MACROBENTHOS OF THE NORTH WESTERN CONTINENTAL MARGIN (200-1000M) OF INDIA WITH SPECIAL REFERENCE TO POLYCHAETES

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By
Anilkumar P. R.

REG. No. - 3291

DEPARTMENT OF MARINE BIOLOGY, MICROBIOLOGY AND BIOCHEMISTRY
SCHOOL OF MARINE SCIENCES
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
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Author

Anilkumar P. R.

Research Scholar
Department of Marine Biology, Microbiology and Biochemistry
School of Marine Sciences
Cochin University of Science and Technology
Kochi – 682 016

Supervising Guide

Prof. (Dr.) R. Damodaran
Professor (Retd.)
Department of Marine Biology, Microbiology and Biochemistry
School of Marine Sciences
Cochin University of Science and Technology
Kochi – 682 016

July 2017

Dedicated to...

My Wife.....

Declaration

I hereby declare that the thesis entitled **“Macrobenthos of the north western continental margin (200-1000m) of India with special reference to polychaetes”** is a genuine record of research work done by me under the supervision and guidance of **Dr. R. Damodaran**, Retired Professor, Department of Marine Biology, Microbiology and Biochemistry, Cochin University of Science and Technology and no part thereof has been presented for the award of any other degree, diploma or associateship in any University or Institution earlier.

Kochi - 682 016 **Anilkumar P. R.**
July 2017

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I strongly believe that everything happens for a reason, but reasons are unknown at the time of incidence. Only the turning wheels of time have the power to reveal these reasons to us. I thank all the reasons and the creator of all these reasons…the Almighty.

CONTENTS

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ASOMZ	Arabian Sea Oxygen Minimum Zone
CCA	Canonical Correspondence Analysis
CMLRE	Centre for Marine Living Resources & Ecology
CTD	Conductivity – Temperature – Depth
DO	Dissolved Oxygen
EAS	Eastern Arabian Sea
FORVSS	Fishery & Oceanographic Research Vessel *Sagar Sampada*
IIOE	International Indian Ocean Expedition
JGOFS	Joint Global Ocean Flux Studies
mT	Million Tonnes
NEAS	North Eastern Arabian Sea
OC	Organic Carbon
OM	Organic Matter
OMZ	Oxygen Minimum Zone
PCA	Principle Component Analysis
POC	Particulate Organic Carbon
PRIMER	Plymouth Routines in Multivariate Ecological Research
SEAS	South Eastern Arabian Sea
SIM	Spring Inter Monsoon
SM	Summer Monsoon
SST	Sea Surface Temperature
TOC	Total Organic Carbon
WIM	Winter Monsoon

Chapter 1

INTRODUCTION

Contents

1.1 INTRODUCTION

The world's oceans cover 70% of our planet and are home to a wide variety of organisms. The marine ecosystem is the largest on earth and it consists of two dissimilar but mutually dependent provinces: the pelagic, encompassing the water column and benthic, consisting of the sediment matrix. Marine sediments cover the sea floor and forms the single largest ecosystems in terms of area covered (Snelgrove, 1998; Bacci et al., 2009). According to recent estimates, the marine environment harbours 0.7 to 1.0 million species. Among these, 2, 26,000 are currently known and 7, 00,000 are in collections awaiting description (Appeltens et al., 2012a). Marine species are overwhelmingly benthic (98%) rather than pelagic (2%). The benthic province encompasses from intertidal area up to the deepest trenches and its most vital feature is the heterogeneity in environmental features. Hedgepeth (1971) described four major physiographic features of the sea floor as continental shelf (areas with depth <200 m), continental slope (200-2000 m), continental rise (2000-4000 m) and abyssal plain (>4000 m). The continental shelf varies in width from a few to hundreds of kilometres and generally extends to a water depth of 200 m, although it can extend to 500 m depth. The continental slope is the zone of the ocean bottom between the continental shelf and continental rise which is characterized by a sharp gradient in depth over short distances. At the edge of the continental slope, the bottom levels out progressively to form the area designated as continental rise (Fig. 1.1).

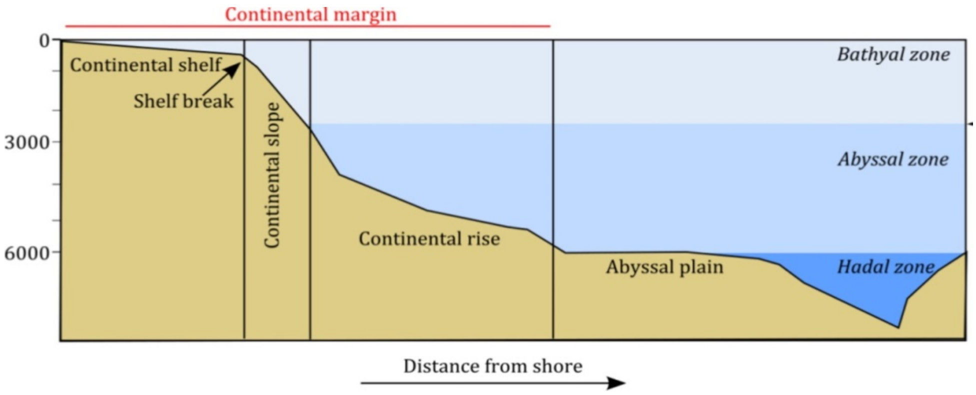


Fig. 1.1 Cross-section of the ocean floor showing physiographic and ecological depth zones. (Based on Thistle, 2003).

The continental margins, which consist of continental shelf, slope and rise, are regarded as the transition between the continents and the ocean. This is relatively a narrow zone (100–4000 m depth) accounting for about 15% of the seabed, and covering three million square kilometers. This region exhibits extreme topographical heterogeneity, sharp environmental gradients and tectonic activity (Levin et al., 2001; Carney, 2005). Continental margins play a key role in global biogeochemical cycles. They provide habitats for diverse faunal communities, thereby contributing significantly to marine biodiversity (Levin et al., 2010; Vanreusel et al., 2010; Levin and Sibuet, 2012) and are considered as one of the potential hot spots of biodiversity (Weaver et al., 2004; Dell'Anno and Danovaro, 2005; Danovaro et al., 2009).

1. 2. Physical environment of the deep sea

The deep sea benthic environment begins at the shelf break, which for most oceanic regions is located around 200 m water depth (Thistle, 2003). The deep sea is characterized by extreme physical properties and such an environment plays a significant role in the life history of its fauna (Gage and Tyler, 1991).

Pressure is one of the chief environmental factor acting on deep sea organisms. For every 10 m depth the hydrostatic pressure increases by 1 atm and therefore at 200 m depth, the hydrostatic pressure is 20 atm. Although most of the deep sea is under pressures between 200 and 600 atm, pressure generally ranges from 20 to 1,000 atm. With the increased depth, deep sea experience much lower temperature. Deep sea water temperatures generally range between -1 °C and 4 °C, with the exception of bottom waters in the Red Sea (up to 21.5 °C) and the Mediterranean (13 °C), as well as near hydrothermal vents. Salinity is more or less constant throughout the depths of the deep sea, except for brine pools and some areas with high evaporation (e. g. the Mediterranean Sea and Red Sea). Currents near the deep seabed are generally slow (< 10 cm s-^{1}) (Thistle, 2003).

In marine ecosystems, oxygen plays a fundamental role in structuring the dispersal patterns of an extensive range of organisms ranging from microbes to marine mammals (Gilly et al., 2013). The surface layers of the ocean usually acquire oxygen from diffusion and mixing from the atmosphere. At high latitudes this water sinks to the ocean floor, supplying oxygen to deep-sea life. Long periods of inaccessibility to the surface with resulting respiration, sluggish circulation and oxygen-poor source waters can reduce dissolved oxygen (DO) concentrations at intermediate depths (Levin 2003). In some of the major oceans, this effect is unusually prominent. Where primary production by photosynthetic life is very high due to processes like upwelling, a vast quantity of organic matter (OM) is generated. The decay of this OM consumes so much oxygen that the mid-water depths show a dramatically low DO levels relative to the water just above or below. All these processes, together with sluggish circulation results in the formation of persistent low-oxygen zones in the oceans called oxygen minimum zones (Helly and Levin, 2004; Fuenzalida et al., 2009; Paulmier & Ruiz-Pino 2009).

This oxygen minimum zone (OMZ) generally occurs at depths about 200 to 1,000 meters, depending on local circumstances. These zones are found world-wide, typically along the western coast of continents.

They are widespread, permanent features in many areas of the Indo-Pacific, eastern Pacific, and eastern South Atlantic (Levin, 2003; Helly and Levin, 2004), and are expanding due to anthropogenic influences (Diaz and Rosenberg, 2008, Stramma et al., 2010). Among the OMZs, those in the Pacific and Indian Oceans are strongest, with oxygen concentration falling between 0.5 mlL^{-1} to zero at the core. In the Atlantic Ocean the DO values are at <45 µmol_kg $^{-1}$, i.e. ~1 mlL^{-1} (Gilly et al., 2013). All OMZs generally exhibit a similar oxygen profiles, but the DO levels, thickness and depth of occurrence may vary regionally (Helly & Levin, 2004). Among the OMZs around the world, the Arabian Sea OMZ is the thickest (1230m) and most intense in terms of mean DO concentrations at the OMZ cores (DO <20 µmol_kg $-^{1}$, Stramma et al., 2010; Acharya and Panigrahi, 2016). Although OMZs are developed in the water column, their effects are experienced strongly at the sea floor (Levin et al., 2000; Devol & Hartnett, 2001). The OMZ core is dominated by a distinctive group of meiofauna and bacteria, and is unfavourable to all but a few hypoxia-tolerant macro and megafaunal species. At upper and lower boundaries of OMZs, relatively oxic conditions support an abundant, progressively more 'normal' benthic community

A number of studies have been carried out on impacts of the OMZs on bathyal macrofauna in the Pacific and Atlantic Oceans, namely Chile margin (Gallardo et al., 2004; Palma et al., 2005; Quiroga et al., 2005; Sellanes et al,. 2007, 2010); Peru margin (Levin et al,. 2002; Gutierrez et al., 2006); off Namibia (Zettler et al., 2009, 2013). Reviews are available, discussing macrobenthic community patterns and diversity across different

OMZs world-wide (Diaz & Rosenberg, 1995; Levin & Gage, 1998 ; Rogers, 2000 ; Levin et al., 2001 ; Gray et al., 2002 ; Levin et al., 2002; Levin, 2003; Levin et al., 2009a ; Gooday et al., 2010 and Levin & Sibuet 2012).

In the Indian Ocean, deep-sea macrobenthos investigations from the Arabian Sea region in relation to the OMZ have been carried out for the Oman margin in the NW Arabian Sea (Levin et al., 2000) and more recently on the Pakistan slope (Gooday et al., 2009; Hughes et al., 2009; Levin et al., 2009b; Murty et al., 2009) and in the shelf region in the eastern Arabian Sea (Ingole et al., 2010; Hunter et al., 2011, 2012; Levin et al., 2013; Joydas & Damodaran, 2014). Although weaker than the Arabian Sea OMZ, the benthos impacted with the OMZ in the Bay of Bengal was described by Raman et al., (2014). Benthic fauna under OMZs have evolved morphological and physiological adaptations to maximize oxygen uptake (Childress & Seibel, 1998; Levin, 2003). There are oxygen thresholds below which most taxa are eliminated through physiological intolerance to hypoxia and above which selected taxa are able to take advantage (Levin et al., 2009a). In the deep sea environments impacted with OMZs the species richness is low and dominance is high (Levin & Gage, 1998; Menot et al., 2010). Also it has been shown that deep-sea macrobenthos indices (abundance, biomass, diversity, size spectra) varied in relation to the OMZ or the bottom-water oxygen concentration (Levin et al., 2000, 2002, 2009b; Gallardo et al., 2004; Palma et al., 2005; Quiroga et al., 2005; Gooday et al., 2009; Hughes et al., 2009; Sellanes et al., 2010; Ingole et al., 2010; Hunter et al., 2011, 2012; Raman et al., 2014). In OMZ settings carnivory is rare or absent among macrofauna (Sperling et al., 2013).

1.3. Food supply to the deep sea

Another characteristic of the deep sea environment is the absence of sunlight. Hence deep sea is generally a heterotrophic system, except for chemosynthetic habitats such as hydrothermal vents and cold seeps. At these locations primary production depends on chemosynthetic bacteria which use hydrogen sulphide and methane to fix carbon (Van Dover, 2000). In the absence of photosynthesis, the deep sea bottom fauna rely on organic matter produced in the euphotic zone that sinks through the water column and ends up at the seafloor (Rowe and Staresinic, 1979; Gage and Tyler, 1991). The processes that relate to the transport of organic matter produced in the sun-lit waters to the seafloor are collectively termed “the biological pump” (Ducklow et al., 2001). The particulate organic matter (POM) that is exported from the euphotic zone comprises phyto and zoodetritus, in addition to bacteria, protists, faecal pellets and inorganic compounds (Gage, 2003). The efficiency of the biological pump (i.e. amount produced vs. amount transported) varies substantially between geographic regions (Lutz et al., 2002; Buesseler et al., 2007) and seasons (Lutz et al., 2007). The amount of POM that ultimately ends up at the deep sea floor depends on water depth, sinking velocity and decomposition rate of the POM particles (De La Rocha and Passow, 2007). The biological pump is inefficient in deep sea, since on an average only 0.5 - 2 % of surface primary production reaches the deep sea floor (Lutz et al., 2002; Buesseler et al., 2007), making this an energy deprived environment.

The quantity and quality of settling organic matter is the most important determinant of the standing stock and composition of the deep sea benthos (Ruhl and Smith, 2004; Wei et al., 2010). The continental slope environment has been acknowledged to be a site of remineralization and burial of huge quantities of organic carbon (Premuzic et al., 1982; Walsh et al., 1985). The impact of pelagic processes, such as primary productivity and the resulting sedimentation on the benthic ecosystem and vice versa is designated as benthic-pelagic coupling. Sedimentation events have been shown to affect the organisms associated with deep sea sediments, manifested as enhanced biomass or metabolic activity (Danovaro et al., 1999; Pfannkuche et al., 1999; Sommer and Pfannkuche, 2000; Brown et al., 2001), or shifts in the vertical distribution within the sediment column (Shimanaga et al., 2000; Sommer and Pfannkuche, 2000; Veit-Kohler et al., 2011).

1.4. Deep sea biodiversity

The biodiversity of marine life is probably as great as or greater than, that found on land, but is far less well documented. At the phylum level, marine biodiversity is twice as that of the land's; of the 33 described phyla, 13 are known only from marine environments (May, 1988). Important phyla such as echinoderms, ctenophores, chaetognaths, pogonophores and brachiopods are exclusively marine. High diversity on continental margins has been recognized since the 1960s (Hessler and Sanders, 1967). In the past few decades, considerable attention has been given to the study of continental margin biodiversity (Flach and Thomsen, 1998; Tselepides et al., 2000; Palma et al., 2005; Gooday et al., 2009;

Hughes et al., 2009; Sellanes et al., 2010, Ingole et al., 2010; Abdul Jaleel et al., 2014; Joydas & Damodaran, 2014; Raman et al., 2014; Abdul Jaleel et al., 2015). A number of environmental factors can influence benthic community patterns (Carney, 2005). Biological diversity or biodiversity can be characterized at various organizational levels, namely genotypes, taxa and functional groups. Generally, biodiversity is determined as the number of taxa (i.e. taxon richness), mostly assessed at the species level, that are living in a given area. As a consequence of limited sampling effort, the total number of species inhabiting this planet and its oceans is a big unknown. Knowledge of the biological communities associated with locally restricted habitats in the deep sea has significantly increased during the last decade (Levin et al., 2001; Vanreusal et al., 2010).

1.5. Benthos

The fauna found living at the sea floor can be classified into two major groups according to the areas they customarily inhabit - benthic and benthopelagic fauna. The benthic fauna (benthos) are the organisms found living on or within the seabed either for feeding, breeding or for resting at any time during their life history. The benthopelagic fauna are those organisms found living in the water column immediately above the sea bed. The term benthos was coined by Haeckel, adapting from the Greek which stands for ‘depths of the sea’. The investigations on benthic community date back to the middle of the eighteenth century and one of the pioneers to study benthos was Carl von Linnaeus (1707-1778). All the earliest studies on benthos were focused only on the qualitative aspects, i.e., the list of species inhabiting on or in a given type of bottom. It was

John Peterson (Peterson, 1911; 1913; 1918) who first categorised animal communities of sea bottom as epifauna and infauna. He also made first quantitative approach to benthic studies and expressed the number of individuals and weight of benthos per unit of area.

Benthos comprises an enormous variety of organisms. For convenience, benthos has been classified into several somewhat overlapping categories based on habitat, individual size, and taxonomy. All these classifications are arbitrary and vary according to authors (Thiel, 1975). Based on the habitat, benthic organisms could be divided into two major groups namely soft-bottom benthos and hard-bottom benthos. Soft-sediment habitats are common in coastal areas throughout the world, but only a small fraction of the macrobenthos that resides on or buried in sediments has been described (Snelgrove et al., 1997; Snelgrove, 1999). Three functional groups of benthos could be recognised. They are the infauna, epifauna and hyper-benthos, i.e. organisms living within the substratum, on the surface of the substratum and just above it (Pohle and Thomas, 2001). Depending on the size benthos has been classified into macrobenthos - all organisms having a size larger than 0.5mm; meiobenthos – all organisms within a size range from 0.063 mm to 0.5mm; microbenthos – all organisms having a size smaller than 0.063mm. This classification purely depends on the mesh size of the sieves used to separate them. The smallest of all size group, microbenthos, includes those organisms that are not retained in the finest sieve used (63µm) for meiobenthos separation which includes bacteria and most protozoans. For meiobenthos, the lowest size credited is 63µm and the upper limit depends upon the mesh size of the sieve used for separating macrobenthos from meiobenthos. Taxonomically, it is made up of crustaceans such as ostracods and harpacticoid copepods; pseudocoelomate phyla, especially nematodes, and to a lesser extent gastrotrichs and kinorhynchs; and smaller representatives of phyla that are usually thought of as constituents of the macrofauna (Fenchel, 1978). The foraminiferans are sometimes considered to belonging meiofauna but even though single celled they are repeatedly as large as macrofaunal species and often treated as a distinct assemblage (Buzas and Gibson, 1969; Lagoe, 1976). The fraction considered to be the macrofauna is made up of smaller metazoan animals representing most of the typical marine invertebrate phyla (Sanders and Hessler, 1965), retained on a 500 µm sieve during processing of samples, although in recent years, the use of 300 µm sieves (instead of 500 µm) is also becoming popular. Macrofaunal taxa in the deep sea are less abundant than in shallow water and thus a smaller mesh size is needed to compensate for the decreased density (Bett, 2013; 2014). Important taxonomic groups represented among macrofauna are the polychaetes, crustaceans and molluscs, along with echinoderms and other minor phyla such as echuroids, sipunculids etc. Among these, annelid worms are the most abundant and represented by numerous tube-building and burrowing species. The dominant crustacean fauna include amphipods, isopods, tanaids, mysids, ostracods and a few small-sized decapods. Molluscs are chiefly represented by a variety of burrowing bivalves and a few gastropods that live in or at the surface. Phylum Echinodermata represented by brittle stars, sand dollars, sea cucumbers, starfishes and heart urchins.

1. 5.1. Significance of benthos

Benthic production is of key importance when assessing biological productivity in aquatic environments, as they contribute to secondary production and to sustain demersal fishery. Benthos are important in channeling nutrients from microscopic producers and consumers to larger consumers. Most of the macrofauna are detritivores (either suspension or deposit feeders) and feed upon the organic material raining down from the upper euphotic zone (Carlson et al., 1997; Snelgrove, 1998). The burrowing activities of benthic animals results in repacking of sediments with increased sediment oxygenation, through bioturbation. Moreover, benthos form a source of nourishment for many commercially important demersal fishes and also secondarily influences the availability of food for pelagic forms, since many benthic organisms, particularly macrofauna, spend part of their lifecycle usually as eggs and larvae, although some adult benthic organisms migrate seasonally or daily into the water to spawn or to feed (Armonies, 1988; 1994).

1. 6. Background of the study

Owing to the early studies in the Aegean Sea, which was faunistically very poor, the deep sea was thought to be 'azoic' beyond 300 fathoms (~550m), and this led to the postulation of the 'azoic theory' by Forbes (1844). This was later disproved by a telegraph cable-laying industry, which resulted in an international race to sample to the greatest depths of the ocean (Mills, 1983). Later, the HMS *Challenger* expedition (1872-1876) led directly to the 'heroic' age of deep-sea exploration, withexpeditions covering many areas of the world's oceans (Menzies et al., 1973; Mills, 1983). The true extent of deep-sea biodiversity became evident when Sanders et al. (1965) studied benthic communities along a transect between southern New England and the Bermuda Islands. They were more diverse on the middle of the continental slope rather than on the shelf or the abyss (Sanders, 1968; Rex, 1981). Over the past 50 years advancements in marine technology have improved our perception about deep sea habitats. From the beginning of serious deep-sea exploration in late 1860s until the mid-1960s, benthic species diversity was generally believed to be much lower in the deep sea (Ekman, 1953; Marshall, 1954; Bruun, 1957).Before 1960s, most deep-sea sampling was conducted using coarse-mesh trawls and dredges yielding low numbers of species and individuals (Mills, 1983). Perhaps the most theoretically important and unexpected result to emerge from deep-sea exploration was its unusually high species diversity (Hessler and Sanders, 1967). Hessler and Sanders, 1967 initiated a persistent fascination with the quantification and explanation of high local diversity in the deep sea. With the introduction of new sampling equipment, the deep sea floor is now proven to harbour some of the highest levels of local species diversity (Hessler and Sanders, 1967; Sanders, 1968; Sanders and Hessler, 1969; Rex, 1983; Grassle, 1989; Grassle and Maciolek, 1992; Rex et al., 1997; Gooday et al., 1998; Paterson et al., 1998; Snelgrove and Smith, 2002; Stuart et al., 2003; Mendez, 2007; Ingole et al., 2010; Rex and Etter, 2010; Abdul Jaleel et al., 2014). Analyses of macrofaunal species composition for 146 quantitative box core samples collected from depths of 600–3500m between Cape Hatteras and Charleston Bump yielded 1300 species, of which over 30% were new to science (Hilbig, 1994). However it is still ambiguous whether or not deep-sea diversity actually exceeds that of shallow-water regions (Gray, 1994; McClain and Schlacher, 2015).

Local diversity within deep sea sediments is not spatially uniform but varies amongst and within oceanographic basins. There are two assumed large-scale (macro-ecological) geographic gradients in benthic biodiversity: (i) a latitudinal gradient of decreasing alpha diversity from the equator to the poles (Rex, 1981; Rex et al., 1993; 2000; Rex and Etter, 2010) and (ii) a parabolic bathymetric gradients of alpha diversity (Paterson and Lambshead, 1995). Several deep sea taxa become more species rich with decreasing latitude; evidence for this pattern in the southern hemisphere is less convincing (Culver and Buzas, 2000; Brandt et al., 2007). Both evolutionary and ecological processes (mainly nutrient input) have been proposed as potential causes of the latitudinal diversity gradient (Stuart et al., 2003). The latitudinal diversity gradient is more pronounced in the Atlantic especially in the north than the south. The pole-ward decrease in species richness has been observed from gastropods, isopod and bivalves in the North Atlantic (Rex et al., 1993; Rex et al., 2000; Rex and Etter, 2010) and for benthic foraminifera in the North and South Atlantic (Culver and Buzas, 2000). Cumaceans also displayed a peak in diversity at the equator in samples from the North and South Atlantic (Gage et al., 2004). Conversely, benthic nematodes did not appear to display a pole-ward decrease in diversity (Lambshead et al., 2000).

In addition to a monotonic latitudinal gradient, marine biodiversity often displays a unimodal bathymetric trend with a peak at the mid to lower continental slope (reviewed by Rex and Etter, 2010). In a remarkable comparative study, Sanders (1968) showed that contrary to general belief, benthic diversity (in this case polychaetes and bivalves) increased with depth from shallow coastal areas to 2000m, the limit of his study, reaching levels comparable to that found in tropical soft bottom communities at subtidal depths. Rex (1973; 1976) subsequently found that the diversity of gastropods also increased from shelf to bathyal depths, but then decreased markedly with increasing distance out onto the abyssal plain. This parabolic depth pattern is particularly well established in the North Atlantic, with peaks at intermediate bathyal depths and reduced levels of diversity at upper bathyal and abyssal depths (Rex, 1981; 1983; Maciolek et al., 1987; Etter and Grassle, 1992; Paterson and Lambshead, 1995; Levin et al., 2001; Rex and Etter, 2010). However, this pattern is not universal for all regions or all taxa of the deep sea, and the depth at which this peak occurs varies between taxa (Rex et al., 1997; Bett, 2001; Stuart et al., 2003; Rex and Etter, 2010). Rowe et al. (1982) reported a macrofaunal diversity peak at around 3000 m in the Northwest Atlantic, whereas Etter and Grassle (1992) reported a diversity peak between 1200 m and 1500 m in the same region. Rex (1983) reported that the diversity peak was located at around 2000 m for polychaetes but around 3000 m for other taxa (gastropods, protobranchia and cumaceans) in the Northwest Atlantic. In the Northeast Atlantic, there is evidence for a diversity peak for polychaetes at 1500 m (Paterson and Lambshead, 1995), although Bett (2001) recorded a diversity peak at 400 m for macrofauna and Gage et al., (2000) failed to find clear evidence for a peak in macrofaunal diversity at 1400 m in this region.

Many studies conducted around the world reveal that benthic abundance and biomass decreases with distance from land and with depth, reflecting the fact that these metrics are positively correlated with food availability Thiel, 1975; Rowe, 1991; Smith and Demopoulos, 2003; Johnson et al., 2007; Wei et al., 2010), since the amount of food reaching the ocean floor decreases with increasing depth. Indeed, abyssal macrofaunal density is very low (10s -100s individuals m^{-2}) (McClain et al., 2009; Wei et al., 2010). However, this decline is not uniform (Gage, 2003) and regions with high productivity is an exception to this since such areas show elevated abundance and biomass, regardless of their depth (Rex and Etter, 2010). Further north in the Faroe-Shetland Channel, Narayanaswamy et al., (2005; 2010) reported an increase infaunal biomass with depth, contrary to other such studies; while diversity exhibited a parabolic pattern, with a maximum at 350-550m. Rowe et al., (1982) observed that, on the margin off New England, densities and biomass of macrofauna (>420 mm) showed significant declines with increasing water depth. In the northern Bay of Biscay (2100–4100 m) macrofaunal densities decreased exponentially with increasing bathymetric depth, but they also showed substantial seasonal and interannual fluctuation (Dinet et al., 1985). (Dinet et al., 1985). The average body size of deep sea benthos decreases with depth and the ocean-floor benthos tends to be dominated by small organisms to a greater extent than in shallow water.

In India, majority of the benthic studies have been carried out on the shelf and inshore areas. The major efforts in studying the benthos of the

Indian subcontinent began with the work of Annandale (1907). In comparison with the Bay of Bengal, the Arabian Sea has been extensively studied covering various aspects, and it was concluded that the Bay of Bengal is less productive than the Arabian Sea (Nair and Pillai, 1983). Seshappa (1953) and Kurian (1953) were the earliest to carry out a detailed study on the bottom fauna off Malabar and Travancore coasts on the west coast of India. Following them, a number of isolated investigations were carried out on shallow water benthos of the country (Ganapati and Lakshmana Rao, 1959; Radhakrishna and Ganapati, 1969;1971; Damodaran, 1973; Parulekar, 1973; Parulekar and Wagh, 1975; Parulekar et al., 1976; 1982; Ansari, et al., 1977a; 1977b; 1982; Harkantra et al., 1980; 1982; Ansari and Parulekar, 1981; Parulekar and Ansari, 1981; Rodrigues et al., 1982; Raman and Adiseshasai, 1989; Adiseshasai, 1992; Ansari et al., 1996; Raut, 1997;Joyadas, 2002; Vijayakumaran, 2003; Ingole and Koslow 2005; Ingole et al., 2005; Raut et al., 2005; Pavithran et al., 2007). The diversity, distribution, abundance and community structure of macrobenthos in relation to the environmental influences on them are described by various workers from the west coast of India (Jayaraj et al., 2007; 2008a, b; Joydas and Damodaran, 2009; Joydas et al., 2009; Musale and Desai, 2010; Smitha, 2011; Abdul Jaleel et al., 2014; Joydas and Damodaran, 2014; Abdul Jaleel et al., 2015). Of these, the studies carried out by Joydas and Damodaran (2009), Abdul Jaleel (2012) and Abdul Jaleel et al. (2014) is most comprehensive, covering varying depths (30m to 1000m), along as many as 17 transects between Dwaraka (23° N) and Cape Comerin (7° N). The main objective of these studies was to elucidate distribution patterns and standing crop of benthos in shelf and slope region, their species richness and diversity and relate these to the prevailing environmental conditions.

Deep sea benthic fauna of Arabian Sea were collected during the voyages of the RIMS *Investigator* I and II between years 1885 and 1925 (reviewed in Gage et al., 2000). Benthic samples of the John Murray Expedition (1933-1934) evinced a more or less azoic zone between 100-1200m depth along the western continental margin of the Arabian Sea (Sewell 1934a, b, reviewed in Gage et al., 2000). Later, the International Indian Ocean Expedition, IIOE (1962-65) reported high standing crop in the deep Arabian Sea (Neyman et al., 1973). The pattern of seasonal upwelling and non-stationary eddies resulting in replenishment of nutrients was suggested as the reason for this peak in standing crop (Gage et al., 2000). In the past two decades, considerable attention has been given to the oxygen and organic matter availability, as well as sediment characteristics on benthic communities of the Arabian Sea continental margins (Lamont and Gage, 2000; Levin et al., 2000; Cowie and Levin, 2009; Gooday et al., 2009; Hughes et al., 2009; Levin et al., 2009; Hunter et al., 2011; 2012; Levin et al., 2013; Joydas and Damodaran, 2014; Abdul Jaleel et al., 2014).

Levin et al. (2000), investigated macrobenthic community structure within and beneath the OMZ in the eastern Arabian Sea (Oman margin). The study dealt with macrofaunal abundance, biomass, body size, taxonomic composition, diversity and lifestyles with respect to various environmental conditions. They reported that the OMZ was dominated by soft bodied surface deposit feeding polychaetes (86-99% of macrofauna). Lamont and

Gage (2000) observed varying morphological adaptations of polychaete species, in response to the low dissolved oxygen in the Oman margin. The major adaptations included enlargement in size and branching of branchiae to increase respiratory area, as observed in spionids and cossurids. In the Pakistan margin (eastern Arabia Sea), the intensity and magnitude of the permanent OMZ varies with season with the shoaling of upper OMZ boundary during the southwest monsoon. This results in the expansion of the OMZ to regions at ~140m depth. With the availability and quality of organic matter, as well as with the oxygen concentrations, a drastic change in benthic taxonomic composition and community structure is reported to happen in the lower OMZ boundary (Cowie and Levin, 2009). While analysing faunal responses of foraminiferans, macrofauna and megafauna, Gooday et al., (2009) found depressed species diversity along the OMZ core, and that this was more pronounced for macrofauna and megafauna than for foraminiferans. In the OMZ impinged Pakistan margin between 700-1100m depth, Levin et al., (2009) suggested that among the various environmental parameters, food availability is understood to greatly influence the faunal abundance; while oxygen and organic matter influence the pattern of diversity and dominance. The density of polychaetes was low in the Pakistan margin as reported from Oman (Hughes et al., 2009). The qualitative and quantitative pattern in distribution of macrofauna over a broad bathymetric transect (30m to 2545m) was studied by Ingole et al., (2010). Information on deep sea benthos from the other parts, chiefly around the central Indian Ocean is also available (Ingole, 2003; Ingole and Koslow, 2005; Ingole et al., 2005; Pavithran et al., 2007). In recent years, fishery activities have been extended towards deeper areas of the sea due to the advancements in modern sampling and processing techniques. Besides fishery activity, many parts of the deep sea are under pressure of mining and extraction for many of its resources. Impacts of such anthropogenic activities can be properly studied only if baseline information is available on the fauna and the relation of faunal diversity to various forms and scales of habitat heterogeneity (Menot et al., 2010). From the Indian subcontinent, information on the faunal associations of benthos with respect to polychaetes and free living nematodes at a community level of organization vis-à-vis abiotic factors that regulate species composition, abundance or their diversity from the shelf region is available (Sajan, 2003; Joydas and Damodaran 2014). Detailed study of benthos, with emphasis on the polychaete fauna of continental margin beyond 200 m in the South Eastern Arabian Sea (SEAS) with systematic and repeated sampling have been carried out by Abdul Jaleel et al., 2014. But the information on the benthos from the continental slope region of NEAS is scarce. There is a dearth of data on benthic faunal associations of continental margin beyond 200 m in the North Eastern Arabian Sea (NEAS) with consistent and repeated sampling. The present study is an attempt to generate baseline information on quantitative and qualitative aspects of macrobenthos of the NEAS continental margin (200–1000 m) and its relationship with environment. This is the first systematic attempt of its kind for the area.

1. 7. Objectives

The main objectives of the present study are:

- To estimate the standing crop of macrobenthos of north eastern Arabian Sea continental margin (from 200 to 1000m) with its spatio-temporal variations
- To study the qualitative and quantitative composition of macrobenthos along the study area
- To understand the community structure of polychaetes in relation to the hydrographical parameters and sediment characteristics
- To study impact of the Arabian Sea OMZ on macrobenthic communities along the NEAS continental margin

The study is a part of effort of the project "Benthic fauna of continental slope from 200-1000m depths of Arabian sea and Bay of Bengal" funded by the Centre for Marine Living Resources and Ecology (CMLRE), Ministry of Earth Science, Government of India, to gain information on the marine benthos in the Exclusive Economic Zone (EEZ) of India.

Chapter 2

MATERIALS AND METHODS

Contents

2. 1. Study area

The study area was located on the continental slope region off west coast of India in the Eastern Arabian Sea. The **Arabian Sea** is a small region of the north-western Indian Ocean bounded on the east by India, on the north by Pakistan and Iran, on the west by the Arabian Peninsula, on the south, approximately, by a line running from the South extremity of Addu Atoll (Maldives), to the Eastern extreme of Ràs Hafun (Africa, 10°26'N). It lies between 8 to 24ºN lattitudes and 50 to 77ºE longitudes. The shelf area off Arabian Sea is quite extensive with maximum width of 160 kms in the north (Mumbai) and minimum width of 48 kms off Cranganore (Kerala). The gradient along the shelf is gradual and low (0.50). The area (>40m) is characterised by silt and clay deposits and rich in organic matter (Nair and Pylee, 1968). The shelf break in the eastern Arabian Sea region occurs between 80 and 110 m. The sediments along the shelf edge are largely composed of foraminiferan tests or globigerina oozes.

The Arabian Sea, with an area of 6.2×10^6 km, covers about 1% of the global ocean surface. However, approximately 5% of the global phytoplankton production is concentrated in this area. The Arabian Sea is deeper than 3000 m in many places (max. depth 4652 m), and the basin is more or less enclosed in the south by the Central Indian Ridge, the Carlsberg Ridge, and the Chagos–Laccadive (or Maldive) Ridge. Therefore, bottom water enters the basin from the west, through the Owen Fracture Zone, rather than from the south (Tomczak and Godfrey, 1994). Terrigenous (i.e., land-derived) deposits cover the major part of the continental slope to a depth of about 2,700 m. Below this, deposits consists of biogenous origin (E.g. calcareous as well as radiolarian oozes) while basins below 4,000 metres are covered by red clay. The eastern Arabian Sea is characterised by intense coastal upwelling during the southwest monsoon, along with reversed circulation and mixed layer deepening during the northeast monsoon (Qasim 1977; 1982). The seasonal upwelling, which results in high surface productivity and transport of increased particle flux from the euphotic zone (Qasim, 1977; 1982; Sen Gupta and Naqvi, 1984). For the northern and western Arabian Sea, a very high mean annual particulate organic carbon fluxes into the deep ocean have been described (Witte, 2000). The high organic production and limited sources of water replenishment result in rapid utilization of oxygen and development of an intense and unusually deep oxygen minimum layer in the water column between depths of 100m and 1300 m, where oxygen concentrations are <0.5ml $^{-1}$ (Wyrtki, 1973; Qasim, 1982; Helly and Levin, 2004). Such a hypoxic layer at intermediate depths has significant consequences for the quantity and quality of organic matter reaching the deep sea from the water column**.** This results in settling of unrecycled organic matter (Angel, 1984; Cowie, 2005). Thus, an enhanced flux of labile organic material is delivered to the deep sea benthic boundary. In regions where OMZ is in contact with the sediments of the continental margin, they have a profound impact on the distribution and biomass of bottom living organisms. When considering the vertical flux and processes that occur in the benthic boundary layer and within the surface sediments, the Arabian Sea continental margin and its surface sediments have greatest importance (Walsh, 1991; Naqvi and Jayakumar, 2000; Cowie, 2005).

2. 2. Sampling locations

For sampling of benthos, the 7 transects were determined along the NEAS (Goa, Ratnagiri, Dabhol, Mumbai 1, Mumbai 2, Veraval and Porbandar – designated as T1 to T7), with 3 sites representing 200m, 500m and 1000m depths in each transect in three surveys (*in toto* 63 stations, 21 sites). The geographical position of the sampling stations fixed between latitude 15°25'N- 21°30'N and longitude 67°28'E- 77°15'E. The geographical positions of the 21 sites are given in Table 2.1 and Figure 2.1. Stations sampled in the continental slope of Arabian Sea (from South to North) with depths and geographic positions.

Table 2.1: Details of the sampling location

Name of the transect	Station No	Depth (m)	Latitude (N)	Longitude (E)
Goa (T1)	1	200	15 25’	72 48’
	2	500	15 25’	72 39’
	3	1000	15 25’	72 31’
Ratnagiri (T2)	4	200	16 18’	72 25’
	5	500	16 18’	72 14’
	6	1000	16 18’	72 04’
Dabhol (T3)	7	200	17 24’	71 20’
	8	500	17 24’	71 12’
	9	1000	17 24’	71 08’
Mumbai 1 (T4)	10	200	18 30’	70 26’
	11	500	18 30’	70 14’
	12	1000	18 30’	70 06’
Mumbai 2 (T5)	13	200	19 34’	69 48’
	14	500	19 34’	69 27’
	15	1000	19 34’	69 22’
Veraval (T6)	16	200	20 30’	69 43’
	17	500	20 30’	69 31’
	18	1000	20 30’	69 19’
Porbandar (T7)	19	200	21 30’	68 00’
	20	500	21 30’	67 42’
	21	1000	21 30’	67 28’

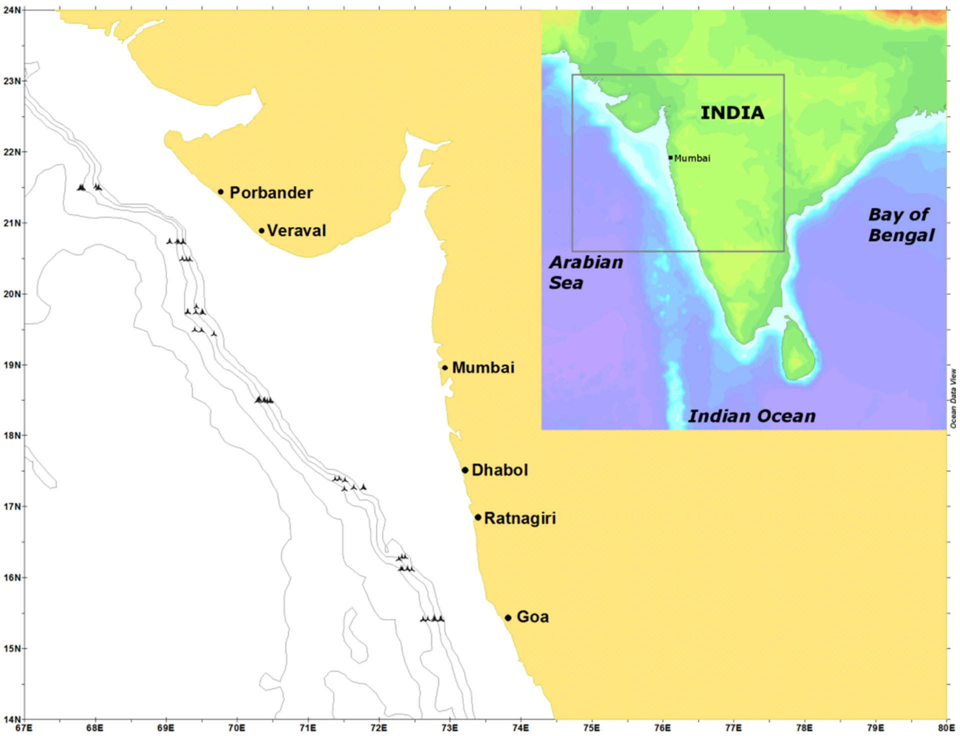


Fig 2.1. Map showing locations of sampling

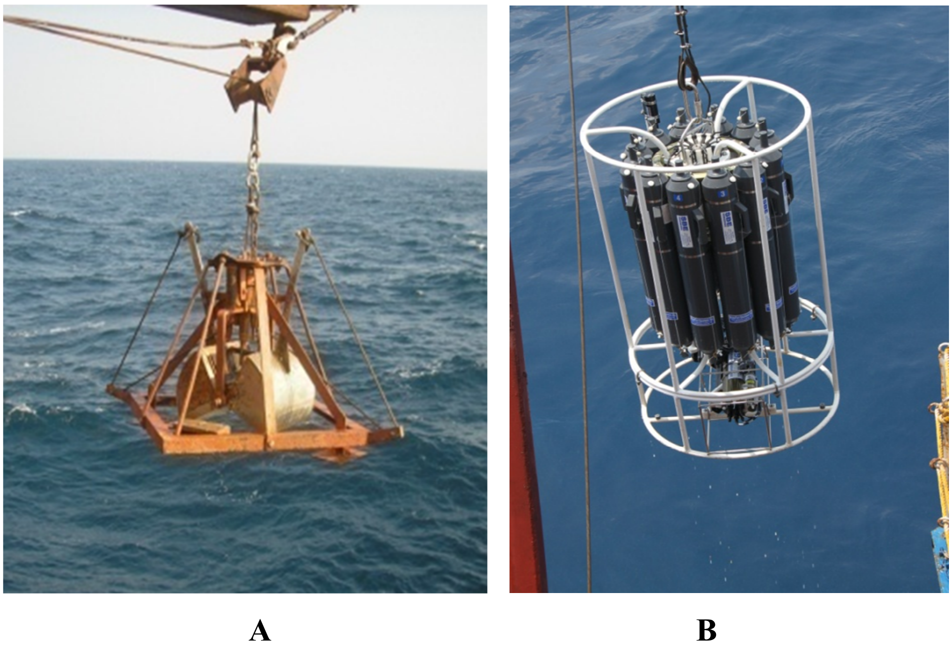
2. 3. Methodology

2.3.1 *Sample collection*

Three dedicated cruises (Cruise No.219, Cruise No. 228 and Cruise No. 254) were carried out onboard (Fisheries and Oceanographic Research Vessel) FORV *Sagar Sampada* India for collecting sediment samples for the present study on the Macrobenthos, as part of the project 'Studies on Benthic Fauna of Continental slope from 200-1000m depths of Arabian Sea and Bay of Bengal'. A modified version of Smith McIntyre grab having a bite area of $0.2m^2$ (Fig. 2.2 A) for deep sea sampling was used for the collection. Sediment samples from three different pre determined depth ranges (200, 500 and 1000 m) of respective transect was obtained.

Each transect was situated every one degree latitude apart. Sea-Bird CTD (Fig.2.2.B) was used for procuring hydrographical parameters such as temperature and salinity whilst Winkler's method was used for estimating oxygen onboard in the lab. Immediately after the grab hauling the undisturbed nature of sample was ascertained. Replicate sampling was made from different grab haulings of each station.

A test sieve of 0.5 mm mesh was used for separating macrobenthos and sieving was carried out onboard over a wooden platform under gently running sea water flow. After sieving, the organisms were carefully separated and together with residual sediment were fixed in 5-7% (neutral) formaldehyde containing Rose Bengal stain, labelled and stored for further examination



A **B**

Fig 2.2. A. Modified Smith McIntyre Grab; B. CTD Rosette

2. 3. 2. *Analysis of biological samples*

In the shore laboratory, the sediments were washed again under tap water and the material preserved in 5% formaldehyde. For qualitative enumeration, each sample was examined under a binocular microscope. The organisms were separated into different taxonomic groups (polychaetes, crustaceans, molluscs and other groups) for further identification. Polychaetes were identified up to species level as this group was dominant among the macrobenthos. Primarily, the keys of Fauvel (1953) and Day (1967) were used for the identification, supplemented with more recent taxonomic publications (e.g. Fauchald, 1977; Maciolek, 1985; Imajima 1990a-c; 1992a, b). Validity and taxonomic status of species were also checked and updated from the World Register of Marine Species (WoRMS, www.marinespecies.org). Other groups were identified to higher taxonomic levels to the extent possible, with the help of standard taxonomic references and available expertise. Prior to identification, wet weight of each group was determined by using a high precision electronic balance (SartoriusAG–ME215P, with a precision of 0.01 mg). Each sample was properly labelled and transported to shore laboratory for further analysis. Samples for the analysis of sediment properties such as texture and organic matter content were also obtained from each station from the same grab sample. Approximately 250 g of wet sediment from each station was taken for this purpose and it was oven dried at 60° C overnight.

2.3.3. *Textural Analysis*.

At the shore laboratory the samples were subjected to sediment particle size analysis using a particle size analyzer(Sympatec, Germany).

The percentage of each grade (sand, silt, clay) was calculated and plotted on ternary graphs based on the nomenclature suggested by Sheppard (1954).

2.3.4. *Estimation of Organic matter content*

During the study, organic matter was estimated by the wet oxidation method of El Wakeel and Riley (1957). Organic matter was expressed as % of sediment dry weight examined.

2. 3. 5. *Data Analysis*

Various diversity indices are widely used in ecology for comparison of communities on spatial and temporal scales as well as for the assessment of environmental quality. The discriminating ability of diversity indices vary, depending on the type of study being conducted and on other aspects of the samples. For the analysis of diversity and community structure, different approaches were adopted in this study, which include univariate (species richness, Shannon-Wiener diversity, species dominance and evenness), multivariate (Multi-Dimensional Scaling) and graphical (species area plots, k-dominance curves, Canonical Correspondence Analyses etc.). In the present study, statistical software PRIMER 5 & 6 (Plymouth Routines in Multivariate Ecological Research), SPSS 17, PAST (Paleontological STatistics) software, and ORIGIN 8 was used for the data analysis and representation.

In order to determine whether the number of species collected over the whole study is adequate to describe the species composition of the area, a species accumulation plot (PRIMER 5) was used, which plots the cumulative number of species against the cumulative number of samples (grabs). Various species estimators (such as CHAO1, CHAO2, Jacknife, UGE, SOBS etc., available in PRIMER 6) were used to predict the true number of species that would be observed as the number of samples tend to be infinity. Univariate diversity indices such as species richness (Margalef's index, d), Species equitability (Pielou's index, J'), species diversity (Shannon- Wiener index, H') and species dominance (Simpson's index, λ') were worked out for polychaetes using PRIMER 6. The aim of these statistical indices is to reduce multivariate complexity of species assemblage data into a single index. Species richness is a count of the number of species represented in a fixed number of individuals. Species equitability or evenness shows how evenly the individuals are distributed among the different species and species dominance shows the dominance of particular species among a given number of individuals. Species diversity index takes into account the number of species in a sample and also their relative abundance. The index is high in samples that have large numbers of unique species, or have greater species evenness.

Bray-Curtis similarity (PRIMER 6) was calculated with suitable transformation (square root) for the species-abundance data to group the samples with similar community composition following the procedure described by Clarke and Warwick (1994). Bray-Curtis similarity index and group average linkage were used for cluster analysis and non-metric multi-dimensional scaling (nMDS) ordination (Ludwig and Reynolds, 1988). To compare the biodiversity between the depth ranges, dominance plots (in

PRIMER 6) were drawn by ranking the species in decreasing order of their abundance. Relative abundance expressed as ‘percentage of abundance’ in the sample was plotted against the increasing rank in the x-axis, the latter on a log scale.

A Principal component analysis (PCA) was also conducted on environmental data to detect trends of variation of environmental characteristics across the study area. This analysis also uses an ordination plot to project the points of greater similarities closer together while samples more dissimilar are further apart. Unlike biological data, environmental data usually have mixed measurement scales, and similarity methods, such as normalized euclidean distance used in PCA, are more appropriate for environmental data (Clarke and Warwick, 2001). A useful exercise before conducting PCA is to examine the environmental data in a draftsman scatter plot to ascertain whether there are variables that are highly correlated with one another, which may then be omitted from the PCA. The BVSTEP routine (PRIMER 6) was performed to identify the influential species in the study area, which determine the patterns in the community structure. It involves stepwise algorithm which operates sequentially in both forward and backward-stepping phases. At each stage, a selection was made of the single best species to add to or drop from the existing selected set. Typically this procedure started with a null set, picked the best single variable (maximizing ρ), then adding a second variable which gave the best combination with the first, then adding a third to the existing pair. The backward elimination phase then intervened, to check whether the first selected variable can be dropped, the combination of second and third selections alone not having been considered before. The algorithm proceeded in this fashion until no further improvement was possible by the addition of a single variable to the existing set or more likely here, the stopping criterion is met (exceeds 0.95).

By using the BIOENV sub-routine of PRIMER 6, the relationships between the environmental parameters and the biological distribution patterns in the study area were examined. For this, the species similarity matrix was computed for “rank correlation” with normalized Euclidean distance, calculated for the environmental data matrix (Clarke and Ainsworth, 1993). The rank correlation coefficient used for this analysis is a simple Spearman coefficient (ρ). An attempt was also made to link selected polychaete species abundance with the measured environmental variables using Canonical Correspondence Analysis (CCA) (ter Braak and Smilauer, 2002). The PAST software (version 2.17) was employed using a subset of important species, identified using BVSTEP and SIMPER tools in PRIMER-6. The CCA is a linear function of the two sets of variables (abiotic and biotic) so that the correlation between the two functions is maximized (Poore and Mobley, 1980; ter Braak and Smilauer, 2002). Geometrically, the method looks at the relative positioning of the subjects in the two-dimensional space, the variables with the highest coefficients in each of these linear functions are assumed to define that function and hence the key features relating the two data sets may be assessed from a pair of coefficient vectors (Poore and Mobley, 1980). The CCA plot was useful in determining which environmental factor influenced the distribution of the selected species. Monte Carlo permutation test (with forward selection) was used to test the significance of environmental variables explained the variance of species distribution and abundance (P <0.05 level).

Some qualitative and quantitative aspects of NEAS margin macrofauna have been compared with data collected concurrently from SEAS (cited as Abdul Jaleel, 2012) and the north-east coast of India (north western Bay of Bengal) (cited as Rao, 2009).

Chapter 3

HYDROGRAPHY & SEDIMENT CHARACTERISTICS

Contents

3.1. INTRODUCTION

All organisms exist only as parts of a complex entity, made up of interacting abiotic and biotic elements. Since organisms cannot live as isolated units, their activities are strongly influenced by their external circumstances. Thus, physicochemical or abiotic factor are the key determinants of existence for an organism in a certain environment. The boundaries of the ‘niche’ or functional position of any organism depend on the variation of physicochemical parameters (Kinne, 1963). The important physicochemical factors which play crucial role in the life history of benthic animals include hydrographical parameters (temperature, salinity and dissolved oxygen), sedimentological parameters (Sand, Silt and Clay) and organic matter content of the sediment. Sea floor sediments are in constant interaction with the overlying water, which is in turn responsible for the most physicochemical factors such as the dissolved oxygen, dissolved and particulate organic matter within the sediment regime.

Because several properties of marine environment usually vary together, the effects of variation of a single factor is seldom evident in natural conditions.

Temperature controls the rate of fundamental biochemical processes in organisms and there by changes in the environmental temperature can influence organismal as well as community level processes (Brown et al., 2004; Allen et al., 2006).Any change in temperature is bound to affect the many chemical processes taking place in plant or animal tissue, and so affects organisms as a whole. The continuous circulation of the oceans and their enormous heat capacity ensure that the extent of temperature variation in the sea is small despite great geographical and seasonal differences in absorption and radiation of heat (Tait, 1968). With the increased depth, deep sea experience much lower temperature. Seasonal and inter-annual variations in temperature are virtually unknown in the deep sea. In general, the metabolic rates of organisms increase with an increase in the ambient temperature to the level of tolerance of the organisms.

Salinity is also a major factor controlling macrofaunal distribution in sediments. Salinity is remarkably constant throughout the depths of the deep sea. As with temperature, macrofaunal organisms exist under all salinity regimes from fresh water to brine seep areas.

Oxygen is another important factor among the physicochemical parameters, influencing distribution and habitat conditions of macrofauna. Bottom water oxygen concentrations in the deep sea vary from near zero to over 7ml/l (Rex et al., 1993). In the benthic environment the distribution of macrofaunal communities is correlated with oxygen availability. When the supply of oxygen to the bottom is interrupted by various conditions like column stratification or increased consumption rates without replenishment, characteristic phenomena like hypoxia (DO<0.5ml/l) may occur.

When describing the habitat of macrobenthos, grain size is a key factor, since it directly determines spatial and structural conditions and indirectly determines the physical and chemical milieu of the sediment (Rex et al., 1983). The size, shape and composition of sediment particles determine the water flux through sediments, which in turn controls the physical and chemical regime within the sediments. In this network of abiotic factors that influence the habitat of macrobenthos, grain size plays a dominant role. Sediments in the marine environment may be terrigenous or biogenic in origin. Rivers play a vital role in transporting sediments from continents to oceans. Coarse sediments of terrigenous origin are commonly found on the continental slope and rise, by the transportation of turbidity currents and sediment slumps. Biogenic sediments are largely the hard skeletal parts of planktonic as well as benthic organisms. Sediments composed of more than 30% such skeletal components are termed oozes. This may be either calcareous (tests of foraminiferans, coccolithophores and pteropods) or siliceous (tests of radiolarians and diatoms) origin. Calcareous oozes are the most common biogenic sediment and about 48% of the world ocean floor is covered by calcareous oozes (Rothwell, 2005; Huneke, 2011). Siliceous oozes are common in areas with high biological productivity, such as the upwelling zones near equator and the polar oceans.

Along with sediment texture another important parameter is the organic matter content of the sediments, since it represents a potential source of food directly for deposit feeders and indirectly for suspension feeders.The benthos below the euphotic zone in most areas of the sea totally dependent on the supply of energy and matter from the pelagic system through sedimentation of organic matter which forms a link between the water column and the sea-bed. The hydrographic and biological processes in the water column will determine the quantity and quality of food supply to the benthos (Smetacek, 1984). High benthic biomass and density in near shore areas can be due to the rich primary production in near shore waters. The supply of food to subtidal benthic environment depends on the proximity to shore and water depth (Levinton, 1982).Continental slopes are the sites of accumulation of high concentrations of organic matter. The enhanced organic matter is generally caused by a combination of river-induced nutrient input, the coupling of pelagic and benthic systems, and local or regional upwelling of fertile, highly productive deep water (Mantoura et al., 1991; Biscaye et al., 1994). The characteristics of organic matter in the sediment matrix are considerably different compared to what originally settled on the surface because of the increasing dominance of recalcitrant matter with age and hence depth into the sediment (Middelburg, 1989).Recent investigations in Quaternary sediments of the Pacific and Atlantic oceans indicate that primary productivity is the principal control for the formation of organic-rich deposits (Calvert et al., 1992; Calvert and Pedersen 1992).

The present chapter gives an account of the hydrographical as well as sedimentological parameters of the slope area of NEAS.

3.2. RESULTS

3.2.1. Hydrographical conditions

The hydrographic variables examined in the present study were bottom water temperature (°C), salinity and dissolved oxygen (ml/l). Data on the hydrographical conditions for the NEAS margin coast during *FORVSS* 219, 228 and 254 are presented in Tables 3.3 to 3.5 and Figures 3.1 to 3.7.

3.2.1.1 Bottom water temperature

During *FORVSS* 219 (2003 December, WIM) bottom water temperature varied appreciably within each depth class. At 200m the temperature variation was from 16.11ºC (Mumbai 1) to 19.86ºC (Veraval) with a mean of 18.03±1.27ºC. In the 500m depth contour, the observed range of temperature was 11.53ºC (Ratnagiri) to 13.85ºC (Mumbai 2) with a mean value of temperature 12.38±0.97ºC. In the stations around 1000 m depths the temperature varied from 7.69^{0}C (Goa) to 9.33^{0}C (Mumbai 1) with a mean value of temperature 8.60±0.53ºC.

During the second sampling (SM) at the year 2004-2005 (*FORVSS* 228) bottom water temperature along the study area varied from 16.1 ºC Porbandar to 7.82 ºC with a mean temperature 11.73±2.962 °C. At 200m, the temperature varied between 14.60 ºC (Mumbai 1) to 16.13 ºC

(Porbandar) with a mean temperature value of 15.33±0.62ºC. For the 500m depth the observed temperature range was from 11.63ºC (Goa) to 13.16 ºC (Porbandar) with the mean value of temperature 12.32±0.51ºC. At the 1000m depth stations the bottom temperature of study area ranged from 7.82 ºC (Goa) to 10.20 ºC (Veraval) with a mean value of 9.25±0.92 ºC.

During *FORVSS* 254 (SIM, 2007) the bottom water temperature shows higher values towards the northern transects. The bottom water temperature of the NEAS at 200m depth class ranged between 15.1 ºC (Goa) to 17.3 ºC (Porbandar) with a mean value of 16.2±0.89ºC. The temperature variation at 500m varied from 11.9ºC (Goa) to 13.1ºC (Porbandar) with a mean value of 12.5±0.44ºC. In the 1000m depth stations temperature varied from 9.6ºC (Goa and Dabhol) to 10.2ºC (Veraval and Porbandar) with a mean value of 9.90±.27^{0}C.

The bottom water temperature along the NEAS region decreased with increasing depth (R^2= 0.8729) with significant differences between depth classes (ANOVA F2,62=269.6,P<0.001).

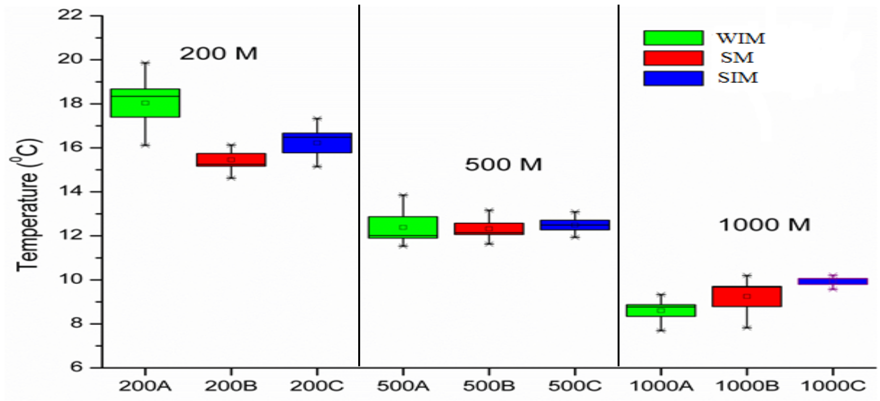


Figure 3.1: Bottom water temperature (ºC) at each depth class
A: WIM, B: SM, C: SIM, (Whiskers: Range, Box: SD, Inner hexagon: Mean, Line within Box: Median)

3.2.1.2Bottom water Salinity

During Winter Monsoon sampling *FORVSS* 219 the bottom water salinity varied from 35.21 (Dabhol) to 35.61 (Veraval) with a mean value of 35.37±0.17. Within each depth range, salinity did not showed much variation. From 200m depth stations along NEAS, the salinity varied from 35.21 (Dabhol) to 35.61 (Veraval) with a mean value of 35.37±0.17. At 500m depth the salinity varied from 35.49 (Ratnagiri) to 35.81 (Porbandar) with a mean value of salinity of 35.62±0.13. From the 1000m stations the salinity ranged from 35.18 (Goa) to 35.40 (Mumbai 1) with a mean salinity of 35.32±0.08. Even though the variation of salinity was negligible it showed an increase towards the northern part of the west coast.

Salinity along the NEAS region during summer monsoon (*FORVSS* 228) did not vary appreciably among depth or latitude. From the 200m range of salinity was between 35.33 (Goa) and 35.84 (Porbandar) with mean salinity 35.56±0.17; from that of 500m was between 35.45 (Goa) and 35.68 (Veraval) with a mean value of 35.57± 0.09; from 1000m salinity was between 35.20 (Goa) and 35.51 (Veraval) with mean salinity 35.38±0.13.

During *FORVSS* 254, SIM the salinity at 200 m depth ranged between 35.35 (Goa) to 36.03 (Porbandar) with mean value of 35.70±0.27. In the 500 m the salinity varied from 35.45 (Goa) to 35.77 (Porbandar) with mean salinity of 35.60±0.11. At 1000m, salinity ranged between 35.31 (Goa) to 35.52 (Porbandar) with mean salinity of 35.44±0.08.

Comparatively higher salinity can be observed from transects of northern side of the west coast.

Salinity for the NEAS region as whole, varied significantly with depth ($F_{2,62}$=6.76,P<0.001), season ($F_{2,62}$=3.31,P<0.05 and latitude ($F_{2,62}$=9.76,P<0.001). Except for SIM 2007, higher salinity were observed at ~500m depth stations when compared to 200m &1000m. Progressive increase in salinity were observed from south to northern sites.

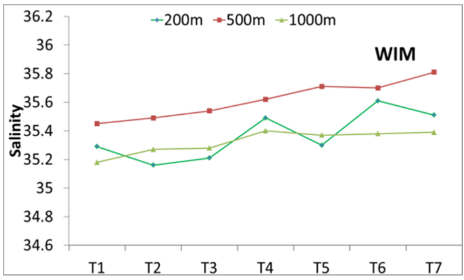


Figure 3.2: Bottom water salinity during WIM (FORVSS cruise 219)

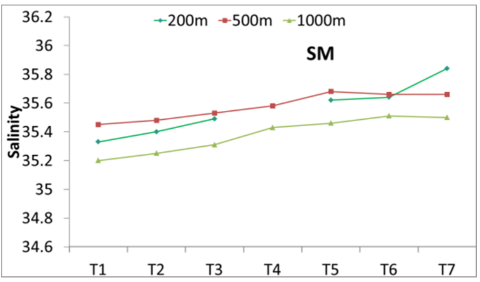


Figure 3.3: Bottom water salinity during SM (FORVSS cruise 228)

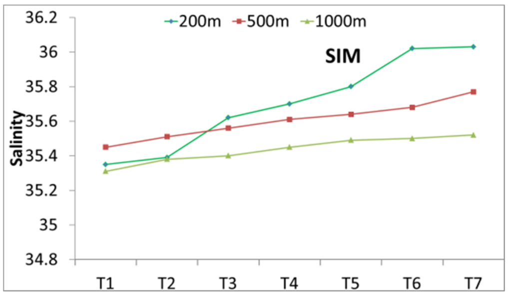


Figure 3.4: Bottom water salinity during SIM (FORVSS cruise 254)

3.2.1.3Bottom water dissolved oxygen

During sampling *FORVSS*219 (WIM) along the NEAS, the bottom water dissolved oxygen varied extensively. Within each depth range, dissolved oxygen (DO) showed distinct pattern. In various depth stations located along NEAS, the bottom water DO at 200m depth ranged from 0.18 ml/l (Ratnagiri) to 0.94 ml/l (Dabhol) with a mean value of 0.45±0.25 ml/l and that of 500m depth ranged from 0.07 ml/l (Ratnagiri) to 0.85 ml/l (Dabhol) with a mean value of 0.28±0.26 ml/l. In the depth stations around 1000m, DO ranged from 0.11ml/l (Veraval) to 1.17 ml/l (Goa) with a mean value of 0.45±37 ml/l. The dissolved oxygen concentration of winter monsoon(*FORVSS* 219) in the NEAS was lowest at 500m depth class when compared to its shallow and deeper counter parts.

Dissolved oxygen during *FORVSS* 228 (SM) also varied considerably. In the around 200mdepth stations, the DO values ranged from 0.48 ml/l (Veraval and Porbandar) to 0.63 ml/l (Mumbai 2) with a mean value of 0.51±0.06 ml/l. The observed range of DO in 500m depth was from 0.16 ml/l (Veraval) to 0.54 ml/l (Mumbai 2) with a mean value of 0.35±0.14 ml/l. Dissolved oxygen in the 1000m depth varied from 0.47 ml/l (Porbandar) to 0.81ml/l (Mumbai 1) with a mean value of 0.68±0.12 ml/l. In the SM also, DO level was low at 500m depth.

During *FORVSS* 254 (SIM) distribution of DO varied with depth. In the depth stations around 200m the DO value ranged from 0.10 ml/l (Porbandar) to 0.29 ml/l(Mumbai 1) with a mean value of 0.15±0.06 ml/l. For 500m depth the observed range of oxygen was from 0.07ml/l

(Porbandar) to 0.18 ml/l (Ratnagiri) with a mean value of 0.13±0.06 ml/l. At 1000m depth, bottom DO showed variation from 0.12 ml/l (Porbandar) to 0.38 ml/l (Ratnagiri) with a mean value of 0.27±0.09 ml/l.

The lowest of oxygen concentration in the bottom water was observed during *FORVSS* 254 (SIM).Considerable depletion (<0.2ml/l) in bottom water DO at almost all sites in the NEAS were observed during this season. DO values varied significantly between seasons (ANOVA $F_{2,62}$=4.38, P=0.018) and depths (ANOVA $F_{2,62}$=13.319, P=0.00).

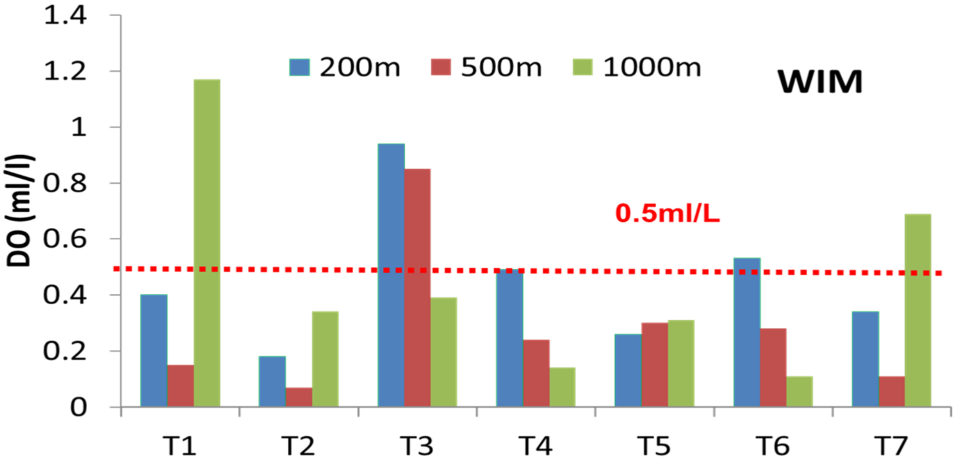


Figure 3.5: Bottom water Dissolved Oxygen during WIM (FORVSS cruise 219) Dotted red line indicates DO value of 0.5 ml/l

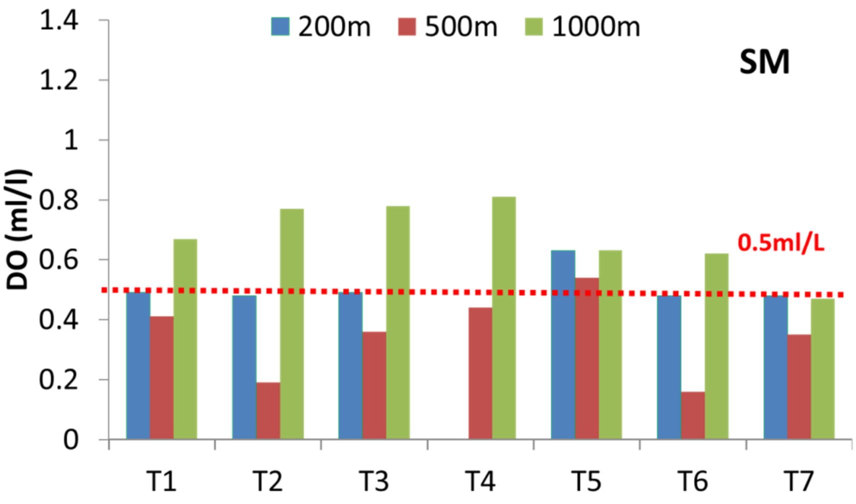


Figure 3.6: Bottom water Dissolved Oxygen during SM (FORVSS cruise 228) Dotted red line indicates DO value of 0.5 ml/l

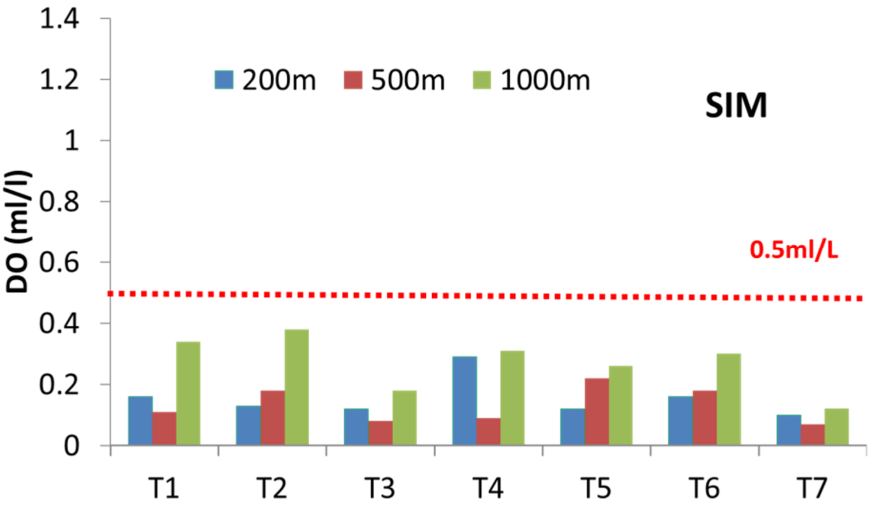


Figure 3.7: Bottom water Dissolved Oxygen during SM (FORVSS cruise 254) Dotted red line indicates DO value of 0.5 ml/l

3.2.2. Sediment characteristics

3.2.2.1. Sediment Texture

Data on the sediment texture and organic matter for the NEAS during *FORVSS* 219, 228 and 254 are presented in Tables 3.6 to 3.8 and Figures 3.8 to 3.15. Overall, the ratio of sand, silt and, clay varied depending on the location and depth.

During *FORVSS* 219 (WIM), 21 stations were examined for sediment nature. The predominant textural class, dominating at a majority of stations during that time was clayey silt. However, composition-wise there were appreciable differences.

At 200m depth stations of NEAS sand (%) varied between 4.67% (Veraval) and 64.27% (Ratnagiri; Mean value 37.20±23.42%); silt 17.61% (Ratnagiri) and 57.88% (Dabhol) with mean value of 37.94±15.44% and clay 14.66% (Mumbai 2) and 37.67% (Veraval) mean value of 24.86±8.31 %. The predominant textural classes within this depth were silty sand and clayey-silt.

Above 500m, In the NEAS sand (%) varied between 1.81% (Dabhol) and 44.60% (Mumbai 1) with a mean value of 14.02±14.20 %; silt from 33.93% (Mumbai 1) to 63.93% (Dabhol) with a mean value of 53.59±10.82 and clay from 21.48% (Mumbai 1) to 39.24% (Veraval) with a mean value of 32.39±6.79.Clayey silt still being the predominant textural class.

Within depths 1000m, sand (%) varied between 5.85% (Dabhol) and 20.04% (Mumbai 1) with a mean value of 10.14±6.55; silt from 46.75%

(Mumbai 1) to 61.93% (Dabhol) with a mean value of 56.19±5.87 and clay from 28.39% (Mumbai 1) and 39.63% (Veraval) with a mean value of 33.66±3.41,Clayey silt was predominant textural class.

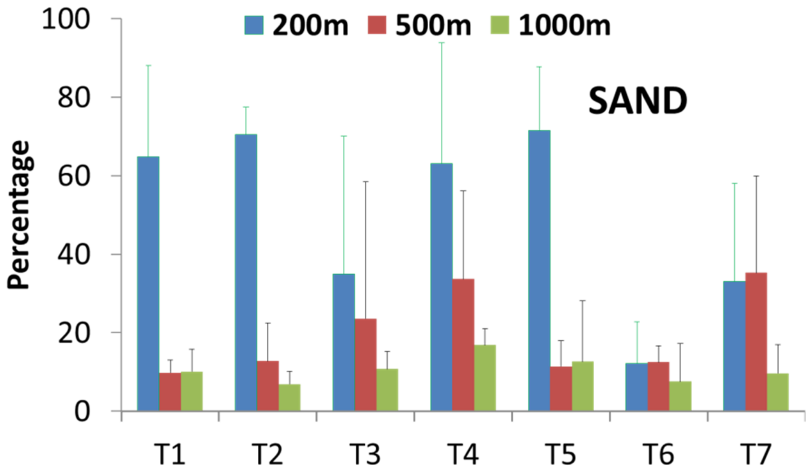


Figure 3.8: Sand percentage of sediment along the NEAS sites

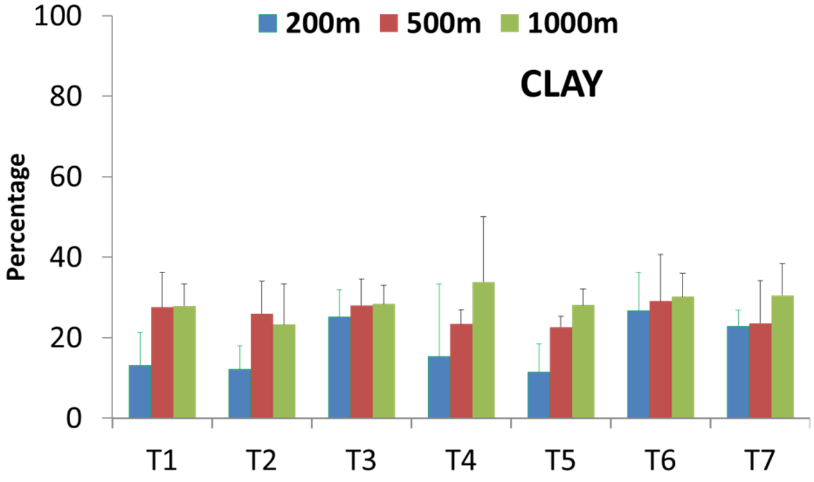


Figure 3.9: Clay percentage of sediment along the NEAS sites

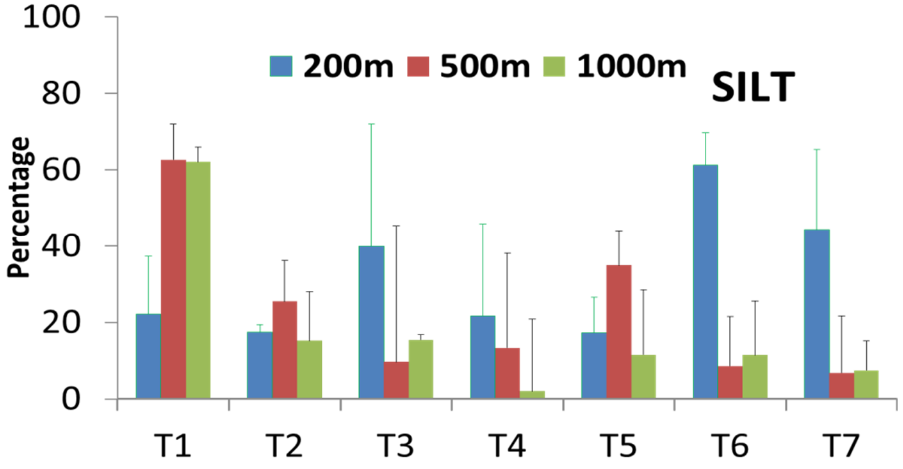


Figure 3.10: Silt percentage of sediment along the NEAS sites

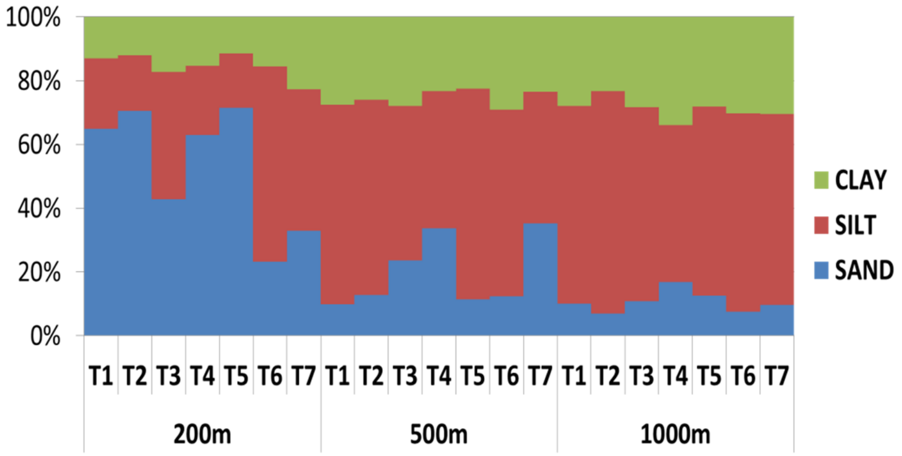
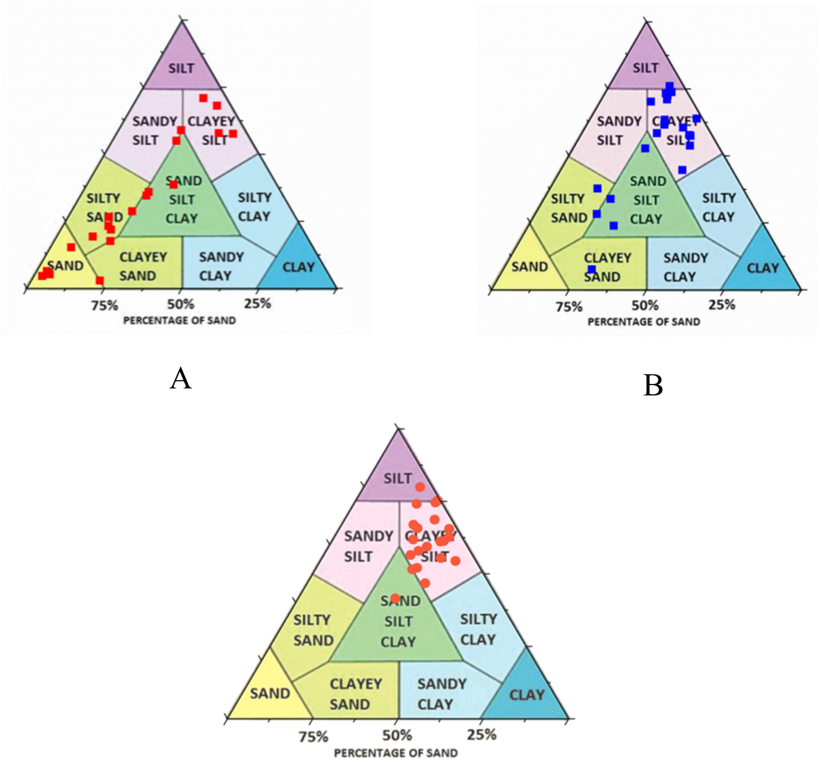


Figure 3.10: Sediment texture composition at each study sites



A

B

C

Figure 3.11: Ternary diagram according to Sheppard's textural classification A: 200m; B: 500m; C:1000m

During *FORVSS* 228 (SM) along NEAS, 20 stations were examined for sediment nature. The predominant textural class, dominating at a majority of stations during summer monsoon also was clayey silt. However, there was considerable variation in composition

At the 200m depth of NEAS stations, sand (%) varied between 24.25% (Veraval) and 75.02% (Dabhol) with a mean of 57.03±17.93%; silt 2.89% (Dabhol) and 55.04% (Veraval) with a mean of 25.75±17.01% and clay 11.61% (Ratnagiri) and 22.09 % with a mean of 17.22± 4.25% (Dabhol).

The predominant textural classes within this depth were silty sand, clayey sand and sand.

In the 500m depth, sand (%) varied from 7.90% (Veraval) and 63.84% (Dabhol) with a mean of 32.42±21.94%; silt 7.63% (Dabhol) and 61.65% (Goa) with a mean of 41.91±21.66% and clay 19.82% (Porbandar) and 31.53% (Veraval) with a mean of 25.67±3.85%, clayey silt was the most predominant textural class from the NEAS in the summer monsoon.

Within depths 1000m, sand (%) varied between 2.26% (Veraval) and 79.91 % (Ratnagiri) with a mean of 29.90±27.21%; silt 3.55 % (Ratnagiri) and 65.49% (Veraval) with a mean of 44.84±21.96% and clay 16.54% (Ratnagiri) and 32.25% (Veraval) with a mean of 25.26±5.74%, the predominant textural class being clayey silt followed by sandy silt.

During *FORVSS* 254 along the west coast 21 stations were examined for sediment nature. The predominant textural class, dominating at a majority of stations during that time was clayey silt followed by sand. However, it showed considerable variation in composition.

At 200m, sand (%) varied between 4.59% (Porbandar) and 92.77% (Mumbai 1) with a mean value of 54.89±41.64%; silt 4.60% (Mumbai 1) and 70.94 % (Veraval) with a mean value of 32.80±31.49% and clay 2.62% (Mumbai 1) and 27.28% (Porbandar) with a mean value of 12.31±10.30%. Majority of stations from 200m depth of NEAS was sandy in nature. All the other stations showed sandy silt sediment.

At 500m, sand (%) varied 4.49% (Mumbai 2) and 46.88% (Porbandar) with a mean value of 13.10±15.18%; silt 37.81% (Porbandar) and 76.07% (Mumbai 2) with a mean value of 67.83±13.37% and clay 15.30%

(Porbandar) and 21.20 % (Dabhol) with a mean value of 19.07±2.36%. The predominant textural class was clayey silt.

For depths located at 1000m, sand (%) varied between 0.74% (Mumbai 2) and 14.61% (Dabhol) with a mean value of 7.56±5.35%; silt 61.86 % (Dabhol) and 75.23% (Mumbai 2) with a mean value of 69.60±5.17% and clay 18.39% (Ratnagiri) and 26.40% (Porbandar) with a mean value of 22.84±2.52%, The predominant sediment texture was clayey silt and silt.

Sediment composition varied significantly with depth. For sand% $F_{2,62}=12.935$, $p<0.001$; Silt% $F_{2,62}= 9.992$, $P<0.001$; Clay% $F_{2,62}=8.15$, $P<0.001$.

3.2.2.2. Organic matter

Overall, sediment organic matter (%) during winter monsoon (*FORVSS*219**)** in the NEAS at 200m depth varied from 2.52% (Veraval) to 5.16% (Porbandar) with a mean of 3.78±1.05%. The OM at 500 m depth stations varied from 4.52% (Mumbai 1) to 11.94% (Goa) with a mean percentage 8.76±2.63%. At 1000m depth stations of NEAS, OM varied from 5.0% (Veraval) to 9.39% (Mumbai 2) with a mean percentage 7.30±1.52%.

During *FORVSS* 228 in the summer monsoon, OM increased with increasing with depth. Notably high values of organic matter level have been observed from stations at 1000m (Mumbai 2, Dabhol, Mumbai 1) and 500m depth (Mumbai 2, Goa, Ratnagiri, Ponnani) . The organic matter percentage variation at 200m depth was from 2.67% (Goa) to 6.32% (Ratnagiri) with a mean percentage 3.97±1.57%.The OM at 500 m depth stations varied from 0.95% (Mumbai 1) to 12.82% (Mumbai 2) with a mean percentage 6.73±4.76%. At 1000m depth stations OM varied from 2.20% (Porbandar) to 12.88% (Mumbai 2) with a mean percentage 7.60±3.95%.

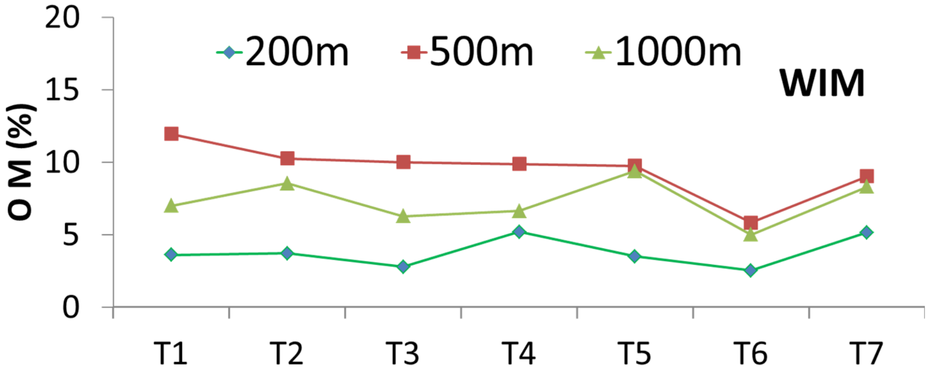


Figure 3.12: Sediment organic matter (%) during WIM (FORVSS cruise 219)

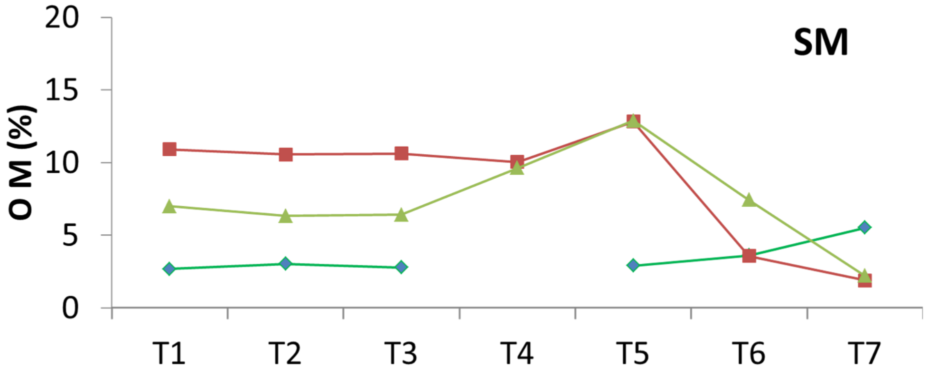


Figure 3.13: Sediment organic matter (%) during SM (FORVSS cruise 228)

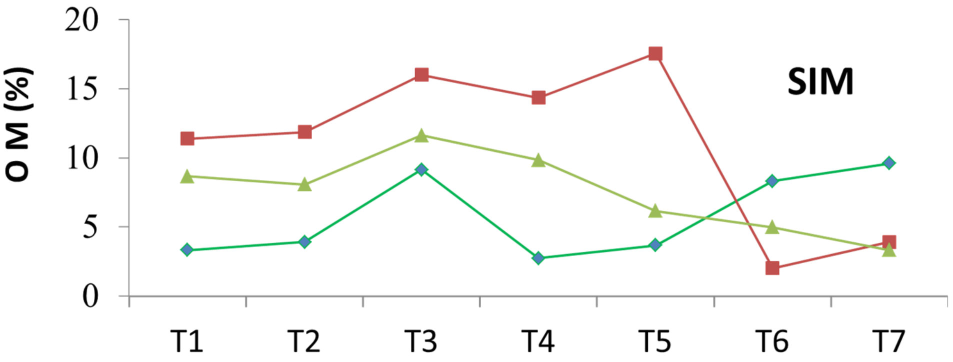


Figure 3.14: Sediment organic matter (%) during SIM (FORVSS cruise 254)

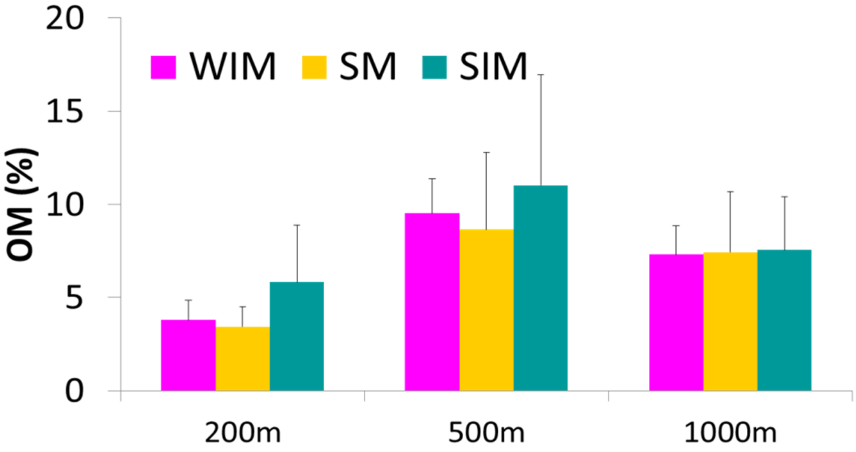


Figure 3.15: Mean Sediment organic matter (%) at each depth class during three seasons (FORVSS cruise 219, 228 &254)

During *FORVSS*254 (SIM) OM showed higher values at 500m and 1000m depth stations when compared to 200m. When the depth stations of 500m and 1000m taken in to consideration, 500m depth stations showed notably high values (Mumbai 2, Dabhol, Mumbai 1). At 200m depth the OM varied from 2.73% (Mumbai 1) to 11.63% (Dabhol) with a mean percentage 6.17±3.59%. The OM at 500 m depth stations ranged from

2.02% (Veraval) to 17.52% (Mumbai 2) with a mean percentage 11.02±5.94%. At 1000m depth stations at the OM varied 3.32% (Porbandar) to 9.85% (Mumbai1) with a mean percentage 7.17±2.40%.

During the study, organic matter percentage was less than 6% at most 500 and 1000m sites. Significant depth wise variation was observed in the organic matter composition along the study area (Depth: $F_{2,62}=26.94$, $P<0.001$) while temporal variation was not observed and statistically not significant. ($F_{2,62}=0.783$, $P<0.824$)

3.2.3. Principal Component Analysis

The sets of eight environmental variables were subjected to PCA to obtain detailed information on the pattern of variation. The pattern of variation in environmental data in relation to depth and location was depicted in the PCA ordination using two important PC axes [Figure 3.16]. The analysis The Eigen value and ratios of explained variances are presented in Table 3.1 Table 3.2, where principal component variance is in progressive decline. The first three components represent most of the total variance which explained 85.7% of the total variance between stations. Sand and silt percentage along with depth and bottom water temperature contributed significantly to the PC1(Eigen value 3.63), which accounted for 45.3 % of the variance in the data. Second axes (Eigen value 1.85), which explained 23.2% of the total variance, consisted primarily of hydrographical variables, viz. bottom water salinity and DO. PC3 ordination was contributed by DO and Clay percentage.

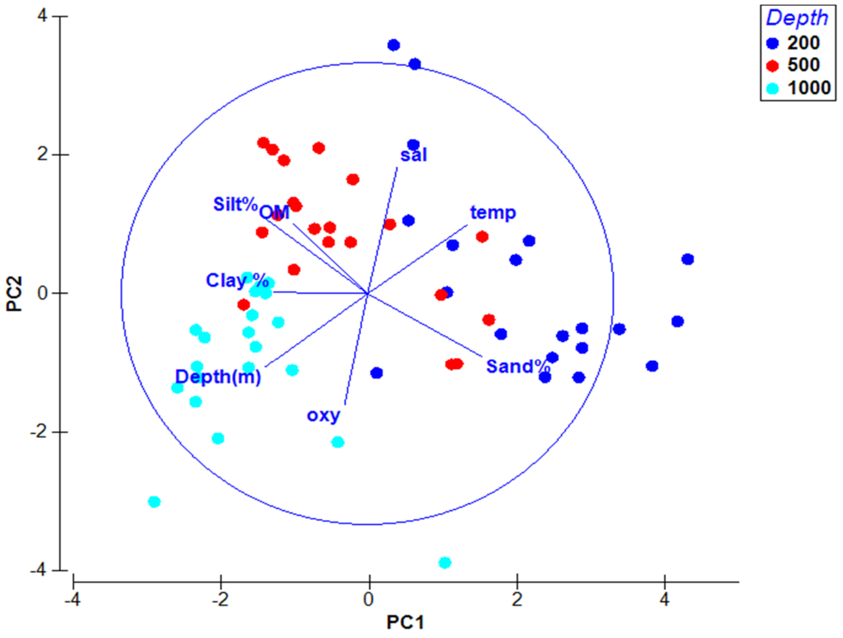


Figure 3.16: PCA plot showing ordination of environmental variables and stations

Table 3.1: Eigen values and percentages of explained variability of each axis

PC	Eigen values	%Variation	Cumulative %Variation
1	3.63	45.3	45.3
2	1.85	23.2	68.5
3	0.943	11.8	80.3
4	0.622	7.8	88.1
5	0.518	6.5	94.5

Eigenvectors

Table3.2: Coefficients in the linear combinations of variables making up PC's)

Variable	PC1	PC2	PC3	PC4	PC5
Temperature	**-0.400**	-0.330	-0.388	-0.213	0.230
Salinity	-0.118	**-0.562**	-0.053	**0.401**	**-0.711**
Oxygen	0.065	**0.495**	**-0.590**	-0.256	**-0.513**
Organic Matter	0.312	-0.273	0.273	**-0.776**	-0.284
Clay %	0.391	-0.022	**-0.497**	0.183	0.126
Silt%	**0.429**	-0.320	-0.148	-0.009	0.188
Sand%	**-0.457**	0.264	0.203	-0.058	-0.147
Depth	**0.423**	0.288	0.337	0.299	-0.159

3.3.DISCUSSION

Among the hydrographical parameters, salinity showed least spatial variation in the study area. Though the variation was small, a general increase in salinity at 500m depth was observed. Salinity also showed a progressive increase towards north also. During the winter monsoon season, low saline water from Bay of Bengal joins the northward flowing equatorial Indian Ocean water and flows as a northward surface current along the west coast of India (Pankajakshan and Ramaraju, 1987). The lower salinity of the southern part of the study area may be due to this incursion of low saline waters from Bay of Bengal to the south west coast (Darbyshire, 1967; Wyrtki, 1971). Hareesh Kumar and Mathew (1997) noticed that the maximum northward extension of this low saline water is up to about 12 ºN in January but could be traced upto 17 ºN in February-March. The eastern Arabian Sea is in connection with two landlocked seas, the Red Sea and the Persian Gulf, which contribute high saline waters to the Arabian Sea at a depth of about 500m and 200m respectively (Rochford, 1964; Shenoi et al., 1993). Shenoi et al. (2004) also reported patches of high saline water in the shelf break and continental slope region of the Arabian Sea at a depth range between 180-600m. The higher salinity noticed in the NEAS can be due to the effect of Persian water (Wyrtki, 1971). Varma et al. (1980) studied the thermohaline structure in the Northern Arabian Sea. They found that Persian Gulf water was present at about 300m.

In the present study, there was a decrease in bottom temperature with depth and latitude. Towards the northern latitudes the temperature tends to increase. Qasim (1982) noticed such an increase of temperature from south to north in the deeper waters. The Persian Gulf water mass is characterised by temperature ranges of 13 to 14 ºC and temperature ranges of the Red Sea water mass is 10 to 12 ºC were also reported from 10 ºS (Shenoi et al., 2004).

In the NEAS, DO values were very low. According to Cowie (2005), amongst the various environmental parameters that differ across continental margins, especially beneath areas of upwelling, bottom-water oxygen concentrations and organic matter content exhibit some of the sharpest gradients. In all the three seasons, dissolved oxygen concentration was lower at 500m sites rather than 200 and 1000m depth sites. Also there was considerable depletion (<0.5ml/l) of oxygen throughout study irrespective of depth, latitude or season. This depletion of oxygen in the northern latitudes of Arabian Sea is associated with the impingement of OMZ over the continental margin (Sen Gupta et al., 1976, 1980; Qasim et al., 1982; Levin et al., 2009; Ingole et al., 2010; Hunter et al., 2011, 2012). These workers have reported restricted mixing, high organic production, sinking and decomposition of great amounts of organic matter as the reasons for this oxygen depletion. The Arabian Sea OMZ is the thickest of all OMZ (1230m, Acharya and Panigrahi, 2016) and second-most intense in the world tropical ocean (Kamykowski and Zentara, 1990), with near total depletion of oxygen at depths from 200 to 1000 m (Morrison et al., 1998); indeed, suboxic levels (<5 µmol O2/kg) exist over much of that depth range (Naqvi, 1991). Oxygen minimum zones generally form where resilient upwelling leads to high surface productivity that descends and degrades, depleting the oxygen within the water column. OMZ formation is also strongly inclined by stagnant circulation, long residence times and the presence of oxygen-depleted source waters (Sarmiento et al., 1988). The Arabian Sea OMZ impinges on 285,000 km2 of continental margin sediments between depths 150 and 1500m (Cowie et al., 1999; Helly and Levin, 2004) and accounts for 30% of the world's OMZ impacted margins (<0.2ml/l; Helly and Levin, 2004). The dissolved oxygen concentration was found to be higher in 1000m sites. Correspondingly progressive increase in bottom DO below OMZ core was observed on the Indian margin (Ingole et al., 2010), Pakistan margin, below 1150m (Gooday et al., 2009), Oman margin (Levin et al., 2000), eastern Pacific Ocean (Levin et al., 1991) and Chile margin (Quiroga et al., 2005).

The nature of substrata along the continental slope region of NEAS showed considerable variation. Seven different types of substrata was noticed, which were clayey silt, sandy silt, sand, clayey sand, silty sand, silt, silty clay. Though, seven types were observed, clayey silt, silty sand, sandy silt, and sand were the major sediments. With the increase in depth, sand was replaced by finer sediment, mainly with silt. Most of the deeper stations showed clayey silt sediment. The dominance of the coarse sediments in the shallow shelf edge and upper slope is attributed to the active hydrodynamic conditions prevalent in this region. The steep depth gradients of the upper slope may also enable downward transport of finer particles like silt to higher depths, where the physical activities tend to be more stable (Hashimi et al., 1978; Hashimi and Nair, 1981; Rao and Veerayya, 2000). The presence of relict, coarse-grained sediments on the outer shelf area is a common occurrence on many continental margins including the eastern Arabian Sea (Rao and Wagle, 1997; Ingole et al., 2010). Rao and Wagle (1997) stated that the slope of the eastern Arabian Sea is characterized by clayey silt sediments with abundant biogenous carbonate tests. The present results are also in agreement with the reports from the Indian continental margin (Ingole et al., 2010).

The distribution of organic carbon along the Arabian Sea was discussed earlier by several workers (Marchig, 1972; Kolla et al., 1981; Paropkari et al., 1987, 1992, 1994; Calvert et al., 1995). They observed higher concentrations of organic carbon along upper slope (150–1500 m depth) sediments where the oxygen minimum zone (OMZ) impinges on the sea floor (Marchig, 1972; Von Stackelberg, 1972; Kolla et al., 1981; Paropkari et al., 1987, 1992, 1993a,b, 1994). In the present study also, organic enriched sediments were observed along the slope of NEAS. In the Arabian Sea organic carbon enrichments of >8% with maxima of up to 12–

16% (Paropkari et al., 1987, 1992, 1993a,1994) are reported even in areas where productivity is low to moderate (<0.50 gCm^{-2} day-1). Cowie et al. (2009) reported that it is common to find sediments containing 4 to 20% of organic carbon in OMZs. Within OMZ impacted regions, sediments are characterised by a high organic carbon content (Ingole et al., 2010) and preservation of labile organic compounds such as amino acids, lipids and photosynthetic pigments (Smallwood et al., 1999; Vandewiele et al., 2009; Woulds and Cowie, 2009). Ingole et al. (2010) reported silty sediments with higher organic carbon from 1001m, Coondapur (4.4%). Mendez (2007) reported a maximum of 20% of organic matter from the south eastern Gulf of Carolina and in the eastern Arabian Sea, Rao and Wagle (1997) reported organic content up to 8% in the margin sediments. Paropkari et al. (1987) reported that the organic matter present in the continental margin of western India is principally of marine origin.

In the present study, sediment OM showed considerable variation with respect to depth as well as latitude. In general, more organic matter is retained in the fine sediments i.e., silt or clay. Most of the stations showed clayey silt sediment texture. Particularly, the deeper stations (500 & 1000m) showed comparatively high percentages of finer particles like silt and clay. The highest mean value was noticed in the 500m depth. The OM content in sediments depends on three factors according to Trask (1939): (i) the quantity of OM produced in the surface waters in a given unit of time, (ii) degree of conservation or preservation of OM and (iii) rate of sedimentation. The higher organic matter in the shallower and deeper areas may be attributed to the fine-grained nature of the sediments and to the variation in the benthic productivity (Paropakari et al., 1987). While studying the organic matter in the Honavar area, Narayana and Prabhu (1993) noticed that the grain size and biologic productivity are the major contributing factors for the variation in OM.

The present study has shown relatively high OM values in 500m depth zone. The association between organic matter and grain size is considered to be due to the adsorption capacity of organic matter onto clays and the similarity in the settling velocity of organic particles and clays (Kemp, 1971) whereas, Kidwai and Nair (1972) have appended the associated reducing condition, to aid the preservation of organic matter. The association between clay content and the organic carbon is probably the result of great surface area presented by a large volume of clay particles and of the chemically active nature of clays (Abdul Jaleel, 2012). Kolla et al. (1981) stated that the high OM content in the sediments of the Indian continental margins is primarily due to its preservation, which result from the impingement of low oxygenated water on the sea floor and from the high sedimentation rates. However, Calvert et al. (1991) suggest that anoxic condition in the water column may not be a prerequisite for the preservation of organic matter in marine sediments.

Sediment organic carbon is mainly shaped by the total carbon flux, the rate of mixing and the organic matter degradability. The flux of organic matter from surface productivity to the seafloor has been proven to exert considerable control on benthic standing stocks (Soltwedel, 2000). The energy content of sedimenting OM generally decreases with increasing water depth because of the degradation processes within the water column. The increase of organic matter could be attributed to the preservation of deposited organic matter by fine grained nature of the sediments and similarity in settling velocity of fine grained sediments and organic matter (Trask, 1939) coupled with higher rates of sedimentation in these regions, which prevents its destruction through rapid burial (Subbarao, 1960).

Table 3.3: Hydrographic parameters of bottom water during FORVSS Cruise 219

Station No	Transect	Depth (m)	Temperature (°C)	Salinity	Dissolved Oxygen (ml/l)
1	Goa	203	16.87	35.29	0.4
2	Goa	503	11.62	35.45	0.15
3	Goa	1003	7.69	35.18	1.17
4	Ratnagiri	191	18.96	35.16	0.18
5	Ratnagiri	470	11.53	35.49	0.07
6	Ratnagiri	976	8.44	35.27	0.34
7	Dabhol	200	17.61	35.21	0.94
8	Dabhol	505	11.64	35.54	0.85
9	Dabhol	1002	8.24	35.28	0.39
10	Mumbai 1	230	16.11	35.49	0.49
11	Mumbai 1	500	12.01	35.62	0.24
12	Mumbai 1	875	9.33	35.40	0.14
13	Mumbai 2	194	18.34	35.30	0.26
14	Mumbai 2	350	13.85	35.71	0.3
15	Mumbai 2	1004	8.77	35.37	0.31
16	Veraval	203	19.86	35.61	0.53
17	Veraval	505	12.42	35.70	0.28
18	Veraval	1000	8.87	35.38	0.11
19	Porbandar	200	18.49	35.51	0.34
20	Porbandar	452	13.61	35.81	0.11
21	Porbandar	991	8.88	35.39	0.69

Table 3.4: Hydrographic parameters of bottom water during FORVSS Cruise 228

Station No	Transect	Depth (m)	Temperature (°C)	Salinity	Dissolved Oxygen (ml/l)
22	Goa	230	15.05	35.33	0.49
23	Goa	520	11.63	35.45	0.41
24	Goa	958	7.82	35.2	0.67
25	Ratnagiri	210	14.62	35.4	0.48
26	Ratnagiri	470	12.66	35.48	0.19
27	Ratnagiri	950	8.52	35.25	0.77
28	Dabhol	220	15.25	35.49	0.49
29	Dabhol	558	12.1	35.53	0.36
30	Dabhol	950	8.62	35.31	0.78
32	Mumbai 1	520	11.95	35.58	0.44
33	Mumbai 1	1000	9.67	35.43	0.81
34	Mumbai 2	200	15.81	35.62	0.63
35	Mumbai 2	490	12.59	35.68	0.54
36	Mumbai 2	1010	9.76	35.46	0.63
37	Veraval	202	15.86	35.64	0.48
38	Veraval	530	12.14	35.66	0.16
39	Veraval	1006	10.2	35.51	0.62
40	Porbandar	215	16.13	35.84	0.48
41	Porbandar	500	13.16	35.66	0.35
42	Porbandar	1025	10.13	35.5	0.47

Table 3.5: Hydrographic parameters of bottom water during FORVSS Cruise 254

Station No	Transect	Depth (m)	Temperature (ºC)	Salinity	Dissolved Oxygen (ml/l)
43	Goa	203	15.14	35.35	0.16
44	Goa	490.9	11.93	35.45	0.11
45	Goa	847	9.57	35.31	0.34
46	Ratnagiri	200	15.53	35.39	0.13
47	Ratnagiri	521	11.97	35.51	0.18
48	Ratnagiri	860	9.74	35.38	0.38
49	Dabhol	218	16.76	35.62	0.12
50	Dabhol	503	12.49	35.56	0.08
51	Dabhol	817	9.64	35.4	0.18
52	Mumbai 1	242	15.29	35.7	0.29
53	Mumbai 1	575	12.38	35.61	0.09
54	Mumbai 1	878	10.05	35.45	0.31
55	Mumbai 2	213	16.48	35.80	0.12
56	Mumbai 2	540	12.68	35.64	0.22
57	Mumbai 2	850	10.11	35.49	0.26
58	Veraval	217	17.02	36.02	0.16
59	Veraval	534	12.90	35.68	0.18
60	Veraval	827	10.17	35.5	0.3
61	Porbandar	216	17.33	36.03	0.1
62	Porbandar	520	13.09	35.77	0.07
63	Porbandar	933	10.21	35.52	0.12

Table 3. 6: Sediment characteristics during FORVSS Cruise 219

Station No	Transect	Depth (m)	Clay (%)	Silt (%)	Sand (%)	Organic Matter (%)
1	Goa	203	21.3	34.6	44.2	3.61
2	Goa	503	37.1	53.8	9.0	11.94
3	Goa	1003	33.6	62.6	3.8	6.99
4	Ratnagiri	191	18.1	17.6	64.3	3.71
5	Ratnagiri	470	34.9	57.8	7.3	10.26
6	Ratnagiri	976	34.8	55.5	9.7	8.53
7	Dhabol	200	33.0	57.9	9.2	2.78
8	Dhabol	505	34.3	63.9	1.8	10.01
9	Dhabol	1002	32.8	61.4	5.9	6.27
10	Mumbai 1	230	28.0	38.6	33.4	5.19
11	Mumbai 1	500	21.5	33.9	44.6	4.52
12	Mumbai 1	875	28.4	51.6	20.0	6.63
13	Mumbai 2	194	14.7	23.3	62.1	3.50
14	Mumbai 2	350	24.2	63.5	12.4	9.75
15	Mumbai 2	1004	31.9	61.1	7.0	9.39
16	Veraval	203	37.7	57.7	4.7	2.52
17	Veraval	505	39.2	44.7	16.1	5.83
18	Veraval	1000	34.6	46.8	18.7	5.00
19	Porbandar	200	21.3	36.0	42.7	5.16
20	Porbandar	452	35.5	57.5	7.0	9.03
21	Porbandar	991	39.6	54.4	5.9	8.30

Table 3.7: Sediment characteristics during FORVSS Cruise 228

Station No	Transect	Depth (m)	Clay (%)	Silt (%)	Sand (%)	Organic Matter (%)
22	Goa	230	13.2	26.6	60.2	2.67
23	Goa	520	25.0	61.7	13.4	10.92
24	Goa	958	27.1	57.9	15.0	7.00
25	Ratnagiri	210	11.6	19.3	69.1	6.33
26	Ratnagiri	470	23.2	52.8	24.0	10.56
27	Ratnagiri	950	16.5	3.6	79.9	3.03
28	Dabhol	220	22.1	2.9	75.0	2.79
29	Dabhol	558	28.5	7.6	63.8	6.41
30	Dabhol	950	28.8	59.4	11.9	10.62
32	Mumbai 1	520	27.5	23.9	48.6	0.95
33	Mumbai 1	1000	18.4	29.6	52.0	10.03
34	Mumbai 2	200	16.2	21.9	61.9	2.91
35	Mumbai 2	490	24.2	58.5	17.4	12.82
36	Mumbai 2	1010	28.4	41.5	30.1	12.88
37	Veraval	202	20.7	55.0	24.3	3.62
38	Veraval	530	31.5	60.6	7.9	3.56
39	Veraval	1006	32.3	65.5	2.3	7.42
40	Porbandar	215	19.6	28.8	51.7	5.52
41	Porbandar	500	19.8	28.3	51.9	1.90
42	Porbandar	1025	25.4	56.5	18.1	2.20

Table 3.8: Sediment characteristics during FORVSS Cruise 254

Station No	Transect	Depth (m)	Clay (%)	Silt (%)	Sand (%)	Organic Matter (%)
43	Goa	203	4.7	5.2	90.1	3.32
44	Goa	491	20.6	72.5	7.0	11.39
45	Goa	847	22.8	65.7	11.4	8.66
46	Ratnagiri	200	6.6	15.3	78.1	3.92
47	Ratnagiri	521	19.6	73.3	7.1	11.87
48	Ratnagiri	860	18.4	74.1	7.5	8.07
49	Dabhol	218	20.3	59.0	20.7	11.63
50	Dabhol	503	21.2	73.8	5.0	16.02
51	Dabhol	817	23.5	61.9	14.6	9.14
52	Mumbai 1	242	2.6	4.6	92.8	2.73
53	Mumbai 1	575	21.1	71.1	7.8	14.36
54	Mumbai 1	878	21.1	66.9	12.0	9.85
55	Mumbai 2	213	3.2	6.4	90.3	3.68
56	Mumbai 2	540	19.4	76.1	4.5	17.56
57	Mumbai 2	850	24.0	75.2	0.7	6.17
58	Veraval	217	21.5	70.9	7.6	8.31
59	Veraval	534	16.3	70.3	13.4	2.02
60	Veraval	827	23.7	74.6	1.7	4.98
61	Porbandar	216	27.3	68.1	4.6	9.61
62	Porbandar	520	15.3	37.8	46.9	3.92
63	Porbandar	933	26.4	68.7	4.9	3.32

Chapter 4

STANDING STOCK OF MACROBENTHOS

Contents

4. 1. INTRODUCTION

In the history of ocean biology, systematic deep sea research (>200m) dates back to the year 1872 (H.M.S. Challenger). With the advancements in marine biology and development of effective sampling gears like grabs quantitative study on shallow water benthos were initiated (Peterson, 1915). However, the first quantitative assessment of deep-sea benthic fauna took place only in 1949 (Zenkevitch, 1963). Later Sanders et al., (1965) collected semi-quantitative samples using a modified anchor dredge, which was designed to haul at a given depth.

The density and biomass of marine benthic macrofauna generally shows exponential decline with increasing water depth, distance from land, and decreasing latitude from polar and temperate towards tropical latitudes (Rowe and Menzel, 1971; Rowe et al., 1974; Haedrich and Rowe, 1978; Gage and Tyler, 1991; Levin and Gooday, 2003; Wei et al., 2010; Degen et al., 2015). Several environmental as well as biological factors such as food availability, substrate characteristics and hydrodynamic processes are important in determining these patterns (Rosenberg, 1995).The limited availability of food in the deep sea leads to a higher share of smaller organisms in total community metabolism. Thiel's (1975) size structure hypothesis for the deep sea (i.e. low food concentration in the deep sea leads to a higher share of smaller organisms in total community metabolism) has been corroborated by more recent studies which found a decrease in mean body mass or body size with increasing water depth (McClain et al., 2006; Rex et al., 2006; Wei et al., 2010).

Annandale (1907) started benthic studies from the Indian waters. The quantitative studies on benthic fauna of Arabian Sea are much more recent, and the earlier reports belong to shallow subtidal areas and shelf of south west coast (Kurian, 1953; Seshappa, 1953). In the case of the west coast of India, majority of the qualitative studies on benthos have been restricted in and around various estuaries and in coastal waters (Damodaran, 1973; Parulekar et al., 1980; Vizakat et al., 1991; Ansari et al., 1994; Sarladevi et al., 1996; Gopalakrishna and Nair, 1998). Harkantra et al., (1980) reported that along the entire west coast of India, up to 75m, polychaetes were the most abundant group, followed by crustaceans and molluscs. Some authors have indicated the abundance of minor phyla like echiuroids, sipunculids (Harkantra and Parulekar, 1994) and echinoderms (Harkantra et al., 1980) in certain regions. In recent years, a number of detailed investigations on macrofauna along the continental margin of EAS based on both qualitative and quantitative aspects have emerged (Hughes et al., 2009; Gooday et al., 2009; Ingole et al., 2010; Musale and Desai, 2010; Smitha, 2011; Hunter et al., 2011, 2012; Abdul Jaleel, 2012; Joydas and Damodaran, 2014; Abdul Jaleel et al., 2014, 2015).

The benthos of the continental shelf of the east and west coast of India were subjected to detail investigation. As far as the abundance and biomass of shelf macrofauna is considered, it is found to be higher in the south west coast of India, when compared to the northwest, north east and south east coasts (Ganesh and Raman, 2007; Joydas and Damodaran, 2009; Damodaran, 2010). Both in the east and west coast, macrofaunal density and biomass decreased with increasing depth and the dominant group in terms of density was polychaetes, followed by crustaceans and mollusc (Ganesh and Raman, 2007; Jayaraj et al., 2007, 2008; Joydas and Damodaran, 2009; Damodaran, 2010).

The very first information on benthic community of the deeper parts of the eastern Arabian Sea (EAS) were gathered during the voyages of R.I.M.S. Investigator I and II between 1885 and 1925. A more or less azoic zone was described between 100-1200m depth of the western Indian continental margin, in the Arabian Sea (John Murray Expedition, 1933-1934). Subsequently, the International Indian Ocean Expedition (1962-65) revealed abundant benthic biomass in the deep Arabian Sea (Neyman et al., 1973). Based on the limited observations along deeper EAS, comparatively high biomass of benthos was reported between 500 and 600m, contrasting with relatively low standing crop between 800 and 900m (Parulekar et al., 1982a). In the central and western Indian Ocean, deep-sea benthic fauna including both macrofauna and meiofauna exhibit comparatively high biomass from 1500-2000m depth, and low biomass beyond 5500m, and concurrently decreasing density with increasing depth (Parulekar et al., 1982b). Along a single bathymetric transect of the south eastern Arabian Sea (SEAS) continental margin Ingole et al., (2010) documented lowest benthic biomass and densities within the OMZ region (1001m) along with a gradual increase in density and biomass of macrofauna at basin depths (~2500m).

More recently, a detailed study on macrobenthos from continental margin of the south eastern Arabian Sea was carried out, emphasising the taxonomic, ecological and zoogeographical importance of the area (Abdul Jaleel, 2012; Abdul Jaleel et al., 2014). The study was the first of its kind, surveying a substantially large area of the upper continental slope of the SEAS (7-15 ºN), with consistent and repeated sampling. Densities were found to be lowest along the most northerly transect where dissolved oxygen (DO) concentrations were extremely low (<0.15 ml/l, i.e.<6.7µmol l^{-1}). Beyond the realm of impact of the OMZ (i.e. mid-slope, ~1000 m), the density decreased while species diversity increased.

In recent years,the Arabian Sea margin has been subject to numerous studies with regards to benthos and influence of OMZ on macrofauna (Levin et al., 2000; Lamont and Gage, 2000; Cowie and Levin, 2009; Gooday et al., 2009; Hughes et al., 2009; Murthy et al., 2009; Levin et al., 2009; Hunter et al., 2011, 2012; Joydas and Damodaran, 2014; Ingole et al., 2010; Abdul Jaleel, 2012; Abdul Jaleel et al., 2014). Similarly benthic studies in relation to OMZ have also been conducted from the Bay Bengal (Rao, 2009; Sarma et al., 2013; Raman et al., 2014). The OMZ in the eastern Arabian Sea is located between 150 and 1500m depths (Helly and Levin, 2004; Hunter et al., 2011) and is more intense towards the north. In regions where OMZs are in contact with the seafloor they have a strong impact on the abundance and diversity of benthic organisms (Levin et al., 2000).

In the marine ecosystem, benthic invertebrates are considered to be important links in energy flow, from the standpoint of secondary production and also recycling of organic matter (Crisp, 1984). Quantitative data on benthos is a prerequisite for estimation of demersal fishery potential (Damodaran, 1973; Parulekar et al., 1982a). Such estimates are vital for developing rational management measures for fisheries and other marine natural resources.

This chapter describes the patterns in abundance and biomass of macrofauna in the continental margin beyond 200m in the North Eastern Arabian Sea (NEAS), in spatial and temporal scales as well as the quantitative contribution of various taxonomic groups of macrobenthos. This is the first attempt to employ consistent and seasonally resolved sampling across 7 transects and at 3 depths (21 sites).

4. 2. RESULTS

Data on abundance and biomass of macrofauna along north-western Indian continental margin were obtained by analysing 108grab samples collected over a wide latitudinal (1525’N to 21 30’N) as well as bathymetric range (200 to 1000 m), during three surveys in three seasons, investigating macrobenthos in relation with depth, latitude and season.

Density of macrobenthic faunal groups during the surveys is given in Tables 4.1 - 4.3. A total of 6583 organisms were collected in the grab samples, which were distributed in 10 diverse taxonomic groups. Of these, polychaete were the dominant (59%) followed by crustaceans (16%), mollusc (12%) and other groups (13%) (Figure 4.1). Other groups consists of all remaining taxa such as nemertines, echinoderms, sipunculids, fishes and anthozoans which were represented in few numbers. Macrobenthos was totally absent in some station during the sampling, and in some stations patchiness of polychaetes with high abundance was noted, which masked the overall trend in the study area, so these stations were excluded in detailed statistical analysis. The macrobenthic density varied between 8 Ind.m^{-2} (FORVSS 254, SM, Veraval, 200m) and 4099 Ind.m^{-2} (FORVSS 219, WIM, Ratnagiri, 500m), with an overall mean of 156.86±140 Ind.m^{-2}. Macrofaunal biomass was determined by weighing the organism in wet condition after the organism were sorted in to four major groups, i.e. polychaetes, crustaceans mollusc, and other groups. Biomass of macrobenthos ranged from 0.021 gm^{-2} (FORVSS 254,SM, Veraval 500m) to 58.43 gm^{-2} (FORVSS 228, Mumbai 2, 200m) with a mean of 1.76±2.1 gm^{-2} [Tables 4.4 - 4.6]. In the entire study area, polychaetes contributed 38% while crustaceans and molluscs contributed 16% and 12%, respectively [Figure 4.2].

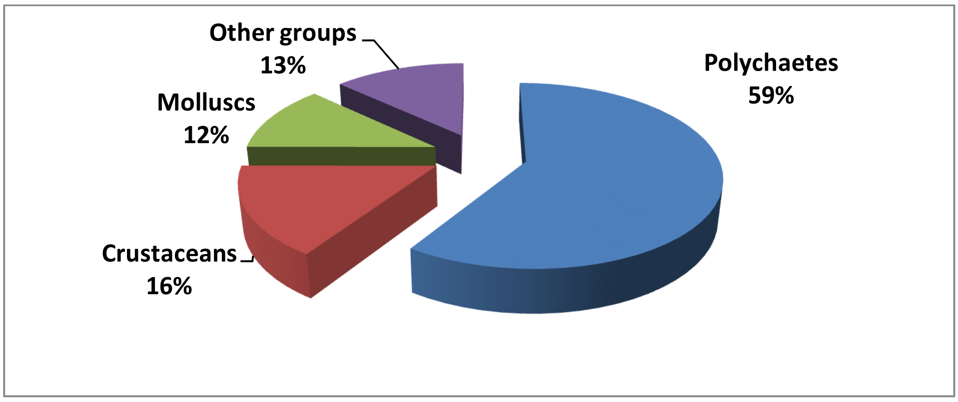


Figure 4.1. Relative density distribution of macrofaunal groups in the study area

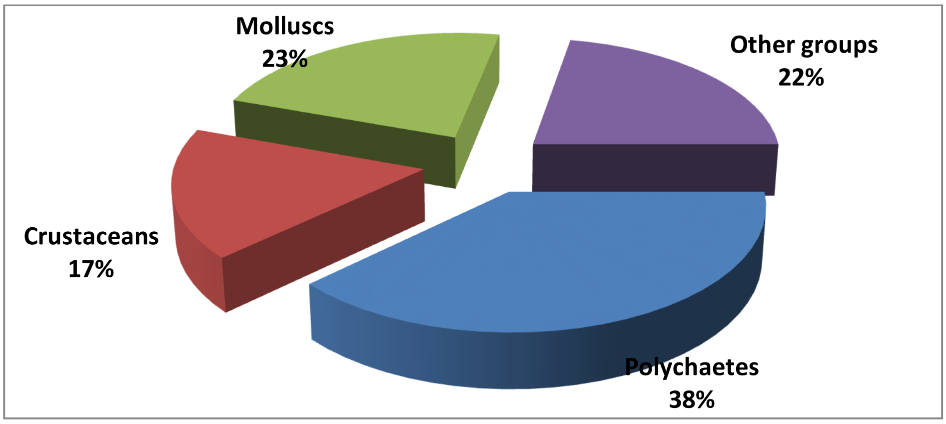


Figure 4.2. Relative Biomass distribution of macrofaunal groups in the study area

The ANOSIM tool was performed, as the data were in non-parametric in nature, to test the significant differences in density and biomass of macrofauna and faunal groups during the study. Density and biomass of macrofauna showed significant variation with depth (R=0.198 & 0.218 respectively with P=0.1%). There were no significant temporal as well as latitudinal variations in density and biomass in the present study.

4. 2. 1. Bathymetric variation in density and biomass

a) Macrofaunal density

As there were no significant temporal variations in numerical abundance between surveys [Figure 4.4] (ANOSIM R =0.164, P=4.3%), data from all three seasons were pooled and the mean density for each site was calculated (based on the 6 grab samples collected from each sampling sites) [Figure 4.3.]. Among the three depth categories, mean density was lowest at 200m (118±101.4Ind.m^{-2}) and highest at 1000m (216.71±155.83 Ind.m^{-2}), with intermediate values at 500m (128.28±136.28 Ind.m^{-2}) [Figure 4.5.]. The total macrofaunal density increased by 65% from 200 to 1000m, and the slope was curvilinear (R^2=0.4772) [Figure 4.6.]. Density increased by 13% from 200 to 500m, and further by 45% from 500m to 1000m. The mean density of macrofauna at each depth is summarised in Table 4.7.

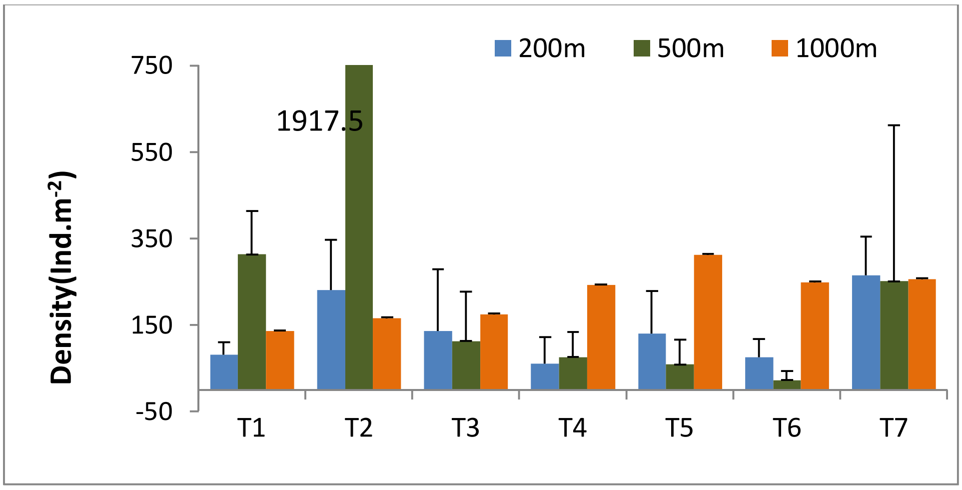


Figure 4.3. Mean density of macrofauna at each sampling site

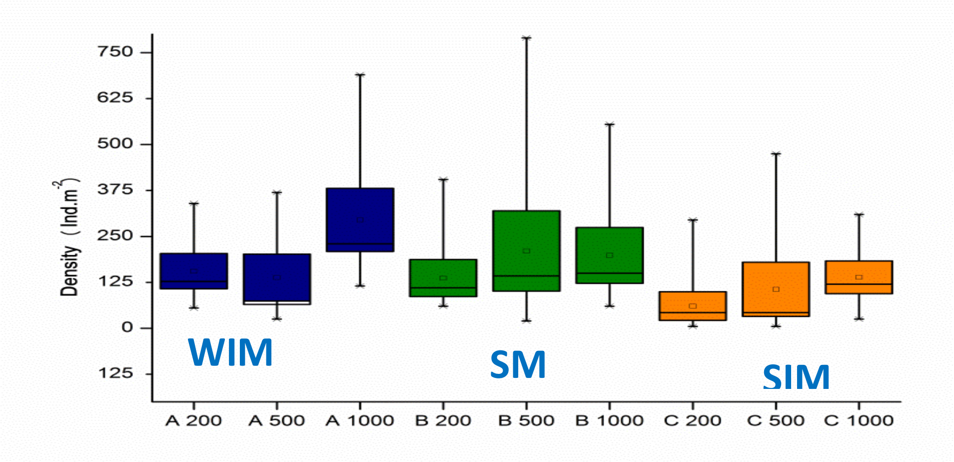


Figure 4.4 Mean density of macrofauna (for three depth classes in three seasons)

(Box: SD, Whisker: Range, Square: Mean) A: WIM, B: SM, C: SIM

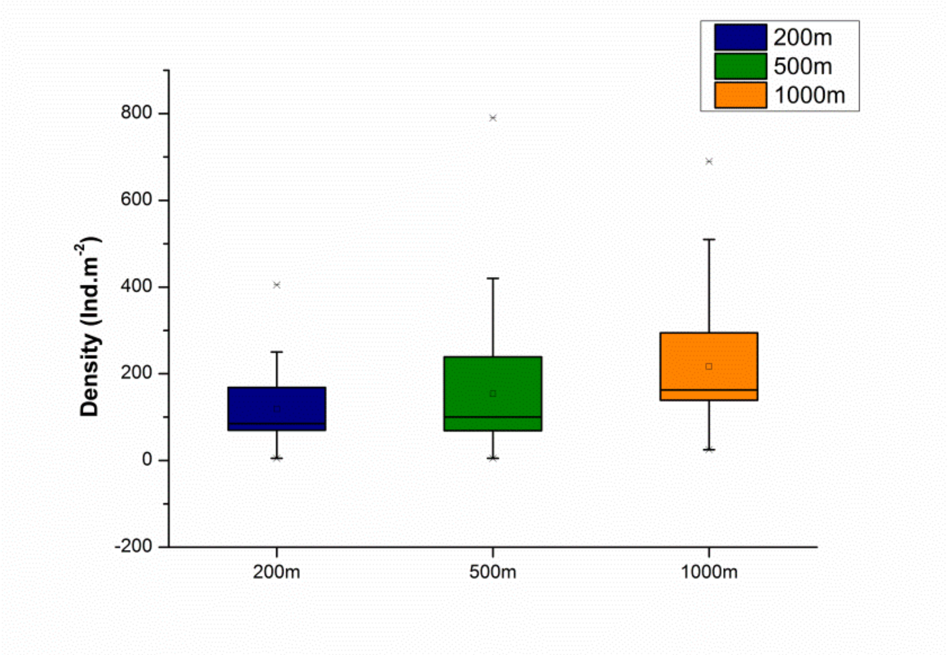


Figure 4.5 Mean density of macrofauna at each depth classes

(Box: SD, Whisker: Range, Square: Mean)

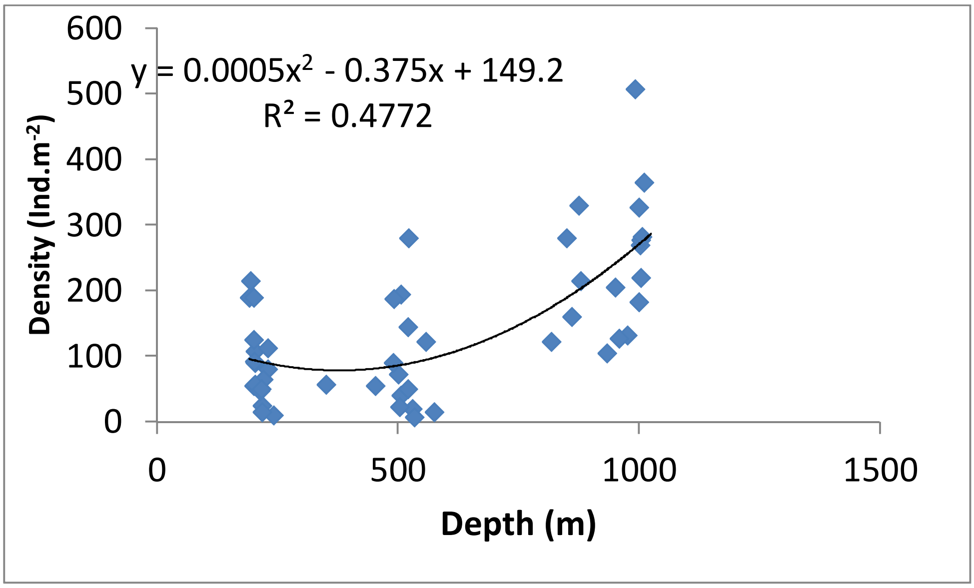


Figure 4.6. Scatter plot showing relation of faunal density with depth

At the 200m depth, the mean density was 160.43±89.68 Ind.m^{-2} in the WIM, 141.67±98.06 Ind.m^{-2} in the SM and 53.21±60.44 Ind.m^{-2} in the SIM [Table 4.7., Figure 4.4.]. The mean density at the 500m depth category were 132.5±128.86 Ind.m^{-2}, 192.5±180.52 Ind.m^{-2} and 89.58±105.45 Ind.m^{-2} in the WIM, SM and SIM seasons, respectively; while the values were 296.43±115.24 Ind.m^{-2}, 161.43±106.29 Ind.m^{-2} and 128.21±77.82 Ind.m^{-2} at the 1000m depth category. In the SIM, the mean density was slightly lower, when compared to the WIM and SM.

b) Macrofaunal biomass

The mean biomass at sites ranged between 0.052±0.05 gm^{-2} (500m, Veraval) and12.039±20.61, (500m, Ratnagiri). [Figure 4.7]. The lowest mean biomass was found at the 200m depth (1.22±1.72 gm^{-2}) and highest at 1000m (2.09±1.67gm^{-2}); with an intermediate value at 500m (1.29±2gm^{-2}) [Figure 4.9.]. The total macrofaunal biomass increased by 71% from 200 to 1000m, and this variation with depth was found to be statistically significant (ANOSIM R =0.218, P=0.1%) [Figure 4.9]. From 200 to 500m the increase in biomass was about 6%, and it increased further by 62% from 500m to 1000m. Similar variation in biomass with depth was seen in three seasons [Table 4.8., Figure 4.8]. At the shelf edges (200m depth ranges), the mean biomass was 1.67 ±1.76 gm^{-2}, 1.36±2.3 and 0.66±1 gm^{-2} during WIM, SM and SIM seasons respectively [Table 4.8., Figure 4.8.]. Mean biomass distribution at upper slope region was 1.77 ±3.22 gm^{-2}, 1.37±2.1 and 0.73±1.15 gm^{-2} during WIM, SM and SIM seasons respectively Mean biomass values at the mid slope region (1000m), were 2.62±1.5 gm^{-2}, 2.57±1.9 gm^{-2} and 1.09±1.19 gm^{-2} during the WIM, SM and SIM seasons, respectively.

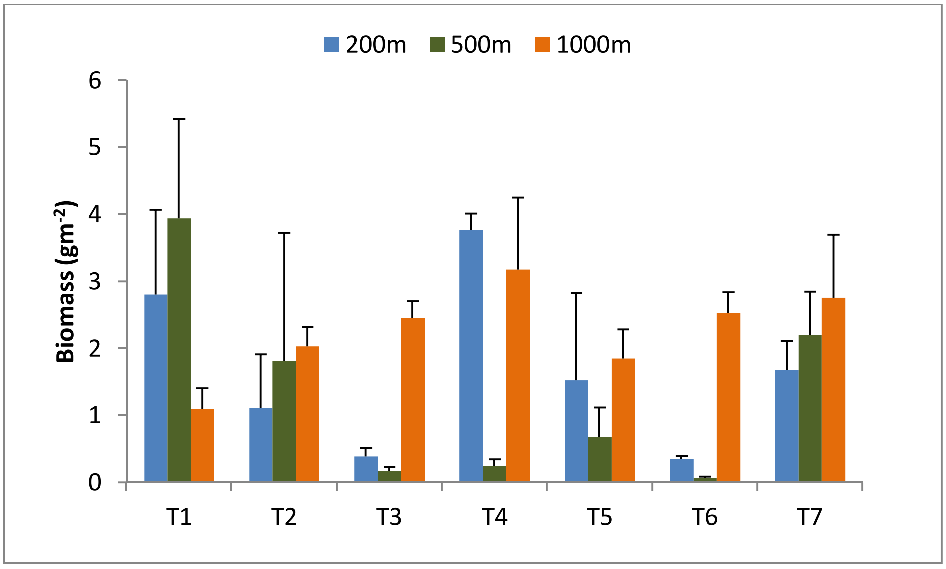


Figure 4.7. Mean biomass of macrofauna at each sampling site

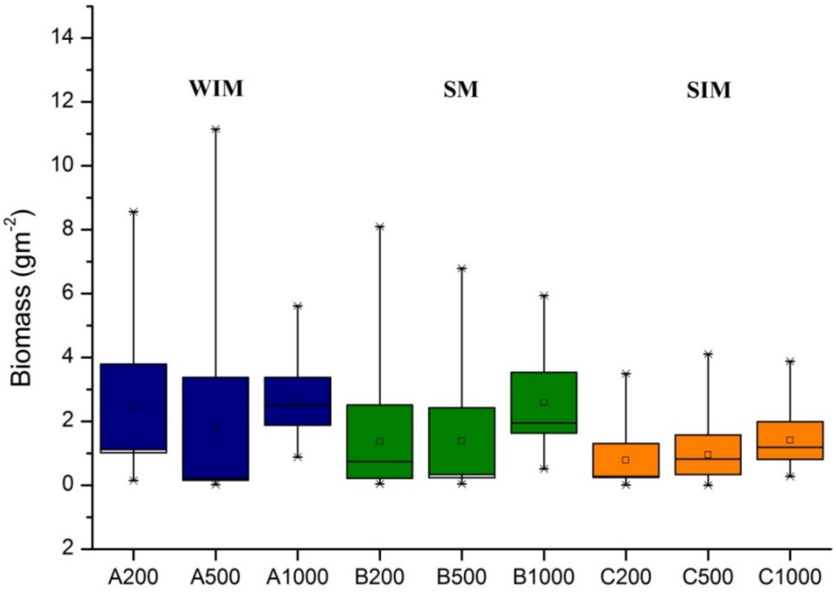


Figure 4.8. Mean biomass of macrofauna (for three depth classes in three surveys) (Box: SD, Whisker: Range, Square: Mean) A: WIM , B: SM, C: SIM

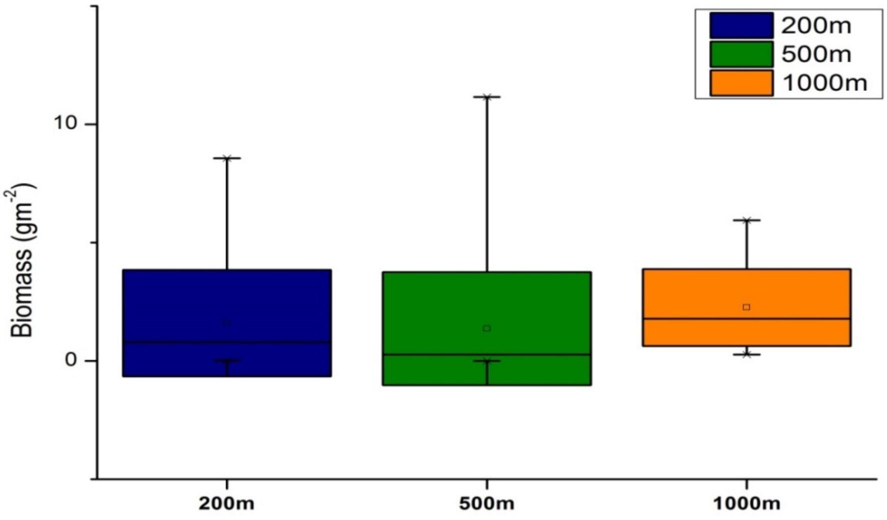


Figure 4.9. Mean biomass of macrofauna at the three depth classes

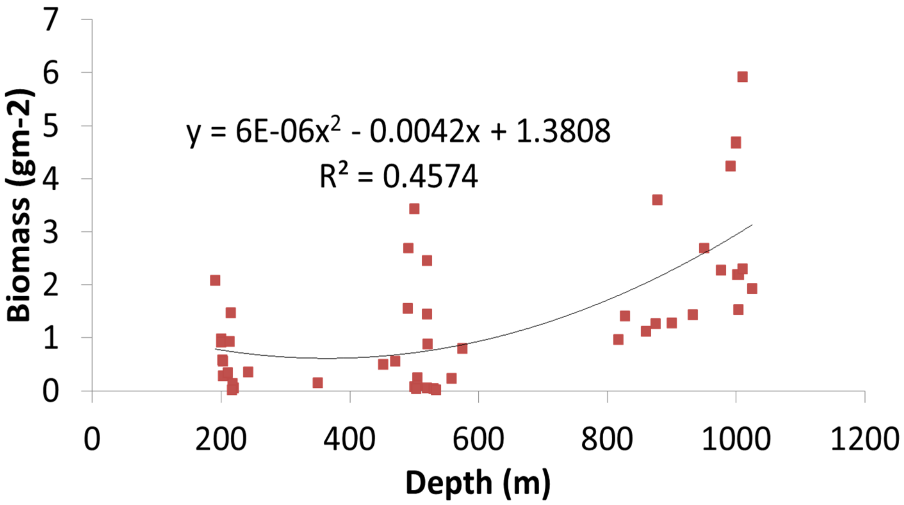


Figure 4.10. Scatter plot showing relation of faunal biomass with depth

4. 2. 2. Latitudinal and temporal variation in density and biomass

The bathymetric transects sampled during the study were situated about 1° apart, and environmental characteristics such sediment texture, organic content and dissolved oxygen also showed progressive changes along the study area. Distinct distribution patterns and faunal composition was noticed at various transects. Macrofaunal density and biomass of at each site during the three surveys is presented in Tables 4.1.- 4.6.

Latitudinal variation in numerical abundance of macrobenthos at each site is presented in Figure 4.3. Even though there was no significant variation in density between latitudes (ANOSIM R =0.11, P=10.1%) and surveys (ANOSIM R =0.128, P=6.4%), some transects showed considerable deviation from the general observed patterns. The mean density at the shelf edge (200m) was lowest at Porbandar (53.33±89 Ind.m^{-2}) and highest at Ratnagiri (231.66±115 Ind.m^{-2}). At the upper slope region (500m), the minimum value was recorded at Veraval (23±19 Ind.m^{-2}) and maximum at Goa (313.33±100 Ind.m^{-2}) and at deeper mid-slope region (1000m) sites, the densities werelower at Goa (135±77 Ind.m^{-2}) and highest at Mumbai 2 (313±152 Ind.m^{-2}). The northern transects, especially Mumbai, Veraval and Porbandar were characterised by relatively low macrofaunal density than the southernmost transect particularly in shallow depth strata. In all transects, mean macrobenthic densities were highest at the deeper sites (1000m) except at Ratnagiri, where the density maximum was recorded at the shelf edge.

Total biomass varied with transects and seasons, but the variation were not found to be statistically significant (latitude: ANOSIM R = 0.048, P=9.4%; season: R = -0.024, P=86.2%). At the shelf edge (200m), the mean biomass was lowest at Veraval (0.295±0.31 gm^{-2}) and highest at Goa (2.801±3.99 gm^{-2}). Temporal variation in total macrofaunal biomass at this depth was readily apparent at Goa [Figure 4.7]. In the upper slope (500m), the mean macrofaunal biomass was relatively high at Goa (3.943±3.73 gm^{-2}) and low at Veraval (0.052±0.049 gm^{-2}). The total macrofaunal biomass progressively decreased from Goa, northwards up to Veraval in the upper slope area. A remarkable observation during the study was that the biomass at 500m sites towards the north were extremely low when compared to other sites. Mean macrofaunal biomass at mid slope sites were highest at Mumbai 1 and lowest at Goa, with values3.177±1.78 gm^{-2} and 1.09±0.75

gm^{-2} respectively. At this depth class, seasonal variations were found to be high at Veraval [Figure 4.7].

4. 2. 3. Density and biomass of major faunal groups

Macrofauna is composed of various taxa such as annelids, crustaceans, molluscs, fishes, echinoderms, nemertines, echiuroids and sipunculids, for the purpose of analysis, according to the contribution to the total density and biomass of macrofauna, they were grouped into Polychaetes, Crustaceans, Molluscs and other groups. Other groups include echinoderms, nemertines, echiuroids and sipunculids in minor abundance. The percentage contribution of major groups to the density and biomass of macrofauna at each depth category are shown in Figure 4.11&4.12.

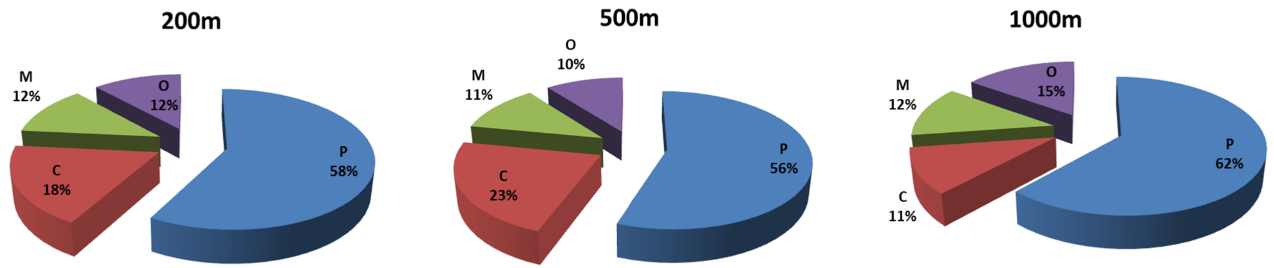


Figure 4.11. Contribution of major faunal groups to density of macrobenthos at each depth ranges. P: Polychaetes, C: Crustaceans, M: Molluscs & O: Other Groups

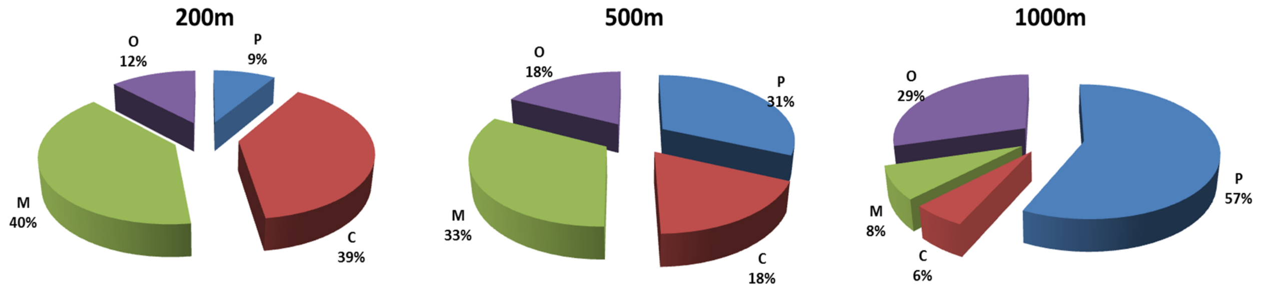


Figure 4.12. Contribution of major faunal groups to biomass of macrobenthos at each depth ranges P: Polychaetes, C: Crustaceans, M: Molluscs & O: Other Groups

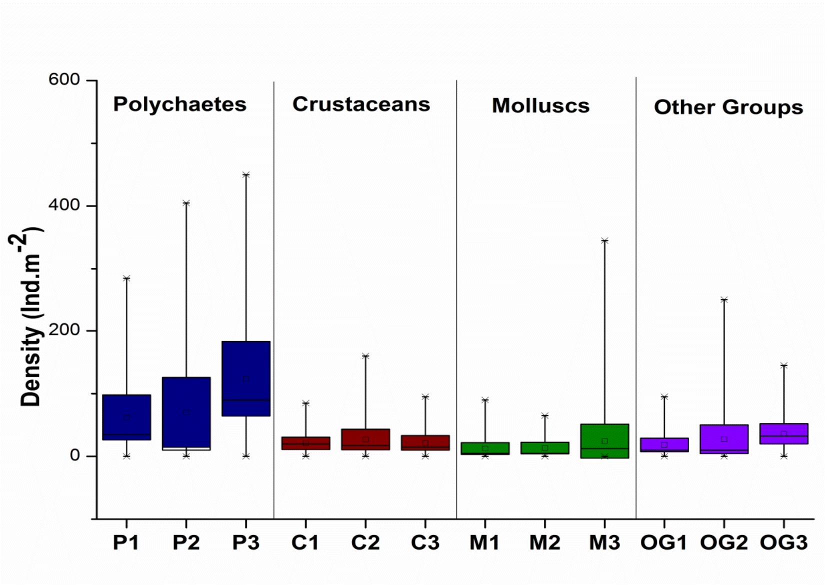


Figure 4.13 . Mean densities of the macrofaunal groups at each depth class. P: Polychaetes, C: Crustaceans, M: Molluscs, OG: Other Groups, 1: 200m, 2: 500m , 3: 1000m

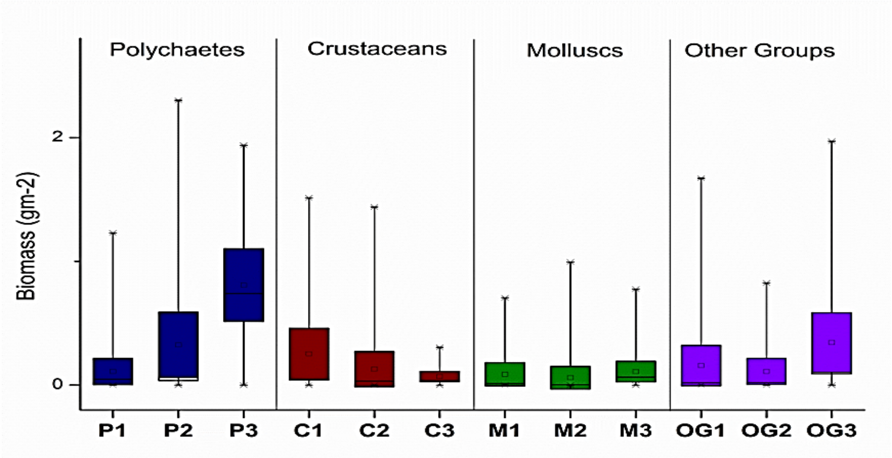


Figure 4.14. Mean biomass of the macrofaunal groups at each depth class P: Polychaetes, C: Crustaceans, M: Molluscs, OG: Other Groups. 1:200m, 2: 500m, 3: 1000m.

Mean density and biomass of the macrofaunal groups in the three depth classes are shown in figure 4.13 and 4.14.

a) Polychaetes

Polychaetes were the principal group in terms of number of individuals, representing 59% of all organisms collected during the study. Their densities exceeded 50% of total macrofauna in all depth classes, while the biomass varied considerably from 9 to 57% of total macrofauna. The abundance of polychaetes reflected that of macrofauna as a whole. Polychaete density has shown considerable variation, it varied between nil values and 3750 Ind.m^{-2} (FORVSS 219, Ratnagiri 500m) in the entire study [Tables 4.1.- 4.3.]. There was no significant difference in polychaete density between seasons or surveys (ANOSIM R =0.02, P=9.2%), but the differences between depth classes were found to be statistically significant (ANOSIM R =0.212, P=0.1%). The mean density of polychaete varied appreciably with depth, and the mean value was found to be highest at 1000m (126.92±762.039 Ind.m^{-2}) and lowest at 200m (58.97±356.7 Ind.m^{-2}), with an intermediate value at 500m (66.39±391.63 Ind.m^{-2}) [Figure 4.13]. Mean polychaete density for the entire study area was found to be 84.09±503.5 Ind.m^{-2}. The relative abundance of this group was 58%, 56% and 62%, at 200m, 500m and 1000m respectively [Figure 4.11].

The mean density of polychaetes at 200m was 75.36±60.9 Ind.m^{-2}, 70.42±86.0 Ind.m^{-2} and 30.77±62.2 Ind.m^{-2} during WIM, SM and SIM seasons, respectively. At 500m depth, the mean density was 71.82 ±118.8

Ind.m^{-2}, 68.33±101.5 Ind.m^{-2} and 55.71±112.9 Ind.m^{-2}, respectively during WIM, SM and SIM seasons. At the 1000m depth, the mean density decreased from WIM and SM to SIM respectively as follows 172.5±116.9 Ind.m^{-2}, 101.79±137.1 Ind.m^{-2} and 79.29±83.1 Ind.m^{-2}

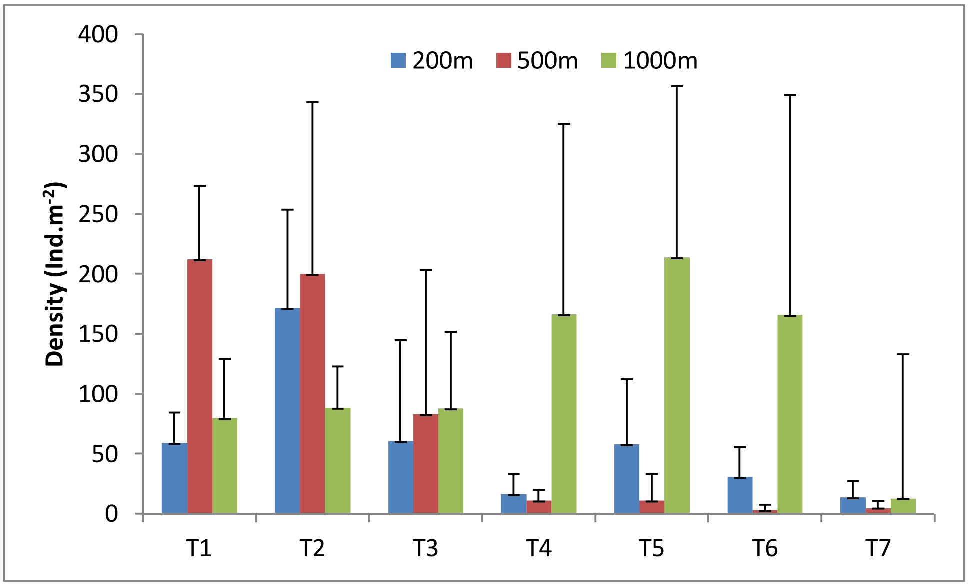


Figure 4.15. Density of polychaetes at each sampling site

Mean polychaete density at each site is presented in Figure 4.15. At the 200m depth, highest mean polychaete density was observed at Ratnagiri (171.66±81.59 Ind.m^{-2}), while the lowest density was at Porbandar (14±12.94 Ind.m^{-2}). Variation in density was noticed between surveys at the mid slope of northern transects. During the WIM and SM season, polychaetes were found in high abundance at deeper sites of Mumbai1, Mumbai 2, Veraval and Porbandar, but the abundance decreased to meagre levels or absence during SIM season.

The biomass of polychaetes ranged between nil and 5.560 gm^{-2} (SM, Dabhol 500m) [Table 4.4. - 4.6.], with a contribution of 38% to the total macrofaunal biomass in the study area [Figure 4.2]. There was no significant difference in the biomass between surveys (ANOSIM R =0.01, P=24.7%) but the bathymetric variations were found to be statistically significant (ANOSIM R =0.247, P=0.1%). Latitudinal variations were also found to be of no significance (ANOSIM R =0.001, P=47.7%). The mean biomass increased with increasing depth and the value was 0.02± 0.03 gm^{-2} at 200m, 0.08± 0.14 gm^{-2} at 500m and 0.24±0.23 gm^{-2} at 1000m [Figure 4.14]. In the entire study, polychaete biomass showed an increasing trend with depth and the relative contribution of this group to total biomass were 9% at 200m, 31% at 500m, and 57% at 1000m [Figure 4.12].

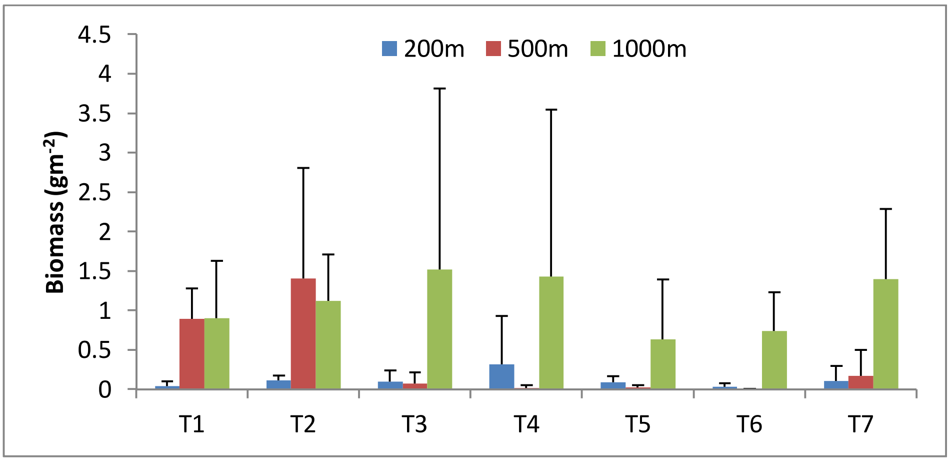


Figure 4.16. Biomass of polychaetes at each sampling site

Biomass of polychaete for each sampling site is presented in Figure 4.16. Among the 200m sites, comparatively high biomass was recorded Mumbai 1 (T4, 0.32±0.6 gm^{-2}), while low values were recorded at Veraval

(T6, 0.04±0.03 gm^{-2}). At 500m depth, the mean polychaete biomass was highest at Ratnagiri (1.41±1.39 gm^{-2}), while Veraval (0.0027±0.003 gm^{-2}) recorded the lowest biomass. At 1000m depth category, the mean polychaete biomass value was highest at Dabhol (1.52±2.29 gm^{-2}) with highest standard deviation and lowest at Mumbai 2 (0.63±0.76 gm^{-2}).

b) Crustaceans

Crustaceans were chiefly represented by the amphipods, decapods, post larval stages and ostracods, while other groups such as isopods, caprellids, tanaids and cumaceans were also recorded in some stations. Density of crustaceans in the study area varied from nil (SIM, Mumbai 1 &2 at 500m) to 410 $Ind.m^{-2}$ (SM, Porbandar at 500m) [Tables 4.1.- 4.3.]. Mean density of crustaceans at each site is presented in Figure 4.17. There were no significant differences between depth classes (ANOSIM R =0.017, P=80.1%) and between latitudes (ANOSIM R =0.041, P=6.4%). Relatively higher densities of crustaceans were recorded during the SM season when compared to WIM and SIM season. Though mean density variation was not statistically significant among the three depth class, crustaceans mean density was highest at 500m (27.92±32.43 $Ind.m^{-2}$)and lowest at 200m (20.83±19.55 $Ind.m^{-2}$)with an intermediate value at 1000m depth (22.76±23.38 $Ind.m^{-2}$). Their abundance contributed about 18% of macrofauna at 200m, 23 % at 500m and 11% at 1000m [Figure 4.11.]. Amphipods were among the more consistently abundant group among crustaceans, which were represented in most of the sites and contributed more than 50% to the total crustacean density. Decapods were the second dominant group among crustaceans, which contributing 24% to total crustacean abundance. Ostracods (9.14%), mysids (2.9%), cumaceans (2.49%), tanaids (2.08%), isopods (1.66%) and caprellids (1.52%) were relatively less abundant.

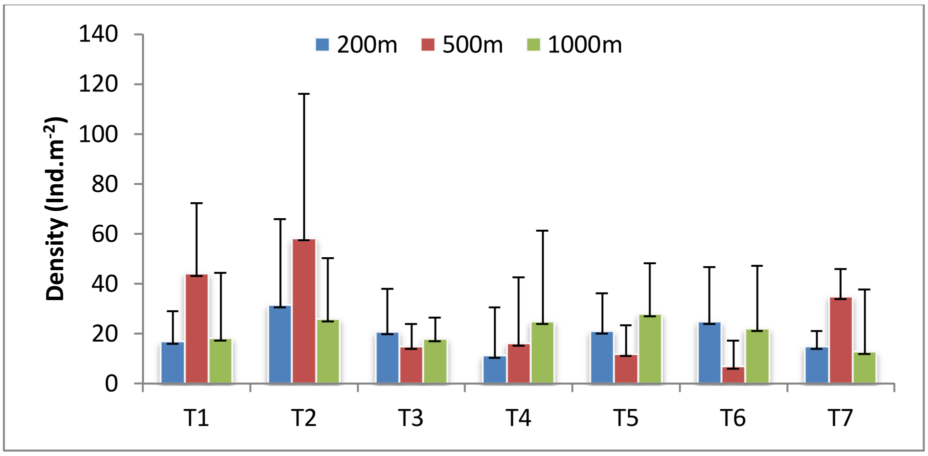


Figure 4.17. Density of crustaceans at each sampling site

Crustacean biomass in the study area ranged from nil (SIM, Mumbai 1 &2 at 500m) to 3.31 gm^{-2} (WIM, Goa 200m) [Tables 4.1.- 4.3.] with a mean of 0.26±0.75 gm^{-2},and formed about 17% of the total biomass [Figure 4.2.]. At 200m, the biomass value ranged between 0.05±0.09 (T4, Mumbai 1) and 1.12±2.25 gm^{-2} (T1, Goa) with a mean of 0.46±1.1 gm^{-2}. At 500m, the range was 0.014±0.016 (T4, Mumbai 1) to 0.70±1.05 gm^{-2} (T1, Goa) with a mean of 0.2±0.53 gm^{-2} and at 1000m, the range was from 0.04±0.06 (T6, Veraval) to 0.42±0.87 gm^{-2} (T2, Ratnagiri) (mean, 0.12±0.36 gm^{-2}). The biomass of crustacean at each sampling site is presented in Figure 4.18. Crustaceans contributed about 39%, 18% and 6% to the total biomass at 200m, 500m and 1000m respectively [Figure 4.12].The mean biomass of crustaceans in each depth class is shown in Figure 32.

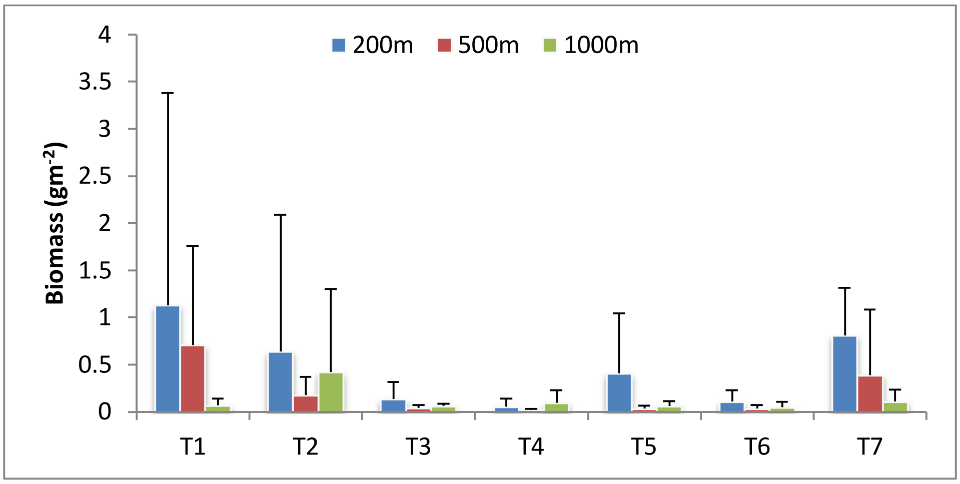


Figure 4.18. Biomass of crustaceans at each sampling site

c) Molluscs

Among the molluscs, the bivalves constituted a major group followed by gastropods and scaphopods. *Amygdalum anoxicolum* was one of the dominant bivalves obtained and which was represented in the several stations. Small gastropods were well represented in the study area. Some of the species identified were *Crassatella* sp., *Acila* sp., *Ancilla* sp., etc.

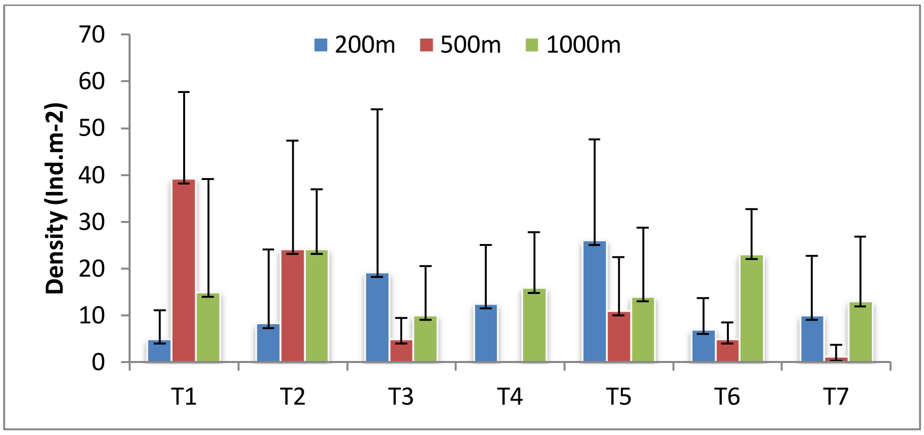


Figure 4.19. Density of molluscs at each sampling site

The mean density of molluscs at each sampling site is shown in figure 4.19. The highest abundance of molluscs was obtained at the 1000m depth category (17.02±14.64 Ind.m^{-2}) and lowest abundance was at 200m (12.63±18.80 Ind.m^{-2}) and intermediate density was at 500m (13.75±18.41 Ind.m^{-2}) [Figure 4.11]. Spatio-temporal variation in density and biomass of mollusc was statistically not significant.

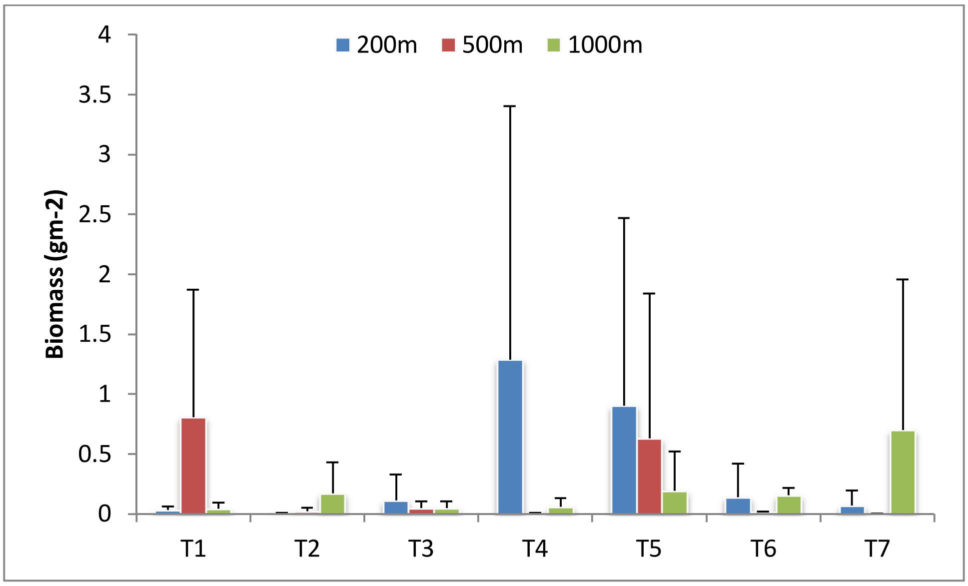


Figure 4.20. Biomass of molluscs at each sampling site

The wet weight of mollusc was taken with shell, but larger specimens (>3g) were not included when considering mean values. Mollusc represented about 23% of the total biomass [Figure 4.2.]. Biomass of mollusc varied from nil to 57 gm^{-2} [Tables 4.4.- 4.6.] with an average of 0.23±0.69 gm^{-2} for the present study. The biomass of molluscs at each sampling site is given in Figure 4.20. There was no noticeable difference in mean biomass values between depth category even though a slight decrease in mean biomass of mollusc with depth was as observed, with high values (0.30±0.91 gm^{-2}) at shallow depth (200m), lowest values (0.18±0.49 gm^{-2}) at deeper stations (1000m) and intermediate value at 500m (0.21±0.62 gm^{-2}) [Figure 4.14].

d) Other Groups

Other groups represented in the samples were echinoderms, foraminiferans (large sized), ophiuroids, nematodes, nemertines, oligochaetes, sipunculids, fishes etc. These groups contributed more than 10% to the total density in the study area [Figure 4.1]. The biomass of these groups varied from nil to 4.23 gm^{-2} [Table 4.4.- 4.6.] and they accounted for 22% of total macrofaunal biomass in the entire study [Figure 4.2.]. Figures 4.21&4.22 depict the mean densities and biomass of these groups.

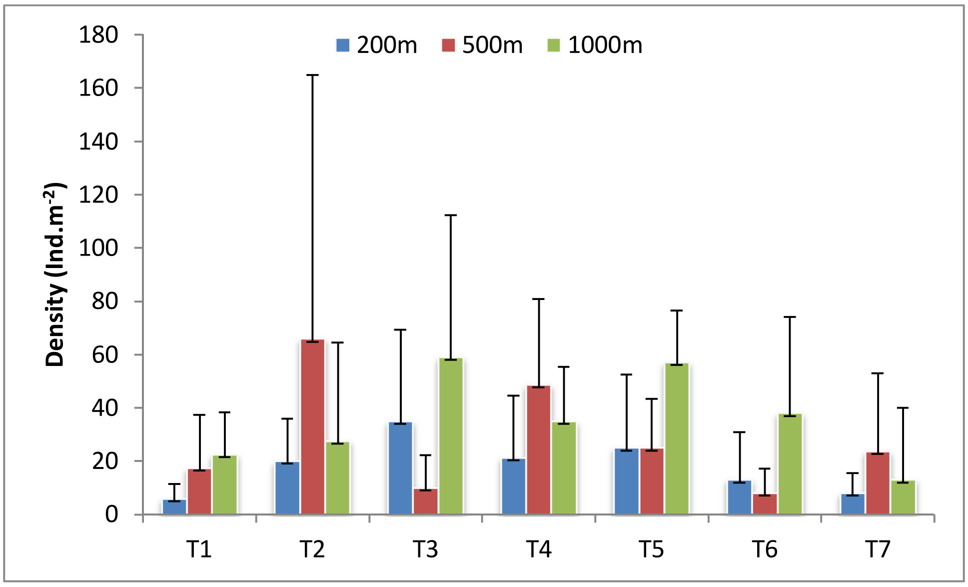


Figure 4.21. Density of 'other groups' at each sampling site

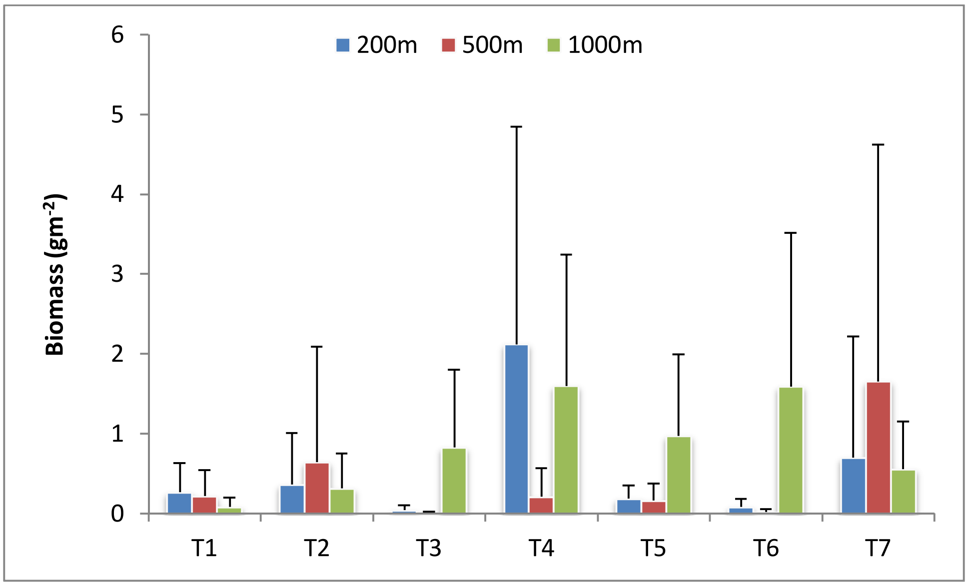


Figure 4.22. **Biomass of 'other groups' at each sampling site**

4. 2. 4. Influence of environmental characteristics on standing stock

Analysis of environmental parameters revealed that they vary with depth and latitudes in the study area (detailed in Chapter 3). Values of density and biomass were tested for correlation with the measured environmental variables using Spearman's correlation, as the data were non-parametric in nature. Sediment texture characteristics and hydrographical parameters were used for this analysis. Results of the analyses are presented in Table 4.9.

Macrofaunal density, showed significant correlation with hydrographical parameters and geographical parameters. Total macrofaunal density showed weak negative correlation with temperature ($r=-0.330$, $p<0.01$) and salinity($r=-0.158, p<0.01$) while it displayed positive correlation with DO($r=0.257, p<0.05$), depth($r=0.262$, $p<0.05$) and latitude($r=0.260$, $p<0.05$). Polychaete density correlated negatively with temperature($r=-0.394, p<0.01$) and salinity($r=-0.652$, $p<0.01$) and positively correlated with depth($r=0.293$, $p<0.05$) and latitude($r=0.431$, $p<0.01$). Crustacean density (with silt; $r=-0.280$, $p<0.05$)and other groups density (with clay; $r=0.412$, $p<0.01$) are the only density parameters having direct correlation with textural characteristics of the sediments. Organic matter did not show correlation with density.

Macrofaunal biomass was negatively correlated with bottom water DO ($r=-\ 0.392$, $p<0.01$) and positive correlation with clay ($r=0.257$, $p<0.05$). Among the biomass variables, only polychaete biomass correlated with temperature ($r=-0.329$, $p<0.01$) and salinity ($r=-0.454$, $p<0.01$) of bottom water. Total biomass was negatively correlated with clay ($r=-0.314$, $p=0.005$) and silt content ($r=-0.356$, $p=0.001$) while it was positively correlated with sand ($r=0.377$, $p=0.001$).As in the case of density, organic matter content of the sediment did not show any correlation with biomass. Other abiotic parameters, did not show any correlation with biomass variables are silt and latitude.

4. 2. 5. Trophic support to fishery

The average macrobenthic biomass for the study region was found to be 1.76 gm^{-2} (1760 kg km^{-2}). According to Sanders (1956), most species of macrobenthos have a life span of about one year and the annual production is about twice the standing crop for these organisms. Considering this opinion and using the conversion factor of Parulekar et al.,(1980), according to which dry weight is equivalent to 22% of wet weight and organic carbon is 34.5% of dry weight, the annual macrofaunal production in the study area is about 267.168 kgC $km^{-2}yr^{-1}$. The organic carbon value for the study area, where total area is 26,620 km^2 (Sanjeevan et al., 2010) is $7.1x10^6$ kgC yr^{-1}. According to the laws of energy transfer, 10% of total organic carbon is expected to be assimilated by the next trophic level. For coastal waters, 60% of the live weight is expected to be fishes and for offshore waters 40% is considered to be represented by fish (Steel, 1974). This value is converted to live weight by multiplication by a factor of 10. By this calculation, the macrofauna of the study area alone can be said to contribute to about 0.03mTof fish biomass.

4. 3. DISCUSSION

A total of 108 grab samples collected during 3 surveys from 63 sampling stations yielded 10 diverse taxonomic groups of macrofauna. Of the total fauna, 54% organisms were polychaetes, followed by crustaceans (19%) and other groups (16%), while molluscs contributed only 11%. Polychaetes represent a major component of macrobenthic assemblages, in terms of abundance, diversity and biomass, at every bathymetric level (Gambi and Giangrande, 1986; Abbiati et al., 1987; Baldrighi et al., 2013; Langeneck et al., 2017). A concurrent study in the south eastern Arabian Sea (SEAS) reported polychaetes as the dominant component, representing over 70% of total macrofauna (Abdul Jaleel, 2012). Along the OMZ impinged margin of the north western Bay of Bengal also, polychaetes were the major macrofaunal group and contributed about 91% of total abundance (Rao, 2009).

Density of macrofauna varied from total absence in many shallow stations to 4099 Ind. /m^2 (Ratnagiri 500m). Macrofaunal exhibited a higher density and biomass at higher depth during the present study. Even though the density showed a general increasing trend towards higher depth (1000m), the increase is not uniform since lowest value were at the mid depth (500m), rather with that of shallow (200m). In general benthic assemblages on continental slopes show bathymetric patterns of decreasing abundance related to decreasing food availability, oceanographic processes and local-scale ecological processes (Hessler and Sanders, 1967; Dayton and Hessler, 1972; Rowe et al., 1974, 1982; Rowe, 1983; Gage and Tyler, 1991; Etter and Grassle, 1992; Flach and Heip, 1996; Cosson et al., 1997; Levin et al., 2001; Gage, 2002; Carney, 2005; Rex et al., 2006; Wei et al., 2010; Bernadino et al., 2016; Vedenin et al., 2016).

Even though abundance and biomass of macrofauna showed significant variation with depth, there was no significant temporal as well as latitudinal variation in standing crop. Previous studies conducted in the eastern Arabian Sea (EAS) margin reported an inverse relationship of faunal density with depth (Parulekar et al., 1982 a, b). A study conducted by Ingole et al., (2010) in the north eastern Arabian Sea observed lowest abundance at 525m depth (528±156 Ind.m^{-2}) and relatively high biomass was recorded at the shelf edge and upper slope, i.e. at 102m and 525m with a lowest biomass at 1001m. Studies conducted along the continental shelf of the EAS as a whole reported a similar depth-related declining pattern in abundance and biomass of macrobenthos up to 200m (Damodaran, 2010). Standing crop of macrofauna in the SEAS continental slope showed high abundance along shelf edge and upper slope with a decreasing density towards the deep (Abdul Jaleel, 2012). Simultaneous studies conducted along the north west margin of Bay of Bengal also revealed a sharp decline from 200 to 1000m (Rao, 2009). From the Bay of Bengal margin, Raman et al., (2014) observed that depth played an important role in faunal abundance/diversity and its relationship remains parabolic for total macrofauna. In contrast to the above observations, distribution pattern of macrofauna in the NEAS showed increasing trend towards deeper areas, but the abundance was more or less similar to the isobathic sites of the SEAS (Abdul Jaleel, 2012). It is difficult to compare present study quantitatively to other similar studies along the margin of Pakistan, Oman etc. principally because of the difference in sampling techniques.

The eastern Arabian Sea, represents a series of complex environments including a thick permanent, oxygen depleted zone or OMZ (Flach and Thomsen, 1998; Tselepides et al., 2000; Palma et al., 2005; Acharya and Panigrahi, 2016). Even though, it is one among the most biologically productive regions (Ryther and Menzel, 1965), mainly due to the upwelling during the summer monsoon and convective mixing during the winter monsoon (Madhupratap et al., 1996; Wiggert et al., 2005). Deep sea benthic biological and biogeochemical process within the OMZ were investigated in the Indian Ocean region, the Oman margin in the NW Arabian Sea (Levin et al., 2000) and more recently on the Pakistan slope (Gooday et al., 2009; Hughes et al., 2009; Levin et al., 2009b; Murty et al., 2009) and the West Indian shelf in the eastern Arabian Sea (Ingole et al., 2010; Hunter et al., 2011, 2012; Levin et al., 2013; Joydas and Damodaran, 2014). The structure of macrofaunal communities in OMZs usually shows reduced diversity and high dominance in comparison with non-OMZ slope environments (Levin et al., 2001). Since macrofauna of the OMZs are generally dominated by small-bodied polychaetes, often biomass is reduced. It has been proven that deep-sea macrobenthos abundance, biomass, diversity and size spectra are varying in relation to the OMZ or the bottom-water oxygen concentration (Rosenberg et al., 1983; Arntz et al., 1991; Levin et al., 2000, 2002, 2003, 2009b; Gallardo et al., 2004; Palma et al., 2005; Quiroga et al., 2005; Gooday et al., 2009; Hughes et al., 2009; Sellanes et al., 2010; Raman et al., 2014).

Previous studies of open-ocean OMZ benthos have observed high densities of hypoxic-tolerant faunas aggregating in the lower part of the OMZ (Thompson et al., 1985; Levin 2003; Hughes et al., 2009). A number of studies are available on the bathyal macrobenthos in relation to the OMZ (DO <0.5 ml/l) from different regions of the world Ocean: Chile margin (Gallardo et al., 2004; Palma et al., 2005; Quiroga et al., 2005; Sellanes et al., 2007, 2010); Peru margin (Levin et al., 2002; Gutierrez et al., 2006); off Namibia (Zettler et al., 2009, 2013). Many authors have also reviewed current knowledge on macrobenthic community structure and diversity under OMZs conditions (Diaz and Rosenberg, 1995; Levin and Gage, 1998; Rogers, 2000; Levin et al., 2001, 2002, 2009a; Gray et al., 2002; Levin 2003; Gooday et al., 2010; Levin and Sibuet, 2012; Raman et al., 2014). Previous investigations on benthic fauna in relation to OMZs established that exteme OMZ have a profound impact on both qualitative and quantitate aspect of benthic fauna and the present study in the NEAS reinforced and elaborated the existing foundation.

The Arabian Sea OMZ impinges upon the Indian continental margin at bathyal depths (100-1500m) resulting in changes in oxygen availability and sediment geochemistry, causing faunal abundance decrease in the shelf edge and upper slopes areas (200 and 500 m sites) of the present study, while standing crop increases at depth (1000m) where OMZ conditions relax noticeably.

A concurrent study on macrofaunal communities (>500 µm) in the South Eastern Arabian Sea (SEAS) continental margin (200–1000 m) between 7° 00′and 14° 30′ N latitudes (Abdul Jaleel, 2012) revealed that the biomass of macrofauna exhibited considerable spatial variation in which depth wise variation was highly significant. This study observed dominance of small sized organisms at 200m and comparatively larger ones in the deeper sites; hence decrease in biomass was not as significant as that of density. A similar observation was made from the present study also. Mean individual size of the dominant group polychaetes at each depth were as follows, 0.005±0.007gm (200m); 0.006±0.012 gm (500m) and 0.024±0.037gm (1000m). Among the three depth categories studied along the SEAS, highest macrobenthic biomass was observed at the ~200m depth (7.52±4.47gm^{-2}), whereas in the case of NEAS, highest value was observed at 1000m (2.26±1.63 gm^{-2}) followed by 200m (1.56±2.22 gm^{-2}). The mean biomass for the NEAS margin as a whole was found to be 1.76±2.1 gm^{-2}, while in the SEAS, it is found to be 6.03±3.73 gm^{-2}. The influence of

Arabian Sea OMZ is diminishing towards the SEAS region. It is minimal or absent in the southernmost transect (Cape Comorin, lat. ~7° 10' and long. 77° 20') and where density is 1555±193 Ind.m^{-2} with a biomass of 7.64±4.52 gm^{-2}. The oxygen concentration of the site was in the range of 0.245-1.12 ml/l. The southern transects, especially Cape (872±570 Ind.m^{-2}) and Kollam (982±505 Ind.m^{-2}) had relatively high macrobenthic density and the northernmost transect of SEAS (Karwar, 412±291 Ind.m^{-2}) had the lowest density. The OMZ impact on macrofauna is assumed to start from the Karwar transect, which lies in the northernmost part of the SEAS. The main difference of NEAS macrofauna density and biomass to that of SEAS margin is that under the extreme OMZ the faunal standing stock was poor in the northern part of the NEAS, while the OMZ conditions were considerably less intense in the southern part of the NEAS and further south (SEAS). An almost similar trend of increasing standing stock was observed at deeper depth strata where OMZ relaxed considerably.

Along thenorth western Bay of Bengal margin, benthic macrofauna recorded a sharp decline in density from 200-1000m more or less similar results, with a mean abundance of 1230 Ind.m^{-2}. Beyond the continental shelf (~200-500m) and upper slope, coinciding with the OMZ, there was a rise in the macrofaunal abundance (mean 2300 nos.m^{-2}). On the basis of the findings presented in Rao (2009), information on macrofauna are gathered for inshore locations, shelf area and the upper slope. In the case of inshore locations, mean biomass showed a tendency to increase with depth i.e. 4.9, 7.5, 8.4 g.m^{-2} at 10m, 20m and 30m respectively. Beyond this depth biomass decreased (5.4, 5.8, 4.2, 2.0 and 1.5g.m^{-2} at 30, 50, 100, 150 and 150 to 200m respectively). A steady rise in the biomass was observed in the upper slope (~200-500m, 5.62- 5.98 gm^{-2}). However biomass decreased to the minimum at 1000m ($0.6g.m^{-2}$).

A comprehensive analysis of standing stock in the deep-sea benthos by Rex et al., (2006) revealed that the upper continental slope is characterised by high macrofaunal biomass, which decreases with depth more rapidly than that of smaller sized benthic groups (Rowe and Menzel, 1971; Rowe et al., 1974). Studies conducted by various workers from different regions of the world ocean revealed that extreme OMZ conditions have a profound impact on both qualitative and quantitate aspect of benthic fauna (Levin et al., 2001, 2002, 2003, 2009a; Gallardo et al., 2004; Palma et al., 2005; Quiroga et al., 2005; Gutierrez et al., 2006; Sellanes et al., 2007, 2010; Zettler et al., 2009, 2013; Hughes et al., 2009; Gooday et al., 2010; Ingole et al., 2010; Levin and Sibuet, 2012; Hunter et al., 2011, 2012; Raman et al., 2014).

Table 4.1.Density of macrofauna (Ind.m^{-2}) during FORVSS Cruise 219

Station No:	Transect	Depth (m)	Poly-chaete	Crust-acea	Mollusc	Other Groups	TOTAL
1	Goa	203	95	30	5	0	130
2	Goa	503	225	63	53	28	369
3	Goa	1003	130	43	30	18	221
4	Ratnagiri	191	120	43	0	28	191
5	Ratnagiri	470	3750	118	48	183	4099
6	Ratnagiri	976	53	28	23	31	135
7	Dabhol	200	168	35	45	72	320
8	Dabhol	505	160	13	5	18	196
9	Dabhol	1002	118	25	20	108	271
10	Mumbai 1	230	30	23	20	44	117
11	Mumbai 1	500	8	5	0	61	74
12	Mumbai 1	875	265	25	20	21	331
13	Mumbai 2	194	100	28	38	52	218
14	Mumbai 2	350	0	18	8	34	60
15	Mumbai 2	1004	168	18	28	66	280
16	Veraval	203	23	48	5	15	91
17	Veraval	505	3	15	5	18	41
18	Veraval	1000	225	13	28	63	329
19	Porbandar	200	13	20	10	13	56
20	Porbandar	452	0	20	0	35	55
21	Porbandar	991	250	43	175	40	508

Table 4.2.Density of macrofauna (Ind.m-2) during FORVSS Cruise

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Station No.	Transect	Depth (m)	Poly-chaetes	Crust-aceans	Moll-uscs	Other Groups	Total
22	Goa	230	60	15	5	5	85
23	Goa	520	275	45	45	25	390
24	Goa	1050	80	5	15	35	135
25	Ratnagiri	210	160	60	20	30	270
26	Ratnagiri	470	1320	40	25	20	1405
27	Ratnagiri	950	90	45	20	55	210
28	Dabhol	220	15	15	5	35	70
29	Dabhol	558	85	20	10	10	125
30	Dabhol	1010	20	10	0	20	50
31	Mumbai 1	200	Not sampled				
32	Mumbai 1	520	10	30	0	35	75
33	Mumbai 1	1000	120	95	30	60	305
34	Mumbai 2	200	25	10	25	5	65
35	Mumbai 2	490	30	15	20	30	95
36	Mumbai 2	1010	25	15	5	10	55
37	Veraval	202	55	15	5	20	95
38	Veraval	530	10	5	5	0	20
39	Veraval	1006	185	45	25	30	285
40	Porbandar	215	25	240	0	0	265
41	Porbandar	500	10	410	0	30	450
42	Porbandar	1025	25	10	10	45	90

Table 4.3.Density of macrofauna (Ind.m^{-2}) during FORVSS Cruise 254

Station No:	Transect	Depth (m)	Poly-chaete	Crust-aceans	Moll-uscs	Other Groups	Total
43	Goa	203	30	13	10	8	60
44	Goa	491	115	20	28	0	163
45	Goa	847	30	3	10	15	58
46	Ratnagiri	200	143	23	0	18	183
47	Ratnagiri	521	240	13	20	8	280
48	Ratnagiri	860	120	30	5	0	155
49	Dabhol	218	0	8	15	3	25
50	Dabhol	503	0	3	13	3	18
51	Dabhol	817	83	5	10	23	120
52	Mumbai 1	242	3	5	0	0	8
53	Mumbai 1	575	10	0	0	5	15
54	Mumbai 1	878	160	13	3	25	200
55	Mumbai 2	213	13	5	15	8	40
56	Mumbai 2	540	0	0	0	0	0
57	Mumbai 2	850	210	8	5	23	245
58	Veraval	217	0	8	0	0	8
59	Veraval	534	0	5	0	8	13
60	Veraval	827	10	10	0	5	25
61	Porbandar	216	0	30	5	15	50
62	Porbandar	520	0	5	45	0	50
63	Porbandar	933	45	40	10	0	95

Table 4.4.Biomass of macrofauna (gm^{-2}) during FORVSS Cruise 219

Station No.	Transect	Depth (m)	Poly-chaetes	Crust-aceans	Moll-uscs	Other Groups	Total
1	Goa	203	0.080	3.310	0.043	0.003	3.435
2	Goa	503	1.015	0.528	4.563	0.578	6.683
3	Goa	1003	1.225	0.150	0.035	0.125	1.535
4	Ratnagiri	191	0.143	1.818	0.000	0.125	2.085
5	Ratnagiri	470	3.058	0.368	30.530	1.880	35.835
6	Ratnagiri	976	1.433	0.088	0.023	0.733	2.275
7	Dabhol	200	0.273	0.365	0.303	0.025	0.965
8	Dabhol	505	0.173	0.010	0.048	0.013	0.243
9	Dabhol	1002	0.388	0.085	0.110	1.610	2.193
10	Mumbai 1	230	0.640	0.095	2.215	4.228	7.178
11	Mumbai 1	500	0.008	0.013	0.000	0.053	0.073
12	Mumbai 1	875	0.875	0.268	0.098	0.020	1.260
13	Mumbai 2	194	0.153	0.210	1.768	0.143	2.273
14	Mumbai 2	350	0.000	0.060	0.010	0.075	0.145
15	Mumbai 2	1004	0.438	0.008	0.395	1.355	2.195
16	Veraval	203	0.033	0.243	0.008	0.005	0.288
17	Veraval	505	0.003	0.050	0.008	0.043	0.103
18	Veraval	1000	0.920	0.023	0.190	3.565	4.698
19	Porbandar	200	0.023	0.768	0.155	0.028	0.973
20	Porbandar	452	0.000	0.005	0.000	0.495	0.500
21	Porbandar	991	1.868	0.160	1.550	0.660	4.238

Table 4.5. Biomass of macrofauna (gm^{-2}) during FORVSS Cruise 228

Station No.	Transect	Depth (m)	Poly-chaetes	Crust-aceans	Moll-uscs	Other Groups	Total
22	Goa	230	0.035	0.045	4.030	0.307	4.417
23	Goa	520	1.041	0.039	1.287	0.082	2.449
24	Goa	1050	1.051	0.049	0.065	0.119	1.284
25	Ratnagiri	210	0.133	0.091	0.000	0.122	0.346
26	Ratnagiri	470	0.459	0.037	0.039	0.026	0.560
27	Ratnagiri	950	0.879	1.168	0.430	0.218	2.695
28	Dabhol	220	0.028	0.003	0.012	0.014	0.058
29	Dabhol	558	0.064	0.061	0.085	0.039	0.249
30	Dabhol	1010	5.560	0.056	0.000	0.310	5.925
31	Mumbai 1	200	Not sampled				
32	Mumbai 1	520	0.008	0.032	0.009	0.000	0.050
33	Mumbai 1	1000	2.820	0.000	0.000	1.849	4.669
34	Mumbai 2	200	0.131	0.084	57.813	0.397	58.424
35	Mumbai 2	490	0.051	0.004	1.246	0.254	1.554
36	Mumbai 2	1010	1.065	0.109	0.066	1.059	2.299
37	Veraval	202	0.062	0.015	0.640	0.189	0.906
38	Veraval	530	0.006	0.015	0.017	0.000	0.038
39	Veraval	1006	0.285	0.090	0.166	0.385	0.926
40	Porbandar	215	0.246	1.219	0.000	0.000	1.465
41	Porbandar	500	0.341	0.041	0.000	3.059	3.442
42	Porbandar	1025	0.932	0.103	0.176	0.720	1.930

Table 4.6. Biomass of macrofauna (gm^{-2}) during FORVSS Cruise 254

Station No:	Transect	Depth (m)	Poly-chaetes	Crust-aceans	Moll-uscs	Other Groups	Total
43	Goa	203	0.028	0.028	0.014	0.332	0.374
44	Goa	490.9	0.639	0.523	0.290	0.000	0.813
45	Goa	847	0.429	0.020	0.000	0.005	0.026
46	Ratnagiri	200	0.077	0.007	0.000	0.837	0.845
47	Ratnagiri	521	0.709	0.025	0.119	0.025	0.169
48	Ratnagiri	860	1.055	0.055	0.009	0.000	0.064
49	Dabhol	218	0.000	0.013	0.036	0.061	0.110
50	Dabhol	503	0.000	0.000	0.041	0.001	0.042
51	Dabhol	817	0.636	0.002	0.025	0.323	0.350
52	Mumbai 1	242	0.005	0.035	0.000	0.000	0.035
53	Mumbai 1	575	0.062	0.000	0.000	0.742	0.742
54	Mumbai 1	878	0.605	0.632	0.007	2.924	3.562
55	Mumbai 2	213	0.017	0.032	0.757	0.125	0.913
56	Mumbai 2	540	0.000	0.000	0.000	0.000	0.000
57	Mumbai 2	850	0.168	0.019	0.049	0.038	0.105
58	Veraval	217	0.000	0.024	0.000	0.000	0.024
59	Veraval	534	0.000	0.019	0.000	0.002	0.021
60	Veraval	827	1.319	0.065	0.000	0.021	0.086
61	Porbandar	216	0.000	0.027	0.051	3.412	3.490
62	Porbandar	520	0.000	0.004	1.439	0.000	1.443
63	Porbandar	933	1.393	0.023	0.013	0.000	0.036

Table 4.7. Range & mean density (Ind.m^{-2}) of macrofauna at three depths

	WIM	SM	SIM
200m	56-320 (160.43±89.68)	65-270 (141.67±98.06)	7.5-182.5 (53.21±60.44)
500m	41-369 (132.5±128.86)	20-450 (192.5±180.52)	12.5-280 (89.58±109.4)
1000m	135-508 (296.43±115.24)	50-305 (161.43±106.29)	25-245 (128.21±77.82)

Table 4.8. Range & mean biomass (gm^{-2}) of macrofauna at three depths

	WIM	SM	SIM
200m	0.29-3.44 (1.66±1.76)	0.06- 4.42 (1.36±2.29)	0.01-1.75 (0.66±1.0)
500m	0.07-6.68 (1.77±3.22)	0.04-3.44 (1.38±2.1)	0.-2.69 (0.73±1.15)
1000m	1.26-4.7 (2.63±1.5)	0.93-5.93 (2.58±1.9)	0.14-3.60 (1.09±1.19)

Table 4.9: Spearman correlation analysis of standing stock of macrofaunal groups with environmental variables

	Temperature	Salinity	DO	OM	Clay	Silt	Sand	Depth	Latitude
Polychaete Density	**-0.394**	**-0.652**	0.225	0.163	0.217	-0.020	-0.096	**0.293**	**-0.431**
Crustacean Density	0.020	**-0.275**	**0.303**	-0.092	0.240	**-0.280**	0.046	-0.040	0.075
Molluscan Density	**-0.277**	**-0.383**	0.094	0.212	0.237	-0.047	-0.071	0.196	0.240
Others Density	**-0.311**	**-0.380**	**0.303**	-0.045	**0.412**	-0.227	0.056	**0.273**	0.032
Total macrofaunal Density	**-0.330**	**-0.518**	**0.257**	0.073	0.250	-0.120	-0.038	**0.262**	**0.260**
Polychaetes Biomass	**-0.329**	**-0.454**	-0.168	0.082	**0.293**	0.233	**-0.357**	**0.296**	0.211
Crustacean Biomass	0.120	-0.244	**-0.252**	-0.026	0.179	0.119	-0.223	-0.089	0.113
Molluscan Biomass	-0.040	-0.198	**-0.285**	0.153	**0.259**	0.149	**-0.275**	0.019	0.059
Others Biomass	-0.033	-0.199	**-0.358**	0.164	**0.291**	0.092	-0.209	0.016	0.044
Total Biomass	0.021	-0.244	**-0.392**	0.113	**0.257**	0.085	-0.227	-0.028	0.059

*Values in **bold** are significance level $p < 0.05$; **shaded** cells are p value <0.01*

Chapter 5

DIVERSITY AND COMMUNITY STRUCTURE OF POLYCHAETES

5. 1. INTRODUCTION

Long professed as a stable environment, the deep sea is actually dynamic and heterogonous over various spatio-temporal scales (Glover et al., 2010; Rex and Etter, 2010). Continental margins are considered major reservoirs of marine biodiversity harbouring millions of species spanning across 33 phyla of which many are exclusively marine (Sanders and Hessler, 1969; Rex, 1983; Etter and Grassle, 1992; Snelgrove et al., 1992; Levin et al., 2001; Brandt et al., 2007). While biodiversity patterns are still poorly described on most continental margins, recent studies show that margin biodiversity is correlated with a range of ecosystem functions and services (Danovaro et al., 2007; Levin and Sibuet, 2012). The vast pool of biodiversity on continental margins, are summed across many margin habitat types e.g. cold seeps (Cordes et al., 2008, 2010), coral mounds

(Buhl-Morthensen et al., 2010), foraminifera beds (Gooday et al., 1998, 2010), open slopes and oxygen minimum zones (Levin et al., 2010).

Most of the species diversity in marine ecosystems comprises of invertebrates living in (infauna) or on (epifauna) sediments. The benthos reside within the sediments in these habitats form one of the richest reservoirs of biodiversity in the oceans and perhaps on earth itself (Snelgrove, 1999). The most dominant constituents of macrofauna are the polychaetes (Phylum Annelida, class Polychaeta). They are ubiquitous in distribution both in terms of abundance and diversity, over varying habitats ranging from estuaries and shallow sub tidal areas to deep sea (Fauchald, 1977; Grassle and Maciolek, 1992, Ward and Hutchings, 1996; Blake and Grassle 1994; Levin et al., 2000, 2009; Narayanaswamy, 2005; Hughes et al., 2009). They are a key component of marine ecosystems (Grassle and Macioleck, 1992; Paterson et al., 2009), with approximately 12,000 taxonomically valid species (Hutchings and Fauchald, 2000; Jirkov, 2001; Rouse and Pleijel, 2001) in more than 85 families (Fauchald and Rouse, 1997; Read, 2014), and with an additional ~6000 species yet to be discovered (Appeltans et al., 2012). However, more phylogenetic analyses of species, genus and family relationships are needed to unravel the true diversity of Polychaeta (Reusher, 2013). From the deep sea as a whole 768 species were recorded belonging to 52 families (Paterson et al., 2009).The fossil record of this class dates back to the lower Cambrian (Conway Morris and Peel, 2008; Vinther et al., 2011), and suggests that most family clades were present prior to the break-up of Pangea. Polychaetes appeared to have survived all consequent major extinction events (Reuscher, 2013).

Polychaetes are widespread, with species that live in the coldest ocean temperatures of the abyssal plain, to forms which can tolerate the extremely high temperatures near hydrothermal vents. They have developed different living strategies to help them adapt to such adverse habitats; which includes, morphological as well as physiological adaptations, diverse feeding and reproductive modes. The use of polychaetes for assessing health of marine environment has been widely accepted (Sivadas et al., 2010; Murugesan et al., 2011). Some opportunistic polychaete species take advantage and responded quickly to environmental perturbations (Grassle and Grassle, 1974; Levin et al., 2000; Paterson et al., 2011; Abdul Jaleel et al., 2015). Since they form the major component of soft sediment macrofauna, polychaete community patterns mirrored the distribution pattern of macrobenthic fauna as a whole (Fauchald, 1973; Hughes et al., 2009; Abdul Jaleel et al., 2014).

Polychaetes depend on organic matter produced in the euphotic zone for their nourishment, directly or indirectly. They show varying modes of feeding which includes omnivory and carnivory, obtaining food either by scavenging or predation, deposit feeding, by consuming bottom sediments as a whole only digesting the organic materials present in it, and suspension feeding, by filtering out organic particles from the overlaying waters. Based on observations of shallow-water species, each polychaete family have been assigned one or several functional groups, i.e. groups that utilise the same resource in similar ways (Gaston, 1987; Jumars et al., 2015).The classification proposed by Fauchald and Jumars (1979) had long been the only work on functional groups of polychaetes, and consequently has been extensively used in studies on polychaete community structure (> 1600 citations). However, in recent years the knowledge on polychaete morphology, life habits, and phylogeny has gained momentum (Penry and Jumars, 1990; Lindsay and Woodin, 1995; Rouse and Pleijel, 2001; Mistri et al., 2002, Guieb et al., 2004; Tzetlin and Purschke, 2005; Struck et al., 2011; Würzberg et al., 2011). Jumars et al., (2015) proposed a revised definition of polychaete functional groups, since recent studies suggests that many polychaete species may be multimodal and may adapt to utilize what resources are available. Also advanced techniques such as isotope, fatty acid analyses, or feeding experiments become more frequent in the deep sea (Levin et al., 1999; Witte et al., 2003; Sweetman and Witte, 2008; Jeffreys et al., 2013). Trophic interactions of polychaetes have been described from many slope regions of the Northern Indian Ocean, in the continental margin of Pakistan (Hughes et al., 2009), Oman (Levin et al., 2000) and India (Ingole et al., 2010; Abdul Jaleel, 2012; Abdul Jaleel et al, 2014).

Deep sea polychaetes are mainly dominated by deposit feeders (Hessler and Jumars, 1974; Paterson et al., 1998; Glover et al., 2001; Aberle and Witte, 2003; Sweetman and Witte, 2008) which more or less continuously ingest food particles (Jumars et al., 2015). The deposit feeding polychaetes play a crucial role in marine ecosystems, by acting as channels for sedimentary organic matter to return back to the marine food web, by forming primary food sources for other benthic as well as bentho-pelagic fauna. The deposit-feeding and burrowing activity of polychaetes enhance bioturbation, which ultimately results in the degradation or redistribution of organic matter within sediment layers (Fauchald and Jumars, 1979; Levin et al., 1997). Suspension feeders gather material from the water column and they typically decrease in overall significance with increasing depth (Jumars and Gallagher, 1982; Gage and Tyler, 1991). Carnivores, which select and prey upon other living organisms and are generally rare in deep-sea communities (Jumars and Gallagher, 1982). Compared with other feeding types, carnivores are more strongly affected by the decrease in food availability in the deep sea. Pelagic larval stages of polychaetes enrich the pelagic plankton community and form a food source for many organisms in the water column. The significant role of polychaetes in the benthic food web as well as their importance to the pelagic communities in the form of planktonic larvae, makes them of high importance in benthic-pelagic coupling processes. Polychaetes also directly interact with infaunal meiofauna, protists and bacteria *via* competition, predation and facilitation process (Levin and Edesa, 1997; Levin et al., 1997; Van Nugteren et al., 2009).

In an ecosystem, biodiversity can be measured in several ways. The identification of organisms at species level is the basis of all such studies. A community is often defined as "a group of organisms inhabiting a particular environment, interacting with each other and with environment which is separable from the other groups by means of ecological survey" (Mills, 1969). Major community properties are the number of species present and the measures of species diversity. The different approaches used to describe a community includes (a) physical (by discrete habitat boundaries), (b) taxonomical (by the identity of dominant indicator species), (c) interactive (by the existence of strong interaction among the species) and (d) statistical (by pattern of assemblages of various species) (Morin, 1999).

Deep sea community as a whole shows two large-scale diversity patterns: (i) a latitudinal gradient of decreasing alpha diversity (From the equator to the poles; Rex, 1981; Rex et al., 1993, 2000; Rex and Etter, 2010) and (ii) a parabolic bathymetric distribution (Paterson and Lambshead, 1995). The latitudinal gradient is much more noticeable in the North Atlantic with a drop in species richness of gastropods, isopod and bivalves in the North Atlantic (Rex et al., 1993; Rex and Etter, 2010).There is still discussion are going on about the existence of latitudinal gradients of diversity. The parabolic depth pattern is principally well established with peaks at intermediate (i.e. bathyal) depths and reduced levels of diversity at upper bathyal and abyssal depths (Rex, 1981, 1983; Maciolek et al., 1987; Etter and Grassle 1992; Paterson and Lambshead, 1995; Levin et al., 2001; Rex and Etter, 2010). However, this depth pattern is not universal for all areas and the depth at which this peak occurs varies between different taxa (Rex et al., 1997, Bett, 2001; Stuart et al., 2003). Gray (1997) opined that generality of these hypotheses are in dispute since more quantitatively comparable data is needed from the tropical areas and southern hemisphere to prove or disprove the hypothesis. The above-mentioned findings and the scarcity of such comprehensive data highlight the need for systematic regional scale studies on deep sea benthos.

Benthic community composition and diversity is influenced by the quality and quantity of food inputs (Gooday and Turley, 1990; Ruhl and Smith, 2004) and hydrodynamic disturbance (Thistle et al., 1985; Grassle and Morse-Porteous, 1987), as well as by water depth (Jumars and Gallagher, 1982; Flach et al., 2002), sediment grain size (Etter and Grassle, 1992; Leduc et al., 2012b), sediment mobility (Levin et al., 1994a) and bottom-water oxygen concentration (Levin et al., 2000). Rex et al., (1997) opined that ecological, oceanographic and historical processes influence diversity on spatial and temporal scales. Among the environmental parameters that impact the benthic fauna on the continental margin of the Arabian Sea, oxygen and organic matter are of particular importance (Hunter et al., 2011, 2012). Several recent studies have described changes in the structure and composition of benthic faunas across OMZs, including the Arabian Sea OMZ (reviewed in Levin, 2003, Levin et al., 2009; Hunter et al., 2011, 2012; Raman et al., 2014). Studies conducted by Ingole et al., (2010) and Abdul Jaleel et al., (2014) reported that there is reduction in diversity and dominance of some polychaete taxa in the OMZ core region of western Indian continental margin.

Continental margin biodiversity is facing growing threats from anthropologic activities such as bottom fishing, oil and gas extraction, and sewage dumping (Smitha et al., 2008; Ramirez-Llodra et al., 2010; Levin and Sibuet, 2012). Therefore, attempts to describe and quantify continental margin biodiversity patterns are important to identify biodiversity hotspots and to develop conservation policies, which may include designation of areas for permanent protection within the framework of marine protected areas (Smitha et al., 2008; Ramirez-Llodra et al., 2010; Levin and Sibuet, 2012). The present study aims to generate a base line information on diversity and distribution of polychaetes in a well-known OMZ impacted continental margin of the NEAS.

5. 2. RESULTS

5. 2. 1. Univariate indices of polychaete diversity

A total of 121 polychaete species were collected from 3 repeated surveys at twenty one sampling sites, falling in 66 genera and 24 families. The families with highest number of species identified were Ampharetidae (17), Sabellidae (15), Paraonidae (13), Spionidae (10) and Capitellidae (8). These families together contributed 52% of the total species richness. BioDiversity Pro software which provides several measures of diversity, was used to identify '*Uniques*' - those species that were found only in one depth range; '*Duplicates*' -identical species occurring at two depth ranges and *'Ubiquitous'* - species occurring at all depth ranges (Colwell and Codington,1994).

In the present study altogether 92 'unique species' were identified. They accounted for 76% of total species richness and 12% of the total density of polychaetes. Of these unique species, 6 were found at 200m depths, 13 from the 500m and 73 species occurred at 1000m depths. In each depth range uniques represented 22%, 41% and 73 % of the total species richness at 200m, 500m and 1000m respectively. Occurrence of '*Duplicates*' from the 200m and 500m were 2 species, and 200m and 1000m were 8 species. A total of seven species had occurrence at 500m and 1000m depth (Table 5.1); Ubiquitous species identified from the study area included *Prionospio cirrifera, Paraprionospio pinnata, Linopherus* sp1*, Ancystrosyllis parva, Ampharete acutifrons, Nereis* sp*, Polydora* sp*, Tharyx* sp*, Cossura coasta, and Ampharete* sp.

Table 5.1: List of species designated as *Duplicates* and their depth of occurrence

Species	**200m**	**500m**	**1000m**
Amphinomid sp1	✓	✓	
Pisione africana	✓	✓	
Phyllodoce fristedti	✓		✓
Paralacydonia paradoxa	✓		✓
Onuphis eremita		✓	✓
Tharyx marioni		✓	✓
Cirratulus sp1	✓		✓
Paraonides lyralyra	✓		✓
Levinsenia gracilis	✓		✓
Levinsenia oculata	✓		✓
Lumbriclymne sp1	✓		✓
Mellinopsides capensis		✓	✓
Isolda sp1		✓	✓
Amphecteis gunneri		✓	✓
Sabellides capensis		✓	✓
Euchone capensis		✓	✓
Un Identified polychaete	✓		✓

Major species that has high relative abundance are *Prionospio cirrifera* (68.1%)*, Linopherus sp1* (4.2%), *Ampharete acutifrons* (2.6%) and *Paraprionospio pinnata* (2%). Species like *Tharyx marioni*, *Ampharete* sp.1, *Aedicira belgicae, Paraonides lyra lyra, Aedicira* sp.1, *Aricidea* sp.1 and *Levinsenia gracilis* contributed to less than 2%.

It was found that total species count (S) increased with increasing depth i.e. 27 species at 200m, 32 at 500m, and 100 species at 1000m depth strata. However, total number of species collected in each season did not varied significantly with season (Table.5.3 -5.5).

5. 2. 2. Spatio- temporal variation in polychaete diversity

a) Temporal variation

The species number (S), richness (d), diversity (H'), evenness (J') and dominance (λ') at each station during the three surveys is given in Tables 5.3-5.5. During the winter monsoon (WIM), total number of species in a station varied between nil (Mumbai 2, 500m and Porbandar, 500m) and 17 (Veraval, 1000m and Porbandar, 1000m) (mean 7.27±5.53); it varied between total absence (Porbandar, 200m) to 16 (Mumbai I, 1000m) (mean 6.16±3.88) during summer monsoon (SM). Absence of polychaetes were recorded at 7 stations along 200m and 500m depth sites during spring inter monsoon (SIM) and the stations were Dabhol, Veraval, Porbandar and 500m station at Mumbai 2. The maximum number of species (25) at a station was recorded at Ratnagiri (1000m) during SIM, with a mean value of 7.14±6.81 for this season.

Species richness (d) during WIM ranged from nil (Mumbai I, 500m, Mumbai 2, 500m and Veraval, 500m and Porbandar, 500m) to 3.14 (Porbandar, 1000m) (mean 1.14±1.15); between nil (Porbandar, 200m) and 2.63 (Ratnagiri, 1000m) (mean 1.14±0.81) during the SM. During the SIM, many sampling sites located at 200 and 500m of the NEAS showed absence of macrofauna particularly polychaetes (Dabhol, Veraval, Porbandar, Mumbai I and Mumbai 2) with a maximum value of 5.01 (Ratnagiri, 1000m) (mean 0.92±1.3). Temporal variation in evenness was not recorded during the study and the mean value recorded was 0.48±0.37 (WIM), 0.65±0.31 (SM) and 0.48±0.43 (SIM). The minimum value of Shannon-Wiener diversity during WM was nil (Mumbai 2, 500m) and maximum was 3.49 (Dabhol, 1000m) (mean 1.60±1.35), whereas in the SM, diversity was comparatively similar with WM with the value ranging between nil (Porbandar, 200m) and 3.11 (Goa, 1000m) (mean 1.62±0.91). During SIM the value ranged between nil (200 and 500m stations of Dabhol, Veraval, Porbandar, 200m station at Mumbai I and 500m station at Mumbai 2) and 4.28 (Ratnagiri, 1000m) (mean 1.76±1.20).

The result of ANOSIM (Table.5.2) indicated that season was not a significant factor determining polychaete species richness and diversity, as there is no statistically significant variation among diversity indices [Species number (S) (R=0.01, P=26.5%), Simpson richness (d') (R=0.021, p = 14.5%), Shannon-Wiener diversity (H') (R = 0.025, p = 10.4%), Evenness (J') (R = 0.014, p = 18%) and dominance (λ') (R = 0.019, p = 15.6%)]

Table 5.2. ANOSIM analysis of spatio-temporal variation of univariate indices

Univariate indices	Group	ANOSIM R Value	P Value
Species No. (S)	Depth	0.29	0.1%
	Transect	0.091	7.7%
	Season	0.01	26.5%
Species richness (d)	Depth	0.329	0.1%
	Transect	0.062	13.6%
	Season	0.021	14.5%
Species evenness (J’)	Depth	0.291	0.1%
	Transect	0.12	4.1%
	Season	0.014	18%
Species diversity (H’)	Depth	0.345	0.1%
	Transect	0.114	4.9%
	Season	0.025	10.4%
Dominance (λ’)	Depth	0.292	0.1%
	Transect	0.111	3.7%
	Season	0.019	15.6%

Table 5.3. Diversity indices of polychaete in FORV *Sagar Sampada* cruise No. 219

Station	Transect - Depth	S	N	d	J'	H'(log2)	Lambda'
1	GOA-200m	5	85	0.900	0.435	1.011	0.683
2	GOA-500m	11	125	2.071	0.870	3.009	0.156
3	GOA-1000m	10	62.5	2.176	0.708	2.352	0.327
4	RTG-200m	3	107.5	0.428	0.201	0.318	0.909
5	RTG-500m	6	4022.5	0.602	0.115	0.298	0.926
6	RTG-1000m	7	20	2.003	0.980	2.750	0.112
7	DBL-200m	4	217.5	0.557	0.136	0.271	0.932
8	DBL-500m	2	170	0.195	0.111	0.111	0.971
9	DBL-1000m	14	77.5	2.988	0.919	3.497	0.098
10	MB1-200m	3	40	0.542	0.887	1.406	0.391
11	MB1-500m	1	15	0.000	0.000	0.000	1.000
12	MB1-1000m	14	285	2.300	0.734	2.793	0.197
13	MB2-200m	3	132.5	0.409	0.589	0.933	0.648
14	MB2-500m	0	0	0.000	0.000	0.000	0.000
15	MB2-1000m	11	77.5	2.299	0.864	2.989	0.144
16	VRV-200m	2	45	0.263	0.503	0.503	0.798
17	VRV-500m	1	5	0.000	0.000	0.000	1.000
18	VRV-1000m	17	177.5	3.089	0.758	3.098	0.177
19	PBR-200m	1	12.5	0.000	0.000	0.000	1.000
20	PBR-500m	0	0	0.000	0.000	0.000	0.000
21	PBR-1000m	17	162.5	3.143	0.853	3.488	0.108

Table 5.4. Diversity indices of polychaete in FORV *Sagar Sampada* cruise No. 228

Station	Transect - Depth	S	N	d	J'	H'(log2)	Lambda'
22	GOA-200m	4	90	0.667	0.429	0.859	0.705
23	GOA-500m	8	162.5	1.375	0.787	2.360	0.226
24	GOA-1000m	10	47.5	2.331	0.938	3.116	0.111
25	RTG-200m	4	157.5	0.593	0.218	0.436	0.878
26	RTG-500m	3	1520	0.273	0.022	0.035	0.993
27	RTG-1000m	12	65	2.635	0.752	2.696	0.264
28	DBL-200m	3	12.5	0.792	0.865	1.371	0.391
29	DBL-500m	4	57.5	0.740	0.383	0.765	0.758
30	DBL-1000m	5	25	1.243	1.000	2.322	0.167
31	MB1-200m	Not sampled					
32	MB1-500m	2	10	0.434	1.000	1.000	0.444
33	MB1-1000m	16	185	2.873	0.769	3.077	0.168
34	MB2-200m	5	115	0.843	0.711	1.651	0.416
35	MB2-500m	4	27.5	0.905	0.639	1.278	0.537
36	MB2-1000m	11	222.5	1.850	0.604	2.091	0.352
37	VRV-200m	8	35	1.969	0.897	2.692	0.170
38	VRV-500m	2	7.5	0.496	0.918	0.918	0.487
39	VRV-1000m	7	220	1.112	0.407	1.144	0.659
40	PBR-200m	0	0	0.000	0.000	0.000	0.000
41	PBR-500m	2	10	0.434	1.000	1.000	0.444
42	PBR-1000m	7	87.5	1.342	0.756	2.121	0.290

Table 5.5. Diversity indices of polychaete in FORV *Sagar Sampada* cruise No. 254

Station	Transect - Depth	S	N	d	J'	H'(log2)	Lambda'
43	GOA-200m	3	30	0.588	0.515	0.817	0.698
44	GOA-500m	5	115	0.843	0.783	1.818	0.329
45	GOA-1000m	7	27.5	1.810	0.949	2.664	0.142
46	RTG-200m	5	142.5	0.807	0.358	0.831	0.744
47	RTG-500m	5	480	0.648	0.278	0.646	0.807
48	RTG-1000m	25	120	5.013	0.922	4.280	0.056
49	DBL-200m	0	0	0.000	0.000	0.000	0.000
50	DBL-500m	0	0	0.000	0.000	0.000	0.000
51	DBL-1000m	14	82.5	2.946	0.887	3.377	0.115
52	MB1-200m	1	5	0.000	0.000	0.000	1.000
53	MB1-500m	2	10	0.434	1.000	1.000	0.444
54	MB1-1000m	16	160	2.956	0.743	2.972	0.221
55	MB2-200m	3	12.5	0.792	0.960	1.522	0.304
56	MB2-500m	0	0	0.000	0.000	0.000	0.000
57	MB2-1000m	9	210	1.496	0.703	2.230	0.275
58	VRV-200m	0	0	0.000	0.000	0.000	0.000
59	VRV-500m	0	0	0.000	0.000	0.000	0.000
60	VRV-1000m	2	10	0.434	1.000	1.000	0.444
61	PBR-200m	0	0	0.000	0.000	0.000	0.000
62	PBR-500m	0	0	0.000	0.000	0.000	0.000
63	PBR-1000m	3	45	0.525	1.000	1.585	0.318

b) Bathymetric variation in polychaete diversity

Numbers of species (S), richness (d), diversity (H'), evenness (J') and dominance (λ') indices at each site during the study are depicted in Figures 5.1-5.5 and tables 5.3 to 5.4. Overall, the number of polychaete species in the study area showed significant bathymetric variation with considerably higher values towards the deeper sites (mean 11.14±5.46) with that of the intermediate 500m (mean 2.76±2.95) and shelf edge 200m (mean 2.85±2.11) depths. Number of polychaete species at 200m depth strata varied from total absence at many station [Dabhol (SIM), Porbandar (SM&SIM) and Veraval (SIM)] to 8 at Veraval (SM) with mean of 2.85±2.11. The mean species number at 500m depth was 2.76±2.95. At 1000m depth stations, number of polychaete species varied from 2 (Veraval, SIM) to 25 (Ratnagiri, SIM) with a mean value of 11.14±5.46.

The mean value for species richness (d) was more or less similar at 200m (0.51±0.47) and 500m (0.47±0.54) but was relatively higher values at 1000m contour (2.22±1.03). Species richness (d) at 200m varied from nil (Porbandar in all season and Dabhol, Mumbai I and Veraval in SIM) to 1.96 (Veraval). Species richness (d) at 500m depths ranged from nil (WIM - Mumbai 1&2, Veraval, Porbandar; SIM - Dabhol, Mumbai 2, Veraval and Porbandar) to 2.07 (Goa) . Along 1000m depth ranges species richness (d) varied from 0.43 (Veraval) to 5.01 (Ratnagiri). Diversity (H') at 200m stations was nil (Porbandar in all season and Dabhol, Mumbai I and Veraval in SIM) and highest at Veraval (2.69); and the mean diversity for this depth category was 0.73±0.73. At 500m, the minimum value of species diversity was zero (WIM-Mumbai I&II, Veraval, Porbandar; SIM-

Dabhol, Mumbai 2, Veraval, Porbandar) and maximum was 3.00 at Goa (mean 0.71±0.87). At 1000m stations the observed range was from 1(Veraval) to 4.28 (Ratnagiri) with a mean of 2.64±0.79.

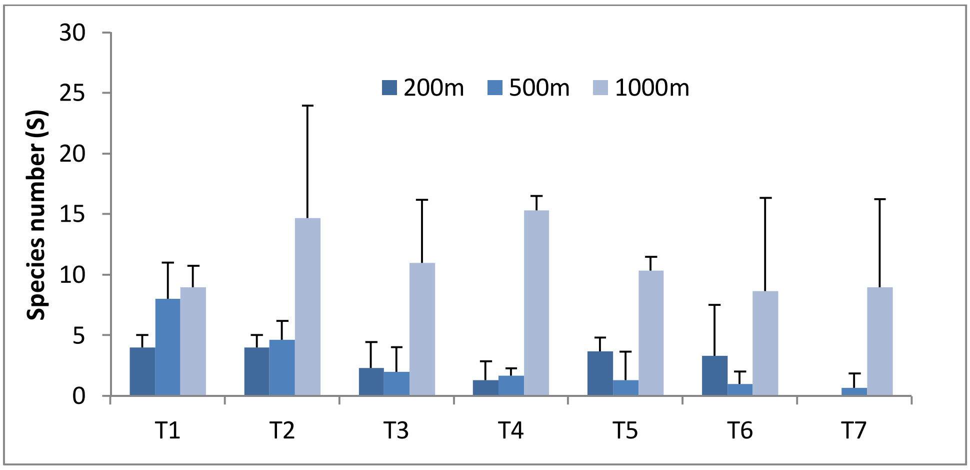

Figure5.1. Mean Species number (S) in each site along the study area

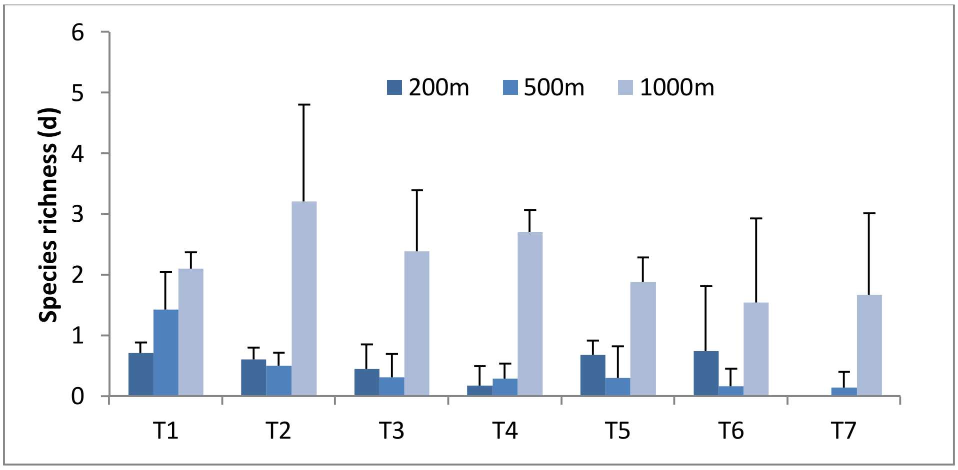

Figure 5.2. Mean Species richness (d) in each site along the study area

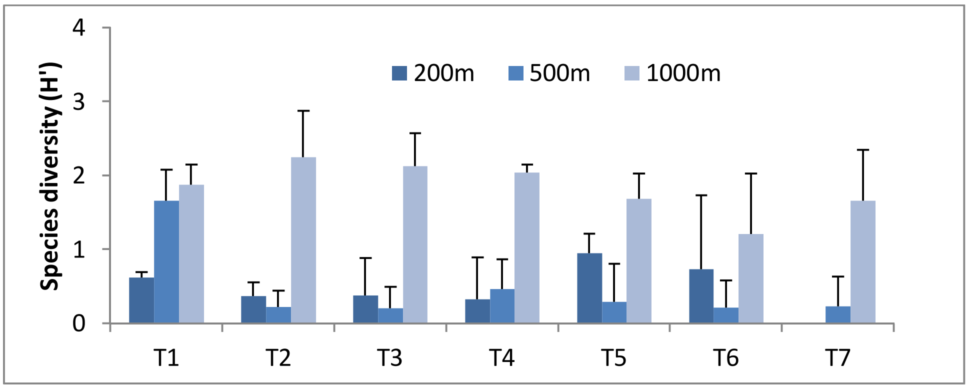

Figure 5.3. Mean Species diversity (H') in each site along the study area

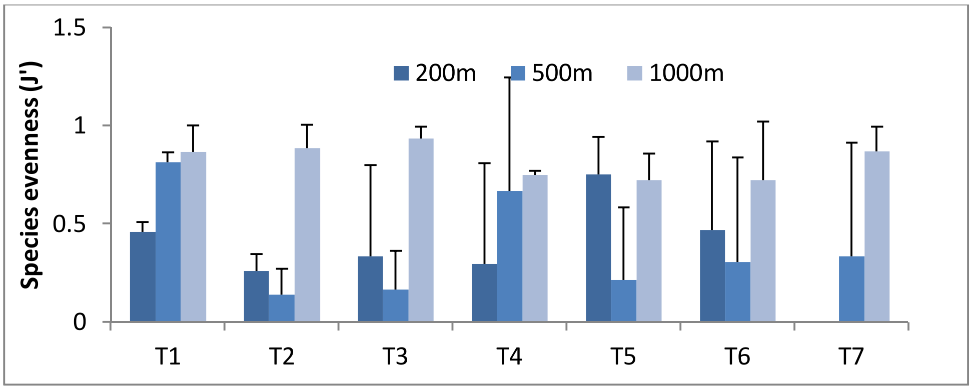

Figure 5.4. Mean Species evenness (J') in each site along the study area

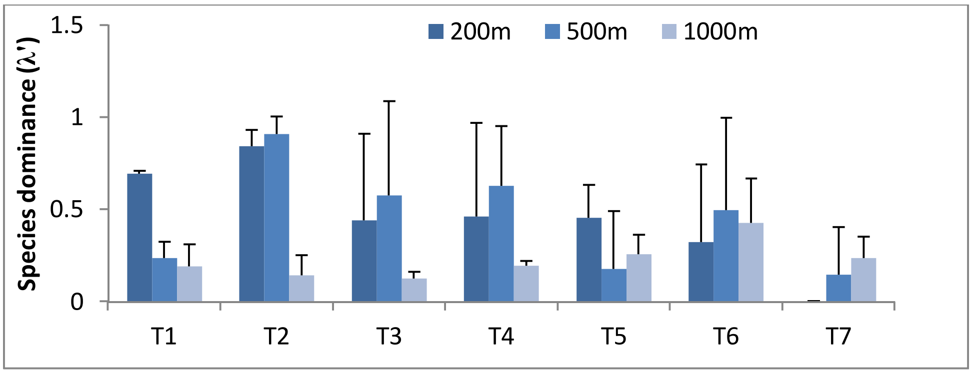

Figure 5.5. Mean Species dominance (λ') in each site along the study area

Table 5.6. Mean diversity indices in each depth ranges

Diversity Indices	200m	500m	1000m
No of Species (S)	0-8 (2.85±2.11)	0-11 (2.76±2.95)	2-25 (11.14±5.46)
Margalef richness (d)	0-1.96 (0.51±0.47)	0-2.07 (0.47±0.54)	0.43-5.01 (2.22±1.03)
Pielou's Evenness (J')	0-0.96 (0.39±0.34)	0 -1 (0.40±0.42)	0.41-1 (0.82±0.15)
Shannon diversity (H'(log2))	0 -2.69 (0.73±0.72)	0-3.0 (0.71±0.87)	1-4.28 (2.65±0.79)
Simpson dominance (λ')	0-1 (0.53±0.36)	0-1 (0.48±0.38)	0.06-0.66 (0.23±0.14)

The mean evenness index for polychaetes at each depth category were compared, and the values were found to be highest at 1000m (0.82±0.15) followed by 500m (0.40±0.42) and were lowest at 200m (0.39±0.34). The 200m and 500m depth ranges more or less similar in terms of diversity indices. Relatively high evenness and low species dominance was observed at deeper depths (1000m) [Table 5.6].

The result of ANOSIM (Table.5.2) indicated that the depth was a significant factor determining polychaete diversity. All diversity indices varied significantly with depth (Table 5.2.). Species number (S) (R=0.29, P=0.1%), Simpson richness (d') (R=0.329, p = 0.1%), Shannon-Wiener diversity (H’) (R = 0.345, p = 0.1%), Evenness (J’) (R = 0.291, p = 0.1%) and dominance (λ’) (R = 0.292, p = 0.1%).

c) Latitudinal variation in polychaete diversity

To study the latitudinal variation in species richness and diversity in the study area, the data each transect were pooled and the variations were analysed, the result revealed that the polychaete species number (s) varied from 3.33±5.61 (Porbandar) to 7.78±7.01 (Ratnagiri). The species richness (d) variation was negligible and it ranged from 0.60±1.05 (Porbandar) to 1.44±1.56 (Ratnagiri). However, species diversity (H’) was highest at the southernmost transect Goa (2.00±0.91) and lowest at northernmost transect (Porbandar 0.91±1.26). Relatively low evenness was found at Porbandar transect (J: 0.40±0.48) and highest dominance was found at Ratnagiri transect (λ’, 0.63±0.38). On the other hand highest evenness and lowest dominance was recorded at Goa transect (J: 0.71±0.20; λ’: 0.38±0.25). To check the statistical significance of latitudinal variations in polychaete diversity ANOSIM was performed on transect wise pooled diversity data. The number species (S), Margalef’s species richness (d), diversity (H’), dominance (λ’) and evenness did not varied significantly between transects (Table 5.2). In general, a statistically significant latitudinal trend was not observed in univariate polychaete diversity indices or measures, even though at 200m and 500m depths species number and richness decreased northwards.

5. 2.3. Distributional techniques

Distributional techniques are numerical tools that combine observations of species occurrence or abundance at known locations. They are used to predict species distributions across landscapes.

a) Species-area plots and species estimators

In most ecological systems, the number of species obtained increases nonlinearly with the area sampled. Larger areas are likely to contain more numbers of species. A Species-area plot gives an idea about the number of species may present in a habitat and the number of species can find each time we sample. Species area plot for the polychaete community in the north eastern Arabian Sea margin were constructed based on 108 grab samples, which helps to determine if the species collected during the surveys adequately describe the actual species composition of the study area. The plot approaches the asymptote, indicating that the study area was sampled sufficiently [Figure 5.6]. During first survey 68 species were obtained and during the second there was an addition of 29 species, while in the third survey fewer species were added (24 species). This further indicated that required sample size was attained with the third survey.

Species estimators were used to predict the true number of species that would be observed as the number of samples tend to be infinity. The total number of species predicted by the species estimators [Figure 5.7] varied from 111 (Michaelis-Menten) to 253 species (Chaos 2), while the total number of species observed (Sobs) in the samples was 121. The number of polychaete species estimated by Chao1, Jacknife1, Jacknife II, Bootstrap and UGE were 121, 189, 239, 149 and 121 respectively. As per these species estimators, it was found that around 50 to 100 % of the expected species was collected from the north eastern Arabian Sea through the three surveys. Based on the estimators, the study area was sampled sufficiently in terms macrofaunal polychaetes.

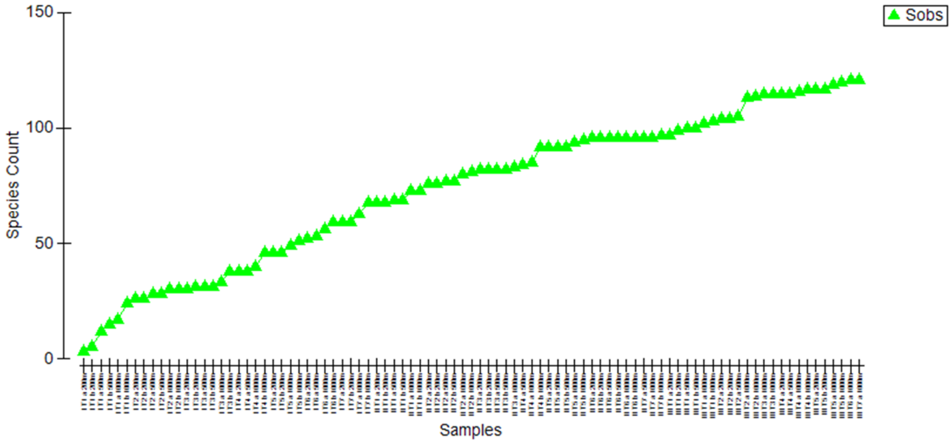

Figure 5.6. Species area plot of polychaetes in the study area.

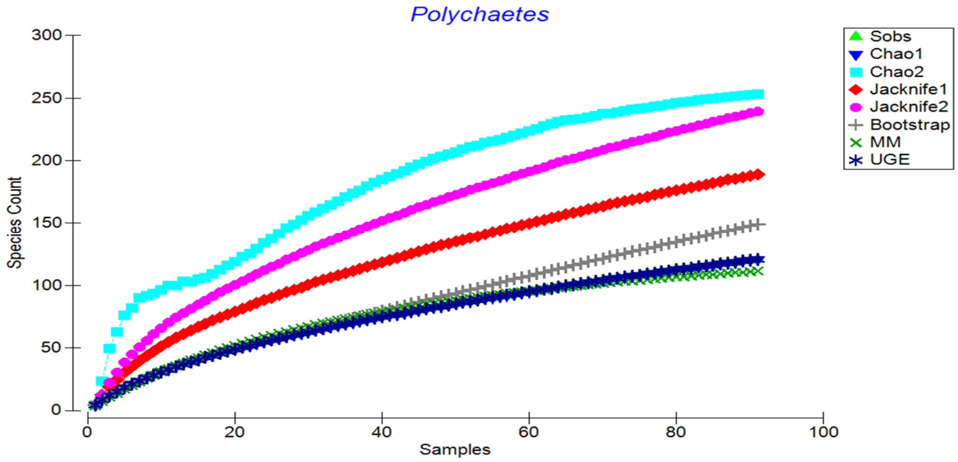

Figure 5.7. Species estimators for polychaetes in the study area

b) k-dominance curve

This curve is constructed by plotting ranked species in order of importance in the x axis while the cumulative contribution of each of these to the total density is plotted along the y axis. The k-dominance plots measures the intrinsic diversity and in this plot the lower lines represent samples with higher diversity. In the present study, multiple k-dominance plots were constructed for all surveys, transects and depths using statistical software PRIMER [Figures 5.8-5.11].

During WIM all 200m and 500m sites except at 500m Goa transect and 200m Mumbai 1 transect were shown less than 7 species and rank1 species contributed more than 80% of the total abundance [Figure 5.8]. It is inferred that these sites would have a low species diversity index. Porbandar 1000m and Dabhol 1000m sites showed comparatively low dominance (~20%) and had highest diversity.

During SM [Figure 5.9], highest dominance was observed at the 500m station of Ratnagiri, where the most abundant species *Prionospio cirrifera*, contributed more than 99% of the total abundance. The highest diversity observed during this season was at the 1000m station off Goa while the most species rich station was 1000m station of Mumbai 1 transect.

During the SIM [Figure 5.10], high dominance was recorded at Mumbai 1 (200m) where the most dominant species was a singleton *Paralacydonia paradoxa* and second most dominance was recorded from Ratnagiri (500m station), where the rank 1 species was *Prionospio* *cirrifera*. The highest diversity observed during this survey was at off Ratnagiri (1000m).

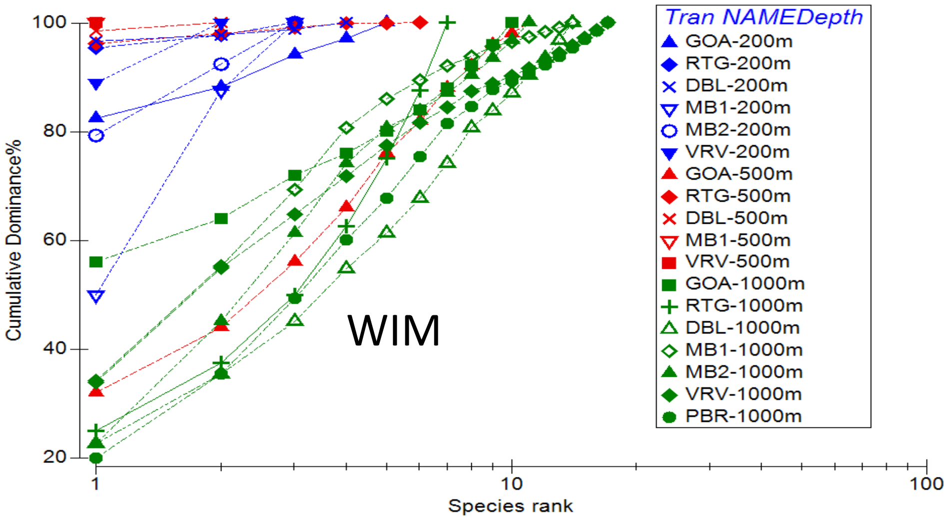

Figure 5.8. **k-dominance curve for polychaetes during FORVSS Cruise 219**

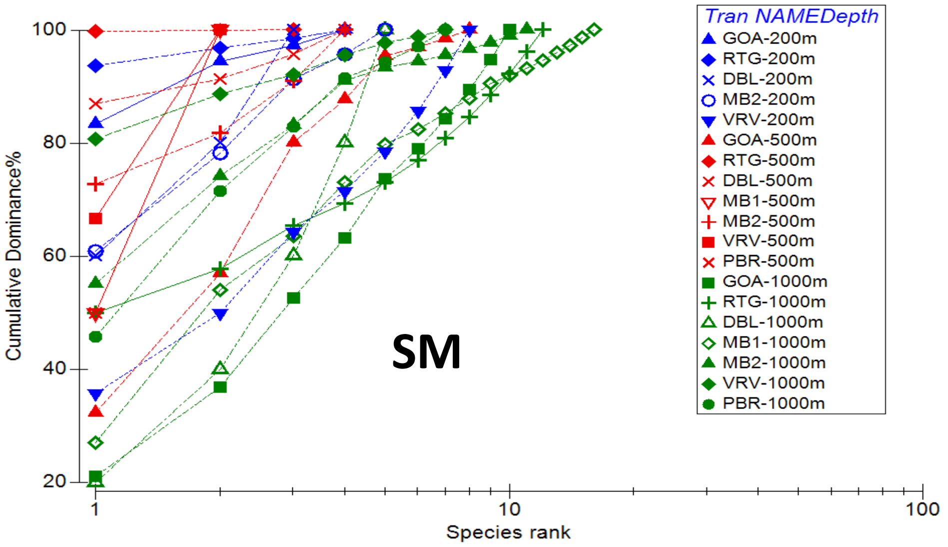

Figure 5.9. **k-dominance curve for polychaetes during FORVSS Cruise 228**

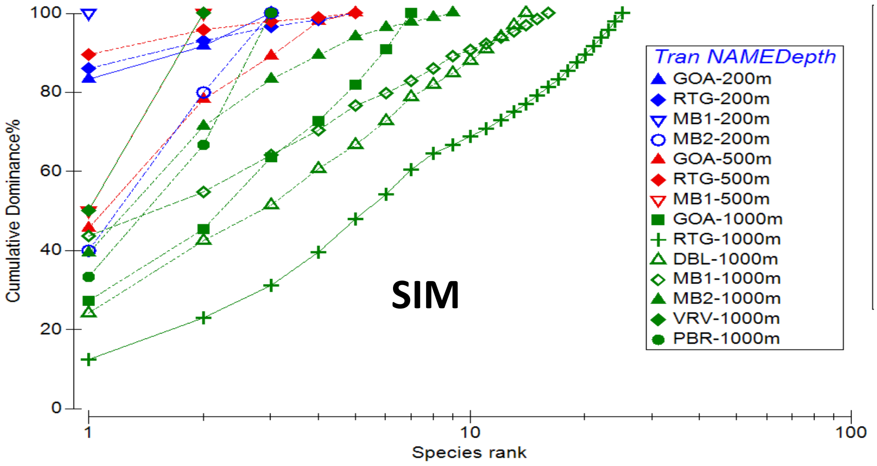

Figure 5.10. **k-dominance curve for polychaetes during FORVSS Cruise 254**

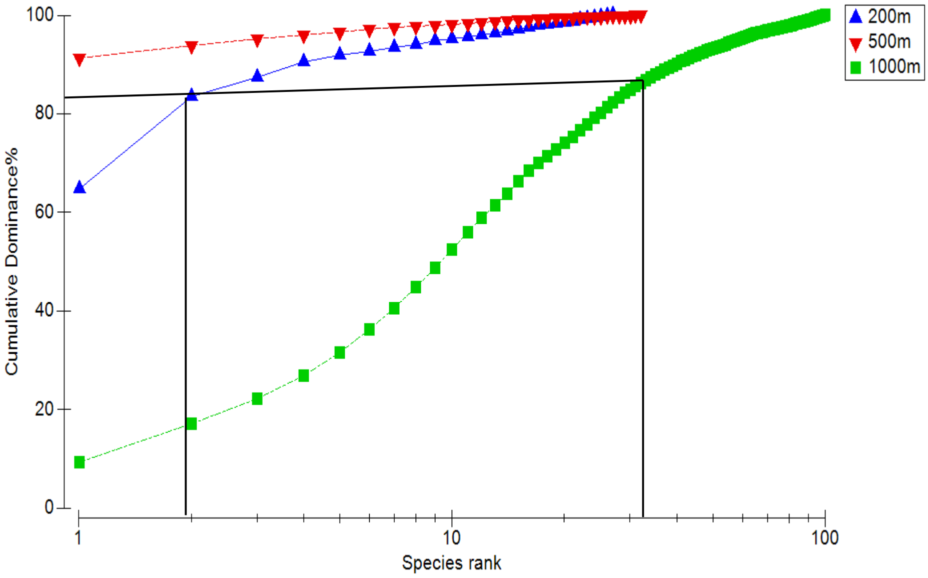

Figure 5.11. **k-dominance curve for polychaetes at each depth ranges**

To understand the overall bathymetric trend in polychaete diversity of the study area, depth wise pooled data were used to construct the k-dominance curve (Figure 5.11). From the plot, it was found that at 500m depth a single species dominated and contributed 90% cumulative dominance. The single species dominance at 500m depth was due *Prionospio cirrifera.* Similarly, 2 species contributed to 82% of the cumulative dominance at 200m depth ranges and the 2 species contributing to the dominance at 500m are *Prionospio cirrifera* and *Linopherus* sp1. A marked difference was observed in the contribution of cumulative dominance at 1000m depths compared to other depths, where 33 species together accounted for 82% of faunal abundance. Among these species, *Ampharete acutifrons* and *Linopherus*sp1 were the most abundant.

5. 2. 4. Multivariate Analysis of polychaete community structure

Multivariate analysis was used to compare polychaete community structure along and across the transects in the study area. Similarity matrices were constructed based on polychaete species data from the 108 stations stretched over the north eastern Arabian Sea. The whole set of data were square root transformed in order to reduce the impact of patchiness or heterogeneity on the assessment of the community similarities (Clarke and Warwick, 2001).

Based on the similarity matrix polychaete community data along the north eastern Arabian Sea were tested over survey, depth and latitude. ANOSIM tests for variation of polychaete community structure with respect to survey (Global R: 0.038, 10.6%) and latitude (Global R:

0.107,8%) did not showed any significant variation, but showed significant bathymetric variations (Global R: 0.474, 1%).

1) Multivariate analysis based onfamily-level data

Taxonomic sufficiency is the identification of taxa to taxonomic levels higher than species without significant loss of information. This approach has been proposed as a surrogate for the typical analysis of species - abundance data (Muniz and Pires-Vanin, 2005). There are few comparative studies conducted in deeper water which is using taxonomic sufficiency for community level analysis of macrofaunal polychaetes (Narayanaswami et al., 2003, Abdul Jaleel, 2012). In the present study, polychaete species abundance data from each station was aggregated to the family level. Based on the Bray–Curtis index as the similarity measure, spatial differences in the polychaete abundance were determined with a non-metric multidimensional scaling (nMDS) ordination analysis (Clarke and Green, 1988; Clarke, 1993). The significance of differences between sites was examined by the randomisation test analysis of similarities (ANOSIM).

The nMDS plot revealed that, the sites are congregated in to three major groups - northern shallow, southern shallow and mid-slope assemblage as in Figure 5.12. Northern shallow sites are 200m and 500m sites of Mumbai 1, Mumbai 2 and Veraval as well as 500m of Porbandar. Southern shallow group consist of shallow (200m and 500m) depth sites of Goa, Ratnagiri and Dabhol. All mid slope sites (1000m) were grouped in to a single cluster. ANOSIM R values revealed that this spatial grouping of sites according to faunal assemblages are statistically significant (ANOSIM R=0.429, P=1%). Global test on bathymetric variation also gives significant differences in assemblages (ANOSIM R =0.421, P=0.1%) but variation between 200m and 500m depth sites at family level are not significant (ANOSIM R=0.014, P=37%). Temporal variation among the assemblage were not found to be significant (ANOSIM R=-0.019, P=74.1%).

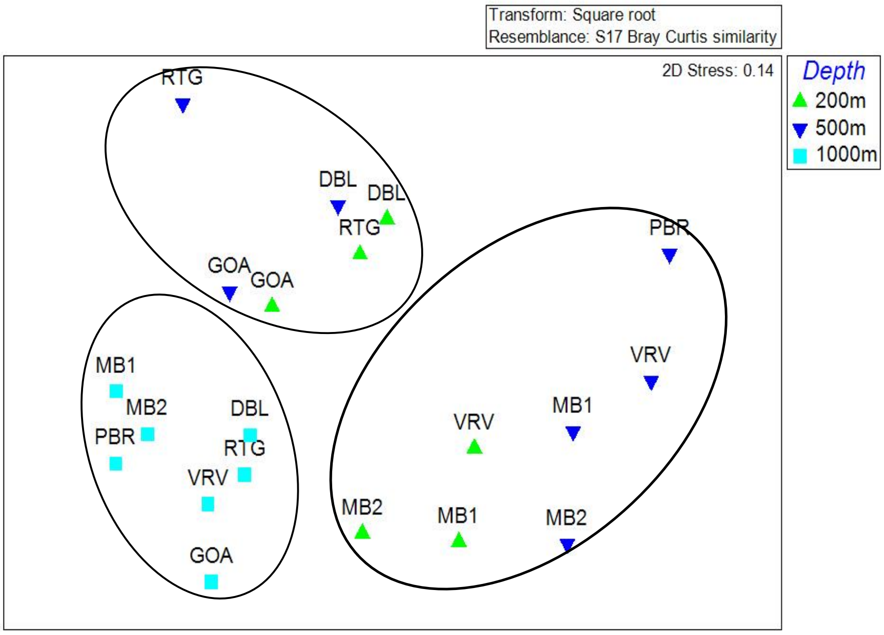

Figure 5.12. nMDS for polychaete family level data at each site

2) Multivariate analysis based onspecies-level data

The polychaete assemblage composition in the NEAS margin was analysed using multivariate techniques based on species-level data. The Bray-Curtis similarity matrices were computed from the squared-root transformed density data in order to reduce the impact of the abundant or dominant species on the assessment of the community similarities.To identify the similarities among sites, a dendrogram was constructed (Figure 5.13.) using hierarchical agglomerative clustering based on group average linkage. To check whether the grouping is statistically significant, SIMPROF test was also done on the cluster formed.

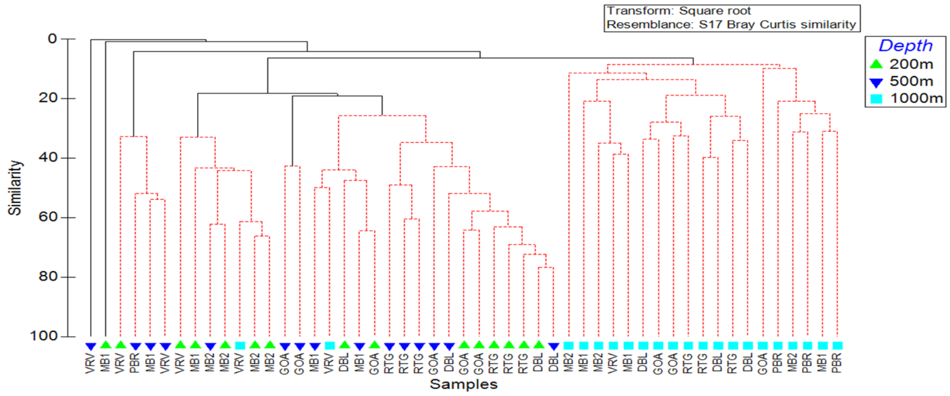

Figure 5.13. Dendrogram showing the significant clusters using polychaete species data for all stations.

All the stations were groupedinto five significant clusters (p=<0.05), of which most of the 1000m stations formed a distinct group away from shallow 200m and 500m stations. The shallower stations were distinguished as two different clusters, with a north-south distinction. It is very clear that depth or some depth related factors were most critical in shaping the polychaete assemblages.

Since temporal variations were not significant, in order to get a better picture of the faunal assemblages of the study area, the station wise data were pooled in to site wise data. Altogether six grab data were thus used for representing each site.

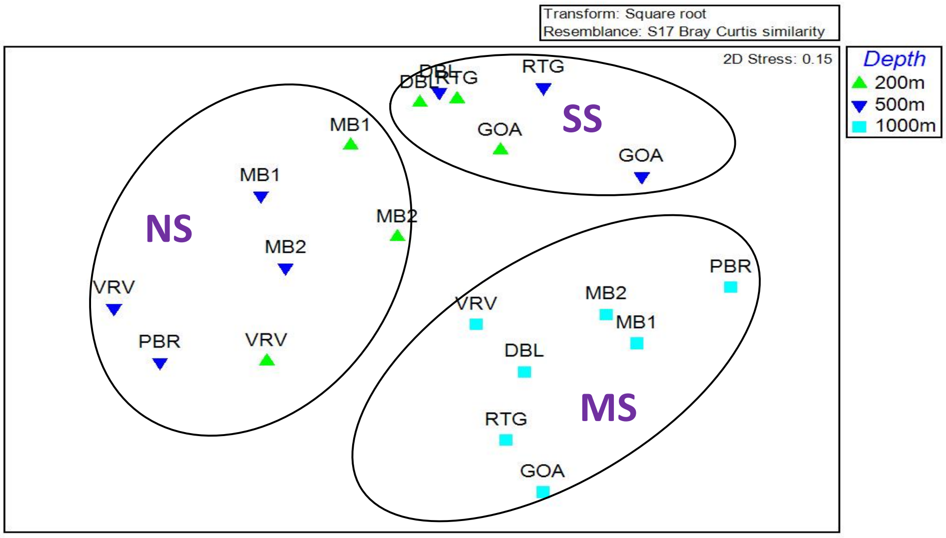

Figure 5.14: nMDS using polychaete species data for each site; NS – Northern Shallow (200 & 500 m) assemblage; SS - Southern Shallow (200 &500 m) assemblage; MS – Mid slope (1000m) assemblage.

Based on the pooled density data, Bray-Curtis similarity matrices were computed on square root transformed data. To get a 2D representation of the assemblages nMDS plot (Figure 5.14) were drawn. It was found that three distinct spatial assemblages were ordinated and it was named as mid-slope (MS), north shallow (NS) and south shallow (SS) assemblages. The north shallower assemblage consists of 200m and 500m depth sites of Mumbai 1, Mumbai 2, Veraval and Porbandar. These sites were very distinct from south 200m and 500m depth (SS) namely Goa, Ratnagiri and Dabhol. The mid slope assemblage comprised all the 1000m sites of the study.

5. 2. 5. Biological characteristics of polychaete assemblages

Similarity percentage analysis (SIMPER) was carried out to identify the species characterising the above defined polychaete assemblages. Presence or absence of certain characteristic species or relative abundance of common species was the basis of similarity and dissimilarities between assemblages. To test the null hypothesis, i.e. there was no significant faunal differences existed between the each pair of identified assemblages, ANOSIM was performed. The result revealed that significant variation in species composition existed among these groups (ANOSIM R=0.645, P=0.1%).

a) Southern shallow assemblage (SS)

Average similarity between the sites of this group was 38.76%. The southern shallow assemblage (SS) was characterized by high abundance of *Prionospio cirrifera*, which contributed 85% to the total density followed by *Prionospio pinnata* (3.25%) and *Cossura coasta* (2.91%). The dissimilarity between the SS and northern shallow (NS) assemblage was 87.21% and with mid-slope (MS) assemblage was 87.7%. This dissimilarity was mainly caused the absence of species such as *Prionospio pinnata, Ampharete acutifrons, Cossura coasta* and *Amphecteis gunneri* at NS and the presence of *Aricidea sp, Aedicera belgicae, Levinsenia oculata* and *Levinsenia gracilis* at mid slope sites (MS). High abundance of *Prionospio cirrifera* and *Prionospio pinnata* in the SS rather than NS and

MS assemblages also caused this dissimilarity. Low abundance of *Linopherus sp1, Polydora sp, Cossura coasta, Ancystrosyllis parva, Ampharete sp* and *Nereis spp* in the SS sites when compared tothe northern shallow assemblage contributed to its dissimilarity. As with the mid-slope assemblage also, the decrease in number of *Amphaete acutifrons, Tharyx dorsobranchialis, Linopherus sp1, Cossura coasta, Ampharete sp* and *Paraonides lyra lyra* caused the dissimilarity.

Ecological characteristic of this assemblage with prevailing environmental conditions are depicted in Table 5.7. The southern shallow assemblage is characterized by high density of polychaetes (440.45 ± 1055.32 ind/m^2). While the species number was lower than mid-slope assemblage, but it was found to be higher than northern shallow assemblage (2.94 ± 1.73). Species richness, species diversity and evenness was very low for this assemblage (H'=0.67 ± 0.70; d' = 0.39 ± 0.34; j= 0.50 ± 0.29). While comparing the sediment texture of this assemblage to other assemblages, the percentage composition of sand is higher than the other two assemblages. Organic matter percentage in the sediment was also higher when compared to other two assemblages of the study area (7.79± 4.25 % of sediment). Despite being isobathic with the NS assemblages, the bottom water temperature and salinity was higher in the NS (14.08 ± 2.41°C and 35.43 ± 0.12 ppt). Dissolved oxygen value was slightly higher than the northern shallow assemblage but much lower than mid-slope assemblage (0.32 ± 0.26 ml/l).

b) Northern shallow assemblage (NS)

Average similarity identified through SIMPER, between the sites of this assemblage is 25.08%. The dominant and characteristic species identified from this mid-slope assemblage were*Polydora sp (40.04%), Prionospio cirrifera (23.72%), Linopherus sp1 (18.51%) and Ancystrosyllis parva (7.86%).* Environmental conditions of this assemblage was characterised by extreme low dissolved oxygen (0.29 ± 0.17ml/L), high salinity (35.68 ± 0.17 ppt) and higher bottom water temperature than other assemblage (14.92 ± 2.51). Species number is found to be lowest (2.37 ± 1.30) when compared to other assemblage. Many stations even showed total absence of polychaetes.

c) Mid-slope assemblage (MS)

Based on SIMPER procedure, the average similarity identified between the sites in this assemblage is 25.35%. The dominant and characteristic species identified from this assemblage were *Tharyx dorsobranchialis* (10.5%), *Aricidea spp* (10.01%), *Prionospio cirrifera* (7.49%), *Ampharete acutifrons* (7.37%), *Tharyx spp* (6.78%), *Lumbrineris aberrans* (5.79%), *Cossura coasta* (4.46%), *Levinsenia oculata* (4.25%), *Levinsenia gracilis* (4.08%), *Aedicira belgicae* (3.97%), *Prionospio sp1* (3.87%), *Prionospio pinnata* (2.82%), *Notomastus spp* (2.74%), *Nereis spp* (2.56%), *Heteromastus filiformis* (2.36%) and *Terebellides stroemi* (2.16%).

The dissimilarity between the SS and MS assemblage was 87.7 % and from northern shallow assemblage to mid-slope assemblage is 90.59.

These dissimilarities were caused by the difference in the species composition of these sites. Presence of *Aricidea sp, Aedicera belgicae, Levinsenia oculata* and *Levinsenia gracilis* at deeper sites was a noted difference. Decrease in the density of *Prionospio cirrifera* and *P. pinnata* at mid-slope assemblage and increase in the density of *Amphaete acutifrons, Tharyx dorsobranchialis, Linopherus sp1, Cossura coasta, Ampharete sp* and *Paraonides lyra lyra* were also responsible for this dissimilarity.

The MS assemblage was characterised by high values in species diversity indices such as species diversity (2.13 ± 0.74), species number (6.79 ± 3.63) and richness (1.27 ± 0.65). The averaged values of environmental parameters of these sites are as follows. Textural composition of the assemblage as whole was clay: 27.26 ±6.31%, silt: 56.88 ±16.64% and sand: 15.87 ±18.97%. Organic matter composition of the mid slope area was 7.36±2.57 %. Dissolved oxygen concentration of bottom water was 0.47±0.27 ml/L. Average bottom water temperature and salinity of the mid slope assemblage were 9.26±0.81^{o}C and 35.38±0.10,respectively.

Table 5.7: Ecological characteristic of identified assemblages

Assemblage	**Southern Shallow**	**Northern Shallow**	**Mid slope**
Cluster-	SS	NS	MS
Location	GOA, RTG, DBL	MB1, MB2, VRV & PBR	GOA, RTG, DBL,MB1, MB2, VRV & PBR
Depth	200 & 500 m	200 & 500 m	1000 m
Sediment Texture	Clay % 21.96 ± 9.29	Clay % 22.53 ±9.18	Clay % 27.26 ±6.31
	Silt % 41.98 ± 25.46	Silt % 46.25 ±22.47	Silt % 56.88 ±16.64
	Sand % 36.07 ± 31.16	Sand % 31.22 ±28.20	Sand % 15.87 ±18.97
DO	0.32 ± 0.26	0.31 ± 0.17	0.47 ± 0.27
OM	7.79± 4.25	6.34 ± 4.49	7.36± 2.57
Temp	14.08 ± 2.41	14.92 ± 2.51	9.26 ± 0.81
Salinity	35.43 ± 0.12	35.68 ± 0.17	35.38 ± 0.10
Density	440.45 ± 1055.32	36.05 ± 45.33	119.49 ± 117.93
S	2.94 ± 1.73	2.37 ± 1.30	6.79 ± 3.63
H'	0.67 ± 0.70	0.82 ± 0.69	2.13 ± 0.74
d'	0.39 ± 0.34	0.39 ± 0.33	1.27 ± 0.65
j	0.50 ± 0.29	0.81 ± 0.20	0.84 ± 0.15

Table 5.8: Dominant and characteristic species (density %) of identified assemblages

Assemblage	**Southern Shallow (SS)**	**Northern Shallow(NS)**	**Mid slope (MS)**
Average similarity	38.76	25.08	25.35
	Prionospio cirrifera (85%)	*Polydora* sp (40.04%)	*Tharyx dorsobranchialis* (10.5%)
	Parprionospio pinnata (3.25%)	*Prionospio cirrifera* (23.72%)	*Aricidea* spp (10.01%)
	Cossuracoasta (2.91%)	*Linopherus* sp1 (18.51%)	*Prionospio cirrifera* (7.49%)
		Ancystrosyllis parva (7.86%)	*Ampharetea cutifrons* (7.37%)
			Tharyx spp (6.78%)
			Lumbrineris aberrans (5.79%)
			Cossura coasta (4.46%)
			Levinsenia oculata (4.25%)
			Levinsenia gracilis (4.08%)
			Aedicira belgicae (3.97%)
			Prionospio sp1 (3.87%)
			Paraprionospio pinnata (2.82%)
			Notomastus sp1 (2.74%)
			Nereis sp1 (2.56%)
			Heteromastus filiformis (2.36%)
			Terebellides stroemi (2.16%)

5. 2. 6. Feeding guild composition

Due to the high density in the soft bottom, polychaetes, are naturally important components of food webs and acting as detritivores and/or primary and secondary consumers (Checon et al., 2017). Generally five feeding groups of polychaetes are recognized and they are surface and subsurface deposit feeders, suspension (or filter) feeder, carnivores and omnivores (or herbivores) (Fauchald and Jumars, 1979; Jumars et al., 2015). The available food resources in the sediments are thereby partitioned between these trophic guilds. The polychaete species are developed and adapted to suite each of the feeding modes. For example in Aphroditidae and Nereididae, development of sensory appendages such as antennae and eye spots are reformed for carnivory and omnivory. Glycerinates, Paralacydoniidae, and Nereididae have conspicuous and usually retractable jaws. Nephtyidae, Nereididae and Aphroditidae have well developed parapodia for swimming and Syllidae have masticatory gizzards. Suspension feeders, such as Chaetopteridae possess prominent filtering apparatus like palps. In Sabellidae and Serpulidae food-gathering tentacles are well developed. They lay buried in the sediment with only palps or tentacles projecting out; these species are usually sessile and are mostly tube dwellers. The range of selectivity and position of the species in the sediment shows considerable diversity among deposit feeders,; the species may be either selective or non-selective deposit feeders. Based on the location in the sediment matrix, they are divided into surface deposit feeders (sediment surface) or sub-surface deposit feeders (buried within the sediment). In general non selective deposit feeders like Capitellidae and Orbiniidae tend to have a retractable pharynx that facilitates faster ingestion of sediment. Some families such as Maldanidae and Magelonidae have their prostomium modified in to wedges or shovels. Surface deposit feeders such as Spionidae and Cirratulidae customarily have well developed tactile and food capturing tentacles.

According to the feeding mode, all the identified polychaete species in the present study were classified into the following trophic guilds namely; carnivores (CVR), surface deposit feeders (SDF), subsurface deposit feeders (SSDF) and those species which could not be confidently classified into any of these were grouped as unknown (U).

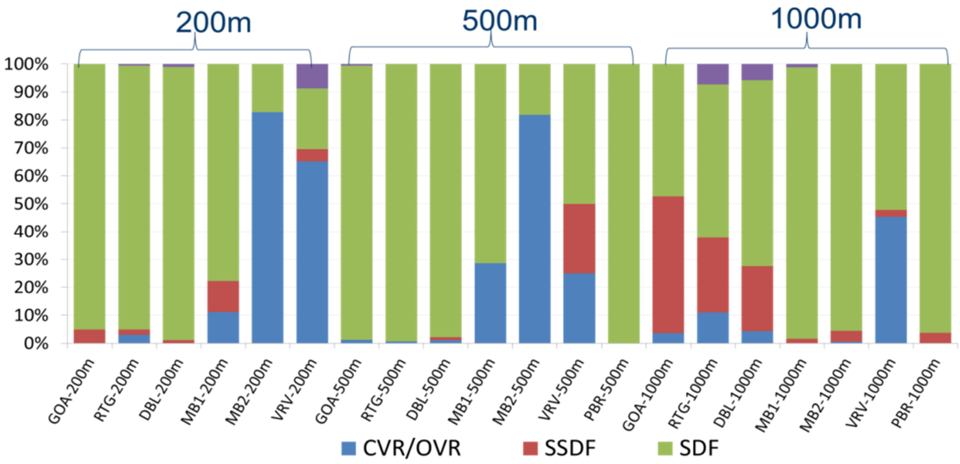

Figure 5.14. Polychaete feeding guilds distribution in the study area

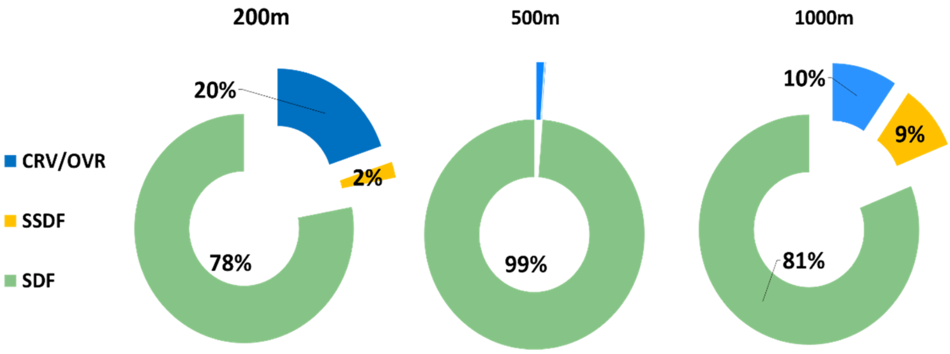

Figure 5.15. Polychaete feeding guilds distribution at each depths

Surface deposit feeders were the most dominant feeding guild represented in the study area (91%). The relative abundance of SDF varied from 17.3% (200 m at Mumbai 2,) to 100%. (500 m Porbandar). Carnivores constituted 6% of polychaetes along the whole study area and varied from 0% (Porbandar 500m) to 82% (200 m at Mumbai 2). Sub surface feeders represented only by 2% in the study area. In most of the sites their contribution was less than 25% and they were even absent in 6 sites, and at Goa 1000m, its contribution was nearly 50%.

Depth wise variation in feeding guild composition was analysed and found that surface deposit feeders contributed more than three quarters at each depth. The most striking feature was that, at 500m depth, the relative abundance of surface deposit feeders was 99%.

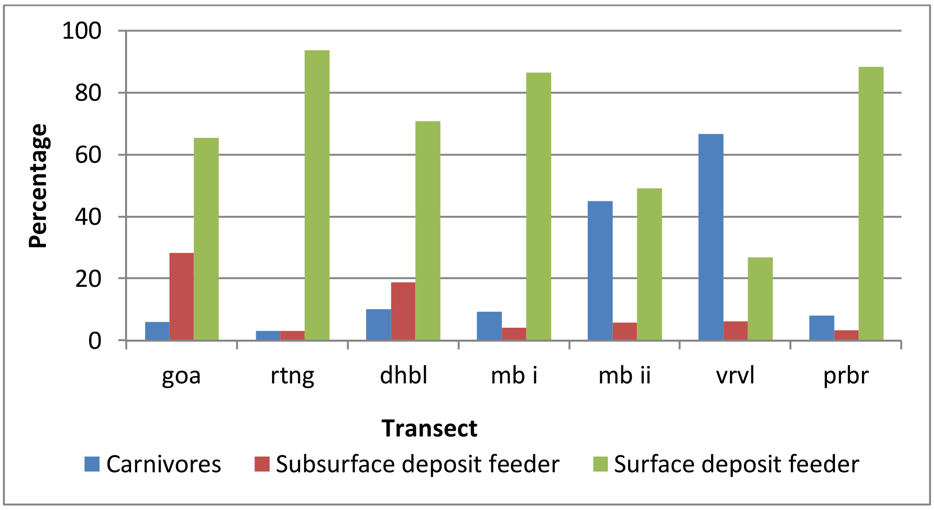

Figure 5.16. Polychaete feeding guilds relative distribution at each sites

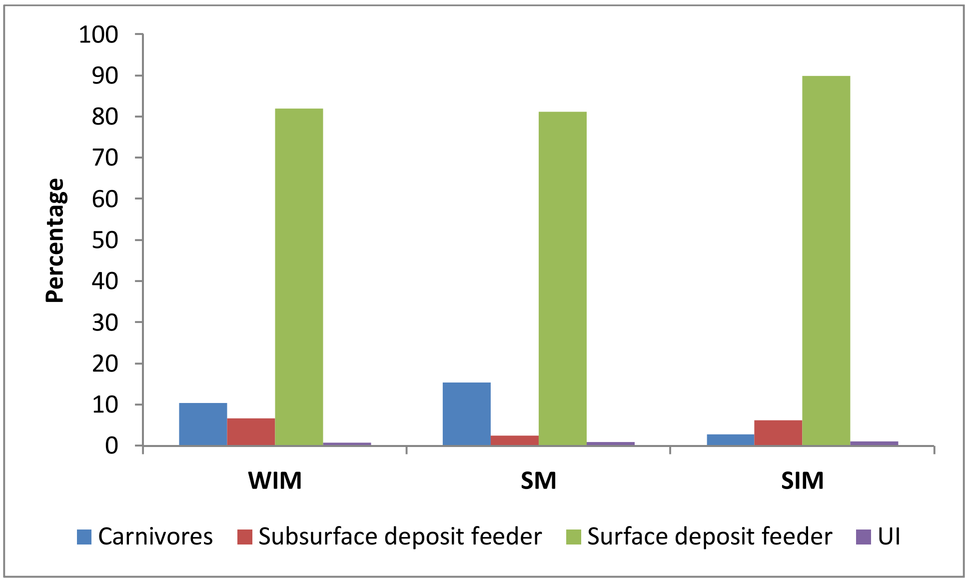

Figure 5.17. Seasonwise distribution of polychaetes feeding guild

5. 2. 7. Relating polychaete community to environmental variables

In the present study, polychaete density was positively correlated with organic matter content of the sediment (0.376, $p<0.05$). Species richness of polychaetes were positively correlated with depth (0.623, $p<0.001$), silt, sand and organic matter content of sediment (respectively 0.323, 0.298 and 0.347, $p<0.05$) and it was negatively correlated with bottom water temperature (-0.696,$p<0.001$) and salinity (-0.346$p<0.05$). Species diversity (H') showed a positive correlation with depth (0.652, $p<0.001$), sand and silt (0.307 and 0.298, $p<0.05$) but a negative correlation was observed with salinity (0.347, $p<0.01$). Mean individual body weight or average body weight was correlated positively with depth (0.385,$p<0.01$). Also mean individual polychaete biomass showed a negative correlation with bottom water temperature (0.298, $p<0.05$) and DO was not correlated with any of the indices.

Eight environmental variables with polychaete species abundance data were subjected to BIOENV analysis and the result [Table 5.9] revealed that depth, salinity and temperature were the best subset of environmental variables in the study area, that could explain the variation in faunal composition with Spearman correlation coefficient, ρ of >0.460. At 500m depth ranges the environmental variable that has high correlation is OM (ρ =0.514)

TABLE 5.9. BIOENV Results (Spearman rank correlation)

Assemblage		Variables	Correlation
250m	a)	Salinity	0.338
	b)	Temperature, Salinity	0.239
	c)	Salinity, OM %	0.161
500m	a)	OM %	0.514
	b)	OM %, Clay %	0.425
	c)	Temperature, OM %, Clay %	0.409
1000m	a)	Salinity	0.333
	b)	Salinity, Silt %	0.269
	c)	Salinity, Sand %	0.259
NEAS	a)	Depth, Salinity	0.477
	b)	Temperature, Salinity	0.460
	c)	Salinity	0.438

The Canonical Correspondence Analysis (CCA) ordination (Figure5.18.) shows the degree of inter-dependence between environmental factors and how they influence the distribution of 34 selected species identified using SIMPER and BVSTEP. The CCA axis 1 and 2 explained 38.16% and 26.15% of variation in species distribution, respectively. Axis 1 (eigenvalue 0.332) showed a strong negative correlation with temperature and positive correlation with depth and oxygen. Axis 2 (eigenvalue 0.228), which was strongly correlated with sand and clay content of sediment. CCA axes 3 and 4 together explained 28.63% of differences among the sampling sites (eigenvalue 0.13 and 0.11, respectively). Species such as *Prionospio cirrifera*, *Linopherus sp1*, *Pisione africana* and *Ampharete* SP1 were characteristic of the sandy sediments with relatively high temperature and salinity, and with low DO concentrations along the southern NEAS shelf edge.

Species such as *Paraprionospio pinnata*, *Ampharete acutifrons, Polydora* sp1*Amphecteis gunneri* and *Jasmineira elegans* showed affinity towards high saline, low DO mid depth sites. The species which showed preference to low saline, relatively high DO and deeper sites were *Aricidea longobranchiata* , *Euclymene* sp1, *Cossura coasta, Onuphis eremita*, *Pista* sp1 etc.

Most of the species oriented towards the deeper, relatively cooler finer sediments with high OM, these included *Chone* sp1, *Mellina* sp1, *Aedicira belgicae, Tharyx marioni, Heteromastus filiformis, Terebellides stroemi* and *Lumbrineris aberrans*.

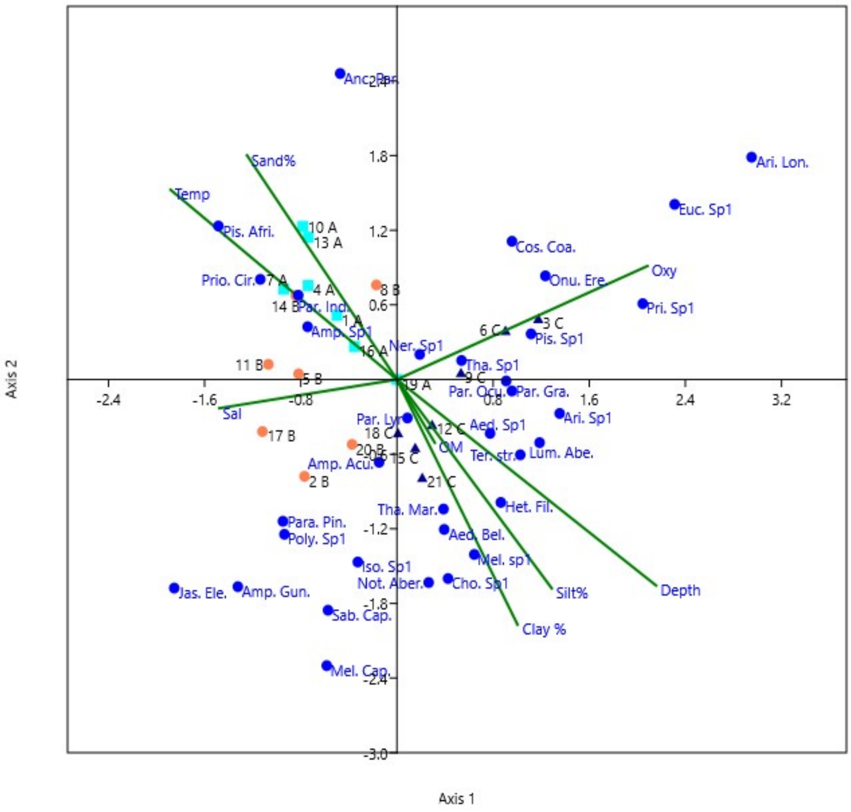

Figure 5.18: CCA plot of most important polychaete species

Table 5.10: Polychaete species selected for CCA Analysis

Sl No	Species	Abbreviation	Sl No	Species	Abbreviation
1	*Linopherus* sp1	Par. Ind.	18	*Levinsenia gracilis*	Par. Gra.
2	*Pisione africana*	Pis. Afri.	19	*Levinsenia oculata*	Par. Ocu.
3	*Ancystrosyllis parva*	Anc. Par.	20	*Cossura coasta*	Cos. Coa.
4	*Nereis* sp1	Ner. Sp1	21	*Notomastus aberans*	Not. Aber.
5	*Onuphis eremita*	Onu. Ere.	22	*Heteromastus filiformis*	Het. Fil.
6	*Lumbrineris aberrans*	Lum. Abe.	23	*Euclymene* sp1	Euc. Sp1
7	*Polydora* sp1	Poly. Sp1	24	*Melinna* sp1	Mel. sp1
8	*Prionospio cirrifera*	Prio. Cir.	25	*Mellinopsides capensis*	Mel. Cap.
9	*Paraprionospio pinnata*	Para. Pin.	26	*Isolda* sp1	Iso. Sp1
10	*Prionospio* sp1	Pri. Sp1	27	*Amphecteis gunneri*	Amp. Gun.
11	*Tharyx marioni*	Tha. Mar.	28	*Sabellides capensis*	Sab. Cap.
12	*Tharyx* sp1	Tha. Sp1	29	*Ampharete acutifrons*	Amp. Acu.
13	*Aricidea longobranchiata*	Ari. Lon.	30	*Ampharete* sp1	Amp. Sp1
14	*Aricidea* sp1	Ari. Sp1	31	*Terebellides stroemi*	Ter. str.
15	*Aedicira belgicae*	Aed. Bel.	32	*Pista* sp1	Pis. Sp1
16	*Aedicira* sp1	Aed. Sp1	33	*Jasmineira elegans*	Jas. Ele.
17	*Paraonides lyralyra*	Par. Lyr	34	*Chone* sp1	Cho. Sp1

5.3. DISCUSSION

The polychaete community of North Eastern Arabian Sea (NEAS) margin is represented by 121 species, falling in 66 genera and 24 families. The species diversity of the present study was found to be very low compared to the SEAS. A similar comprehensive study conducted in the south eastern Arabian Sea recorded as many as 194 polychaete species in 107 genera and 37 families (Abdul Jaleel et al., 2014). From the Pakistan margin 22 species were obtained with a dominance of single species *Linopherus* sp. comprising over 83% of the total individuals (Levin et al., 2009). Polychaete assemblages along a transect on the Oman margin reported around 125 species (Levin et al., 2000). Out of the 24 families from the NEAS, important families in terms of number of species represented were Ampharetide (17 species), Sabellidae (15), Paraonidae (13), Spionidae (10), and Capitellidae (8). The above families together contributed 52% of total polychaete abundance. From the SEAS,families best represented in the study area in terms of number of species were the Spionidae (25 species) followed by Paraonidae (15), Cirratulidae (14), Capitellidae (9), Terebellidae (9), Nereidae (8), Lumbrineridae (8), Onuphidae (8) and Amphaeritidae (8).The numerically dominant species of SEAS were *Tharyx dorsobranchialis* (11.1% of total polychaetes). In the SEAS margin, lowest species count was recorded at the shallow depth (200m, 114 species) followed by the deeper sites (1000m, 134 species), while relatively high species count was obtained at the intermediate depth (500m, 144 species) (Abdul Jaleel, 2012; Abdul Jaleel et al., 2014). In the present study also lowest species count was recorded at the shallow depths (200m, 27 species) followed by the intermediate depth sites (500m, 32 species), while relatively high species count was obtained at the deeper depth sites (1000m, 100 species). Ingole et al., (2010) reported 14 families from a bathymetric transect extending from shelf to lower slope of south eastern Arabian Sea and Spionidae found to be dominating in abundance. Hunter et al., (2012) reported dominance of two polychaete families, the Cirratulids (*Cirratulus* spp.; *Tharyx* spp. *Monticellina* spp) and the Oweniids (*Owenia* spp.) between 800 and 1100 m depth. The OMZ core locations (mean 213 m) of Bay of Bengal margin harbored good populationsof spionids (notably *Prionospio cirrobranchiata*) with a contribution up to 86% to overall abundance. In the upper OMZ, Cossuridae contributed heavily (46%). At the lower OMZ boundary (426–1004 m) Cirratulids accounted for a sizable population (36%). The spionids *Prionospio pinnata* (10.6%) and *Spiophanes* sp. (3.1%) also occurred in high densities (Raman et al., 2014).

5.3.1. Patterns of Species diversity

Even though OMZs are developed in the water column, their effects are experienced intensely at the sea bottom (Devol and Hartnett, 2001). Benthic communities in the core regions of OMZs typically exhibit low levels of diversity and species richness with high dominance by a few tolerant species (Levin, 2003). Levin and Gage (1998), proposed an oxygen threshold (<0.45 mll-1) above which effects of oxygen concentration on macrobenthic diversity are minimal but below which oxygen becomes a critical factor and influences evenness and diversity. However, where oxygen levels are lowest as in the core of the intense Chilean OMZ near Antofagasta, diversity is strongly depressed (Palma et al., 2005). The species number and species richness showed significant increase with increase in depth. Comparatively low species richness and diversity observed at shelf edge and upper slope sites of northern most transects in the present study. Impingement of the Arabian Sea OMZ (ASOMZ) is well established in the shelf edge and upper slope sites of the present study. Oxygen deficiency limits the species richness, diversity and evenness of benthic fauna (Levin, 2003). Similar observations of depressed diversity and richness have also been reported from the margins of Chile (Palma et al., 2005; Sellanes et al., 2007) Oman and Pakistan (Levin et al., 2000; Levin et al.,2009a; Hughes et al., 2009; Gooday et al., 2010) and also in SEAS (Abdul Jaleel et al., 2014). Ingole et al.,(2010) revealed depressed diversity and species richness at 500m and 1000m at 14ºN of Indian continental margin. According to this study, the upper slope community was dominated by Spionidae (*Paraprionospio pinnata*), and mid slope fauna were dominated by Cossuridae and Cirratulidae (1001m).

The relationships between oxygen and macrofaunal diversity on the NEAS margin are similar to those seen in Pakistan, Oman, Bay of Bengal and Chilean margins with a decreased diversity in the OMZ core region. Absence of polychaetes were observed from many stations of the NEAS region (WIM: Mumbai 2, 500m, Porbandar 500m, SIM: Dabhol 200m & 500m, Mumbai2 500m,Veraval 200m & 500m, Porbandar 200m & 500m). All the stations have a DO below critical minimum (<0.5ml/l). In the Pakistan margin species richness and diversity have become minimal between 700 and 850 m, later in the 800 and 900 m depth which increases rapidly and reaches maximal values at 1000 m. The near absence of macrofauna on the Pakistan margin beyond 700m depths suggests that the oxygen levels in these sites were below a critical threshold (Woulds et al., 2007, 2009; Levin et al., 2009). Hunter et al., (2012) reported absence of macrofauna in the OMZ core (540 m; [O2] = 0.35 μmol l^{-1}). Also In the lower OMZ boundary (800–1100 m), highest faunal density and biomass of polychaetes were found at 800 m. Results from the present study is also in agreement with their observations with higher density of polychaetes towards 1000m depth. The lower boundary of the ASOMZ was observed around the 1000m depth, where DO levels began to rise (Helly and Levin, 2004; Woulds et al., 2007). Increase in bottom DO at below the OMZ 'core' has been reported on the Indian (Ingole et al., 2010; Hunter et al., 2012), Pakistan (Gooday et al., 2009; Hughes et al., 2009) and Oman (Levin et al., 2000) margins. During the three seasons sampled, WIM and SM shows consistently lower value of polychaete density in the OMZ core region (500m) with an increasing value towards 1000m depth except for SIM season. The mean polychaetes density for each depth class during different seasons is as follows.

Table: 5.11 Mean polychaetes density (Ind.m^{-2}) for each depth class

	200m	500m	1000m
WIM	75.36±60.9	71.82 ±118.8	172.5±116.9
SM	70.42±86.0	68.33±101.5	101.79±137.1
SIM	30.77±62.2	55.71±112.9	79.29±83.1

In addition to polychaetes in the Pakistan margin, crustaceans and molluscs also exhibited reduced species richness within the OMZ region (Hughes et al., 2009; Levin et al., 2009).The concurrent studies conducted by Rao (2009), along the north east BOB were substantiated with the present study. Within the Bay of Bengal OMZ, oxygen gradient is the main source of habitat heterogeneity influencing macrofaunal species diversity, richness and evenness (Gooday et al., 2010; Raman et al., 2014). In the upper slope (~200m) of Bay of Bengal OMZ sites, where the impingement of OMZ was noticed, polychaetes showed high dominance and constituted 98% of the total macrofauna. Among them *Aonidella cirrobranchiata*, *Cossura coasta* and cirratulids showed high abundance, all together they constituted 66-98% of the total polychaete abundance. The percentage contribution of polychaetes was lowest at 1000m (62%) and highest at intermediate depth (~75%). Spionidae, Cossuridae and Cirratulidae accounted for most of the polychaetes between 200-500m; Paraonidae, Trochochaetidae and other polychaetes (e.g. Amphinomidae, Eunicidae and Nereidae) appeared to be important at 1000m. In the Pakistan margin, the amphinomid *Linopherus* spp. dominated the macrofauna between 700 and 1100m (Levin et al., 2009). Also from the North West coast of India, the 700 to 850 m depth polychaete assemblage is enormously dominated by the *Linopherus* sp (Gooday et al., 2010).In the Indian and Oman continental margin spionid *Prionospio* spp. was observed in high densities in OMZ impacted regions (Ingole et al., 2010; Levin et al., 2000). On the SEAS margin, polychaete diversity increased between 200–1000m. Distinct assemblages were characteristic of the three depth divisions (200m, 500m and1000m) with a more species rich and diverse fauna when compared to the NEAS (Abdul Jaleel et al., 2014). Similar observations of low species richness and high dominance have been reported below OMZ settings throughout the world (Thistle et al., 1985, 1991; Levin, 2003; Gallardo et al., 2004; Hughes et al., 2009). With increasing depth, as the OMZ condition began to ease, the dominance of these forms decreased and diversity was higher.

As far as the eastern Arabian Sea as a whole is considered, southern transects (Cape, Trivandrm and Kollam) were more species rich than those of the north. Species diversity decreased progressively to the north, with the lowest values in T9 (H': 2.37±1.07) (Abdul Jaleel et al., 2014). In continuation with the above finding, species richness and diversity is found to decreas towards the north. The lowest species richness and diversity at the northern transects in the present study are mainly due to the influence of extreme hypoxic condition prevailing in the eastern Arabian Sea (Levin et al., 2009; Joydas and Damodaran, 2014). Even though, during SM season, there was an increase in DO values but this favourable condition did not incite any response in polychaete density values. This may be due to the lack of heterogeneity of substrate, food and/or quality of organic matter (labile or refractory) (Levin, 2003). Despite there is no significant spatio-temporal as well as latitudinal variation of diversity, there was difference in the species composition.

5.3.2. Polychaete assemblages

Estimating the expected number of species from a sample of individuals relies on the relative abundance of different species (Gage and May, 1993; May, 1993). Characteristically, from deep sea sediments macrofaunal samples yield 24–56 species per hundred individuals sampled (Snelgrove and Smith, 2002). It should be noted that the species accumulation curves based on the present study sampling had reaching an asymptote. It is therefore expected that most of the polychaete species have been sampled.

Investigation of polychaete community structure in the NEAS continental margin revealed the existence of 3 distinct assemblages in the three depth classes (21 sites). In the present study multivariate analysis depicted the ordination of deeper sites separately from the other two shallow depth sites. Results indicated that a higher dissimilarity exists between deeper and shallow sites rather than among the shallow groups. The higher dissimilarity between the sites suggests that there are distinct polychaete communities at each site, despite similarities in the presence of many common species. Results of the SIMPER analysis indicate that the relative abundance of the most abundant species were responsible for the greater dissimilarity between sites. The most abundant species belonged to the spionid family especially *Prionospio* spp.

Spionidae is typically the most commonly found polychaete family in deep sea soft sediments (Glover et al., 2002; Hughes and Gage, 2004; Shields and Hughes, 2009) and relatively well represented in the study area also. Spionids are often considered as interface feeders, meaning the animals can switch from surface deposit feeding to suspension feeding as water current speeds and the flux of suspended food increases (Taghon et al., 1980). The ability to take advantage of both deposited and suspended food could provide spionids with a competitive advantage over other polychaetes at the NEAS (Tilstone et al., 2009). The most abundant spionids from the NEAS were *Prionospio cirrifera* and the widespread deep sea species are *Prionospio cirrifera, Prionospio pinnata, Linopherus sp1, Ancystrosyllis parva* and *Ampharete acutifrons.*

The northern and southern shallow assemblages in the study area were found to be under naturally disturbed condition due to intense ASOMZ. A thorough analysis of regionalized data (northern and southern regions) showed good biological ordination with a reliable stress value, lower than 0.2 (Clarke, 1993). It was revealed that the major distinctions of the northern shallow (NS) assemblage was the dominance of *Polydora sp., Prionospio cirrifera, Linopherus sp1* and *Ancystrocyllis parva*. In the southern shallow (SS) assemblage, high abundance of certain species such as *Prionospio cirrifera, P. pinnata and Cossurra coasta* were noted. Among the mid slope (MS) assemblages distinction in community is mainly due to the occurrence of *Tharyx dorsobranchialis, Aricidea spp, Prionospio cirrifera , Ampharete acutifrons ,Tharyx spp, Lumbrineris aberrans, Cossura coasta, Levinsenia oculata,Levinsenia gracilis, Aedicira belgicae and Prionospio* sp1.These species are best adapted for the prevailing conditions like low DO level and relative high abundance of freshly deposited organic matter. In the SEAS continental margin, polychaete community showed the presence of 6 distinct groupings over three depth classes (27 sites). A prominent assemblage of certain polychaete species were present in the southern region (Cape to Kollam) with a discrete community detected in the area from Kochi to Karwar. Another distinct assemblages observed from SEAS were at the shelf edge (200m), upper slope (500m) and deeper sites (1000m) (Abdul Jaleel, 2012).The polychaete species distributionpattern of SEAS, related well to the deviation in the sediment as well as environmental heterogeneity. The shelf edge (200m) and upper slope (500m) sites of SEAS were observed to be influenced by naturally occurring reduced oxygen conditions. (Abdul Jaleel, 2012).

In general, along the continental margins, distribution of polychaete species is mainly influenced by gradients in abiotic parameters with increasing water depth, such as a reduction in light penetration, increasing hydrostatic pressure, decreasing temperature, bottom nature, and often the presence of oxygen minimum zones (Carney, 2005) and biotic parameters such as primary productivity, quantity and quality of OM settled in the bottom (Diaz and Rosenberg 1995; Pearson and Rosenberg 1978; Snelgrove and Butman, 1994; Levin et al., 2001; Laine, 2003). Macrofaunal species diversity is known to reach its maximum at mid slope depths (Carney et al., 1993) and species diversity is influenced by environmental parameters. Environmental parameters can co-vary with depth and hence it is not always easy to expect or interpret how a change in an environmental parameter will influence diversity.

The BIOENV analysis revealed that depth salinity and temperature were the best subset of environmental variables to explain community patterns; and these parameters caused the best similarity between biotic and abiotic data. However, diversity differences between assemblages were associated, in major part, with variability in sediment composition and bottom water DO. The distribution of benthic fauna in relation to sediment heterogeneity are often delineated on the basis of bottom substrate type (Sanders, 1968; Gray, 1974; Jayaraj et al., 2008). Also the distribution of polychaete species with depth is mostly credited to gradients in various environmental parameters (Warwick, 1988; Wei et al., 2010; Abdul Jaleel, 2012; Abdul Jaleel et al., 2014; Khan et al., 2017). The biology, physiology and ecological interactions of marine organisms are also influenced by environmental cues (Rex, 1976; Carney, 2005). Organic matter may serve as the food source to most benthic organisms. In the present studypolychaete density was positively correlated with organic matter content of the sediment (0.376, $p<0.05$). The species richness of polychaetes were positively correlated with depth, silt, sand and organic matter content of sediment but the species diversity only correlated with depth, silt and sand. In addition to the environmental parameters, mean individual body weight or average body weight was positively correlated with depth.

Statistical tools could not clearly identify a single master variable controlling polychaete species distribution. Since entire study area was under the strong influence of the ASOMZ, no significant spatial (bathymetric) patterns were noted in polychaete density and diversity, despite the modest bathymetric gradients in DO. In the SEAS, where the influence of the ASOMZ is much less pronounced, the influence of DO gradients could be clearly observed in the distribution of polychaetes (Abdul Jaleel et al., 2014).

The Canonical Correspondence Analysis (CCA) ordination conveyed a better picture of the degree of inter-dependence among environmental factors and how they influenced the distribution of selected species. The CCA plot showed that there is a strong negative correlationwith temperature while there is a positive correlation with depth and oxygen (CCA axis 1). Axis 2 was strongly correlated with sand and clay content of sediment. The salinity distribution along the NEAS margin showed an increasing trend towards northern sites. The intrusion of high-saline Persian Gulf water in the northern transects (Luis and Kawamura, 2004) bring about in a latitudinal dissimilarity in the case of salinity. The robust relationship of important species assemblages to the specific environments of certain regions or depths through the whole study (across 7 transects, 21 sites and 3 collections) may provide strong indication of the adaptations and tolerance level of specific macrofauna community to the particular environmental conditions pertaining in the NEAS region.

As it goes from the deeper to shallow depths of core OMZ, polychaete abundance were found to be adversely affected. Distinct communities with depth were evident in the CCA. Affinities of certain species to certain environmental conditions or preference to certain habitat were established. Along the southern NEAS shelf edge, species such as *Prionospio cirrifera*, *Linopherus sp1, Pisione africana* and *Ampharete* SP1 were characteristic of the sandy sediments with relatively warm and low saline water with low DO concentrations. Species such as *Paraprionospio pinnata, Ampharete acutifrons, Polydora* sp1*, Amphecteis gunneri* and *Jasmineira elegans* showed affinity towards high saline, low DO environment at mid depth sites. The species showed preference towards environment possessing low saline water with relatively high DO at deeper sites were *Aricidea longobranchiata* , *Euclymene sp1, Cossura coasta, Onuphis eremita* and *Pista* sp1. Many other species oriented towards the deeper, relatively cooler, finer sediments with high OM were *Chone* sp1*, Mellina* sp1*, Aedicira belgicae, Tharyx marioni, Heteromastus filiformis, Terebellides stroemi,* and *Lumbrineris aberrans.* Usually species such as

Prionospio pinnata, P. cirrifera, P. cirrobranchiata (Family Spionidae), *Levinsenia gracilis, Aricidea fauveli* (Family Paraonidae) and *Linopherus* sp1were found to dominate in the OMZ. (Narayanaswamy et al., 2010). As with the physiological adaptations, *Paraprionospio pinnata* species was found to possess four different pyruvate oxido-reductases which is associated with anaerobic metabolism in OMZ benthos, in order to cope up with deleterious effect of hypoxic conditions (Gonzalez and Quinones, 2000).

At the OMZ-impinged Pakistan margin, macrofauna substantially influenced the fate of OM within the sediments. The polychaete *Linopherus* spp., which occurred in extraordinary abundances at Pakistan margin, consumed between 45–80 % of the isotope-labelled OM settled down between 850 and 1800 m (Woulds et al., 2007). In an environmentally disturbed or stressed area, increased densities of small, fast growing and quickly colonizing adaptable species are established (Ellis et al., 2000; Levin et al., 2009). *Paraprionospio pinnata* recognised to favour silty sediments with high organic matter content (Sukumaran and Sarladevi, 2009) and this species is also well fitted to flourish under low oxygen conditions (Levin, 2003). *Paraprionospio pinnata* and *P. indica* is highly adapted with low oxygen conditions, with elaborate branchial structures that enhance oxygen diffusion and enzymatic adaptations for anaerobic metabolism (Gonzalez and Quinones, 2000; Quiroga et al., 2007; Levin et al*.,* 2009b). A great majority of the studies conducted in the OMZs of continental shelves, slopes, basins and fjords have reported the occurrence of spionids or cirratulids (Tarazona et al*.,* 1988; Levin et al*.,* 1991; Arntz et al*.,* 1991; Diaz and Rosenberg, 1995; Levin and Gage, 1998; Levin et al., 2000; Gutierreze et al*.,* 2000; Sellanes et al*.,* 2007; Levin et al., 2009a; Hughes et al*.,* 2009; Ingole et al*.,* 2010; Abdul Jaleel et al., 2014; Khan et al., 2017).

Nevertheless, the present study indicates that in core of OMZ region, even *Prionospio cirrifera* and majority of the polychaetes could not thrive the extreme hypoxic conditions. One possibility for the intolerance or absence of these species can be due to the formation of H2S in the extreme hypoxic condition (Naqvi, 1994). Normally, during the preliminary phases of oxygen depletion, facultative bacteria switch over to the use of nitrate ions for oxidation of organic matter (denitrification) (Naqvi, 1994; Morrison et al., 1999). As a result, nitrate is reduced to free nitrogen, with nitrate as one of the several intermediates. Once nitrate and nitrite are completely removed from the environment, bacteria will use sulfate ions as reduction substrate, which will eventually end up in production of hydrogen sulfide. *Prionospio* sphas been reported to disappear completely when sulfide levels increase in the hypoxic environments (Josefson and Widbom, 1988; Nilsson and Rosenberg, 2000; Quiroga et al*.,* 2007). However, the present study cannot prove this as sulfide measurement was not taken but may be one of the reasons for complete absence of polychaetes observed at multiple sites.

5.3.3. Functional ecology

Benthic fauna as a whole rely up on the organic matter from the photic zone except for some chemosynthetic communities (Gage and Tyler, 1991; (Rex et al., 2006).The quality and degree of the organic matter deposition are considered to be the primary factors regulating the structure of benthic assemblages (Gooday and Turley, 1990; Graf, 1992). In the marine environment there is a unimodal relationship between diversity and food availability (Levin et al., 2001). Different types of feeding modes and adaptations have found among benthos to thrive energy deprived habitat like deep sea. Polychaetes exhibit all major feeding strategies and consequently different polychaete species simultaneously will take advantage from different food sources and availability (Fauchald and Jumars, 1979, 2015; Grassle and Maciolek, 1992). Furthermore many polychaete families such as Spionidae and Chaetopteridae can switch between guilds—that either suspension feed or deposit feed depending on local conditions and their feeding histories (Dauer et al., 1981; Jumars et al., 2015). In terms of functional ecology the NEAS were characterised by the high abundance of surface deposit feeders (86%). Gaston (1987) found that surface deposit feeders dominated in most areas on the continental shelf of the Middle Atlantic Bight. A Similar observation was reported from Indian continental shelf (Jayaraj et al., 2007) and continental slope (Ingole et al., 2010; Abdul Jaleel et al., 2014).

In general the deep sea sediments mostly dominated by surface deposit feeding polychaetes (Gage and Tyler, 1991). The SDF taxa (*P. cirrifera, T. dorsobranchialis, P. pinnata*, ampharetids) are characterized by small body size, proliferating branchiae and subsequently having a higher surface area-volume ratio and are ideally suited for utilizing abundant OM under severe OMZ settings (Levin, 2003; Levin et al., 2009; Abdul Jaleel et al., 2014; Khan et al., 2017). The bathymetric distribution of polychaete functional groups is directly influenced by the quantity, quality, and location (buried or in benthic boundary layer) of organic matter available in the sediments. In the present study, sediment OM showed considerable variation with respect to depth as well as latitude. The organic carbon percentage of the entire continental slope of the western Indian margin ranged from 2 to 16% within the oxygen minimum zone (Paropkari et al., 1992) and is predominantly of marine origin (Fontugne and Duplessy, 1986; Paropkari et al., 1987, 1992; Calvert et al., 1995). From the present study also, high organic carbon values >15% were observed. In general, more organic matter is retained in the fine sediments i.e., silt or clay. Most of the stations showed clayey silt sediment texture in the NEAS region. Especially the deeper stations showed comparatively high percentages of finer particles like silt and clay. In accordance to this observation, present study has recorded low organic matter value in the depth range of 200m. Comparatively low organic carbon percentage in the upper slope is because of the hydrodynamic activities and associated winnowing, The present study has shown relatively high OM values in 500m depth zone. Kolla et al., (1981) have specified that the high organic matter content in the sediments of the Indian continental margin is principally due to its preservation, which result from the impingement of low oxygenated water on the sea floor and from the high sedimentation rates. But Calvert et al., (1991) suggested that anoxic condition in the water column may not be a prerequisite for the preservation of organic matter in marine sediments. Since ASOMZ core is located around 500m depth, the observed increase in organic matter at 500m may be attributed to impingement of OMZ along with the preservation and due to high production in the upper photic zone. In the polychaete community, surface deposit feeders represented 78% of polychaetes in the 200m, 99% at 500m and 81% at 1000m depth ranges. High numbers of SDF group of polychaetes were related to recently settled food in such a food-limited area (Gaston, 1987). Also surface deposit feeders (SDF) prefer to feed directly on freshly deposited organic matter at the sediment-water interface, while sub-surface deposit feeders (SSDF) mainly consumed on older organic matter below the surface sediments (Rosenberg, 1995, Muniz andPires, 1999, Dolbeth et al., 2007; Khan et al., 2017).

The relative abundance of all feeding types was comparable with macrofaunal community observations from similar depths on the SEAS continental margin (Abdul Jaleel, 2012). However, studies from the NE Atlantic suggest that the relative abundance of surface deposit feeders is highest at mid-slope bathyal depths, although subsurface deposit feeders become more abundant at lower slope bathyal depths and on the abyssal plain (Flach et al., 1998; Hughes and Gage, 2004). Among polychaete feeding guilds, suspension and deposit-feeding species are more likely to be affected by changes in nutritional quality. The ability to switch between suspension and deposit feeding may be advantageous with change in hydrodynamics and food supply. For example, Wieking and Kroncke (2001), observed substantial increases in spionid polychaetes that can switch feeding modes in the central North Sea following a decade of increasing North Atlantic Oscillation index and accompanying changes in primary productivity. True carnivores which are highly motile, with higher oxygen requirement, meagrely represented in the study area. OMZ adapted taxon like *Linopherus* sp. (facultative omnivore with extensive gills) were abundant in some sites, similar to the observations made from Pakistan margin, NW Arabian Sea Margin (Gooday et al., 2010; Levin et al., 2011).

Little is known about the macrofaunal community associated with Indian continental margin and the present study provides an important insight into the polychaete community of the NEAS margin especially at Indian region.

Chapter 6

SUMMARY AND CONCLUSION

Deep sea benthic fauna of the northern Indian Ocean have gained attention in recent years, owing to the overall significance of this region in global biogeochemical cycles. However, the qualitative and quantitative aspects of benthos in this region remain poorly known relative to other parts of the world ocean. Within the northern Indian Ocean, the Arabian Sea is a unique system, being characterized by coastal upwelling, convective mixing, intrusion from landlocked seas (Persian Gulf, Red Sea) and the central Indian Ocean, high biological production, massive seasonal phytoplankton blooms and a perennial open ocean Oxygen Minimum Zone (OMZ).

The present study provides baseline data on standing stock of macrobenthos and community structure of polychaetes in the continental slope (200-1000m) of the North Eastern Arabian Sea (NEAS, Lat: 15 .25’ to 21 .30’ and Long: 72 .48’ to 67 .28’) based on systematic, seasonally resolved sampling along three depth contours in seven bathymetric transects between December 2003 and May 2007. The surveys were carried out on board FORV *Sagar Sampada* as part of the project “Benthic fauna of continental slope from 200-1000m depths of Arabian sea and Bay of Bengal" funded by the Centre for Marine Living Resources and Ecology (CMLRE), Ministry of Earth Science, Government of India, to gain information on the marine benthos in the Exclusive Economic Zone (EEZ) of India.

During the study, 63 stations (108 grabs) were surveyed, representing replicates of 21 sites at 200, 500 and 1000m depths, along 7 transects (located between Goa and Porbandar). The study area was characterized by significant spatial heterogeneity and seasonal variations in hydrographic parameters. In general, salinity was highest along the 500 m contour, with a gradual increase from south to north at all depths. Bathymetric trend of decreasing temperature with increasing depth was prominent. The shelf edge and upper slope sites of the study area evinced the impingement of the Arabian Sea OMZ (ASOMZ), and were characterized by significantly oxygen depleted conditions (<0.3 ml/l), with increasing severity towards the north. At the mid-slope (1000m), which fell beyond the core of the ASOMZ, dissolved oxygen (DO) values were relatively higher.

In the NEAS margin, surface sediments showed significant bathymetric variations, with sand-dominated substrates at the shelf edge, and progressive shift towards finer (clayey silts) sediments in the mid-slope. The organic matter (OM) content of sediments was relatively higher at the OMZ core region (500 m depth), followed by the mid-slope, while OM was lowest in the sandy sediments of the shelf edge. Temporal or seasonal variations were not evident in sediment OM content during the present study.

In the NEAS margin average macrofaunal biomass was1.8 gm^{-2}(nil to 58.43 gm^{-2}) and average density of 156 ind.m^{-2}(nil to 4099 Ind.m^{-2}),with significant spatial variations. When compared to the shelf edge (200m) and upper slope (500m), relatively higher standing stock was noted at the mid-slope (1000m), contradicting the general trends predicted for the deep sea. The standing stock at mid-slope depths were comparable to isobathic depths in the South Eastern Arabian Sea (SEAS), which were also studied in concurrent surveys. Polychaetes were the dominant group among macrofauna (59%), followed by crustaceans (16%). Other groups represented were bivalve molluscs, nemertines, sipunculids etc. The spatial trends in polychaete standing stock mirrored that of macrofauna as a whole.

A total of 121 species of polychaetes were represented in the NEAS margin, in 66 genera. Polychaetes were altogether absent at several station in the study area, particularly in the shelf edge and upper slope. Polychaete species richness and diversity increased with increasing depth in the study area, while latitudinal and temporal variations were not significant. High density and dominance of certain species was observed at some stations in the upper slope, while extremely low density (<10 Ind.m^{-2}) was observed in many stations in the shelf edge and upper slope.

Multivariate analysis of polychaete species composition revealed that assemblages in the mid-slope were distinct from those of the shelf edge and upper slope, being characterised by relatively high species richness and diversity. In the latter region, regional distinctions (north and south) were also observed, owing to variations in relative abundance of common species. Thus, three distinct assemblages could be identified in the NEAS margin – the southern shallow (SS), northern shallow (NS) and mid-slope (MS) assemblage. These distinctions also reflected distinctions in functional ecology across the slope in the NEAS, which were in turn strongly influenced by the impingement of the ASOMZ, and also affected by the spatial variations in sediment characteristics.

The communities at the shelf edge and upper slope, which are under the influence of the ASOMZ core, were characterized by low density and diversity, with relative dominance of small-sized opportunists such as *Prionospio cirrifera*, *Prionospio*. sp1, *Cossura coasta, Paraonis* sp1. and *Tharyx* sp. These genera are widely reported to be significant components of macrofauna under OMZ conditions throughout the world ocean. Within this OMZ impinged region in the NEAS margin, the northern region (Porbandar, Veraval and Mumbai 2) was severely impacted, relative to the southern part (Mumbai 1 to Goa) which was also reflected in the macrofaunal standing stock and polychaete species composition. A marginal increase in DO levels towards the mid-slope, along with the shift to finer sediments, supported more diverse assemblages at densities comparable to the SEAS. The NEAS margin could thus be delineated into an extremely OMZ impacted region (shelf edge and upper slope) and relatively less impacted mid-slope (1000m), with distinct biological characteristics.

The present study reveals low macrobenthic standing stock and polychaete diversity in NEAS when compared to SEAS (mean density: 584

Ind.m^{-2}, mean biomass: 6.03gm^{-2}, total 195 polychaete species) where oxygen deficiency was less pronounced. The environmental conditions, particularly sediment texture and OM, in the northern part of the SEAS (Kochi-Bhatkal), were comparable to isobathic depths of the NEAS, while DO levels showed significant differences owing to the impingement of the ASOMZ in the NEAS. In the SEAS, the shelf edge and upper slope sires were characterised by high density and clear-cut dominance of certain opportunistic polychaete species. By contrast, macrofaunal was absent or meagrely represented at these depths in the NEAS, owing to the extremely low DO. These observations emphasise the key role of DO and the ASOMZ in determining benthic standing stock and community structure in the eastern Arabian Sea.

Oxygen minima are undergoing expansion and intensification globally, due to anthropogenic activities as well as natural processes. The present study, provides a robust dataset on macrobenthic standing stock and community structure in a continental margin impinged by the Arabian Sea OMZ, which is known to be the thickest and second most intense in the world. It reveals the reduction in standing stock and diversity of fauna and diminished ecosystem functions under severely oxygen depleted conditions (<0.2 ml/l). The study is limited to the 1000m depth contour, where OMZ conditions only begin to relax. Further studies need to be undertaken in the NEAS beyond the present study area, to generate a complete picture on benthos in the Arabian Sea.

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