8

Shelf Sediments and Biodiversity

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Opposite page: Sediment banks off Maputo Bay, Mozambique. © José Paula.

WHAT ARE CONTINENTAL SHELVES?

Together with continental slopes and rises, continental shelves (geologically defined differently from the legal definition, as defined in Article 76 of UNCLOS) form the submerged margins of continents (Figure 8.1). Shelves are amongst some of the flattest portions of the Earth's surface (Pinet 2009) and act as halfway houses for sediment transported from the coast to the deep ocean basins. The shelves of the East African continental margin form connections between the steep upper continental slope and the adjoining coastal plain and comprise passive continental margins, having originated at the edge of divergent tectonic plates that spread (rifted) away from the mid-Indian oceanic ridge (Scrutton 1982). The continental margins of the Western Indian Ocean (WIO) are in contrast to many of the eastern Indian Ocean margins which formed instead by subduction processes. These margins are tectonically active and frequently experience earthquakes or volcanic eruptions. Passive margins, such as those in the Western Indian Ocean, are subsiding areas, often characterised by thick accumulations of sediment where fluvial sediment supply is high (Scrutton

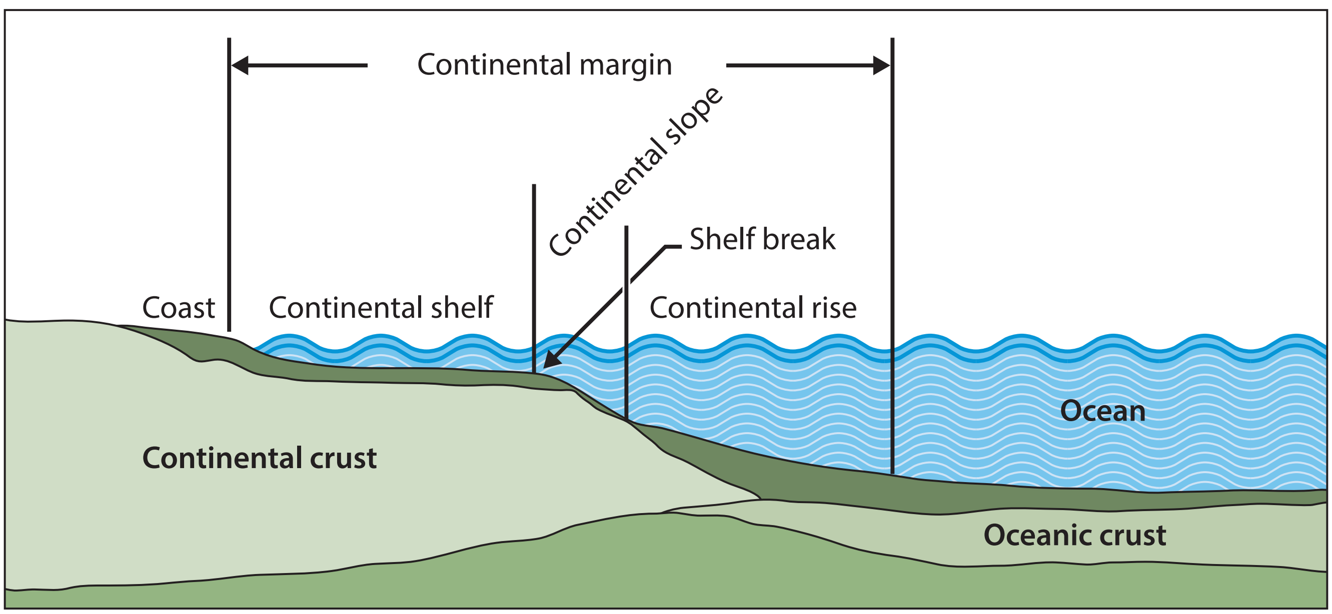

Figure 8.1. Schematic of the components of a generalized passive continental margin.

1982). Typically, the shelves of passive margins have a gentle gradient (Pinet 2009), though this can vary with some shelves being particularly steep (eg Green and others, 2007). Each shelf is separated from the continental slope by the shelf break or edge, where the gradient increases sharply. In many instances, the shelf break approximates the lowstand shorelines associated with glacial maxima ie periods of very low sea level coincident with glaciation phases. On average, the shelf break is located at a depth of about 140 m (Gross 1972), but this too can vary according to local conditions. Many shelves can be shallower, with some shelf breaks occurring at depths of 100 m or shallower (eg Green 2009a).

The location of the shelf break, which determines the width of the shelf, is a function of interactions between sedimentation processes, sea level changes and tectonics (uplift or subsidence). In addition, reefs and submerged shorelines, for example, form barriers, allowing sediment to accumulate between them and the shore, cutting off sediment supply to deeper water (eg Puga-Bernabéu and others, 2011). These also produce significant volumes of carbonate sediment in the form of rubble and bioclastic detritus (eg Flemming and Hay 1988). Continental margins with poor sediment supply, such as in arid regions, tend to have narrower continental shelves. They are characterised by little sediment transport by rivers, or by redistribution of recent sediments by longshore and geostrophic currents (Scrutton 1982, Green 2009a). The WIO is notable for its narrow shelves (Figure 8.2), with the exceptions of the central Mozambican region, where sediments from the largest river in East Africa, the Zambezi River, have extended the shelf break some 140 km offshore, and off parts of the Malagasy west coast, where large rivers such as the Betsiboka have been similarly influential. The East African shelf only averages 15-25 km in width (UNEP-GEF 2008), compared to a global average of around 80 km (Shepard 1963, Pinet 2009). Other areas where the shelf widens considerably beyond the local average are off the Thukela River in South Africa, the Limpopo River in southern Mozambique, the Ruvuma, Rufiji and Pangani rivers in Tanzania, and the Tana and Sabaki Rivers in Kenya. In parts of Kenya, northern Mozambique and the east coast of South Africa, the shelf break is as little as a few hundred metres to <4 km from the coast (Flemming 1981, Abuodha 2003, Green 2009a).

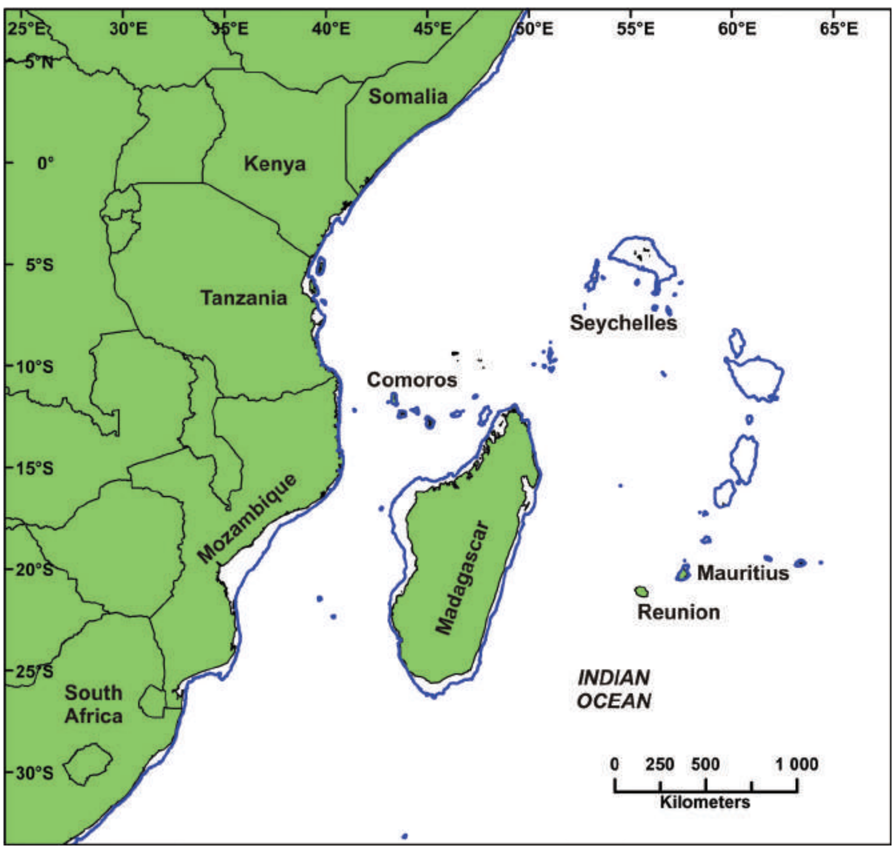

Figure 8.2. The western Indian Ocean region showing the 200 m bathymetric contour (adapted from IOC and others, 2003).

TYPES OF SEDIMENT

Assuming that the coral reef area in the Western Indian Ocean is around 13 000 km^2 (derived from Muthiga and others, 2008, Ahamada and others, 2008, UNEP-GEF 2008), when compared to the estimated total shelf area (Table 8.1), it is apparent that the vast majority of the sea bed of the shelf in the western Indian Ocean comprises unconsolidated sediments. These are terrigenous sediments derived mainly from erosion of the continents. Where there is an increased supply of these sediments, the shelf break is pushed further offshore as the newly-eroded sediments accumulate over older layers. Large quantities of the surface sediments on continental shelves are relict, in other words, deposited during earlier cycles of sea level rise and fall. Many of the sediments have been reworked by erosion cycles associated with varying sea levels and are exposed as palimpsest (relict) pavements along the mid and outer shelves, exposed to the action of fringing shelf-edge currents such as the Agulhas Current (Green and MacKay in press). These may be interspersed with submerged shorelines of varying ages which have added small, in situ quantities of rubble and bioclastic debris to the shelf system (Green and MacKay in press). Along the east coast of South Africa, the relict sediment is thinly overlain by a sheet of Holocene aged material, on average no more than 10 m thick with a few localised depocentres up to 30 m thick, usually associated with the localised convergence of littoral and geostrophic currents. The nearshore sediments are thus younger than those on the outer shelf (Flemming and Hay 1988), typically being produced by deposition of sand, silt, and clay from rivers, with subsequent redistribution by longshore currents (Flemming and Hay 1988). However, where these riverine clastic sediment inputs are small, biogenic (bioclastic) sedimentation, produced by erosion of the skeletal carbonate remains of marine organisms, can dominate. The type of sediment can thus change substantially along and across a shelf, depending on the relative contributions from carbonate and/or clastic sediment production.

The outer continental shelf and upper slope are locally incised by old river courses (Green 2009b, Green and others, 2013) that have been infilled by up to 60 m of Holocene aged sediment. Submarine canyons, particularly in northern South Africa and northern Mozambique (Parson and Evans 2005, Green 2011), are also a common feature at the shelf edge and upper slope. Submarine canyons that strongly impinge onto the shelf may act as sediment traps for littoral sediment, or can modify the nearshore currents, inducing localised deposition of sediment (Green 2009a). It is now thought that the majority of these features do not actively transfer sediment to the adjacent deep ocean basin (Green and others, 2008).

Table 8.1. Estimates of continental shelf areas of the WIO to the 200 m depth contour, ie FAO Area 51. NB: the South Africa component of the WIO only extends to latitude 31°18 S. Source: Sea Around Us Project.

Country	Shelf km^2	%
Comoros	1 618	0.4
Kenya	8 874	2.4
La Reunion	182	0.05
Madagascar	124 551	33
Mauritius	39 855	10.6
Mozambique	79 451	21
Seychelles	48 787	12.9
Somalia	47 511	12.6
South Africa	9 768	2.6
Tanzania	16 929	4.5
TOTAL WIO shelf area	377 526	

The distribution patterns of the various sediment textures (mud, sand, gravel etc.) on the shelf vary according to proximity to river mouths, depth, wave action and currents (Nichols 2009), with the fine fractions (mud and fine sand) being the most easily dispersed. There are few available studies on shelf sediment distribution patterns in the WIO; qualitative reference is made to muddy sediments off river mouths, such as on the Sofala Bank in Mozambique, and Malindi-Ungwana Bay in Kenya (Munga and others, 2013). Detailed studies have been confined to the east coast of South Africa, and were undertaken by Flemming and Hay (1988) and Bosman and others (2007); surface sediment distributions described in the latter have been recently improved and expanded by Green and MacKay (in press) and Figure 8.3 below. Knowledge of these patterns is important, as they enable us to understand the habitat requirements of the biodiversity of shelf organisms, as well as having implications for exploitation of both renewable (Figure 8.3) and non-renewable resources (eg sand extraction, heavy minerals of terrigenous origin) associated with particular sedimentary facies.

BIODIVERSITY AND SHELF SEDIMENTS

Organisms associated with the sea bed are termed benthos, and the faunal component may be divided into infauna

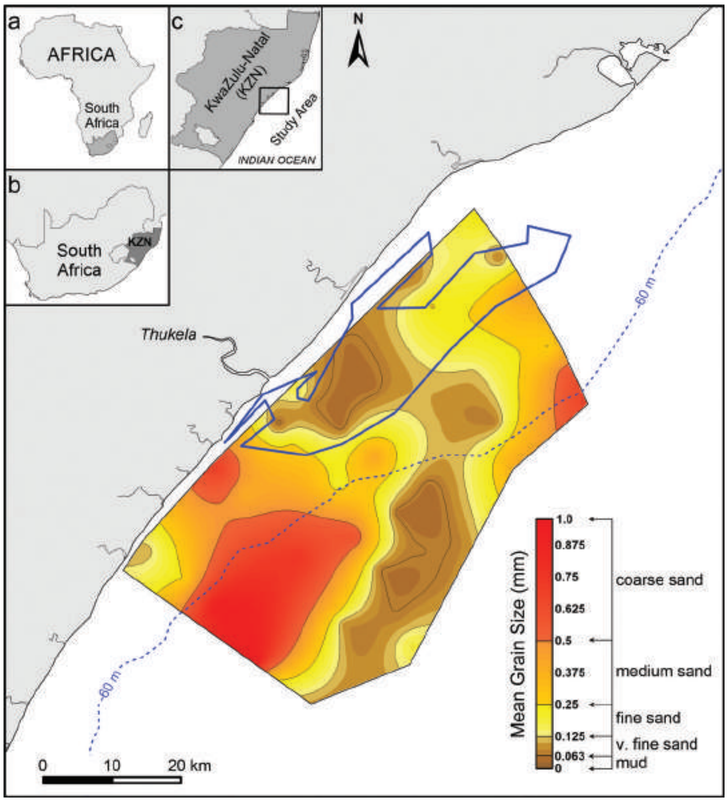

Figure 8.3. Map showing the distribution of surface sediment facies off the coast of central KwaZulu-Natal, South Africa (after Green and MacKay in press), and the close association of the shallow prawn trawling grounds (outlined in blue) with the finer facies (Oceanographic Research Institute, unpubl. data).

(found in the sediment), epifauna (on the sediment) and demersal (just above the sediment). Further distinctions can be made on the basis of the size of the organism: macrofauna (such as amphipods, isopods, gastropods and polychaetes) are >1 000 µm, meiofauna (rotifers, harpacticoid copepods, nematodes) are between 45 and 1 000 µm, while microfauna (ciliates) are <45 µm. Then there are the benthic microalgae or microphytobenthos (cyanobacteria, benthic diatoms, and flagellates) which form a layer on shelf sediments in the euphotic zone and which can contribute substantially to continental shelf productivity (Gattuso and others, 2006); these are more correctly considered as bentho-pelagic, as they can be suspended in the water column, particularly during turbulent seas, thereby forming part of the plankton. Also included in the benthos are the non-planktonic foraminifera, either living or dead, with carbonate tests which are typically <1 000 mm in diameter.

Sediment characteristics such as texture, grain size and composition are important drivers of benthic species composition, albeit in combination with other factors such as depth and temperature (Snelgrove and Butman 1994, Reiss and others, 2009). Generally, unconsolidated sediments support high diversity, and macrobenthic invertebrates are a major contributor to this (Hall 2002, Gray and Elliott 2009). Classically, polychaete worms predominate in the macrobenthos, followed by crustaceans, molluscs and echinoderms (Gray and Elliott 2009). The benthic infauna, be they deposit-feeders from sediments or suspension-feeders from the water column, or those which are capable of both, provide an important link to higher trophic levels like the demersal ichthyofauna. However, studies of benthic macro-infauna of tropical marine sediments are far fewer than their temperate counterparts (Alongi 1990) and, as with the paucity of information on sediment characteristics of the region, there are very few infaunal studies on shelf sediment habitats in the WIO. Consequently, literature on these fauna from the region are limited (Mackie and others, 2005).

Generally, a decline in diversity of macrobenthic fauna with increasing latitude may be expected, albeit reportedly less so for the infauna and sessile epifauna than for mobile epifauna (Hillebrand 2004, but see Gray and others, 1997). This was demonstrated for polychaete and molluscan taxa from the equatorial Seychelles relative to their counterparts at high latitudes in the Atlantic and Pacific (Mackie and others, 2005). There is evidence, though, that there are considerable differences between some WIO benthic macrofaunal taxa from tropical oceanic islands and the adjacent east African mainland (Taylor 1997, Crame 2000), possibly as a result of the influence of reefs as well as mainland terrigenous inputs. Another example of the non-generality of the relationship between latitude and diversity is that of MacKay and others (in press), who found that the soft sediment shelf macrobenthos of the central KwaZulu-Natal Bight on the east coast of South Africa (~28-29ºS) are abundant and rich, and are comparable to some of the highest levels of richness in marine unconsolidated sediments found elsewhere, as reported by Gray and others (1997). MacKay and others (in press) found Annelida (760 taxa), Arthropoda (535 taxa), Mollusca (163 taxa), Echinodermata (75 taxa), Sipuncula (60 taxa) and Cnidaria (54 taxa) to be dominant; other phyla were Brachiopoda, Bryozoa, Chordata, Echiura, Nematoda, Nemertea and Platyhelminthes. The Annelida were dominated by Polychaeta which were particularly diverse (49 families). Amphipod crustaceans (34 families) dominated the Arthropoda, followed by the isopods. At the individual taxon level, a hermit crab and a sipunculid worm were most abundant. Although molluscan shell material was prevalent in bioclastic sediments (as crushed shells), live molluscs were not particularly abundant. Grain size was an important driver of macrobenthic community composition, probably due to its influence on sediment organic content and infaunal feeding modes, and riverine outflow was positively influenced abundance and diversity, probably due to increased food supply in the form of macrophytic detritus and suspended organic matter. The study by MacKay and others (in press) supersedes the generalized review by McClurg (1988), based on limited sampling in the same geographic area, and appears to be the only study of its kind in the WIO, and for which results are available.

It is possible that the diversity of benthic macrofauna of the KwaZulu-Natal Bight may differ markedly, at least at lower taxonomic levels, from that elsewhere in the WIO, owing to the unique nature of this part of the south-east African shelf. The proximity of a semi-permanent upwelling cell and a large river mouth (Lutjeharms 2000), together with their relatively high latitude, probably mean that the soft sediment shelf habitats differ from those further north, with implications for the benthic macrofaunal community composition. Having said this, it is, however, notable that there are marked similarities in some of the larger demersal shelf fauna found in several countries of the region. The prawns (shrimps) *Penaeus indicus* and *Metapenaeus monoceros* comprise the majority of targeted catches by shallow-water (<50 m) industrial trawlers from South Africa to Kenya, and Madagascar (see Chapter 21), and many of the bycatch species from these fisheries co-occur as well (Brinca and others, 1983, Bianchi 1992, Fennessy and others, 2004, Munga and others, in review). The trawl grounds for these fisheries probably coincide closely with very fine sand or mud (mean grain diameter <0.1 mm) sediment types, as described earlier for the east coast of South Africa, mud being the preferred habitat for these prawns (de Freitas 2004). Members of the family Sciaenidae (croakers; Fennessy and others, 2004) are prominent among the fishes in these mud-dominated shelf habitats, and can be considered indicators of the presence of prawns (Pauly and Neal 1985).

Broadly, it may be expected that the demersal ichthyofauna on WIO sediments conform to the "bathymetric progression" patterns described by Longhurst and Pauly (1987) for unconsolidated sediments in tropical waters. Thus, in inner shelf waters associated with river mouths, members of the Sciaenidae and Cynoglossidae would predominate owing to their preference for turbid or muddy habitats, while Sparidae, Triglidae, Sauridae and Haemulidae are probably more predominant over inner shelf substrata with less mud. Some of these families probably persist into deeper shelf water, being joined by some of the upper slope taxa such as the Squalidae. Thus depth, too, (as a proxy for other physico-chemical parameters such as temperature, salinity, etc.) is influential (Bianchi 1992, Dulvy and others, 2008). The shelf communities are probably quite distinct from those on the slope, as described generally by Longhurst and Pauly (1987). Indications that these generalized soft sediment demersal community patterns also prevail in the WIO, or at least in its trawlable areas, are available from unpublished survey reports, notably those emanating from the RV Fridjtof Nansen, including those by Brinca and others (1983), Bianchi (1992), Johnsen and others (2008), Alvheim and others (2010), as well as from the recent South West Indian Ocean Fisheries Project (van der Elst and others, 2009, www.swiofp.net), although the information on sediment composition in the trawlable areas is lacking. Thus, the association of demersal fish communities with particular substratum types has not been demonstrated in the WIO, other than in a general sense by Bianchi (1992), and by Fennessy (in press) in a South African study with limited scope. As described in other regions (eg Gaertner and others, 1999), this association may be expected to be particularly close for demersal fishes which are in direct contact with the substratum, such as flat fishes and gurnards, and some species are probably specifically linked to substrata and/or turbidity associated with riverine plumes (as is the case with some invertebrates, as described above). Furthermore, it is anticipated that these associations are also a function of the composition of the benthic infauna which are the prey of demersal fishes; again, while these interdependencies are at least partially understood in other regions (eg Darnaude and others, 2004), similar studies are virtually non-existent for the WIO shelf.

Only recently did de Lecea and others (2013) demonstrate these dependencies indirectly on the South African east coast, where their isotope-based study revealed that the soft-sediment demersal food web in a nutrient-poor shelf environment was controlled by total suspended solids of terrestrial origin, via riverine input, with macrobenthos as probable intermediaries. In this case, omnivory was a widespread strategy amongst the sampled demersal organisms, shown by the low variability in trophic position across a wide variety of taxa. This "eat whatever is available" strategy was suggested to be a function of a nutrient-poor environment, and has important implications for ecosystem functioning; a flexible diet can impart resilience, such that changes in species composition may not appreciably affect overall functioning of the system. Untiedt and Mackay (in press) also showed that the infaunal community in this shelf area was dominated by organisms which had a variety of feeding modes, enabling them to adapt to an environmentally variable and heterogeneous shelf environment. Overall, ecosystem models showed that the infauna dominate the shelf benthic food web, with a high reliance on riverine detritus, and with important links to nearby estuaries (Scharler and others, in review). Although these studies were once-off and were confined to the east coast of South Africa, there may well be analogies with soft-sediment shelf habitats elsewhere in the WIO, which is generally nutrient-poor (Mengesha and others, 1999; see also this report – Chapter 16, primary productivity), but with some areas influenced by riverine inputs (UNEP-GEF 2008).

IMPACTS ON SHELF SEDIMENTS

While rivers are important providers of nutrients and sediments to shelf habitats, they are also a source of pollutants, such as persistent organic pesticides and heavy metals, which can accumulate in shelf sediments, particularly if the wave energy is low and the shelf dominated by muddy deposition (eg Palanques and Diaz 1994). Other sources which add to this load are marine disposal outfalls and dumping of harbour dredge spoil. As anthropogenic impacts in the coastal zone and catchments are increasing, levels of these contaminants on the shelf are also likely to be increasing, but studies for which published results are available are extremely limited, and are mostly based on isolated (once-off) sampling. Sediments and demersal invertebrates on the shelf off the Tana and Sabaki rivers in Kenya in the early 1990s were not highly contaminated with heavy metals, which were recorded at levels lower than those in other tropical environments (Everaarts and Niuwenhuize 1995). Carter (2006) found metal levels in mud off the Thukela River in South Africa which exceeded toxicity threshold effect levels. Abundance and richness of shelf macrobenthic infauna off Reunion increased with exposure to slight enrichment from industrial effluents rich in organic matter (Bigot and others, 2006). Results of sampling in 2007 and 2008 during the WIO-Lab project (www.unep.org/NairobiConvention/, UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA 2009), albeit conducted mainly at inshore hotspots, indicated (with some qualification) that sediments from Madagascar and Tanzania had average concentrations of some metals which were higher than those suggested in the WIO Environmental Quality Guidelines (UNEP 2009).

CONCLUSIONS

Generally, there are no long-term datasets available for shelf sediments in the WIO which can be used to examine habitat and biodiversity trends. Some of the demersal industrial fisheries described in Chapter 21 may provide long-term biodiversity indices based on monitoring of catches, although these are confined to quite specific localities, are focused only on fisheries' target species, and the fishing itself alters the ecosystem in which it takes place. From a biodiversity perspective, perhaps it is fortunate that most of the soft-sediment shelf in the region does not support fisheries, apart from shallow inshore areas which are readily accessible to small-scale gill and seine nets, and some specific muddy banks harbouring (declining) industrial-scale prawn trawling. This is mainly attributable to the low productivity of the shelf soft sediments in terms of their demersal biomass (Neyman and others, 1973), the low densities making fishing non-viable.

So the main pressures on shelf sediments in the region are in the form of terrigenous pollutants in the vicinity of river mouths, altered nutrient supply as a result of impoundments (reduced riverine input), and the potential disruption of habitats by the extraction of non-renewable resources (heavy minerals and hydrocarbons). Prospecting for the latter has produced extensive data sets on sediment distribution, but these are not readily available to environmental managers. Such information would reveal patterns in sediment type, depth and latitude, information that could be used to assess community patterns. Sediment cores, derived either from prospecting or from independent research, would also provide historical baselines against which to assess changing pressures and drivers, such as levels of pollutants and climate change. However, knowledge of the shelf communities suffers from a lack of the taxonomic capacity required to recognize faunistically distinct regions so as to assist conservation management (Mackie and others, 2005); countries and partnerships in the WIO need to foster such skills by sampling hitherto undescribed habitats and publishing their results.

References

Abuodha, P.A. (2003). Geomorphology of the Kenyan coast: Not as a result of sea-level change alone. *Boletim Geologico, Mozambique* 43, 2-7

Ahamada, S., Bijoux, J., Cauvin, B., Hagan, A., Harris, A., Koonjul, M., Meunier, S. and Quod, J.P. (2008). Status of the Coral Reefs of the South-West Indian Ocean Island States: Comoros, Madagascar, Mauritius, Reunion, Seychelles. In *Status of coral reefs of the world: 2008*. (ed. Wilkinson, C.) pp. 105-118. Townsville, Australia

Alongi, D.M. (1990). The ecology of tropical soft-bottom benthic ecosystems. *Oceanogr. Mar. Biol. Ann. Rev* 28, 381-496

Alvheim, O., Torstensen, E., Fennessy, S.T., Groeneveld, J.C., Mackay, F., Zaera, D. and Bemiasa, J. (2010). *Cruise reports 'Dr. Fridtjof Nansen' West Madagascar*. SWIOFP/ASCLME/FAO Cruise 2, 25 August–3 October 2009. FAO-NORAD Project No.: GCP/INT/003/NOR. Institute of Marine Research, Bergen, Norway

Bianchi, G. (1992). Zonation of demersal fishes of the East Africa continental shelf. A study based on the surveys of the R/V '*Dr. Fridtjof Nansen*'. In *Demersal assemblages of tropical continental shelves. A study based on the data collected through the surveys of the R/V 'Dr. Fridtjof Nansen'*. PhD thesis, University of Bergen, Norway

Bigot, L., Conand, C., Amouroux, J.M., Frouin, P., Bruggemann, H., and Grémare, A. (2006). Effects of industrial outfalls on tropical macrobenthic sediment communities in Reunion Island (Southwest Indian Ocean). *Mar. Pollut. Bull.* 52(8), 865-880

Brinca L., Da Silva, A.J., Sousa, I.M. and Saetre, R. (1983). *A survey on the fish resources at Sofala Bank - Mozambique, September 1982*. Reports on surveys with the R/V Dr Fridtjof Nansen. Institute of Marine Research, Bergen, Norway

Bosman, C., Uken, R., Leuci, R., Smith, A.M. and Sinclair, D. (2007). Shelf sediments off the Thukela River mouth: complex interaction between fluvial and oceanographic processes. *S. Afri. J. Sci.* 103, 490–492

Carter, R. (2006). *Environmental investigation programme to determine potential cumulative effects of outfalls and discharges to sea off the KwaZulu-Natal coast*. Unpublished report prepared for the CoastWatch Project: Wildlife and Environment Society of South Africa

Crame, J.A. (2000). Evolution of taxonomic diversity gradients in the marine realm: evidence from the composition of recent bivalve faunas. *Paleobiology* 26, 188- 214

De Freitas, A.J. (2004). The Penaeoidae of southeast Africa: IV. *The Family Penaeidae: Genus Penaeus*. *Investig. Rep. Oceanogr. Res. Inst.* 59, 1 – 112

Darnaude, A.M., Salen-Picard, C., Polunin, N.V.C. and Harmelin-Vivien, M.L. (2004). Trophodynamic linkage between river runoff and coastal fishery yield elucidated by stable isotope data in the Gulf of Lions (NW Mediterranean). *Oecologia* 138, 325-332

de Lecea, A.M., Fennessy, S.T. and Smit, A.J. (2013). Processes controlling the benthic food web of a mesotrophic bight (KwaZulu-Natal, South Africa) revealed by stable isotope analysis. *Mar. Ecol. Prog. Ser.* 484, 97-114

Dulvy NK, Rogers SI, Jennings S, Stelzenmüller V, Dye SR and Skjoldal HR. (2008). Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *J. App. Ecol.* 45, 1029–1039

Everaarts J.M. and Niuwenhuize J. (1995). Heavy metals in surface sediment and epibenthic macroinvertebrates from the coastal zone and continental slope of Kenya. *Mar. Pollut. Bull.* 31, 281-289

Fennessy, S.T. (in press). Subtropical demersal fish communities on soft sediments in the KwaZulu-Natal Bight, South Africa. *Afri. J. Mar. Sci.*

Fennessy S.T., Mwatha, G.K. and Thiele, W. (eds.) (2004). Report of the regional workshop on approaches to reducing shrimp trawl bycatch in the western Indian Ocean. *FAO Fisheries Report* 734, 58. Mombasa, Kenya

Flemming, B.W. (1981). Factors controlling shelf sediment dispersal along the southeastAfrican continental margin. *Mar. Geol.* 42, 259-277

Flemming, B. and Hay, R. (1988). Sediment distribution and dynamics on the Natal continental shelf. In *Coastal ocean studies off Natal, South Africa*. (ed. Schumann, E.H.) pp. 4780. SpringerVerlag, Berlin

Gaertner, J.C., Mazouni, N., Sabatier, R. and Millet, B. (1999). Spatial structure and habitat associations of demersal assemblages in the Gulf of Lions: a multicompartmental approach. *Mar. Biol.* 135, 199-208

Gattuso, J.P., Gentili, B., Duarte, C.M., Kleypas, J.A., Middelburg, J.J., and Antoine, D. (2006). Light availability in the coastal ocean: impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. *Biogeosciences* 3, 489-513

Gray, J.S. and Elliott, M. (2009). *The ecology of marine sediments: from science to managemen*t. Oxford University Press

Gray, J.S., Poore, G.C.B., Ugland, K.I., Wilson, R.S., Olsgard, F. and Johannessen Ø. (1997). Coastal and deep-sea benthic diversities compared. *Mar. Ecol. Prog. Ser.* 159, 97-103

Green, A.N. (2009a). Sediment dynamics on the narrow, canyon-incised and current swept shelf of the northern KwaZulu-Natal continental shelf, South Africa. *Geo-Mar. Lett.* 29, 201-219

Green, A.N. (2009b). Palaeo-drainage, incised valley fills and transgressive systems tract sedimentation of the northern KwaZulu-Natal continental shelf, South Africa, SW Indian Ocean. *Mar. Geol.* 263, 46-63

Green, A.N. (2011). Submarine canyons associated with alternate sediment starvation and shelf-edge wedge development: northern KwaZulu-Natal continental margin, South Africa. *Mar. Geol.*284, 114-126

Green, A.N., Goff, J.A. and Uken, R. (2007). Geomorphological evidence for upslope canyon-forming processes on the northern KwaZulu-Natal shelf, South Africa. *Geo-Mar. Lett.* 27, 399-409

Green, A.N., Ovechkina, M. and Uken, R. (2008). Nannofossil age constraints on shelf-edge wedge development: implications for continental margin dynamics, northern KwaZulu-Natal, South Africa. *Cont. Shelf Res.* 28, 2442-2449

Green, A.N., Dladla, N.N. and Garlick, G.L. (2013). Spatial and temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa. *Mar. Geol.* 335, 148-161

Green, A.N. and MacKay, C.F. (in press). The role of ravinement in separating relict versus passive sediment populations unconsolidated sediment distribution of the KwaZulu-Natal Bight. *Afri. J. Mar. Sci.*

Gross, G.M. (1972). *Oceanography: A View of the Earth.* Englewood Cliffs: Prentice-Hall, Inc.

Hall, S.J. (2002). The continental shelf benthic ecosystem: current status, agents for change and future prospects. *Environ. Conserv.* 29, 350-374

Hillebrand, H. (2004). Strength, slope and variability of marine latitudinal gradients. *Mar. Ecol. Prog. Ser.* 273, 251–267

IOC, IHO and BODC (2003). *Centenary Edition of the GEBCO Digital Atlas*. Published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans, British Oceanographic Data Centre, Liverpool, U.K

Johnsen, E., Krakstad, J.O., Ostrowski, M., Serigstad, B., Strømme, T., Alvheim, O., Olsen, M., Zaera, D., André, E.R., Dias, N., Sousa, L., Sousa, B., Malauene, B. and Abdula, S. (2008). *Surveys of the living marine resources of Mozambique: Ecosystem survey and special studies*. FAO-NORAD PROJECT NO: GCP/INT/003/NOR27. September – 21 December 2007. Cruise reports "Dr Fridtjof Nansen". Institute of Marine Research, Bergen

Longhurst, A.R. and Pauly, D. (1987). *Ecology of tropical oceans*. Academic Press, Orlando, Florida

Lutjeharms, J.R.E., Valentine, H.R., and van Ballegooyen, R.C. (2000). The hydrography and water masses of the Natal Bight, South Africa. *Cont. Shelf Res.* 20, 1907-1939

MacKay, C.F., Untiedt, C.B. and Hein, L. (in press). Local habitat drivers of macrobenthos on the northern, central and southern KwaZulu-Natal Bight, South *Afri. J. Mar. Sci.*

Mackie, A.S., Oliver, P.G., Darbyshire, T., and Mortimer, K. (2005). Shallow marine benthic invertebrates of the Seychelles Plateau: high diversity in a tropical oligotrophic environment. *Philos. T. Roy. Soc. A.* 363, 203-228

Mengesha, S., Dehairs, F., Elskens, M. and Goeyens, L. (1999). Phytoplanton nitrogen nutrition in the Western Indian Ocean: Ecophysiological adaptations of neritic and oceanic assemblages to ammonium supply. *Estuar. Coast. Shelf S.* 48(5), 589-598

McClurg, T.M. (1988). Benthos of the Natal continental shelf. In *Coastal Ocean studies off Natal, South Africa*. *Lecture notes on coastal and estuarine studies* (ed. Schumann E.H.) No 26, pp. 178-208. Springer-Verlag, Berlin

Munga, C.M., Mwangi, S., Ong'anda, H., Ruwa, R., Manyala, J., Kimani, E. and Vanreusel, A. (in review). Comparing fish bycatch of shrimp trawlers with catches made by artisanal fishers in Malindi-Ungwana Bay, Kenya. *Western Indian Ocean J. Mar. Sci.*

Munga, C.N., Mwangi, S., Ong'anda, H., Ruwa, R., Manyala, J., Groeneveld, J.C. and Vanreusel, A. (2013). Species composition, distribution patterns and population structure of penaeid shrimps in Malindi-Ungwana Bay, Kenya, based on experimental bottom trawl surveys. *Fish. Res.* 147, 93-102

Muthiga, N., Costa, A., Motta, H., Muhando, C., Mwaipopo, R. and Schleyer M.H. (2008). Status of coral reefs in East Africa: Kenya, Tanzania, Mozambique and South Africa. In *Status of coral reefs of the world: 2008*. (ed. Wilkinson, C.) pp. 91-104. Townsville, Australia

Neyman, A.A., N. N. Sokolova, N. G. Vinogradova and F.A. Pasternak. (1973). Some patterns of the distribution of bottom fauna of the Indian Ocean. In *The Biology of the Indian Ocean* (ed. Zeitschel, B.) pp. 467-474. Chapman and Hall, London

Nichols, G. (2009). *Sedimentology and stratigraphy*. 2nd edition. Wiley-Blackwell

Parson, L.M., and Evans, A.J. (2005). Seafloor topography and tectonic elements of the Western Indian Ocean. *Philos. T. Roy. Soc. A.* 363, 15-24

Pauly, D. and Neal, R. (1985). Shrimp vs. fish in Southeast Asian fisheries: the biological, technological and social problems. In *Recursos Pesqueros Potenciales de Mexico: La Pesca Acompanante del Camaron*. Progr. Univ. de Alimentos, Inst. Cienc. del Mar y Limnol., Inst. Nal. de Pesca. pp. 487-510. UNAM, Mexico D.F.

Palanques, A., and Diaz, J.I. (1994). Anthropogenic heavy metal pollution in the sediments of the Barcelona continental shelf (Northwestern Mediterranean). *Mar. Environ. Res.* 1, 17-31

Pinet, P.R. (2009). *Invitation to Oceanography*. Jones and Bartlett Publishers. 5th edition

Puga-Bernabéu, A., Webster, J.M., Beaman, R.J., and Guilbaud, V. (2011). Morphology and controls on the evolution of a mixed carbonate-siliciclastic submarine canyon system, Great Barrier Reef margin, north-eastern Australia. *Mar. Geol.* 289, 100-116

Reiss, H., Degraer, S., Duineveld, G.C.A., Kröncke, I., Aldridge, J., Craeymeersch, J.A., Eggleton, J.D., Hillewaert, H., Lavaleye, M.S.S., Mol,l A., Pohlmann, T., Rachor, E., Robertson, M., Van den Berghe, E., van Hoey, G. and Rees, H.L. (2009). Spatial patterns of infauna, epifauna and demersal fish communities in the North Sea. *ICES Journal of Marine Science* 67, 278-293

Scharler, U., van Ballegooyen, R. and Ayers, M. (in press). A system-wide perspective of the KwaZulu-Natal Bight ecosystem, eastern South Africa. *Afr. J. Mar. Sci.*

Scrutton, R.A. (ed.) (1982). *Dynamics of Passive Margins*. Geodynamics Series vol. 6. American Geophysical Union

Sea Around Us Project – Fisheries, Ecosystems and Biodiversity. *EEZ Waters Of Mozambique*. www.seaaroundus.org/eez/508.aspx Accessed 28 Nov 2014.

Shepard, F.P. (1963). *Submarine Geology*. Harper and Row, New York

Snelgrove, P.V.R. and Butman, C.A. (1994). Animal-sediment relationships revisited: causes versus effects. *Oceanogr. Mar. Biol. Ann. Rev* 32, 111-177

South West Indian Ocean Fisheries Project (SWIOFP). www.swiofp.net

Taylor, J.D. (1997). Diversity and structure of tropical Indo-Pacific benthic communities: relation to regimes of nutrient input. In *Marine biodiversity: patterns and processes* (ed. R.F.G. Ormond, J.D. Gage and M.V. Angel), pp. 178–200. Cambridge University Press

UNEP-GEF (2008). *Transboundary diagnostic analysis of land-based sources and activities in the Western Indian Ocean Region*. UNEP-GEF WIO-LaB Project addressing land based activities in the Western Indian Ocean

UNEP (2009). *Guidelines for the establishment of environmen-*

tal quality objectives and targets in the coastal zone of the western Indian Ocean (WIO) region. WIO-LaB Technical Report Series No. 01/2009, United Nations Environment Programme, Kenya, Nairobi

UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA (2009). *Regional synthesis report on the status of pollution in the western Indian Ocean region*. UNEP, Nairobi, Kenya

United Nations Environment Programme. *Nairobi Convention*. www.unep.org/NairobiConvention/

Untiedt, C.B. and MacKay, C.F. (in press). Macrobenthos distribution and feeding modes within three oceanographic feature areas of the KwaZulu-Natal Bight, South Africa. *Afri. J. Mar. Sci.*

van der Elst, R.P., Groeneveld, J.C., Baloi, A.P., Marsac, F., Katonda, K.I., Ruwa, R. and Lane, W.L. (2009). Nine nations, one ocean: A benchmark appraisal of the South Western Indian Ocean Fisheries Project (2008-2012). *Ocean Coast. Manag.* 52, 258-267