Sr/Ca in Calcitic Tests of Benthic Foraminifera - A Potential Water-Depth Proxy?

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Abstract: Well-preserved low-Mg calcite tests of modern benthic foraminifera from a depth transect off SW Norway show decreasing Sr/Ca with increasing water depth (r = –0.84). The Mg/Ca ratios also decrease with increasing water depth, although in a curvilinear fashion. Moreover, the inter- and intra-species scatter is apparently larger than for Sr/Ca. A majority of the analysed specimens have Mn/Ca < 200 µmol/mol, and show Sr/Ca, Mg/Ca that fall within published ranges for benthic foraminiferal calcite, indicating that pristine biogenic calcite has been analysed. The uniform temperature and salinity of bottom waters below ~800 m moreover indicate that neither temperature nor salinity can explain the observed Me/Ca trends. The Sr/Ca and Mg/Ca depth trends cannot be explained by dissolution since bottom waters are generally supersaturated with respect to calcite, and dissolution is only observed in a few specimens. Moreover, a regular increase in sedimentary organic content with depth needed to invoke a decrease in porewater pH and concomittant calcite dissolution is not observed. We tentatively ascribe the decreasing Sr/Ca and Mg/Ca trends to depth-related physiological phenomena. The relatively small intra- and interspecies scatter at a given water depth, as well as the linear decrease in Sr/Ca ratios with increasing water depth observed in modern oceans, may render the Sr/Ca in calcitic benthic foraminifera a potential water-depth proxy for fossil deposits.

Keywords: Benthic foraminifera, Sr/Ca, paleowater-depth proxy.

INTRODUCTION

In basin modelling, reconstructing the palaeowater depth is of the utmost importance. Some hint may be provided from seismic reconstruction combined with sedimentology and palaeontology, but the various sedimentary structures, preserved biota and ichnofossils will only indicate relative water-depths. At best we may be able to resolve the palaeowater depth to "within the photic zone" (i.e. above ~ 200 m).

Below this depth, which also roughly coincides with the storm-wave base, *in situ* sedimentary structures and biota become scarce, and it thus becomes notoriously difficult to estimate the palaeowater depth. This is because various environmental factors such as water pressure, substrate, oxygen level, temperature and nutrient availability all influence the benthic community in a complex manner [e.g. 1-3]. Hence, finding an unbiased proxy for water-depth *per se* would be of utmost importance.

Several studies have pointed to certain metal/calcium ratios (Me/Ca) in the calcitic tests of planktic and benthic foraminifera as potential palaeoenvironmental proxies; i.e. a possible relationship has been proposed for both Mg/Ca and Sr/Ca and the ambient water temperature, and a pressure-related effect has been proposed for Sr incorporation [1, 4-7].

However, varying calcification rates and preferential dissolution of biogenic carbonates have also been suggested to govern the frequently observed linear decrease in Me/Ca with increasing water depth; dissolution of less stable Mg-enriched biogenic carbonate has been suggested to start well above the calcite lysocline [8-10].

Recent carbonate dissolution data, based on ultrastructural investigations on the tests of the planktonic foraminifer *Neogloboquadrina pachyderma* sin from the Norwegian-Greenland Sea, show generally good carbonate preservation with only minor dissolution in the deepest part of the Norwegian basin, whereas poor preservation is recognized along the continental margins off Norway and Greenland. The enhanced dissolution in the latter areas is accompanied by generally low carbonate contents of the surface sediments. The carbonate preservation pattern cannot be explained by the water mass characteristics as calcite supersaturation is observed down to water depths of ca. 3800 m in all parts of the Norwegian-Greenland Sea. Hence, other factors favoring supralysoclinal calcite dissolution have to be considered, including pore water chemistry in surface sediments and at the water-sediment interface [11].

Here we present Mg/Ca, Sr/Ca, and Mn/Ca data from apparently well-preserved single and multispecies samples,

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spanning water depths from 216 m to 3940 m on the continental slope and rise in the southern Norwegian Sea (cf. 12] (Fig. **1** and Table **1**). The temperature of the Norwegian Sea bottom water (NSBW) below 800 m only drops by ca. 0.1 °C (from -0.9 °C to -1.0 °C at the sea floor), and the deep water is homohaline (<34.91 ‰) below ca. 400 m [12, 13] (Fig. **1**). Hence, any Me/Ca variation in the tests below this depth cannot be attributed to temperature and salinity variation. In this paper we discuss other possible explanations for the observed Me/Ca depth trends; including preferential dissolution of metal-enriched shell sites and depth-related physiological phenomena.
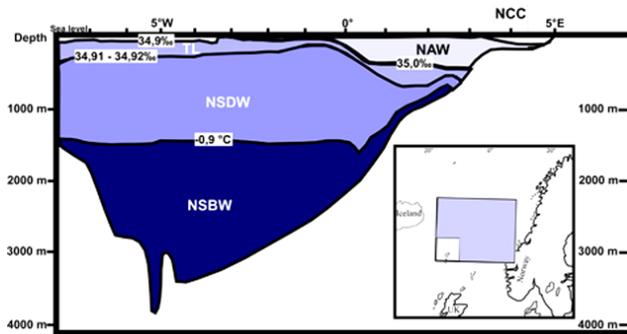
Fig. (1). Study area off SW Norway (light bluish area of inset picture) and water masses in the investigated area (see Table **1** for accurate geographical position). *Note* that the homohaline and homothermal NSBW covers the continental slope already below ca. 800 m water depth. NCC = Norwegian Coastal Current; NAW = North Atlantic Water; TL = Transition layer; NSDW = Norwegian Sea Deep Water; NSBW = Norwegian Sea Bottom Water. SL = Sea level (modified from Mackensen *et al.*, [12]).

MATERIAL AND METHODS

The undisturbed surface sediment samples selected for the present study were originally collected by Mackensen *et al.* [12] by means of a vented box corer and treated with Rose Bengal stained alcohol. The samples were soaked in distilled water and sieved; the >125 µm fraction was subsequently air-dried and stored in glass vials. Samples taken from water depths shallower than ca. 600 m stem from gravelly sand and sandy gravel with occasional pebbles and boulders, considered to be a lag deposit. Below ca. 600 m water depth and down to ca. 1500-1600 m the middle to lower continental slope is covered with hemipelagic mud, and below this depth the lower continental slope and rise are covered with foraminiferal oozes ($CaCO_3$ > 30 %). However, the deepest sample (3940 m water depth) contains only 8% $CaCO_3$, which may be attributed to enhanced dissolution and/or terrigenous dilution [12 and references therein] (Table **1**). The organic carbon content (weight %TOC) varies between ca. 0.5% and 1.3% below ca. 800 m; above this depth and below ca. 3000 m the TOC is less than 0.5% [12]. The sediment samples have been washed and sieved according to the procedures outlined in Mackensen *et al.* [12], and benthic foraminifera were subsequently picked from the 0.125 mm - 2.0 mm size fraction prior to metal analysis (Tables **1** and **2**). Twenty seven single-species samples and six multi-species samples were selected for Me (= Mg, Sr, and Mn)/Ca analysis; multi-species samples were included only when insufficient material from single species was available for analysis. The following epibenthic species were analysed: *Cibicides*

lobatulus, Oridorsalis umbonatus, and *Cibicides wuellerstorfi*. Investigated infaunal species are *Cassidulina teretis* and *Melonis barleeanum* [cf.2].

Approximately 1 mg of each sample from the first batch of low-Mg calcitic (LMC) benthic foraminifera (labelled with an asterisk in Table **2**) was transferred to an acid-rinsed screwcapped polypropylene tube and dissolved in 3 ml 0.15 M suprapure nitric acid. The polypropylene tube was heated in a water bath for 3 hours to ensure complete dissolution of the foraminiferal calcite. These samples were not crushed prior to dissolution and metal analysis. The second batch of single species samples and the multi-species samples were crushed gently with a glass pestle, and removal of siliciclastic material was facilitated by vibrating the samples in an ultrasonic methanol bath; the ensuing particle laden methanol was removed by means of a small syringe. The ultrasonic methanol treatment was repeated four times; after this treatment no particles were visible in the methanol surfactant. The crushed and cleaned samples were subsequently transferred to an acid-rinsed screwcapped polypropylene tube and dissolved in 2.5 ml 0.15 M suprapure nitric acid for a minimum of 24 hours prior to the ICP-MS and AAS analysis. In the first batch of single-species samples calcium and magnesium were determined by means of AAS. For calcium determination a subsample from each of the dissolved foraminifera was dissolved 100 times and determined at the most sensitive line with an air acetylene flame. No ions from the dissolved foraminifera are expected to interfere with the Ca and Mg analyses. Estimated precision for the AAS determination is 5% for both Ca and Mg. Magnesium was determined by means of ICP-MS in the second batch of single species samples and in the multispecies samples. Magnesium, strontium, and manganese were analysed on a VG PQ2 plus inductively coupled plasma-mass spectrometer equipped with a Meinard nebuliser and a water cooled quartz spray chamber kept at 5 °C. Standard Ni sampling and skimmer cones were used. The forward power to the plasma was 1350 W. The instrument was operated in pulse mode and a 30 sec peak-jump procedure was used. The ICP-MS analytical precision is 5% for Mg, Sr, and Mn.

Statistical Treatment

Several statistical procedures and tests were performed on the Mg/Ca and Sr/Ca data sets, based on the assumption of the parental population´s normality. The latter was corroborated visually on probabilty plots where the data follow approximately straight lines. Snedecor´s *F*-test and Student´s *t*-test were used to assess the difference between population variances and population means, respectively. For linear correlations we employed Pearson´s correlation coefficient *r* and Fisher´s test for the level of significance. Linear regressions were calculated from the depth averaged data and their statistical significance was tested by means of Fisher tests. Except where commented upon, the levels of significance (risk of error) are less than 5%.
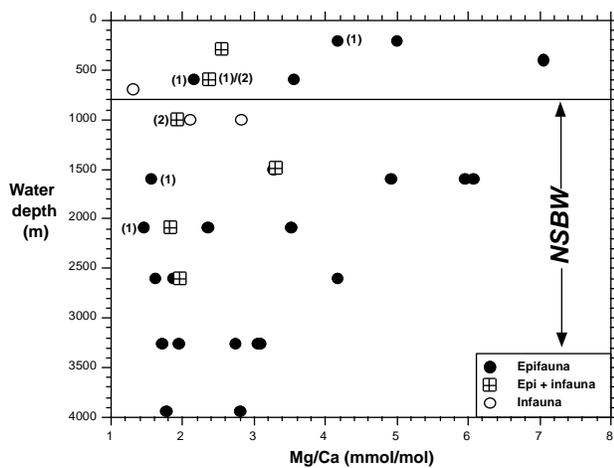
RESULTS

Mg/Ca in Calcitic Benthic Foraminifera

The Mg/Ca ratios in the investigated LMC (low-Mg calcite) benthic foraminifera tests from the southern

Table 1. **Investigated Benthic Foraminifera, Geographical Sampling Position Water Depth (m), and Sediment Type at Sampling Sites**

| Species	Latitude	Longitude	Water Depth (m)	Sediment
Cibicides lobatulus	62° 28' 3" N	4° 27' 3" E	216	Gravelly sand and sandy gravel
Cibicides spp.; Melonis barleeanum	60° 24' 0" N	12° 25' 4" W	300	Gravelly sand and sandy gravel (CaCO₃ ~42%)
Cibicides lobatulus	63° 59' '7" N	12° 05' 7" W	406	Gravelly sand and sandy gravel
"	62° 46' 8" N	3° 53' 7" E	605	"
Cibicides spp.; M.barleeanum; C.teretis	"	"	"	"
Cassidulina teretis	62° 32' 20" N	1° 14' 37" E	700	Terrigenous, hemipelagic mud
"	65° 16' 0" N	8° 48' 8" W	1002	"
"	62° 56' 6" N	1° 02' 0" E	"	Hemipelagic mud (CaCO₃ > 20%)
C.teretis; O.umbonatus	"	"	"	"
C.wuellerstorfi; C.teretis; O.umbonatus	63° 09' 8" N	0° 34' 3" E	1497	Pelagic foram ooze (CaCO₃ > 30%)
Oridorsalis umbonatus	"	"	"	"
Cibicides wuellerstorfi	66° 36' 4" N	2° 39' 3" E	1600	"
"	67° 04' 8" N	7° 18' 9" W	2093	"
Oridorsalis umbonatus	"	"	"	"
C.teretis; C.wuellerstorfi; M.barleeanum; O.umbonatus	"	"	"	"
Cibicides wuellerstorfi	67° 02' 3" N	6° 35' 4" W	2604	"
Oridorsalis umbonatus	"	"	"	"
C.wuellerstorfi; O.umbonatus	"	"	"	"
Cibicides wuellerstorfi	66° 20' 2" N	0° 21' 3" W	3260	"
Oridorsalis umbonatus	"	"	"	"
"	65° 25' 3" N	4° 44' 5" W	3940	Hemipelagic mud (CaCO₃ ~8%)

Norwegian Sea range from 1.32 mmol/mol to 7.07 mmol/mol, and there is apparently no trend versus water depth (Fig. **2** and Table **2**).

Fig. (2). Mg/Ca ratios in LMC benthic foraminifera tests from the southern Norwegian Sea. Samples labelled (1) have Mn/Ca > 128,6 μmol/mol, and those labelled (2) are predominantly composed of infaunal species (see Table **2**). NSBW = Norwegian Sea Bottom Water (homothermal and homohaline).

Sr/Ca in Calcitic Benthic Foraminifera

The Sr/Ca ratios in the LMC benthic foraminifera tests from the southern Norwegian Sea range from 0.75 mmol/mol to 2.2 mmol/mol (Table **2**), and the Sr/Ca ratios apparently decrease with increasing water depth (Fig. **3**). Moreover, the intra-depth scatter in Sr/Ca is apparently less compared to that observed for the Mg/Ca ratios (Figs. **2**, **3**).
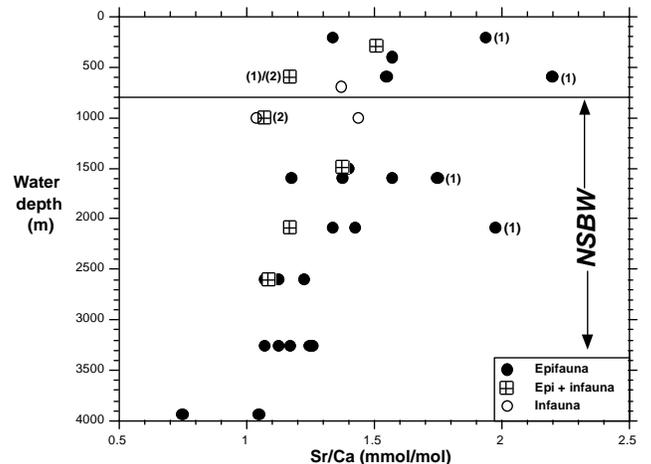
Fig. (3). Sr/Ca ratios in LMC benthic foraminifera tests from the southern Norwegian Sea. See Fig. (**2**) for explanation of labels.

Table 2. Me/Ca Ratios of the Investigated Single-Species and Composite Species Samples

Species in Sample	Life Strategy	Water Depth (m)	Sample Weight (mg)	Size Fraction (mm)	Sr/Ca (mmol/mol)	Mg/Ca (mmol/mol)	Mn/Ca (µmol/mol)	Comments
Cibicides lobatulus*	E	216	1	>250	1.34	5.01	na	Stained pink by Rose Bengal
Cibicides lobatulus*	"	216	0.91	>150	1.94	4.18	376	High Sr/Ca, and Mn/Ca[1]
Cibicides spp.; Melonis barleeanum	E; I	300	3.06	125 - 250	1.51	2.55	35.1	
Cibicides lobatulus*	E	406	1.2	>250	1.57	7.07	na	
Cibicides lobatulus	E	605	0.9	>250	1.55	3.56	na	
Cibicides lobatulus	E	"	1.88	125 - 1000	2.2	2.16	175	High Sr/Ca, and Mn/Ca[1]
Cibicides spp.; M.barleeanum; C.teretis	E; I; I	"	0.77	125 - 1000	1.17	2.39	271.3	High Mn/Ca; infauna[1/2]
Cassidulina teretis	I	700	0.79	125 - 1000	1.37	1.32	74	Infauna
Cassidulina teretis*	I	1002	0.9	125 - 250	1.04	2.82	na	Infauna
Cassidulina teretis	I	"	1.16	125 - 250	1.44	2.1	124	Infauna
C. teretis; Oridorsalis umbonatus	I; E	"	1.37	125 - 250	1.07	1.93	66.4	Predominantly infauna[2]
Cibicides wuellerstorfi; C. teretis; O.umbonatus	E; I; E	1497	0.58	125 - 250	1.38	3.31	103.1	
Oridorsalis umbonatus	E	"	1.71	125 - 250	1.4	3.28	121	
Cibicides wuellerstorfi*	E	1600	0.4	>250	1.18	4.93	na	
Cibicides wuellerstorfi*	E	"	1.1	>250	1.38	5.95	na	
Cibicides wuellerstorfi*	E	"	1.9	>250	1.57	6.08	na	
Cibicides wuellerstorfi	E	"	2.36	>250	1.75	1.57	143.3	?High Sr/Ca and Mn/Ca[1]
Cibicides wuellerstorfi*	E	2093	0.9	125 - 1000	1.43	3.52	na	
Cibicides wuellerstorfi	E	"	2.73	125 - 1000	1.98	1.47	128.6	High Sr/Ca and Mn/Ca[1]
Oridorsalis umbonatus	E	"	1.24	125 - 1000	1.34	2.36	118	
C. teretis; C.wuellerstorfi; M.barleeanum; O.umbonatus	I; E; I; E	"	2.39	125 - 1000	1.17	1.84	103	
Cibicides wuellerstorfi	E	2604		>250	1.07	1.62	57	
Cibicides wuellerstorfi*	E	"	1.1	>250	1.23	4.18	na	
Oridorsalis umbonatus	E	"	1.49	125 - 250	1.13	1.87	36	
C.wuellerstorfi; O.umbonatus	E; E	"	2.17	125 - 1000	1.09	1.97	48.5	
Cibicides wuellerstorfi*	E	3260	0.5	>150	1.07	3.11	na	Stained pink by Rose Bengal
Cibicides wuellerstorfi*	E	"	1.1	>150	1.17	2.76	na	"
Cibicides wuellerstorfi*	E	"	1.9	>150	1.26	3.07	na	"
Cibicides wuellerstorfi	E	"	2.2	>250	1.68	1.39	93.5	
Cibicides wuellerstorfi	E	"	3.02	>250	1.25	1.95	48	
Oridorsalis umbonatus	E	"	1.86	>150	1.13	1.72	24	
Oridorsalis umbonatus*	E	3940	1	125 - 250	0.75	2.81	na	
Oridorsalis umbonatus	E	"	1.41	125 - 250	1.05	1.77	42	

Note that multi-species samples were included only when insufficient material from single species was available for analysis E = epibenthic species. I = infaunal species [2]. Samples labelled with an asterisk were not crushed prior to AAS and ICP - MS analysis (see text). [1] and [2]; see Fig. (2) for explanation. Samples composed predominantly of infaunal species and with Mn/Ca > ~129 µmol/mol and Sr/Ca > ~1.7 mmol/mol are not discussed further (see Table **3** and text).

Table 3. Me/Ca Results from Epibenthic Single-Species and Composite (epi- and Infauna) Species Samples

Species in Sample	Water Depth (m)	n	Sr/Ca (mmol/mol)	SD	Mg/Ca (mmol/mol)	SD
Cibicides lobatulus	216		1.34		5.01	
Cibicides spp.; Melonis barleeanum	300		1.51		2.55	
Cibicides lobatulus	406		1.57		7.07	
"	605		1.55		3.56	
Cibicides wuellerstorfi; C. teretis; O.umbonatus	1497		1.38		3.31	
Oridorsalis umbonatus	1497		1.4		3.28	
Cibicides wuellerstorfi	1600	3	1.38	0.195	5.65	0.6267
"	2093		1.43		3.52	
Oridorsalis umbonatus	"		1.34		2.36	
C. teretis; C.wuellerstorfi; M.barleeanum; O.umbonatus	"		1.17		1.84	
Cibicides wuellerstorfi	2604	2	1.15	0.1131	2.9	1.81
Oridorsalis umbonatus	"		1.13		1.87	
C.wuellerstorfi; O.umbonatus	"		1.09		1.97	
Cibicides wuellerstorfi	3260	5	1.29	0.23	2.46	0.76
Oridorsalis umbonatus	"		1.13		1.72	
Oridorsalis umbonatus	3940	2	0.9	0.2121	2.29	0.7354

SD = Standard deviation. n = number of samples (see Table **2**). *Note* the generally smaller SD of Sr/Ca compared to Mg/Ca at similar water depths.

DISCUSSION

Contamination and Diagenesis

Inspection under a binocular microscope revealed little or no sediment attached to the surface of the foraminifera tests prior to the methanol treatment (see above). Moreover, the surface of Rose-Bengal stained and non-stained tests of the same species appeared pristine.

Most authors recognize that as long as the Mn/Ca ratio observed in analysis of foraminiferal LMC tests stays below ca. 100-200 µmol/mol, there is apparently negligible contamination of the biogenic Me/Ca ratio [14-16].

The Mg/Ca values fall within the ranges reported for modern LMC benthic foraminifera, and all but four of the Sr/Ca values (i.e. Sr/Ca > 1.68 mmol/mol) also fall within the reported range [1, 17] (Tables **2** and **3**). The four samples containing high Sr/Ca ratios also have Mn/Ca ratios > 128,6 µmol/mol (see Table **2**). Thus most of the Mg/Ca and Sr/Ca values appear not to be influenced by siliciclastic contamination and/or authigenic mineral precipitation.
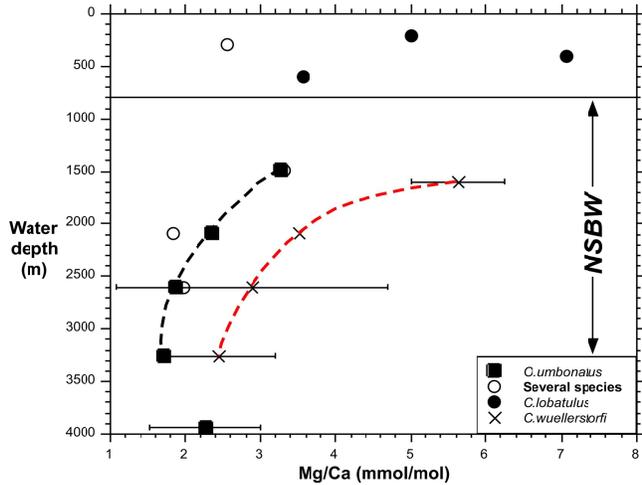
Me/Ca Versus Water Depth

In the following discussion of the Me/Ca versus water depth graphs we discard epifaunal species samples with Mn/Ca > ~129 µmol/mol and Sr/Ca > ~1.7 mmol/mol from further discussion, since these may be contaminated (see above; Tables **2** and **3**; and Figs. (**2**, **3**): samples labelled "1"). Moreover, we also reject infaunal species samples or mixed assemblage samples composed *predominantly* of infaunal species from the discussion (labeled "2" on Figs. (**2**, **3**); see Table **2**), since Me/Ca in infaunal foraminiferal

calcite may have been influenced by porewaters with metal compositions significantly different from those of the oceanic bottom waters [2, 5].

Mg/Ca Versus Water Depth

The Mg/Ca ratios of the calcitic epibenthic and mixed (predominantly epibenthic) assemblage samples vary between ~2.4 and ~7 mmol/mol above 800 m water depth (Tables **2** and **3**; Fig. **4**). Below this depth (and down to 3260 m) there appears to be two curvilinear trends where the Mg/Ca ratios decrease with increasing water depth; one composed of *O. umbonatus* and the other by *C. wuellerstorfi* (Fig. **4**). The Mg/Ca ratios decrease by a factor of 3-4 with increasing water depth within these two slightly offset trends [1]. The apparent offset to higher average Mg/Ca for the deepest (3940 m water depth) samples may reflect some reworking from shallower parts of the continental slope and/or the effect of sediment mixing by bioturbation (see below). In another study on calcitic shells of modern epibenthic foraminifera, Rosenthal *et al.* [1] suggested that Mg/Ca increases exponentially with increasing temperature (and thus decreasing water depth). However, in the present study the bottom waters are practically homothermal and homohaline (see above) below ca. 800 m, which indicate that the observed depth trends (Fig. **4**) must be attributed to other factors, such as enhanced dissolution of Mg-enriched shell parts and/or decreasing growth rates associated with e.g. a depth-controlled decrease in food supply. The apparently parallel depth trends may be controlled by different vital effects and/or different epibenthic microhabitat preferences induced by variation in food supply ultimately resulting in different calcification rates and thereby variation in Mg/Ca [cf. 2, 9, 12, 18]. In this respect it should be noted that

modern *O. tenus* (*O. umbonatus*) species are reported to secrete calcite with very light carbon- isotope compositions ($\delta^{13}C$ values as low as -1.39 ‰ PDB; cf. [19], which is perhaps conformable with an infaunal life strategy.

Fig. (4). Mg/Ca ratios versus water depth for epibenthic samples and mixed assemblage samples predominantly composed of epibenthics. Error bars are standard deviations of the analyses where more than one sample was analysed at a particular water depth (applies to all figures; see Table **3**). *Note* (1) the apparent parallel curvilinear Mg/Ca versus water depth trends for *O. umbonatus* (black curve) and *C. wuellerstorfi* (red curve) within the NSBW = Norwegian Sea Bottom Water (see text), (2) the offset to a higher average Mg/Ca at 3940 m water depth for *O. umbonatus*.
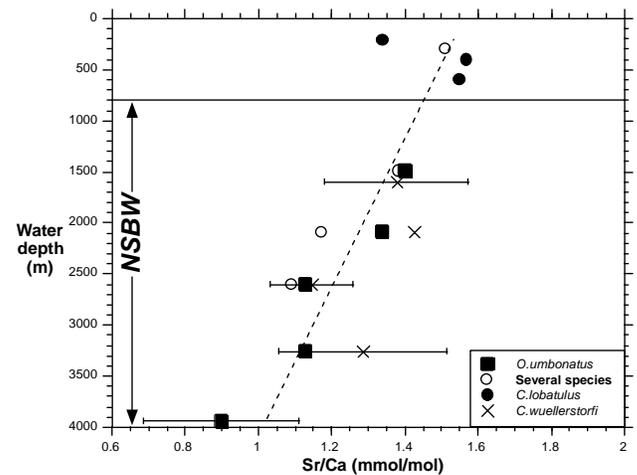
Sr/Ca Versus Water Depth

The Sr/Ca ratios of the epibenthic and mixed (predominantly epibenthic) assemblage samples vary between 0.75 mmol/mol and 1.68 mmol/mol (Table **2**), and the Sr/Ca ratios correlate negatively with increasing water depth ($r = -0.84$; $n = 16$). A negative correlation is also apparent for the data below 800 m water depth; i e. within the homothermal and homohaline NSBW ($r = -0.80$; $n = 12$) (Tables **2** and **3**; and Fig. **5**). Pearson´s correlation coefficient improves to $r = -0.96$ when only the *Oridorsalis umbonatus* data are included (Fig. **5**; $n = 5$); linear regression of the latter data set gives the "best fit" line between water depth (WD) and (Sr/Ca); *WD = –4664 (Sr/Ca) + 8182*. However, a Fisher test shows that this regression line is not significantly different from the regression line where all the Sr/Ca data are included ($r = -0.84$; $n = 16$) (Table **3** and Fig. **5**).

Me/Ca Versus Water Depth Trends Controlled by Dissolution of the LMC Epibenthic Foraminifera Shells?

We do not think that dissolution of the studied foraminifera shells can explain the observed Mg/Ca and Sr/Ca versus water depth trends, for the following reasons:

1. Dissolution is only observed in some specimens (see above).

2. Supersaturation with respect to calcium carbonate is observed down to water depths of approximately 3800 m in all parts of the Norwegian-Greenland Sea [11].

3. High $CaCO_3$ content (>30%) and little variation in the organic content (weight %TOC) below ca. 1500 m where decreasing Sr/Ca and Mg/Ca ratios are observed. The deepest sample has the lowest TOC value (<0.5%), which does not suggest that corrosive bottom waters induced by metabolically derived CO_2 was responsible for calcite dissolution and hence the low Me/Ca ratios [12] (Table **1**; Figs. **5**, **6**; and see above).

4. There is no evidence to suggest that the character of pore-water influences Sr and Mg concentrations in modern epifaunal taxa [5].

5. McCorkle *et al.* [9] observed linearly decreasing Sr/Ca, Cd/Ca, and Ba/Ca in calcitic benthic foraminifera below 2500 m water depth from the Ontong-Java Plateau, and a covarying sharp decrease in these ratios below the calcite saturation depth at 3 km. Our data show a linear depth trend for Sr/Ca and apparent curvilinear trends for Mg/Ca, but neither ratio decreases abruptly at depth.

Fig. (5). Sr/Ca ratios versus water depth for epibenthic samples and mixed assemblage samples predominantly composed of epibenthics. *Note* that the Sr/Ca ratios decrease linearly with increasing water depth. A best fit regression (dashed line) gives *WD = –5064.53 (Sr/Ca) + 8488.78*; r = –0.84.

Sr/Ca in Benthic Foraminifera Shells as a Water-Depth Proxy?

Modern Foraminifera-Calibration Line

Rosenthal *et al.* [1] observed linearly decreasing Sr/Ca ratios with increasing water-depths that could not be fitted to the *in situ* temperature profile. These authors therefore inferred that the linear global decrease in Sr/Ca with increasing water depth suggested that the partition coefficient of Sr (D_{Sr}) in foraminiferal shells (both calcitic and aragonitic) probably is a pressure-related phenomenon. However, Rosenthal *et al.* [1] realized that a pressure dependence of the thermodynamic coefficients could not solely explain the large magnitude of the Sr/Ca change.

It is recognized that there is a strong relationship between ambient water temperature and the Mg/Ca composition of calcitic benthic foraminifera shells [e.g. 1]. The curvilinear

Mg/Ca versus water depth observed in our study material is hence a puzzle given the homothermal and homosaline bottom-water conditions. We have no explanation for this other than that there may also exist depth-related (non thermal) physiological processes that govern the curvilinear Mg/Ca versus depth trends. The two curvilinear trends observed in Fig. (**4**) may be related to species-specific effects on magnesium uptake, and the larger intra-species scatter in Mg/Ca compared to Sr/Ca (Table **3**) may signal a generally higher intra-species and single-shell Mg/Ca variation [cf. 14, 20]. Part of the intra-species Mg/Ca and Sr/Ca variation (Table **3** and Figs. **4**, **5**) may also be attributed to reworking of older specimens by bioturbation and/or transportation of specimens from shallower parts of the continental slope, since the majority of our samples were from death assemblages (i.e. not stained pink by Rose Bengal; Table **2**). The apparent higher intra-shell and intra-species variation for Mg/Ca compared to Sr/Ca, as well as a predominant temperature effect on magnesium uptake in foraminifera, makes it difficult to use Mg/Ca as a water-depth proxy. However, the generally smaller intra- and inter-species Sr/Ca variation observed in the present data set, as well as a global linear decrease with increasing water depth (Fig. **5**) [cf. 1] would seem to favour the use of Sr/Ca as a water depth proxy (Fig. **6**). In this respect it should be noted that a linear regression of data above 3 km water depth extracted from the global Sr/Ca data compiled by Rosenthal *et al.* [1; their fig. 7] was not statistically different (significant at $\frac{1}{2}\alpha = 0.025$) from the regression line based on our data set (Fig. **6**). We have not extracted Sr/Ca data below 3 km from fig. 7 in Rosenthal *et al.* [1], since these are most likely influenced by dissolution [9].

Although we have no data on Sr/Ca in the NAW, NSDW, NSBW (see Fig. **1**) and porewater, published data on Sr/Ca in the oceans show only spatial gradients of 2-3% globally and relatively higher Sr/Ca ratios in the deeper parts [21]. However, since we observe lower Sr/Ca ratios in the foraminifera tests with depth, and the analysed taxa are predominantly epifaunal, we do not think that variation in Sr/Ca of the bottom- and porewaters can explain the trend shown in Fig. (**5**).

The application of only Rose Bengal stained specimens in constructing the Sr/Ca versus water depth calibration line would probably decrease the Sr/Ca variance at a given depth (see above), and hence reduce the 95% prediction intervals for mean and individual water depths at a given Sr/Ca ratio [cf. 22].

Sr/Ca Ratios in Fossil Foraminifera-Implications for Palaeowater Depth Estimation

To decipher the possible effects of various environmental factors on calcareous benthos and pelagos, several studies have focused on the chemistry of their tests and skeletons. These studies have shown that in many cases we may be able to estimate water depths indirectly by means of temperature, salinity and nutrient availability proxies (e.g. temperature: Mg/Ca; temperature and salinity: $\delta^{18}O$ and $\delta^{13}C$; nutrient availability: Cd/Ca and Ba/Ca; [1; and refs. therein]. Thus, in the modern ocean, where the chemical compositions diagnostic of the various water-masses are known, we may be able to infer specific water depths based on the chemical

composition of *in situ* foraminifera tests. However, extrapolating this relationship back in time is problematic as the hydrographic and chemical conditions at specific water depths have varied [e.g. 23]. As we have inferred above, the Sr/Ca of well preserved LMC benthic foraminifera may be a potential water depth proxy, but caution must nevertheless be exercised when using the modern Sr/Ca versus water depth calibration line to predict water depths for fossil deposits:

1.   Scanning electron microscopy (SEM) and possibly cathodoluminescence microscopy (CL) must be used to assess shell preservation, in addition to the chemical criteria outlined above [cf. 9, 11, 24].

2.   Several epibenthic species from the same stratigraphic level should be subjected to analysis.

3.   The fossil species investigated should preferentially be of the same species, or at least the same genus, as those included in the calibration study. This is important because even though the investigated species in this study apparently show no differential vital effects, differential taxon-specific vital effects have been suggested for other modern benthic species; e.g. *C. wuellerstorfi* and *Uvigerina* species [5].
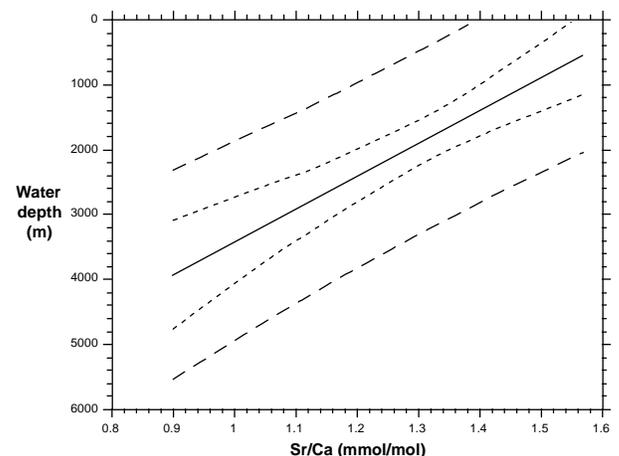
Fig. (6). Sr/Ca as a water depth proxy. Regression line *WD = −5064.53 (Sr/Ca) + 8488.78*; R^2 = 0.71 (significant at $\alpha=0.005$). Narrow and wide belts delineated by dashed lines are the 95% confidence and prediction intervals for the mean and individual water depths at a given Sr/Ca ratio.

CONCLUSIONS

Surface sediments from a depth transect (ca. 200 m to 4000 m) off SW Norway were sampled to assess the influence of water depth on the incorporation of Mg, and Sr into low-Mg shells of epibenthic foraminifera. Bottom waters in the investigated area are homohaline and homothermal below ~800 m water depth, and any depth trend in Me/Ca cannot therefore be attributed to depth changes in temperature and salinity. Moreover, there is no evidence to suggest that dissolution of the foraminifera shells govern the observed Me/Ca trends. The Mg/Ca ratios decrease in a curvilinear fashion with water depth, a feature also observed in areas where there apparently is a strong covariance between the ambient water temperature and

uptake of magnesium into benthic foraminifera shells. The curvilinear, species-specific trends observed in our study thus seem to indicate that other depth related factors than decreasing temperature also govern the magnesium uptake into benthic foraminifera shells. The Sr/Ca ratios decrease linearly with increasing water depth, and there is apparently no differential vital effect exerted on the strontium uptake by the investigated epibenthic species. Hence, we propose that the best fit regression line for Sr/Ca versus water depth may potentially be used in estimating palaeowater depth for fossil deposits.

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