Allchin, Douglas. 1997. "James Hutton and Coal." *Cadernos IG/UNICAMP* 7:167-183.

JAMES HUTTON AND COAL

Douglas Allchin

Keywords: James Hutton; coal; Plutonism; phlogiston

ABSTRACT

James Hutton addressed coal in several publications relating to geology, combustion and theories of matter. As a common theme, coal shows how one can unify Hutton's thinking in these various contexts. Coal was important as a critical example in arguing for heat in geological processes, as a geological agent itself and as an example for understanding light, heat and fire. in all cases, Hutton focuses on understanding the natural economy and what fuels it. Hutton's views on coal thereby suggest considering more deeply his works on phlogiston and the solar substance.

1. INTRODUCTION: OF COAL AND CULM

Fascination with James Hutton (1726-1797) often begins with his theory of the earth, as popularized by John Playfair, adapted by Charles Lyell, and later celebrated by biographers Archibald Giekie and E. B. Bailey (1967). Yet recent studies have also led us to appreciate more fully Hutton's extensive other work outside geology—in chemistry and philosophy (e.g., Gerstner, 1968; Donovan and Prentiss, 1980; Allchin, 1992). Hence, we are learning to recast the former "founder" or "father" of modern geology—and champion of inductivist methodology—as a complex natural philosopher, whose views were strongly shaped by theology (e.g., Gould, 1987; Allchin, 1994). In this paper, I contribute further to this understanding of Hutton through a thematic analysis of his views on coal. From an exclusively geological perspective, the topic of coal may seem somewhat peripheral compared to Hutton's grand system and "global machine." By viewing coal as central, however (I contend), one can see more clearly the themes that unify Hutton's diverse works from his own perspective.

Hutton's first publication in 1777, for example, though ostensibly modest, concerned coal. The British Parliament had passed an act specifying taxes on the transport of coal-dust, differentiating between coal and culm. Coal would cake, making it suitable for common domestic hearths, whereas culm would not, making it suitable only for lime- or brick-kilns. But, in practice, no simple test allowed custom officials to distinguish between the two types and thereby to enforce the Act. Hutton published his solution: "If, when a handful of it is thrown into a red-hot shovel, the pieces burn without melting down or running together," it is "decidely" to be considered culm (Playfair, 1805, p. 49). Hutton's method was adopted and brought with it "considerable financial relief to Scotland" (Bailey, 1950, p. 363).

Hutton's focus on coal and culm may seem anomalous—particular, pecuniary, and crudely practical—in the context of the expansive scale and grand theoretical nature of his later, now more renowned, **Theory of the Earth**. Yet this apparently peripheral topic offers an important first clue to deciphering several fundamental themes through which Hutton viewed and interpreted the world. Indeed, Hutton would return to distinctions among types of coal in both his 1785 (1788) and expanded 1795 versions of the **Theory of the Earth**. As detailed below, he viewed coal as substantive in supporting his notion of plutonism (§2), while it was also relevant to addressing the harshest criticisms about sources of heat (§3). In other publications Hutton used coal as a frequent and sometimes pivotal example in his recurring discussions of combustion, light and heat, and the structure and properties of matter (§4). Moreover, coal was central in his accounts of the organic economy of the earth, a conception that vividly reflects his most fundamental philosophical and theological aims (§5). In short, coal is a focal point for linking Hutton's works and for contributing to a deeper understanding of his pursuits as a natural philosopher.

2. COAL AND PLUTONISM

When Hutton (1788) first presented his theory of the earth, he argued vigorously for the role of heat as a geological agent—in consolidating strata under the seas and in subsequently elevating them. We now often view Hutton's observations at Glen Tilt and the Isle of Arran as canonical examples illustrating Hutton's argument. But, for Hutton, coal became critical. What was a relatively brief argument in his 1788 essay (pp. 235, 239-42) had, by 1795, become expanded into a full chapter on "The Nature of Mineral Coal, and the Formation of Bituminous Strata, investigated" (vol. 1, Chap. 8., pp. 558-620). (By contrast, Hutton deferred his discussion of Glen Tilt to the third volume of his 1795 work, which remained unfinished and unpublished at his death.) "There is," Hutton declares, "not perhaps one substance in the mineral knigdom by which the operation of subterraneous heat is, to common understanding, better examplified than that of mineral coal" (1795, p. 617). For Hutton, coal was crucial in showing the effects of heat versus water, and he even considered the argument based on coal to be powerful enough alone to carry the entire burden of proof for his theory:

> ". . . *from vegetable bodies produced upon the habitable earth, they are now become a mineral body, and the most perfect coal,—a thing extremely different from what it had been, a thing which cannot be supposed to have been accomplished by the operation of water alone, or any other agent in nature with which we are acquainted, except the action of fire or heat. It is therefore impossible for a philosopher, reasoning upon actual physical principle, not to acknowledge in this a complete proof of the theory which has been given, and a complete refutation of that aqueous operation* . . ." (1795, pp. 563-564).

Hutton announces, "Here is one of the absolute proofs of the igneous theory" (p. 613). Indeed, so important was coal that "the subject of this chapter is a touch-stone for every theory of the earth" (p. 561).

Coal was significant to Hutton, first, as an example of a mineral that cannot be formed, or consolidated, by water. Coal, along with other forms of sulphureous rock and siliceous rocks, are all insoluble in water (1788, p. 231-238; 1795, vol. 1, p. 51-69). (What makes the sulphureous rocks insoluble, he informs us, is, in fact, phlogiston; 1788, p. 236; 1795, p. 63.) But coal is unique in showing a spectrum of forms that make evident further the exclusive effect of heat. Hutton's concerns, here, intersect once again with the distinctions he articulated earlier in 1777. The difference between fusible (oily, inflammable) and infusible (fixed) forms of bituminous matter now represent extremes in a process of transformation through distillation (1788, p. 239-242; 1795, p. 69-74, 569-573):

> *"Thus we have one species of coal which is extremely fusible, abounds with oil, and consequently is inflammable; we have another species again which is perfectly fixed and infusible in the fire; therefore, we may conclude upon principle, that, however, both these coals must have undergone the operation of heat and fusion, in bringing them to their present state, it is only the last that has become so much evaporated as to become perfectly fixed, or so perfectly distilled, as to have been reduced to a caput mortuum"* (p. 569).

As distillation is a process of heat alone, Hutton argues, the mineral nature of coal dramatically demonstrates the incontrovertible role of heat in forming these strata, and consequently also in forming the strata in which coal is embedded (1795, p. 559, 561-565, 608-609, 612-614, 618). By presenting coal as an example that cannot be explained by any other means than heat—"as these changes are perfectly explained by the one theory, and absolutely inconsistent with the other" (p. 564)—Hutton hopes to seal his case for the role of heat in geological processes. Hence, he feels confident in declaring coal as a "touch-stone" for deciding among alternative theories.

Hutton's argument, here, is multi-layered, resting on substantial and diverse knowledge about coal, which Hutton takes as unproblematic but which he must articulate for his readers. First, he addresses the origin, or natural history, of coal, explaining how it is derived from plants. Second, based on our understanding of the composition of combustible materials in plants, he is then able to describe the nature of different types of coal, which is fundamental to explaining how proper coal forms through distillation. The argument thus takes him far afield from geology, into the chemistry of life.

First, Hutton describes how coal strata form. Plant material is delivered to the bottom of the sea (1795, p. 575-580), often mixed with other earthy material (p. 573-575, 580-587), and is then embedded between other strata (p. 590-592); coal's similarites with peat and fossil wood, along with embedded plant fossils, confirm further that coal has such a vegetable origin (p. 587-590). "Those strata [of mineral coal] are evidently a deposite of inflammable substances which all come originally from vegetable bodies" (p. 617). Here, at least, Hutton suggests partial agreement with others (p. 561).[2] This prepares the way for considering the more significant details of *how* coal forms chemically, based on plant material as the source of coal's capacity for burning—"according to the common observations of mankind, the eminent quality by which coal is to be distinguished" (1795, p. 610).

Hutton then builds on ideas from his earlier publications on heat, light and fire (1792, pt.2; 1794). There he details the nature of phlogiston in plants, animals and the natural economy (Allchin 1994). Phlogiston was, of course (for Hutton), the substance that allows things to burn and is given off as heat and light when they burn. Hutton viewed it specifically (and idiosyncratically) as a variation of the "solar substance," and he sometimes referred to it as "fixed light." Unlike other phlogistonists, though, Hutton distinguished between two species of phlogiston: one was associated with combustibility and carbonic matter; the other was associated with inflammability and hydrogen (or inflammable air). Hence, when coal burns, there are two distinct processes: the volatile, inflammable element (hydrogen) combines with vital air (oxygen) to form water and produces an observable flame; at the same time, the fixed, combustible element (carbon) combines with oxygen to form fixed air (carbon dioxide) and produces heat and glowing light (1792, §4.16; 1794, p. 229-230; 1795, p. 607-609). "All animal and vegetable bodies contain both those different chymical substances united; and this phlogistic composition is an essential part of every animal and vegetable substance" (1795, pp. 607-608). Hence, when coal forms (initially) from plant material, both species of phlogiston are present.

All coal does not remain the same, however. Some coal loses its inflammable, or volatile (hydrogenous), phlogiston. Here, Hutton gives a deeper chemical explanation for his earlier distinction between types of coal. Fusible (or, sometimes, "bituminous" or "inflammable") coal retains its original oils, allowing it to fuse and burn with a flame. By contrast, infusible coal (also called "perfect coal," "proper coal," "coak," "cinder," "charcoal," or "charred" coal) loses its oils and volatile elements, leaving only the carbonic, combustible species of phlogiston (1788, p. 239-242; 1795, p. 69-74, 568-573). The two forms of coal vary in their composition of phlogiston, accounting for their differing properties in burning—and clueing us to their origin.

Hutton is careful to note that this distinction about phlogistic properties should not be confused with another characteristic commonly used to assess the quality of coal. The natural history of coal makes it clear that coal may *also* contain varying amounts of earthy material, which will also affect its combustibility. The more that plant material was mixed with earthy material in forming the coal, the lower its potential for burning and the more it will leave ashes. In this case, the important feature is the proportion of phlogistic material, not the proportion of the different *types* of phlogistic material. Hutton introduces a striking example to illustrate the two distinctions simultaneously: kennel coal, also known as parrot coal, exhibits properties of the stratification due to its earthy layers, while at the same time exhibiting the volatility of the bitmunious coal (1795, p. 582-586). When the coal is burned on one axis, the volatile (phlogistic) elements escape between the earthy layers and the coal burns quietly with a steady flame; when turned such that the layers extend horizontally, however, the volatile elements are largely trapped and burn with "violent cracking and explosions" when they do escape--hence, the crackling sound suggestive of a parrot. The curious, but extended example illustrates for Hutton how we must consider the composition of coal both in terms of its earthy/combustible elements and its types of phlogiston.

The distinction about types of coal based on their phlogistic elements—so clearly gaining salience from Hutton's own personal life and intellectual history—is central to Hutton's overall argument. Hutton focuses, not on the composition of coal itself, but on the *transformation* from bituminous to "proper" coal. This occurs only through distillation. Thus: "to what I would call more particularly the attention of mineral philosophers is this, that is inconceivable to have this effect produced by means of water" (1795, p. 612). Here, ultimately, one must admit a role for heat, because there is no other known method for transforming coal except distillation.

> "*In the process of vegetation, there are produced oily and resinous substances; and from the collection of these substances at the bottom of the ocean, there are formed strata, which have afterwards undergone various degrees of heat, and have been variously changed, in consequence of the effects of that heat, according as the distillation of the more volatile parts of those bodies has been suffered to proceed.*" (1788, p. 239)

> "*The production of coal from vegetable bodies, in which that phlogistic substance is originally produced, or from animal bodies which have it from that sources, is made by heat, and by no other means, so far as we know*." (1795, p. 612-613).

Ulitmately, heat—and heat alone—can transform an oily plant substance into bitumen and then eventually into a coal "destitute of fusibility and volatility," one that "burns without flame or smoak" (1788, p. 240-241).

Hutton thus had little patience for and railed against those who said that "bituminous matter is infiltrated with the water, impregnates certain strata of earth with bituminous matter and thus converts them into mineral coal, and bituminous strata" (1795, p. 563). For Hutton, the phlogistic nature of different types of coal, properly understood, leads to only one conclusion: the role of heat in this and other geological processes. For those not ready to follow Hutton's concepts on phlogiston or his distinction about types of coal, of course, the whole argument is lost. In this respect, Hutton exercised a broader view than many of his contemporaries and critics (and many later commentators, as well: Bailey could only complain that "his wording is very obscure hereabouts"; 1967, p. 92). Though Hutton himself considered this argument central and conclusive, critics rarely addressed it, reflecting as well as anything, perhaps, the divergent contexts in which they framed geology and chemistry.

3. COAL AND SUBTERRANEAN HEAT

Hutton suffered severe criticisms, of course, for his claims about the role of heat in geological processes (see Gerstner, 1971, for summary of the views of Thompson, Kirwan, Deluc and Murray). Hutton had not firmly addressed the simple but obvious question: what causes this heat? For the most part, Hutton tried to fend off the problem, suggesting that the answer itself was buried deep beneath the earth where it was ultimately inaccessible to human investigators:

> ". . . *how describe an operation which man cannot have any opportunity of perceiving? Or how imagine that, for which, perhaps, there are not proper data to be found? We only know, that the land is raised by a power which has for principle subterraneous heat; but how that land is preserved in its elevated station, is a subject in which we have not even the means to form conjecture*." (1788, p. 284-85)

Elsewhere—especially in his explicit replies to Kirwan (1795, Chap. 2)—Hutton emphasized that his arguments only led to subterranean fire as a conclusion, that he was reasoning from effect to cause, without making any prior suppositions. "The present question is not," he had urged his readers, "what had been the cause of heat." Rather, one could conclude that heat was common to the basic processes of consolidation and uplift "without explaining the means employed by nature in procuring the power of heat" (1788, p. 262). Hutton asserted that heat was simply "natural to the bowels of the earth" (p. 261). Still, Hutton was vulnerable to his avowed agnosticism.

But in confiding, "I should confess my ignorance with regards to the means of procuring fire" (1795, p. 240), Hutton only feigned naiviety. Indeed, it should puzzle the historical observer why, given Hutton's near obsession with efficient cause and his philosophical commitments to reconciling ends and means, that he was not more forthcoming in an explanation. One can only guess that Hutton's interests were more in the form of his arguments and their theological structure, than in persuading his contemporaries on particulars or addressing his critics on their own terms. In this case, Hutton did clearly intimate his ideas:

> "*According to my theory, the strata of this earth are composed of the materials which came from a former earth; particularly these combustible strata that contain plants which must have grown upon the land. Let us then suppose the subterraneous fire supplied with its combustible materials from this source, the vegetable bodies growing upon the surface of the land. Here is a source provided for the supplying of mineral fire, a source which is inexhaustible or unlimited, unless we are to circumscribe it with regard to time, and the necessary ingredients; such as the matter of light, carbonic matter, and the hydrogenous principle.*" (1795, vol. 1, p. 243)[4]

Coal was not only evidence for subterranean heat, it was the very cause of it! Moreover, the supply of coal was self-sustaining, based on the cyclic nature of the system itself (see also §5 below).

Hutton was rarely explicit, however, about coal fueling his geological processes. Still, in his non-geological works he carefully detailed how coal is a source of fuel (chemically) and how it receives its phlogiston from plant materials, which in turn receive it from the sun, the source of all "solar substance" (1792, Chaps. 3-4; 1794, p. 153-178). Phlogiston, in some form—and in vast quantities— must power the geological cycles:

> "*Fire, and the consumption of phlogistic substances, is a great and necessary operation in the oeconomy of this world. There is constant fire in the mineral regions;—fire which must consume the greatest quantity of fuel; the consolidation of the loose materials, stratified at the bottom of the sea, depends upon the heat of that fire; and the permanency of the land of this earth, above the surface of the sea, depends upon that consolidation of the strata, and upon the great masses of stone which had been in a melted state in the mineral regions.*" (1794, p. 320-21)

Hutton pursued the role of coal often implicitly. Thus, he reasoned about the distribution of mountains and their relative elevation based on the past action of coal and, therefore, where one might expect to find coal still buried today (1795, p. 596-604). Essentially, Hutton profiled the role of coal by postulating that precisely where we see the effects of its prior action, the coal should be exhausted and no longer present:

> "*. . . it will be natural to suppose that the bituminous or combustible part among those stratifcations, may have been mostly consumed upon some occasion during those various and long continued operations [of consolidation and elevation]...*" (p. 599)

First, he claimed that coal beds are more common under flatlands than under mountains: where the coal was not ostensibly used in uplift. Second, he claimed that coal beds are less common under higher mountains than under low mountains: the coal was apparently used to consolidate some strata more completely or compactly, and mountains persist where this rock has been better able to resist "the powers which have been employed in leveling what has been raised from the bottom of the sea" (p. 601). Third, much of the coal of Scotland, lying under flat terrain, should have been exposed to less fire, hence it would also be less thoroughly distilled and thereby exhibit the distinctive fusible quality that we do, in fact, find; indeed, where there are igneous intrusions, the coal beds predictably show edges of more perfect coal (p. 604). The evidential basis for Hutton's claims are incomplete and surely contestable. Yet his reasoning shows clearly how he perceived coal as a source of subterranean heat, and how its action historically would lead to several consequences in the present that could be checked against actual observations.

Finally, Hutton was criticized not only for failing to explain the source of heat, but also for not explaining how the heat could be intermittent in time and place (e.g., see Gerstner, 1971, p. 354, on Thomson's 1790 critique, also echoed by Murray in 1802). Hutton had at hand a response in the patchy distribution of coal that he noted in other contexts (for example, in the formation of mountains just mentioned above). Hutton never completed the argument. But clearly he had an answer implicit in his explanatory framework, based on his views about coal as the source of subterranean heat. Again, we may speculate that Hutton was not motivated to persuade his critics on issues that seemed peripheral to the structure of his own carefully assembled argument.

Coal was thus critical for Hutton in a second context, as well—namely, as the source of subterranean heat that fueled his geological cycles. Once again, awareness of Hutton's other writings contribute to understanding his position more fully.

4. COAL, COMBUSTION AND PHLOGISTON

Some critics did interpret Hutton as suggesting that coal was a source of subterranean heat. But they all dismissed the notion as manifestly absurd. Kirwan, Murray and others, in the wake of Lavoisier's discoveries on combustion, contended that coal could not possibly burn below the surface of the earth where there was no oxygen, or vital air. Even Playfair (1802) sidestepped any mention of burning coal, as if the hint that something might burn without oxygen would plainly subvert his effort to give Huttoninan theory wider appeal. One might well imagine that Hutton was unschooled in chemistry and combustion. However, as noted above, he compiled two lengthy dissertations on light, fire and heat (Hutton 1792; 1794). In these, Hutton articulated a sophisticated view of phlogiston and its observable effects. —And he often discussed coal to illustrate shortcomings in Lavoisier's explanations. The two publications offer yet deeper insight into Hutton's perspectives—and reveal how his now renowned geology fit within a much larger network of thinking.

Hutton was among a group of late phlogistonists who generally accepted the role of oxygen in combustion, but found Lavoisier's accounts insufficient (Allchin 1992). Most objections concerned heat, light, and what we would now call energy. Hutton distinguished clearly between interactions of matter and the production of heat and light so that he could focus on what he considered most relevant. When coal burns, for example:

> "*there are produced two distinct effects; first, by the oxigenating of the gravitating carbonic substance, there is produced fixed air, or carbonic acid in an elastic state. Secondly, in thus changing the nature of the coal, there is produced a great quantity of light and heat; it is only this last event, or effect, with regard to which there is any difficulty, or any dispute to be made*" (1794, p. 153-54; see also 1796, p. 13).

Hutton agreed fully with Lavoisier that carbon and oxygen combine to form carbon dioxide. But Hutton was far more concerned about the fire. Lavoisier attributed the heat and light to *calorique*, which Hutton interpreted as latent heat, released from oxygen. Hutton argued that when carbon burns and changes from solid to gas (and while no oxygen is fixed), latent heat is absorbed, not released. Hence, Lavoisier did not adequately identify the source of fire (1792, §2.13). Hutton situated this example in the context of the controversial inflammation of hydrogen (producing water), arguing that, likewise, Lavoisier's concept of *calorique* could not explain the prodcution of a liquid from two gases (1792, §§1.8, 2.5). In this way, he began to dissociate oxygen from the critical production of fire, ascribing it instead to phlogiston (released from the fuel—either carbon or hydrogen—which is oxygenated).

Hutton delved further in challenging Lavoisier's role for oxygen. He considered a case where oxygen was available but apparently did not support continued combustion of coal:

> "*Now, if it can be shewn that a burning coal, though placed in circumstances the most favorable for its oxygenation, may nevertheless lose its heat, and cease to burn entirely, it is certain, that it is not alone by the* calorique *of the vital air that the fire is supported.*" (1796, p. 13)

Hutton invited others to compare a single coal burning in open air to a group of coals burning in proximity. Hutton notes that the single coal—with free access to oxygen-rich air—is indeed unable to sustain its burning, while a bed of coals continues to kindle: why? Oxygen does not supply heat. Hutton concludes instead that the heat produced by the release of phlogiston from other nearby coals is necessary to kindle the coal and promote its release of phlogiston (1794, p. 156-170). In the same way, hydrogen does not burn even when in the presence of oxygen unless the mixture is first ignited (1792, §2.6). Hence, oxygen does not *cause* burning, though it may sometimes be involved in the process—and it is certainly not the reason for the source of heat and light. Likewise, oxygen does not—cannot—explain the release of heat during the sulphuration of iron or other metals! (Hutton, 1798). Hutton is therefore not disturbed by imagining that subterranean fires might burn without oxygen. Coal might well release its phlogiston as heat in some other way, yet undocumented, without oxygen.

Hutton's concerns about heat and light carried him well beyond even remotely geological topics. He considered the nature of light and matter: fixed light is a repulsive force, in opposition to gravity, but which has no weight (1792, pt. 3; 1794, pt. 6). Hutton considered, too, the relationship between light, heat and electricity, concluding that light was "primitive" and released from phlogistic bodies, occasionally turning into heat (but never conversely) (1794, pts. 1-5). Hutton was also able to theorize on ultimately quite practical applications: for example, how does one control the burning of coal to maximize the heat while minimizing the flame? The question flowed naturally from his analysis, already elaborated above, about different types of phlogistic bodies. In this case, low heat allows the carbonic, combustible matter to burn, while it evaporates, without kindling, the volatile, inflammable oil (1794, p. 193). The distinction between types of phlogiston was widely important and extended along many dimensions—and (in tribute to Hutton's insights) maps crudely modern understanding of organic compounds based on their relative saturation, or degree of hydrogenation. Hence, the combustible form of phlogiston contributes to conductivity, opacity and ductility; the inflammable form contributes to non-conductivity, transparency and friability. Not the least of these distinctions was the color of light released by each substance and the different properties of each color of light: inflammable bodies release blue light, which tends to radiate farther as light before becoming heat (hence, largely visible blue flames); by contrast, combustible bodies release red light, which more easily converts into heat (hence, red embers indicate strong heat). Hutton even proposed explicit experiments to investigate the heating powers of blue light, relative to white light, based on an analogy with the heating powers of red light (pp. 216-234, 290-310).

Complex phlogistic views permeated Hutton's thinking. Though historians have heretofore generally peripheralized these works (as though to save Hutton from the embarassment of being associated with such a notorious concept), they prove valuable for interpreting Hutton's overall thinking and thus merit deeper consideration.

5. COAL AND THE ECONOMY OF NATURE

For Hutton, coal lies at the intersection of geology, the chemistry of living things, physics and philosophy—all topics that also contribute to understanding the economy of nature. Using coal as a thematic focus, then, one can readily appreciate Hutton's world view and the natural theology that partly motivated and guided his work.

Hutton viewed the world as a self-sustaining system, a "global machine," whose ultimate purpose (final cause) was as a place for humans, plants and animals to live:

> "*This globe of the earth is a habitable world; and on its fitness for this purpose, our sense of wisdom in its foundation must depend.*" (1788, p. 209-210)

Hutton aimed to understand the means (efficient causes) toward that end. The role of Hutton's great geological cycles has been the most widely profiled of these means and Gould (1987), for example, has nicely summarized Hutton's argument in this context. In his **Theory of the Earth**, therefore, Hutton ultimately argued not so much for the role of heat in geological processes, or for the age of the earth, as for the existence of and mechanisms for a "soil cycle," whereby plants could grow and animals and humans feed. It is worth noting, in particular, how Hutton underscored the interaction of complementary geological forces in creating a balanced system: "the several powers which concur, counteract, or balance one another" (1788, p. 210). Thus, the decay of the earth, so necessary for the production of soil, is complemented by its renovation (1788, pt. 4). Dissolution of the land is coupled with consolidation under the sea (pt. 2). The wasting of the land is restored by uplift (pt. 3). In this way the system is self-sustaining through a great geological *soil cycle* (pt. 1). In finding "no vestige of a beginning,—no prospet of an end," we should foremost be reminded of "the succession of worlds" and the "system by which they are intended to continue" (1788, p. 304).

The central importance of cycles first appeared in Hutton's 1749 M.D. dissertation (Donovan and Prentiss, 1980), where Hutton discussed circulation of the blood in the context of the circulation of the macrocosm. Hence, it should not surprise us to find cycles throughout Hutton's later thinking. Hutton also described a *coal cycle*, for example. At one level, coal merely seems to particiate as one element in the soil cycle (§2, above). But as a source of subterranean heat, it is not a passive physical element. Rather, it has a much more important and active role in fueling the geological cycles themselves (§3). Hoever, coal is consumed in consolidating strata—and must be replaced. Hutton thus shows also how new coal will be formed from burned and dead vegetable and animal matter and incorporated into the strata of each subsequent world (1795, Chap. 8). Critics largely missed the implications here and thereby claimed that any source of Hutton's heat must exhaust itself. For Hutton, coal is able to fuel the soil system by virtue of its phlogiston:

> "*But, the mineral fire must have for principle fixed light or phlogiston, as well as the fire upon the surface of this earth. . . . Where then is the source of this light . . .; unless from the influence of the sun?*" (1794, p. 320-321).

Hence the sun, as a source of the "solar substance," also contributes significantly to maintaining the coal cycle and ensures its continuity. Coal is lost, coal is replaced—and the means for its cycling are part of the system itself (§2).

Phlogiston, too, has its own role in the natural economy. Phlogiston, so necessary for fueling geological operations, is also necessary for fueling life. Animals depend on plants for food and use their phlogiston to produce animal heat:

> "*The constitution of animal bodies necessarily requires phlogistic matter; for, those bodies are chiefly composed of combustible and inflammable substanes. At the same time, there does not appear to be any generation of that necessary substance in animal bodies; . . . But, animal bodies receive this phlogistic substance in their food, which is all ultimately of vegetable production.*" (Hutton 1794, p. 321-322).

Eventually animals would consume all the plant material—were there not means for plants to grow and incorporate phlogiston from the sun. The "composition" of phlogiston in plants in sunlight perfectly balances its use in animals, just as geological restoration balances the wasting of the land. The parallel between phlogistic and geological systems is, in fact, explicit in the organization of Hutton's 1788 and 1792 publications. The 1788 "Theory of the Earth" on the "Composition, Dissolution, and Restoration of Land" identifies the problem of the "dissolution of the solid earth" in the first section, then two sections describe "consolidating the Strata" and "the Production of Land"; the final section summarizes the "System of Decay and Renovation." In the same way, the 1792 dissertation on phlogiston first discusses, in separate sections, the "decomposition" of phlogiston and then its "composition" in plants, then recapitulates in the final section "its place in the System of this World." Phlogiston is lost and replenished, just like soil. The phlogistic processes are balanced, part of a self-sustaining natural economy.

Moreover, the transfer of phlogiston is coupled with the cycling of matter. Animals, just like burning coals, use oxygen to produce heat:

> "*. . . heat which is necessary to animal life, and which, like that of fire, is produced by means of the oxigenating operation of atmospheric air*" (1794, p. 322).

But, in an exactly complementary way, plants release oxygen as they incorporate phlogiston:

> "*But, this is not all; for, instead of having any of their substances oxigenated by atmospheric air, as is the case with breathing animals, vegetables secrete and emit tht very oxigenating substance, when growing in the sun,* i.e.*, when, by means of the solar light, they are composing phlogistic substances in their leaves.*" (1794, p. 323)

Hutton refers to investigations by Ingen-Housz that confirm the production of oxygen precisely when plants are exposed to light. In addition, Hutton identified specifically how plants take carbonic matter from fixed air (carbon dioxide) and the hydrogenous principle from water, in each case, liberating vital air (oxygen) (1792, pts. 3-4, 1794, pt. 7). The process thereby complements the burning of both the combustible and inflammable types of phlogistic matter (in coal, for example, §2 above) and accounts for the origin of each. Hutton links the flow of phlogiston from the sun with the exchange of carbon dioxide, water and oxygen between plants and animals. In so doing, Hutton ostensibly acknowledges (without strictly identifying or labeling) an *oxygen cycle*, a *carbon cycle*, and a *hydrogen cycle* intimately linked to water.

Finally, Hutton also addressed a *water cycle* as yet another vital component of the natural economy. Water, in evaporating and then condensing, produces rain—and Hutton published his theory on the role of latent heat in rain (1792, pt. 1). Rain is important in the soil cycle, contributing to the decay of the land and thus the formation of soil for plants. The rain is also important in agriculture (note Hutton's unpublished *Principles of Agriculture*; Bailey 1950, p. 359-360) and for plant growth generally, providing further for the composition of phlogiston. Like the soil cycle, the water cycle, too, depends on the sun, although more on its heat than its light.

All these cycles—the soil cycle, the coal cycle, the oxygen cycle, the carbon cycle, the hydrogen cycle and the water cycle—were important for Hutton because they support life on earth. And all rely, directly or indirectly, on phlogiston or some other variant of the "solar substance." Hence, Hutton highlighted the central role of the sun in fueling the natural economy:

> "*the light of the sun, which is the principle of our fire, is continually flowing into this planet, for the purpose of actuating the terraqueous system of this earth, and for enlivening animal and vegetable bodies.*" (1794, p. 324)

Light and heat are among the most important elements for the natural philosopher to understand in interpreting the design of the world:

> "*Thus the wonderful constitution of light and heat, . . . may be traced through many proceses in the wise oeconomy of nature, or in the system of this world, where ends and means are the proper subjects of our science.*" (1794, p. 305-306)

Hutton's thinking encompassed the whole of the natural economy, as well as its cycles and parts individually, and he perceived how the "solar substance"—the principle that can distinguish coal from all other minerals—activated it all. No wonder he viewed heat as important geologically.

In Hutton's view of nature, the modern ecologist might easily recognize the fundamental concepts of mineral cycles and energy flow now used to describe ecosystems. Hutton, however, was no ecologist. He was a natural philosopher, motivated theologically:

> "*The proper purpose of philosophy is to see the general order that is established among the different species of events, by which the whole of nature, and the wisdom of the system, is to be perceived.*" (1792, p. 262)

His aim was to understand the system's design, to find "the perfect adjustment of ends and means," "to trace the efficient, as well as to perceive the final cause" (1792, p. 260-261) and to revel in the contemplation of divine creation:

> "*When, in studying the system of nature, we observe, that every thing is in action for some purpose; that opposite powers are continually balancing each other, or alternately prevailing; and that the general end view is to contribute every thing requisite for the necessities for the conveniences of animal life, we find ourselves pleased with this subject of contemplation, and interested in what relates to nature.*" (1792, p. 246)

In his numerous writings on geology, phlogiston, light, heat and fire, rain, agriculture, and a theory of matter, Hutton had, by his own measure, certainly succeeded.

6. COAL AND JAMES HUTTON

In analyzing many of Hutton's well-known works using coal as a focal point, I hope to have underscored not only how natural theology permeated Hutton's "science," but also how his works on phlogiston are central benchmarks, even for interpreting his geology, within Hutton's own conceptual framework. At the same time, I hope to have illustrated how recent views that Hutton's thinking was governed more by theory than by observation or experiment (e.g. Gould, 1987) are as misguided as earlier views that cast him as a pure Baconian inductivist. Rather, Hutton perceived a synergistic balance between theory and observation, striving to understand both divine ends (final cause) and natural means (efficient cause). He measured his conceptual claims in terms of documented observations and—in a way not always fully appreciated, I think—framed prospective experimental investigations, as well. Hutton's views on coal, appearing throughout his publications, indicate how we might assemble those works together into a more complete and more textured interpretation of Hutton as a natural philosopher.

REFERENCES

ALLCHIN, D. Phlogiston after oxygen. **Ambix**, vol. 39, p. 110-116, 1992.

ALLCHIN, D. James Hutton and phlogiston. **Annals of science**, vol. 51, p. 615-635, 1994.

BAILEY, E. B. James Hutton, founder of modern geology. **Transactions of the Royal Society Edinburgh**, vol. 63(B), 1950.

BAILEY, E. B. **James Hutton - the founder of modern geology**. Amsterdam: Elsevier, 1967. 161p.

DONOVAN, A. & PRENTISS, J. James Hutton's medical dissertation. **Transactions of the American Philosophical Society**, vol. 70, no. 2, 1980.

GERSTNER, P. A. The reaction to James Hutton's use of heat as a geological agent. **British journal for the history of science**, vol. 5, p. 353-362, 1971.

GOULD, S. J. **Time's cycle, time's arrow**. Cambridge, MA: Harvard University Press, 1987.

HUTTON, J. Theory of the earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the globe. **Transactions of the Royal Society Edinburgh**, vol. 1, pt. 2, p. 209-304, 1788.

HUTTON, J. A chymical dissertaion concerning phlogiston, of the principle of fire. Part II in **Dissertations on different subjects in natural philosophy**, Edinburgh, 1792.

HUTTON, J. **Dissertation on the philosophy of light, heat, and fire**. Edinburgh, 1794.

HUTTON, J. **Theory of the earth with proof and illustrations**. London: Cadell, Junior and Davies, and Edinburgh: Willam Creech, 1795. 2 vols.: 620p. and 567p.

HUTTON, J. Dissertation on the philosophy of light, heat, and fire: abstract. **Transactions of the Royal Society Edinburgh**, vol. 3, "History," p. 7-16, 1796.

HUTTON, J. An examination of a new phenomenon which occurs in the sulphurating of metals: abstract. **Transactions of the Royal Society Edinburgh**, vol. 4, pt. 1, p. 27-36, 1798.

PLAYFAIR, J. **Illustrations of the Huttonian theory of the earth**, Edinburgh: William Creech, 1802.

PLAYFAIR, J. Biographical account of the late Dr. James Hutton, F.R.S. Edin. **Transactions of the Royal Society Edinburgh**, vol. 5, pt. 3, p. 39-99, 1805.

NOTES

[1] [updated 2002] Program in the History of Science and Technology, University of Minnesota, Minneapolis MN 55455, USA; allchin@pclink.com.

[2] Hutton is certainly not unique in recognizing the vegetable origin of coal; Playfair, for example, notes that Buffon, Arduino and Kirwan all acknowledged this (1802, pp. 148-150; one may easily add others—Bergman and Murray, for example). But Hutton goes further by considering the

process of transforming plants into coal: "it remains to know by what means, from a vegetable body, this bituminous matter is produced" (1795, p. 575)—that is, whether by heat or by water. In so doing, Hutton makes significant distinctions about types of coal not fully addressed by others.

[3] Hutton also discusses plumbago as a further extreme of distillation (1795, p. 615-617).

[4] Hutton presented these ideas in this passage not so much to argue for them but merely to illustrate that his critic, Kirwan, did not show that this theory was in any way misconceived.