Burial Rates, Growth Rates, and Size Distributions of Deep-Sea Manganese Nodules

Abstract. *The size distributions of deep-sea manganese nodules are consistent with a simple model of uniform growth at a few millimeters per million years and with the same probability of burial for all nodules, regardless of size. The model suggests that most nodules spend 1 million years or less on the sea floor.*

The observation that many more deep-sea manganese nodules are found on the sea floor than in the underlying sediments has puzzled marine geologists for a long time (*1-3*). Bender *et al.* (*1*) have shown, however, that this observation is consistent with the slow growth rate of nodules relative to sediment accumulation rates. This report concerns an attempt to determine whether the abundance and size distributions of nodules on the sea floor are consistent with their observed growth and burial rates.

The simplest model to relate these observations is based on the assumptions that nodules grow uniformly with time and that the probability of their burial depends solely on the number of nodules present—not on their size or age. These assumptions can be expressed as

$$D - D_0 = 2Gt \tag{1}$$

and

$$dN/dt = -BN \tag{2}$$

where D is the nodule diameter (millimeters) at time t, D_0 is the nodule diameter at time 0, G is radial growth rate (millimeters per million years), t is time (million years), dN/dt is the number of nodules buried per unit time and area (square meters), and B is a burial constant [1/(million years)]; $D_0 \neq 0$ is required by the unexplained size gap between the smallest nodules (a few millimeters in diameter) collected in most samples and associated micronodules that are less than 1 mm in diameter.

Equation 2 is integrated to

$$N = N_0 e^{-Bt} \tag{3}$$

or

$$\ln N = \ln N_0 - Bt \tag{4}$$

where N_0 is the number of nodules per unit area in the smallest size class. Substituting from Eq. 1 yields

$$\ln N = \ln N_0 - \frac{B}{2G}(D - D_0) \tag{5}$$

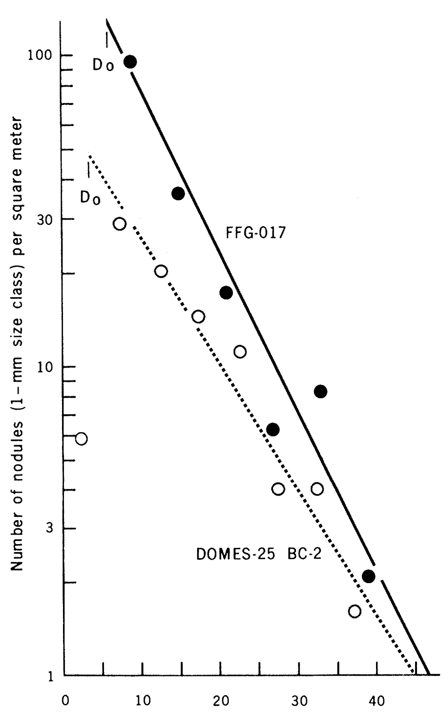
If this model is realistic, a plot of ln N against D should yield a straight line with a slope of half the ratio of the burial rate to the growth rate and a value of N_0 at D_0.

Very few samples that contain sufficient nodules to yield statistically reliable size distributions have been described in the literature. However, Andrews *et al.* (*4*) and Macdougall (*5*) have published photographs of nodules collected from the northern equatorial Pacific by means of free-fall grabs (FFG's) and box cores (BC's), from which size distributions can be measured.

Figure 1 is a plot of the number of nodules per 1-mm size class per square meter of sea floor for FFG-017 [9°3'N, 146°29'W; water depth, 5180 m (*4*)] and DOMES-25 BC-2 [14°15'N, 124°59'N; water depth, 4560 m (*5*)]. These data fit the model of Eq. 5 very well. In fact, the lack of curvature in the best-fit lines argues strongly against any dependency of the burial probability on the size (or weight) of nodules as long as their growth rate is independent of size. For FFG-017, $B/2G = 0.12$ mm^{-1}, and for a D_0 of 6 mm (the smallest nodule in the grab), $N_0 = 130$ m^{-2}; whereas for BC-02, $B/2G = 0.094$ mm^{-1}, and for a D_0 of 3.5 mm, $N_0 = 49$ m^{-2}.

How well do these values of $B/2G$ agree with independent data on nodule growth and burial? For the upper 4 m of sediment cores in the collections of the Scripps Institution of Oceanography (*2*) and the Lamont-Doherty Geological Observatory (*6*), the distribution of buried nodules is uniform with depth and, by comparison with surface nodules collected in piston cores in the same collections (Fig. 2), yields a B value of 0.24 m^{-1}. An average sedimentation rate for nodule-bearing pelagic clays is about 4 m per million years, so that B is about 0.96 per million years, yielding for FFG-017 a value of 4 mm per million years for G, the average growth rate. This is well within the range of radiometrically measured growth rates of nodules (*7*), and is virtually identical to the average of 5.0 ± 1.5 mm per million years measured by Macdougall (*5*) for nodules Mn 7402 FFG-37, Mn 7601 20-B2, and MSN 150G, collected near FFG-017. For BC-2, Macdougall (*5*) dated six nodules that have an average growth rate of 6.7 ± 0.7 mm per million years ($\pm$ 1 standard deviation). The measured growth rates are independent of nodule size—supporting Eq. 1. Thus, for BC-2, $B = 2.9$ per million years, a value that agrees fairly well with the pooled core data.

Equation 2 needs to be tested by determining the size distributions of associated surficial and buried nodules (they should be identical); however, no such data are currently available. Also, to rigorously test the model presented in this



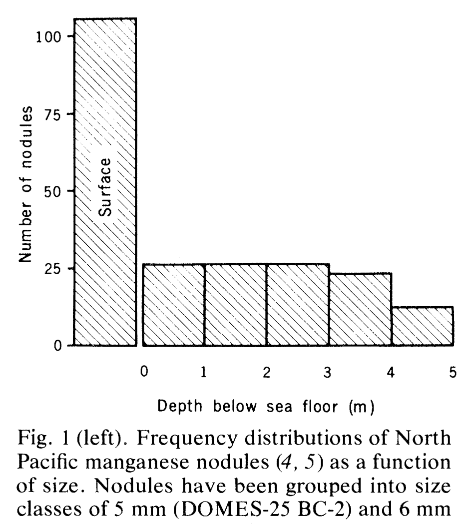


Fig. 1 (left). Frequency distributions of North Pacific manganese nodules (*4, 5*) as a function of size. Nodules have been grouped into size classes of 5 mm (DOMES-25 BC-2) and 6 mm (FFG-017). Lines are least-squares fits to the data, except that the 0- to 5-mm point has been excluded from the BC-2 regression; D_0 is the smallest nodule size in the population. Fig. 2 (right). Numbers of surficial and buried manganese nodules (*8*) recovered in sediment cores in the collections of the Scripps Institution of Oceanography (*2*) and the Lamont-Doherty Geological Observatory (*6*).

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report, burial and growth rates of nodules from a single location are required. Nevertheless, the promising first results have a number of implications for theories of nodule formation:

1) The process that keeps nodules at the sea floor (that is, that determine B) is independent of nodule size for $D > D_0$. The mechanism is not yet known, although displacement by benthic organisms (*8, 9*) and exhumation and downslope migration (*10*) on slopes or in areas of erosion are now favored.

2) The approximate residence time of nodules on the sea floor prior to burial ranges from about 300,000 years at BC-2 to 1 million years at FFG-017.

3) Claims of very rapid nodule growth (*11*) are not consistent with size and burial rate data.

4) The absence of nodules smaller than D_0 (usually 3 to 6 mm) implies that the mechanism that keeps nodules from being buried cannot distinguish these small particles from the associated sediments. Since we do not know the mechanism, however, it seems pointless to speculate about the factors that determine D_0 and its variation from sample to sample. Also, the lack of small nodules suggests that nuclei (clay lumps, rock chips, fish teeth and other skeletal remains, and fragments of older nodules) are essential for the initiation of nodule growth.

5) Locations with populations of nodules of a single size must either be effectively nondepositional (*12*) (in which case, $B = 0$), or they must lack a mechanism for continuously forming new nodules, in which case the number of nodules must decrease exponentially with time (the density of nodule coverage should be negatively correlated with nodule size). These alternatives, as well as the basic assumptions of the model, can be tested by an appropriately designed program to sample nodules and associated sediments.

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Magnesium Interaction with the Surface of Calcite in Seawater

Abstract. *Magnesian calcite overgrowth containing 4 (± 2) mole percent magnesium carbonate forms on calcite exposed to natural seawater near the ocean surface. This magnesian calcite is approximately 30 percent less soluble in seawater than pure calcite. The formation of the magnesian calcite of reduced solubility may have a major influence on calcite accumulation in deep sea sediments.*

Recently determined values for the apparent solubility of calcite in seawater (*1-3*) are approximately 30 percent less than the value for pure calcite predicted from thermodynamic considerations (*3*). A possible explanation for this discrepancy is that a layer of magnesian calcite, of greater stability than pure calcite, forms at the seawater-calcite interface. It has been predicted (*4, 5*) that a magnesian calcite containing 2 to 7 mole percent $MgCO_3$ would be more stable than pure calcite in seawater. The Mg content of magnesian calcite overgrowths on calcite from seawater, at supersaturations significantly higher than normally found in the marine environment, has been quite variable and always higher than predicted for minimum solubility [see (*6*) for summary]. These findings have led to considerable controversy over the relative influences of thermodynamic and kinetic factors in determining the composition and stability of magnesian calcites in the marine environment (*6-9*).

To help resolve these problems we have produced magnesian calcite overgrowths on Iceland spar calcite rhombs from natural seawater at a saturation state, with respect to calcite, typical of near-surface seawater. Carefully cleaved rhombs of Iceland spar calcite, approximately 0.5 cm in diameter and containing less than 1 mole percent $MgCO_3$, were soaked in double-distilled water to relieve any surface strain associated with cleaving. Individual rhombs were then soaked in Gulf Stream surface seawater that had been diluted to 35 per mil salinity and equilibrated with air. A large solution to solid ratio (10,000 to 1 by weight) was used to ensure near constancy of the solution composition. The ratio of the $CaCO_3$ total ion molal product to the apparent solubility product of calcite in seawater was 5.1 (*3*). After they were soaked in the seawater for 3 days and for 7 days the calcite rhombs were removed from the seawater and either air-dried or immersed in distilled water for approximately 5 seconds to remove any adhering seawater and then air-dried. The composition of the surface and growth layers was determined by scanning Auger spectroscopy.

The Auger analysis was conducted with a Physical Electronics Industries scanning Auger microscope, model 545. The depth profile of the relative atomic concentration ratio of Mg and Ca was obtained by sputter removal of surface layers from the sample with a 2-kV argon ion beam. A quantitative determination of the relative atomic concentrations of Mg and Ca was obtained by comparison of both the Mg and Ca peak-to-peak amplitudes to the peak-to-peak amplitude of a silver standard. Appropriate relative sensitivity and scale factors were then used to determine the Mg/Ca concentration ratio (*10*). The total error in the relative atomic concentration of Mg and Ca is estimated to be less than 25 percent.

The results of these experiments are presented in Fig. 1. The Mg/Ca ratio on the surface of the calcite sample, which was not washed in distilled water, was approximately 0.24. A lower concentra-