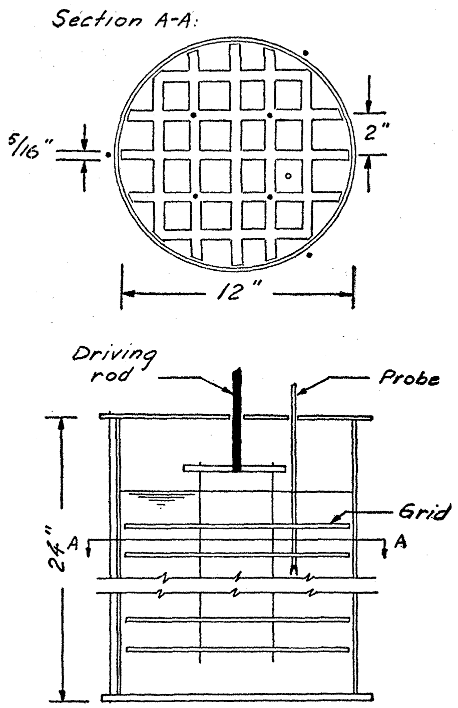

Fig. 1. Grid agitator used to generate homogenous turbulence in a liquid. The driving rod is connected to an eccentric on a variable-speed drive.

carried to some depth in the water by the mechanism of turbulent diffusion.

This report summarizes the results of an experimental study of the mechanism of air entrainment as it is related to significant fluid properties and to turbulence artificially induced by a moving grid in a container of liquid. The surface tension, viscosity, and density of the liquid determine the

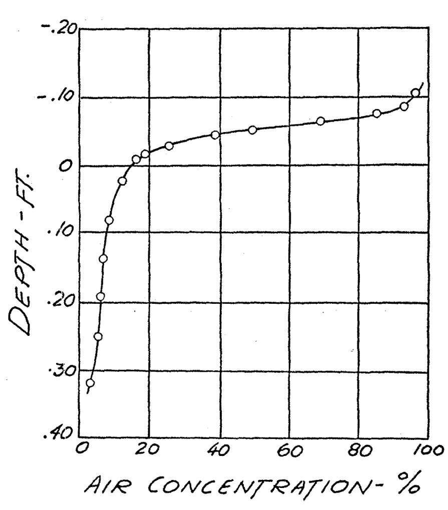

Fig. 2. Typical distribution of air entrained into water through the free surface by turbulence. Negative values of depth result from bulking of the air-water mixture.

amount of air entrained and the size and concentration of the air bubbles within the liquid for any given degree of turbulence. This interrelationship can be expressed as

$$C = \phi(\epsilon, \rho, \mu, \sigma, \gamma) \qquad (1)$$

where C is the mean air content by percent of volume in the container, ϵ is the diffusion coefficient, ρ is the density, μ is the viscosity, σ is the surface tension, and γ is the specific weight of the liquid.

The turbulence was generated by a grid agitator moving vertically in simple harmonic motion in a transparent container of the liquid (see Fig. 1). The amplitude and frequency of the stroke and the geometry of the agitator were varied. The liquids used were water, ethyl alcohol, methyl alcohol, and sugar-water solutions at different temperatures. These liquids permitted significant changes in the fluid properties. An electrical probe similar to that developed by Lamb and Killen (*2*) was used to measure the concentration of air at any level. A typical distribution of the air is shown in Fig. 2.

Since the eddy coefficient cannot be readily evaluated, the dimensional analysis of the problem proceeded from the following relationship

$$C = \phi'(v, l, d, \rho, \mu, \sigma, \gamma) \qquad (2)$$

where the diffusion coefficient (ϵ) of Eq. 1 has been replaced by v, the mean velocity, l, the stroke, and d, the grid spacing of the agitator.

Application of the π theorem resulted in the following relationship

$$C = \phi''\left(\frac{l}{d}, \frac{vl\rho}{\mu}, \frac{v^2\rho l}{\sigma}, \frac{lg}{v^2}\right) \qquad (3)$$

where the first term in parentheses is a dimensionless geometry parameter and the remaining terms are forms of the familiar Reynolds (R), Weber (W), and Froude (F) numbers.

Equation 3 was evaluated from results of these tests to be

$$C = 0.013\ (R^{0.21}\ W^{0.68}\ F^{0})$$

The exponent of the Froude number averaged near zero, indicating that gravity has a negligible effect on air entrainment for the liquids tested.

Visual observation of the entrainment process indicates that entrainment occurs when the surface undulations form breaking waves. Then turbulent mixing carries the air bubbles deep into the liquid. Decreasing the surface tension results in greater surface action and greater air entrainment; similarly, the greater the turbulence, the greater the air entrainment. Decreasing the viscosity permits more bubbles to be carried into the fluid (*3*).

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Pre-Columbian Littorina littorea in Nova Scotia

Abstract. *Littorina littorea*, an abundant northeast North American gastropod, was thought to have been introduced from Europe about 1840. Shells of that species found in ancient Micmac Indian camp sites in Nova Scotia have been radiocarbon-dated as pre-Columbian. Failure of *L. littorrea* to extend its range southward before 1840 may have been due to oceanographic factors.

Littorina littorea (Linn.) is probably the most abundant intertidal gastropod occurring between the Gulf of St. Lawrence and southern New Jersey. Long native in Europe from the White Sea to Gibraltar and in the British Isles (*1*), it was first recorded from North America about 1857 when Willis reported it from Halifax, Nova Scotia (see *2*). Its subsequent progressive colonization of more southerly localities has been well documented by Morse (*3*), who states that it first occurred at Portland and Kennebunk, Maine, in 1870; at Salem and Provincetown, Massachusetts, in 1872; at Woods Hole, Massachusetts, in 1875; and at New Haven, Connecticut, in 1880. Morse also stated (*3*) that he had received specimens from Bathurst, Bay of Chaleur, Gulf of St. Lawrence, in 1855, and Dawson (see *2*) reported that he had collected it at Pictou on

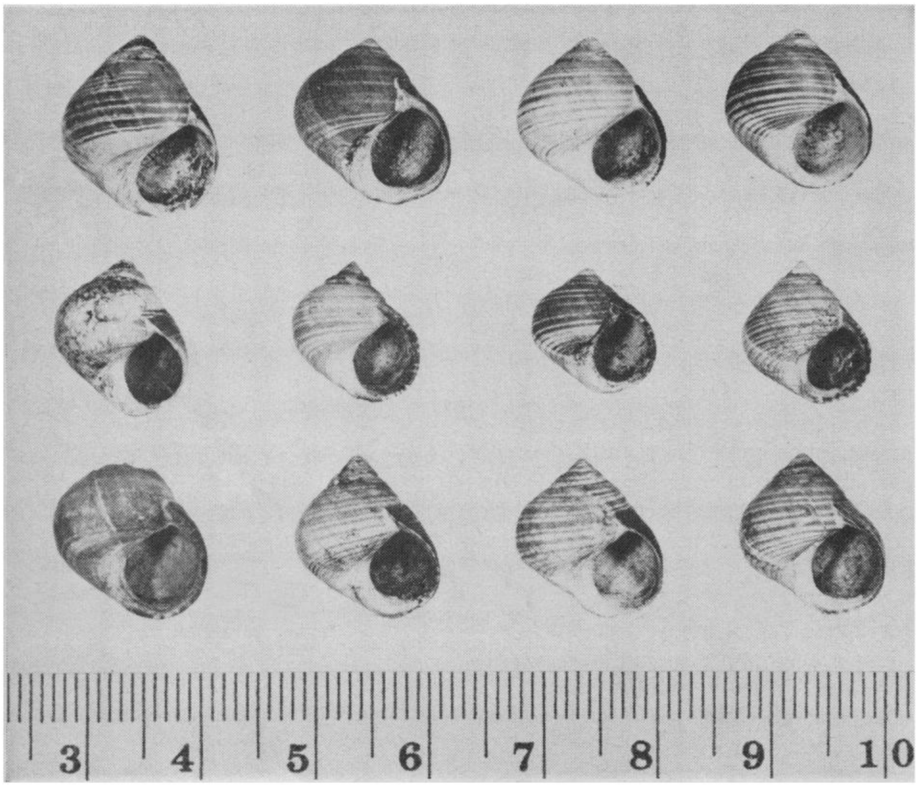

Fig. 1. *Littorina littorea* from Reid Site, Indian Point, St. Margaret's Bay, Halifax County, Nova Scotia (scale is in centimeters).

Northumberland Strait, Nova Scotia, in 1840 and believed that because of its wide distribution it was "a regular and probably aboriginal member of the fauna of Acadia." Because of the rapid southward spread of the species shortly after its discovery, modern workers (*1*) have discounted Dawson's views and accepted Ganong's theory (*2*) that *L. littorea* was introduced to the Halifax region about 1840 by commerce and that its southward spread was a direct result of that introduction.

During the summer of 1960, one of us (J.S.E.) was engaged in archeologic investigations of Micmac Indian camp sites (*4*) near Halifax, Nova Scotia. At Reid Site, Sand Cove, and at Frostfish Cove (both at Indian Point, St. Margaret's Bay, Halifax County), specimens of *Littorina littorea* were found among undisturbed hearth debris and were associated with *Cepaea hortensis* (Müller), other shells, bones, charcoal, and prehistoric artifacts. The only artifacts in the site of later origin were rusty, wrought-iron nails in a line that probably had once been a rail fence. The valves of *Mercenaria mercenaria* (Linn.) which were present were unusually thick and exhibited crowded lines of growth, conditions which normally indicate a cold environment close to the lower limit of tolerance for *M. mercenaria* (*5*). Reindeer (*Rangifer tarandus*) bones, absent from older deposits, were also found and provided further evidence that the climate had been cold and was becoming colder. From this information a date corresponding to the latter stages of the Little Ice Age was tentatively assigned—that is, the 13th century.

Radiocarbon dating of 12 of the *Littorina littorea* shells from Reid Site gave an age of 700 ± 225 yr B.P. (*6*) and showed that the original estimate of age was approximately correct.

The specimens which were submitted for dating are shown in Fig. 1. Their dimensions are apparent in the figure. A 13th specimen, which was not submitted for dating, measured as follows: height, 16.6 mm; width, 15.0 mm; whorls, four and a half; aperture length, 12.8 mm; and aperture width, 9.5 mm. The specimens show no essential divergence in pattern or form from specimens now living near Halifax or elsewhere within the North American range of the species. Figure 1 indicates that the population is normally variable and implies no lack of genetic diversity.

The conclusion that *Littorina littorea* was native to the Halifax area before the advent of European culture appears well founded. It is also probable that Dawson was correct and that *L. littorea* may have occurred in the Northumberland Strait area, a region which today supports a distinctive warm-water fauna. Its failure to spread southward before the middle of the 19th century may have been the result of oceanographic factors. Drift-bottle studies (*7*) indicate that the major surface circulation on the Nova Scotian shelf is such that pelagic eggs and larvae of *L. littorea* spawned in the Halifax area would probably be carried out to sea and perish. It appears likely, then, that increased commerce between Halifax and one or more ports in southwest Nova Scotia or New England caused the species to colonize areas, just prior to 1870, from which further extension of its range southward could be mediated by the more favorable long-shore ocean currents which occur in that region (*8*).

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8. We are grateful to W. J. Clench and J. C. Medcof for helpful comments and suggestions. This research was supported by the National Museum of Canada and the Nova Scotia Museum of Science.

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