ZoBell and his contributions to the geosciences

Henry L. Ehrlich

Department of Biology, Rensselaer Polytechnic Institute, Troy, NY 12180-3590 USA

ABSTRACT

Claude ZoBell recognized that some bacteria serve as geologic agents. His work in marine microbiology, including barobiology, and in petroleum microbiology had a significant impact on the geosciences. He showed that microbial life existed in all parts of the oceans and developed methods for observing it. He and his students anticipated the current interest in deep subsurface microbiology in their studies in petroleum microbiology, and by demonstrating the existence of viable bacteria at depths as great as 350 cm within deep-sea sediments. He proposed a bacterial role in the origin of petroleum. He felt that bacteria growing in sediment facilitated migration of petroleum from its site of formation to oil traps, a concept that about 35-40 years later was applied by others to microbially enhanced oil recovery. His observations and those of others of bacterial attack of petroleum hydrocarbons led to the concept of bioremediation of oil pollution. ZoBell's recognition that some microbes serve as geologic agents culminated in his founding of the Geomicrobiology Journal in 1978 and serving as its first editor-in-chief.

Claude ZoBell's scientific interests were wide-ranging, as reflected in his personally prepared bibliography, which by 1975 included 248 publications. By 1932, having joined the faculty of Scripps Institution of Oceanography, these interests were concentrated on marine microbiology [3, 5], and by 1941 included petroleum microbiology [14]. Although ZoBell seems to have recognized the geological significance of the research findings from his laboratory early on, -- he spoke of bacteria as geologic agents in a publication in Petroleum World in 1943 [17] and as geochemical agents in an article in Science in 1952 [23] --, geoscientists in general accepted the notion of a microbial role in some geologic processes only gradually. Some microbiologists before him (e.g., Winogradsky, Omeliansky, Beijerinck, and Bavendamm, to name a few), with whose work ZoBell was quite familiar [18, pp. 3-9; 92-93; 100-104; 108-112; 136-139; 150-157; 158-166; 167-169; 200-208], had studied some other biological activities of potential significance to geology, but their findings made no greater impression on geoscientists in their time than his did. Many geoscientists in those days felt that they could explain geochemical processes to their satisfaction in purely physicochemical terms.

ZoBell recognized that when bacteria or other microbes act as geologic agents, they influenced, indeed controlled, certain geochemical reactions in specific instances. Bacteria may do so by directly catalyzing a chemical reaction, such as the oxidation of ferrous ion to ferric oxide, for instance. They may also do it by consuming certain compounds, like oxygen in an oxygen-limited environment, thereby creating anaerobic conditions that will permit reactions like bacterial reduction of ferric compounds. Furthermore, they may generate metabolic products, as, for instance, sulfide in sulfate reduction, which may then

Microbial Biosystems: New Frontiers
Proceedings of the 8th International Symposium on Microbial Ecology
Bell CR, Brylinsky M, Johnson-Green P (ed)
Atlantic Canada Society for Microbial Ecology, Halifax, Canada, 1999.

react with metal ions and precipitate them as metal sulfides. In the absence of bacteria, any of these reactions would proceed at a very much slower rate or, as in the case of sulfate reduction, not at all under environmental conditions prevailing in the Earth's biosphere.

ZoBell's first significant impact on geology was through his investigations in petroleum microbiology that began during World War II and continued into the 1970's. These investigations included studies on the origin of petroleum, the natural formation of petroleum reservoirs, hydrocarbon metabolism of bacteria, petroleum pollution, and bioremediation. His reports on the subject appeared in journals such as World Oil, Petroleum World, Proceedings of the American Petroleum Institute, Sedimentary Petrology, and Industrial and Engineering Chemistry. The impact of these studies on petroleum geology can be attributed to the economic importance that petroleum was assuming during this time.

ZoBell proposed a bacterial role in the origin of petroleum [14, 22, 24, 26]. In an article in World Oil in 1950 [22], he suggested that microbial modification of organic remains in sediments could contribute precursors for oil formation by lowering their oxygen and nitrogen content and increasing their carbon and hydrogen content, and produce methane and other hydrocarbons directly. In that article he also suggested that hydrogenation of unsaturated fatty acids and their subsequent decarboxylation might contribute to petroleum formation. Although a bacterial role in the initial processing of organic matter from which petroleum derived appeared certain to ZoBell and has become generally accepted, evidence from lab experiments that bacteria were directly responsible for hydrocarbon production in significant quantities remained equivocal in 1952 [11], and he later largely abandoned the idea of direct microbial formation of hydrocarbons in large amounts from organic matter for lack of supportive evidence [26].

In connection with the natural accumulation of petroleum in reservoirs (oil traps), ZoBell concluded that some bacteria promoted release of petroleum from oil-bearing materials such as sediment particles by destroying the mineral particle to which the oil was adsorbed and/or by generating surface active agents that released the oil from such particles [20, 22, 24]. He also suggested that some metabolic products such as methane could lower the viscosity of oil, and with microbially generated CO_2 could generate pressures that facilitate petroleum migration [20, 22, 24], concepts that about 35-40 years later were applied by others to microbially enhanced oil recovery (MEOR)[1, 4, 12].

ZoBell's observations [11, 17, 18, 19, 28, 29, 30, 36] and those of others that some bacteria are able to attack petroleum hydrocarbons led to the concept of bioremediation of oil pollution in recent times.

Although isolated microbiological studies of parts of the marine environment had been undertaken for several decades preceding ZoBell's work [18], he was the first true marine microbiologist who examined all parts of the ocean environment systematically. Thus, he showed that microbial life existed in all parts of the oceans. To accomplish this objective, he developed special methods for observing it [3, 18, 27, 35]. To avoid the use of Nansen bottles made of brass to collect water samples in the deeper oceans, he and a collaborator perfected a method for collecting samples from the water column in a sterile, evacuated container with a sealed capillary intake tube that was broken in situ by a messenger-activated system [32, as cited in 18]. This design culminated in the J-Z bacteriological water sampling bottle (13, as cited in 18 and 25; 15]. The brass of Nansen bottles has the disadvantage of releasing trace amounts of toxic metals into seawater collected with it, which could poison microbes in the water samples. Further, he and his student Carl Oppenheimer, devised a method for culturing bacteria in liquid medium under elevated hydrostatic pressure [35]. His sampling and pressurized culturing methods enabled him and his student Richard Morita to demonstrate convincingly for the first time during the Danish Galathea expedition of 1950-1952 that microbial life existed even in deep-sea trenches [3, 23, 34 as cited in 27]. It was also in connection with these findings that ZoBell and Morita [33] clearly demonstrated that a portion of the bacteria they recovered from hadal depths (7,000 to 10,000 m) were barophilic. Among the organisms from these depths, they found aerobes and anaerobes, including starch hydrolyzers, nitrate reducers, ammonifiers and sulfate reducers.

ZoBell addressed the question of the lower limits of the biosphere at least as far back as 1946 in his book, "Marine Microbiology", chapter VI [18]. In this book, he commented on the then common belief that bacteria would not be found widely distributed in ancient sediments, although evidence to the contrary was being obtained "in certain deeply buried deposits containing organic matter" [18, p. 93]. He pointed out that in 1940, Rittenberg [9], who was one of his students, reported detection of viable bacteria in ocean sediment cores longer than 350 cm from a water depth of 566 m. In 1950, he and Morita recovered viable bacteria from deep-sea sediment samples from water depths ranging from 1720-5032 m taken during the Mid-Pacific Expedition mounted by Scripps Institution of Oceanography and the U.S. Naval Electronics Laboratory [6]. More specifically, they found that viable aerobic and anaerobic bacteria were recoverable from globigerina ooze at sediment depths as great as 275 and 319 cm. The sediment cores were obtained at a water depth of 5032 m [6]. Indeed, they were able to culture aerobic bacteria but not anaerobic ones from red clay at sediment depths as great as 400 to 750 cm, the sediment cores coming from a water depth in excess of 4000 m [6]. ZoBell was aware of a potential contamination problem in coring sediments and described a method of retrieving core centers for culturing by aseptic dissection of cores. His assumption was that the centers of the cores were not contaminated in the coring process [16, p. 128]. In 1946, he believed that temperature and availability of organic matter and water were limiting factors in long-term survival of microbes in sediments [18, p. 93]. He felt that low temperature and anaerobic conditions in bottom deposits were "most conducive to longevity of bacteria in a dormant state" [18,31]. Since he and Morita knew the sediment at these depths to be very old, they wondered how the bacteria in them could have remained viable for such very long times [6]. They considered autotrophy by hydrogen consumption in sulfate reduction as shown by Sisler and ZoBell [10], and oligotrophy and carbon recycling as possible explanations. ZoBell also wondered about microbes at the subsurface on land. For evidence of long-term survival of living bacteria at great subsurface depths on land, ZoBell cited Issachenko's claim [2] of detecting bacteria in discharges from oil wells 2000 m deep [18]. It seems clear from the previously mentioned studies and from some others on petroleum deposits (see discussion above) [9; 18, p.90-93; 24; 31] that ZoBell and his students anticipated the current interest in deep subsurface microbiology on land and in the sea [7, 8].

ZoBell's recognition that some microbes serve as geologic agents led to his founding of the Geomicrobiology Journal in 1978 and serving as its first editor-in-chief. After reaching an agreement with Crane Russak & Co., Inc. in New York City in September 1976 to publish the Geomicrobiology Journal, ZoBell nominated an Editorial Board divided into (1) an Editorial Advisory Board consisting of Preston Cloud (USA), Sebastiano Genovese (Italy)), Tadoshiro Koyama (Japan), S. I. Kuznetsov (USSR), J.R. Postgate (England), Wilhelm Schwartz (West Germany), and P.A. Trudinger (Australia), (2) Associate Editors consisting of T.D. Brock (USA), H.L. Ehrlich (USA), Wolfgang Krumbein (West Germany), R.Y. Morita (USA), and J.J. Skujins (USA), and (3) Members of the Board of Editors consisting of Martin Alexander (USA), J.B. Davis (USA), Y.R. Dommergues (France), Tom Fenchel (Denmark), Kaare Gundersen (Sweden), R.O. Hallberg (Sweden), Akihito Hattori (Japan), Peter Hirsch (West Germany), M.V. Ivanov (USSR), K.C. Marshall (Australia), J. William Schopf (USA), M.P. Silverman (USA) Shinya Tsuru (Japan), and Teh Fu Yen (USA). The specialties of these individuals represented the scope of geomicrobiology covered by the Journal. In consultation with the Editorial Board, ZoBell established a publication policy in 1977 and assembled the first journal issue later that year. This first issue did not, however, appear until December 1978, in part due to production problems encountered by the publisher.

In the preface to the first issue, ZoBell stated that the aim of the Journal was to "provide for the exchange of ideas and information in a highly interdisciplinary field of science, i.e., geomicrobiology and biogeochemistry." He defined the scope of geomicrobiology as embracing "(a) the microbial transformation and mobilization of elements and minerals, (b) the mineralization of organic matter, (c) the diagenesis of bottom sediments, (d) soil formation, (e) production of such gases as H_2, N_2, H_2S, NH_3, CH_4, C_2H_6, CO, and CO_2, (f) the microbial transformation of fossil fuels, (g) the fractionation of isotopes, (h) calcium carbonate precipitation, and (i) paleomicrobiology." He explained that "bacteria and allied microorganisms in soil or aquatic environments might influence the adsorption, concentration, elution, chelation, solubilization, oxidation, or reduction of various elements, minerals, or combinations thereof." He also felt that "much more must be learned about how microbial activities influence the genesis and migration of petroleum, the sulfur cycle, manganese precipitation, and environmental conditions, especially the pH, Eh, oxygen tension, and surface tension in soil, sediment, and the hydrosphere." He pointed out that "practical problems in geomicrobiology include microbial beneficiation of ores, the part played by bacteria in the movement of oil in oil-bearing sediments, effects on radionuclides, and the microbial corrosion of iron, concrete, etc."

In late 1980, ZoBell announced that he would resign as editor-in-chief of the Journal with the completion of volume 2, owing to poor health. On the urging of the publisher, he accepted an appointment as chairman of the Editorial Advisory Board. ZoBell proposed to the publisher that Ehrlich succeed him as editor-in-chief. The publisher agreed to the proposal, and Ehrlich accepted the subsequent offer by the publisher of the appointment. Ehrlich served as editor-in-chief until 1997, when he became co-editor-in-chief with William C. Ghiorse. In honor of ZoBell's 80th birthday, the Journal issued a Festschrift [5] under the special editorship of Richard Y. Morita. The Journal has gone through a number of changes, not least of which was a change in publisher. Taylor & Francis took over the Journal in 1987.

The Geomicrobiology Journal represents the culmination in ZoBell's perception of the relation of microbiology to geology.

References

1. Adkins JP, Tanner RS, Udegbunam EO, McInerney MJ, Knapp RM (1992) Microbially enhanced oil recovery from unconsolidated limestone cores. Geomicrobiol J 10:777-86.
2. Issachenko BL (1940) On the microorganisms of the lower limits of the biosphere. J Bacteriol 40:379-381.
3. McGraw DJ (1993) Claude E. ZoBell, Hadal bacteria and the "azoic zone." V International Congress on the History of Oceanography. Proceedings. (in press).
4. McInerney MJ, Westlake DWS (1990) Microbially enhanced oil recovery. In: Ehrlich, HL and Brierley, CL (eds) Microbial Mineral Recovery. McGraw-Hill, New York, pp 409-445.
5. Morita RY (1985) Dedication (Festschrift in honor of Claude Ephraim ZoBell). Geomicrobiol J 4:101-102.
6. Morita RY, ZoBell CE (1955) Occurrence of bacteria in pelagic sediments collected during the Mid-Pacific Expedition. Deep-Sea Res 3:66-73.
7. Parkes RJ, Cragg BA, Bale SJ, Getliff JM, Goodman K, Rochelle PA, Fry JC, Weightman AJ, Harvey, SM (1994) Deep bacteria biosphere in Pacific Ocean Sediments. Nature (London) 371:410-413.
8. Pedersen K (1993) The deep subterranean biosphere. Earth-Sci Rev 34:243-260.
9. Rittenberg SC (1940) Study of some long cores of marine sediments. J Mar Res 2:208-217.
10. Sisler FD, ZoBell CE (1950). Hydrogen-utilizing sulfate-reducing bacteria in marine sediments. J Bacteriol 50:749-757.
11. Stone RW, ZoBell CE (1952) Bacterial aspects of the origin of petroleum. Ind Eng Chem 44:2564-2567.
12. Tanner RS, Udegbunam EO, McInerney MJ, Knapp RM (1992) Microbially enhanced oil recovery from carbonate reservoirs. Geomicrobiol J 9:169-195.
13. ZoBell CE (1941) Apparatus for collecting water samples from different depths for bacteriological analysis. J Mar Res 4:173-188.
14. ZoBell CE (1941) References on the possible role of microorganisms in the genesis of petroleum based upon recent observations. Report of Conference on the Origin of Oil, Amer. Assoc. Petrol. Geol., Tulsa, Oklahoma, pp. 39-44.
15. ZoBell CE (1942) Bacteria of the marine world. Sci Monthly 55:320-330.
16. ZoBell CE (1942) Changes produced by microorganisms in sediments after deposition. J Sediment Petrol 12:127-136.
17. ZoBell CE (1943) Bacteria as geologic agents with particular reference to petroleum. Petroleum World 10:30-43.
18. ZoBell CE (1946) Marine Microbiology. Chronica Botanica Company, Waltham, MA.
19. ZoBell, CE (1946) Action of microörganisms on hydrocarbons. Bacteriol Rev 10: 1-49.
20. ZoBell CE (1947) Bacterial release of oil from oil-bearing materials. World Oil 126:36-47 (as cited by ZoBell, 1952)
21. ZoBell CE (1948) Microbial transformation of hydrocarbons. J Gen Microbiol 2: viii-x.

22. ZoBell CE (1950) Bacterial activities and the origin of oil. World Oil 130:128-138 (as cited by ZoBell, 1952)
23. ZoBell CE. (1952) Bacterial life at the bottom of the Philippine Trench. Science 115:507-508.
24. ZoBell CE (1952) Part played by bacteria in petroleum formation. J Sediment Petrol 22:42-49.
25. ZoBell CE (1954) Some effects of high hydrostatic pressure on apparatus observed on the Danish Galathea Deep-Sea Expedition. Deep-Sea Res 2:24-32.
26. ZoBell CE (1963) The origin of oil. Int Sci Technol, August issue, pp. 42-48.
27. ZoBell CE (1964) Hydrostatic pressure as a factor affecting the activities of marine microbes. In: Editorial Committee of Sugawara Festival Volume. Recent Researches in the Fields of Hydrosphere, Atmosphere and Nuclear Geochemistry. Maruzen Co, Ltd, Tokyo Japan, pp. 83-116.
28. ZoBell CE (1964) The occurrence, effects and fate of oil polluting the sea. International Conference on Water Pollution Research, London. Pergamon Press, Oxford, UK, pp. 85-118.
29. ZoBell CE. (1969) Microbial modification of crude oil in the sea. Proc. API/FWPCA
30. Conference on Prevention and Control of Oil Spills. Amer. Petrol Inst Publ No 4040, Washington, DC, pp. 317-326.
31. ZoBell CE (1971) Sources and biodegradation of carcinogenic hydrocarbons. API/EPA/FWPCA Conference, Prevention and Control of Oil Spills. Amer Petrol Inst, Washington, DC, pp. 441-451.
32. ZoBell CE, Anderson DQ (1936) Vertical distribution of bacteria in marine sediments. Bull. Amer. Assoc. Petrol. Geol. 20:258-269.
33. ZoBell CE, Feltham CB (1934) Preliminary studies on the distribution and characteristics of marine bacteria. Bull Scripps Inst Oceanog Tech Ser 3:279-296.
34. ZoBell CE, Morita RY (1957) Barophilic bacteria in some deep sea sediments. J Bacteriol 73: 563-568.
35. ZoBell CE, Morita RY (1959) Deep-sea bacteria. Galathea Report, Copenhagen 1:139-154.
36. ZoBell CE, Oppenheimer CH (1950) Some effects of hydrostatic pressure on the multiplication and morphology of marine bacteria. J Bacteriol 60:771-781.
37. ZoBell CE, Prokop JF (1966) Microbial oxidation of mineral oils in Barataria Bay bottom deposits. Z Allg Mikrobiol 6:143-162.