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Article abstract

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In the samples examined low magnesium forms (Group I) occur in all three water-masses and in a late-glacial beach sample. The intermediate magnesium form *Ephidiella arctica* (Group 2) and the high magnesium forms (Group 3) *Quinqueloculina arctica* and *Q. seminulum* occur in the Upper Watermass. Populations of the low magnesium species *Buccella inusitata*, *Islandiella helenae* and *Nonionellina labradorica* are each found in both Upper and Deep Watermasses. The low magnesium Value of *Quinqueloculina stalkerii* may indicate that the form should be placed in another genus.

MAGNESIUM IN 19 SPECIES OF EASTERN CANADIAN HOLOCENE FORAMINIFERA

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The tests of 18 benthonic and one planktonic species of modern Foraminiferida from 8 bottom samples recovered from the eastern Canadian shelf fall into two, or perhaps three groups with respect to mean mole percent $MgCO_3$, as follows: Group 1 - 0 to 2.5 % $MgCO_3$; Group 2 - 2 to 5 % $MgCO_3$; and Group 3 - 5 to 9 % $MgCO_3$. The watermass characteristics and depth of each population are: Upper Watermass, -1 to 3 or 5 C, 33 o/oo salinity, 62 m and 73 m; Intermediate Watermass, 0 C, 34 o/oo salinity, 99m; and Deep Watermass, 4 to 5 C, 35 o/oo salinity, 263 m, 431 m, 475 m, 479 m and 509 m.

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INTRODUCTION

Of the elements present in small quantities in the tests of foraminifera, magnesium is particularly significantly and worthy of close study. The reasons for this are several. (1) Knowledge of the chemical composition of the test, including, in particular, the magnesium content, is a necessary first step in the understanding of the mechanism of test formation. (2) The presence of magnesium in solid solution in the calcite of the test implies that it may be intimately involved in the metabolism of the organism whereby the test is secreted.

(3) If the amount of magnesium present is due to hereditary factors, and if it is constant for the taxon, then it is of classificatory importance.

(4) If the variation in amount of magnesium is ecologically controlled, it may be used as an ecological indicator of past environmental conditions in fossil forms, assuming that diagenetic changes can be evaluated. However, before inferences can be drawn concerning fossil forms, it seems to be advisable first to relate the magnesium variations in modern tests to the environments in which the animals live, for modern environments can be more precisely defined than ancient ones and diagenetic effects are absent.

Chave (1954) used the X-ray diffraction method in a study of magnesium in the calcitic shells of marine organisms. Because the method detects magnesium in substitution in the calcite lattice, it may be assumed to be biogenic if diagenesis can be ruled out. Chave found (1), a linear relationship between magnesium content and environmental water temperatures, and (2), in general, a decrease in magnesium content with increase in phylogenetic level of the organism. This latter conclusion was based upon the gradients of least square regression curves of temperature versus magnesium content for the taxonomic groups studied. The magnesium content of the Foraminiferida ranged from 0.33 to 15.9 mole percent $MgCO_3$.

Blackmon and Todd (1959) used the method of X-ray diffraction to determine the magnesium content

of foraminiferal tests from many parts of the world. Their study was useful in several ways. It showed magnesium to be of classificatory and possibly of ecological importance. Many families, genera and species were represented in the study of a general way, and the specimens that were analyzed were collected from many different climatic zones and environments from the Arctic to the Tropics. The authors commonly analyzed only one (occasionally a few) specimen per species, or if several specimens were used, they were ground down, and an aggregate sample was used for analysis. Thus, the variance of the species population with respect to magnesium was not determined. Only four Canadian species were analyzed.

Dodd (1967) reviewed the literature with respect to magnesium and strontium in calcareous organisms and concluded that the concentration of these elements in carbonate skeletons is controlled by four major factors: (1) Water chemistry - other factors being equal, the Mg/Ca and Sr/Ca ratios in skeletal material should be constant relative to those ratios in the water in which they formed. (2) Other environmental factors - Magnesium shows a strong positive correlation with temperature in calcitic skeletons. (3) Mineralogy - Calcite is generally high in magnesium and low in strontium relative to aragonite. (4) Physiology of the organisms - In general the phylogenetically more advanced forms have lower magnesium and strontium values.

The magnesium content of modern species of the benthonic foraminiferal family Milliolidae of Cleveland Bay, North Queensland Shelf, Australia, were studied by Ponder and Glendenning (1974) using the X-ray diffraction method. The authors believed that environmental temperature variation was minimal for this relatively shallow tropical watermass. They concluded that magnesium content could not be used for determining paleotemperatures or paleodepth, nor as an aid to classification, because of its overlapping variance in the populations they examined.

This report presents the results of X-ray diffraction analysis for magnesium in populations of 19 species of the Order Foraminiferida from the eastern Canadian continental shelf, and one species of late-glacial age from M tis Beach, Qu bec. All species are benthonic except only *Globigerina pachyderma* s.l.

METHOD

The X-ray diffraction method was employed utilizing the shift in diffraction lines that results when magnesium substitutes for calcium in the calcite lattice. The apparatus consisted of a Siemens Kristalloflex IV X-ray generator with copper target and nickel filter, and Debye-Scherrer cameras with revolving spindles. The excitation constants for the unit were 35kV and 20mA. $\lambda_{CuK\alpha}$ wave length 1.5418A^o was used.

Because the wall of the foraminiferal test is fine-grained, the single test diffracts as a powder under the X-ray beam and non-destructive analysis is possible. The whole foraminiferal test was mounted on the revolving spindle of the Debye-Scherrer camera and was subjected to the X-ray beam. The films were read on a Kirem light box. The 112 and 444 lines were generally the most readable giving least variation in d-values and the most reproducible results.

ESTIMATE OF ACCURACY

An estimate of probable accuracy of the method including reading error is in the order of ± 1.0 mole percent $MgCO_3$.

The mean magnesium percentage and its variation are reported for each population, and an attempt is made to relate the values to factors of temperature, salinity and depth of the watermass in which the populations were living.

RESULTS

The results are tabulated in Table 1 which shows, for each species population, the mean mole percent $MgCO_3$, standard deviation and magnesium group, frequency, station number and position, geological age, depth of occurrence of the sample, name of the watermass layer, temperature and salinity of the watermass.

CONCLUSION

Reference to Table 1 shows that species have mean mole percent $MgCO_3$ values ranging from zero (*Globigerina pachyderma*) to 8.0 (*Quinqueloculina seminulum*), but most populations are less than 1.0. The estimated experimental error is in the order of 1 mole percent $MgCO_3$, and thus, for most species the error is a high value in relation to the mean. Similarly, values of standard deviation range from 0.2 (*Globobulimina auriculata*) to 1.3 (*Elphidium clavatum*), and thus experimental error is also high in relation to these values. It is therefore apparent that the method of X-ray diffraction is not sensitive enough to permit sufficiently precise analysis of mean and variance of magnesium amounts in these species populations.

Nevertheless, although the experimental error is relatively high the species populations do appear to fall into at least two, possibly three, groups with respect to mean mole percent $MgCO_3$. The three groups are as follows:

GROUP 1, low in magnesium, approximate range 0 to 2.5 mole percent $MgCO_3$: *Globigerina pachyderma*, *Bulimina exilis*, *Bulimina subaenariensis*, *Buccella inusitata*, *Bulimina aculeata*, *B. marginata*, *Islandiella helenae*, *Elphidium bartletti*, *E. clavatum*, *E. incertum*, E.sp., *Globulimina auriculata*, *Quinqueloculina stalkerii*, *Nonionellina labradorica*, *Elphidium articulatum* and *Glandulina laevigata*.

GROUP 2, intermediate in magnesium, approximate range 2 to 5 mole percent $MgCO_3$: *Elphidiella arctica*. Because this group is based upon only one specimen, it is tentatively suggested.

GROUP 3, high in magnesium, approximate range 5 to 9 percent $MgCO_3$ or perhaps higher: *Quinqueloculina arctica* and *O. seminulum*.

Three main watermasses are recognized in the region covered by the samples as follows: Upper Watermass, -1 to 3 or 5^oC, 33 o/oo salinity, 62 m and 73 m; Intermediate Watermass, 0^oC, 34 o/oo salinity, 99 m; and Deep Watermass, 4 to 5^oC, 35 o/oo salinity, 263 m, 431 m, 475 m, 479 m and 509 m.

In the samples examined low magnesium forms (Group 1) occur in all three watermasses and in the late-glacial beach sample. The species *Buccella inusitata*, *Islandiella helenae*, *Nonionellina labradorica* and *Elphidium bartletti* are each found in both Upper and Deep Watermasses. The first three species named are present in populations of adequate size, but *Elphidium bartletti* is represented by only one specimen in the deep sample S43-4 (263 m) and thus may be less reliable. The wide temperature tolerance of populations of *Islandiella helenae* (-1 to 3^oC and 4 to 5^oC) seems surprising because this species, under the names of *Cassidulina teretis* = *Islandiella teretis*, has been thought to be restricted to temperatures of 3^oC and below (Fillon and Hunt 1974, p. 15). Displacement into deep water is a possibility although not considered likely for sample S49-B. Alternately, more than one species, or subspecies, may be present in these two *Islandiella helenae* populations; if so, the differences are not obvious from the morphology. Another possibility is that the species, although preferring water below 3^oC, is not seriously affected by slightly higher temperatures.

The miliolids are usually thought to be high magnesium forms, and *Quinqueloculina stalkerii* would be expected to be high in magnesium as are the other quinqueloculines *Q. arctica* and *Q. seminulum*. Its low magnesium values (mean % $MgCO_3$ = 0.9) are surprising and may indicate that the calcite metabolism of *Q. stalkerii*, a species that agglutinates sand grains on the wall, is profoundly different from that of *Q. arctica* and *Q. seminulum* which do not. All the quinqueloculines are from two bottom samples (depths, 62 and 73 m) with similar temperature and salinity values, which suggests that genetic rather than environmental

TABLE 1

SPECIES	FREQUENCY	MOLE % MgCO ₃			GROUP	STATION	POSITION	AGE	DEPTH M	WATERMASS LAYER	TEMPERATURE °C	APPROXIMATE SALINITY o/oo
		ESTIMATED EXPNT. ERROR MOLE %	MEAN	STANDARD DEVIATION								
<i>Globigerina pachyderma s.l.</i>	12	1	0.0	0.6	1	S43-28	46°52'N 54°04'W	Modern	Surface	Upper	Variable	33
<i>Brizalina subaenariensis</i>	20	1	0.0	0.6	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>Buccella inusitata</i>	21	1	1.1	0.8	1	S43-18	Ditto	Modern	73	Upper	-1 to 3	33
<i>B. inusitata</i>	11	1	0.0	0.4	1	S43-28	46°52' 54°04'	Modern	479	Deep	4 to 5	35
<i>Bulimina aculeata</i>	5	1	0.0	0.6	1	S49-B	Cabot Strait 47°39' 59°46'	Modern	509	Deep	4 to 5	35
<i>B. exilis</i>	22	1	0.2	0.9	1	S43-28	46°52' 58°04'	Modern	479	Deep	4 to 5	35
<i>B. marginata</i>	11	1	0.0	0.6	1	S43-28	Ditto	Modern	479	Deep	4 to 5	35
<i>Elphidium articulatum</i>	1	1	0.8	-	1	S43-15	46°23' 54°12'	Modern	99	Inter- mediate	0	34
<i>E. bartletti</i>	14	1	1.2	1.0	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>E. bartletti</i>	1	1	0.4	-	1	S43-3	43°52.3' 62°52.8'	Modern	263	Deep	4 to 5	35
<i>E. clavatum</i>	4	1	1.0	1.3	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>E. clavatum</i>	3	1	0.1	1.2	1	HV-19	Metis Beach P.Q.	Late- glacial	-	-	-	-
<i>E. clavatum</i>	8	1	0.2	0.7	1	HV-19	Metis Beach P.Q.	Late- glacial	-	-	-	-
<i>E. clavatum</i> (combined)	11	1	0.2	0.8	1	HV-19	Metis Beach P.Q.	Late- glacial	-	-	-	-
<i>E. clavatum</i>	15	1	1.0	0.7	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>E. incertum</i>	21	1	0.0	0.5	1	S43-28	46°52' 58°04'	Modern	479	Deep	4 to 5	35
<i>E. sp.</i>	19	1	1.0	0.6	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>Glandulina laevigata</i>	1	1	0.0	-	1	S43-28	46°52' 58°04'	Modern	479	Deep	4 to 5	35
<i>Globobulimina auriculata</i>	3	1	0.7	0.2	1	S43-27	46°37' 58°30'	Modern	431	Deep	4 to 5	35
<i>Islandiella helenae</i>	21	1	0.7	0.5	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>I. helenae</i>	8	1	0.2	0.7	1	S49-B	Cabot Strait 47°39' 59°46'	Modern	509	Deep	4 to 5	35
<i>Nonionellina labradorica</i>	15	1	0.5	0.4	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>N. labradorica</i>	16	1	1.2	0.5	1	S43-34	47°16' 59°47'	Modern	475	Deep	4 to 5	35
<i>Q. stalkeri</i>	5	1	0.9	0.8	1	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>Elphidiella arctica</i>	1	1	3.6	-	2	S43-66	44°00' 50°52'	Modern	62	Upper	-1 to 5	33
<i>Quinqueloculina arctica</i>	1	1	7.5	-	3	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33
<i>Q. seminulum</i>	1	1	8.0	-	3	S43-66	44°00' 50°52'	Modern	62	Upper	-1 to 5	33
<i>Q. seminulum</i>	1	1	5.8	-	3	S43-18	46°49' 55°36'	Modern	73	Upper	-1 to 3	33

factors may account for the large difference in magnesium content. Ponder and Glendening (1974) reported the mole percent $MgCO_3$ in tests of *Quinqueloculina philippinensis* range from 8.5 to 21.6 with a mean of 13.1 ($s=4.0$). There was a slight decrease of magnesium content with depth (range 3 to 20 fathoms). Adventitious agglutinated material on the test wall is not mentioned in the description of this species (Ponder 1975). Blackmon and Todd (1959) reported *Quinqueloculina sulcata* d'Orbigny, 26 to 28°C water temperature, 13 mole percent $MgCO_3$; *O. lamarkiana* d'Orbigny, 20 to 30°C water temperature, 12 to 16 mole percent $MgCO_3$; *Q. seminulum* Linné, 0°C water temperature, 10 mole percent $MgCO_3$. Thus, magnesium values for the species of *Quinqueloculina* from the eastern Canadian shelf here presented are depressed when compared with those reported by Ponder and Glendening (1974) and Blackmon and Todd (1959). This may be explained by the generally lower watermass temperatures experienced by the eastern Canadian shelf specimens (-1 to 5°C).

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ANNOTATED FAUNAL LIST

BRIZALINA SUBAENARIENSIS (CUSHMAN)

- Bolivina subaenariensis* CUSHMAN, 1922, U.S. Nat. Mus., Bull. 104, pt. 3, p. 46, pl. 7, fig. 6; CUSHMAN, 1937, Cushman Found. Foram. Res. Sp. Pub. No. 9, p. 156. The genus *Brizalina* Costa, 1856 is suggested for forms which lack basal chamber lobes, crenulations or retral processes.

BUCCELLA INUSITATA ANDERSON

- Buccella inusitata* ANDERSON, 1952, Washington Acad. Sci. Journ., v. 42, no. 5, p. 148, Figs. 10a-11c; LOEBLICH and TAPPAN, 1953, Smithsonian Misc. Coll., v. 121, no. 7, p. 116, pl. 22, fig. 1.

BULIMINA ACULEATA D'ORBIGNY

- Bulimina aculeata* D'ORBIGNY, 1826, Tableau methodique de la classe Cephalopodes. Ann. Sci. Nat., Paris, v. 7, p. 269. Forms with apical spines are included.

BULIMINA MARGINATA D'ORBIGNY

- Bulimina marginata* D'ORBIGNY, 1826, Ann. Sco. Nat. v. 7, p. 269, no. 4, pl. 12, fig. 10-12. Forms without apical spines, but with small spines or crenulations on chamber margins are included.

BULIMINA EXILIS BRADY

- Bulimina elegans* d'Orbigny var. *exilis* BRADY, 1884, Rep. Voy. Challenger (Zool.) v. 9, p. 399, pl. 50, figs. 5,6.

- Bulimina exilis* Brady. CUSHMAN & PARKER, 1940. Contr. Cushm. Lab. Foram. Res., v. 16, pt.1, p. 11, pl. 2, figs. 18-21.

ELPHIDIELLA ARCTICA (PARKER & JONESO)

- Polystomella arctica* PARKER and JONES, 1864, in BRADY, Trans. Linn. Soc., London, Zool., v. 24, p. 471, pl. 48, fig. 18.

- Elphidiella arctica* (Parker and Jones). CUSHMAN, 1939, U.S.G.S. Prof. Pap. 191, p. 65, pl. 18, figs. 11-14.

ELPHIDIUM ARTICULATUM (D'ORBIGNY)

- Polystomella articulata* D'ORBIGNY, 1839, Voy. dans l'Amérique méridionale, Foraminifères, p. 30, pl. 3, figs. 9, 10.

ELPHIDIUM BARTLETTI CUSHMAN

- Elphidium bartletti* CUSHMAN, 1933, Smithsonian Misc. Coll. v. 89, no. 9, p. 4, pl. 1, fig. 9; 1939, U.S.G.S., Prof. Pap. 191, p. 64, pl. 18, fig. 10.

ELPHIDIUM CLAVATUM CUSHMAN

Elphidium incertum (Williamson) var. *clavatum* CUSHMAN, 1930, U.S. Nat. Mus., Bull. 104, pt. 7, p. 20, pl. 7, fig. 10. (Not *Polystomella umbilicatula* var. *incerta* Williamson, 1858).

Elphidium clavatum CUSHMAN. LOEBLICH and TAPPAN, 1953, Smithsonian Misc. Coll. v. 121, no. 7, p. 98, pl. 19, figs. 3-10. This form is referred to *Elphidium excavatum* (Terquem) forma *clavata* Cushman, by Feyling-Hanssen, (1972, The foraminifer *Elphidium excavatum* (Terquem) and its variant forms. Micropaleontology, v. 18, no. 3, p. 337-354, pl. 1-6).

ELPHIDIUM INCERTUM CUSHMAN

Not *Polystomella umbilicatula* var. *incerta* WILLIAMSON, 1858, Recent Foraminifera of Great Britain, p. 44, pl. 3, fig. 82a.

Elphidium incertum (WILLIAMSON). CUSHMAN, 1930, U.S. Nat. Mus., Bull. 104, pt. 7, p. 18, pl. 7, figs. 5-9. This forms is referred to *Elphidium excavatum* (Terquem) forma *alba* by Feyling-Hanssen, (1972, Micropaleontology, v. 18, no. 3, p. 337-354, pl. 1-6).

GLANDULINA LAEVI GATA (D'ORBIGNY)

Nodosaria (Glanduline) *laevigata* D'ORBIGNY, 1826, Ann. Sci. Nat., v. 7, p. 252, pl. 10, fig. 1-3.

Glandulina laevigata D'ORBIGNY, 1846, Foraminifères fossiles du bassin tertiaire de Vienne, p. 29, pl. 1, figs. 4, 5.

Pseudoglandulina laevigata (d'Orbigny) CUSHMAN & McCULLOCH, 1950, Allan Hancock Pacific Exped. v. 6, p. 325, pl. 42, fig. 4.

GLOBIGERINA PACHYDERMA (EHRENBERG) s.l.

Aristerospira pachyderma EHRENBERG, 1861, K. Preuss. Akad. Wiss., Berlin, p. 276, 277, 303.

Globigerina pachyderma (Ehrenberg), BE, 1960, Contr. Cush. Found. Foram. Res. v. 11, pt. 2, no. 209, p. 64-68, text fig. 1.

Globorotalia pachyderma (Ehrenberg), VILKS, 1975, Jour. Foram. Res. v. 5, no. 4, p. 313-325, pls. 1-3.

Thick-walled encrusted *C. pachyderma* specimens are not common in the sample. The specimens analyzed are not the encrusted type but are similar to Vilks's plate 1, figs. 1-3, and plate 2, fig. 1. *Globigerina incompta* Cifelli 1961, may also be synonymous.

GLOBOBULIMINA AURICULATA (BAILEY)

Bulimina auriculata BAILEY, 1851, Smithsonian Contr., v. 2, art. 3, p. 12, pl. 0, figs. 25-27.

ISLANDIELLA HELENÆ FEYLING-HANSEN

Cassidulina teretis LOEBLICH & TAPPAN, 1953. (not *C. teretis* Tappan, 1951), Smithsonian Misc. Coll., v. 121, no. 7, p. 121, pl. 24, figs. 3, 4.

Islandiella helenae FEYLING-HANSEN, 1976, Jour. Foram. Res., v. 6, no. 2, p. 154-158, t.f.s. 1-4.

NONIONELLINA LABRADORICA (DAWSON)

Nonionina labradorica DAWSON, J.W., 1860, Can. Nat., v. 5, p. 191, fig. 4.

Nonion labradoricum (Dawson). LOEBLICH & TAPPAN, 1953, Smithsonian Misc. Coll., v. 121, no. 7, p. 86, pl. 17, figs. 1, 2.

Nonionellina labradorica (Dawson). VOLOSHINOVA, 1958, Mikrofauna SSSR, Sbornik 9, VNIGRI, Trudy, no. 115, p. 117-191, pl. 1-16.

QUINQUELOCULINA STALKERI LOEBLICH & TAPPAN

Quinqueloculina fusca Brady. CUSHMAN, 1948 (not Brady, 1870), Cushman Lab. Foram. Res. Spec. Pub. 23, p. 33, pl. 3, figs. 16, 17.

Quinqueloculina stalkereri LOEBLICH & TAPPAN, 1953, Smithsonian Misc. Coll., v. 121, no. 7, p. 40, pl. 5, figs. 5-9.

This calcareous imperforate form is characterized by the presence of a small amount of fine sand grains which is incorporated into the wall.

QUINQUELOCULINA ARCTICA CUSHMAN

Quinqueloculina arctica CUSHMAN, 1933, Smithsonian Misc. Coll., v. 89, no. 9, p. 2, pl. 1, figs. 3a-c.

QUINQUELOCULINA SEMINULUM LINNAEUS

Serpula seminulum LINNAEUS, 1767, Systema Natura, p. 1264, ed. 12.

Quinqueloculina seminulum (Linnaeus) CUSHMAN, 1917, U.S. Nat. Mus., Bull. 71, pt. 6, p. 44, pl. 11, fig. 2.