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Tracing Beach Sand Provenance and Transport using Foraminifera: Preliminary Examples from Northwest Europe and Southeast Australia

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Abstract

Foraminifera are marine Sarcodine Protozoa that possess tests (shells) that are preservable in the fossil record. These tests may either be constructed using organically cemented detritus (agglutinating or arenaceous forms), or secreted using calcium carbonate (calcareous forms). Their ecology embraces planktonic and benthonic modes, although planktonic forms generally inhabit the open ocean and seldom live in coastal waters in any abundance, while benthonic foraminifera exist on substrates from abyssal plains to high intertidal areas. There are many species of foraminifera that are niche-specific, making them ideal for palaeoenvironmental analysis (Boersma, 1978; Brasier, 1980; Murray, 1991; Culver, 1993).

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23 Tracing Beach Sand Provenance and Transport using Foraminifera: Preliminary Examples from North-west Europe and Southeast Australia

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INTRODUCTION

Foraminifera are marine Sarcodine Protozoa that possess tests (shells) that are preservable in the fossil record. These tests may either be constructed using organically cemented detritus (agglutinating or arenaceous forms), or secreted using calcium carbonate (calcareous forms). Their ecology embraces planktonic and benthonic modes, although planktonic forms generally inhabit the open ocean and seldom live in coastal waters in any abundance, while benthonic foraminifera exist on substrates from abyssal plains to high intertidal areas. There are many species of foraminifera that are niche-specific, making them ideal for palaeoenvironmental analysis (Boersma, 1978; Brasier, 1980; Murray, 1991; Culver, 1993).

In coastal studies, foraminifera have been employed in a number of investigations, as indicators of Quaternary sea-level change (Scott and Medioli, 1978, 1986; Gehrels, 1994; Haslett *et al.,* 1998a,b), for establishing coastal palaeoenvironments and sedimentary biofacies (Murray and Hawkins, 1976; Martin and Liddell, 1989; Kotler *et al.,* 1992; Boomer and Godwin, 1993; Haslett, 1997a,b), as sediment transport indicators in tidal (Brasier, 1981; Thomas and Schafer, 1982; Wang and Murray, 1983; Michie, 1987; Murray, 1987; Gao and Collins, 1992, 1995; Cole *et al.,* 1995), wave-dominated (Moore, 1957; Jones, 1958; Loose, 1970; Pizat, 1970; Blanc-Vernet, 1974; Blanc-Vernet *et al.,* 1979; Seibold and Seibold, 1981; Murray *et al.,* 1982; Sneh and Friedman, 1984; Venec-Peyre and Le Calvez, 1986; Snyder *et al,* 1990; Davaud and Septfontaine, 1995) and aeolian environments (Glennie, 1970; Kameswara Rao *et al,* 1989), and as monitors of coastal environmental pollution (Alve and Nagy, 1986; Alve, 1990, 1991a,b, 1995a,b, 1996; Shariri *et al,* 1993; Bernhard and Alve, 1996; van Geen,

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1999). The value of foraminifera as sediment transport indicators in tidal environments has been realised (Murray, 1987), and is being developed (e.g. Gao and Collins, 1995). Although the same is also true to an extent for some wave-dominated environments, the study of foraminiferal assemblages on sand-grade beaches has been neglected.

Foraminifera seldom live on beaches (Murray, 1973) and their occurrence in these environments is due to post-mortem transport, therefore identified species with known ecologies can act as sediment provenance tracers, and depending on their source area, can indicate transport processes. The aim of this study is to explore hypothetical beach foraminifera assemblages emplaced under various wave hydro-dynamic conditions (fairweather, storm and tsunami), in order to assess the potential of foraminifera as sediment provenance and transport tracers in sand-enriched beach environments. New data on samples collected from wave-dominated environments at a number of north-west European and south-east Australian beach sites are then used to evaluate the models.

MODELLED FORAMINIFERA ASSEMBLAGES

Three different wave hydrodynamic conditions are modelled in relation to foraminifera transport and deposition on sand-grade beaches. Foraminifera are simplified into two groups representing planktonic and benthonic models of life. Coastal zone morphology is based upon Reading and Collinson's (1996) definitions:

(a) A *beach* occurs between the landward limit of swash action and Mean Low Water (MLW). Additional beach morphological subdivisions include the *back-shore* which lies between the landward limit of swash action and Mean High Water (MHW), the *foreshore* between MHW and MLW, and the *beach face* which is the slope (c.<16°) seaward of a berm (Pethick, 1984) where swash and backwash are active (the beach is usually flat on the landward side of a berm *(syn.* backshore) where occasional swash (mainly under storm or high tidal conditions) may occur, but backwash is eliminated by percolation of the swash into the beach sediment).

(b) The *shoreface* occurs between MLW and the mean fairweather wave base.

(c) The *offshore-transition zone* occurs between mean fairweather and storm wave bases.

(d) The *offshore zone* occurs seaward of the mean storm wave base.

The following models of hydrodynamics and sediment transport processes operating at the coast provide a basis upon which exploratory studies and tests can be performed.

Fairweather Wave Conditions

According to Stokes' wave theory, where wave orbital motion is not closed, mass transport velocities and direction vary throughout the water column down to wave base, with a strong onshore flow at the bed and an offshore return flow at mid depths (Pethick, 1984). Under these conditions, it is expected that onshore movement of foraminifera would be predominantly by bedload transport of larger benthonic species that lived on the shoreface (Figure 23.1). Smaller species suspended by bottom turbulence may be carried onshore, but if suspended higher in the water column are more likely to be entrained into the offshore return flow. Surface waters under fair-weather conditions also flow onshore and may hold small planktonic foraminifera in suspension. Smaller suspended benthonic and planktonic specimens on reaching the beach face may not be deposited if energy levels are too high, but would be retained in suspension by backwash activity and transported alongshore to low energy environments, such as estuaries. Under fairweather conditions, a foraminiferal beach assemblage comprising mainly larger benthonic tests may be recognised.

Storm Wave Conditions

The hydrodynamics of storm wave conditions are different from fairweather waves. The principal difference derives from onshore winds which blow across the sea surface, setting up onshore surface currents (Alien, 1982). This onshore flow is balanced by offshore bottom currents. This results in a net offshore transport of bedload sediment, so that finer sediment deposited in the offshore-transition zone during fairweather conditions is overlain by coarser sediment derived from the beach and shoreface (Johnson and Baldwin, 1996). Therefore, during storm conditions, it is expected that benthonic species will be transported offshore (Figure 23.1), except

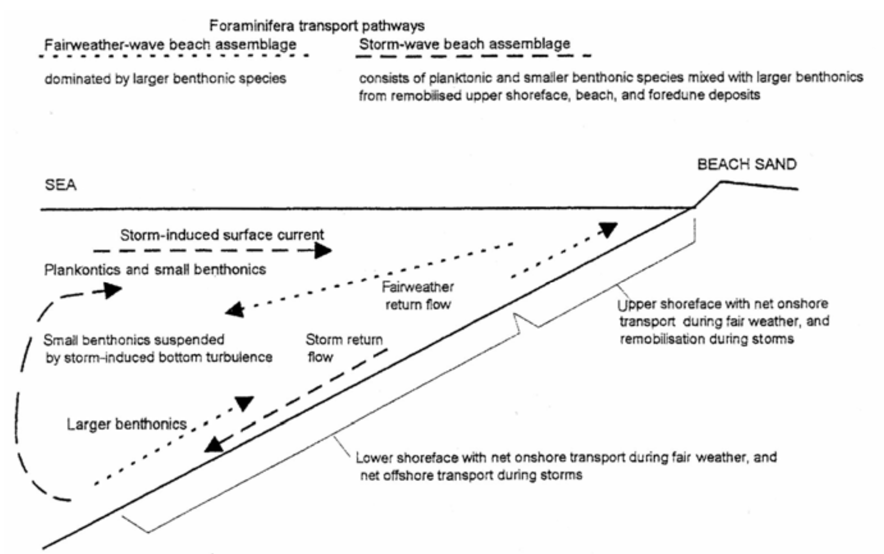

Figure 23.1 Hydrodynamic conditions and foraminifera transport pathways in the inner shelf environment

for the upper shoreface and swash zone where transport onto the beach may occur (Reading and Collinson, 1996). This offshore transport may account for the presence of nearshore foraminifera in offshore deep water > 100m (e.g. Pizat, 1970; Blanc-Vernet, 1974; Blanc-Vernet *et al.,* 1979), although they may also mark the position of former shorelines (Murray, 1979a). Small benthonic specimens held in suspension may be entrained into onshore flowing surface currents and delivered to the beach. Murray (1987) states that in the Celtic Sea waves associated with Force 10 south-westerly gales can suspend sediment, including foraminifera, down to depths of 180 m, which he argues may become entrained in the tidal currents of the severely macrotidal Severn Estuary.

In addition to small benthonic species, planktonic species living in the surface waters may also be transported onshore during storms. Indeed, Murray (1976) suggests that planktonic foraminifera are almost entirely allochthonous in continental shelf waters and sediment, and that the size and abundance of specimens decreases with distance from their open ocean habitat, as they settle out landward across the shelf. Thus, only very small planktonie specimens *(c.* 140 (Jim) are found in estuarine environments (Murray and Hawkins, 1976; Murray, 1980). Based on Murray's (1976) model, it may be argued that under storm conditions the size and/or abundance of planktonic foraminifera delivered to a given coastline may be expected to increase.

Under storm conditions, a foraminiferal beach assemblage may be characterised by planktonic and smaller benthonic foraminifera specimens. However, such assem-blages can be skewed by specimens reworked from pre-storm upper shoreface and beach sediments.

Tsunami Wave Conditions

Seismic disturbance of the sea-floor, including submarine slides, and asteroid impacts can create tsunami waves which may propagate on a pan-oceanic scale (Myles, 1985). At sea, tsunami are of low wave height but long wavelength, compared to storm waves (lida and Iwaski, 1981). In addition, the strong onshore winds present during storms are likely to be absent during tsunami events, unless both occur simultaneously. Calculations performed using Stokes' wave theory indicate that only large tsunami 5m high can match the bottom drift velocities produced by storm waves of 10-15s period and 7-10 m height (Bryant, in press). These types of storm waves can produce onshore drift velocities sufficient to entrain fine sand out to the shelf edge. In contrast, earthquake-generated tsunami, with typical open-ocean wave heights of less than 1 m, can only replicate this type of sediment transport on the inner shelf. In 20 m depth of water, even though the shoreline may be eroding, large storm waves of 7-10 m height can produce onshore bottom drift of 2.0 m s^{-1} while tsunami under 2 m in height can only generate current speeds of 1.0m s^{-1}. While both these types of storm and tsunami wave types have similar heights and hydrodynamic characteristics outside the surf zone, they differ in that storm waves will inevitably break and dissipate much of their energy within the surf zone. Tsunami, being long waves, are unlikely to break before reaching the shore. Tsunami waves are also characterised by long duration times for onshore flow near the bed. These can exceed that generated by a single storm wave by a factor of 40-90 times. Finally, tsunami and storms differ in that tsunami wave trains generally consist of no more than around 12 large waves, whereas storms can generate waves for periods of hours if not days. Hence transport of foraminifera under tsunami waves is not sustained. Upon flooding the shore, tsunami effectively transport sediment landward through turbulent suspension and translation; but some of this material may return seaward under stronger and more prolonged backwash. Resultant foraminifera assemblages are expected to comprise species (both planktonic and benthonic) that originally occurred within the surf zone or were previously deposited on the shore. Also, because of the relatively rapid transport and deposition, size sorting may not occur and assemblages of mixed test sizes may result, although this is dependent on an initial unsorted source. This assemblage may not be very different from storm-emplaced assemblages, and is unlikely to be characteristic. The main difference between emplacement of foraminifera by storm waves and by tsunami occurs in the run-up. Tsunami waves can generate run-up heights 30 times greater than their wave height and can sweep several kilometres inland. This penetration inland can only be duplicated on flat coastlines by storms if they are accompanied by a significant storm surge. Storm waves are incapable of flinging debris beyond cliff tops whereas tsunami can override complete headlands up to 130m high (Bryant *et al,* 1997).

BEACH FORAMINIFERA ASSEMBLAGES FROM NORTH-WEST EUROPE AND SOUTH-EAST AUSTRALIA

To explore the validity of the theoretical models discussed above, a number of beach sediment samples were collected from a number of wave-dominated coastlines in north-west Europe (Figure 23.2; Bird and Schwartz, 1985) and south-east Australia (Figure 23.3; Short and Wright, 1981, 1984; Short and Hesp, 1982; Bird and Schwartz, 1985). Samples of 500 g were collected from the beach face and air dried. No sieving of the sediment was undertaken, but foraminifera were concentrated using a flotation technique, by immersing the sediment in sodium polytungstate (cf. Savage, 1988), stirring, and decanting the floated fraction onto filter paper. Foraminifera float due to the presence of air in chambers of the dried tests, and so can be recovered from the floated fraction by picking, using a 000 sable paintbrush. The non-floated fraction was retained and examined for any specimens that failed to float. European species were identified with reference to Murray (1979b), and the Australian species with reference to Albani (1979) and Yassini'and Jones (1988, 1995).

The foraminiferal assemblages are given in Tables 23.1 and 23.2. Generally, foraminifera abundance in the samples is relatively low with between 10 and 193 tests recovered. The preservational condition of most tests is generally good. Most identified species are capable of either epiphytic, epifaunal or infaunal life in relatively shallow water on the inner shelf, although some *(Elphidium williamsoni* and *Trocham-mina inflatd)* only live on tidal flats and saltmarshes. These intertidal species only occurred together at Barneville, and indicate that longshore currents are actively transporting sediment to the beach from nearby tidal embayments, such as Baie du Mont St Michel (Larsonneur, 1989). Test size is generally large *(c.* 250-500 μm), and small (c. 140 μm) planktonic foraminifera were only encountered at Gerroa, which is

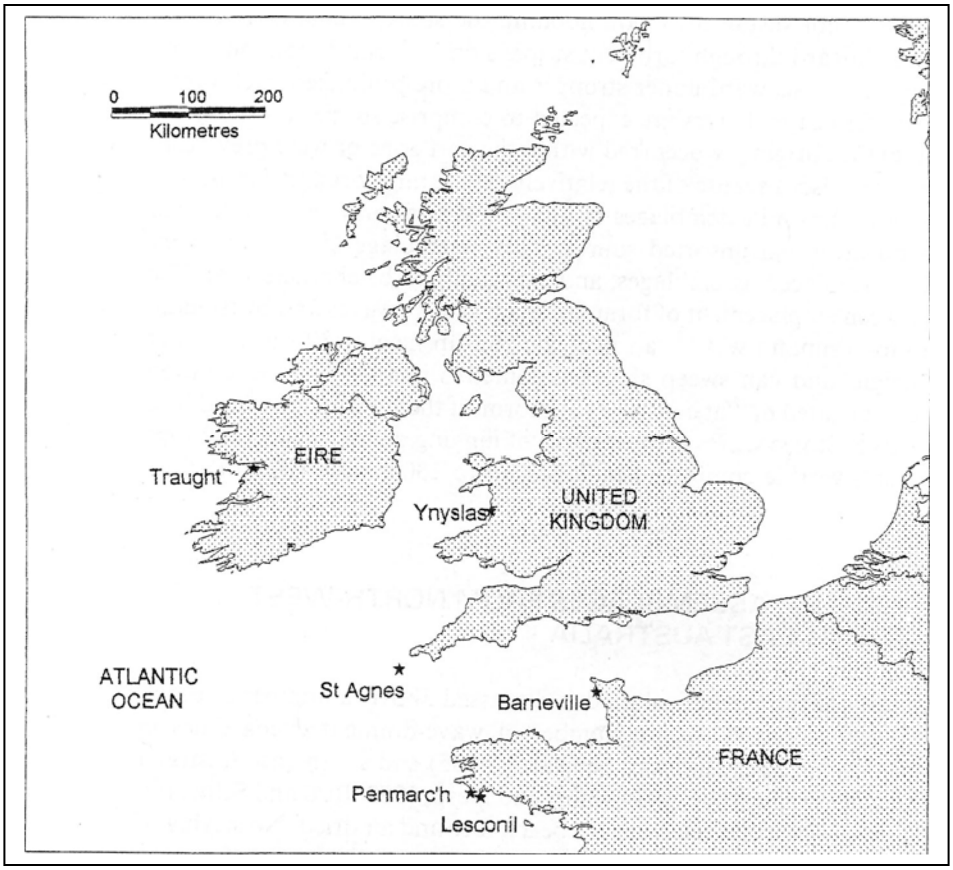

Figure 23.2 European beach sand sample locations

located at the downdrift end of Seven Mile Beach (Wright, 1970), from Shoalhaven in the south to Gerroa in the north, and implies onshore and alongshore transport of tests. All assemblages, according to the theoretical models introduced above, are compatible with transport and deposition during fairweather wave conditions, when large benthonic tests are derived from shallow inner shelf waters.

Detrended Correspondence Analysis

The conspicuous variance in species composition is explored here using Detrended Correspondence Analysis (DCA), a useful ordination technique for recent and fossil assemblages (Davies, 1998), which can be performed on low abundance (>10) raw counts (rather than percentages). All counting groups are included in the DCA. Species ordinations are plotted separately for European and Australian samples against the first two ordination axes in Figures 23.4 and 23.5. These describe the relationship between species composition and the most important controlling environmental factors. Clusters of points are interpreted as assemblage groups, which have

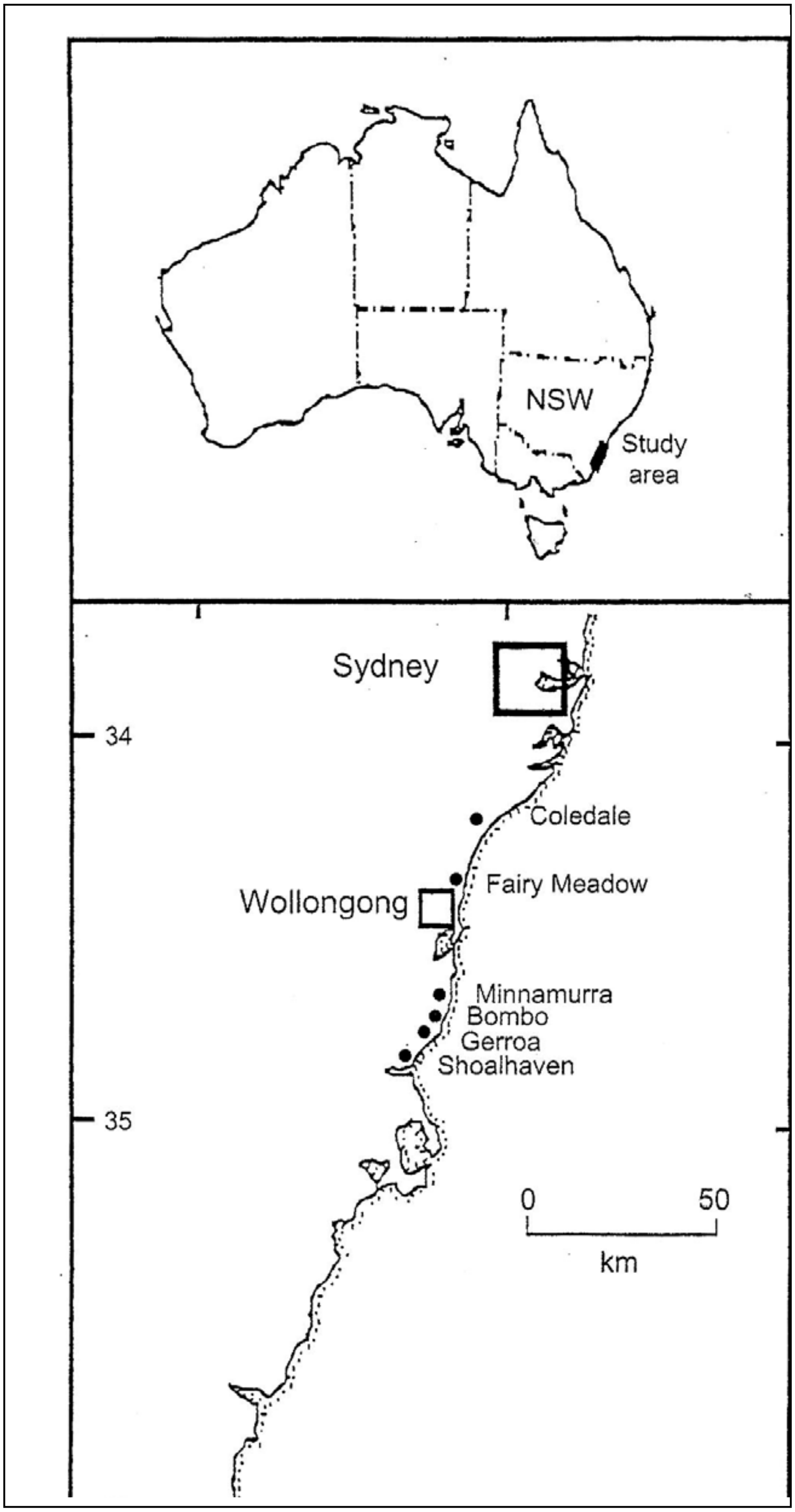

Figure 23.3 Australian beach sand sample locations

Table 23.1 Raw foraminiferal assemblage counts for European beach sand samples, with author attributions and sample collection dates. Environmental information given for each species indicates its life habitat

Species	Barneville	Lesconil	Penmarc'h	St. Agnes	Traught	Ynyslas	Environment
1 *Ammonia beccarii* var. *aberdoveyensis* Haynes	0	0	0	0	0	2	Inner shelf
2 *Ammonia beccarii* var. *batavus* Hofker	21	0	1	0	6	9	Inner shelf
3 *Brizalina variabilis* (Williamson)	0	0	0	1	0	0	Inner shelf
4 *Cibicides lobatulus* (Walker & Jacob)	0	138	2	177	21	0	Inner shelf
5 *Elphidium macellum* (Fichtel & Moll)	9	11	4	9	69	20	Inner shelf
6 *Elphidium williamsoni* Haynes	2	0	0	0	1	0	Intertidal
7 *Elphidium* sp. indet.	1	0	0	0	0	0	
8 *Glabratella millettii* (Wright)	0	0	0	0	0	1	Inner shelf
9 *Lamarckina haliotidea* (Heron-Allen & Earland)	2	0	0	0	0	0	Inner shelf
10 *Massilina secans* (d'Orbigny)	0	0	0	0	0	2	Inner shelf
11 *Planorbulina mediterranensis* d'Orbigny	0	4	0	0	0	0	Inner shelf
12 *Quinqueloculina seminulum* (Linne)	2	16	6	4	1	54	Inner shelf
13 *Rosalina williamsoni* (Chapman & Parr)	0	0	0	2	0	0	Inner shelf
14 *Trochammina inflata* (Montagu)	1	0	0	0	0	0	Intertidal saltmarsh
15 Unidentified specimens	2	0	0	0	0	1	
TOTAL	40	169	13	193	98	89	
Collection date	Aug. 95	Sep. 97	Sep. 96	Sep. 96	Aug. 98	Mar. 94	

Environmental information from Murray (1991).

similar environmental constraints. Species falling outside these clusters are not considered further. With reference to the dominant species these assemblage groups can be cross-referenced with faunal associations of Murray (1991) to aid interpretation. Table 23.3 summarises this information and indicates that in both European and Australian samples two prominent assemblage groups may be recognised. Group 1 in each case consists of species (although not the same characteristic species) that inhabit phytal and/or sandy substrates, which generally reflect non-turbid, clear water environments. Group 2 is characterised by *Ammonia beccarii* in both European and Australian samples, which tolerates muddy substrates, and therefore more turbid environments. An examination of the occurrence of this species in the samples corroborates this interpretation. In Europe, *Ammonia beccarii* is most abundant at Barneville, which is situated on a macrotidal coastline, close to the muddy Baie du Mont St Michel (Larsonneur, 1989), and in Australia it only occurs in samples from Seven Mile Beach (at Shoalhaven Heads and Gerroa), which is proximal to the outlet of the Shoalhaven River, which has a high fine sediment discharge into the inner shelf region (Wright, 1970). Therefore, it appears that species composition in beach sand assemblages is determined by the substrate conditions in the shoreface and

Table 23.2 Raw foraminiferal assemblage counts for Australian beach sand samples, with author attributions and sample collection dates. Environmental information given for each species indicates environments in which tests have been recovered, whether alive and *in situ*, or dead and derived

Species	Coledale	Fairy Meadow	Minnamurra	Bombo	Gerroa	Shoalhaven Heads	Environment
1 *Ammonia beccarii* (Linne, 1767)	0	0	0	0	2	5	Lagoonal to estuarine
2 *Anomalina nonionoides* (Parr, 1932)	4	1	0	4	1	2	Lagoonal and intertidal[a]
3 *Bulimina* spp.	0	0	0	1	0	2	Intertidal to middle shelf
4 *Cibicides refulgens* (de Montfort, 1808)	0	0	0	16	7	12	Intertidal to inner shelf
5 *Cibicidoides floridanus* (Cushman, 1918)	3	0	2	2	2	5	Intertidal to continental slope
6 *Cornuspira foliaceus* (Philippi, 1844)	1	0	0	1	0	0	Estuarine and inner shelf
7 *Elphidium advenum* (Cushman, 1922)	0	0	0	0	1	0	Lagoonal to inner shelf
8 *Elphidium crispum* (Linne, 1758) group	3	2	2	11	12	30	Intertidal to inner shelf
9 *Glabrateila australensis* (Heron-Allen & Earland, 1932)	2	0	0	0	3	3	Intertidal to sheltered embayments
10 Miliolid group[b]	4	1	2	21	14	10	Intertidal to inner shelf
11 *Parrelina* spp.	2	4	0	1	1	14	Intertidal to inner shelf
12 Planktonic foraminifera	0	0	0	0	2	0	Stenohaline (open ocean)
13 *Rosalina australis* (Parr, 1932)	2	1	2	4	1	4	Tidal channels and inner shelf[a]
14 *Textlaria candeiana* (d'Orbigny, 1839)	0	0	0	4	0	0	Estuarine to middle shelf
15 *Trochulina dimidiata* (Jones & Parker, 1862) group	29	12	2	56	17	20	Intertidal to inner shelf
TOTAL	50	21	10	121	63	107	

All samples collected during April 1998.
° Yassini and Jones (1988). All other environmental information from Yassini and Jones (1995).
* Miliolid group includes all species belonging to the Soborder Miliolina.

offshore-transition zone. This is potentially valuable in (palaeo)environmental studies where species composition in (palaeo)beach sand could indicate particle size in the source area regardless of the collected samples' particle size.

DISCUSSION

If the proposed models are accepted, the foraminifera results from the beach sand samples all indicate transport from the inner shelf region and deposition under fair-weather wave conditions. Indeed, only very few non-inner shelf species were encountered in the present study of beach sand samples. This is not surprising as most samples were collected from beach faces at the end of the summer. However, other

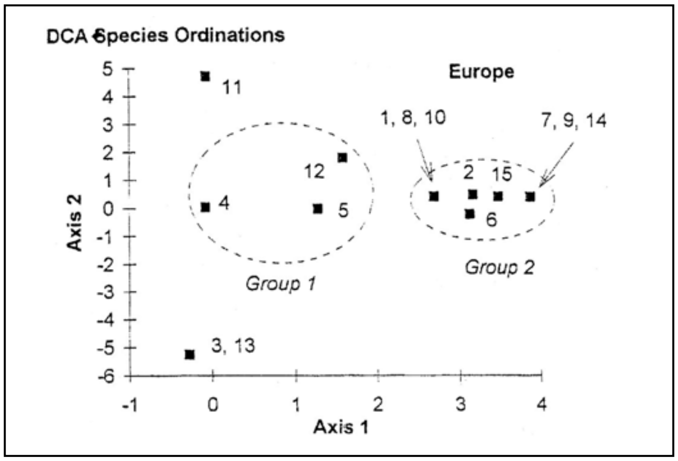

Figure 23.4 Results of Detrended Correspondence Analysis of European beach sand fora-miniferal assemblages (Axes 1 and 2). Assemblage Group 1 represents species indicative of a non-turbid source environment whilst Assemblage Group 2 represents a turbid source environment. Species numbers are those given in Table 23.1

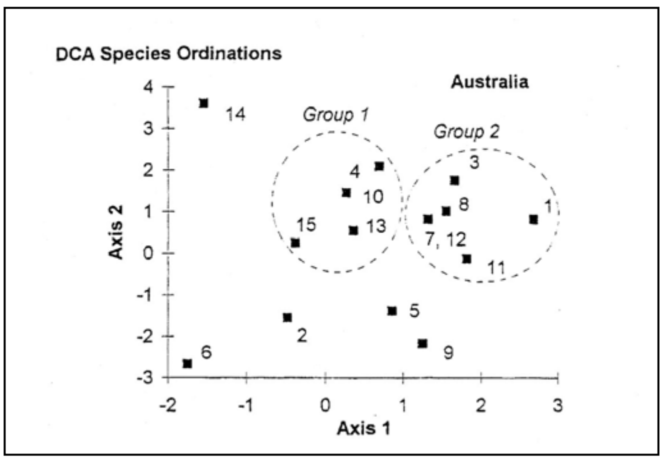

Figure 23.5 Results of Detrended Correspondence Analysis of Australian beach sand fora-miniferal assemblages (Axes 1 and 2). Assemblage Group 1 represents species indicative of a non-turbid source environment, whilst Assemblage Group 2 represents a turbid source environment. Species numbers are those given in Table 23.2

factors not addressed in detail by the models need evaluation. Taphonomic processes may play a significant role in determining resultant foraminiferal beach assemblages. The models focus on the delivery of new tests to the beach environment; however, tests that become integrated components of beach sediment may also be reworked to produce cumulative assemblages, although physical damage, abrasion and dissolution should increase with residency time. Also, temporal changes in wave energy may produce transient assemblages. For example, an assemblage emplaced under

Table 23.3 Summary of assemblage groups derived from Detrended Correspondence Analysis for both European and Australian beach sand samples. A comparison is made with faunal associations of Murray (1991). Assemblage group 1 in both cases represents a non-turbid source environment, whilst assemblage group 2 represents a turbid source

Species ordination group	Characteristic species	Additional species	Murray's association	Shelf substrate type	Depth
North-west Europe					
Group 1	*Cibicides lobatulus*	None	*C. lobatulus*	Seaweed	0–900 m
	Elphidium crispum	None	*E. crispum*	Seaweed	0–25 m
	Quinqueloculina seminula	None	*Q. seminula*	Sand	20–120 m
Group 2	*Ammonia beccarii*	8 others	*A. beccarii*	Muddy sand	0–60 m
Eastern Australia					
Group 1	*Trochulina dimidiata*	Miliolid group *Cibicides refulgens* *Rosalina australis*	*T. dimidiata*	Shelly coarse sand	5–7 m
Group 2	*Ammonia beccarii*	*Elphidium crispum* *Parrelina* spp.	*A. beccarii*	Mud, sand	0–25 m

fairweather conditions may be reworked during a storm, and small tests transported as bedload under fairweather conditions may become suspended under storm wave energy conditions and transported alongshore. These taphonomic effects are difficult to incorporate into the models at present and further research is required; in particular, high temporal resolution sampling at individual sites, and less of an *ad hoc* approach than was adopted in this preliminary study. The same is true regarding the role of tidal currents.

It is possible that the sample location along a beach profile is also important, as the active beach face may, for example, always yield an assemblage indicative of fair-weather conditions as described by the models, as smaller specimens may not be deposited here due to prohibitively high energy conditions. They may be deposited, however, from swash on the landward side of a berm during high tides in fairweather conditions, or by berm-overtopping storm waves. Samples from the landward side of the berm may therefore yield very different assemblages and could be biased toward assemblages attributable to storm wave conditions or tsunamis, which are more likely to overtop berms. This is obviously-an area upon which further studies will be based.

The only comparable work to the present study is that of Davaud and Septfontaine (1995) who investigated transported foraminifera in a barrier and lagoon sedimentary environment on the Tunisian coast in the Mediterranean. They encountered foraminifera in barrier (beach) and lagoon sediments which were epiphytes that lived on seagrass leaves, similar to DCA Group 1 here (Table 23.3). However, shoreface sediments lacked foraminifera. The seagrasses form subtidal meadows in the offshore-transition zone between water depths of 4 and 35m, therefore the onshore transport of this assemblage is considered to occur during storm conditions when the wave base is lowered to within the depth range of the meadows. They also argue that the lack of foraminifera in the shoreface suggests that fairweather waves do not actively transport tests onshore. While the present study suggests that if storm waves do introduce epiphytic tests onto the shoreface they may be rapidly transported to the beach by fairweather waves in the immediate post-storm period, this is not tenable for their lagoon assemblages, which must have been introduced by storm waves overtopping the barrier. Davaud and Septfontaine (1995) also suggest that foraminifera preservation could reflect transport processes, in that bedload-transported specimens would be more abraded than those transported in suspension.

The use of foraminifera as sediment provenance and transport tracers may not be the best technique to employ when studying contemporary coasts, as more sophisticated tracing devices provide more fully quantitative results (e.g..Lee *et al.,* see Chapter 22). However, foraminifera have great potential in palaeoenvironmental studies. This study demonstrates that species composition can be used to distinguish between onshore transport from a shelf source and alongshore transport from an intertidal source (which could allow current development to be established through time, given adequate stratigraphic material). Species composition is also a discriminator of the sedimentological characteristics of the shelf source area, whether turbid or non-turbid, which could be extremely useful in monitoring changing sedimentological regimes through time. The relationship of foraminifera to hydrodynamic conditions requires further investigation as certain parts of a beach profile will only yield evidence of a particular hydrodynamic state. For example, and according to the model predictions, sediments from active beach faces could yield an assemblage indicative of fairweather conditions, whereas sediment landward of berms could yield assemblages emplaced by overtopping storm or tsunami waves.

CONCLUSION

Foraminifera have a demonstrated value in coastal sediment tracer studies, and this study addresses their potential for sand-grade beaches. The models that have been introduced here are simplistic, but have facilitated this preliminary investigation, which has provided encouraging results. The models predict that deposition under fairweather wave conditions is characterised by an assemblage of large benthonic foraminifera tests, and that an assemblage of small planktonic and benthonic tests, mixed with reworked large benthonic specimens, is characteric of storm wave and, probably, tsunami deposition. Samples collected from European and Australian beach faces comprise almost exclusively large benthonic tests, indicating fairweather deposition. However, variation in species composition appears to reflect substrate conditions at source, and can also be used to distinguish between onshore and alongshore derived specimens. The need for further investigations is apparent, especially the study of possible spatial and temporal assemblage variations along a beach profile, the effects of taphonomic processes, and the role of tidal currents superimposed on wave transport. The use of foraminifera may not be cost-effective in studying sediment provenance and transport to contemporary beaches, but its potential application to palaeoenvironmental studies is considerable, as it provides a means for establishing shelf palaeoenvironments and coastal palaeohydrodynamics, including temporal changes in onshore and alongshore current activity.

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