Reports

Manganese Nodules on the Sea Floor: Inverse Correlation Between Grade and Abundance

Abstract. *The grade of copper and nickel in manganese nodules is negatively correlated with their abundance on the sea floor, within small regions and in the Pacific Ocean as a whole. Although the correlation tells nothing about estimates of commercially mineable reserves at particular sites, it contradicts an assumption on which many predictions with respect to manganese nodule resources are based.*

Enormous quantities of manganese nodules litter and pave the deep sea floor, and some of them contain nickel and copper in grades richer than those that are being mined on land. Thus a reasonable expectation has grown that the deep sea floor is about to be mined economically. This expectation has been heightened by an attempt by Deepsea Ventures, Inc., to stake a claim by application to the U.S. State Department (*1*). However, the claim is in legal limbo pending the resolution of controversies about the ownership and distribution of potential royalties which have been among the factors prolonging the United Nations Conference on the Law of the Sea.

The political and legal positions of various nations rest in part upon estimates of the amount and value of the metals in the nodules. These estimates, in turn, are based on scientific data and assumptions which merit analysis.

The unifying characteristic of manganese nodules as a group is that every individual property of the nodules is highly variable, and information about them can only be expressed statistically (*2*). For example, the amount of the sea floor covered by nodules ranges from 0 to 100 percent and tends to be patchy on all scales. The grade of various elements is almost as variable (*3*); in the Pacific, nickel is reported to range from 0.06 to 2.46 percent (by weight), and copper from 0.01 to 2.12 percent. This variability was early recognized, and so resources of various metals were initially estimated by multiplying the average grade by the average abundance by the area of a region with apparently consistent abundance. It was further reasoned that particularly desirable sites must exist where high-grade combined with high-nodule abundance would make mining potentially profitable under present economic conditions. On this assumption industrial investigators began to search for such sites, which many observers concluded would be available in large numbers.

As part of the U.S. government's contribution to knowledge about seabed resources, information about manganese nodules was collected in the United States as part of the International Decade of Ocean Exploration (IDOE) (*4*). These data have been used for the determination of distribution functions for individual properties of nodules. Archer (*5*) summarized much of this early IDOE information and found, not surprisingly, that the probability of finding many properties declines geometrically as the value of the properties increases. Thus, of 2310 essentially random sea-floor photographs, 85 percent showed no nodules, 7 percent showed up to 25 percent of the sea floor covered by nodules, and 2.4 percent showed a coverage of 75 to 100 percent. Likewise, the frequency distribution of the grade of nickel plus copper in 530 nodule locations declines from 23 percent for a grade between 0.25 and 0.50 percent, to 6 percent for a grade between 1.25 and 1.50 percent, to 2 percent for a grade between 2.25 and 2.50 percent.

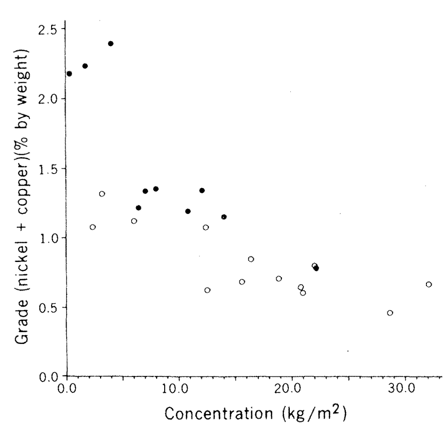

Fig. 1. (Open circles) Grade versus concentration for 13 sites in the South Pacific Ocean, 10°58′S to 11°08′S, 156°07′W to 156°21′W. (Solid circles) Grade versus concentration for ten sites in the North Pacific Ocean, 10°50′N to 11°01′N, 153°15′W to 153°35′W.

Estimates of reserves and resources based on these distribution functions (*5*, *6*) were arithmetically far more satisfactory than those based on mere averages. One need merely identify the economic cutoff of grade and abundance and multiply. For example, if 10 percent of the photographs showed an acceptable abundance and 10 percent of the analyses gave acceptable grades, then 1 percent of the sea floor would be suitable for mining.

However, this arithmetic was based on the assumption that grade and abundance are independent variables, and this relationship does not seem to be generally true. The first evidence of an inverse relationship between grade and abundance was derived from an analysis of all available Pacific data as a function of geological age (*2*). The percentage of samples with 1.0 percent or more nickel decreased from 33 percent to zero as the crustal age increased from 20 million to 120 million years. At the same time the percentage of photographs showing nodules increased from 10 to 47 percent. Any possible significance associated with this observation was obscured by the sampling methods. The photographed and analyzed nodules were from sediment of the same age but not necessarily from the same place.

We have studied locations for which both chemical analyses and information on nodule abundance are publicly available. Data for this study came from the Scripps Institution of Oceanography Sediment Data Bank, which includes the data originally compiled under the IDOE program plus much additional information collected since 1973 (*7*). Most data collected in industrial exploration efforts remain proprietary and could not be included.

At some of these locations the sea floor was photographed at or near the site where nodules were sampled. At others, a large undisturbed sample was collected with a box core and photographed on shipboard. At most of the sites nodules were collected by grab samplers, which sample a precisely measured area, and the nodules were weighed to determine concentrations in kilograms per square meter.

One consistent set of observations can be derived from 75 stations largely in the

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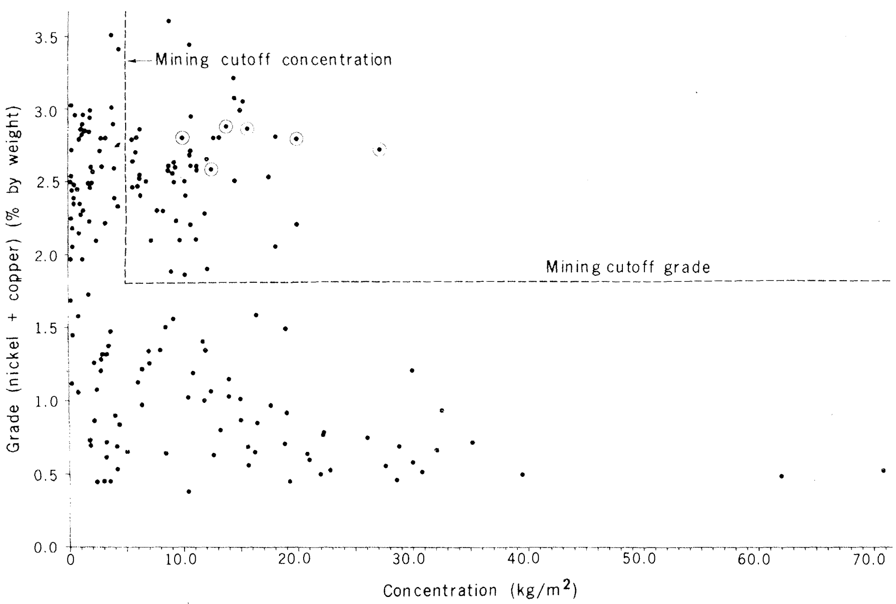

Fig. 2. Grade versus concentration for all sites in the Pacific Ocean for which information about both is available. Circled points indicate samples collected from within the mine site proposed by Deepsea Ventures, Inc. Cutoff grade and concentration values are form Holser (*6*) and Kildow *et al.* (*13*).

South Pacific, where nodules were collected by the research vessel *Vityaz* and analyzed by Skornyakova and her colleagues (*8*). The copper content ranges from 0.1 to 1.1 percent, the nickel content from 0.25 to 1.5 percent, and the concentration from 0.2 to 77 kg/m^2. The grade of each metal is inversely correlated with concentration at the 99.9 percent confidence level. Each correlation coefficient is only −.36, and so grade cannot be calculated from concentration. This weak correlation reflects the fact that regional variations occur, and low grades of nickel and copper seem to be associated with any sea-floor concentration of nodules.

Within most small areas, the correlation between grade and surface concentration is much stronger. Thirteen of the samples from near 11°S, 156°W, give a correlation coefficient for grade (nickel plus copper) versus concentration of −.81 at the 99.9 percent confidence level (Fig. 1). Samples collected from ten sites near 11°N, 153°W, give a correlation coefficient of −.84, also at a 99.9 percent confidence level (Fig. 1). In this area all samples above the cutoff grade of 1.8 percent copper plus nickel were found in concentrations below the cutoff of 5 kg/m^2 (*9*), whereas all nodules below the cutoff grade occurred in higher concentrations.

This negative correlation is apparently related to local topography. A number of investigators (*8*, *10*) have noted that nodules are usually more abundant on hilltops and slopes than in the valleys and at the base of hills. Skornyakova and her co-workers (*8*) also found a higher concentration of iron in nodules from hilltops, possibly connected to underwater weathering of volcanic rocks, which leads to a decrease in the copper and nickel content of the nodules there. On the other hand, Piper *et al.* (*11*) obtained different results in their study of a small area centered at about 15°N, 126°W (within the area selected as a mine site by Deepsea Ventures, Inc.). They found nodule concentrations to be greater in the valleys than on the hilltops, and their analyses show no correlation between nodule grade and abundance.

Thus the inverse relationship we note between grade and abundance is not universal. But is it the exception or the general rule? The negative correlation holds when we consider data for all of the 182 Pacific Ocean sites where we know both grade and concentration in kilograms per square meter (Fig. 2). The correlation coefficient is −.40, at the 99.9 percent confidence level. The average concentration for samples below cutoff grade is 14 kg/m^2; for samples above cutoff grade, however, concentrations average only 6.7 kg/m^2.

What about the northeastern equatorial Pacific area where the mining potential is greatest? Between 0° and 20°N and 100°W and 180°W there are some 74 stations for which we have both chemical analyses and nodule-abundance data from photographs. The abundances have been divided into three classes as follows: (i) less than 20 percent, (ii) between 20 and 50 percent, and (iii) more than 50 percent. The mean grade of nickel plus copper and the standard deviation (in parentheses) for each of the three classes are as follows: (i) 2.09 percent (0.51), (ii) 1.80 percent (0.64), and (iii) 1.47 percent (0.58). Differences between the means of adjacent classes are significant at about the 95 percent confidence level.

One hundred twenty-two of the stations shown in Fig. 2 are from the northeastern equatorial Pacific. These include the data from Schatz (*12*), which are frequently cited as evidence that grade and abundance are uncorrelated. Even by themselves the Schatz stations do show a weak negative correlation between grade and concentration, but at only the 80 percent confidence level; these data alone are not enough to convince one that grade and abundance are related. When all available data for the northeastern equatorial Pacific are included, however, the correlation coefficient is −.28, at the 99.9 percent confidence level.

The assumption that grade and abundance are independent can cause a considerable overestimation of nodule resources. Although there are localities for which this assumption is true, there seems to be little reason for doubting that the grade of nickel and copper in manganese nodules is in general negatively correlated with their abundance, even in the region of greatest commercial interest. The basic assumption which has been used in most estimates of potential marine reserves and resources of these metals, therefore, is unjustified and probably wrong. The data do not in any way suggest that mining the sea floor for copper and nickel is not feasible or that commercially exploitable mine sites do not exist. The data do warrant the larger conclusion that some aspects of the debate on the law of the sea have been based on an optimistic misconception.

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Blue-Green Algal Inhibition of Diatom Growth: Transition from Mesotrophic to Eutrophic Community Structure

Abstract. *Cell-free filtrates of axenic or bacterized cultures of the dominant blue-green algae from a freshwater lake inhibited the growth of diatoms isolated from the same lake. Lake waters, collected during blue-green algal blooms, also inhibited diatom growth. In situ observations over a 5-year period indicate that diatom bloom populations vary inversely with the levels of the preceding blue-green algal populations. Blue-green algal dominance of eutrophic lakes is attributed to this allelopathy, and dilution is proposed as one cause for the limited occurrence of blue-green algal dominance in marine waters.*

The metabolic products of blue-green, prokaryotic algae play a role in determining annual bloom sequence in eutrophic freshwater lakes (*1*). These algae are also influential in some of the long-range, successional changes (oligotrophic-mesotrophic-eutrophic) in community dominance which occur as a lake ages. One of the most significant of these changes is the replacement of the diatom blooms of mesotrophic lakes by the offensive blue-green algal blooms of eutrophic lakes.

This change in dominance brings with it manifold undesirable effects. Blue-green algae not only produce unpleasant tastes, odors, colors, and floating clumps; they are also an unsatisfactory food for many organisms higher in the trophic structure. They are, in fact, detrimental, even toxic, to many organisms, including humans (*2*), which might coincidently ingest them during feeding or drinking activities. In contrast, as a diatom bloom depletes the lake's store of excess macronutrients (phosphorus, nitrogen, and carbon), it evidences no toxicity and produces neither visual nor olfactory offense; moreover, since diatom blooms occur in the spring or fall, human contact (swimming) is minimized. Diatoms are also an excellent food for zooplankton and fish. Furthermore, when diatom blooms subside, senescent cells fall into the hypolimnion, carrying much of their nutrient load out of the productive epilimnion. These nutrients are essentially unavailable for further algal growth until the fall turnover. On the other hand, planktonic blue-green algae die off rapidly, lysing and releasing most of their nutrients directly into the epilimnion. These nutrients are immediately recycled by bacterial, blue-green algal, or other growth.

In culture, diatoms are favored over blue-green algae in their responses to physical and chemical conditions which characterize the spring; that is, they are more efficient at harvesting nutrients and are more responsive to increased light. Nevertheless, in eutrophic lakes spring blue-green algal blooms displace the spring diatom blooms common to mesotrophic lakes. Therefore, light and nutrients alone do not exercise a definitive influence in situ. The bloom sequence of Linsley Pond, a eutrophic kettle lake in North Branford, Connecticut, demonstrates this.

In the first winter of my study (1971–72) the blue-green algal population of Linsley was consistently high (Fig. 1). In the following spring no diatom bloom occurred. Instead, blue-green algae dominated the plankton throughout the spring and summer. In the second winter (1972–73) a moderate blue-green algal bloom occurred. In the following spring a short-lived, but readily discernible, diatom bloom developed. This bloom consisted of various Fragilariaceae (*3*), culminating in a period of *Asterionella formosa* (800) (*4*) dominance. Blue-green algae dominated the plankton for the remainder of the summer. In the third winter (1973–74) no blue-green algal blooms occurred. The plankton of the following spring was dominated by a long-lived diatom bloom characterized by its diversity of com-

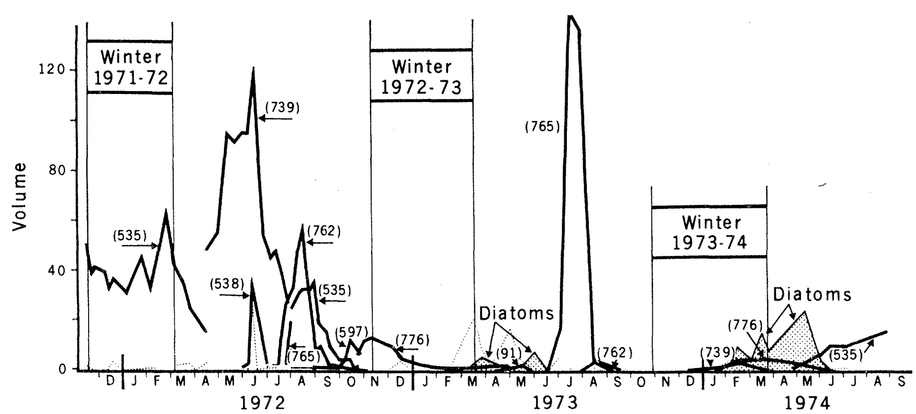

Fig. 1. Blue-green algal and diatom populations of Linsley Pond over a 3-year period. Volume numbers represent the cell volume calculated as the volume of the nearest geometric solid, for example, a sphere or a cylinder. The numbers represent the cell volumes (in cubic centimeters × 10^{-6} per milliliter of water) as calculated from cell counts (hemacytometer, Sedgewick Rafter, or membrane filter counts). Samples for counting were collected on a weekly (first year) or biweekly (subsequent years) schedule from the surface and from depths of 2.5 m, 5 m, 9 m, and 13.5 m (bottom). (Solid lines) Blue-green algae; (shaded areas) diatoms; (dotted lines) mixed flagellated forms. Numbers in parentheses represent Linsley Pond culture collection numbers. The corresponding Latin names are as follows: *Oscillatoria rubescens* (535), *Oscillatoria agardhii* (739), *Anabaena holsaticum* (538), *Anabaena elenkenii* (762), *Anabaena circinalis* (765), *Pseudanabaena galeata* (597), *Oscillatoria elegans* (776), and *Synechecoccus* sp. (91).

