Research paper

Inside story: An X-ray computed tomography method for assessing dissolution in the tests of planktonic foraminifera

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ARTICLE INFO

Article history:
Received 17 November 2009
Received in revised form 17 July 2010
Accepted 19 July 2010

Keywords:
Foraminifera
Dissolution index
X-ray computed tomography
XDX
Δ[CO3²⁻]

ABSTRACT

X-ray computed tomography (CT) provides an insight into the progression of dissolution in the tests of planktonic foraminifera. Four species of foraminifera (*G. ruber* white, *G. sacculifer*, *N. dutertrei* and *P. obliquiloculata*) from Pacific, Atlantic and Indian Ocean core-top samples were examined by CT and SEM. Inner chamber walls began to dissolve at Δ[CO₃²⁻] values of 12–14 μmol/kg. Close to the calcite saturation horizon, dissolution and precipitation of calcite may occur simultaneously. Inner calcite of *G. sacculifer*, *N. dutertrei* and *P. obliquiloculata* from such sites appeared altered or replaced, whereas outer crust calcite was dense with no pores. Unlike the other species, there was no distinction between inner and outer calcite in CT scans of *G. ruber*. Empty calcite crusts of *N. dutertrei* and *P. obliquiloculata* were most resistant to dissolution and were present in samples where Δ[CO₃²⁻] ≥ −20 μmol/kg. Five stages of preservation were identified in CT scans, and an empirical dissolution index, XDX, was established. XDX appears to be insensitive to initial test mass. Mass loss in response to dissolution was similar between species and sites at ~0.4 μg/μmol/kg. We provide calibrations to estimate Δ[CO₃²⁻] and initial test mass from XDX.

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1. Introduction

Variations in atmospheric CO₂ content on glacial–interglacial time-scales are ultimately driven by the carbonate ion ([CO₃²⁻]) content of the deep ocean (Broecker and Peng, 1982, 1987; Sundquist and Broecker, 1985; Broecker and Maier-Reimer, 1992). Because so many processes may play a role in controlling deep ocean [CO₃²⁻] (review by Archer et al., 2000), many attempts to reconstruct deep water chemistry focus on an assessment of carbonate dissolution in sediments.

Fluctuations in carbonate preservation have been reconstructed from direct measurements of carbonate content of sediment cores (Farrell and Prell, 1989, 1991). Other properties of bulk sediment such as colour, or proportion of coarse to fine fraction carbonate (Broeckes and Clark, 1999), can also indicate preservation state. However, properties of carbonates preserved in sediments reflects processes at the sea surface as well as those at the seafloor. Many processes in the surface ocean influence the quantity and character of carbonate in sediments. A change in productivity, or a shift in ecosystem toward or away from carbonate producing species, not only alters the amount of carbonate produced, but also the efficiency with which the various biological phases are transported to the deep ocean (Passow and de la Rocha, 2007). Dilution of carbonates by silicates and terrigenous materials attenuates the carbonate signal.

In addition to direct controls on carbonate export, conditions in the surface ocean also indirectly affect the nature of carbonates found in sediments. Properties of the sediment flux control susceptibility of carbonates to dissolution, thus modifying the relationship between deep water calcite saturation (Δ[CO₃²⁻]) and carbonate dissolution. Particle size has a strong effect on carbonate solubility (Keir, 1980). Bioturbation and rain rate control the exposure time of carbonates to deep water sufficiently that accumulation rates can increase despite decreased deep water calcite saturation (Archer, 1991). Above the calcite saturation horizon, acidity produced by the oxidation of organic material within sediments is the most significant cause of carbonate dissolution (Parker and Berger, 1971; Berner, 1977; Martin and Sayles 1996; Emerson and Bender, 1981). A change in the ratio of organic to inorganic carbon arriving at the seafloor alters dissolution intensity (Archer and Maier-Raimer, 1994).

The tests of planktic foraminifera make up a significant part of the inorganic carbon exported from the surface ocean and deposited on the seafloor (Langer, 2008) and the preservation state of the calcite tests can be used to monitor carbonate dissolution. Many semi-quantitative ways of assessing the preservation state of tests have been developed since Arrhenius (1952) compared the ratio of complete tests to fragments. Similar fragmentation indices have been developed for various species (Berger, 1968; Ob, 1969; Bé et al., 1975; Ku and Oba, 1978; Thunell, 1976; Hebbeln et al., 1990; Mekik...
and Francois, 2006). Other indices include the relative abundance of dissolution resistant and dissolution susceptible species (Berger, 1970); the ratio of benthic to planktic tests (Metzler et al., 1982) and the abundance of organic linings of certain types of benthic foraminifera, preserved after the calcite test has dissolved (Le and Shackleton, 1992; de Vernal et al., 1992). There are also scanning-electron microscopy methods which relate corrosiveness of deep water to breakdown of the test surface (Henrich, 1989; Dittert and Henrich, 2000). However, because dissolution is initiated on the inside of the test (Brown and Elderfield, 1996) the outer appearance may not be sensitive to the first signs of alteration.

The susceptibility of inner calcite to dissolution means that tests become lighter while test size remains fairly constant (Lohmann, 1995). The simplest way to quantify dissolution is to weigh the tests and test mass has been used to reconstruct changes in deep ocean \([\mathrm{CO}_3^{2−}]\) (Broecker and Clark, 2001a,b, 2002). This approach works well over constrained areas but it is complicated by the fact that environmental conditions such as nutrient availability (de Villiers, 2004) or temperature influence the thickness of the test walls and therefore the initial mass of the test.

Another consideration, receiving increased attention at the moment in light of increasing atmospheric CO2 and consequent acidification of the surface ocean, is that the \([\mathrm{CO}_3^{2−}]\) of the waters where foraminifera form may control how much they calcify, as first reported by Herron-Allen (1915). The association between \([\mathrm{CO}_3^{2−}]\) and test mass has been corroborated by more recent evidence. Spero et al. (1997) and Bijma et al. (1999) found that *Orbulina universa* in culture experiments responded to increased \([\mathrm{CO}_3^{2−}]\) by increased calcification. Barker and Elderfield (2002) found test mass increased in parallel with \([\mathrm{CO}_3^{2−}]\) for *Globigerina bulloides* in the Atlantic and there are now several records which show changes in shell mass reflecting glacial–interglacial cycles (e.g. Barker et al., 2004). The potential use of test mass as a proxy for foraminifera form may control how much they calcify, as increasing \([\mathrm{CO}_3^{2−}]\) in surface water \([\mathrm{CO}_3^{2−}]\) requires development of a method which reliably in order to distinguish the effect of surface water \([\mathrm{CO}_3^{2−}]\) on initial test mass from the effect of deep water \([\Delta \mathrm{CO}_3^{2−}]\) post-mortem.

In this study we use the imaging technique of X-ray computed tomography (CT) to examine foraminifera tests from core-top samples from sites with a range of \([\Delta \mathrm{CO}_3^{2−}]\). The method allows observation of the test interior and so provides a new insight into the progression of dissolution.

2. Samples and methods

2.1. Foraminifera species

Four species of planktonic foraminifer were examined: *Globigerinoides ruber* (d’Orbigny, 1839) (white variety); *Globigerinoides sacculifer* (Brady, 1877) (without a sac-like final chamber); Neogloboquadrina dutertrei (d’Orbigny, 1839) and *Pulleniatina obliquiloculata* (Parker and Jones, 1865). Their resistance to dissolution, according to the categorisation of Berger (1970), increases along with their depth habitat. The surface dweller *G. ruber* was rated ‘very susceptible’ to dissolution, ranking first out of the 22 species rated by Berger. Like *G. ruber*, *G. sacculifer* also lives in the mixed layer; it was described as ‘susceptible’ by Berger (5 out of 22). The thermocline dwellers *N. dutertrei* (16 out of 22) and *P. obliquiloculata* (18 out of 22) are considered ‘resistant’ to dissolution.

2.2. Calcite saturation

CT scans of foraminifera tests were compared to calcite saturation \(\Delta [\mathrm{CO}_3^{2−}]\) of the water overlying the core-tops. \(\Delta [\mathrm{CO}_3^{2−}]\) is defined as:

\[
\Delta [\mathrm{CO}_3^{2−}] = [\mathrm{CO}_3^{2−}]_{\text{IN SITU}} - [\mathrm{CO}_3^{2−}]_{\text{SATURATION}}
\]

i.e. the difference between the measured carbonate concentration \([\mathrm{CO}_3^{2−}]_{\text{IN SITU}}\) and the calculated theoretical value of calcite saturation \([\mathrm{CO}_3^{2−}]_{\text{SATURATION}}\) (e.g. Berger et al., 1982).

\(\Delta [\mathrm{CO}_3^{2−}]\) was calculated by the CO2SYS program (Pele et al., 2005) using GLODAP (Key et al., 2004) and World Ocean Atlas (WOA) (Locarnini et al., 2006) data according to the method in Yu and Elderfield (2007). The depth where \(\Delta [\mathrm{CO}_3^{2−}]\) is zero is defined as the calcite saturation horizon.

2.3. Details of core-tops

The main sample set used in this study was collected from the Ontong Java Plateau (OJP) in the Pacific. This has become a classic area for studying the effects of dissolution (e.g. Berger, 1970; Bonneau et al., 1980; Hebbeln et al., 1990; McCorkle et al., 1995; Dekens et al., 2002) due to there being little seasonal temperature variation and small geographic range over a depth transect spanning the calcite saturation horizon. In order to study foraminifera exposed to water with a wide range of calcite saturation states we also used core tops from the Mid-Atlantic Ridge (MAR), the Caribbean and the Ceara Rise in the Atlantic. From the Indian Ocean box cores from the Ninety-East Ridge and from the east of Madagascar (McCave, 2001) were used. The core-tops, where dated, are Holocene in age. Due to low sedimentation rates some samples from the Indian Ocean date from the early Holocene. Table 1 summarises details of the cores.

2.4. Sample preparation

Samples prepared from fresh sediment (Caribbean, MAR and Ceara Rise core-tops) were placed in jars with deionised water. Jars were shaken overnight. Samples were then sieved and thoroughly rinsed in deionised water. Foraminifera were picked from the 300–355 μm size fraction. A large sample (ideally 70–100 tests) was weighed on a microbalance to obtain average test mass.

2.5. X-ray computed tomography (CT) scanning

Computed tomography uses X-rays to produce images of an object from many different angles. The X-ray attenuation calculated from these ‘shadow images’ is used to create virtual cross-sectional slices through the object showing details of the inner structure. The greyscale values of the images are maps of the X-ray density, a property which depends both on the mineral density (atomic number) and the arrangement of the material (thickness and microporosity).

Foraminifera were scanned using a SkyScan 1072 micro-CT desktop scanner (Van Dyck and Sasov, 1998; Sasov and Van Dyck, 1998). This system uses an air-cooled point X-ray source and gives a resolution of ~7 μm in the scanned cross-section. Scans are sufficiently high resolution to show all but the very smallest inner chambers of foraminifera tests and while not resolving the pores completely, their presence or absence can be detected.

CT scanning was carried out at the Department of Earth Sciences, University of Cambridge. Tests were glued to the sample holder using water soluble glue so that they could be afterwards recovered. Tests were scanned in small batches of 8 to 10 tests. They were carefully arranged so that, as far as possible, they did not touch each other and the apertures faced in the same direction. All samples were scanned under the same conditions: anode voltage was set at 80 kV and the rotation step was 0.9°. A 0.5 mm Al filter was used to cut out the softest X-rays and therefore reduce beam hardening effects. Exposure time was 4.5 s which gave a total scan time of around 50 min.

Cross-sections were reconstructed by SkyScan’s own software which uses the Feldkamp cone-beam algorithm (Feldkamp et al., 1984). A 10% beam hardening correction was applied to reduce this artefact. The threshold values for the greyscale of the reconstructed slices were kept constant (scan value 0.010 was set to colour 255
2002). Used here, have been dated to between 3 and 6 ka (Barker et al., 2007; Dekens et al., 60


3. Progression of dissolution in the tests of planktonic foraminifera

3.1. Observations from CT and SEM

Most of the tests examined here had already undergone at least minor diagenesis. They had been altered from ‘glassy’ transparent tests to ‘frosty’ white ones. Glassy tests were abundant in samples from shallow sites on the Ceara Rise and in the Caribbean where Δ[CO$_3^-$] values were greater than 40 μmol/kg. Although glassy tests often had thin walls, particularly G. ruber, they appeared well preserved. Many tests of G. ruber retained their spines. Another indication of the excellent preservation of these samples was the presence of aragonitic pteropods. Tests from these highly supersaturated sites were firm and resistant to being crushed. CT scans gave a very dark, sharp image where the inner chambers were clearly delineated and the pores of the outer wall apparent.

Tests from sites where Δ[CO$_3^-$] was between 20 and 10 μmol/kg were usually white and opaque, but appeared reasonably well-preserved. Pore structures could often be distinguished in CT (Fig. 1(b)) and the inner chambers were present (Fig. 1(i)). SEM shows that even in well preserved tests slight separations exist between layers of calcite (Fig. 1(a), (k)). As dissolution proceeds, these gaps widen (Fig. 1(c), (m)). The development of such microporosity, i.e. porosity below the resolution of the scanner, results in a lighter grey colour in the scanned image. The first signs of dissolution apparent in CT scans were that the thin walls of the smallest inner chambers became blurred and paler in colour.

CT scans of tests from sites with progressively lower calcite saturation recorded the advance of dissolution from the smallest inner chambers to the larger chambers. Chamber walls became increasingly pale, indistinct and finally absent. In G. ruber, which lacks an outer crust (Caron et al., 1990), the pale colour affected the whole of the test (Fig. 1(j)). In G. sacculifer, N. dutertrei and P. obliquiloculata a distinction developed between pale, porous inner calcite and a darker outer layer (Fig. 1d, n). We use the definition of Brown and Elderfield (1996) where ‘inner calcite’ defines all the chambers inside the test as well as the calcite of the inner part of the outer wall. ‘Outer calcite’ refers to the outer part of the outer wall of the test, also called crust calcite.

The outer calcite of G. sacculifer, N. dutertrei and P. obliquiloculata was also altered by dissolution. Pore structures were less clearly defined (Fig. 1(m)) than in scans of tests from shallower sites (Fig. 1(k)). SEM of tests from sites around the calcite saturation horizon showed pores were often blocked with coccoliths and other detritus (Fig. 1(h)) while those from shallower sites had empty pores (Fig. 1(g)).

Poor preservation of tests from sites where Δ[CO$_3^-$] was close to zero was also identifiable under the binocular microscope. The outer test surface was dull and powdery and tests were easy to crush, forming small particles. CT showed that by this stage the smallest chamber walls of all four species were usually missing. Tests of G. ruber were scarcer at these depths and the tests which were present tended to have thicker chamber walls, particularly of the final chamber, than those from shallower sites.

The distinction between light inner calcite and dark outer calcite in CT scans was very conspicuous (Fig. 1(f)) at sites where deep water was slightly undersaturated with respect to calcite. Although the form of the larger inner chamber walls was usually present, the walls themselves often appeared thickened and distorted, often with irregular edges (Fig. 1(p)). Even though tests appeared altered and partially dissolved, the width of the outer test wall, taking into account both the dark outer layer and the pale inner layer, was frequently as thick, or even thicker, as that of well preserved tests.

The material lining the inside of the outer wall may be partially composed of remnants of inner calcite or minerals precipitated during diagenesis (Section 5.2). SEM showed that it also contained sedimentary particles, particularly coccoliths (Fig. 1(e), (o), white arrows). This phase was incorporated into the test and was not completely removed by ultrasonication. Although the material is diffuse and probably makes up less than 10% of the total test mass, it could contribute to the distortion of geochemical proxies based on analysis of poorly preserved tests. δ$^{18}$O in coccoliths is extremely variable, being enriched by 1% in some species and depleted by 2.5%.
Mg/Ca of coccolith calcite is much lower than that of planktonic foraminifera, at ~0.4 mmol/mol (Stoll et al., 2001) and would act to reduce measured Mg/Ca if not entirely removed before analysis.

The pale, porous material inside tests decreased with increasing water depth until, for *N. dutertrei* and *P. obliquiloculata*, eventually only the outer crust remained. Extremely dissolved *G. sacculifer* did not quite reach this stage and a small amount of the inner part of the penultimate chamber was always present even in the most dissolved samples. Between $-15$ and $-20 \mu$mol/kg $\Delta$[CO$_3^{2-}$] core-top samples consisted mainly of the outer crust calcite of thermocline and deep dwelling species.

The exterior surface of the outer test wall was etched and corroded at sites where deep water was undersaturated with respect to calcite. The outer surface of tests showed structural breakdown and loss of material from the outer wall, as previously documented by Bonneau (1978).

### 3.2. Variation in initial wall thickness

One immediate insight from CT is that the initial thickness of the test wall can vary widely, both within and between sample sets. The more heavily calcified, deeper dwelling foraminifera species had the widest range of wall thickness as well as the thickest walls. For example *P. obliquiloculata* from shallow samples on the OJP and WIND transects contain tests with a range of wall thicknesses (from ~25 $\mu$m to ~45 $\mu$m).

Under the binocular microscope the thick-walled type had a very shiny outer layer and appeared more heavily calcified. Despite the clear difference between end members individual test mass from the 1616 m sample (in this case a larger size fraction of 355–425 $\mu$m was used) on the OJP showed a normal distribution.

The sample set from along the coast of Madagascar in the western Indian Ocean had the widest range of wall thickness, presumably because of the wide geographical and age range of these samples. *N. dutertrei* from the OJP also showed fluctuations in average test thickness between different samples. Such variation reflects the observation of Parker (1962) that there is a large amount of morphological variation in *N. dutertrei*. Srinivisan and Kennett (1976) suggested that thin walled forms are subtropical species, while the thick walled forms inhabit sub-tropical waters but Cifelli (1982) notes that both thin and thick walled are found together in plankton tows in tropical regions. Darling et al. (2000) suggest that

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**Fig. 1.** Effect of dissolution on test structure and its appearance in SEM and CT scans. Tests come from the OJP and are from the 300 to 355 $\mu$m size fraction. Black rectangles on CT scans show approximate position of the SEM image to the left. Water depths (and $\Delta$[CO$_3^{2-}$] in $\mu$mol/kg) are given. (a) to (f) Scans of *G. sacculifer*. Scale bars on SEM images 5 $\mu$m. (a) SEM and (b) CT images of tests from 1616 m (13.8). (c) SEM and (d) CT of tests from 2445 m (4.3). (e) SEM and (f) CT of *G. sacculifer* tests from 3711 m ($-11.8$). (g) and (h) SEM scans of the outer surface of the final chamber of *N. dutertrei*. (g) Test from 1616 m (13.8) and (h) test from 2301 m ($-2.3$). Scale bar 10 $\mu$m. (i) and (j) Scans of *G. ruber* from 2301 m (4.9 $\mu$mol/kg). (i) SEM (scale bar 5 $\mu$m) and (j) CT. (k) to (p) Scans of *P. obliquiloculata*. SEM images are of polished sections, scale bars are 10 $\mu$m. (k) SEM and (l) CT of well preserved tests from 1616 m (13.8). (m) SEM and (n) CT of tests from 2301 m (4.9). (o) SEM and (p) CT scans of tests from 4025 m ($-14.7$).
there is high genetic diversity in *N. dutertrei*. To date, three genetic types have been identified (Darling et al., 1997, 1999, 2003). Genetic differences may contribute to the wide variation in *N. dutertrei* tests compared to the more homogenous appearance of *G. sacculifer*, where only one genetic type has so far been recognised (Darling et al., 1996).

Variation in wall thickness means that test mass for each species is not geographically constant. *G. ruber*, *G. sacculifer* and *N. dutertrei* tests from the Atlantic/Caribbean (where surface water [CO$_3$]$^-$ is ~105 μmol/kg) are 20–25% heavier than those from the OJP in the Pacific (where surface water [CO$_3$]$^-$ is ~75 μmol/kg).

Assuming that the average mass for a test in a sample was initially that of those from the shallowest site from each transect, tests can sustain a large loss of mass before they disintegrate. Extremely dissolving *P. obliquiloculata* have lost ~50% of their initial mass. *G. sacculifer* and *N. dutertrei* can lose ~40%, and even the thin-walled and fragile *G. ruber* can lose ~30%, of initial mass. As previously observed, significant dissolution of foraminifera tests occurs where deep water is supersaturated with respect to calcite (Brown and Elderfield, 1996). In this study, more than half of the mass lost occurred above the calcite saturation horizon.

CT scans show negligible dissolution of tests at sites where $\Delta$[CO$_3$]$^-$ is above 20 μmol/kg. Linear regressions fitted for OJP (all samples) and Ceara Rise (the four sites where $\Delta$[CO$_3$]$^-$ was below 20 μmol/kg) illustrate sensitivity of test mass to $\Delta$[CO$_3$]$^-$_. Despite the difference in initial mass, the effect of dissolution on test mass was similar for all four species at the two sites. Mass of *G. ruber_ decreased by 0.38 (±0.19) μg/μmol/kg at the OJP, where tests were 18 μg, and by 0.20 (±0.11) μg/μmol/kg at the Ceara Rise where average mass was 22 μg. *G. sacculifer_ tests were 23 μg at the OJP, where mass decreased by 0.47 (±0.16) μg/μmol/kg and 27 μg at the Ceara Rise, where mass decreased by 0.51 (±0.38) μg/μmol/kg. Mass of *N. dutertrei_ decreased by 0.34 (±0.18) μg/μmol/kg at the OJP where tests were 26 μg and by 0.32 (±0.20) μg/μmol/kg at the Ceara Rise where test mass was 34 μg. Mass of *P. obliquiloculata_ are similar at the two sites, being 33 μg at the OJP, where mass decreased by 0.41 (±0.06) μg/μmol/kg and 31 μg at the Ceara Rise where mass decreased by 0.40 (±0.26) μg/μmol/kg.

These values are consistent with those of Broecker and Clark (2001a), who used a larger size class (355–415 μm) of *G. sacculifer, N. dutertrei_ and *P. obliquiloculata_ from the OJP, Ceara Rise and Ninety-East Ridge but found a similar gradient (0.30±0.05 μg/μmol/kg) between test mass and $\Delta$[CO$_3$]$^-$_. Rosenthal and Lohmann (2002) also found a response in the same range, 0.31 μg/μmol/kg, for *G. sacculifer_ (300–400 μm size fraction) from the Sierra Leone Rise.

$\Delta$[CO$_3$]$^-$ therefore correlates with mass lost to dissolution, $\Delta M$, where,

$$\Delta M = \text{mass}_{\text{INITIAL}} - \text{mass}_{\text{MEASURED}}$$(1)

mass$_{\text{INITIAL}}$ is the original mass before any dissolution effect, and mass$_{\text{MEASURED}}$ is the actual measured mass. Values used for mass$_{\text{INITIAL}}$ are averaged from samples above 20 μmol/kg, for sites where there are samples available from these depths. For the OJP sample set, mass$_{\text{INITIAL}}$ was that of the shallowest sample in the transect. Fig. 2 shows $\Delta$[CO$_3$]$^-$ versus $\Delta M$ with one regression plotted for all samples of one species.

As well as similar sensitivity to $\Delta$[CO$_3$]$^-$, tests reached a similar minimum mass (Table 2). *G. ruber_ and *G. sacculifer_ from the OJP reached a minimum mass of around 12 μg in the core-tops where they were still found in sufficient quantity to take a sample. Tests of *N. dutertrei_ and *P. obliquiloculata_ reached a minimum mass of ~15 μg. These species were still very abundant in the deepest samples used in this study. Tests of *N. dutertrei_ and *P. obliquiloculata_ with mass of ~15 μg appeared as if they could still thin further. The linear correlation between $\Delta$[CO$_3$]$^-$ and $\Delta M$ suggests that ‘dissolution resistance’ is sensitive to initial test mass. *G. ruber_ and *G. sacculifer_ are lost first from assemblages only because they are lighter initially and *N. dutertrei_ and *P. obliquiloculata_ are preserved to lower $\Delta$[CO$_3$]$^-$ values because they are more massive.

As described in Section 3.1 (Fig. 1p) the early stages of dissolution did not have a measurable effect on the thickness of the test walls. The term ‘wall thickness’ here refers to the whole distance across the test wall, i.e. the width from the outer to the inner edge, irrespective of whether the intervening material has become more porous. The walls of partially dissolved tests from around the calcite saturation horizon were often as wide as those of well preserved samples. Like test mass, test volume decreased linearly with decreasing $\Delta$[CO$_3$]$^-$_. Due to the porous nature of the inner material of the test around the calcite saturation horizon, density is lowest for samples from these depths. Below the calcite saturation horizon density (mass/volume) increased as the porous inner material dissolved.

3.3. Greyscale as dissolution indicator

The development of microporosity as spaces and gaps developed within the test wall (Fig. 1c, m), and the addition of disintegrated material to the inner walls of the test (Fig. 1e, o), meant that during the initial stages of dissolution the colour of the scanned images generally became lighter. Within a certain range, greyscale indicates dissolution. For example greyscale correlates with $\Delta$[CO$_3$]$^-$ for *G. sacculifer_ from between 20 and −10 μmol/kg on the OJP ($r^2 =0.72$) and *P. obliquiloculata_ below 20 μmol/kg on the OJP ($r^2 =0.79$). As dissolution progressed, the dark colour values of the outer crust dominated, and the correlation between greyscale and $\Delta$[CO$_3$]$^-$ broke down.

The initial width of the test wall exerts some control on the colour values of the scans. Tests of *G. ruber, G. sacculifer_ and *N. dutertrei_ from the Atlantic gave lower greyscale values than Indo-Pacific samples due to their greater initial mass. Taking the ratio of light (greyscale values 171 to 210) to dark (greyscale values 0 to 170) pixels in the scanned image circumvents this problem to some extent and allows one regression to be fitted for all sample sets for one species. This greyscale ratio correlates well with $\Delta$[CO$_3$]$^-$ for *G. ruber_ ($r^2 =0.52$); *G. sacculifer_ ($r^2 =0.55$) and *P. obliquiloculata_ ($r^2 =0.53$) but less well for *N. dutertrei_ ($r^2 =0.24$).

In principle greyscale should provide a measure of dissolution. However, greyscale values are skewed by sediment, or authigenic precipitates (Section 5.2), inside the test. These phases are not removed by physical methods such as ultrasonication, and the appearance of such material in CT scans must be removed by hand. As tests dissolve and interact with the sediment, what is selected as part of the test becomes increasingly subjective.

4. Towards an independent measure of dissolution in foraminifera tests: establishing dissolution index XDX

Due to the complex way in which dissolution proceeds there is no simple, measurable quantity that identifies its progression. Greyscale values of CT scans can indicate preservation state of foraminifera tests, and may provide a useful marker of dissolution in some circumstances. However, greyscale can be distorted by clay or sediment inside the test. The approach we have taken, therefore, is to develop an empirical dissolution index, XDX, based on the appearance of the CT scans. The index is based on the premise that dissolution proceeds in a sequence of stages and that the appearance of dissolution features in the CT scans can be recognised by eye. This avoids the need to process the images. The index contains 5 categories from perfectly preserved to extremely dissolved tests (Fig. 3). The key features of each category are as follows:

Dissolution Stage XDX 0: Perfect tests. CT scans show no signs of dissolution. Test walls are imaged as clear dark lines. Pores in the outer wall are often visible. Test walls of *G. ruber_ are often very thin, particularly the final chamber.
Dissolution Stage XDX 1: Well-preserved tests. The first stages of dissolution are evident. Although scans show the test wall as dark and solid the edges may appear indistinct. The smallest inner chambers are missing. Pores may be detectable.

Dissolution stage XDX 2: Poorly preserved tests. CT scans show a difference in colour between pale inner calcite and a dark dense outer layer. The walls of all but the largest chambers are missing. Pores are generally absent.

Dissolution stage XDX 3: Poorly-preserved, partially replaced tests. Around the calcite saturation inner calcite is porous and appears pale in the scanned image. Thick inner chambers and rough edges of the inner suggest replacement of calcite and addition of material. Smallest chambers missing. In species with a gametogenic crust the outer layer of the test is dark with no pores.

Dissolution stage XDX 4: Severely dissolved tests. No inner calcite present; only the outer crust is left. G. sacculifer does not often show stage 4, usually part of the inner calcite of penultimate chamber is present in even severely dissolved tests. This stage is not seen in G. ruber.

It is not possible to show in one CT slice all the factors that decide into which category of dissolution a test should be placed. This necessitates looking at all the slices to ascertain the condition of the small chambers. Fig. 3 shows a typical example of a central section through a test at each XDX stage for G. ruber, G. sacculifer, N. dutertrei and P. obliquiloculata.

In order to test whether this dissolution index was reproducible an experiment was carried out where ten volunteers graded images of 40 tests according to a checklist. The average of the correlation of their results ($r^2 = 0.85$) with HJ’s values suggests that XDX, while essentially subjective, is reproducible.

XDX values are given with 95% confidence interval (CI) (Table 2). In the case of some samples, fewer tests were available than needed to reduce CI to below 0.5. For samples where XDX was close to 0 or 4, as few as 5 tests were needed, as there was less variability in preservation state.

4.1. Estimation of $\Delta[CO_3^{2-}]$ from XDX

Because dissolution index XDX is a based on the processes of dissolution, it is insensitive to fluctuations in test mass and one regression can be plotted for each species from all sample sites (Fig. 4). Although XDX is based on arbitrary categories according to features that can be identified in CT scans, the relationship between

**Fig. 2.** Mass lost to dissolution ($\Delta M$) versus $\Delta[CO_3^{2-}]$ for four species of planktonic foraminifera from the OJP (red circles), Ceara Rise (blue triangles pointing up), MAR (green triangles pointing down) Caribbean Sea (turquoise squares), and western Indian Ocean (filled grey crosses). Section 3.2 explains how $\Delta M$ was obtained. Regressions are fitted for all samples for each species excluding samples from sites where $\Delta[CO_3^{2-}] < 20 \mu mol/kg$ (dashed line). ± values are half width of 95% CI. Unfilled symbols are test mass data of Broecker and Clark (2001a) (355–415 µm size fraction) from the OJP (circles) and Ceara Rise (triangles). Average mass of samples from sites where $\Delta[CO_3^{2-}] < 20 \mu mol/kg$ was used as initial mass for this data.
\[ \Delta [\text{CO}_3^{2-}] \text{ and XDX is approximately linear. Linear regressions were estimated for all data below 20 \mu mol/kg } \Delta [\text{CO}_3^{2-}] \text{ as dissolution appeared to be negligible above this value.} \]

The relationship between XDX and \( \Delta [\text{CO}_3^{2-}] \) is

\[
\Delta [\text{CO}_3^{2-}] = d \times \text{XDX} + \Delta [\text{CO}_3^{2-}]_{\text{CRITICAL(XDX)}} \tag{2}
\]

where \( d \) is a species specific constant and \( \Delta [\text{CO}_3^{2-}]_{\text{CRITICAL(XDX)}} \) is the critical value of \( \Delta [\text{CO}_3^{2-}] \) where dissolution becomes apparent in CT scans, provides a means to estimate \( \Delta [\text{CO}_3^{2-}] \) from XDX for other open ocean sites with low organic carbon content. Values for \( d \) and \( \Delta [\text{CO}_3^{2-}]_{\text{CRITICAL(XDX)}} \) are given in Fig. 4.

The linear relationship between \( \Delta [\text{CO}_3^{2-}] \) and XDX is weakest between 12 and 14 \mu mol/kg.

4.2. Use of XDX to correct dissolution bias in test mass

The relationship between XDX and \( \Delta M \) (loss of test mass due to dissolution) is approximately linear (Fig. 5). XDX can be used to approximate \( \Delta M \) according to,

\[
\Delta M = e \times \text{XDX} \tag{3}
\]

where \( e \) is a species specific constant, given in Fig. 5. An estimate can be made of initial test mass, according to a rearrangement of Eq. (1) to,

\[
\text{mass}_{\text{initial}} = \text{mass}_{\text{MEASURED}} + \Delta M
\]
4.3. Most useful species as dissolution indicators

Correlation between both XDX and Δ[CO$_3^{2-}$] (Fig. 4) and XDX and ΔM (Fig. 5) is weakest for *G. ruber*. One reason for this may be that, as *G. ruber* does not show the more advanced stages of dissolution, the allocation of XDX values may be less accurate for this species. Its lack of an outer crust, and thus the more advanced stages of dissolution, limits the use of this species as a dissolution indicator. The correlation between Δ[CO$_3^{2-}$] and ΔM is also lowest for this species (Fig. 2). This may be due to variation in initial mass, but could also suggest that the association between deep-water Δ[CO$_3^{2-}$] and preservation-state of *G. ruber* is not as clear for this species as for the other species tested here. This appears to be the case for *G. ruber* from the OJP in particular, where the indications of dissolution — greyscale value, the greyscale ratio of light to dark and XDX — all suggest that the shallowest sample of *G. ruber*, from 1616 m on the OJP, is more dissolved than the sample from 2015 m. Taking the test mass of the 1616 m sample as mass$_{INITIAL}$, as we have done here, will lead to an underestimate of mass lost in response to dissolution. Tests of *G. ruber* from the OJP are older than other species from the same sample, and have been mixed upward from deeper in the sediment (Barker et al., 2007). More generally, the high sensitivity to dissolution of shallow-dwelling foraminifera may mean that atypically well-preserved tests are over represented in samples from dissolved sections. The few tests of *G. sacculifer* from the deepest site on the OJP also appeared less dissolved than those from shallower sites. Anomalously well preserved tests may have been protected in microenvironments conducive to good preservation. Enhanced sedimentation rate and the deposition of clays provide protection against dissolution (Pearson et al., 2001; Sexton and Wilson, 2009).

The stages of dissolution were shown most clearly in thermocline dwelling species, *N. dutertrei* and *P. obliquiloculata*, which have a distinct outer crust. A similar pattern of dissolution as that observed in these latter two species was seen in other thermocline dwelling species with a relatively closed form and a thick outer crust: *Globorotalia tumida*, *Globorotalia menardi*, *Globorotalia hirsuta*, *Neo-glabroquadrina pachyderma* and *Globorotalia inflata* (not further discussed here).

5. Dissolution of foraminiferal tests at the seafloor

5.1. Calcite dissolution above the calcite saturation horizon: respiration driven or Mg-dependent dissolution

In this study foraminifera tests from sites highly supersaturated with respect to calcite (Δ[CO$_3^{2-}$]~20 μmol/kg) showed no detectable signs of dissolution. Foraminiferal test mass started to decrease where Δ[CO$_3^{2-}$] was ~15 μmol/kg. The first slight signs of dissolution were...
apparent in CT scans at comparable $\Delta[[CO_3^{2-}]]$ values. Two factors may contribute to the dissolution of foraminifera tests above the calcite saturation horizon. One is that impurities in the test calcite may enhance the solubility of foraminiferal calcite. The other is that acidity produced by the degradation of organic matter promotes dissolution in sediment pore waters.

Although dissolution indices based on foraminifera aim to reconstruct deep water $\Delta[[CO_3^{2-}]]$, considerable calcite dissolution takes place at sites above the calcite saturation horizon due to acidity produced within sediment pore waters by organic matter degradation (Parker and Berger, 1971; Berner, 1977; Martin and Sayles 1996; Emerson and Bender, 1981).

Previous studies have recorded respiration-driven dissolution above the calcite saturation horizon at locations close to sites used here. Benthic flux chambers at 3272 m water depth ($\Delta[[CO_3^{2-}]] \approx 25 \mu mol/kg$) on the Ceara Rise [Site CR2 of Jahnke and Jahnke (2004)] recorded the consumption of oxygen due to the degradation of organic matter. However, CT scans of foraminifera from sites where $\Delta[[CO_3^{2-}]]$ is $\approx 20 \mu mol/kg$ on the Ceara Rise support the observations of Broecker and Clark (2003) that tests are well preserved. The calcite dissolution taking place must be due to dissolution of something other than foraminifera tests.

Further evidence for lack of test dissolution in response to pore water acidity is the similarity of preservation state of tests within one sample. Dissolution rate decreases towards the sediment water interface due to buffering by supersaturated deepwater, Martin and Sayles (1996) record pore water NO$_3^-$ and Ca$^{2+}$ increasing steadily in the top 10 cm of the sediment at 3279 m [site B of Martin and Sayles (1996), $\Delta[[CO_3^{2-}]] \approx 25 \mu mol/kg$] on the Ceara Rise as organic matter is oxidised and CaCO$_3$ is dissolved. They model the maximum rate of CaCO$_3$ dissolution at 3 cm at this site. Core-tops used in our study represent sediment depths of 0–2 to 0–5 cm. Thus samples intersect with the zone of organic matter driven dissolution. Given the gradient in dissolution intensity in the top few cm of the sediment, as long as the mixing rate of tests within the sediment was slower than establishment of the chemical gradient, we should find a range of dissolution states within samples from above the calcite saturation horizon. However, although one sample (GeoB44240), from the shallowest site on the Mid-Atlantic Ridge, contained tests (of G. ruber and G. sacculifer) with a range of preservation states this was generally not the case (Fig. 4). The standard deviation of XDX for samples from above the calcite saturation horizon was not greater than for samples from deeper sites. Samples from these shallow sites typically contained tests with only slight signs of dissolution and did not contain any poorly preserved tests.

Brown and Elderfield (1996) attribute the observation that tests start to dissolve in waters supersaturated with respect to calcite to the fact that tests contain Mg$^{2+}$. Mg-rich calcite being more soluble than pure calcite. Mg incorporation to tests is temperature dependent (Nürnberg et al., 1996) and the ratio of Mg to Ca (in mmol/mol)
increases by ~9% for every 1 °C increase in temperature (Anand et al., 2003). The four studied species live at different depths in the water column and so their Mg/Ca values should decrease in the order G. ruber > G. sacculifer > N. dutertrei / P. obliquiloculata and indeed this order is similar to the dissolution susceptibility ranking of Berger (1970). However, despite their different Mg contents, all four species show a similar loss of mass in response to calcite undersaturation (Fig. 2). G. ruber and G. sacculifer, the Mg/Ca of which should reflect warm mixed layer conditions, did not lose more mass/μmol/kg Δ[CO₃²⁻] than the deeper dwelling, low Mg/Ca species, N. dutertrei and P. obliquiloculata.

The trace amount of Mg²⁺ in foraminiferal calcite is not distributed evenly through the test. Chemical mapping of G. ruber, G. sacculifer, N. dutertrei (Sadekov et al., 2005) and P. obliquiloculata show bands of Mg rich calcite associated with organic layers in the test (Kunioka et al., 2006). Erez (2003) describes two kinds of biomineralized calcite in foraminifera; 5% high Mg primary calcite and 95% secondary low Mg calcite. The former is precipitated in granules along the organic layers that provide the substrate for calcification. This granular calcite may be particularly susceptible to dissolution, as solubility is sensitive to crystal size. X-ray diffraction studies have shown that crystallinity increases with dissolution, as small crystals are preferentially dissolved (Bassinot et al., 2004). In foraminifera calcite crystal size and Mg content may anyway be closely related as Mg²⁺ incorporation can be used to control crystal size in CaCO₃ (Kwak et al., 2005). The increase in crystallinity due to dissolution has been calibrated directly to decrease in Mg/Ca (Nouet and Bassinot, 2007).

Despite the variation in bulk Mg/Ca between species, maximum Mg/Ca values appear to be similar. In the samples examined by Sadekov et al. (2005) the highest Mg/Ca values were between 6 and 8 mmol/mol for G. ruber and G. sacculifer. This is comparable to the highest Mg/Ca values of ~7 mmol/mol, measured in P. obliquiloculata (Kunioka et al., 2006). Maximum Mg/Ca mapped N. dutertrei was only slightly lower, at 5–6 mmol/mol (Sadekov et al., 2005). The similarity of maximum Mg/Ca values could explain why dissolution starts at similar Δ[CO₃²⁻] values for all the species examined here despite characteristically different bulk Mg/Ca.

SEM of tests from sites above the calcite saturation horizon show that in the early stages of dissolution, spaces develop between layers of calcite (Fig. 1(c), (m)). This could be where layers of Mg-rich, low crystallinity calcite have been dissolved out. Other evidence of preferential dissolution of Mg-rich calcite was that crust calcite, low in Mg, was less sensitive to dissolution than inner calcite. The outer crust calcite of partially dissolved tests of G. sacculifer, N. dutertrei and P. obliquiloculata produce a distinct dark layer in CT scans, indicating better preservation of this part of the test. Scans of G. ruber, which lacks a low Mg outer layer, showed no such division of the test calcite.

It has been observed previously that properties intrinsic to tests make them more susceptible to dissolution than pure calcite. Berger (1970) detected an increase in solubility of foraminifera tests at water
depths of 2000–2500 m ($\Delta$[CO$_3^{2-}$]) approximately 4 to 10 μmol/kg) in the central Pacific. These samples were in tubes suspended from wires and were not in contact with the seafloor. Water could pass through the gauze bounding the ends of the tubes and so the tests would be exposed to ambient water. In a parallel experiment with spheres formed from single calcite crystals, the spheres were more resistant to dissolution than foraminiferal calcite. The first increase in solubility for the calcite spheres occurred at 3600 m (Peterson, 1966 cited in Berger, 1970).

The pattern of dissolution observed in CT scans is consistent with the premise that Mg-rich parts of foraminifera tests are particularly susceptible to dissolution. CT scans of _N. dutertrei_ and _P. obliquiloculata_, showed that Mg-rich inner calcite was affected by dissolution before the low Mg outer crust (Fig. 1(f), (o)). Several studies show that _G. ruber_ has a more homogenous distribution of Mg (Eggins et al., 2003; Gehlen et al., 2004) and in this species dissolution affected the whole of the test wall (Fig. 1(i), (j)).

5.2. Processes of dissolution at depths close to and below the calcite saturation horizon: selective preservation or authigenic precipitation

Tests from sites from around the calcite saturation horizon have lost mass (Fig. 2) and appear partially dissolved. However, as described in Section 3.1, the breadth of the test wall is similar, or can be thicker, in tests from sites where $\Delta$[CO$_3^{2-}$] ≈ 0 (such as Fig. 3, XDX stage 3) compared to those from shallow sites. The outer crust calcite, where present, appears dark and solid in CT scans. This surrounds an inner layer composed of porous fine grained material.

One explanation for the thick walls of partially dissolved tests is that in sediments overlain by undersaturated deepwater the most robust thick-walled tests are selectively preserved. Thick walls, both of the outer test and the inner chambers in samples from around the calcite saturation horizon could be a primary feature. In this study the thinnest tests were found in the shallow samples from the Caribbean and Ceará Rise, the sites with the highest $\Delta$[CO$_3^{2-}$]. Thin shells can sustain less mass loss before breaking up than thicker ones. A linear relationship between $\Delta$[CO$_3^{2-}$] and $\Delta M$ (Fig. 2) would mean that, in the same way that fragile thin walled species are lost from assemblages (Berger, 1968), thin walled specimens within a species would be first dissolved. The few specimens of _G. ruber_ from 3411 m on the OJP, although partially dissolved, appeared to have initially thicker walls (~30 μm compared to ~25 μm) than those from shallower sites.

Other studies have also found that tests preserved in sediment become increasingly unrepresentative of surface water forms with increasing depth of deposition. Bé et al. (1975) noted that _G. ruber_ from a deep site (~5500 m in the west central North Atlantic) was different from the _G. ruber_ found in shallower sites, having smaller pores and also a crystalline outer crust. In this study, _G. ruber_ from deep sites tended to have a thicker final chamber than those from shallow sites; presumably because they came from a larger size class but have lost their original final chamber (Berger, 1970). These subtle effects of selective preservation mean that analysed parameters down a depth transect represent not only the effects of dissolution but also changes in the analysed population.

Another explanation for the fine grained material inside foraminifera tests from sites around the calcite saturation horizon would be that it is, at least partially, formed by the precipitation of calcite at the seafloor. Jahnke and Jahnke (2004) reviewed benthic flux data from the Ceará Rise, Cape Verde Plateau and the OJP and found that sediments high (~5%) in CaCO$_3$ underlying supersaturated waters produced little flux of alkalinity despite oxidation of organic matter and increased Ca$^{2+}$ and alkalinity in the sediment. To explain this Jahnke and Jahnke (2004) proposed that CaCO$_3$ must precipitate in the top few millimetres of the sediment surface. Broecker and Clark (2003) suggested a similar mechanism whereby fine layers of calcite (which they called Weyl coatings) precipitate onto the tests of foraminifera at sites where organic matter was degraded in waters supersaturated with respect to calcite.

We saw no evidence of new CaCO$_3$ overgrowths on tests from sites where $\Delta$[CO$_3^{2-}$] ≥ 10 μmol/kg either by CT or SEM. It is possible that small scale features would not be detected using our methods, or it may be that the perfect biominalerised surface of well-protected tests at these high saturation values does not offer a good surface for nucleation of new calcite. Calcite precipitation may be occurring elsewhere in the sediment.

However, at depths close to the calcite saturation horizon, there is some evidence that CaCO$_3$ forms inside the tests of foraminifera. CT of samples from 3000 m on the OJP ($\Delta$[CO$_3^{2-}$] ≈ 0 μmol/kg) once more supports the observations of Broecker and Clark (2003), in this case that foraminifera are appreciably dissolved. This is at a similar depth to Station NS (2972 m on the OJP) of Jahnke et al. (1994) where, again, no Ca$^{2+}$ or alkalinity flux was detected from the sediment even though electrodes show that the degradation of organic matter is consuming oxygen and that calcite is mobilised in the pore waters. SEM and CT of tests from similar sites show signs of calcite precipitation. The observation that pore structures infill in poorly preserved tests (Fig. 1(f), (h), (m)) suggests that calcite may simultaneously precipitate and dissolve within the test. The apparent thickening of the inner chamber walls (Fig. 1(p)) and the fine grained material coating the inside of the outer test wall (Fig. 1(e)) could also be partially formed of CaCO$_3$ precipitated at the sea floor. The presence of coccoliths suggests that some of this material came originally from the sediment (Fig. 1(e), (h)).

One finding of Nouet and Bassinot (2007) may provide evidence for precipitation of CaCO$_3$ inside foraminifera tests at sites close to the calcite saturation horizon. Crystallinity generally increases with water depth as less well ordered calcite, high in Mg, is preferentially dissolved. In their sample from just above the calcite saturation horizon from the Sierra Leone Rise (Station D), Nouet and Bassinot (2007) find an increase in the high Mg calcite phase which had previously been decreasing down the transect. (Although it should be noted that the data of Bonneau et al. (1980) show a similar increase in crystallinity around the calcite saturation horizon in only one _P. obliquiloculata_ of the five species examined.)

Below the calcite saturation horizon the main process affecting foraminifera tests is dissolution. Jahnke et al. (1994) detected a calcite flux from the sediment at 4439 m (their Station US) on the OJP. Scans of foraminifera from similar depths (e.g. the severely dissolved, XDX stage 4, _N. dutertrei_ and _P. obliquiloculata_ in Fig. 3) shows that there is little fine grained material in the inner test and that severe thinning of the test walls has occurred.

6. Conclusions

This work proposes a method of assessing dissolution in the tests of planktonic foraminifera. X-ray computed tomography (CT) provides an insight into the way that dissolution proceeds. Foraminifera tests, from the tropical sites with low organic carbon used in this study, showed a consistent relationship between preservation state, illustrated in the CT scans, and calcite saturation.

Foraminiferal calcite started to dissolve well above the calcite saturation horizon. Damage was apparent to the smallest inner chambers of the test at $\Delta$[CO$_3^{2-}$] values of ~15 μmol/kg. This value was similar for all four species of foraminifera examined here, despite their apparently different dissolution resistance. Test mass started to decrease at comparable values of calcite saturation.

In the intermediate stages of dissolution, CT scans of _G. sacculifer_, _N. dutertrei_ and _P. obliquiloculata_ show a clear distinction between the inner and outer calcite of the test. Inner calcite was disproportionately affected by dissolution, becoming pale and porous, while outer calcite remained solid. Colour values in the tomography scans generally
became lighter as the test dissolved, due to the development of microporosity in the test calcite. Greyscale correlates with $\Delta$[CO$_3^2-$] to some extent and could be a useful indicator of dissolution in some circumstances. However, greyscale values are also affected by initial test mass and by sediment trapped in the test making values difficult to interpret.

At depths close to the calcite saturation horizon ($\Delta$[CO$_3^2-$] between 5 and $-$5 μmol/kg) material was incorporated into the test, illustrated by the infilling of test pores. SEM images of samples from this depth range characteristically show fine-grained porous material on the inside of tests. CT images show this material as a pale phase with irregular edges, which tends to follow the original form of the test. The material contains many coccoliths and originates in part from the sediment. It may also be partly formed from CaCO$_3$ precipitated at the seafloor. This material became less prevalent at progressively deeper sites ($\Delta$[CO$_3^2-$] $\geq$10 μmol/kg), until finally only empty crusts were left.

The pattern of dissolution of the tests of planktonic foraminifera is consistent with the explanation that Mg content, or crystallinity, of inner calcite makes it more susceptible to dissolution than pure calcite. The low-Mg outer calcite of N. dutertrei and P. obliquiloculata was the most resistant to dissolution. Calcite crystals of these species were abundant even in samples from the most undersaturated sites ($\Delta$[CO$_3^2-$] $\geq$−20 μmol/kg) used here. G. ruber, which lacks an outer crust, showed only the early stages of dissolution. This limits the use of G. ruber as a dissolution indicator.

Test mass varies between locations. Tests of G. sacculifer and N. dutertrei from the Atlantic were heavier than those from the Pacific. Wall thickness (hence test mass) within a species varied most for the heavily calcified species N. dutertrei and P. obliquiloculata. Despite variation in initial mass, and the complexity of dissolution processes, loss of test mass (ΔM) was similar between species and sites at $-$0.4 μg/μmol/kg.

We established a dissolution index, XDX, based on stages of dissolution identified in the CT scans. Because XDX is based on the process of dissolution it appears to be insensitive to initial test mass. The relationship between XDX and $\Delta$[CO$_3^2-$] is approximately linear. We provide calibration between both XDX and $\Delta$[CO$_3^2-$] and XDX and ΔM.

Acknowledgements
This study was funded through DFG-Research Center/Cluster of Excellence "The Ocean in the Earth System". H.E. acknowledges funding from the Comer Foundation for the Skyscan 1072 Microtomography System. Many thanks to Linda Booth for sharing some of her extensive knowledge about the foraminifera, and to Nigel Johnson for designing and making sample holders for the Skyscan. Thanks also to the participants of the XDX reproducibility experiment: Jörg Franke, Xavier Giraud, Petra Langebroek, Stefan Steinke, Andreas Mansche, Henning Kuhnert, Stijn De Schepper, Christian Maerz, Jeroen Groeneveld and Nikesh Narayan. Christina de le Rocha suggested many improvements to an earlier version of this manuscript. Thanks to Karen Alexander for proofreading. We are grateful for the comments of M. Regenberg and one anonymous reviewer.

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