Repercussions of differential settling on sediment assemblages and multi-proxy palaeo-reconstructions

A. G. M. Caromel, D. N. Schmidt, and J. C. Phillips

School of Earth Sciences, Wills Memorial Building, Queens Road, Bristol, BS8 1RJ, UK

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Correspondence to: A. G. M. Caromel (aude.caromel@bristol.ac.uk)

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Abstract

Microfossils preserved in marine sediments are at the centre of numerous proxies for palaeoenvironmental reconstructions. Their precision is based on the assumption that they accurately represent the overlying watercolumn properties and faunas. In this paper, we assess the possibility of a pre-depositional bias in sediment assemblages caused by horizontal drift, due to differential settling velocities of sedimenting particles based on their shape, size and density. We calculate the lateral transport undergone by planktic foraminifera and a range of other proxy carriers in several regions with high current velocities. Lateral transport of different planktic foraminiferal species is minimal due to high settling velocities; no significant shape- or size-dependent sorting occurs before reaching the sediment, making planktic foraminiferal ideal proxy carriers. Diatoms, radiolaria and faecal pellets can be transported up to 500 km in some areas. This transport bias suggests that sediment assemblages could contain different proportions of local and imported particles, decreasing the precision of proxies based on these groups and the accuracy of the temperature reconstruction. For example in the Agulhas current, transport can lead to differences of up to 2°C in temperature reconstructions between different proxies. For future palaeoenvironmental reconstructions, further sediment-trapping studies and multi-proxy analyses should attempt to quantify the margin of error associated with particle transport.

1 Introduction

Reconstructing the physical and chemical variables of past marine environments relies on indirect proxies found in the marine sedimentary record. These proxies are usually based on the abundance, morphology and chemistry of organisms whose skeletons preserve in ocean-floor sediments, such as foraminifera, radiolaria and diatoms (Henderson, 2002). Geochemical reconstructions make use of the differential incorporation of a wide range of isotopes and elements into shells, whether actively selected for by
the organisms or passively reflecting the state of the surrounding watercolumn, as well as the ratios of organic molecules produced in metabolic processes modulated by the environment (Henderson, 2002). The relative abundance and morphology of microfossil species in sediment assemblages can be analysed mathematically, for example by the establishment of transfer functions, which compare the assemblage composition to calibration datasets of faunal counts from assemblages of known environmental conditions (e.g. Chen and Prell, 1998; Kucera et al., 2005), allowing us to infer the conditions under which the organisms found in the sediment assemblages lived.

Underlying all of these proxies is the assumption that the sediment assemblage analysed is a true representation of the overlying watercolumn ecosystem and microorganism population for a given location. Whilst attention has been paid to removing potential biases in assemblage composition such as dissolution of foraminiferal and diatom species (e.g. Berger, 1970; Berger and Piper, 1972; Shemesh et al., 1989; Battarbee et al., 2005) and post-depositional reworking of sediments, via re-suspension, sorting and transport of sediments by ocean-floor currents (e.g. Berthois and Le Calvez, 1960; Thiede, 1981; Kontrovitz et al., 1978), the possibility of pre-depositional bias whilst sinking to the ocean floor is largely overlooked.

Yet, settling experiments of various organic and inorganic particles have shown that differences in size, shape and density lead to differences in settling rates between particles (McNown and Malaika, 1950; Fok-Pun and Komar, 1983; Komar and Reimers, 1978; Caromel et al., in preparation). While some of the possible influences are intuitively predictable, others are more complicated to assess. For example, greater size and density both increase the settling velocity; for particles of the same size, those with flatter morphologies have lower sinking rates than more rounded shapes (Caromel et al., in preparation). As a result, particles from different organisms, species or size fractions take varying lengths of time to reach the ocean floor and are therefore affected differently by lateral currents. In general, we would expect horizontal drift to transport particles with lower settling rates over greater distances. This could alter relative abundances of different species and size fractions of microfossils in the sediment assemblages, thereby biasing the perceived link between organisms and their environment and hence the explanatory power of transfer functions and geochemical proxies. The respective settling velocities of the particles, combined with the distance to the seafloor and the strength of the lateral currents encountered, will determine the importance of any sorting bias in the sediment assemblages.

Here, we consider the potential for bias in sediment assemblages by calculating the distance of lateral transport undergone within a fossil group and by comparing and contrasting different proxy carriers. We use planktic foraminifera as our model group as they are widely used as proxy carriers, and a range of other microfossil groups and particles of organic origin to assess potential biases in multi-proxy reconstructions at several high-velocity current locations.

2 Materials and methods

The terminal settling velocities of nine species of planktic foraminifera (Table 1) representing a range of foraminiferal morphologies and densities were determined experimentally (see Caromel et al., in preparation, for full methodology). The settling velocities of dead diatoms and radiolaria, and particles of marine snow, faecal pellets and diatom aggregates were obtained from a number of literature sources (Table 2). Coccoliths, which are the other major biotic contributors to sediments, are thought to undergo dissolution before reaching the sediment in the undersaturated deep water-column, unless exported within faecal pellets (Honjo, 1976). Settling velocities were derived for dead organisms, not taking into account any positive buoyancy from residual cytoplasm, which would lengthen the time spent in the water column.

Kucera et al. (2005) identified the Benguela Current off the south-west coast of Africa as a region where different transfer functions produce discrepancies in sea surface temperature reconstructions. One possible reason could be advection from the Indian Ocean into the Benguela Current. We have therefore chosen a site in the Benguela Current (7.2 °E –19.8 °N) and in the Agulhas Current (32.4 °E –34.2 °N) to test this
hypothesis. Two further sites underlying high-velocity currents were selected, a Gulf Stream-influenced location off the coast of Florida ($-75.6^\circ$ E $30.6^\circ$ N) and one within the Kuroshio Current along the western shore board of the Pacific ($136.8^\circ$ E $30^\circ$ N).

The annual mean velocity depth profiles for the selected locations (Fig. 1) were extracted from a historical run (for the year 2000) of the UVic Earth System Climate Model version 2.9, which replicates broad patterns of present-day ocean circulation (Weaver et al., 2001). The UVic model couples a reduced complexity atmosphere model with a 3-D general circulation ocean model, and has a grid resolution of 3.6° (zonal) by 1.8° (meridional) with 19 unequally spaced depth levels (Weaver et al., 2001). For each depth interval, the eastwards and northwards components of the horizontal velocity were obtained and used as constant throughout the depth interval in the transport calculations. Eastwards and northwards lateral transport components over a given depth interval were calculated separately as the vector sum of the settling velocity and the horizontal current velocity. Total travel distance is the resultant of the total eastwards and northwards transport components.

3 Results and discussion

Predicting water column behaviour is notoriously difficult because of the variety of fluid motions, both organised and disorganised, that occur in the ocean and generate energy transfer and turbulence at a vast range of scales (Peters and Redondo, 1997). Hence we simplified our analysis to derive some general idea about the impact of transport on multi-proxy studies. Our model is a water column without turbulence or stratification, created by temperature and salinity differences, though both are known to influence the settling behaviour of particles. Turbulence has been shown to both accelerate and retard particle settling by resuspension (Ross, 2006) and cause accumulation (Kiorboe, 1997) and disaggregation (Alldredge et al., 1990) of particulates on different energy scales. Particles with the lowest settling velocities are more easily entrained in resuspension (McCave et al., 1995), which would increase the time spent in the watercolumn by particles already travelling the furthest. Stratification results in increased drag on particles at density interfaces (Yick et al., 2009), contributing to accumulation of particles there (Maclntyre et al., 1995). In addition, the decreasing water density and increased water viscosity caused by decreasing temperature with depth, slow down particle settling (Caromel et al., in preparation). Stratification is thus also expected to extend the settling time of particles, with the amplitude of the effect being governed by the sinking rate of the particles (Lande and Wood, 1987). The simplifications therefore leads to our estimates being minimum settling times, so calculations of horizontal transport are at least as large as we suggest.

3.1 Influence on planktonic foraminiferal assemblages

The lateral displacement of any planktic foraminifer is smaller than 10km for all species and sites (Fig. 2). This is due to their high settling velocities, causing them to fall out of the watercolumn within two days at most. As expected, the more heavily calcified species G. truncatulinoides, G. tumida and G. conglobatus travel the shortest distance, as their settling velocities are highest. Orbulina universa exhibits the greatest range of transport distances because of a wide range in settling velocities in this species, despite similar ranges in size to other species (Table 1). This wide range can be attributed to the variability in density in O. universa caused by resorption of the earlier chambers and variable wall thickening (Bé et al., 1973). At first glance, a shape-dependent differentiation in transport is not apparent. There is significant overlap in the distances travelled for all foraminiferal species. As each foraminiferal species has their own size range (Schmidt et al., 2004) though, the distance travelled is governed by the sinking speeds over the species-specific size range. For example, a normal-sized flat G. menardii specimen of 950µm is twice as big as typical rounded G. ruber and G. trilobus but exhibits similar settling velocities (Table 1). Considering specimens of similar sizes across species, as happens in the narrow size fractions picked for trace elements for temperature reconstructions for example, a G. menardii specimen would sink half as fast as one of a rounded species (Caromel
et al., in preparation) and therefore cover twice the distance by lateral transport. Importantly, though, even with this bias in our settling experiments taken into account, the overlap in the ranges of distances travelled between all species remains, which implies that even at high-current velocities, no significant shape-dependent sorting occurs.

The specimens used in the settling experiments ranged 260–1590 µm in size, therefore under-representing smaller size fractions and biasing our results towards higher settling velocities. However, the size fraction generally used for assemblage reconstructions is greater than 150 µm and for geochemical analysis often around 300 µm (Al-Sabouni et al., 2007), therefore at the higher end of settling velocities. Extrapolating from the settling data of the species with the lowest settling velocity, Orbulina universa, we would expect at most a tripling of the maximum distance travelled for the smaller specimens. Even in the Agulhas current, where the current velocities are high and hence the maximum distance travelled, the smaller size fraction would reach a maximum distance of 22.5 km, which should not be sufficient to create significant sorting based on size. In addition, many of the smaller, juvenile stages of the foraminiferal population are removed from the upper watercolumn in larger aggregates and faecal pellets (Hemleben et al., 1989), leading to their export to the sediment faster than as individual tests, reducing the potential for size-dependent sorting.

The very small lateral displacement overall by all shapes and sizes should consequently not introduce a bias in the proportional representation of species and size fractions in sediment assemblages. The discrepancies produced by different calibration techniques of transfer functions in the Benguela region is therefore not likely to be caused by transport of a subset of dead foraminifera by the Agulhas current, but rather by the presence of a displaced live foraminiferal population advected into the region by a ring of Agulhas waters, diluting the local signal (Peeters et al., 2004).

Corrected for dissolution and post-depositional reworking, and allowing for variable microenvironments such as the Agulhas ring, planktic foraminiferal composition can therefore be confidently used in proxies to represent the overlying water column structure in all locations, and the geochemistry of different species from the same samples can reasonably be used to reconstruct different depths of the water column.

3.2 Influence of settling velocity on multi-proxy studies

While settling does not seem to produce a bias in foraminiferal assemblage-based transfer functions, settling velocities of other proxy carriers can range up to two orders of magnitude lower (0.00007 to 0.0048 m s⁻¹) than those of planktic foraminifera of 0.03 to 0.05 m s⁻¹ (Table 2). Consequently, the scope for individual lateral displacement and consequent bias between the different groups of proxy carriers due to sorting is much greater than for foraminifera (Fig. 3). Whilst radiolaria, diatom aggregates, faecal pellets and other particulate matter such as marine snow can rival planktic foraminifera in size, their lower densities and weight result in lower sinking speeds (Takahashi and Honjo, 1983; Aldredge and Gotschalk, 1988; Yoon et al., 2001) and hence greater horizontal drift. Individual diatoms travel the furthest and have the greatest range of distance covered, attributable to their generally small size and consequent very low settling velocities (Table 2).

Overall the amount of transport undergone by diatoms found in sediment assemblages is difficult to assess, as their mode of transport, whether they are exported as individual cells, or as part of flocs or faecal pellets, influences the amount of lateral transport they experience (Fig. 3). In general, small particles are often scavenged by larger ones through turbulence and differential settling (McCave, 1984). Specially, in a bloom situation with high particle densities, mass flocculation into aggregates (Aldredge and Gotschalk, 1989) results in rapid export of diatoms directly below their production zone in surface waters (Kiorboe et al., 1994).

The low settling velocities in the different groups of proxy carriers result in potential transport of tens of kilometres to over a thousand depending on location (Fig. 3). The effect of the export of certain particle types from high-velocity locations is two-fold: firstly, the proxies based on geochemistry or assemblage composition of radiolaria, diatoms or organic signals and coccoliths derived from faecal pellets could be importing
a signal from a distant location compared to proxies based on foraminifera, which will record more local signals as they are transported just a few kilometres. This, in addition to post-depositional sorting, can partly explain instances where temperatures derived from co-occurring alkenones and foraminifera do not agree (Benthien and Müller, 2000; Otkouchi et al., 2002).

Secondly, the wide range of distances travelled within particle types due to differences in current velocities means that, at different sites, assemblages will contain varying proportions of local and imported particles, diluting the local signal to varying degrees, as has been established for example for terrigenous material (Franzese et al., 2006). This implies that correcting the proxy signal for particle transport is not as straightforward as identifying the source location of the imported particles, but requires establishing how much imported and local particles each contribute to the sediment assemblage, also taking into account the proportion of the local population lacking due to exportation. In effect, the signals from smaller or lighter proxy carriers will be smeared over a greater distance and amalgamated with the other signals distributed over that area. This reduces the precision with which variables can be reconstructed for specific locations, which should be reflected in greater error ranges for measurements. In contrast, assemblages of larger and denser proxy carriers such as foraminifera will record more discrete local signals, and precision is dictated solely by the analytical methods used.

In addition to particle properties, variations in current velocity will dictate the geographical and temporal applicability of different proxies. Within the Benguela current (Fig. 3), the distance travelled by all particles in a north-north-westerly direction does not exceed 40 km. Therefore, we would expect no sorting bias in the proxy reconstructions, and sediment assemblages to predominantly reflect the overlying water column properties with minimal import. At the other tested locations, though, radiolaria and faecal pellets can be transported up to 500 km, individual diatoms over 1000 km, whilst foraminifera, marine snow and diatom aggregates travel at most 150 km (Fig. 3). These differences in transport distance result in a vastly different catchment area. For example, in the Agulhas current, particles travelling an intermediate distance (300 km) from the tested site are displaced south-westerly by 1.8° W in longitude and 2.4° S in latitude. In the present-day ocean, temperatures in the original site are consistently 2°C higher than in the catchment area (Locarnini et al., 2010); as a result, temperature reconstructions at this new site could potentially have a large associated error. Despite the shallow water depth of the Florida site, the Gulf Stream can carry the lightest radiolaria and other equivalent particles 2.5° in a northerly direction and 0.7° E. The Kuroshio Current sees large eastwards velocities at shallow and intermediate depths, transporting these particles 2.2° E, with a minimal northerly direction. In both of these locations, temperature profiles with depth are similar at both sites (Locarnini et al., 2010), suggesting that even with export of particles, no error would be introduced given the current temperature distributions.

However, due to changing circulation patterns and intensity over time, for example in glacial-interglacial cycles, transport and its effect on proxies will vary given changing environmental conditions. For example, during the Last Glacial Maximum, shifts in the Angola-Benguela front (Little et al., 1997) and the Kuroshio current (Ujié et al., 2003) changed local current configuration, making the assessment of the effect of transport on these systems currently impossible due to the lack of detailed proxy reconstructions of their flow. In contrast, the Agulhas current and the Gulf Stream were weaker (Franzese et al., 2006; Lynch-Stieglitz et al., 1999; Peeters et al., 2004), implying shorter transport distances and less bias in our ability to reconstruct past environments based on biological proxies.

4 Conclusions

The high settling velocities of planktic foraminifera result in minimal lateral advection of all species by horizontal currents. As a consequence, no size- or shape-dependent sorting should occur in foraminiferal assemblages during deposition, making foraminifera ideal proxy carriers after correcting for post-depositional biases.
Different particle groups exhibit a range of transport distances, diatoms, radiolaria and faecal pellets travelling up to 500 km in high-velocity areas, whilst foraminifera, marine snow and diatom aggregates travel at most 150 km. This suggests that different proxies based on a range of particle types could represent different catchment areas and hence result in a bias in the reconstructed environmental parameter. With transport within diatoms, radiolaria and faecal pellets also covering a wide range of distances depending on location, sediment assemblages will contain differing proportions of local and imported particles, introducing a margin of error in proxy reconstructions. South of the Agulhas current, this could lead to temperature reconstructions up to 2 °C warmer in a modern ocean.

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Table 1. Settling velocity and size of nine species of planktic foraminifera (data from Caromel et al. (in preparation))

| Species                | Velocity m s\(^{-1}\) | Size (µm) | Velocity m day\(^{-1}\) |
|------------------------|------------------------|-----------|-------------------------|
|                        | mean   | min.-max. | mean   | min.-max. | mean   | min.-max. | mean   | min.-max. |  |
| **Globigerinoides ruber** | 0.024  | 0.018–0.033 | 550.1  | 319.3–742.9 | 2073.6  | 1555.2–2851.2 |  |
| **Globigerinoides trilobus** | 0.026  | 0.019–0.039 | 437.5  | 259.2–680.3 | 2246.4  | 1641.6–3369.6 |  |
| **Globigerinoides sacculifer** | 0.030  | 0.022–0.038 | 688.4  | 411.7–953.7 | 2592.0  | 1900.6–3283.2 |  |
| **Orbulina universa** | 0.030  | 0.012–0.050 | 636.1  | 430.2–817.9 | 2592.0  | 1036.8–4320.0 |  |
| **Globorotalia menardii** | 0.032  | 0.017–0.041 | 1088.2 | 712.6–1589.3 | 2764.8  | 1468.8–3542.4 |  |
| **Globorotalia hirsuta** | 0.032  | 0.015–0.039 | 628.1  | 369.4–999.1 | 2764.8  | 1296.0–3369.6 |  |
| **Globorotalia truncatulinoides** | 0.040  | 0.025–0.050 | 626.1  | 467.8–760.2 | 3456.0  | 2160.0–3420.0 |  |
| **Globorotalia tumida** | 0.051  | 0.038–0.058 | 946.0  | 740.5–1334.2 | 4406.4  | 3283.2–5011.2 |  |
| **Globigerinoides conglobatus** | 0.053  | 0.035–0.068 | 597.7  | 468.6–794.6 | 4579.2  | 3024.0–5875.2 |  |

Table 2. Settling velocity of sedimenting particles of organic origin

| Particle                        | Velocity m day\(^{-1}\) | Reference | Velocity m s\(^{-1}\) |
|---------------------------------|--------------------------|-----------|-----------------------|
| Diatoms (dead)                  | 6–60                     | (Smayda, 1970) | 0.00007–0.0007 |
| Diatoms (giant, dead)           | <400                     |           | <0.0046               |
| Diatom aggregates               | 117                      | (Allredge and Gotschalk, 1989) | 0.0014 |
| Marine snow                     | 74                       | (Allredge and Gotschalk, 1988) | 0.0009 |
| Copepod fecal pellets           | 26.5–159.5 (avg 69.9)    | (Yoon et al., 2001) | 0.0003–0.0018 (avg 0.0008) |
| Euphausiidiid fecal pellets     | 16.1–341.1 (avg 122.3)   |           | 0.0002–0.0039 (avg 0.0014) |
| Nassellarian radiolaria         | 14–105                   |           | 0.0002–0.0012 |
| Spumellarian radiolaria         | 25–177                   | (Takahashi and Honjo, 1983) | 0.0003–0.0020 |
| Phaeodarian radiolaria          | 13–416                   |           | 0.0002–0.0048 |
Fig. 1. Annual mean horizontal velocity depth profiles for the selected sites, extracted from a historical run (for the year 2000) of the UVic Earth System Climate Model version 2.9 (Weaver et al., 2001). The horizontal grey lines mark the depth intervals.

Fig. 2. Range of distances travelled by nine species of planktic foraminifera at the selected sites (green square represents the mean).
Fig. 3. Range of distances travelled by sedimenting particles of organic origin at the selected sites (green square represents a mean or single value in the case of marine snow and diatom aggregates).