



ORIGINAL ARTICLE

## The chemical microenvironment of the symbiotic planktonic foraminifer *Orbulina universa*

STEPHANIE KÖHLER-RINK<sup>1</sup> & MICHAEL KÜHL<sup>2</sup>

<sup>1</sup>Microsensor Research Group, Max-Planck-Institute for Marine Microbiology, Bremen, Germany, <sup>2</sup>Marine Biological Laboratory, Institute of Biology, University of Copenhagen, Helsingør, Denmark

### Abstract

Microsensor measurements of CO<sub>2</sub>, O<sub>2</sub>, pH and Ca<sup>2+</sup> in the vicinity of the symbiont-bearing planktonic foraminifer *Orbulina universa* showed major light-modulated changes in the chemical microenvironment due to symbiont photosynthesis, respiration of the holobiont, and precipitation of the calcite shell. Under saturating light conditions, microprofiles measured towards the shell surface showed an O<sub>2</sub> increase of up to 220% air saturation, a decrease in CO<sub>2</sub> concentration to 4.9 μM, and a pH increase to 8.8 due to symbiont photosynthesis. The Ca<sup>2+</sup> concentration decreased to ~9.6 mM in two specimens, while it increased to 10.2–10.8 mM in three other specimens kept in light. In darkness, the respiration of the community decreased the O<sub>2</sub> concentration to 82% of air saturation, CO<sub>2</sub> increased up to 15 μM, the pH decreased to 8.0, and the Ca<sup>2+</sup> concentration increased up to 10.4 mM. These data, and derived calculations of the distribution of HCO<sub>3</sub><sup>-</sup> and CO<sub>3</sub><sup>2-</sup> near the shell, showed that the carbonate system in the vicinity of *O. universa* was significantly different from conditions in the surrounding seawater, both in light and darkness, due to the metabolism of the foraminifer and its associated algae. Experimental light–dark cycles indicated a sufficient CO<sub>2</sub> supply sustaining high carbon fixation rates of the symbiotic algae via conversion of HCO<sub>3</sub><sup>-</sup> or via CO<sub>2</sub> release from calcification and host respiration. Our findings on irradiance-dependent CO<sub>2</sub> and pH changes in the vicinity of symbiont-bearing planktonic foraminifera give direct experimental evidence for the predictions of isotope fractionation models used in palaeoclimatology stating that metabolic processes affect the isotopic carbon signal (δ<sup>13</sup>C) in foraminifera.

**Key words:** Calcification, carbon isotope fractionation, carbonate system, CO<sub>2</sub>, O<sub>2</sub>, pH, and Ca<sup>2+</sup> microenvironment, DBL, inorganic carbon sources

### Introduction

Symbiont-bearing planktonic foraminifera are widespread calcifying protozoa harbouring phototrophic microalgae (e.g. Lee et al. 1965; Bé 1977; Murray 1991; Hemleben & Spindler 1983). They are abundant in the euphotic zone of subtropical and tropical oceans, with highest densities of 10–100 individuals m<sup>-3</sup> found at 10–50 m depths (Bradshaw 1959; Bé 1977). Planktonic foraminifera show diurnal and ontogenetic vertical migration patterns in the water column, and sink into deeper waters during reproduction (Spindler et al. 1978; Hemleben & Bijma 1994). The spinose foraminifer *Orbulina universa* is a ubiquitous species in subtropical and tropical waters and hosts high numbers of the endosymbiotic dinoflagellate *Gymnodinium béii*

(Spero 1987). During daytime, the symbionts are light exposed within the host cytoplasm, which is stretched out along the calcite spines. High photosynthetic activities have been measured (Jørgensen et al. 1985; Rink et al. 1998) and symbiont-bearing planktonic foraminifera can be described as “hot spots” of primary productivity in oligotrophic seas (Spero & Parker 1985; Caron et al. 1995). However, the source of inorganic carbon sustaining symbiont photosynthesis has not been identified. The mechanisms involved in inorganic carbon uptake from the ambient seawater into the foraminiferal cytoplasm and the subsequent carbon fixation remain unknown.

The current knowledge of CaCO<sub>3</sub> precipitation mechanisms in symbiont-bearing planktonic forami-

Correspondence: S. Köhler-Rink, Microsensor Research Group, Max-Planck-Institute for Marine Microbiology, Celsiusstr. 1, D-28359 Bremen, Germany. E-mail: srink@mpi-bremen.de

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nifera is limited. In planktonic foraminifera, the nucleation of  $\text{CaCO}_3$  crystals is facilitated by the existence of surfaces where calcite is deposited upon an organic matrix. The tertiary structure of this so-called primary organic lining is involved in the initiation and direction of calcification (e.g. Hemleben et al. 1977, 1986; Anderson & Bé 1978; Weiner & Erez 1984). The uptake and concentrating mechanisms of calcium and carbonate are energy dependent, and it has been suggested that the ions are stored in an inorganic carbon pool within the foraminiferal cytoplasm (ter Kuile et al. 1989a). Inorganic carbon is initially taken up in the form of bicarbonate ( $\text{HCO}_3^-$ ), which is concentrated as carbonate ( $\text{CO}_3^{2-}$ ) in special vesicles (Anderson & Faber 1984; ter Kuile & Erez 1988b; ter Kuile et al. 1989a; Erez et al. 1994).

Lea et al. (1995) postulated that symbiont photosynthesis can stimulate calcification in planktonic foraminifera. They measured up to three-fold higher calcification rates in *O. universa* under high light conditions as compared with individuals grown in the dark. Inhibition of symbiont photosynthesis with the inhibitor DCMU resulted in smaller shell growth rates of the foraminifer *Globigerinoides sacculifer* (Bé et al. 1982). However, the significance of symbiotic algae in the regulation of calcification and the potential influence of other physiological and biochemical processes await further studies.

Previous microsensor studies (Jørgensen et al. 1985; Rink et al. 1998) investigated the physico-chemical microenvironment of symbiont-bearing planktonic foraminifera and demonstrated that photosynthesis and respiration caused significant changes in  $\text{O}_2$  and pH levels in the vicinity of *O. universa* and *Globigerinoides sacculifer*. Based on these measurements, a diffusion-reaction model of the seawater chemistry in proximity to the shell of planktonic foraminifera was developed (Wolf-Gladrow et al. 1999) that simulates pH and concentration profiles of the carbonate species  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$  and  $\text{CO}_2$  during light and dark situations.

In micropalaeontological studies, stable isotope signatures of fossil foraminiferal shells are used to estimate the physical and chemical conditions of the water mass, wherein the foraminifera precipitated their shell carbonate. Based on the  $^{18}\text{O}/^{16}\text{O}$  and  $^{13}\text{C}/^{12}\text{C}$  isotope ratios conserved in the calcite shells, palaeoclimatic events such as changes in oceanic productivity and temperature changes can be reconstructed (Epstein et al. 1953; Duplessy 1978; Berger et al. 1981; Erez & Luz 1983; Spero & Deniro 1987; Wefer et al. 1999). This technique is based on the assumption that shell calcium carbonate is deposited in equilibrium with the ambient seawater (Emiliani 1954; Anderson & Arthur 1983).

However, experimental measurements in benthic and planktonic foraminifera contradict this assumption (Erez 1978; Kahn 1979; Honjo & Erez 1981; Kahn & Williams 1981; Spero & Deniro 1987; Köhler-Rink & Köhl 2001) and it has been suggested that metabolic processes, so-called vital effects, change the isotopic composition of inorganic carbon ( $\delta^{13}\text{C}$ ) during calcite precipitation in foraminifera (Erez & Honjo 1981; Spero & Williams 1988).

In this study, we present the first direct measurements of the  $\text{CO}_2$  and  $\text{Ca}^{2+}$  microenvironment of symbiotic planktonic foraminifera. Combined measurements of  $\text{CO}_2$ ,  $\text{O}_2$ , pH, and  $\text{Ca}^{2+}$  within the symbiont swarm demonstrated a dynamic response of the community to changing light conditions and a close interaction of photosynthesis, respiration, and calcification. We discuss the importance of foraminiferal metabolism on the chemical microenvironment, the isotopic carbon fractionation, and  $\text{CaCO}_3$  precipitation.

## Material and methods

### *Experimental organisms and sampling site*

Adult specimens of *O. universa* with spherical shell diameters of 570–1000  $\mu\text{m}$  were collected from surface waters near Curaçao, Netherlands Antilles in the Caribbean Sea during 3 weeks in March and April 1999. A Scuba diver captured individual organisms in glass jars at 5–10 m depths in the morning hours (08.00–10.00 h) (see also Rink et al. 1998). Individual specimens were maintained in glass jars with filtered seawater at room temperature (26°C). Measurements were performed on the day of sampling, starting around 11.00 h. Measured *O. universa* were in the pre-gametogenic state (Spero 1988) with symbiotic algae attached to the calcite spines. The number of investigated specimens was restricted to one to three per day due to the time-consuming microsensor preparations and measurements.

At the sampling site, surface waters were characterized by calcium supersaturation and high temperatures up to 28°C. In situ salinity was  $S = 38$  and pH was 8.2. Experiments were conducted in the laboratory of the Caribbean Marine Research Station (CARMABI, Netherlands Institute of Sea Research).

### *Experimental set-up*

Freshly collected foraminifera were placed on a Nylon mesh in a measuring chamber with filtered seawater, as described by Rink et al. (1998). The chamber was mounted in a water bath to reduce

temperature changes. Irradiance ( $0\text{--}1000\ \mu\text{mol photons m}^{-2}\ \text{s}^{-1}$ ) was provided by a fiber optic halogen lamp (Schott KL-1500, Germany) and was varied by neutral density filters (Oriental Inc., USA) inserted in the light path. Quantum scalar irradiance in the set-up was calibrated with a quantum scalar irradiance meter (QSL 101, Biospherical Instruments Inc., USA) at the position of the foraminifer. Experimental light–dark cycles were controlled by an electromechanical shutter (Vincent Assoc., USA) installed between the halogen lamp and the measuring chamber. Signal changes during light–dark cycles were recorded at a time resolution of 1 s. Microsensors were fixed to and positioned with a motorized micromanipulator (Märzhäuser and LOT-ORIEL, Germany). The position of the microsensor tips relative to the foraminiferal shell surface was observed through a dissection microscope (Zeiss, SV 11, Germany). A custom-made program written in LabVIEW (National Instruments, USA) controlled the micromanipulator, shutter, and data acquisition.

Radial microprofiles were measured with a spatial resolution of  $50\text{--}100\ \mu\text{m}$  from the ambient seawater towards the shell surface of *O. universa*. For simultaneous measurements of two chemical compounds within the symbiont swarm, the two microsensors were placed in close proximity ( $<100\ \mu\text{m}$ ) at the shell surface of the foraminifer during experimental light–dark cycles. The size and position of the symbiont swarm was determined by the graded ocular scale of the dissection microscope. The foraminifera were allowed to acclimate to chamber conditions for  $0.5\text{--}1\ \text{h}$  prior to the experiments.

### Microsensors

Microsensors for  $\text{O}_2$ ,  $\text{CO}_2$ , pH, and  $\text{Ca}^{2+}$  were used. Clark-type  $\text{O}_2$  microsensors (Revsbech 1989) were constructed with an outer tip diameter of  $\sim 7\ \mu\text{m}$ , a  $t_{90}$  response time of 0.3 s, and a stirring sensitivity  $<1\%$ . A linear calibration was performed from readings in aerated and  $\text{N}_2$ -flushed seawater, respectively. The  $\text{O}_2$  detection limit was  $\sim 0.1\ \mu\text{M}$ .  $\text{CO}_2$  microsensors with a detection limit down to  $1\ \mu\text{M}$  and a response time of  $\sim 10\ \text{s}$  were composed of an outer glass casing with an internal pH liquid ion-exchange (LIX) microelectrode (de Beer et al. 1997). The  $\text{CO}_2$  microsensor was calibrated in a degassed phosphate buffer (50 mM, pH 8.0) by adding aliquot volumes of 200 mM carbonate solution. pH and  $\text{Ca}^{2+}$  were measured with LIX microelectrodes with tip diameters of  $2\text{--}5\ \mu\text{m}$  and a response time of  $<1\ \text{s}$  (de Beer et al. 2000). The LIX microelectrodes were shielded with an outer casing containing 3 M KCl to reduce electrical noise

(Kühl & Revsbech 2001). The detection limit for  $\text{Ca}^{2+}$  was  $10\ \mu\text{M}$ , and calibration was performed in 1, 10, and 20 mM  $\text{Ca}^{2+}$  solutions with added background ions ( $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$ ) at seawater concentration. pH microelectrodes were calibrated in standard pH buffers (Mettler Toledo, Germany).

$\text{O}_2$  signals were measured with a fast responding custom-made picoammeter. pH,  $\text{CO}_2$ , and  $\text{Ca}^{2+}$  were measured with high impedance mV meters (Mascom, Germany; Keithley, USA). Signals were recorded with a strip chart recorder (GOERZ, Austria) and a custom-built computerized data acquisition system (National Instruments, USA).

### Net $\text{O}_2$ , $\text{CO}_2$ , and $\text{Ca}^{2+}$ fluxes

The area-integrated fluxes,  $Q_t$ , of the measured solutes were calculated (in units of  $\text{nmol h}^{-1}$  foraminifer $^{-1}$ ) from the radial concentration gradient  $dC/dr$ , the surface area of the sphere  $4\pi r^2$ , and the molecular diffusion coefficient ( $D_0$ ) (Jørgensen et al. 1985; Ploug et al. 1997; Rink et al. 1998). The  $\text{CO}_2$  and  $\text{O}_2$  gradients started outside the symbiont swarm towards the ambient seawater.  $\text{Ca}^{2+}$  uptake rates were calculated from gradients directly at the shell surface.

$$Q_t = 4\pi r^2 D_0 \frac{dC}{dr} \quad (1)$$

$D_0$  was  $2.30 \times 10^{-5}\ \text{cm}^2\ \text{s}^{-1}$  for  $\text{O}_2$ ,  $1.83 \times 10^{-5}\ \text{cm}^2\ \text{s}^{-1}$  for  $\text{CO}_2$ , and  $0.79 \times 10^{-5}\ \text{cm}^2\ \text{s}^{-1}$  for  $\text{Ca}^{2+}$  ( $25^\circ\text{C}$ ;  $S=35$ ) according to Broecker & Peng (1974) and Li & Gregory (1974).

## Results

### Microenvironment of $\text{CO}_2$ , $\text{O}_2$ , pH, and $\text{Ca}^{2+}$

The chemical microenvironment was influenced by the presence of a diffusive boundary layer (DBL) surrounding the shell of *O. universa* impeding the solute exchange between the ambient seawater and the foraminifer. The effective DBL thickness was  $250\text{--}800\ \mu\text{m}$ , as determined by the extrapolation of radial concentration gradients at the shell–seawater interface to the ambient seawater concentration (Jørgensen & Revsbech 1985; Ploug et al. 1997; Rink et al. 1998) (Figures 1 and 2). In the light,  $\text{O}_2$  and pH increased and  $\text{CO}_2$  decreased towards the shell surface of *O. universa* due to the photosynthesis by symbiotic microalgae (Figure 1A). The  $\text{O}_2$  concentration and pH increased to  $394\ \mu\text{M}$  (218% air saturation) and pH 8.8, respectively, while the  $\text{CO}_2$  concentration decreased to  $4.9\ \mu\text{M}$  at the shell surface. In the dark, the respiration of the holobiont caused  $\text{O}_2$  and pH to decrease to  $147\ \mu\text{M}$  (82% air

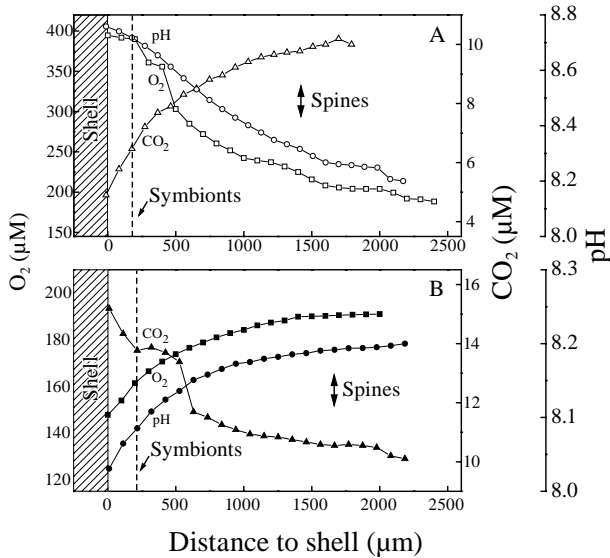


Figure 1. Light (A) and dark (B) concentration profiles of O<sub>2</sub>, CO<sub>2</sub>, and pH measured from the ambient seawater towards the shell surface of a single *Orbulina universa* specimen (scalar irradiance = 130 μmol photons m<sup>-2</sup> s<sup>-1</sup>). The vertical dashed line indicates the start of the symbiont swarm. The arrows indicate the outer extension of the calcite spines.

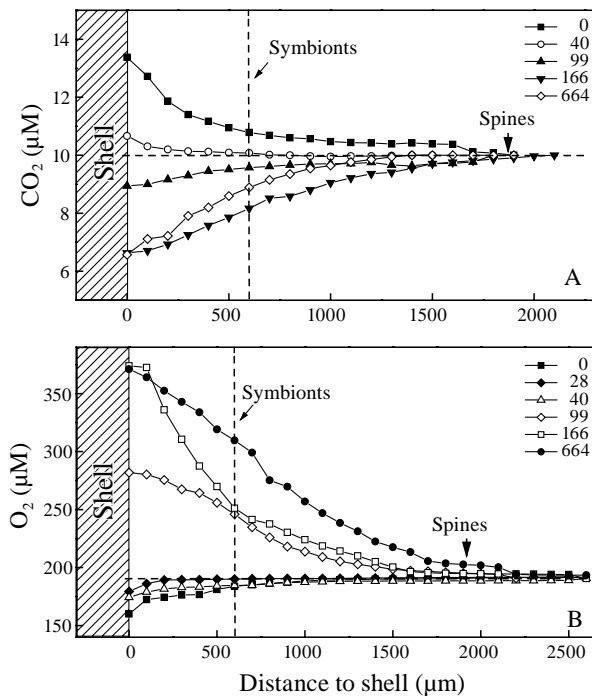


Figure 2. Radial concentration profiles of CO<sub>2</sub> (A) and O<sub>2</sub> (B) measured towards the shell surface of a single *Orbulina universa* specimen as a function of increasing irradiance. The numbers indicate incident irradiance in μmol photons m<sup>-2</sup> s<sup>-1</sup>. The horizontal dashed lines indicate ambient seawater concentrations. The vertical dashed lines indicate the start of the symbiont swarm. The arrows indicate the outer extension of the calcite spines.

saturation) and pH 8.03, respectively, while the CO<sub>2</sub> concentration increased up to 15 μM due to respiration and calcification (Figure 1B). Ambient seawater

concentrations of O<sub>2</sub>, CO<sub>2</sub>, and pH were 190 μM, 10 μM, and pH 8.2, respectively. With increasing irradiance, the CO<sub>2</sub> concentration in the vicinity of the shell surface decreased, whereas the O<sub>2</sub> concentration increased (Figure 2). At an irradiance of 166 μmol photons m<sup>-2</sup> s<sup>-1</sup>, symbiont photosynthesis approached its saturation level, as indicated by both CO<sub>2</sub> and O<sub>2</sub> profiles (Figure 2).

Microprofiles of Ca<sup>2+</sup> measured under light and dark conditions showed a significant concentration change between the ambient seawater and the shell surface of *O. universa* (Figure 3). In some specimens we measured a Ca<sup>2+</sup> decrease towards the shell surface and thus a Ca<sup>2+</sup> uptake of the foraminifer in the light (Figure 3A). Here the Ca<sup>2+</sup> concentration at the shell surface decreased to 9.6 mM, but other specimens showed a Ca<sup>2+</sup> concentration increase in the light of up to 10.8 mM (Figure 3A, B). All dark profiles showed a concentration increase of Ca<sup>2+</sup> at the shell surface.

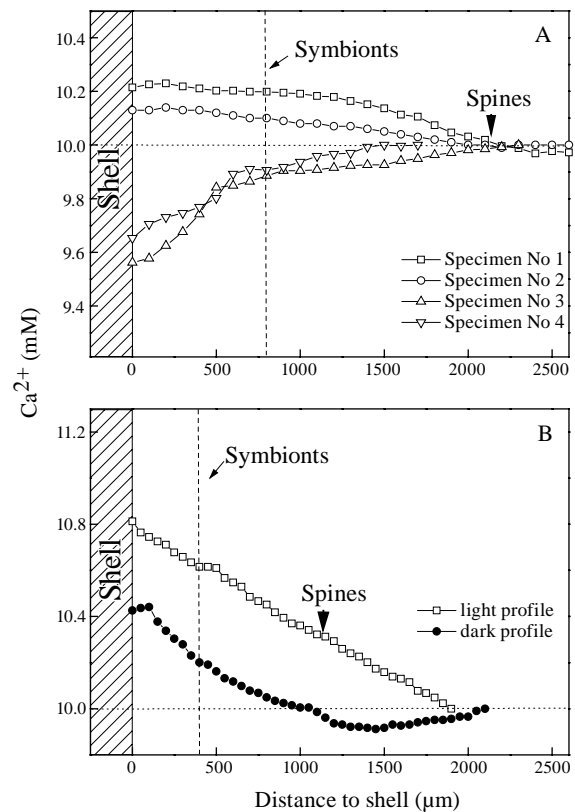


Figure 3. (A) Concentration profiles of Ca<sup>2+</sup> measured in the light (specimen no 1+2: 560 μmol photons m<sup>-2</sup> s<sup>-1</sup>, specimen no 3+4: 260 μmol photons m<sup>-2</sup> s<sup>-1</sup>) towards the shell surface of four different specimens of *Orbulina universa*. (B) Light (600 μmol photons m<sup>-2</sup> s<sup>-1</sup>) and dark Ca<sup>2+</sup> profiles measured in the same specimen. The horizontal dotted lines indicate ambient seawater concentrations. The vertical dashed lines indicate the start of the symbiont swarm. The arrows indicate the outer extension of the calcite spines.

Net O<sub>2</sub> and CO<sub>2</sub> fluxes

Rates of total net O<sub>2</sub> release and CO<sub>2</sub> uptake were calculated from the radial concentration gradients measured from the ambient seawater towards the shell surface as a function of irradiance (Figure 2). The photosynthetic light compensation point of the symbiont–host association, i.e. the irradiance where autotrophic and heterotrophic processes balanced each other and no net O<sub>2</sub> or CO<sub>2</sub> exchange was observed, E<sub>c</sub>, was reached at ~40 μmol photons m<sup>-2</sup> s<sup>-1</sup> (Figure 4). Above 40 μmol photons m<sup>-2</sup> s<sup>-1</sup>, a net O<sub>2</sub> release and a net CO<sub>2</sub> uptake due to photosynthesis were measured. At all irradiance levels, the concentration gradients showed a much higher flux of O<sub>2</sub> as compared with CO<sub>2</sub>. At high irradiance (664 μmol photons m<sup>-2</sup> s<sup>-1</sup>), net O<sub>2</sub> production was 15.6 nmol O<sub>2</sub> h<sup>-1</sup> foraminifer<sup>-1</sup> and net CO<sub>2</sub> uptake was 0.15 nmol O<sub>2</sub> h<sup>-1</sup> foraminifer<sup>-1</sup>. Thus, a high molar O<sub>2</sub>/CO<sub>2</sub> conversion ratio of about 100 was calculated.

## Dynamic microenvironmental changes at the shell surface

We measured pronounced variations in CO<sub>2</sub>, O<sub>2</sub>, and pH at the shell surface of *O. universa* during experimental light–dark cycles (Figures 5 and 6). In the light, symbiont photosynthesis rapidly increased the O<sub>2</sub> and pH concentrations and decreased the CO<sub>2</sub> concentration at the shell surface. When the light was switched off, the respiration of the association resulted in increasing CO<sub>2</sub> levels, and rapidly decreasing levels of O<sub>2</sub> and pH.

The total concentration change at the shell surface between light saturation and darkness was ~22 μM CO<sub>2</sub> and 339 μM O<sub>2</sub>. pH varied about 1.2 units. The concentration changes generally increased with increasing irradiance (Figure 6). The O<sub>2</sub> responded immediately to changing light conditions. pH changed with a short delay, whereas the CO<sub>2</sub> response

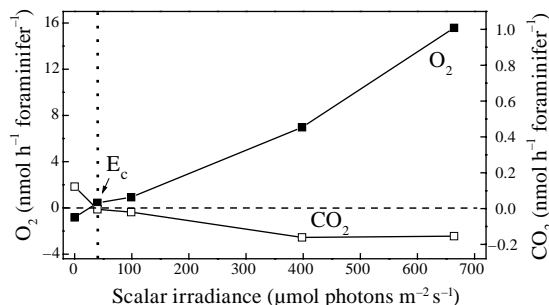


Figure 4. Area-integrated fluxes of O<sub>2</sub> and CO<sub>2</sub> (nmol h<sup>-1</sup> foraminifer<sup>-1</sup>) calculated from concentration gradients at the shell surface of *Orbulina universa* measured at increasing scalar irradiance (Figure 2). Note the different scales for O<sub>2</sub> and CO<sub>2</sub> fluxes. The vertical dotted line indicates the compensation irradiance, E<sub>c</sub>, of ~40 μmol photons m<sup>-2</sup> s<sup>-1</sup>.

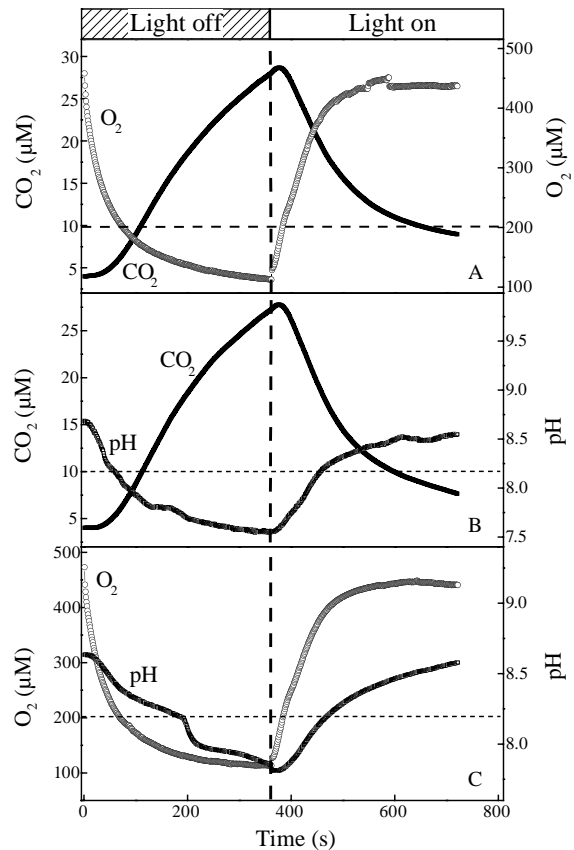


Figure 5. Concentrations of CO<sub>2</sub> and O<sub>2</sub> (A), CO<sub>2</sub> and pH (B), and O<sub>2</sub> and pH (C) measured during experimental light–dark cycles at the shell surface within the symbiont swarm of *Orbulina universa*. The vertical lines indicate the change from dark to light conditions (730 μmol photons m<sup>-2</sup> s<sup>-1</sup>). The horizontal lines indicate ambient seawater concentrations.

showed a delay of 17–100 s after the light–dark switch, i.e. significantly longer than the response time of the CO<sub>2</sub> microsensors. The CO<sub>2</sub> delay decreased from 50 s at 99 μmol photons m<sup>-2</sup> s<sup>-1</sup> to 35 s at 365 μmol photons m<sup>-2</sup> s<sup>-1</sup> (Figure 6).

## Discussion

## Irradiance effects on the chemical microenvironment

The presented data demonstrate the combined effect of symbiont photosynthesis, community respiration, and host calcification on the CO<sub>2</sub>, O<sub>2</sub>, pH, and Ca<sup>2+</sup> levels around the shell of *O. universa*. Our measurements showed a strong influence of the prevailing light conditions on the chemical microenvironment (Figures 1–3). The dynamic CO<sub>2</sub> uptake rates of symbiont photosynthesis with increasing irradiance demonstrated that the CO<sub>2</sub> concentration changes determine the pH surrounding the foraminifer (Figures 1 and 5).

Planktonic symbiont-bearing foraminifera experience different irradiance regimes during their

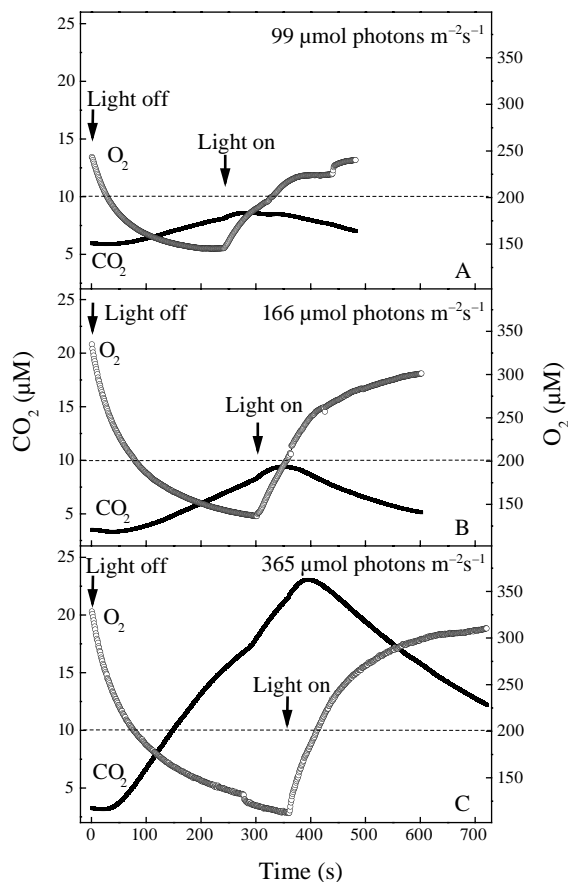


Figure 6. Dynamics of  $\text{CO}_2$  and  $\text{O}_2$  measured simultaneously during experimental light-dark cycles at the shell surface of *Orbulina universa* as a function of increasing irradiance [99 (A), 166 (B), and 365 (C)  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ]. The arrows indicate the change from dark to light conditions. The horizontal lines indicate ambient seawater concentrations.

lifecycle as they migrate vertically in the water column (Bradshaw 1959; Boltovsky 1973). Such migration patterns affect symbiont photosynthesis and, consequently, the local characteristics of the carbonate system due to changing microenvironmental conditions, as indicated by our results. In addition, foraminifera are exposed to diurnal variations in irradiance causing a continuously changing chemical microenvironment over a daily light cycle. Our experimental light-dark cycles do not reflect the effects of slowly varying light conditions, but demonstrate the solute dynamics due to short-term manipulations of the light field.

To evaluate local carbonate system changes in the vicinity of *O. universa* under light and dark conditions, we used the freely available program CO2SYS (v. 1.05) by E. Lewis and D. W. R. Wallace (<http://cdiac.esd.ornl.gov/oceans/co2rprt.html>). The program requires two  $\text{CO}_2$  system parameters to determine the other carbonate system parameters. Assuming steady-state conditions, we calculated bicarbonate and carbonate profiles under light and

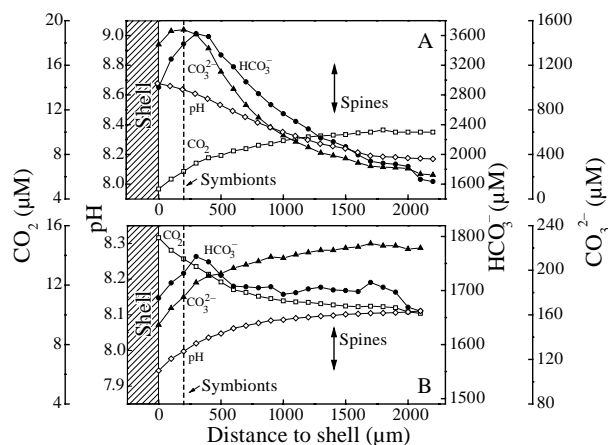


Figure 7. Calculated  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  profiles and measured  $\text{CO}_2$  and pH profiles under light (A) and dark (B) conditions in *Orbulina universa*. Note the different scales in (A) and (B). The vertical dashed line indicates the start of the symbiont swarm. The arrows indicate the outer extension of the calcite spines.

dark conditions using our measured pH and  $\text{CO}_2$  profiles (Figures 1 and 7). The model calculations included carbonate system parameters according to Mehrbach et al. (1973), Dickson & Millero (1987), and Dickson (1990) on the NBS pH scale. The program predicted unrealistic high concentrations of  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  in light, which have not been described in the literature so far. Our calculations thus demonstrated that the carbonate system close to the foraminiferal shell cannot be assumed to be in equilibrium and also indicated that light-enhanced calcification is caused by the  $\text{CO}_2$  uptake of endosymbiotic algae.

The calculated  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  profiles showed a significant concentration increase towards the shell due to the increased pH by photosynthetic  $\text{CO}_2$  fixation (Figure 7A). In the darkness, less pronounced gradients of  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  were predicted. A small  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  decrease towards the shell surface was calculated due to the measured pH decrease. This drop in pH could be explained by respiratory  $\text{CO}_2$  release and/or  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  uptake due to calcification. The relative proportions of  $\text{CO}_2$ ,  $\text{HCO}_3^-$ , and  $\text{CO}_3^{2-}$  in the vicinity of *O. universa* are thus regulated by the combined action of metabolic processes, the equilibrium reactions and the diffusional exchange of the carbonate species between the foraminiferal shell and the ambient seawater (Spero 1991; de Beer et al. 1997; Zeebe & Wolf-Gladrow 2001).

The irradiance-dependent variations in  $\text{O}_2$ ,  $\text{CO}_2$ , and pH in the vicinity of *O. universa* give direct experimental evidence for the suggestion that symbiont photosynthesis and community respiration can influence the isotopic carbon composition of the

shell calcite in symbiont-bearing planktonic foraminifera (Spero & Deniro 1987; Spero & Williams 1988; Spero 1991). In laboratory culture experiments, Spero & Deniro (1987) showed that  $\delta^{13}\text{C}$  values of *O. universa* ranged from +2.77‰ at highest irradiance to +0.45‰ in darkness. Several models were presented to elucidate these so-called "vital effects" on the inorganic carbon signal due to the metabolic processes of symbiont-bearing foraminifera (Spero 1991; Hemleben & Bijma 1994; Zeebe et al. 1999). Zeebe et al. (1999) published a numerical model that calculates the  $\delta^{13}\text{C}$  values of *O. universa* in response to the metabolic processes of the foraminifer and its symbionts. The model predicted significant changes in the seawater  $\delta^{13}\text{C}$  close to the shell surface due to symbiont photosynthesis and holobiont respiration. Generally, a  $\delta^{13}\text{C}$  increase in all inorganic carbon species towards the shell surface under light conditions and depletion of  $\delta^{13}\text{C}$  in the dark was predicted. Our experimental data support these predictions for *O. universa*.

Our study demonstrated that *O. universa* is surrounded by a layer of lower  $\text{CO}_2$  concentration as compared with the ambient seawater during daytime when the symbiotic algae spread out along the calcite spines (Figure 1, 2A). The preferential use of  $^{12}\text{CO}_2$  in photosynthetic carbon fixation (e.g. Wong & Sackett 1978; Spero & Deniro 1987; Goericke et al. 1994) means, however, that close to the shell there is a layer depleted in  $^{12}\text{C}$  and enriched in  $^{13}\text{C}$  relative to the ambient seawater (Zeebe et al. 1999). The light-dependent photosynthetic activity of the symbiotic algae (Figure 2A) will thus influence the  $^{13}\text{CO}_2/^{12}\text{CO}_2$  ratio close to the shell surface and create a gradient in the  $\delta^{13}\text{C}$  (Zeebe et al. 1999). Although photosynthetic  $\text{CO}_2$  uptake is the process dominating the  $\text{CO}_2$  variations close to the shell in the light (Figure 2A), concentration changes of inorganic carbon species affecting the inorganic carbon pools and the exchange with the ambient seawater may also influence the  $^{13}\text{CO}_2/^{12}\text{CO}_2$  ratio (O'Leary 1981; Swart 1983; Zeebe et al. 1999).

In darkness, when the symbionts stay within the foraminiferal calcite chambers, *O. universa* is enclosed in a layer of higher  $\text{CO}_2$  concentration as compared with the ambient seawater (Figures 1B, 2A). This layer would be depleted in  $^{13}\text{C}$  relative to the ambient seawater because the foraminifer and its endosymbionts release respiratory  $\text{CO}_2$  depleted in  $^{13}\text{C}$  (DeNiro & Epstein 1978; Spero & Williams 1988). However, the respiratory effects on carbon fractionation in symbiont-bearing foraminifera might be compensated by the  $^{13}\text{C}$  enrichment due to symbiont photosynthesis at irradiances above the light compensation point ( $>50 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ), when there is a net  $\text{CO}_2$  uptake (Rink et al.

1998). Reduced calcification rates of *O. universa* under dark conditions (Lea et al. 1995) indicate that incorporation of depleted  $^{13}\text{C}$  during the night can play a minor role in total  $^{13}\text{C}$  incorporation. In conclusion, the prevailing light conditions during pre-gametogenic calcification might strongly affect the isotopic ratio of the shell calcite in *O. universa*. We only present data on foraminifera in the pre-gametogenic state, but we speculate that similar microenvironmental controls can affect the isotopic ratio during gametogenic calcification.

#### *Calcium microenvironment of planktonic foraminifera*

The measured  $\text{Ca}^{2+}$  profiles describe the  $\text{Ca}^{2+}$  microenvironment of *O. universa* over a short time period during the growth of the adult spherical chamber. Our data indicate that  $\text{Ca}^{2+}$  uptake does not occur continuously (Figure 3) and that  $\text{Ca}^{2+}$  uptake can vary among individual specimens according to their specific status of calcification within their growth cycle. The  $\text{Ca}^{2+}$  microenvironment in symbiont-bearing foraminifera might also be affected by the daytime (Anderson & Faber 1984) and the feeding frequency (Caron et al. 1987). In addition, prevailing light conditions (Spero & Deniro 1987; Lea et al. 1995) and the ontogenetic state of the organism (Spero 1986; Hemleben & Bijma 1994) could play an important role. Thus, future studies should focus on  $\text{Ca}^{2+}$  measurements in specimens at a defined growth stage to get additional information about growth-specific  $\text{Ca}^{2+}$  dynamics.

Solute exchange processes between the ambient seawater, the intracellular  $\text{Ca}^{2+}$  pool (Anderson & Farber 1984; ter Kuile et al. 1989a) and the site of calcification affect the  $\text{Ca}^{2+}$  microenvironment. Diffusional transport of  $\text{Ca}^{2+}$  ions to the site of calcification was described for perforate and imperforate foraminifera (ter Kuile & Erez 1988b; ter Kuile et al. 1989a; Lea et al. 1995). An enzyme-mediated active  $\text{Ca}^{2+}$  transport was found in imperforate species (ter Kuile et al. 1989a).

The DBL surrounding the shell of *O. universa* is regulating the exchange of  $\text{Ca}^{2+}$  ions between the foraminifer and the surrounding seawater (Jørgensen et al. 1985; Rink et al. 1998). The mass transfer of solutes in the surrounding seawater and in between the network of spines covered by foraminiferal cytoplasm is thus fundamentally different. The calcite spines and the attached cytoplasm limit the local flow of seawater and the DBL impedes the transport of  $\text{Ca}^{2+}$  and  $\text{CO}_3^{2-}$  ions (Wieland et al. 2001; Ploug et al. 2002). It is possible to estimate the mean diffusion time of  $\text{Ca}^{2+}$  ions across the DBL (Jørgensen & Revsbech 1985; Mann & Lazier 1991). By using the diffusion coefficient (D) for

$\text{Ca}^{2+}$  ions in seawater ( $0.79 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$  at  $25^\circ\text{C}$ ) (Li & Gregory 1974) and assuming an average thickness of the DBL of  $400 \mu\text{m}$  ( $z$ ), we calculated a diffusion time of  $t = z^2 / (0.9 \cdot D) \approx 3.5 \text{ min}$ . The transport of ions through a thinner DBL, caused e.g. by faster settling rates to the sea floor or by smaller foraminiferal sizes, would be much faster as the diffusion time is proportional to the square of the diffusion path length.

From the  $\text{Ca}^{2+}$  gradients showing net calcium uptake, we estimated total  $\text{Ca}^{2+}$  uptake rates in *O. universa* of about  $1.4 \text{ nmol Ca}^{2+} \text{ h}^{-1} \text{ foraminifer}^{-1}$ , assuming radial symmetry of the solute distribution. This calculated uptake rate is comparable with the calcification rates measured by Lea et al. (1995), who found an average  $\text{Ca}^{2+}$  uptake of  $1.8 \text{ nmol Ca}^{2+} \text{ h}^{-1}$  in *O. universa* using a stable isotope technique that allowed the precise determination of  $^{48}\text{Ca}/^{44}\text{Ca}$  ratios in single shells.

All  $\text{Ca}^{2+}$  profiles measured in darkness showed a  $\text{Ca}^{2+}$  increase towards the shell. In addition, during experimental light–dark cycles, we locally measured a concentration decrease of  $\text{Ca}^{2+}$  at the shell surface under light conditions and a  $\text{Ca}^{2+}$  increase in darkness relative to the ambient seawater level (data not shown). One explanation for the release of  $\text{Ca}^{2+}$  under dark conditions could be that elevated  $\text{CO}_2$  concentrations and conditions of low pH create unfavourable conditions for the initiation of calcite precipitation. We measured a pH decrease to pH 7.5–7.9 and a  $\text{CO}_2$  increase to  $15\text{--}29 \mu\text{M}$  at the shell surface at a temperature of  $26^\circ\text{C}$  ( $S = 38$ ). Respiratory  $\text{CO}_2$  release by microbial metabolic activity is the dominating process controlling the calcium carbonate dissolution kinetics in deep-sea surface sediments (Archer et al. 1989; Schneider et al. 2000). In addition, reduced calcification rates at elevated  $\text{CO}_2$  concentrations were found in coccolithophorids (Riebesell et al. 2000), in coralline macroalgae (Langdon et al. 2003), as well as in hermatypic corals (Marubini et al. 2001). Similar light-dependent  $\text{Ca}^{2+}$  and pH changes were measured with microsensors at the shell surface of a symbiont-bearing benthic foraminifer (Köhler-Rink & Kühl 2000) and in hermatypic corals (de Beer et al. 2000; Al-Horani et al. 2003). However, the mechanisms behind the calcium dynamics in foraminifera and especially the apparent high calcium release in darkness remain obscure and need further investigation. Recently, the application of microsensors and a range of specific inhibitors in a study of coral calcification pointed to a central role of host Ca-ATPase in the regulation of the calcium dynamics (Al-Horani et al. 2003), and similar studies on foraminifera now seem a natural next step.

#### *Inorganic carbon sources for symbiont photosynthesis and calcification*

Oceanic surface waters represent a large reservoir for dissolved inorganic carbon (DIC). It has been shown that DIC concentrations of seawater can saturate the photosynthesis of symbionts in benthic foraminifera and hermatypic corals (ter Kuile et al. 1989b; Goiran et al. 1996). In planktonic foraminifera, mechanisms of inorganic carbon fixation and DIC supply to the symbiotic algae have not yet been studied.

Inorganic carbon for photosynthetic assimilation and calcite precipitation is supplied from the large seawater reservoir via diffusion across the DBL.  $\text{CO}_2$  can also be supplied from internal sources due to respiration and calcification. In benthic symbiotic foraminifera it was suggested that diffusion is the rate-limiting step for DIC uptake at lower DIC levels (ter Kuile et al. 1989a). Saturation of DIC uptake at higher DIC levels indicated the presence of a rate-limiting enzymatic step. The highest DIC uptake rates were found at pH 8–9 and the authors therefore suggested that  $\text{HCO}_3^-$  is the main inorganic carbon species taken up from the environment, which is then undergoing intracellular conversion to  $\text{CO}_2$ .

Our data show that  $\text{CO}_2$  is not fully depleted at the shell surface of *O. universa*, even under saturating irradiance levels (Figures 1, 2, 5 and 6). This indicates that the symbionts are not  $\text{CO}_2$  limited. Changing light conditions from light to darkness and vice versa showed a time lag in the  $\text{CO}_2$  concentration changes measured at the shell surface (Figures 5 and 6). These changes were apparently not tightly coupled to the fast  $\text{O}_2$  concentration changes due to photosynthesis. Furthermore, much higher total rates of  $\text{O}_2$  release than  $\text{CO}_2$  uptake per individual foraminifer were measured under saturating irradiance. The estimated molar  $\text{O}_2/\text{CO}_2$  conversion ratio per foraminifer of  $\sim 100$  at higher irradiance ( $660 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ) showed that the  $\text{CO}_2$  flux from the ambient seawater is by far not sufficient to support high rates of photosynthetic  $\text{O}_2$  evolution. We therefore speculate that an efficient internal  $\text{CO}_2$  supply mechanism must exist (Rink et al. 1998).

One possibility for a sufficient internal  $\text{CO}_2$  supply, besides respiration and calcification, could be an enzymatic dehydration of  $\text{HCO}_3^-$  to  $\text{CO}_2$ . The symbionts or the host may actively regulate the  $\text{CO}_2$  uptake via the enzyme carbonic anhydrase (CA) (e.g. Tsuzuki & Miyachi 1989; Raven 1994; Nimer et al. 1999). This would require an active uptake of  $\text{HCO}_3^-$  by the symbiont–host association. The fast pH increase of  $\sim 0.65$  units within 100 s in



the light suggests the presence of an active  $\text{HCO}_3^-$  uptake mechanism, which is accompanied by an  $\text{OH}^-$  efflux or  $\text{H}^+$  influx into the cytoplasm of the foraminifer (Badger 1987). Such co-transport of ions during the active transport of  $\text{HCO}_3^-$  has been described for calcifying algae (Borowitzka 1989) and for symbiont-bearing anthozoa (Allemand et al. 1998).

## Conclusion

A close interaction of symbiont photosynthesis, community respiration, and calcification affects the microenvironment of *O. universa* during experimental light–dark cycles. A time delay in  $\text{CO}_2$  changes and an immediate pH change during experimental light–dark cycles indicate an internal  $\text{CO}_2$  supply sustaining the high photosynthetic activity of the symbionts. Conversion of  $\text{HCO}_3^-$  to  $\text{CO}_2$  via CA seems an important internal  $\text{CO}_2$  source for photosynthetic assimilation within planktonic foraminifera, in addition to the  $\text{CO}_2$  supply from host respiration and calcification. Under saturating light conditions, the measured concentration profiles of  $\text{CO}_2$ ,  $\text{O}_2$ , and pH indicate a microenvironment of decreased inorganic carbon due to symbiont photosynthesis in the vicinity of the foraminiferal shell. In darkness,  $\text{CO}_2$  released by respiration and calcification influences the inter-conversion of inorganic carbon species in the vicinity of *O. universa*. The concentration dynamics of  $\text{CO}_2$  and  $\text{Ca}^{2+}$  under light and dark conditions can thus change the calcite saturation state close to the shell. The local pH rise in the vicinity of planktonic foraminifera due to photosynthetic  $\text{CO}_2$  uptake and the subsequent rise in  $\text{CO}_3^{2-}$  increases the degree of  $\text{CaCO}_3$  saturation and can thereby enhance the calcium precipitation at the calcification site of *O. universa*.

The present study strongly suggests that the  $^{13}\text{CO}_2/^{12}\text{CO}_2$  ratio ( $\delta^{13}\text{C}$ ) in close proximity to the shell of *O. universa* is affected by (i) the preferential use of  $^{12}\text{CO}_2$  for carbon fixation by symbiont photosynthesis and (ii) the enhanced  $^{13}\text{C}$  depletion in respiratory  $\text{CO}_2$  by community respiration. Metabolic processes change the  $\text{CO}_2$  microenvironment and thus have an influence on the isotopic signature of the shell calcite in symbiont-bearing foraminifera.

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*Editorial responsibility: Tom Fenchel*