The Gaia Theorem and Minesite-Drainage Chemistry: Implications and Observations

Kevin A. Morin[1] and Nora M. Hutt[1]

[1] Minesite Drainage Assessment Group (*www.mdag.com*)
Suite 3301, 1199 Marinaside Crescent,
Vancouver, British Columbia, Canada V6Z 2Y2

Abstract: Minesites can be considered "open" systems from the perspective of thermodynamics, science, and engineering, because there can be an exchange of energy, inorganic matter, and biological organisms among minesite components, and between a component and the surrounding environment. This concept of open systems can be expanded to include the Gaia Theorem.

The Gaia Theorem, growing out of studies of earth microbes and potential life on adjacent planets, holds that the Earth can be thought of a single living entity, or superorganism, composed of millions of living species and inorganic matter. Organic and inorganic feedback and interactions within the superorganism lead to a large-scale regulation of physical and chemical parameters, like temperature and oxidation state, to maintain optimum living conditions.

By applying fundamentals of the Gaia Theorem to minesites, particularly to the chemistry of waters draining on and from minesites, apparent explanations for observed trends and cyclical patterns become apparent. For example, *Thiobacillus ferrooxidans* is often quoted as capable of accelerating rates of sulphide oxidation by six orders of magnitude, but such acceleration has not been observed under natural conditions. As another example, compilations of chemical analyses of minesite drainage by the authors, involving thousands of analyses spanning decades at several monitoring locations at a minesite, often show repeating patterns of chemistry resembling statistical distributions. While these patterns can be traced in part to secondary-mineral equilibrium, this is not sufficient to explain the cyclical variations.

We discuss the implications of applying the Gaia Theorem to minesite-drainage chemistry. Basically, the Gaia Theorem lies somewhere on the gradational scale between detailed scientific analysis and philosophical views on universal Oneness. As a result, the Gaia Theorem is not fully compatible with either endpoint and offers no detailed lessons for scientific analysis of minesite-drainage chemistry. However, it does highlight the need to include a wider view in our analysis, beyond the principles of only one science, even if a full world-scale view is not possible.

Introduction

Minesites and their components like waste-rock piles and tailings impoundments are located "outside." They are exposed to air, temperature fluctuations, and hydrological events. There can be an exchange of energy, inorganic matter, and biological organisms among minesite components, and between a component and the surrounding environment. Therefore, it is clear that these components are "open systems" from the perspective of thermodynamics, science, and engineering.

Open systems are those that do not have well defined or controlled boundary conditions for some processes that affect them. Since boundary conditions are human-created factors, this means simply that a full and detailed analysis of a minesite component cannot be carried out by humans.

A full and detailed analysis of an energy balance, for example, would have to include factors like geothermal gradients, solar storms, cosmic radiation, electromagnetic fluctuations, and meteorological events including precipitation and evaporation. In practice, such an energy balance is often simplified to just a few factors for which there is measured information, with the assumption that all other factors are insignificant at all times. However, as time passes, humans learn that environmental systems are more complex than previously thought, and are indeed affected by processes once thought insignificant or impossible. The oceans are one example:

> "[Modern monitoring techniques] are revealing a physical ocean more complex and changeable than we ever imagined, more like a weather system than a geological one, complete with turbulence, fronts, and strange abyssal storms." (Ackerman, 2000).

Our work typically involves minesite-drainage chemistry, environmental geochemistry, hydrogeology, hydrology, and contaminant-flowpath analysis. We therefore wonder at times if we are capturing all significant factors in our work, and we wonder if there might be another, very different way of conducting our scientific analyses.

One alternative might be the Gaia Theorem. The Gaia Theorem raises the point of whether we can understand and predict the physical, chemical, and biological processes in a minesite component without using a much larger, integrated approach. Therefore, it is our objective here to reexamine aspects of minesite-drainage chemistry using the Gaia Theorem.

The Gaia Theorem

The Gaia Theorem grew out of studies of earth microbes and potential life on adjacent planets. The formal Theorem was developed primarily by James Lovelock of the United Kingdom and Lynn Margulis of the United States, although their work is built on prior work by many others. One of the latest books that develops the concept well is *The Ages of Gaia* (Lovelock, 1988), but various other publications add details to the concept.

Lovelock (1988) alludes to the mindset needed by humans to appreciate the Gaia Theorem:

> "You may think of the academic scientist as the analogue of the independent artist. In fact, nearly all scientists are employed by some large organization, such as a governmental department, a university, or a multinational company. Only rarely are they free to express their science as a personal view . . . [W]ell-meaning but narrow-minded [peer review of scientific work] ensures that scientists work according to conventional wisdom and not as curiosity or inspiration moves them. Lacking freedom they are in danger of succumbing to a finicky gentility or of becoming, like medieval theologians, the creatures of dogma."
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> Also, "Physical scientists regard biology as extraterritorial and biologists reciprocate; the members of each discipline tend to accept uncritically the conclusions of the other. This is a triumph of expertise over science, and it is expressed with great innocence when scientists try to explain the separation of their findings into physical and biological parts as a necessary consequence of expertise."

Thus, a conventional attitude and approach will not work here according to Lovelock. This raises the first hurdle to our objective of reexamining minesite-drainage chemistry using the Gaia Theorem.

An interesting observation on the previous quotations is that Lovelock is apparently throwing off the shackles and constraints of conventional science and leaving other scientists to their "dogma". In this way, he feels free to create a new approach. However, Lovelock's attitude is in fact typical of many scientists and researchers today. Armstrong (1993) explains:

> "Ultimately in our own day it would be impossible for an expert in one field to feel any competence whatever in another. It followed that every major intellectual saw himself less as a conserver of tradition than as a pioneer . . . The innovator who made such an effort of imagination to break new ground and, in the process, overthrow old sanctities, became a cultural hero . . . In science people were learning that they had to be ready to scrap the past and start again from first principles in order to find the truth."

As a result, the apparent first hurdle to our objective is minor, because re-evaluating older conventional science using the Gaia Theorem is really not so radical or unusual after all. Such attempts to overthrow old sanctities are now expected and encouraged.

The core of the Gaia Theorem is summarized by Lovelock (1988):

> "Through Gaia theory I now see the system of the material Earth and the living organisms on it, evolving so that self-regulation is an emergent property. In such a system active feedback processes operate automatically and solar energy sustains comfortable conditions for life. The conditions are only constant in the short term and evolve in synchrony with the changing needs of the biota as it evolves."

In other words, organic and inorganic feedback work together for large-scale regulation of physical and chemical factors, which lead to relatively comfortable conditions for life on earth. Since one of these feedback systems works properly only in the presence of all other feedback systems, the Earth forms an integrated "superorganism" called Gaia. This becomes the primary hurdle to meeting our objective: can anyone thoroughly understand a small portion of Gaia, like a waste-rock pile or tailings impoundment, without including all of the larger superorganism?

Lovelock (1988) emphasizes that Gaia does not contain mystical qualities and does not require inherent intelligence in the superorganism or supernatural intent. In this way, he makes the Theorem palatable to conventional scientists. Other, less technical versions of the integrated-earth view have been expressed by New Age followers and adherents of the more militant Deep Ecology (e.g., Naess, 1988) and by arguments over "soft green" and "hard green" (Huber, 1999).

Lovelock (1988) continues his illustration, expanding on inorganic and organic aspects of the earth:

> "You also may find it hard to swallow the notion that anything as large and apparently inanimate as the Earth is alive. Surely, you may say, the Earth is almost wholly rock, and nearly all incandescent with heat . . . [T]he difficulty can be lessened if you let the image of a giant redwood tree enter your mind. The tree undoubtably is alive, yet 99% of it is dead. The great tree is an ancient spire of dead wood, made of lignin and cellulose by the ancestors of the thin layer of living cells which constitute its bark. How like the Earth, and more so when we realize that many of the atoms of the rocks far down into the magma were once part of the ancestral life from which we all have come."
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> "When the activity of an organism favors the environment as well as the organism itself,

> then its spread will be assisted; eventually the organism and the environmental change associated with it will become global in extent. The reverse is also true, and any species that adversely affects the environment is doomed; but life goes on."

When these aspects of the superorganism are considered, scale becomes important in defining and observing processes:

> "On a local scale adaptation is a means by which organisms can come to terms with unfavorable environments, but on a planetary scale the coupling between life and its environment is so tight that the tautologous notion of 'adaptation' is squeezed from existence. The evolution of the rocks and the air and the evolution of the biota are not to be separated."

This leads Lovelock to several important observations. First, life is not defined by an individual organism or a group of organisms, but is a planetary-scale phenomenon that is nearly immortal and has no need to reproduce. Second, in the long term, a planet is either fully occupied by life or biologically dead, because partial occupation would not provide sufficient feedback needed to regulate the environment for the continuation of life. Third, Darwin's basic concept of life adapting to its environment is not strictly correct, because "the evolution of the species and the evolution of the rocks, therefore, are tightly coupled as a single, indivisible process". Fourth, the science of ecology is expanded to include the physical environment and a large number of interacting species, which lead to mathematical stability in ecosystem modelling and environmental stability on the earth.

It is important to note that Gaia and its feedback cycles should not be equated with equilibrium, small-scale stability, or deterministic behaviour:

> "There is no complete determinism in the Universe; many things are as unpredictable as a perfect roulette wheel. An ecologist colleague of mine, C.S. Holling, has observed that the stability of large-scale ecosystems depends upon the existence of internal chaotic instabilities. These pockets of chaos in the larger, stable Gaian system serve to probe the boundaries set by the physical constraints to life." (Lovelock, 1988)

Relevant Observations from Minesite-Drainage Chemistry

Since the Gaia Theorem links organic and inorganic systems into one, we will start with a system well known in minesite-drainage chemistry: sulphide oxidation by *Thiobacillus ferrooxidans*. *T. ferrooxidans* is often quoted as capable of accelerating rates of sulphide oxidation by six orders of magnitude, with frequent references to Singer and Stumm (1970) as evidence. Several aspects of that study were discredited shortly after (Morth et al., 1972), but the original paper is still referenced. This is perhaps due to the dramatic impression of such an acceleration or the increased attention for biologists.

However, as many biologists know, one species does not exist by itself within an ecosystem. In minesite components, many species of bacteria, viruses, and single-cell organisms coexist with, or replace, *T. ferrooxidans* (Benner et al., 2000; Edwards et al., 2000a and b; Lee and Fein, 2000; Bargar et al., 2000; Brake et al., 2001). Unfortunately, the effects of these numerous other species have not been documented, but they do not necessarily cause a deviation from equilibrium conditions (Fein and Delea, 1999). In fact, the identities of many species remain unknown at this time.

One can envision that at least one of these species can control the growth and activity of *T. ferrooxidans* since this bacterium is not at the top of a food chain. Put in anthropomorphic terms, one or more species may raise *T. ferrooxidans*, as humans raise cattle. Perhaps *T. ferrooxidans* does the same to some of the other species. According to the Gaia Theorem, all the species plus the inorganic environment will establish a large-scale balance for the comfort of all life. This casts doubt on a “run away” scenario of *T. ferrooxidans* causing sulphide oxidation to accelerate by six orders of magnitude, swamping the ecosystem with great excesses of energy and nutrients and subsequent waste products.

Not surprisingly, large accelerations of sulphide oxidation are actually not often observed. For example, laboratory and field studies with sterile and non-sterile samples showed similar oxidation rates over a range of pH from 1 to 8 (Van Stempvoort and Krouse, 1994; Nicholson, 1994; Kwong et al., 1995; Kirby and Brady, 1998; Morin and Hutt, 1997, 1998, 1999, and 2000). This is one example of a balance attained in an ecosystem involving numerous species and inorganic substrates. However, as explained in the last paragraph of the previous section, small-scale perturbations in the oxidation rate can arise, such as when freshly broken rock surfaces are first exposed in a waste-rock pile or freshly pulverized tailings are discharged to an impoundment.

Another effect that can be examined for physical-chemical-biological feedback is found in routine monitoring of water chemistry at minesites. Over many years to decades of oxidation and weathering, primary minerals within rock and tailings break down to secondary minerals. This suggests that substantial changes in aqueous concentrations should be observed over the decades. At sulphide-bearing minesites, an example of such a change would be a shift in pH from near-neutral values to acidic ones as effective neutralization potential is depleted. Then, as sulphide minerals are depleted and/or coated with secondary-mineral precipitants, aqueous concentrations should decrease through time. The “shrinking core” model is one example of this expectation.

While shifts in pH are common, the available large, long-term monitoring databases of aqueous concentrations reveal cyclical patterns and seasonal variabilities whose extents (expressed as standard deviations) are often independent of pH, time, and flow (Morin and Hutt, 1997 and in press; Morin et al., 2001). In other words, pH and a few other geochemical parameters can often explain much of the long-term variation in aqueous concentrations, but when the effect of these parameters is removed seasonal regularity becomes apparent year after year. Obviously, this regularity reflects the summation of the effects of all other (countless) physical, chemical, and biological processes operating at a minesite. While the regularity can be traced in part to secondary-mineral equilibrium, this is not a sufficient explanation. The detailed explanation cannot be discerned from the database or the knowledge of the minesite, and thus it lies outside current understanding. It may involve so many processes that the explanation may never be known.

The Gaia Theorem Applied to Minesite-Drainage Chemistry

In the preceding section, we can see that there are aspects of environmental geochemistry at minesites that cannot be understood and predicted simply from principles of environmental geochemistry. Can the Gaia Theorem help?

The Gaia Theorem is not compatible with current scientific analysis and investigation, which typically examines a system that is isolated (as much as possible) from its surroundings. This allows close observation of such a system as its conditions are manipulated. Even if an environmental system like a waste-rock pile could be mostly isolated from its surroundings, the Gaia Theorem would say that any degree of artificial isolation changes the system.

Another way of looking at this is through a gradational scale from current scientific analysis to philosophical and religious views of the universe. Each step on the scale is sufficiently different from the other steps that they cannot be reconciled. For example, some Eastern philosophies and religions consider the universe to be an indivisible Oneness (e.g., “Nothing ever exists entirely alone; everything is in relation to everything else.”, Bukkyo Dendo Kyokai, 1984). Also, several Western religions ultimately view God as this Oneness (Armstrong, 1993). These views are even more expansive and all-encompassing than the Gaia Theorem which considers only the earth. As a result, the Gaia Theorem is located somewhere on the scale between detailed scientific analysis and universal Oneness.

Therefore, just as scientific analysis cannot be reconciled with concepts of universal Oneness and God, it cannot be reconciled with the Gaia Theorem. Similarly, the Gaia Theorem cannot be reconciled with the concepts of universal Oneness and God. In the Introduction, we asked whether we are capturing all significant factors in our work, and we wonder if the Gaia Theorem might be another way of conducting our scientific analyses. We thus conclude that the Gaia Theorem indicates we are not capturing all significant factors, but that the Gaia Theorem does not offer a scientific alternative.

This does not mean that the Gaia Theorem offers absolutely no lessons for those conducting scientific analysis of minesite geochemistry, although the lessons are not analytical in nature. As illustrated in the previous section, we can learn more about the environment and about human limitations to knowledge by expanding our views beyond our areas of environmental geochemistry, hydrology, biology, etc. This will at least remind us that we do not know and understand everything needed to make accurate deterministic predictions of environmental systems. It will show us that we must continue learning about other scientific fields to better understand our own limited field of endeavour.

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