past because we need general laws to explain repeated physical events. But geology cannot render a full account of the earth's past without the fundamentally different, but intricately conjoined and equally necessary, concept of time's arrow, so vital because geology also embraces history, and history requires a directional sequence of unique events—in other words, the last five letters of its own name, a story.

As a prerequisite for interest and meaning, history must unfold in a matrix of extensive time—which Lavoisier had already provided by combining his oscillating model of the oceans with empirical evidence for multiple cycles in vertical sections. If each cycle required considerable time (particularly for the formation of pelagic beds, so slowly built from the debris of organisms), then the evidence for numerous cycles implied an earth of great antiquity. By 1789 (and contrary to popular legend), few scientists still accepted a biblical chronology of just a few thousand years for the earth's history. But the true immensity of geological time still posed conceptual difficulties for many investigators, and Lavoisier's forthright claims mirrored the far more famous lines published just a year before, in 1788, by the traditional "father" of modern geology, the Scotsman James Hutton: "Time is, to nature, endless and as nothing." Lavoisier expressed his version of deep time in the more particular light of his model:



> The details that I have just discussed have no other object than to prove this proposition: if we suppose that the sea undergoes a very slow oscillatory movement, a kind of flux and reflux, that these movements occur during a period of several hundreds of thousands of years, and that these movements have already occurred a certain number of times, then if we make a vertical section of rocks deposited between the sea and the high mountains, this section must present an alternation of littoral and pelagic beds.

Within such a matrix of deep time, the concept of a truly scientific history obtains new meaning and promise. At the end of his treatise, Lavoisier therefore touches upon this subject in his characteristically empirical way: by returning to the lowermost layer beneath the recorded sediments of his models and measured sections—a complex of rocks that he had bypassed with the simple label *l'ancienne terre*. Lavoisier now states that he does not regard this foundation as part of the original earth at its time of formation, but rather as a probable series of sediments, much older than the Chalk but also built as a sequence of littoral and pelagic beds (although now hard to identify because age has obliterated the characteristic features of such deposits):

> One will no doubt want to know about the rocks found underneath the Chalk and what I mean by the expression *l'ancienne terre*. . . . This is almost surely not the original earth; on the contrary, it appears that what I have called *l'ancienne terre* is itself composed of littoral beds much older than those depicted in the figures.

In a remarkable passage, Lavoisier then invokes what would become the classic example for juxtaposing the yin of history (time's arrow) and the yang of constant features built by invariant laws (time's cycle) to form a complete science of geology: the directional character of life's pageant, the primary component of the earth's rip-roaring narrative story. (By the way, Lavoisier's particular claims turn out to be wrong in every detail, but I can hardly think of an observation more irrelevant. In 1789 no one knew much about paleontological particulars. I am stressing Lavoisier's keen and correct vision that life would provide the primary source of directional history, or time's arrow.)

Lavoisier bases his claim for the existence of directional history upon a clever argument. He believes that rocks of the *ancienne terre* contain no fossils. But if these rocks include (as he has just argued) the same alternation of pelagic and littoral beds found in younger sediments, then the invariant physical laws of time's cycle should lead us to expect fossils in these strata—for such sediments form in environments that now teem with life. Therefore, time's arrow of directional history must be responsible for the difference. Physical conditions of the *ancienne terre* must have corresponded with later circumstances that generated similar sediments, but the earth must then have housed no living creatures, since these identical rocks do not contain fossils.

Lavoisier then argues that sediments sometimes found below the Chalk (the oldest rocks with marine fossils) but above the *ancienne terre* often contain fossils of plants. He therefore envisages a threefold directional history of life—an original earth devoid of organisms, followed by the origin of vegetation on land, and finally culminating in the development of animal life both in the sea and on land:

> It is very remarkable that the Chalk is usually the youngest rock to contain shells and the remains of other marine organisms. The beds of shale that we sometimes find below the Chalk often include vestiges of floating bodies, wood, and other vegetable matter thrown up along the coasts. . . . If we may be allowed to hazard a guess about this strange result, I believe we might be able to conclude, as Mr. Monge has proposed [the important French mathematician Gaspard Monge, who served with Lavoisier on the revolutionary commission to devise the metric system], that the earth was not always endowed with living creatures, that it was, for a long time, an inanimate desert in which nothing lived, that the existence of vegetables preceded that of most animals, or at least that the earth was covered by trees and plants before the seas were inhabited by shellfish.

And thus, hurriedly, at the very end of a paper intended only as a preliminary study, an introductory model to be filled in and fleshed out with extensive data based on field research, Lavoisier appended this little conjectural note—to show us, I suspect, that he grasped the full intellectual range of the problems set by geology, and that he recognized the power of combining a firm understanding of timeless and invariant laws with a confident narration of the rich directional history of an ancient earth. His last page bubbles with enthusiasm for future plans involving the whole earth, a project so soon cut off by the evil that only men can do. Consider the poignant paragraph just following his speculation about the history of life:

> In the next article, I will discuss in very great detail these opinions, which really belong more to Mr. Monge than to myself: But it is indispensable that I first establish, in a solid way, the observations on which they are based.

I don't know why Lavoisier's execution during the Reign of Terror in 1794 affects me so deeply. We cannot be confident that he would have completed his geological projects if he had lived (for all creative careers must remain chock-full of unrealized plans); and we know that he faced his end with a dignity and equanimity that can still provide comfort across the centuries. He wrote in a last letter:

> I have had a fairly long life, above all a very happy one, and I think that I shall be remembered with some regrets and perhaps leave some reputation behind me. What more could I ask? The events in which I am involved will probably save me from the troubles of old age. I shall die in full possession of my faculties.

Lavoisier needs no rescue, either from me or from any modern author. Yet, speaking personally (a happy privilege granted to essayists ever since Montaigne invented the genre for this explicit purpose more than 200 years before Lavoisier's time), I do long for some visceral sense of fellowship with this man who stands next to Darwin in my private intellectual pantheon. He died through human cruelty, and far too young. His works, of course, will live—and he needs no more.

But, and I have no idea why, we also long for what I called visceral fellowship just above—some sense of *physical continuity*, some sign of an *actual presence* to transmit across the generations, so that we will not forget the person behind the glorious ideas. (Perhaps my dedication to such material continuity marks only a personal idiosyncrasy—but not, I think, a rare feeling, and certainly concentrated among those who choose paleontology for a profession, because they thrill to the objective records of life's continuous history.)

So let me end with a confession—well, not really a confession (for I have nothing to hide or to regard with shame) but rather a testimony. Through incredible good fortune, I was able to buy a remarkable item at auction a few months ago—the original set of proof plates, each personally signed by Lavoisier, of the seven figures (including the three reproduced here) that accompany his sole geological article of 1789. Two men signed each plate: first, in a thick and bold hand, Gabriel de Bory, vice–secretary of the French Academy of Sciences (signed "Bory Vice–Secretaire"); and second, in a much more delicate flow composed of three flourishes surrounding the letters of his last name alone, Antoine-Laurent Lavoisier.

Lavoisier's own flourishes enhance the visual beauty of these plates that express the intellectual brilliance of his one foray into my field of geology—all signed in the year of the revolution that he greeted with such hope (and such willingness to work for its ideals); the revolution that eventually repaid his dedication in the most perversely cruel of possible ways. But now I hold a tiny little bit, only a symbol really, of Lavoisier's continuing physical presence in my professional world.

The skein of human continuity must often become this tenuous across the centuries (hanging by a thread, in the old cliché), but the circle remains unbroken if I can touch the ink of Lavoisier's own name, written by his own hand. A candle of light, nurtured by the oxygen of his greatest discovery, never burns out if we cherish the intellectual heritage of such unfractured filiation across the ages. We may also wish to contemplate the genuine physical thread of nucleic acid that ties each of us to the common bacterial ancestor of all living creatures, born on Lavoisier's *ancienne terre* more than 3.5 billion years ago—and never since disrupted, not for one moment, not for one generation. Such a legacy must be worth preserving from all the guillotines of our folly.