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Review

# The Biogeochemistry of Strontium: a review of H.T. Odum's contributions

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Howard T. Odum spent the late 1940s at Yale University. He completed his doctoral dissertation, "The Biogeochemistry of Strontium," in 1950 under the direction of the famous limnologist and theoretical ecologist G. Evelyn Hutchinson. Without access to notes or personal correspondence, one may only speculate as to why Odum chose to study the global cycle of this trace element. Possibly, Hutchinson suggested the topic: in his own treatise on the biogeochemistry of aluminum and several "lithophilic" trace elements (Hutchinson, 1943), Hutchinson pointed out the uncertainty in the amount of strontium in living terrestrial plants. Strontium was also seen as a means to trace paleoecological processes such as diagenesis of limestones (Odum, 1951a, 1957a, 1957b). Finally, strontium attracted worldwide attention as a notable fission product ($^{90}Sr$) during the post-World War II years. In the early 1950s, the American public was introduced to the word strontium by extensive media coverage of the discovery that radioactive strontium from nuclear bomb testing had entered food chains and, through biomagnification, made milk sufficiently radioactive to warrant warnings against its consumption.

Odum concluded his dissertation after three years of research while moving from Yale to a faculty position at the University of Florida in 1950. He published his doctoral work in a half dozen papers, of which I will review the three most important. The first was "The Stability of the World Strontium Cycle," published in *Science* in 1951; the second and third were published simultaneously in *Publications of the Institute of Marine Science* (Odum, 1957a, 1957b) when Odum was director of the Institute of Marine Sciences, University of Texas. Other papers (e.g., Odum, 1951b, 1951c, 1951d) documented some aspects of the research as short notes.

"The Stability of the World Strontium Cycle" summarized succinctly the global strontium biogeochemical cycles as a mass balance: material entering the oceans, sedimenting out on the ocean floor, undergoing diagenesis to sedimentary and eventually igneous rock, and returning to the continental surface by volcanism and uplift (Fig. 1, taken from Odum, 1951a). "One suspects that the cycle may be closed and stable, because 95% of all matter draining to the sea is estimated . . . to be of sedimentary origin and is again being deposited as sediments. If the 5% of igneous matter draining to the sea is equaled by the sedimentary matter incorporated into igneous rock each year, the cycle will be stabilized and closed, not only for strontium and calcium, but possibly for other elements also (p. 408)." Four lines of evidence are brought to bear on this hypothesis: the balance of Sr/Ca ratios in inputs and outputs; calculation of flux rates; identification of a self-regulating mechanism (basically, biological uptake); and paleochemical data.

Odum's thesis is built on the theoretical foundations of Lotka (1925), Tansley (1935), and

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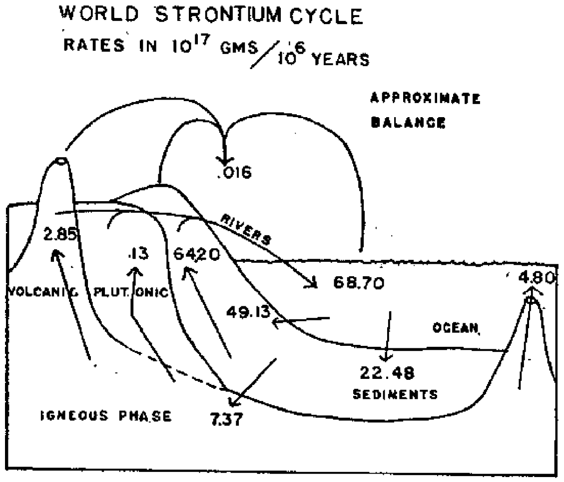


Fig. 1. Global flux of strontium estimated by Odum (1951a).

Hutchinson (1948), and it emphasized self-regulation, biotic–abiotic linkages, cybernetics, and steady state. All three works are cited in this paper. He went so far as to write: “As a stable steady-state pattern in nature involving both living and non-living components, the strontium cycle seems to qualify as one of the large entities which in ecological literature are known as *ecosystems* [*sic*] as defined by Tansley . . . It is suggested that the ‘strontium ecosystem’ is a proper application of the term (p. 411).”

The data supporting Odum (1951a) had to wait six years before seeing publication as two companion monographs (Odum, 1957a, 1957b). Together, “strontium in natural waters” and “Biogeochemical deposition of strontium” provide 300 measurements of Sr and Ca in waters and 900 measurements in biogenic and inorganic materials, most made by Odum himself. In these days of million-dollar, state-of-the-art instruments that require NSF funding to maintain, it is humbling to read that Odum built his own spectrophotometer! “A flame photometer was devised from a qualitative, classroom, Cenco grating spectrograph by mounting a photomultiplier tube opposite the calcium line and another opposite the strontium line. The output of the photomultiplier tube was passed into a dc amplifier and read on a 10 in., zero to 50, microameter [*sic*]. With this apparatus it was possible to read strontium, calcium, and the background blue flame successively in a few seconds by tilting the nebulizer and by throwing a circuit switch to indicate first the calcium emission and then the strontium emission. Standards were made from known carbonate concentrations also dissolved in 20% HCl (as were the samples). Laborious as these methods are, they have insured that all interference of foreign substances was eliminated” (Odum, 1957a, pp. 23–24).

In addition to providing a wealth of new data, Odum was clearly a master of the strontium literature of the time and incorporated his findings into this substantial body of work. Odum proposed a number of hypotheses in these papers as to the cycling mechanisms that could be understood by examining Sr/Ca ratios. Among the important ones: the concentration of strontium is highly correlated with salinity, and many organisms take up Sr in some proportion to the environmental Sr/Ca ratios (a point that had been forgotten until recently “re-discovered” in fisheries science); Sr/Ca declines with the age of limestones, through a process referred to as “replacement,” whereby aragonitic deposits are dissolved, re-crystallize as calcite, while simultaneously losing Sr into ground water, which becomes enriched in Sr as a result. On a global scale, Odum argued that orogenic uplift eventually mixes Sr-depleted surface waters with Sr-enriched ground water to produce a more-or-less constant flux of Sr/Ca into the world’s oceans.

“Biogeochemical deposition of strontium” is an exhaustive treatise, much like the works of Odum’s mentor Hutchinson. My own entrée to the use of strontium has been to use Sr/Ca as an indicator of the past environmental history of individual fish, through microchemical techniques (e.g., Limburg, 1995). The use of strontium/calcium ratios has become an important tool in fisheries, because fresh water often has Sr/Ca ratios 8–10 times lower than the sea, and otoliths take up Sr in proportion to environmental Sr/Ca (although temperature can be a modifying factor). Strontium thus can be used as a tool to help uncover details of fish life history and lifetime habitat use. Odum (1957a, 1957b) covers much of the essential background necessary for understanding how to apply the use of Sr/Ca to track fish migration. Much of the modern strontium literature does not cite Odum’s massive contributions to the fields of biogeochemistry, paleoecology, and biology through this work, not even Schlesinger (1997) in his reference work on biogeochemistry! Nevertheless, re-reading these papers, I am in awe that this young man produced such a careful, comprehensive, and still useful body of work, even while galvanizing the field of ecosystem ecology in other directions.

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