AMPHIPODS OF THE DEEP MISSISSIPPI CANYON, NORTHERN GULF OF MEXICO: ECOLOGY AND BIOACCUMULATION OF ORGANIC CONTAMINANTS

A Dissertation

by

YOUSRIA S. SOLIMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2007

Major Subject: Oceanography

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Approved by:

Co-Chairs of Committee: Gilbert T. Rowe
Terry L. Wade
Committee members: Douglas C. Biggs
Mary K. Wicksten
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ABSTRACT

Amphipods of the Deep Mississippi Canyon, Northern Gulf of Mexico: Ecology and Bioaccumulation of Organic Contaminants. (May 2007)

Yousria S. Soliman, B.S., University of Alexandria (Egypt);
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Co-Chairs of Advisory Committee: Dr. Gilbert T. Rowe
Dr. Terry L. Wade

In five summer cruises during the period 2000-2004, seventy-four box cores were collected from eleven locations from the Mississippi Canyon (480- 2750m, northern Gulf of Mexico), and an adjacent transect (336-2920) to understand the community structure and trophic function of amphipods and for measuring the bioaccumulation of polycyclic aromatic hydrocarbons, (PAHs). Amphipods were discovered to be an important component of the macrofauna of the Mississippi Canyon (40 % of the total faunal abundance). Seventy two species, belonging to nineteen families, were collected from the study area with 61 species from the canyon and only 38 species from the non-Canyon transect. The head of the canyon (480m) was dominated by dense mats (15,880 ind/m^2) of a new amphipod (*Ampelisca mississippiana*). The logarithm of the amphipod abundance decreased linearly with depth. The species diversity (H`) exhibited a parabolic pattern with a maximum at 1100m. The differences in amphipod abundances and biodiversities were correlated with the variation in the amount of available organic matter. The depression in diversity in the canyon head is thought to be competitive exclusion resulting from the dominance by *A.*

mississippiana, but the high species richness is presumed to be a function of the structural complexity of the canyon.

Annual secondary production of *A. mississippiana* was 6.93 g dry wt m^{-2}, based on size-frequency method and corresponding to an estimated univoltine generation from a regression model. The production/biomass ratio (P/B) was 3.11. Production of this magnitude is comparable to shallow marine ampeliscids but are high for the depauperate northern Gulf of Mexico.

The effect of the organic contaminants and the bioavailability to the amphipods was determined through measuring the bioaccumulation of the PAHs. The distribution of PAHs in sediments was different from the distribution in the organisms suggesting preferential uptake/depuration or uptake from pore or bottom waters. The average bioaccumulation factor (4.36 ± 2.55) and the biota sediment accumulation factor (0.24±0.13) for the total PAHs by the ampeliscids were within the range reported for other benthic invertebrates. The average bioaccumulation factors were highest for dibenzothiophenes (up to 132) and alkylated PAHs and lowest for parent high molecular weight PAHs.

DEDICATION

To

My husband *Hesham*, my beloved sons, *Mohanad* and *Yazeed*,
and my kind father, *Soliman*.

ACKNOWLEDGMENTS

The dissertation work is not solely the product of the student. Committee members, other faculty members, family, and friends all play important roles in the completion of the degree. I am grateful to all of them.

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CHAPTER I

GENERAL INTRODUCTION

I.1. Overview

The Gulf of Mexico, is a major production source for gas and oil in the United States (Sassen et al., 2001). In the nineteen nineties, exploitation for oil resources expanded beyond the continental shelf to the slope and deep sea. The deep Gulf of [1]Mexico (>200 m) is considered as an important reserve for oil resources while the resources in the shallow Gulf are declining. There are > 4000 structures in the federally regulated offshore waters of the Gulf of Mexico (Gulf) associated with oil and gas production (Kaiser and Pulsipher, 2004). The number of oil and gas projects in the deep Gulf increased from 16 in 1997 to 118 in 2006 (French et al., 2006). As oil activities expand, concerns are also growing regarding the impacts of these activities on deep sea ecosystems and deep sea organisms. One potential adverse impact to ecosystems of the Gulf may result from the influx of polycyclic aromatic hydrocarbons (PAHs) (Mitra and Bianchi, 2003). PAHs are hydrophobic organic contaminants that tend to accumulate in sediments, jeopardizing the health of deep-water ecosystems. Benthic organisms in the Gulf are vulnerable to chronic inputs of petroleum hydrocarbons because they have limited or no mobility to avoid the exposure.

This dissertation follows the style of Deep-Sea Research II.

I.1.1. Mississippi Canyon

The Mississippi Canyon is the most prominent physiographic feature in the northern Gulf. It plays an important role in conveying sediments and organic matter that moved across the shelf from the Atchafalaya and Mississippi Rivers down to the deep Gulf (Ellwood et al., 2006). These sediments contain organic carbon, nutrients, and organic contaminants. The Mississippi Canyon may be a conduit transporting contaminants from the Mississippi River to the deep sea (Balsam and Beeson, 2003) and linking the quality of the life in different ecosystems.

Canyons are one of the complex ecosystems on the continental margins. The topographic features and circulation patterns of canyons promote the export of the organic matter from the shelf to the deep sea. Thus canyons having a crucial role in the redistribution of carbon and anthropogenic materials derived from marine primary production and terrestrial runoff (Weaver et al., 2004). Canyons have been considered as potential waste disposal sites (Weaver et al., 2004). The enhanced flux of organic carbon in canyons increases the productivity of the benthos (Bosley et al., 2004) and creates hotspots of faunal biomass (Vetter and Dayton, 1988; Rogers et al., 2003). Canyons have complex environmental conditions that affect the structure and function of their benthic communities (Vetter and Dayton, 1988). Distinctive communities are found to occupy canyon ecosystems. These communities are constrained by the canyon’s particular environmental parameters and differ from nearby non-canyon fauna (Rowe, 1971; Ohta, 1983). The species abundance and community structural differences from canyon to canyon appear to be related to downward particle fluxes, topography, and the hydrographic features of individual canyons (Weaver et al., 2004).

I.1.2. Deep water amphipod

Benthic invertebrates are frequently used as bioindicators for the health of marine environments due to their response to anthropogenic and natural stress (Pearson and Rosenberg, 1987; Dauer, 1993). Amphipods are among the most diverse and dominant macrofaunal taxa in deepwater environments (Cartes and Sorbe, 1999; Dickinson and Carey, 1978). They are ubiquitously distributed even in the harsh and confining habitats of deep trenches (Blankenship et al., 2006). Amphipods provide information as both measures and monitors of biodiversity. They integrate the environmental effects in an ecosystem due to their relative immobility, their sensitivity to variety of pollutants, their feeding habit, and the lack of free living larval stages in their developments. Because they lack dispersal, they exhibit a high degree of habitat specificity and niche requirements (Thomas, 1993). So they are very important benthic group for ecological monitoring (Reish and Barnard, 1979). Amphipods are principally deposit feeders and can feed selectively on discrete particles of organic detritus (c.f. Dickinson and Carey, 1978). They recycle organic debris and support the marine ecosystem by allochthonous material (Vetter, 1998). This would suggest that they are sensitive to changes in the quality of food input to the sea floor. Amphipods are sensitive to oil pollution and related compounds (Grosse et al., 1986). Their structure, abundance, and diversity are used as metrics for the effects of oil pollution (Gómez-Gesteira and Dauvin, 2000), and in general, they are considered as good indicators of organic pollution (Mayer-Pinto and Junqueira, 2003).

The systematics and distributions of deep-sea amphipods are relatively well known in comparison to their structure and ecological role in deep-water communities (Thurston, 1979; Gage and Tyler, 1991; Sainte-Marie, 1992). Amphipods from the northern Gulf of Mexico are only sporadically and fragmentally studied. Studies focused on the taxonomy of species of the littoral zone with only 101 species recorded from the large marine ecosystem (LME) of the Gulf (Escobar-Briones and Winfield, 2003). There is a discrepancy between the ecological importance of amphipods and their study in the Gulf of Mexico. The lack of biological data on deep-water amphipods is basically attributable to the absence of adequate sampling, and to samples with a limited number of specimens (Cartes and Sorbe, 1999). Although some studies of deep benthos were carried out on the deep Gulf of Mexico (Rowe and Menzel, 1971; Pequegnat, 1983; Gallaway et al., 2003), only limited information about the community structure of the amphipods is available. Information about changes in amphipod's bathymetric distribution, their diversity as well as their contribution to the overall benthic biomass in the northern Gulf of Mexico is not available. Most of the studies on the structure and function of deep-water epibenthic/ suprabenthic amphipods were carried out in the Mediterranean Sea (Cartes and Sorbe, 1999) and northeastern Atlantic Ocean (Marquiegui and Sorbe, 1999), but very few were carried out regarding infaunal amphipods.

I.2. Integrated study for benthic amphipods in the Mississippi Canyon

Exploiting natural resources in a sustainable manner requires profound integrated knowledge about the dynamics and structures of margin ecosystems including prominent systems such as canyons. This integrated knowledge should link research on biodiversity to physicochemical parameters that control different ecosystems on the margins (Weaver et al., 2004). Several questions about the canyon's amphipods as sensitive organisms and an ecologically important group are raised:

1. What are the dynamics of deep-sea amphipods, composition, abundance and diversity, in the canyon?
2. How does the canyon environment affect the pattern of zonation in deep-sea amphipods?
3. What is the function of the deep sea assemblages of the amphipods in the canyon?
4. What is the influence of enhanced organic carbon flux on deep-sea amphipods?
5. What is the influence of anthropogenic compounds inputs from oil activities on deep-sea amphipods?
6. What other influences might affect the distribution of benthic amphipods inside deep sea channels?

To get answers for these questions, three main categories of information about canyon ecosystems are required to be integrated and compared to non-canyon reference sites:

1. Analysis of benthic amphipods along canyon depth gradients (structure and function) to compare to non-canyon reference sites.
2. Analysis of sediment chemistry including the amount of organic matter, anthropogenic organic components, dissolved organic carbon, POC, dissolved oxygen, nutrients (NO_3^-, SO_4^{-2}, etc), grain size, etc.
3. Measurements of the bioavailability of the anthropogenic materials in the deep sea on the amphipods.

These three categories of information or measurements are close to what is known for sediment assessment as the "triad approach" that is largely used in shallow water for assessing the quality of sediment. However, analysis of benthic faunal groups in the triad approach is used just for community structure while community function is equally if not more important (Fig. 1.1). Individually, the components of the triad approach do not provide adequate information about the quality of different ecosystems. But together, the status of an ecosystem can be assessed by having a clearer picture about the effects of the existing conditions on the structure and function of the benthos as well as the actual effects of any anthropogenic compounds through measuring body residues. For an integrated study for the amphipods from the Mississippi canyon, the three mentioned components will provide different information (Fig. 1.2). Statistical analysis can include data from the different components of these measurements to make the identification of the most important factors causing the different structure and diversity patterns (Fig. 1.2).

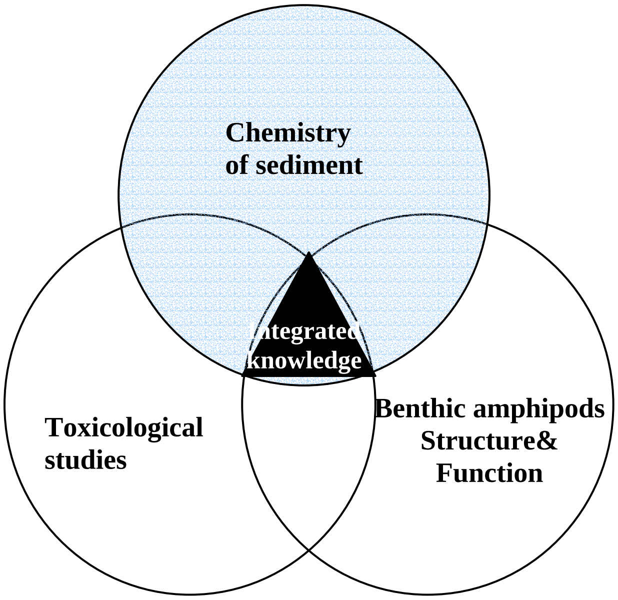

Fig. 1.1. Components of integrated study for benthic amphipods in the Mississippi Canyon.

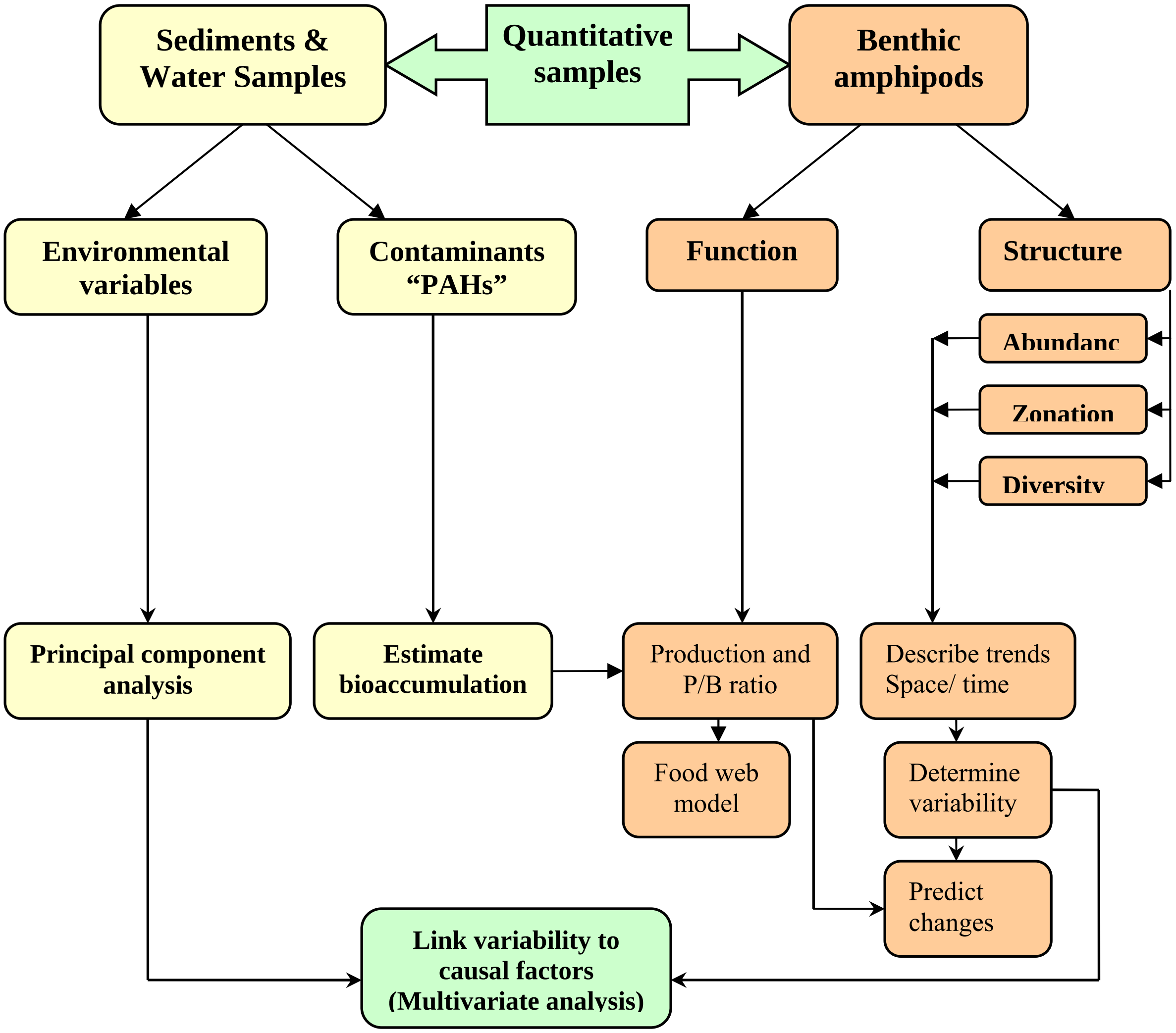

Fig. 1.2. Schematic chart showing the general outline for an integrated study in the Mississippi Canyon using biotic (benthic amphipods), and abiotic environmental information.

1.2.1. Biological measurements

Ecological characteristics of biological communities are divided into structural and functional (elements and performance). Most studies of ecological communities in ocean have focused on defining community structure. However, the study of ecosystem functions, and especially the effects of anthropogenic activities on these functions, is also an important part of benthic studies (Kropp, 2004).

1.2.1.1. Structure of benthic amphipods

Several metrics of community structure are used to describe benthic assemblages in a way that shows different responses for environmental variabilities including anthropogenic inputs. These metrics include abundance, biomass, species richness and measurements of the diversity using different indices on different spatial scales. Abundance of benthic communities was found to decrease as function of depth and distance from shore in many deep sea studies (Rowe, 1983). This is probably due to the decrease in POC flux as function of depth (Rowe et al., 1991).

Different diversity indices such as number of taxa, E(sn), the expected number of species (Sanders 1968, Hurlbert 1971), Shannon and Weaver's index (H`) are commonly used to describe the structure of benthic communities. The former index has the advantage of not being sensitive to the samples size by estimating the species number normalized to the small sample size. In most cases, it is more useful to use a variety of indices that together provide greater insight into how and why diversity varies than does a single index (Levin et al, 2001). Information from these indices can be used to compare the diversity across habitats, sites, gradients, or regions on different scales. Three scales are known for diversity measurements, the first is the change of diversity within the community and is known as α, the second is the change in α diversity between ecosystems is known as β, and the third is more global and it is the change of diversity between regions and is known as γ diversity. Comparison between diversity indices on different scales can be used to infer changes in the environmental quality or ecological conditions. For example, equitability index, which is the ratio of individuals in each taxa to total number of individuals, shows if there is dominance by specific taxa in a specific location. This in turn indicates conditions which preferentially support particular taxa, such as organic carbon enrichment, contamination or other biological factors. Low amphipod abundance and diversity are also used as general indicators of hypoxia, sediment organic carbon loading, and hydrocarbon contamination (Swartz et al., 1986 and Peterson et al., 1996).

Zonation is the way we separate the benthic taxa into zones based on changes in their succession down gradients of physicochemical parameters (e.g. the depth) based on the measurement of percent of similarity. It is a way to compare the community structure over space. Change in species succession indicates a change in the physicochemical parameters such as food availability (organic carbon). Functional feeding groups can be used instead of taxa to describe zonation pattern, and hence the quality of the environment can be predicted. For example, the zones of collector feeders (filter feeders and suspension feeders) indicate organic carbon enrichment.

I.2.1.2. Function of benthic amphipods

Benthic amphipods are efficient consumers of organic detritus (Vetter, 1998) and transfer carbon and energy to higher-level consumers (Mills, 1967b; Sudo and Azeta, 1996; Dauvin, 1988, 1989; Hobson et al, 2002), including demersal fishes (Collie, 1985, 1987; Franz and Tanacredi, 1992; Carlson et al, 1997), and gray whales (Nerini & Oliver, 1983; Kaiser and Spencer, 1994, Dunham and Duffus, 2002, Highsmith et al, 2005). For example, amphipods make up most of food of gray whale in Bering Sea. Amphipods are also important components in the recycling and redistribution of benthic organic matter. Estimating the secondary production of the biotic components is important as a quantitative measure of the functioning of their ecosystem. Production is one of the major paths of energy flow through ecosystems (Waters, 1977), and its estimates is probably one of the most comprehensive assessments for understanding the integrity for ecosystem (Buffagni & Comin 2000, Dolbeth et al, 2005, Dolbeth et al, 2007). Macrobenthic trophic structures are found to be changed in areas with sediment contamination in the northern Gulf of Mexico (Brown et al., 2000). Stressed habitats support smaller species with shorter life spans (Statzner and Moss, 2004), which have higher productivity (Hermsen et al., 2003).

One common measure in the estimations of the secondary production for different trophic levels in different ecosystems is the “Production to Biomass ratio” (*P/B*). This measure allows comparisons between species having different biomasses (Plant and Downing, 1989). It expresses the turnover rate of the biomass of the species, or the amount of time it takes to replace the entire population (Cusson and Bourget, 2005). Reported average yearly P/B ratios in amphipods ranged between 2 and 7 for lower latitude's amphipods (Bluhm et al, 2001). Comparing that with those for crustacea, the mean P/B ratio for suprabenthic crustaceans is 5.5±1.9 while mean P/B ratio for the benthic crustaceans is 2.9±2.12 (Cartes et al, 2000). The P/B ratio is variable with size and longevity of different organisms with temperature and other factors. Small and short lived species have higher P/B ratio than larger long lived species (Mclusky, 1989). The annual P/B ratio for unicellular organisms such as phytoplankton exceeds 100 (Díaz-Uribe et al, 2007, Cruz-Escalona et al, 2007). This high rate of turnover for small organisms is because they have small biomass that sustains an entire ecosystem. Odum (1985) indicated that in stressed environments, the energy of the ecosystem is diverted to maintenance instead of growth and reproduction, so the P/B ratio increases. Changes in macrobenthic trophic function might affect the whole ecosystem by changing rates of processes such as nutrient cycling, and energy transfer (Gaston et al., 1998). Knowledge about the production ratio (P/B) among organisms enables predicting the fluxes of persistent contaminants that may bioaccumulate and then undergo biomagnification in marine food webs.

I.2.2. Near bottom properties and sediment chemistry

In the last decades with the increasing interest in studying deep sea benthic faunal groups distributional and diversity patterns, interests are increasing toward relating these patterns to the existing environmental parameters especially the sedimentary properties. Structures of benthic organisms are found to be related to sediment geochemical properties (Sanders 1968). Sediment properties including sediment grain size, organic carbon content, organic nitrogen, contaminants concentration, dissolved oxygen, and others play vital roles in structuring benthic organisms. Sediments of the northern Gulf of Mexico contain a mixture of terrigenous, petroleum and planktonic hydrocarbons. The relative amounts of these three types vary as a function of location, water depth, and season (Kennicutt et al, 1987). The Mississippi River has a major influence on the spatial distribution of the sediment in the Gulf. The transported river sediment extends to the lower Mississippi Deep-Sea Fan and the adjacent Sigsbee Abyssal Plain (see Balsam and Beeson, 2003). This dominancy of the river derived sediment affects the faunal structure in the northern Gulf (Deegan et al, 1986). The Mississippi Canyon is a major pathway for transporting particulate organic carbon (POC) and other materials derived mainly from the Mississippi River into the deep water. Because of their geomorphology and characteristic hydrodynamics, canyons are able to accumulate detritus and to shunt large quantities of near shore production to the deep-sea floor (see Vetter, 1998), which enhances the faunal abundance due to the organic enrichment (Rowe et al, 1982; Gage and Tyler, 1991; Gage et al, 1995). The enhanced labile organic flux in the canyons as well as the canyon morphological and hydrodynamic features create unique ecosystems. They harbor exceptional densities of unique benthic assemblages that can be used as indicators for individual canyons. The flux of organic carbon and the abundance of the benthos are found to be correlated in several deep sea studies (Sibuet et al, 1989). Amphipod abundance are known to be increased by the enhanced organic material flux, however, their numbers decrease if this flux is beyond a threshold level (Reish and Barnard, 1979).

Dissolved oxygen in the bottom water is another important factor that determines the structure and function of benthic communities. There are some areas located close to big rivers or upwelling areas where the oxygen is minimal or even depleted and these are known as oxygen minimum zone (OMZ), (O_2 <0.5 ml/l). Depletion of the oxygen in the overlying bottom water changes the structure of benthic communities and reduces the diversity (Levin et al, 2001). For example, in the OMZ of the NW Arabian Sea, molluscs and crustaceans disappeared except one amphipod (*Ampelisca*) that was abundant within this oxygen depleted zone (Levin et al, 2000). Sediment grain size provides different interstitial spaces for the benthic organisms. Species diversity is found to be correlated with the heterogeneity of sediment grain size (Etter & Grassle 1992). Higher diversity of amphipods is found to be correlated to the sediment texture. POM is usually inversely proportional to grain size, but does not correlate well with the biomass of the living components (Rowe and Kennicutt, 2001). Other environmental parameters in the canyon environment (such as the bottom currents) are of great importance in affecting the structure of benthic communities. Canyons are known to focus the tidal flow. These currents are found to re-suspend the detrital materials forming a nepheloid layer (Gardner, 1989). Ellwood et al (2006) stated that there is coherent transport of detrital particles from near shore to the deep Gulf. These detrital particles are transported as nepheloid layers currents to the deep Gulf.

I.2.3. Residual burdens of PAHs in amphipods (Bioavailability)

Petroleum production can impact benthic associations due to influx of chronic low level of hydrocarbons (Peterson et al., 1996). The intensive oil and gas exploration in the northern Gulf as well as the horizontal flux from the Mississippi River might be potential sources for chronic pollution with oil as well as other materials in the deep Gulf. The cumulative effect of the chronic pollutants release might jeopardize the health and quality of deep. One potential adverse impact to ecosystems of the Gulf of Mexico may result from this cumulative influx of poly cyclic aromatic hydrocarbons (PAHs) (Mitra and Bianchi, 2003). In aquatic environment, PAHs contamination can result from several anthropogenic sources such as petroleum runoff, industrial processes, and petroleum spills (Hatch and Burton, 1999). Oil pollution from runoff is a chronic environmental problem and major factor in the degradation of the marine ecosystem (see Browsky, et al, 1993). Chronic exposure may be more detrimental to marine ecosystem than the more dramatic oil spills, because organisms can bioaccumulate oil even at low concentrations (see Browsky, et al, 1993).

Benthic organisms are exposed to these organic contaminants and they are known to accumulate aromatic hydrocarbons (Landrum and Robbins, 1990). Elevated concentrations of PAH in aquatic organisms are correlated with chronic hydrocarbon discharges (Neff, 1995). Because PAHs are relatively insoluble in water, they tend to concentrate be transported to the sediments. The result is high concentration in the sediments; with consequent elevated exposure levels for biota that inhabit or feed in surface sediment. Transfer of organic contaminants to the food web is significant through the benthos contribution (see Landrum et al., 2001). It is important to measure the contribution of amphipods as deposit feeders in the bioaccumulation of persistent PAHs from sediment. Bioaccumulation refers to the accumulation of specific contaminants through any route (direct contact or ingestion) in the organism from the surrounding sediment or water with time. Analysis of PAHs in sediment and amphipods can evaluate the potential of benthic amphipods to bioaccumulate individual PAHs from the sediment or surrounding water. Field measurement of body residue is one of the methods that can be used in assessing bioaccumulation. Determination of the residual concentrations of the PAHs is important for environmental impact assessment for an area with high oil and gas activities in the Gulf. Chemical analysis measures the degree of contamination, which does not necessarily reflect the existence of adverse effect. The biological criteria serve as independent evaluations of the ecological quality of the marine ecosystem (Borja, et. al., 2000). The biological evaluations include an assessment of the biological effects resulting from the presence as well as the extent of bioaccumulation of the chemical contaminants.

I.3. Objectives and study results

There are four component studies in this dissertation, each report one or more aspect of the environment in the Mississippi Canyon using amphipods as biomonitor. Because of the discovery of a new amphipod species that carpeted the head of the Canyon, I first described this as a new species (*Ampelisca mississippiana*) (Chapter II). The structure (elements) and function (processes) of amphipods were measured to get insight about the quality of the canyon environment. The effect of the Mississippi Canyon environment on the structure of deep water amphipods was measured in Chapter III, while the function of the ampeliscid bed at the canyon's head was measured in chapter IV. The effect chronic input of PAHs on deep water was measured by determining bioaccumulation factor in amphipods in chapter V. Four manuscripts resulted from the present study. They are either published, submitted or will be submitted for publications as follows:

1. Y. S. Soliman and M. K. Wicksten, 2007. *Ampelisca mississippiana*; A new species (Amphipoda, Gammaridae) from the Mississippi Canyon (N. Gulf of Mexico). Zootaxa 1389, 45-54.
2. Y. S. Soliman and G. T. Rowe, 2007. Deep water amphipods down transects within and adjacent to the Mississippi Canyon (N. Gulf of Mexico). Deep Sea Research II (Under revision).
3. Y. S. Soliman, and G.T. Rowe, 2007. Secondary Production of *Ampelisca mississippiana* Soliman and Wicksten 2007 (Amphipoda, Crustaceana) in the Head of the Mississippi Canyon, Northern Gulf of Mexico. Deep Sea Research II (In revision).
4. Y.S. Soliman and T. L. Wade, 2007. Estimates of PAHs burdens in a population of ampeliscid amphipod carpeted the head of the Mississippi Canyon (N. Gulf of Mexico). Deep Sea Research II (submitted).

CHAPTER II

AMPELISCA MISSISSIPPIANA: A NEW SPECIES (CRUSTACEA: AMPHIPODA: GAMMARIDEA) FROM THE MISSISSIPPI CANYON (N. GULF OF MEXICO) *

A new ampeliscid species (Amphipoda, Gammaridea) was recovered in high densities from a depth of about 480 m at the Mississippi Canyon (28º 32' N, 89º 49' W). *Ampelisca mississippiana* is described and illustrated based on specimens collected from the head of the canyon, where the species formed an ampeliscid mat with average densities of 12,000 ind. m^{-2}. *Ampelisca mississippiana* resembles *A.* *pugetica Stimpson, 1864, and *A. mexicana* Barnard, 1954a, but differs in the shape of the head, absence of corneal lenses, relative lengths of antennae 1 and 2, shape of the segments of pereopods 7, and shape of the carina of the urosome. The new species also resembles *Ampelisca uncinata* Chevreux, 1887, but differs in the shape of the head, the dorsal carina of pleon segment 4, features of some segments of pereopod 7, the second uropod and the mouthparts.

II.1. Introduction

The genus *Ampelisca* is one of the most important and most diverse benthic amphipods (Dauvin and Bellan Santini, 1988). It comprises about 153 species (Kaïm-

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* Reprinted with permission from *Ampelisca mississippiana*: a new species (Crustacea: Amphipoda: Gammaridea) from the Mississippi Canyon (northern Gulf of Mexico Yousria Soliman and Mary Wicksten, 2007, Zootaxa, 1389, 45-54, Copyright 2007 by Magnolia Press.

Malka, 2000). They are commonly found on muddy and sandy bottom from subtidal to intermediate depths on continental slopes (Barnard, 1960).

The Ampeliscidae from the northwestern Atlantic Ocean including the Gulf of Mexico and the Caribbean Sea were examined previously by Barnard (1954a), Mills (1963, 1964, 1967b, and 1971). Twenty-four ampeliscid species were described or re-described from different depths from this geographic area. The taxonomy of the Atlantic ampeliscids is very confusing and far from satisfactory (Reid, 1951). The systematics of genus *Ampelisca* in general is badly confused because of many poor illustrations and descriptions (Barnard, 1960). Many species are known from small numbers of animals, sometimes in a poor state of preservation (Kaim-Malka, 2000).

During sampling on summer cruises in 2000 to 2004, we found large numbers of unidentified ampeliscids at the head of the Mississippi Canyon, northern Gulf of Mexico. This paper describes these amphipods as a new species. We compare it to *A. pugetica*, *A. uncinata* and other similar species. Notes on its ecology are provided.

Abbreviations used in the figures are as follows:

Hd head; Md, mandible; Mxl1, Mxl2, first and second maxilla; Mxlp, maxilliped; P3, P4, P5, P6, P7 pereopods 1–7; Gn1, Gn2 gnathopods 1 and 2; Urs, urosomite; U1, U2, U3 uropods 1, 2 and 3; T, telson.

II.2. Materials and methods

Specimens were obtained from sediment samples collected from the R/V *Gyre* using a 0.2 m^2 GOMEX or Gray-O'Hara box core (Boland and Rowe 1991). All samples were taken at the head of the Canyon, designated as Deep Gulf of Mexico Benthos (DGoMB) station MT1. It is difficult to collect at exactly the same location by box core due to the depth and drift of the ship. However, all samples were taken within 30 seconds of latitude or longitude of each other. Specimens were obtained by sieving the collected mud through a 300 micron sieve, using the gentle flotation method developed by Howard Sanders of the Woods Hole Oceanographic Institution. The specimens were fixed in 10% formalin in seawater. In the laboratory, they were sorted, and then preserved in 70% ethyl alcohol until identification. The specimen to be dissected was immersed in glycerin. Drawings of the separate appendages were made with a camera lucida attached to a phase contrast compound microscope. Type specimens have been deposited in the United States Museum of Natural History (USNM) and the Marine Invertebrates Collection, Texas Cooperative Wildlife Collection (TCWC) at Texas A&M University, College Station. Total lengths (TL, measured from the tip of the rostrum to the end of the telson) are given in millimeters.

II.3. Systematics

Order Amphipoda Latrielle, 1816

Suborder Gammaridea Latrielle, 1803

Family Ampeliscidae Costa, 1857

Genus *Ampelisca* Kröyer, 1842

Ampelisca mississippiana, sp. nov.

Material examined: (Figures 2.1-2.5): *holotype*.-- Adult female; TL 5.6 mm. Northern Gulf of Mexico, head of the Mississippi Canyon (28º 32' 30.7" N, 89º 49' 43.9" W), 480 m, muddy bottom (approximately 73% clay, 25.5% silt and 1.5% sand), 17 June 2000, R.V. *Gyre*. DGoMB station MT1, USNM.

Paratypes,-- 10 females. Mississippi Canyon (28º 32' 6.6" N, 89º 49' 32.2" W), 498 m, 2 June 2001, R.V. *Gyre*. DGoMB sta. MT1, USNM. 15 females. Mississippi Canyon, 28º 33' 12.1" N, 89º 49' 18.5" W, 13 August 2002, 476 m, R.V. *Gyre*, USNM. 16 females. Same location, date and depth as holotype. TCWC cat. No. 2-9119.

Other material,--Approximately 300 individuals, including 3 males, same collecting locations, under study at Texas A&M University.

Etymology.-- The name of the species refers to the Mississippi Canyon, where the specimens are found in abundance.

Description.— Female TL 5.6 mm. Body smooth and rather colorless. Head broad, longer than deep, subequal in length to first 3 body segments, projecting anterodorsally above antenna 1. Distal margin concave. Lower front edge oblique, convexly curved posteriorly. Anteroventral margin with short setae. Corneal lenses absent, ganglia of eyes easily visible under cuticle. Antenna 1 very short and slender, shorter than antenna 2 peduncle, article 1 robust. Peduncular article 2 long, about 1.5x length of article 1. Article 2 slimmer than article 1. Flagellum with 7-9 articles. Antenna 2 as long as body or longer depending on age of specimen. Peduncle long and slender. Peduncle article 4 about same length as article 5. Flagellum with up to 19 articles. Flagellum setae long.

Mandible with spine row with 8 spines. Palp tri-articulate, article 2 longer than either article 1 or 3, slender and setose.

Maxilla 1 with inner lobe conical, ending apically with 1 long seta. Outer plate with 9 spines. Palp bi-articulate, second article with 4 distal sharp cusps, 4 spines and 6 setae. Maxilla 2 normal.

Maxilliped with inner plate reaching to the end of palp article 1 and with several plumose setae; outer plate reaching to end of palp article 2, inner margin of outer plate lined with 8 chisel teeth, round apex with 5 setal spines, outermost two plumose. Palp with four articles, article 4 with nail as long as rest of article.

Coxae 1-4 longer than broad. Coxal plate 1 expanded and rounded distally. Coxae 1 and 2 lower posterior angle with slit and bearing plumose setae on lower margin with row of setae overlying them.

Gnathopod 1 simple and linear, shorter than gnathopod 2; basis long, ischium and merus short, carpus slightly longer than propodus; dactylus shorter than propodus, arched, and bearing several setules along inferior margin and one seta on outer margin; palmar portion weakly developed; armed with sets of comb spines and setal spines.

Gnathopod 2 very slender, longer than gnathopod 1, carpus more than 1.5 times as long as propodus, with heavy sets of setae on distal margin; propodus heavily covered with spinose setae; dactylus about two-thirds of propodus, slightly curved with simple setae on flexor margin.

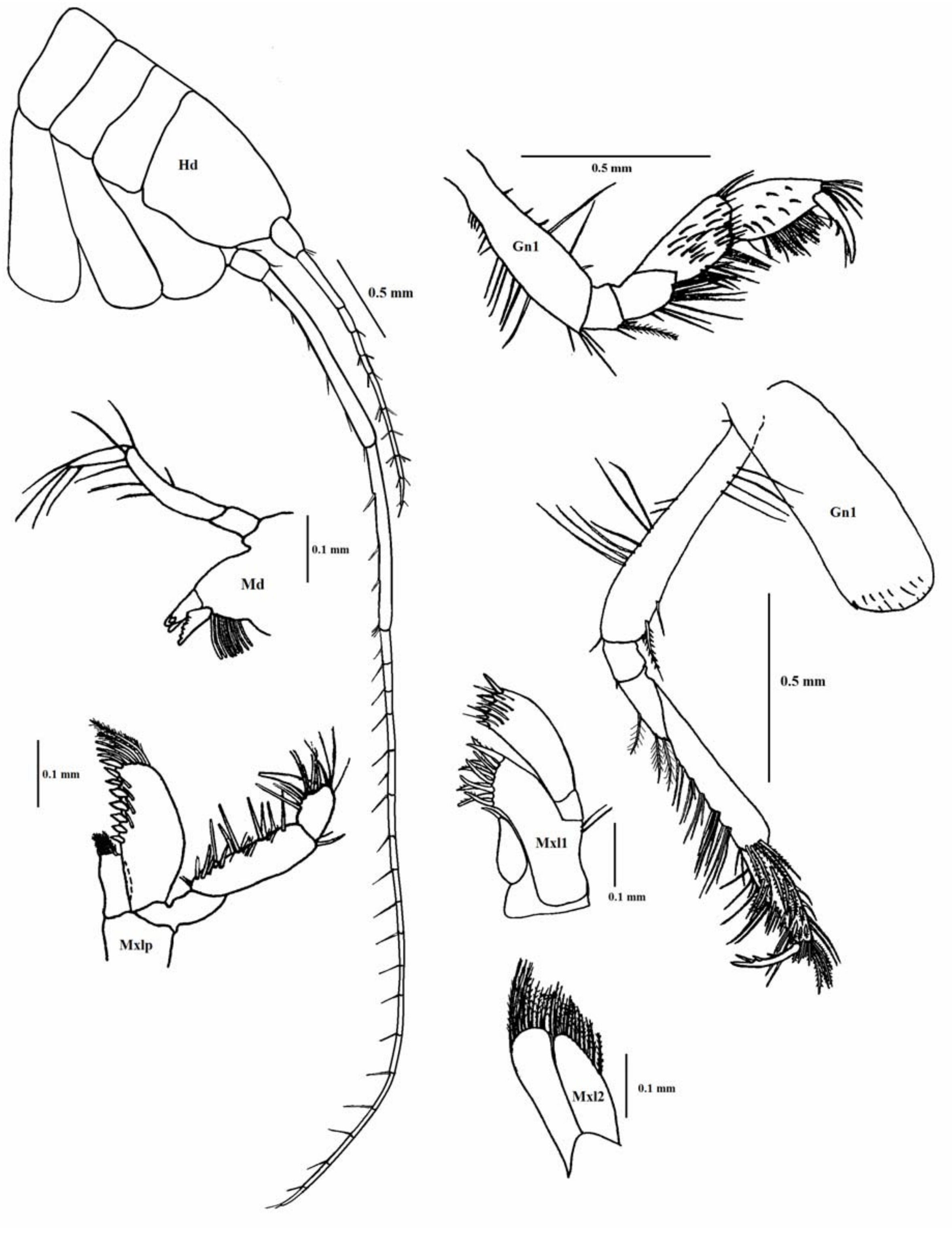

Fig. 2.1. *Ampelisca mississippiana* sp. nov.: female, 5.6mm, holotype. Mississippi Canyon (28º 32' 30.7" N, 89º 49' 43.9" W).

Pereopod 3 and pereopod 4 almost similar. Pereopod 3 merus longer than carpus and propodus combined. Both merus and carpus bearing few long spinose setae at distal anterior margin; carpus with 1 seta on extensor surface; propodus with few simple setae on the extensor surface; dactylus very long and slender, almost straight and significantly longer than both propodus and carpus combined. Pereopod 4 coxa rectangular with rounded distal corner. Pereopod 4 similar to pereopod 3 but with much longer merus and with setae on both sides; distal anterior edge of the merus not produced.

Pereopod 5 with basis having anterior margin fringed with plumose setae, posterior margin with rounded lobe. Carpus slightly longer and broader than propodus and endowed with set of 4-5 comb spines and two short spines, posterior margin with 2 sets of short spines. Propodus with very long setae on the distal end; dactylus very short.

Pereopod 6 with basis roughly rectangular, anterior margin with 3 plumose setae and several spines, posterior margin rounded without any ornamentation. Carpus slightly longer than propodus, anterior margin with several spines, and 2 sets of spines on lateral surface, distal margin with long set of 4-5 comb spines and two short spines . Propodus less broad than carpus, with several spines on anterior margin. Dactylus very short.

Pereopod 7 with basis straight, anterior margin with few short spines and rounded posteriorly, inferior margin of posterior lobe of basis expanded distally, passing distal end of ischium, distal margin fringed with plumose setae. Ischium longer than merus. Merus with large posterior setose lobe produced along entire margin of carpus, fringed by long plumose setae, anterior lobe slightly produced along anterior margin of carpus with 1 spine at blunt apex. Carpus with anterior edge slightly produced and notched.

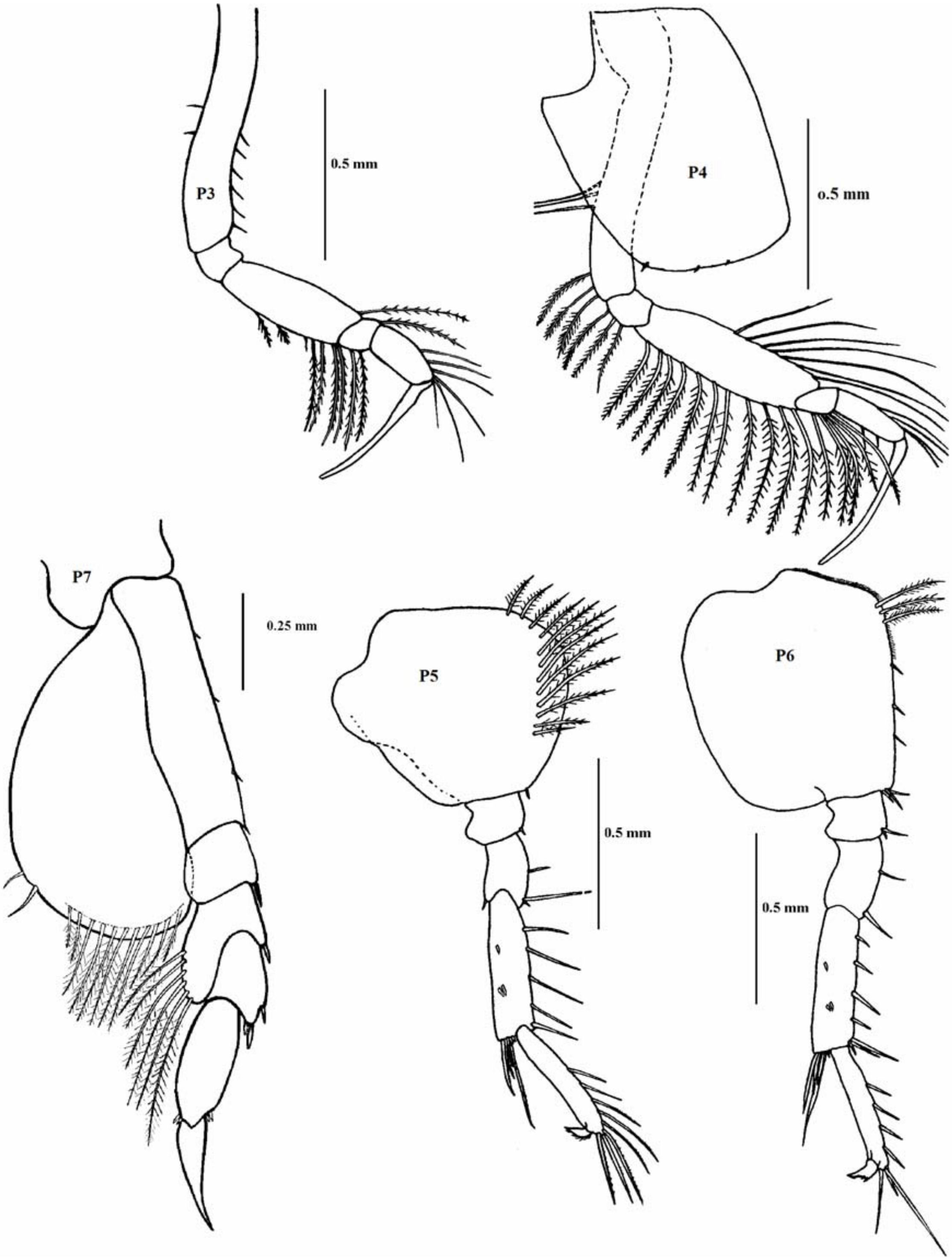

Fig. 2.2. *Ampelisca mississippiana* sp. nov.: female, 5.6mm, holotype. Mississippi Canyon (28º 32' 30.7" N, 89º 49' 43.9" W) P3-P7.

Propodus attached to posterior proximal portion of carpus, with notched distal anterior margin. Carpus and dactylus shorter than propodus. Dactylus broad at base and tapering distally, not curving forward.

Epimeral plate 1 rounded with spine at distal margin and plumose setae at posterior margin. Epimeral plate 2 with inferior margin rounded. Epimeral plate 3 posteroventral corner with acute spine.

Pleon segment 3 with posterior margin slightly convex, lower posterior margin produced into large acute tooth. Dorsal surface of segment with 2 setules.

Pleon segment 4 dorsal surface with prominent wedge-shaped dorsal carina ending acutely above segment 5 and bearing 2 setae at top. Pleon segment 6 with shallow lateral crests. Pleon segments from 1 to 6 with pair of setules.

Uropod 1 reaching as far as mid-rami of uropod 2, rami as long as peduncle, outer and inner rami equal. Inner ramus with 3-4 spines while outer ramus with 1 spine.

Uropod 2 with inner ramus slightly longer than outer ramus. Inner margin of inner ramus and outer margin of outer ramus spinulate. Outer rami with very long subterminal robust toothed seta.

Uropod 3 with peduncle strong, with 3 spines; rami equal in length, long, slender, lanceolate; outer ramus more slender than inner, broadest at proximal end, apical outer margin of inner ramus and inner margin of outer ramus strongly setose.

Telson longer than broad, deeply cleft for more than 70% of length; distal margin acute, apices of lobes with 1-2 setae, strongly notched on outer ridge, and dorsal surface of each lobe with 1-2 fine setae.

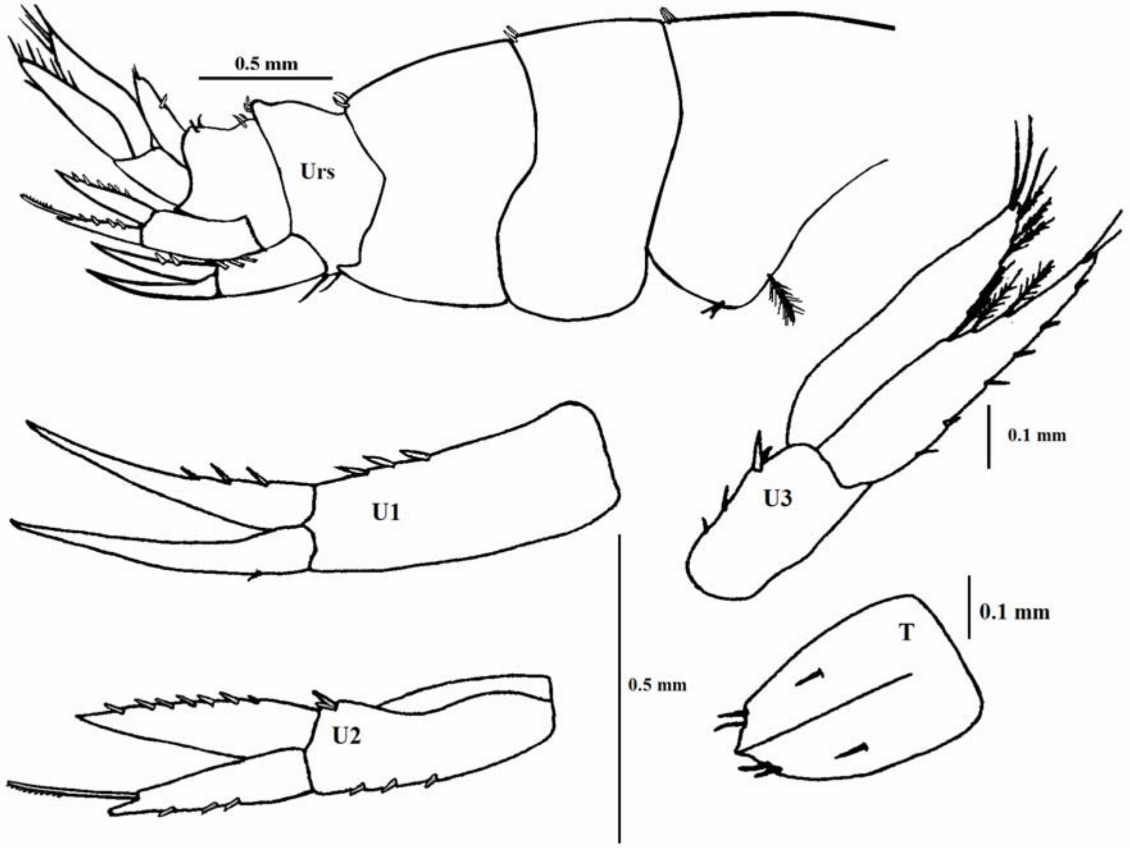

Fig. 2.3. *Ampelisca mississippiana* sp. nov.: female, 5.6mm, holotype. Mississippi Canyon (28º 32' 30.7" N, 89º 49' 43.9" W), Urosome.

Male TL 5.5 mm. Male resemble female in shape of head and length of antennae, differing from female in characters usually sexually dimorphic as follows: presence of setal tufts on peduncle of antennae 1 and 2, gnathopod 1 propodus with palm strongly developed, armed with spines and spinose setae on the palmar side. Spinose setae on Gn1 and Gn2 generally are much heavier in male. Hump on pleon segment 4 more prominent than in female. Dorsal surfaces of pleon segment 3 and pleon segment 4 cristate. Lateral surfaces of pereopod 7 basis with short plumose setae, uropod 3 with apical outer margin of inner ramus and inner margin of outer ramus strongly setose.

Remarks.--- The new species resembles the northwestern Atlantic species *A uncinata*, *A. gibba*, *A. pugetica* and *A. mexicana*. These resemble the new species in the length of antenna 2 that is almost equal to or exceeds the length of the body, antenna 1 shorter than antenna 2, large posterior lobe of the merus of pereopod 7, shape of pleon segment 3, and shape of uropod 3. However they differ from the new species in the shape of the head, presence or absence of corneal lenses, the relative lengths of antennae 1 segments, the shape of the segments of pereopods 7 and the shape of uropod 2. The species are compared in Table 1. Of these species, *A. uncinata* most closely resembles *A. mississippiana* in lacking of corneal lenses. It differs from the new species in the shape of the head (Fig. 2.5), length of the carpus of pereopod 7 and absence of notched anterior edge from the same segment; shape of dactylus of pereopod 7, shape of the dorsal process of pleon segment 4, absence of subterminal robust long seta of uropod 2, and in having two setae instead of one on the apex of the inner lobe of maxilla 1.

Discussion--- According to Barnard and Thomas (1989), the Ampeliscidae is characterized by the extreme constancy of small morphological characters over wide geographic areas. Some of the species that are found in the Gulf of Mexico are also known from the northeastern Pacific with few morphological differences (Barnard, 1954a; Mills, 1965). Barnard (1954a) examined the ampeliscids from the Caribbean Sea and the Gulf of Mexico, and compared them with those from northeastern Pacific

(Barnard 1954b). He found that the differences in the ornamentation of pleon segment 4 for at least 12 species were not enough to separate them as new species. This close relationship between the morphological characters of the northeastern Pacific ampeliscids and those from the northwestern Atlantic was confirmed by Mills (1965). His work related this affinity in the morphological characters to common ancestors that had an amphi-American distribution before the rising of the Central American isthmus. One of those supposed amphi-American species, *A. cristoides* Barnard, 1954, was reinvestigated by Goeke and Heard (1983). They found that specimen from the Gulf of Mexico had a shorter antenna 1 of the female, stronger carina of the urosome, extra tooth on the inner plate of the maxilliped as well as well-developed lateral carinae of pleon segment 3. They described it as a new species, *Ampelisca bicarinata*. Barnard and Thomas (1989) separated *A. burkei*, from Florida, from its eastern Pacific twin *A. lobata* Holmes, 1908, based on differences in shape and setation of article 4 as well as a single spine on article 5 of pereopod 7. These works demonstrated the subtle differences between the species of the Ampeliscidae and the need for care in identifying them.

Ampeliscids have been placed in species groups based on morphologically similar specimens (Kaim-Malka, 2000). Like *Ampelisca mississippiana*, the ampeliscid species *A. pugetica*, *A. mexicana, A. uncinata,* and *A. gibba,* from the northwestern Atlantic share common morphological characteristics including a large posterior lobe on the merus of pereopod 5, pleon segment 3 with a convex posterior edge bearing an acute spine; and uropod 3 having a lanceolate shape. They can be distinguished by features such as the shape of the head, presence or absence of corneal lenses, shape of the dorsal carina of pleon segment 4, shape of the merus and carpus of pereopod 5, shape of uropod 2, and ratio of article 2 to article 1 in antenna 1.

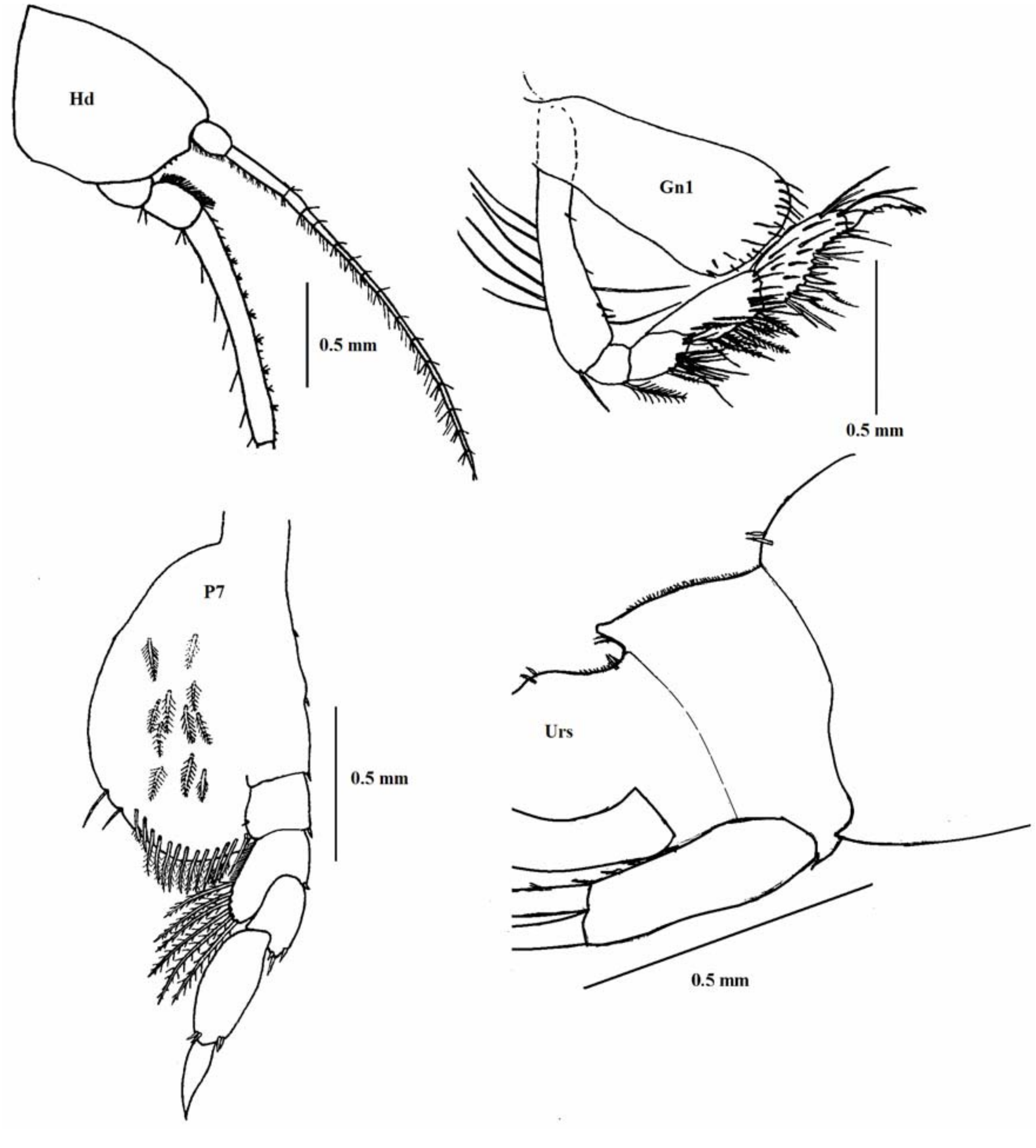

Fig. 2.4. *Ampelisca mississippiana* sp. nov.: male, 5.5 mm. Mississippi Canyon (28º 32' 30.7" N, 89º 49' 43.9" W).

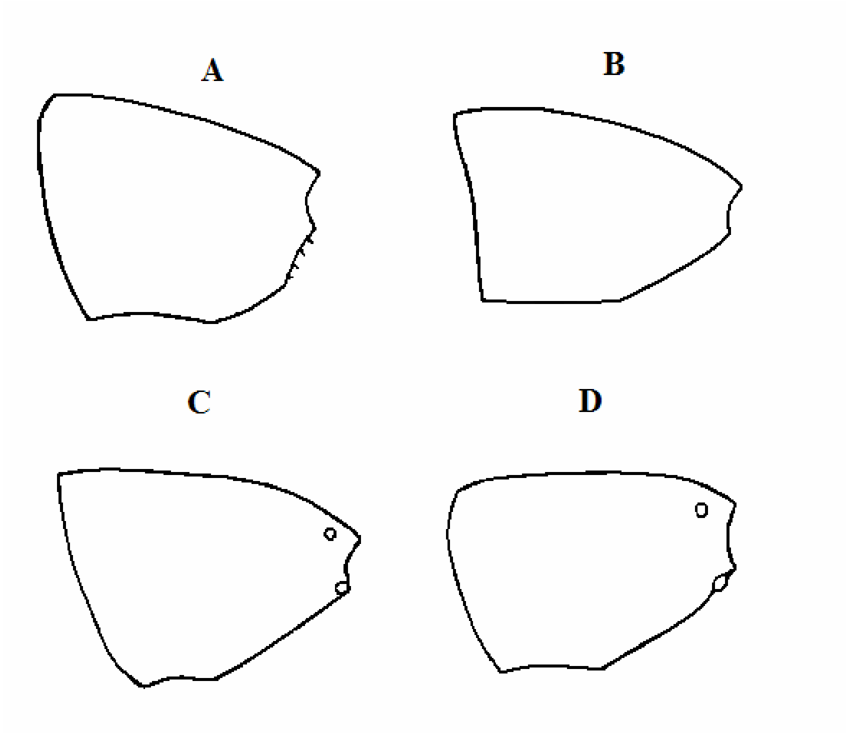

Fig. 2.5. Heads of the ampeliscid species (A) *A .mississippiana*; (B) *A. uncinata*; (C) *A. mexicana*; (D) *A. pugetica*.

Ecological notes.--- *Ampelisca mississippiana* n.sp. was collected from the head of the Mississippi Canyon at a depth of approximately 480 m. The new species was a numerical dominant at the head of the canyon with densities reaching 26,000 ind.m^{-2}. *A. mississipiana* represented more than 85% of the total macrofauna at this location. The sediment at the head of the canyon is muddy, about 73% mud and 25% silt.

Why might *A. mississippiana* occurs at such high densities in this location? Ampeliscid amphipods are known to be tube dwellers collecting suspended and settling matter or raking sediment for feeding (Mills, 1967a). Canyons are known to be a good conduit of sediment and organic matter from the continental shelf to the deep water. Gardner (1989) found that the canyon focuses internal tides, which lead to mixing near the bottom and resuspension of particulate matter producing a nepheloid layer. These sedimentary conditions might explain the existence of such high densities of this species at this location. It is known also that tube builders can withstand the shear of the current and stabilize the sloppy mud.

The *Ampelisca* mat at the head of the canyon is likely to be of great ecological importance in recycling of organic carbon that might be transported from the shelf to the slope and the deep Gulf. The tubes stabilize sediments through reducing resuspension and erosion, which is a common ecological role for all the known sedentary tube burrowers that form mats at high densities (Gage and Tyler, 1991).

Table 2.1. Comparison between the major morphological characteristics of the new species *A. mississippinana* and other similar ampeliscids.

	A. mississippiana	*A. uncinata*	*A. gibba.*	*A. mexicana*	*A. pugetica*
	Present study	Chevreux (1887, 1900), Mills (1976, 1971).	Barnard (1960), Lincolin, (1979), Ruffo, (1982).	Barnard (1954a& 1960)	Barnard (1954a& 1960), Dickinson, (1982), Watling, (1995), Serejo et al (2000).
Size	5-5.7 mm	6.5 mm	7.5 mm	5 mm	9-11 mm
Lenses	Absent	Absent	Present	Present	Present
Antenna 1 (A1)	A1 ≥ art 4 of peduncle of A2, Peduncle. Article 2 = 1.5 x length of article 1. A2: art 4 = art 5	A1 < Peduncle of A2; Peduncle article 2 = 1 to 1.5 x length of article 1. A2: art 4 > art 5.	A1 = art 4 of peduncle of A2; Peduncle article 2 = 1.5 to 2.5 x length of article 1. A2: art 4 ≥ art 5	A1 = peduncle of A2; Peduncle article 2 = 1.3 x length of article1. A2: art 4 ≈ 1.3 art 5.	A1 < peduncle of A2, Peduncle. Article 2 = 2 x length of article 1. A2: art 4 ≥ art 5.
Maxilla 1	Inner lobe apex with one long seta	Inner lobe apex with two setae	Inner lobe apex with one seta	Inner lobe apex with two setae	Inner lobe apex with two setae
Pleon segment 4	Wedge-shaped dorsal carina with two setae at top.	Slightly elevated dorsal keel.	Angular dorsal keel.	Slightly elevated dorsal keel.	Saddle-shaped dorsal carina.
Pereopod 7	Iscium longer than merus. Carpus long (about twice as long as broad) and notched anteriorly. Dactylus straight.	Iscium longer than merus. Carpus short (about as long as broad), without a notch, dactylus curving forward into a fine point.	Ischium is shorter than merus. Carpus short (about as long as broad). Merus with proboscid posterior lobe.	Ischium is shorter than merus. Carpus is very short, without a notch. Merus with large, tumid lobe.	Ischium subequal in length to merus. Carpus long (about twice as long as broad) and notched anteriorly.

Table 2.1. continued:

Uropod 2 rami	Unequal rami; outer ramus with sub-terminal long comb spine.	Unequal rami; outer ramus without terminal seta.	Rami equal to slightly subequal; outer ramus with long seta.	Equal rami; apices of both armed with a single long spine.	Equal rami, apex of outer ramus with a long spine.
Telson	Deeply cleft. Surface of each lobe with 1-2 setae.	Moderately cleft. Surface of each lobe with 4 setae.	Deeply cleft. Surface of each lobe with 4 setae.	Deeply cleft. Surface of each lobe with 3 setae.	Moderately cleft. Surface of each lobe with 3-6 spines

CHAPTER III

EFFECT OF MISSISSIPPI CANYON (N. GULF OF MEXICO) ENVIRONMENT ON THE STRUCTURE AND BIODIVERSITY OF DEEP-SEA AMPHIPODS*

Amphipod abundance and biodiversity were compared on two transects across the continental margin of the northern Gulf of Mexico, one down the trough of the Mississippi Canyon and the second approximately 100 km to the west of the canyon. Amphipods were a remarkably important component of the total macrofauna [2]within the Canyon (40 % of the total faunal abundance) (Northern Gulf of Mexico) compared to the adjacent non-canyon transect (4%). The logarithm of the amphipod abundance decreased linearly with depth, to a minimum on the lower continental rise. Seventy two species belonging to 19 families were collected from the study area with 61 species from the canyon compared to only 38 species from outside the canyon. The head of the canyon (480m) surprisingly was dominated by a dense mat (4,446 – 26,933 ind/m^2) of a new ampeliscid amphipod (*Ampelisca mississippiana*). The species diversity (E(s)) exhibited a unimodal pattern with a maximum at 1100m in both transects, but the parabolic shape was more prominent on the canyon transect. The low in diversity in the canyon head is thought to result from competitive exclusion in the canyon dominated by *A. mississippiana*, but the high species richness (61 spp.) is presumed to be a function of the canyon's greater structural complexity.

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* Submitted to Deep-Sea Research II. Yousria Soliman, Mary Wicksten, and Gilbert Rowe, 2007.

III.1. Introduction

There is a consensus that canyons are one of the least appreciated habitats on continental margins. Great variability is found not only between canyons, but also within individual canyon ecosystems (Weaver et al, 2004). The Mississippi Canyon is the most prominent physiographic feature in the northern Gulf of Mexico. It incises the continental shelf at depths ranging from 50 m to over 1200 m with a width of about 8-16 km (Shepard and Dill, 1966). It plays an important role in conveying sediments and organic matter across the shelf from the Atchafalaya and Mississippi Rivers down to the deep Gulf (Ellwood et al, 2006). Canyons' topographic features and circulation patterns promote the export of organic matter from the shelf to the deep sea, enhancing the productivity of the deep benthos (Bosley et al, 2004). Often hotspots for faunal biomass are encountered (Vetter and Dayton, 1988; Rogers et al, 2003). Nevertheless, species composition inside canyons has been found to differ from nearby non-canyon fauna, with some canyon indicator species (Rowe, 1971; Ohta, 1983).

The present study studied the effect of organic carbon, sediment grain size, anthropogenic carbon, anthropogenic trace metals, and near bottom suspended matter, on bathymetric zonation and abundance patterns along depth gradients in the Mississippi Canyon and along an adjacent parallel reference transect. Four main hypotheses were tested in the present study. H_{01}: There is no difference in amphipod abundance with depth, and between the canyon and the non-canyon transects. H_{02}: There is no difference in amphipod zonation structure (β diversity) between canyon and non-canyon. H_{03}: There is no difference in amphipod species diversity (α diversity) with depth, and between the canyon and the non-canyon transects. H_{04}: The variability of organic carbon influx and sediment grain size had no significant effect on amphipod abundance. Three measurements were used as proxies for organic influx: surface Chla, sediment POC, and near bottom suspended matter.

The dynamics of other faunal groups at comparable depths from other marginal seas and oceans will be compared with that found in the Mississippi Canyon. Understanding factors controlling biodiversity patterns provides an important step toward developing adequate tools for the correct management of deep-sea resources (Levin et al., 2001).

III.2. Study Area

The Mississippi Canyon (MT), and an adjacent parallel transect (C-transect) (Fig. 3.1), extend from the shelf edge to the lower continental slope.

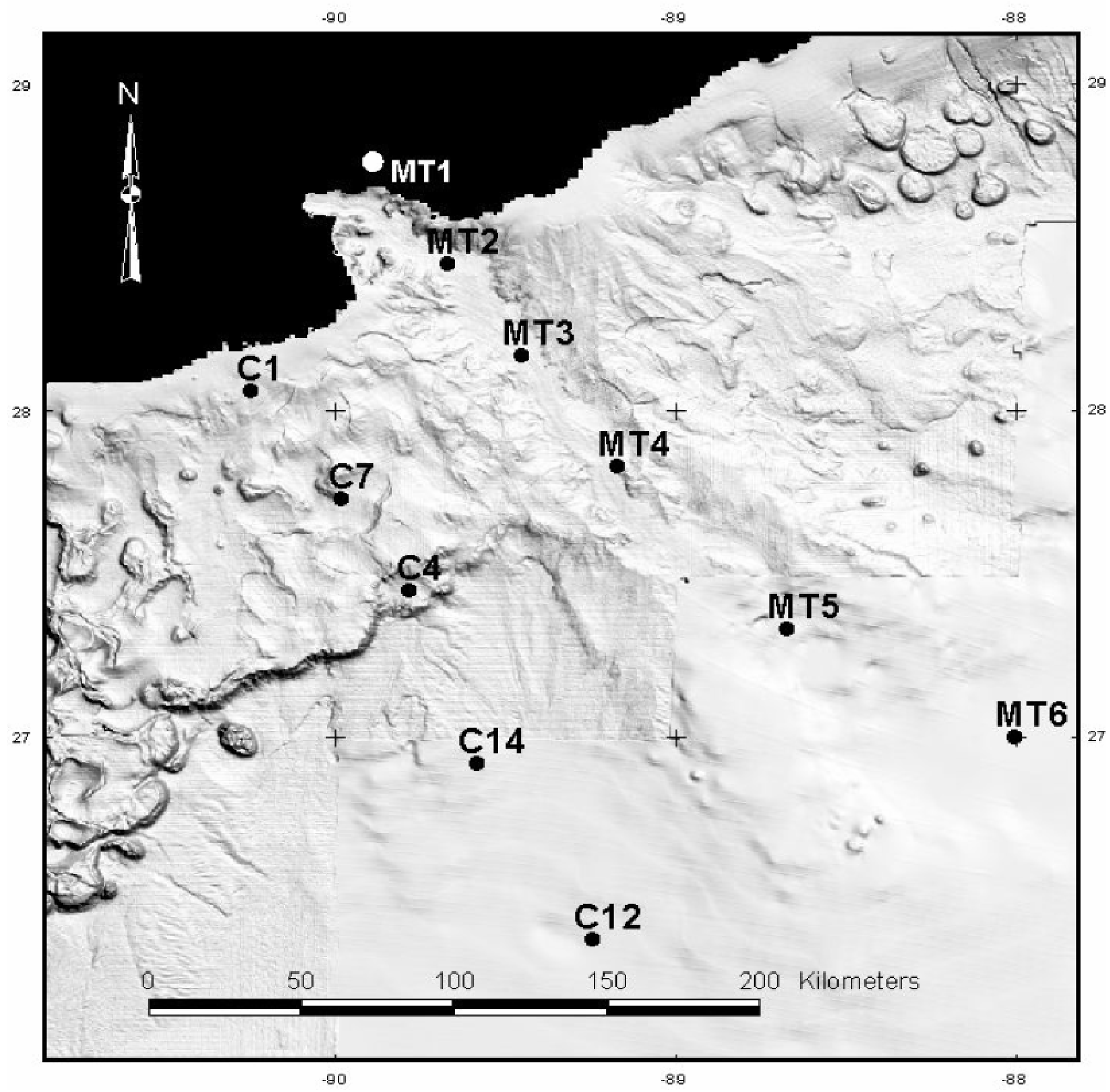


Fig. 3.1. Benthic stations along the Mississippi Trough (MT1-MT6) and a parallel transect (C1-C14), available from Texas Sea Grant College Program, TAMU-SG-00-603.

III.3. Material and methods

III.3.1. Sampling and analysis of benthic amphipods

Benthic amphipods were sampled during 2000-2004 from five (5) replicate boxcores per station using the 0.2 m^{-2} GOMEX or Gray-O‘Hara boxcore (Boland and Rowe, 1991) deployed from the *R.V. Gyre*. Six locations (MT1 through MT6) from depths of 480 through 2275, and 2750 m were selected in the Mississippi Canyon (Table 3.1). Another five locations were selected from a parallel transect (C-transect) (Fig. 3.1), as non-canyon transect. Samples were sieved (size was 300 microns) using the gentle floatation method developed by Howard Sanders of the Woods Hole Oceanographic Institution (WHOI).

The samples were fixed in 10% formalin with filtered sea water and Rose Bengal. On return to the laboratory, the formalin-Rose Bengal solution was changed to a 70% ethyl alcohol solution. Amphipods were identified to species using the taxonomic works of Barnard (1960a, b, 1961, 1962, 1964, 1966, 1969, 1971), Lincoln (1979), and Mills (1963, 1965, 1967b, 1971).

Table 3.1. Sampling stations and their geographical locations in the Mississippi Canyon (MT) and central transect (C), Northern Gulf of Mexico.

Cruise	STATION	Replicate	Depth	Date	Latitude	Longitude
1	C1	1	336	5/30/2000	28.05964	-90.2491
1	C1	2	336	5/30/2000	28.05938	-90.2492
1	C1	3	336	5/30/2000	28.05979	-90.2494
1	C1	4	336	5/30/2000	28.05984	-90.2499
1	C1	5	334	5/30/2000	28.06008	-90.2489
1	C12	1	2922	6/2/2000	26.37942	-89.2414
1	C12	2	2920	6/2/2000	26.38292	-89.2414
1	C12	3	2918	6/2/2000	26.37336	-89.2376
1	C12	4	2920	6/3/2000	26.37973	-89.2403
1	C12	5	2924	6/2/2000	26.37496	-89.2431
1	C14	1	2487	6/1/2000	26.92995	-89.5704
1	C14	2	2495	6/1/2000	26.92983	-89.5645
1	C14	3	2487	6/1/2000	26.92989	-89.5709
1	C14	4	2478	6/1/2000	26.93824	-89.5725
1	C14	5	2487	6/1/2000	26.92956	-89.5714
1	C4	1	1472	5/31/2000	27.45315	-89.7631
1	C4	2	1455	5/31/2000	27.4594	-89.7857
1	C4	3	1452	5/31/2000	27.46017	-89.7795
1	C4	4	1463	5/31/2000	27.45242	-89.776
1	C4	5	1476	5/31/2000	27.45054	-89.7619
1	C7	1	1080	5/30/2000	27.72828	-89.9796
1	C7	2	1070	5/30/2000	27.73286	-89.9772
1	C7	3	1066	5/30/2000	27.73152	-89.9835
1	C7	4	1070	5/30/2000	27.73015	-89.9854
1	C7	5	1072	5/30/2000	27.73044	-89.982
1	MT1	1	480	6/17/2000	28.54188	-89.8289
1	MT1	2	482	6/17/2000	28.53951	-89.8289
1	MT1	3	482	6/17/2000	28.54114	-89.8271
1	MT1	4	481	6/17/2000	28.54059	-89.8288
1	MT1	5	481	6/17/2000	28.54111	-89.825
1	MT2	1	676	6/17/2000	28.45108	-89.6726
1	MT2	2	677	6/17/2000	28.45121	-89.6703
1	MT2	3	676	6/17/2000	28.45055	-89.6727
1	MT2	4	677	6/17/2000	28.45028	-89.6733
1	MT2	5	680	6/17/2000	28.44793	-89.6719
1	MT3	1	983	6/16/2000	28.22041	-89.4961
1	MT3	2	987	6/16/2000	28.21922	-89.4964
1	MT3	3	990	6/16/2000	28.21904	-89.4918
1	MT3	4	988	6/16/2000	28.2176	-89.4938
1	MT3	5	985	6/16/2000	28.22151	-89.494
1	MT4	1	1401	6/15/2000	27.827	-89.1659
1	MT4	2	1401	6/15/2000	27.82836	-89.1647
1	MT4	3	1402	6/16/2000	27.83348	-89.1658
1	MT4	4	1402	6/16/2000	27.82761	-89.1661
1	MT4	5	1401	6/16/2000	27.82802	-89.1679
1	MT5	1	2290	6/3/2000	27.32635	-88.6696

Table 3.1, continued.

Cruise	STATION	Replicate	Depth	Date	Latitude	Longitude
1	MT5	3	2267	6/4/2000	27.3346	-88.6622
1	MT5	4	2263	6/4/2000	27.33652	-88.6595
1	MT5	5	2280	6/4/2000	27.33284	-88.6561
1	MT6	1	2745	6/4/2000	27.00011	-87.9978
1	MT6	2	2750	6/5/2000	27.00149	-87.9882
1	MT6	3	2745	6/5/2000	26.99651	-87.9987
1	MT6	4	2745	6/5/2000	26.99948	-87.9962
1	MT6	5	2743	6/5/2000	27.00165	-87.9991
2	MT1	1	487	6/2/2001	28.53808	-89.8277
2	MT1	2	490	6/2/2001	28.53517	-89.8256
2	MT1	3	485	6/3/2001	28.53883	-89.8303
2	MT1	4	480	6/3/2001	28.54105	-89.8308
2	MT1	5	478	6/3/2001	28.54185	-89.8294
2	MT3	1	980	6/4/2001	28.22455	-89.5126
2	MT3	2	982	6/4/2001	28.22443	-89.5066
2	MT3	3	984	6/4/2001	28.22263	-89.5058
2	MT3	4	984	6/4/2001	28.22083	-89.5054
2	MT3	5	985	6/4/2001	28.22104	-89.5092
2	MT6	1	2740	6/13/2001	26.99068	-88.014
2	MT6	2	2733	6/13/2001	27.0034	-88.0145
2	MT6	3	2741	6/13/2001	26.98583	-88.0113
2	MT6	4	2737	6/13/2001	26.99441	-88.0115
2	MT6	5	2740	6/14/2001	26.98816	-88.0142
3b	MT1	1	470	8/13/2002	28.55335	-89.8218
3b	MT1	2	460	8/13/2002	28.56121	-89.8286
3b	MT1	3	465	8/13/2002	28.55418	-89.823
3b	MT1	4	465	8/13/2002	28.56112	-89.8209

3.2. Measurements for bottom environmental parameters

Subcores were taken from each of the five replicate boxcores for sediment grain size, total organic carbon and sediment organic contaminants. The standard Folk settling method was used to determine sediment grain size (Folk, 1974). Carlo Erba elemental analyzer was used to determine organic carbon and nitrogen. Dissolved organic carbon (DOC) was measured by a high-temperature combustion DOC analyzer. Organic and inorganic carbon were determined by standard LECO combustion. The anthropogenic trace organic carbon and polycyclic aromatic hydrocarbons (PAHs) were measured by NOAA status and trends methods (Denoux et al., 1998; Qian et al., 1998) using gas chromatography–mass spectrometry. Surface seawater chl-a concentrations were estimated from Sea viewing Wide-Field Sensor (SeaWiFS) satellite imagery (Biggs et al. 2007).

III.3.3. Data analysis

III.3.3.1. Univariate and graphical methods

Analysis of variance (using SPSS) was used to test for the effect of canyon and depth on the amphipod abundance. Olmstead and Tuky's test for association (Sokal and Rholf. 1979) was used to measure the ecological representation of each amphipod family and species based on their abundance and frequency of occurrence.

Rarefaction (Sanders, 1968 with modification by Hulbert, 1971), K-dominance (Lambshead et al., 1983), Shannon-Wiener diversity index (H'), and Pielou's Index (Equitability) were calculated using Biodiversity Pro (McAleece et al., 1996) and Primer

6 (Warwick and Clarke, 1991). Two non-parametric estimators, Jacknife second order estimator (Burnham and Overton 1979) and Chao second order estimator (Chao, 1987), were used to estimate the number of species present in the whole area, had the sampling been more intense.

III.3.3.2. Multivariate analysis methods

III.3.3.2.1. Analysis of Amphipods' zonation

Amphipods assemblages (bathymetric zonation) in the Canyon and C transect were interpreted by cluster analysis based on ANOSIM (Analysis of similarity) of the faunal composition (Bray-Curtis similarity and average group linking) in PRIMER version 6. These analyses were performed on mean amphipod densities at the species level. Data were fourth-root transformed prior to the analyses to reduce the influence of over-dominance by numerically abundant species. Rare species were removed prior to the analysis. Presence/ absence transformation was performed to test for indicator species for the two transects.

III.3.3.2.2. Analysis of environmental influences

Principal Component Analysis (PCA) was applied to assess the effect of abiotic factors (Table, 5) on the density of amphipods. Factors used in the PCA included parameters measured in surface water, bottom water and sediment. An initial PCA was used for data of 27 trace metals measured in the sediment, and a subset of metals that accounted for the highest variance was selected to be used in the main PCA. Three factors (total suspended matter (TSPM $mg.l^{-1}$), particulate organic carbon and nitrogen

(PON $\mu g.l^{-1}$, POC $\mu g.l^{-1}$)), were measured in the near bottom water. Chl-a in the surface water column was measured from SeaWIFS satellite images. Surface Chla was adjusted for remineralization to estimate the amount of surface chlorophyll that was possibly reaching the sea floor at different depths. A regression model (Betzer et al. 1984, Berger et al. 1988) was used to calculate the amount of surface chl-a that reached the sea floor as follows:

$$J(Z) = 0.409PP^{1.41} / z^{0.628}$$

where *J*(*Z*) is the amount of chlorophyll reaching the sea floor at depth (*Z*), and PP is the amount of chlorophyll at surface water. Sediment variables utilized in the analysis included temperature, dissolved oxygen, polynuclear aromatic hydrocarbon without perylene (PAHs), dissolved organic carbon (DOC), particulate organic carbon (POC), nitrate (NO_3^-), ammonium (NH_4^+), sediment grain size (%sand, %silt and %clay) and a subset of trace metals. All the data were transformed prior to the analysis to validate the assumption of parametric tests. The mean of each data dimension was subtracted from the data of each dimension $[x1 = (x - \overline{x})]$ and the result was divided by the standard deviation. This transformation produced dimensions of data with a mean equaling zero. This transformation was used for the whole data set except for the grain size data, which was normalized angularly, $x1 = \arcsin(sqrt(x))$, as recommended when percentages are outside the range 30% - 70%.

III.4. Results

III.4.1. Abundance and contribution to total faunal abundance:

A total of 32,889 amphipods were collected throughout the different cruises through the period 2000-2002. About 38 faunal groups were retrieved on the 300-micron sieve from the two transects. Amphipod individuals accounted for 41% of the total macrofaunal abundance in the Canyon while representing only about 4% of the faunal abundance in the C-transect (Fig 3.2). The contribution of amphipods to the total abundances decreased exponentially with depth (R^2= 0.8) in the Canyon. The highest contribution (90%) was found at 500m (MT1), (Fig.3.3). In contrast, on the C-transect, amphipods contributed much less to the total abundance. The maximum contribution was about 10% of the total at 1000m (Fig.3.3). The abundance of amphipods in the Canyon transect was highest at 480m (15,880±7003 ind.m^{-2}), and this decreased to minimal density at (11±1) at 2745m. On the Central transect, the highest amphipod abundance was recorded at 1017m (C7), (314±276 ind.m^{-2}) and it also decreased to a minimum at the deepest stations (C12, C14), (2486-2920 m) to 16 ind.m^{-2} (Table 3.2).

The Shapiro-Wilk test indicated that the Log (abundance+1) for the amphipods (P=0.003) was normally distributed, and the variance was homogeneous with the Levene test (P=0.001). Analysis of variance with the two factors (Depth and Canyon) indicated that mean amphipods were significantly different with both depth (F=99.076, P<0.001) and significantly different between canyon and non canyon (F=21.018, P<0.001) (Table 3.3). We thus rejected the first null hypothesis (H_{01}). There was also significant interaction between the two factors ($P<0.001$). Log ($X+1$) of the abundance decreased linearly with depth on the two transects ($R^2= 0.63$; $P<0.01$), Fig (3.4).

Table 3.2. The total amphipod abundance at different location at each transect from 2000-2002.

	Station	**Depth**	**2000**	**2001**	**2002**	**Average Ind.m-2**
Central Transect	C 1	336	106±63			106±63
	C 7	1071	509±792	119±32		314±276
	C 4	1463	117±71			117±71
	C14	2486	16±6			16±6
	C12	2920	16±18			16±18
Canyon Transect	MT1	481	23441±4580	14590±4024	9614±7309	15880±7003
	MT2	678	971±109			971±109
	MT3	987	414±86	210±33		312±144
	MT4	1401	122±37			122±37
	MT5	2275	20±20			20±20
	MT6	2745	10±5	12±10		11±1.4

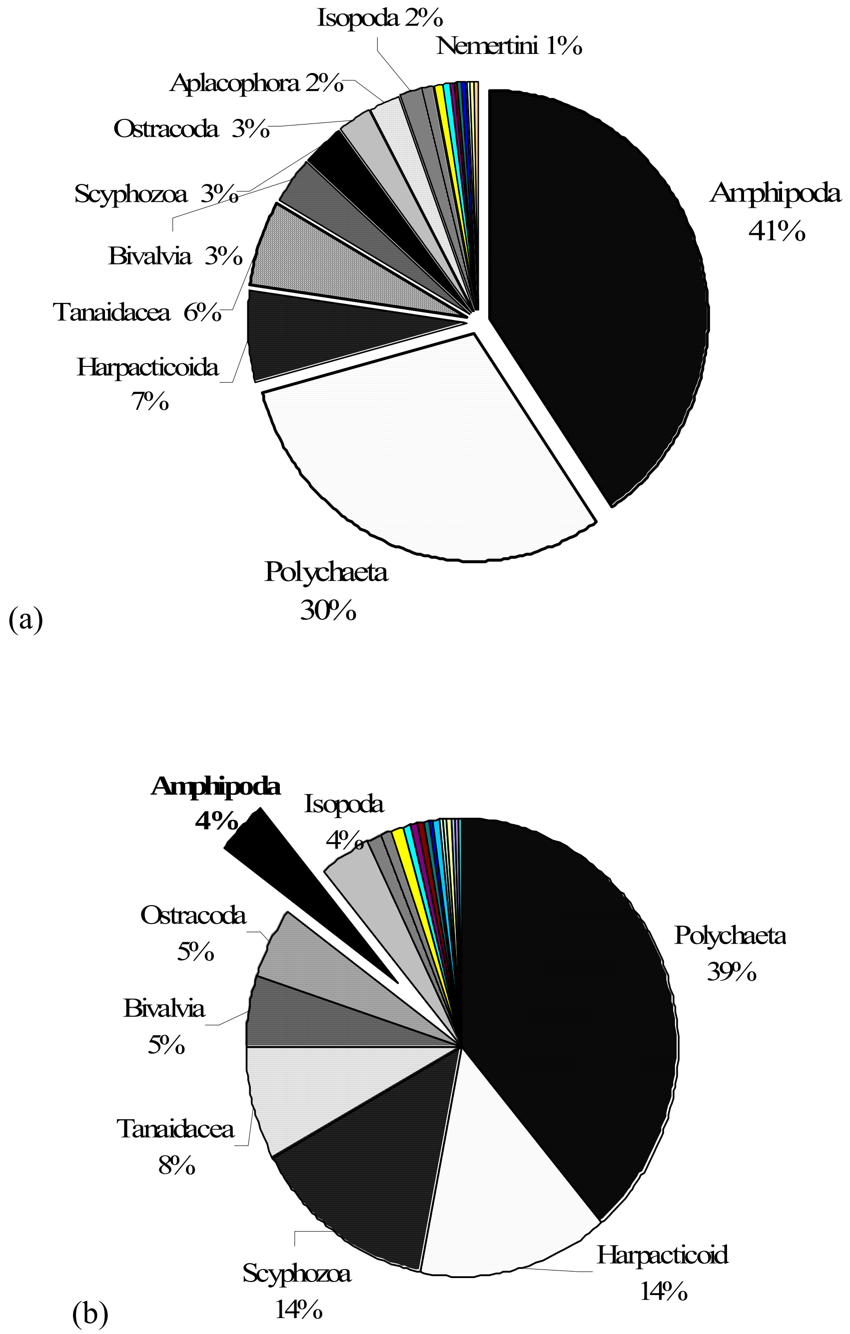


Fig. 3.2. Percentage composition of the major faunal groups collected from the Canyon (a) and the C-transect (b).

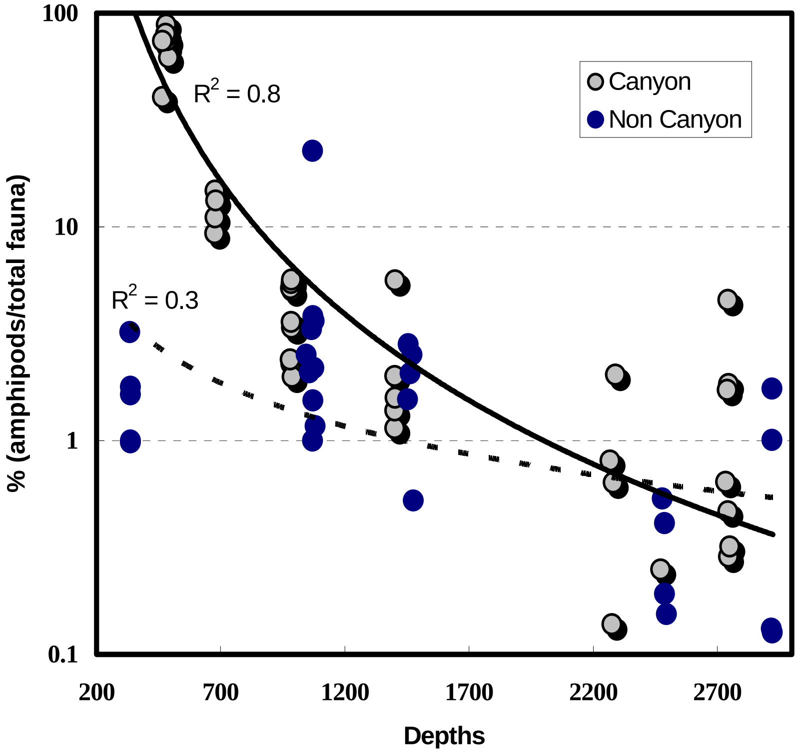


Fig. 3.3. Comparison between the ratio of amphipoda to the total macrofaual densities in Mississippi trough and central transects.

Table 3.3. ANOVA for testing difference in amphipod abundance (Log (N+1)).

	SS	DF	MS	F	P
Depth	14.559	4	3.640	99.076	.000
Canyon	.772	1	.772	21.018	.000
Transect * depth	5.347	4	1.337	5.09	.000

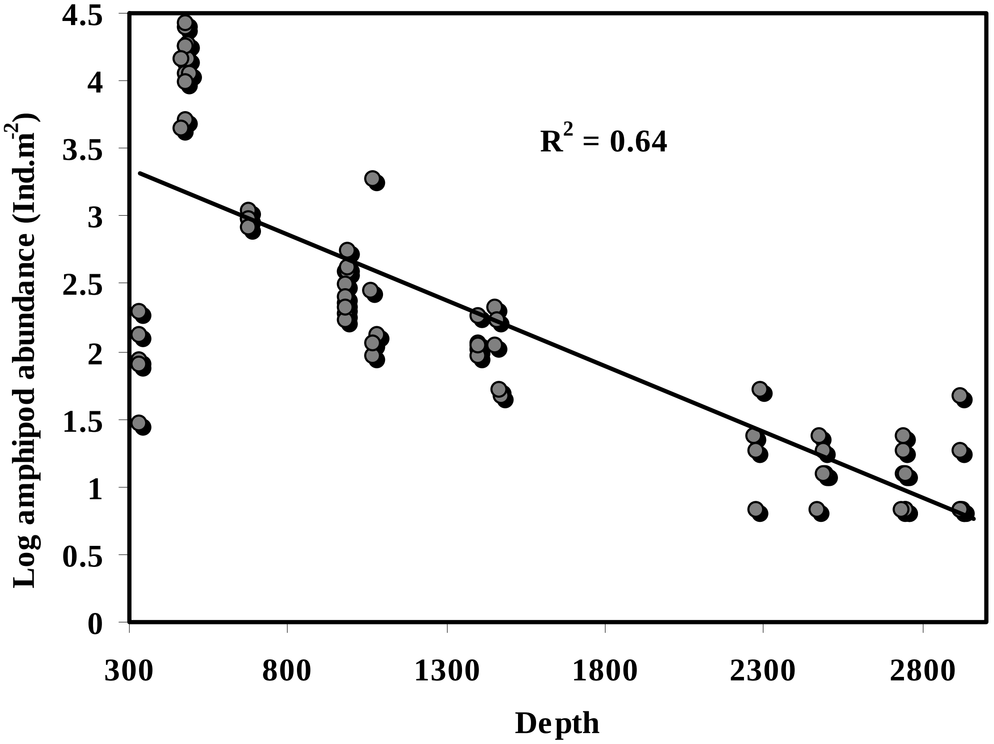


Fig. 3.4. Log10(X+1) transformed amphipoda abundance (N .m-2) versus water depth (m) for MT and C transects.

III.4.2. Spatial distribution

In the Mississippi canyon, *Ampelisca mississippiana*, a new species (Soliman and Wicksten, 2007), was dominant (Table 3.4). It represented about 89% of the total abundance at the canyon's head with average density about 15,880 ind.m^{-2}. *Ampelisca* sp was the second most abundant amphipod in the canyon (average density of 1225 in .m^{-2}) and was characteristic for the canyon's head along with a third species (*Ericthonius* sp, 313 ind.m^{-2}) that represented only 2% of the total amphipod density in the canyon on the continental upper slope. *Phoxocephalus homilis* was most abundant amphipod in the canyon's middle depths and the third most abundant in the canyon in general, with average density of 550 ind.m^{-2}. Other species such as *Leptocheirus sp* and *Leptophoxus molaris* also were abundant and characteristic for the canyon's middle slope zone (Table, 3.4). *Haploops* sp was the characteristic for the lower slope zone (77 ind.m^{-2}). The non-canyon transect was characterized by the relative dominance of a different group of amphipods including *Byblis brachycephala*, *Leptophoxus falcata*, *Metaphoxus simplex*, *Leptophoxus molaris* on the upper slope, *Haploops* sp, *Pardaliscella boeckii*, and *Phoxocephalus homilis*, on the middle slope, and *Haploops* sp and *Rachytrophis* sp on the lower slope. However the densities of all the species in the central transect were very low comparing with the canyon transect (Table 3.4).

A total of 19 families were collected from the study area. The Ampeliscidae was the most dominant in the Mississippi Canyon, followed by Phoxocephalidae, Ischyroceridae and Aoridae. On the other hand, the Lyssianassidae, Melitidae, Synopidae and Oedicerotidae were common families in the canyon. There were several rare families that inhabited the canyon (see fig. 3.5a). The Phoxocephalidae became the dominant family in the non-canyon transect along with other relatively less dominant families, including the Oedicerotidae, Pardaliscidae, Synopiidae. On the other hand, the Ampeliscidae, Aoridae and Melitidae were occasionally represented in the central transect. The Pardaliscidae was almost absent from the canyon and the Ampeliscidae of the canyon included totally different species from those found on the non-canyon transect (Fig.3.5b), and so we rejected the second null hypothesis.

Table 3.4. Abundance and % contribution of the abundant amphipods to the total abundance at each zone of the slope :the upper (336-500m), middle (677-990m) and Lower (>1000m) slope.

Canyon (Mississippi Canyon transect)			**Non-Canyon (Central transect)**		
Upper Slope:					
	N	N%		N	N%
Ampelisca mississippiana	13771	89	*Byblis brachycephala*	12	12
Ampelisca sp.	1225	8	*Byblis sp1*	7	7
Ericthonius sp.	312	2	*Leptophoxus molaris*	8	9
			Leptophoxus falcata	10	11
			Metaphoxus simplex	17	19
			Harpinia sp (A)	12	12
			Phoxocephalus homilis	6	6
Middle Slope					
Leptocheirus sp	123	11	*Byblis brachycephala*	9	7
Leptophoxus molaris	217	18	*Haploops sp*	7	6
Harpinia dellavallie	17	2.0	*Leptocheirus sp*	6	5
Harpinia sp (A)	112	10	*Pardaliscella boeckii*	13	10
Phoxocephalus homilis	550	47	*Leptophoxus falcata*	9	7
			Harpinia pectinata	5	4
			Metaphoxus simplex	10	8
			Phoxocephalus homilis	14	12
			Paraphoxus oculatus	7	6
Lower slope					
Byblis brachycephala	14	8	*Haploops sp*	8	5
Haploops sp	77	46	*Rachytrophis sp.*	46	31
Hippomedon sp	3	2	*Pardaliscella sp*	17	12
Leptophoxus molaris	14	8	*Pardaliscella boeckii*	14	10
Phoxocephalus kergueleni	14	8	*Parpano composturus*	20	13
Paraphoxus oculatus	6	3	*Leptophoxus molaris*	6	4
			Leptophoxus falcata	9	6
			Harpinia pectinata	10	7

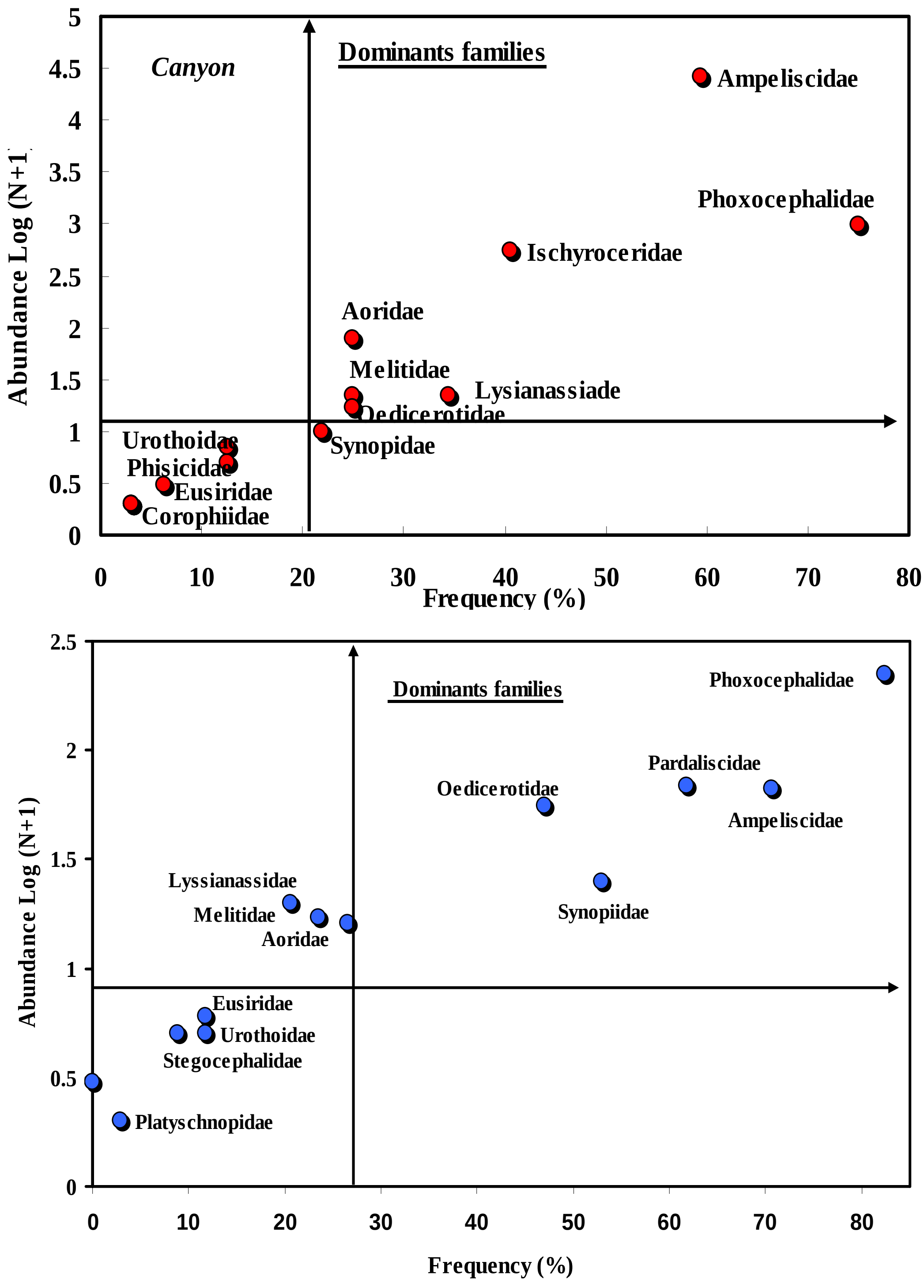


Fig. 3.5. Relationship between frequency of appearance (%) and abundance of amphipod families for Canyon (●) and non-canyon (●) transects.

III.4.3. Bathymetric zonation pattern

MDS of abundant amphipods based on the 4th root transformed data showed that apparent four depth zones could be concluded without overlap for the whole area. The first zone includes the canyon head (MT1) which had the highest amphipod abundance. It proved to be completely dissimilar to the other canyon and non-canyon locations. The second zone included the canyon's intermediate depth between 676 and 1000m. The zone between 1077 and 1450 in the canyon had high similarity to faunal structure of the upper non-canyon zone both in abundance and faunal structure. The last zone extended deeper than 1450 m and had the lowest amphipod abundance (Fig. 3.6). Excluding the canyon's head, three general bathymetric boundaries could be found in the two transects together. The first boundary ranged in depth between 334 and 677m. The second was located between 677 and 1057 and the third one was deeper than 1057 to about 3000m depth (Fig. 3.6). Cluster analysis for the canyon replicates of the different bathyal locations (Bray-Curtis similarity matrix using presence/absence data) revealed the arrangement of the amphipods in the canyon transect in three dissimilar zones (similarity less than 15 %). The first zone included the canyon's head which was inhabited by several species that had limited bathymetric range. These include *Ampelisca mississippiana*, *Ampelisca* sp, *Erichthonius* sp and *Harpiniopsis emeryi*. The second zone included the bathymetric range of the middle slope, and it was dominated by *Phoxocephalus homilis*. The third zone, the lower slope, (< 1000m), was dominated by the ampeliscid *Haploops* sp, Fig (3.7).

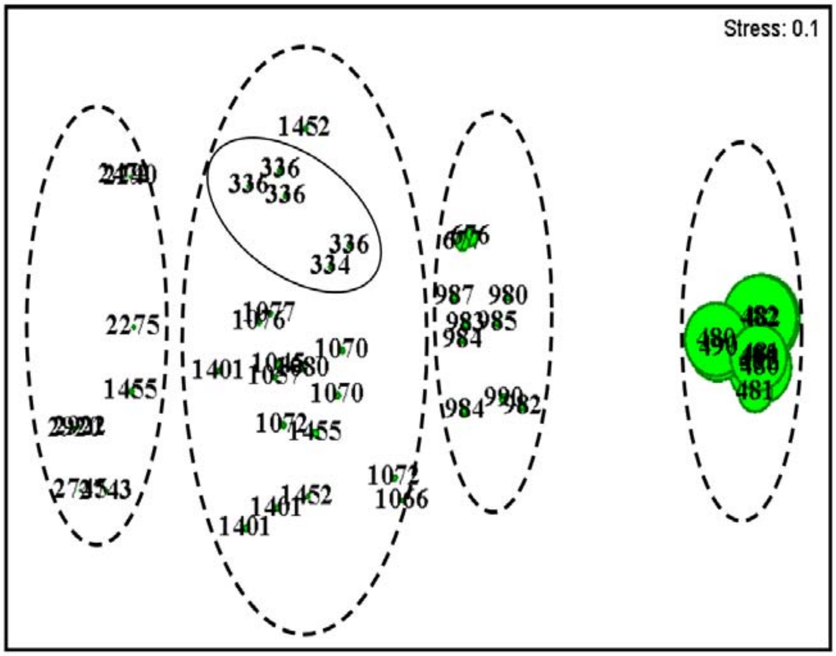
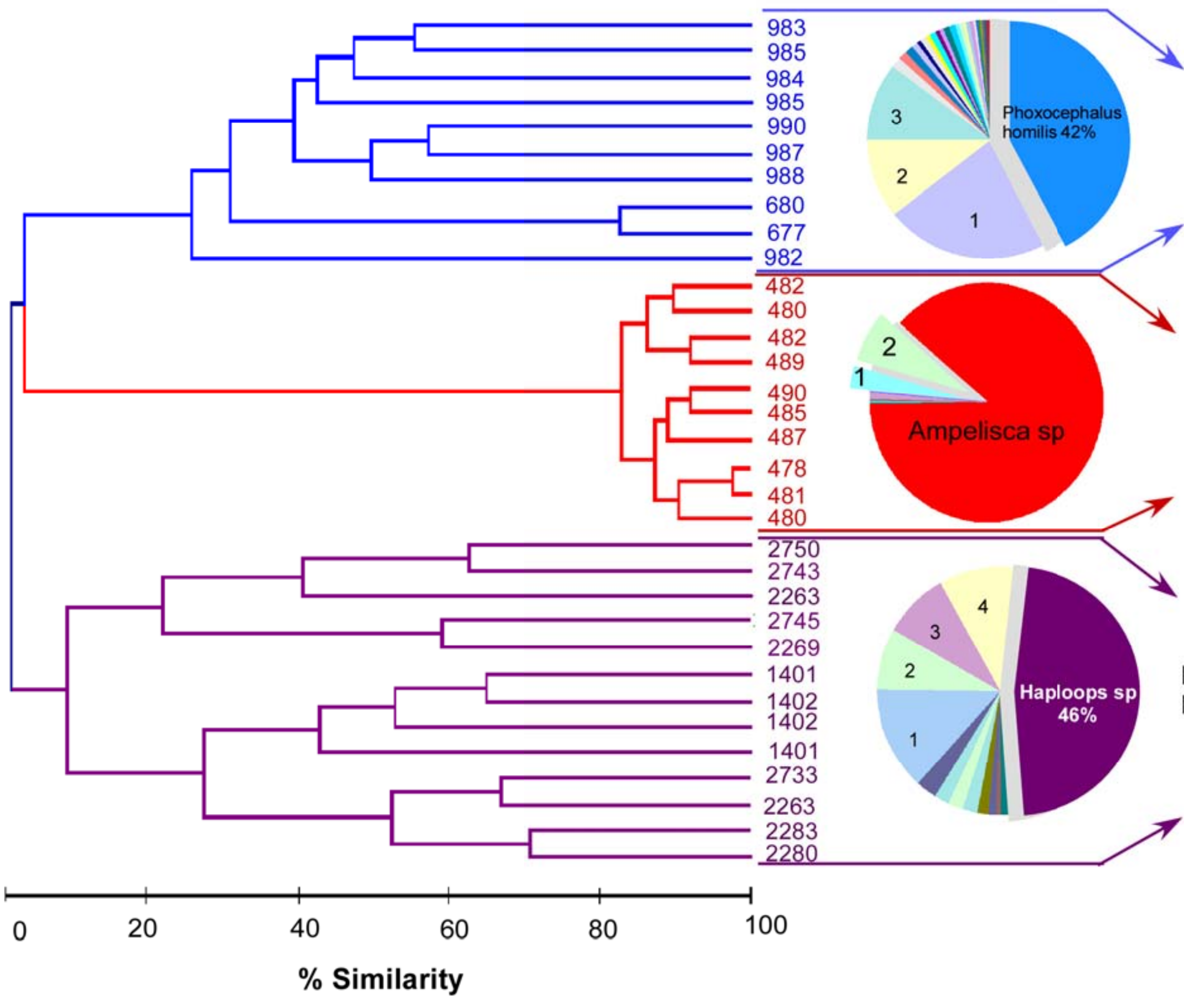


Fig. 3.6. MDS ordination of DGOMB stations as depths, based on Bray–Curtis similarity (4th root transformation) of abundant amphipods. Bubble size equals relative amphipod abundance at the whole area.



Phoxocephalids Zone:
Dominated by P. homilis (42%),
Leptophoxus sp-1- (22)%,
Leptocheirus sp(10%),
Harpinia
sp-3-(10%). P. Homilis is
known as predators while
Leptocheiurus is deposit feed-

Ampelisca Mat Zone:
Ampeliscid assemblage (88%).
Ampelisca sp-2 -(7%). Erichthonius sp (3%). They are
tube builders species and are
known to be suspension feeders (Mills, 19 , Nyssen et al,
2002)

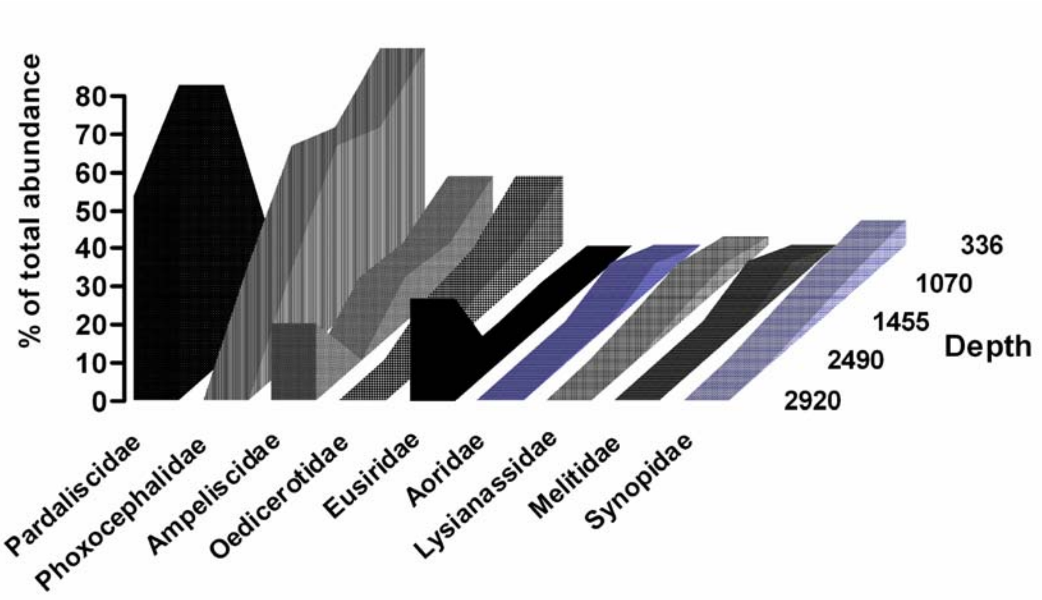
Haploops Zone:
Haploops sp. (46%),
P. Kergueleni-1- (14%).

Fig. 3.7. Cluster analysis for the amphipod samples using Bray–Curtis similarity (4th root transformation) for the abundant amphipods from the canyon and the comparable species composition at each bathymetric zone.

The zonation pattern was prominent also on the family level. The Ampeliscidae showed wide depth range in both transects. The Pardaliscidae contained indicator species for the non-canyon while the Ischyroceridae was mostly restricted to the canyon. The Phoxocephalidae almost disappeared on the lower slope, while the Eusiridae was restricted to the lower slope on both transects. Some families such as Oedicerotidae and Lysianassidae, which were abundant in the upper slope of the central transect, became more abundant at the lower slope of the canyon (Fig. 3.8).

Using the Bray-Curtis similarity measure for presence /absence data, we could define different categories of species for ecologically important locations such as the canyon. Group I in the cluster analysis included species that were restricted to the canyon and can be used as canyon indicators. It included the dominant species *Ampelisca mississippiana*, the abundant *Ampelisca* sp., *Harpiniopsis emeryi*, *Ericthonius* sp., and *Harpinia* sp (B). Group II included non-canyon species and contained species that were commonly found on the central transect but also could be found in the very deep canyon stations. It included *Harpinia pectinata*, *Metaphoxus simplex*, *Paraphoxus oculatus*, *Leptophoxus falcata*, *Byblis brachycephala*, *Haploops* sp, and *Phoxocephalus kerguelena*. Group III included species which had no preference for a specific environment, either canyon or non-canyon. It included *Harpinia dellavallie*, *Harpinia trasovi*, *Eriopisa elongata*, *Leptophoxus molaris*, *Leptocheirus* sp. Group I and it included species such as *Harpiniopsis emeryi*, *Harpinia tarasovi*, *Ericthonius* sp and *Pardaliscella* sp. (Fig. 3.9).

A



B

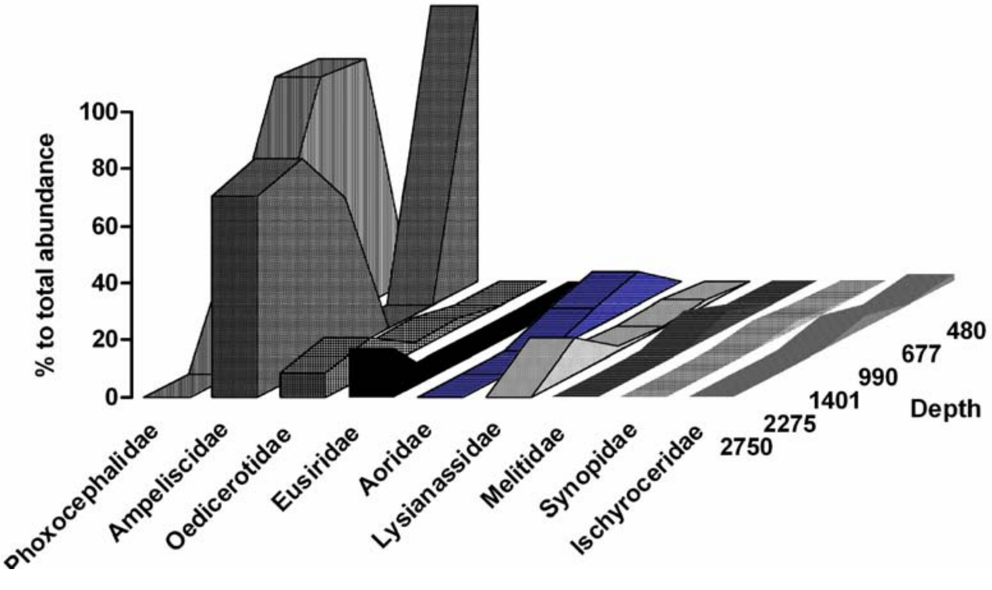


Fig. 3.8. Distribution of the major amphipod families with depth in the Mississippi Canyon (B) and the central transect (A).

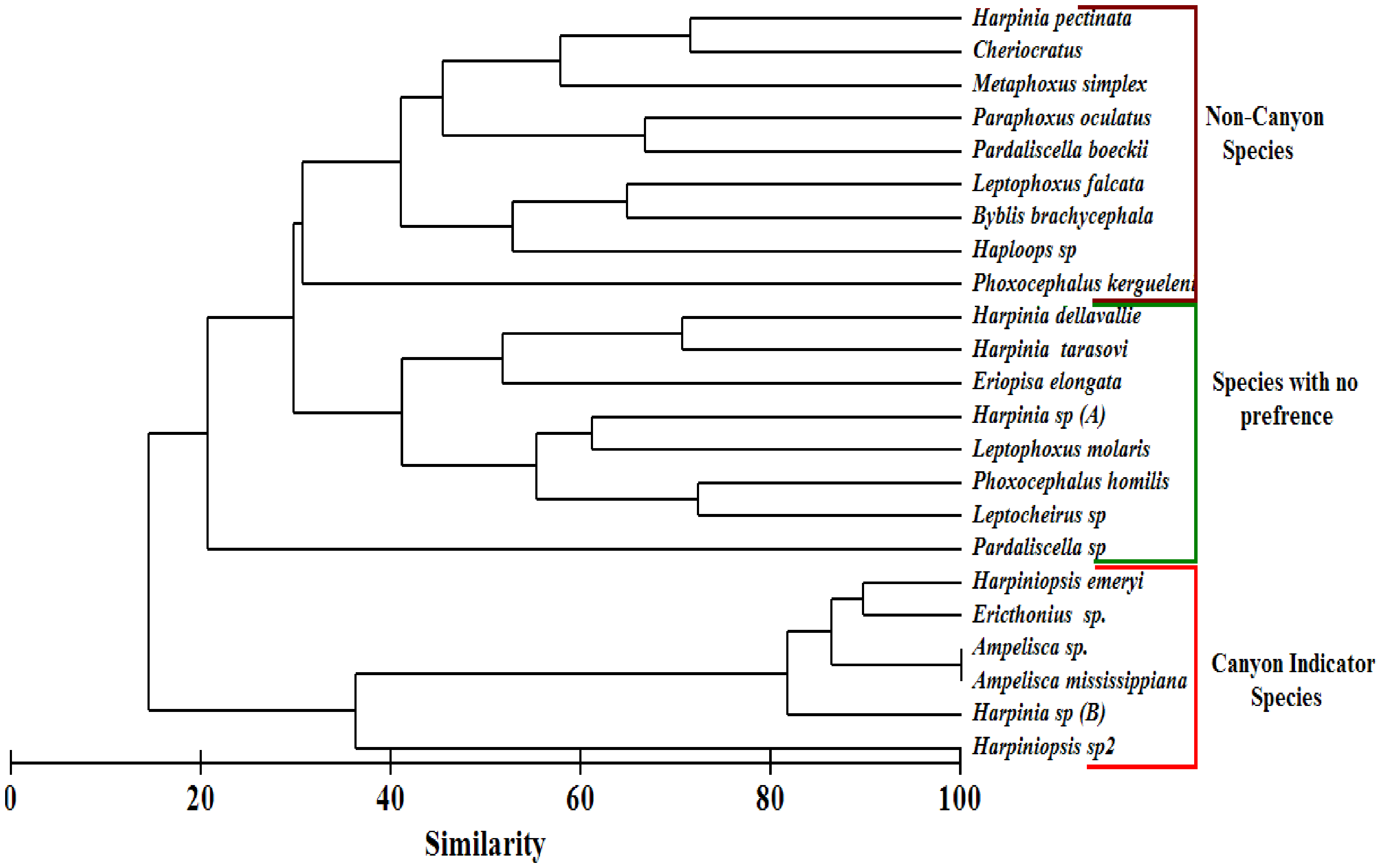


Fig. 3.9. Cluster analysis for the amphipod samples using Bray–Curtis similarity (presence/absence transformation) of amphipods from the canyon and non-canyon transect.

III.4.4. Diversity measurements

Seventy two species were identified from the study area (Fig 3.10). The number of species was higher in the Canyon transect (61 species) than in the non-canyon (38 species) (Fig. 3.11). Generally, the rate of species replacement was gradual across the upper slope depths, rapid at mid-depths, and then gradual again at lower slope. The rapid species replacement was at 677-1000m on the two transects. More than 60 % of the species collected in the two transects were encountered in this depth zone (fig. 3.10) in the Mississippi Canyon.

The Chao and Jacknife estimator curves predicted that the number of species could be close to 100 (96 and 99 for Chao and Jacknife respectively), (Fig. 3.10). They also predicted that the highest replacement of species would be found between 677 and 1401m with the addition of 65 species that represented about 65% of the total species.

The Shannon diversity index exhibited a prominent parabolic pattern on the canyon transect (R^2= 0.6) with a less prominent pattern on the non-canyon (R^2= 0.5). The maximum on both was at about 1100 m (Fig. 3.12). The equitability was higher in the Central transect than in the Mississippi Canyon (Fig. 3.13). There was no significant change in the Central transect with depths while on the Canyon transect the lowest equitability was found at MT1 (Fig. 3.13). Because of the difference in the sample size with depth and with transects, the rarefaction diversity method (Hurlbert, 1971) was used to calculate species richness expected by scaling down all collections to the same sample size. Rarefaction richness in the Mississippi Canyon transect (Fig.3.14) was highest at 1000 m (MT3) and was low at the canyon's head (500 m) as well as at 1200-

1750 m. In the central transect the highest rarefaction diversity was found at C7 (1070m) and the lowest at C12 and C14 (Depth range 2487-2920m). Generally, the canyon's head had the lowest species richness in the whole area while the mid depth at about 1000 m (MT3 and C7) had the highest rarefaction richness.

A K-dominance curve (Lambshead et al.1983) for the Canyon transect illustrates that MT3 (approximately 1000 m depth) had the lowest dominance, while the k-dominance curve of MT1 was elevated indicating the low diversity in the canyon's head. Dominance at 500 m was extremely high with the top ranked *Ampelisca mississippiana* representing about 89% at this location (Fig 3.15a). The dominance decreased with depth, producing the highest evenness at 1000 m. The non-canyon transect mimics the Canyon transect in having the highest diversity of amphipods at the same depth range (1065 m); however, it was different in having the lowest species diversity at great depths, between 2487-2921 m, instead of at 500 m on the canyon transect (Fig. 3.15b). In comparing the k-dominance curves for the two transects, the highest diversity of amphipods in the northern Gulf of Mexico was found at depths of about 1000 m. However, diversity on C transect was generally higher than that in the Mississippi Canyon transect, especially between depths of 336-1463m (fig 3.15c). Based on these results, we rejected the third hypothesis (H_{03}).

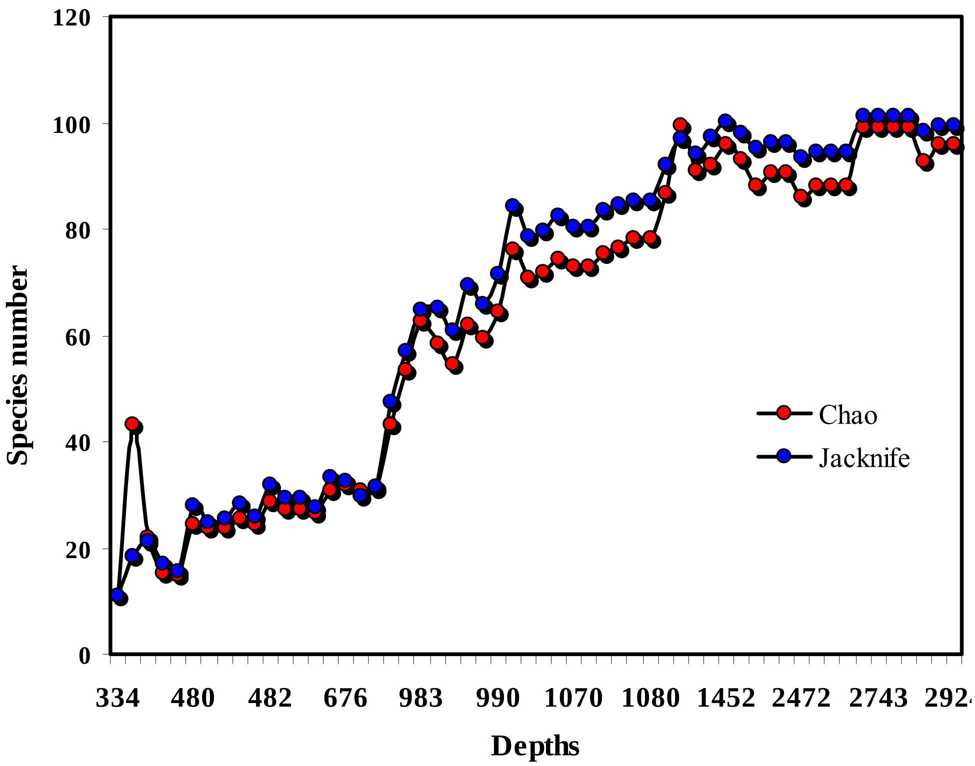


Fig. 3.10. Species accumulation (S) and estimated species accumulation using Chao index and Jacknife index estimators.

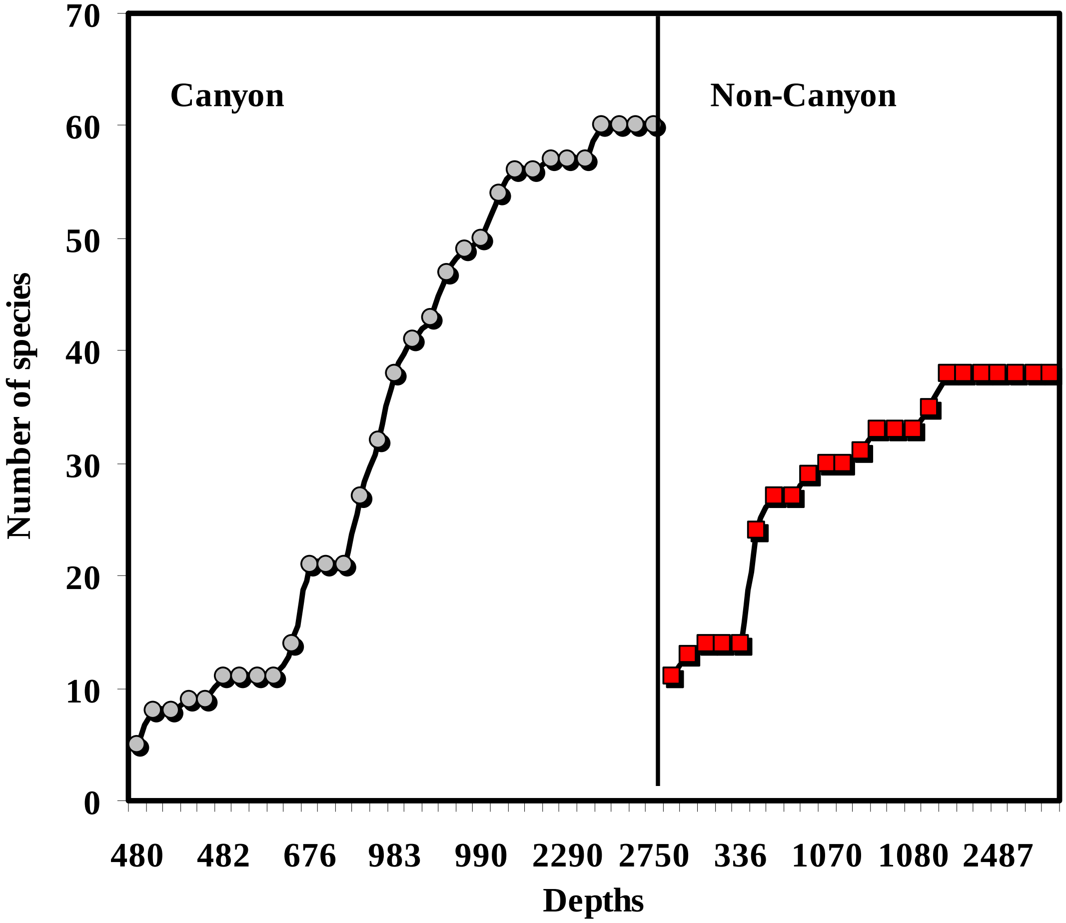


Fig. 3.11. Comparison between the accumulations of amphipod species with depth in canyon vs. non-canyon transects.

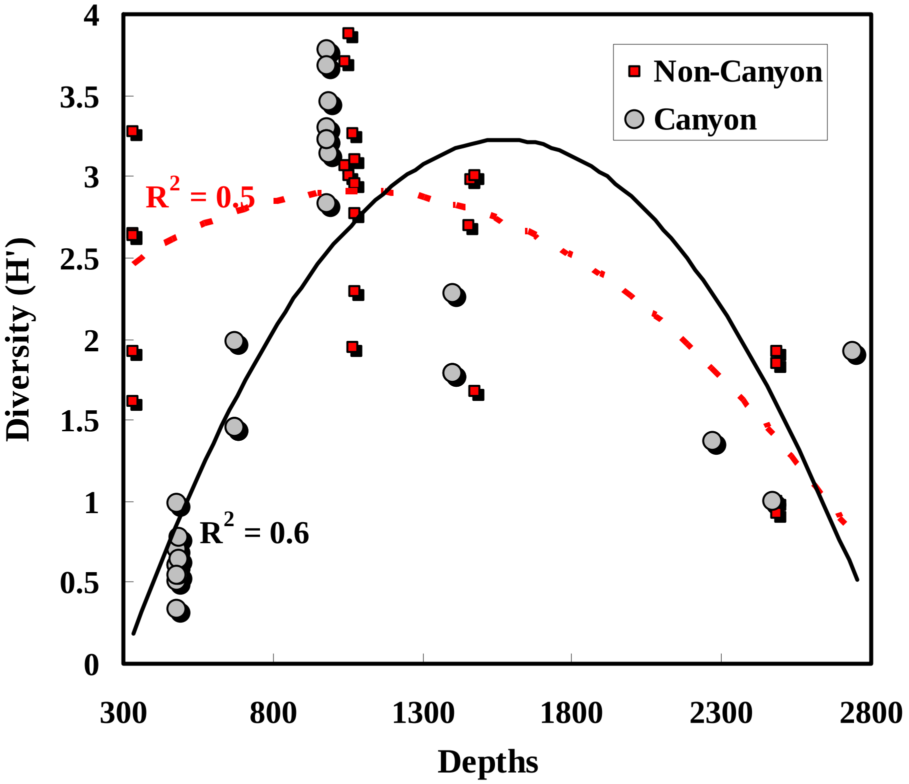


Fig. 3.12. Change in species Shannon diversity index in canyon and non-canyon transects.

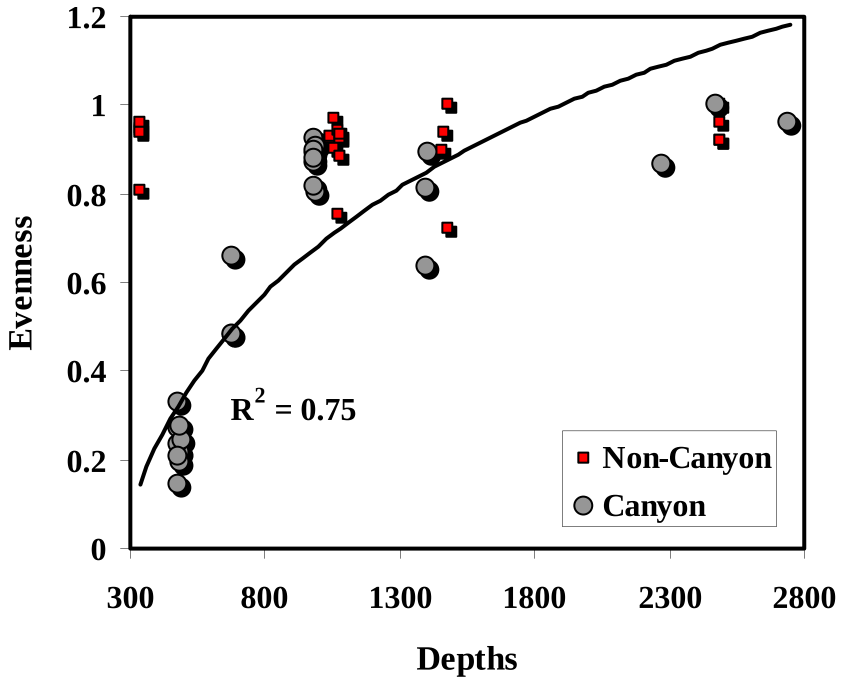


Fig. 3.13. Change in species evenness in canyon and non-canyon transects.

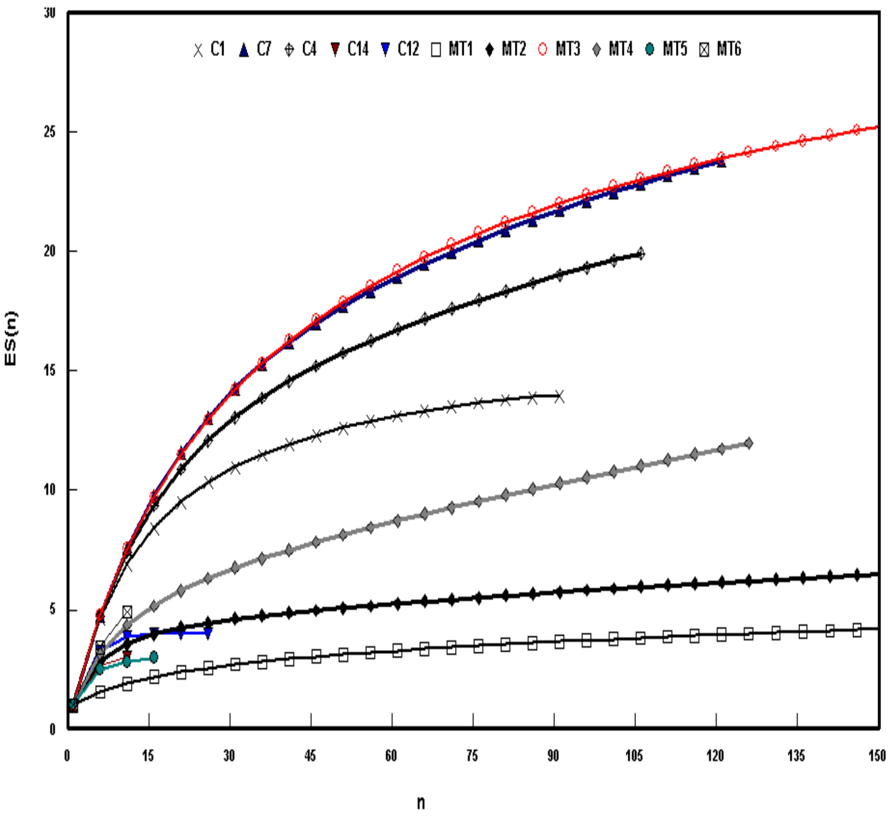


Fig. 3.14. Rarefaction curves for species biodiversity comparing the diversity at different locations in the canyon as well as non-canyon transects.

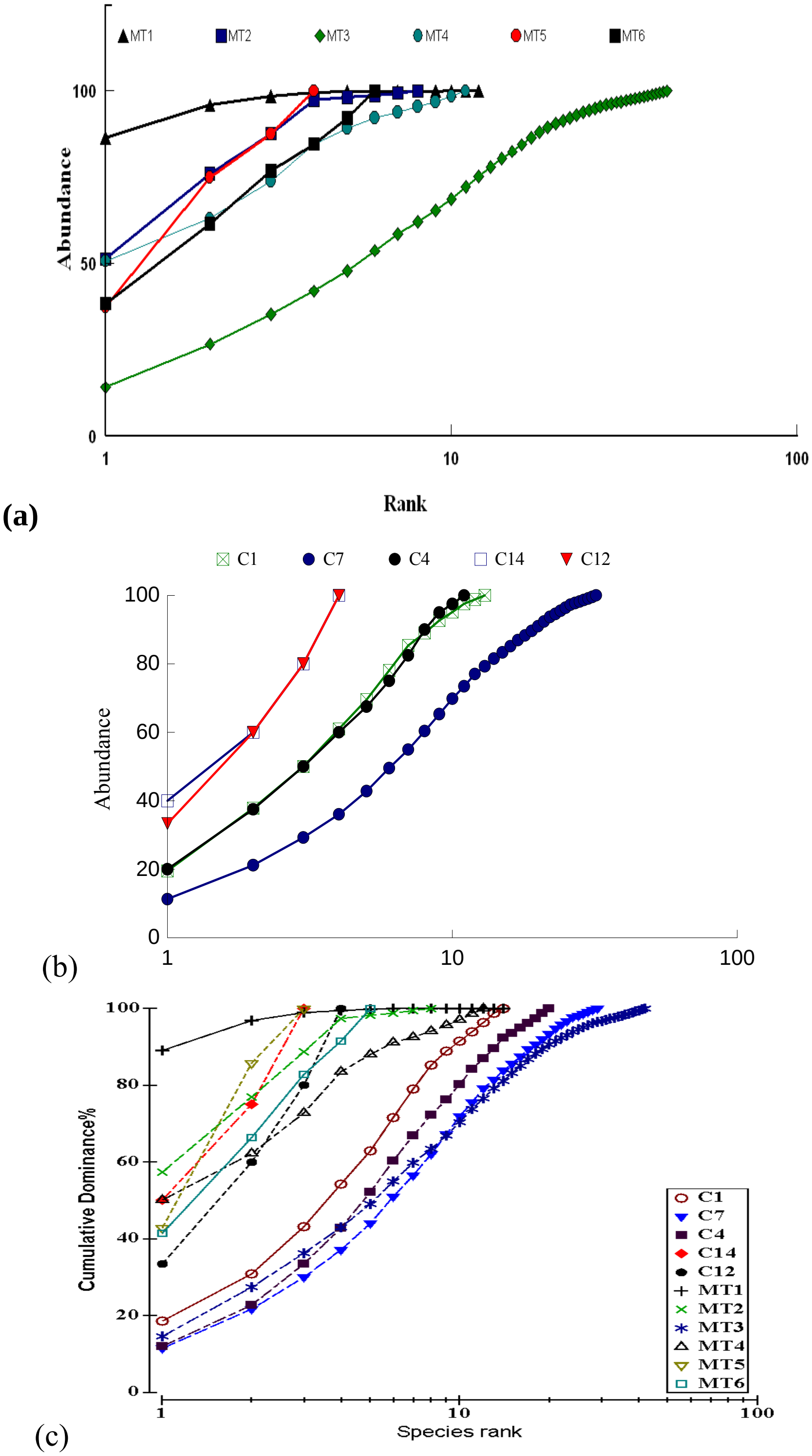


Fig. 3.15. K-dominance curve for the Mississippi Canyon (a) and the central transect (b) and the two transect combined (c).

III.4.5. Environmental gradient influences on amphipods

An array of environmental parameters (Table 3.5) was engaged in PCA analysis to assess the most important factors influencing the dynamic of the amphipods. The initial PCA for metals showed that the first principal component accounted for about 68 % of the total variance in the metals data (Table 3.6). Four metals with highest loading on PC1 were selected to be included in the main analysis of the environmental data representing the trace metals. These were beryllium (Be), iron (Fe), chromium (Cr) and tin (Sn), (Table 3.7). The four selected metals joined 17 other abiotic factors in a PCA to assess the effect of total of 21 abiotic factors over the density and diversity of amphipods (Table 3.5). Before the analysis, all the necessary transformation for the data was performed to validate the assumption of parametric tests. The three first components accounted for 80% of the total variance in the data set (Table 3.8, 3.9). Clay, metals (Fe, Cr, Sn, Be) and sand showed high loading on the first principal component (PC1), which explained 46.5 % of the variation. Percent sand was negatively correlated with PC1, while percent clay, metals and bottom water organics (carbon and nitrogen) were positively correlated with PC1, which is interpreted as high clay, in “organic-rich” areas. Consequently, high associated metals are in areas close to the head of the canyon and high sand and consequently low metals are in areas far from the canyon. These results could be concluded due to the heterogeneity of the sediment. PC2 contributed with 19 % to the total variance and it had high positive loading with sediment POC, chlorophyll transported to the bottom and temperature. PC2 is interpreted as depth gradient in POC flux and temperature (Fig. 3.17). PC3 contributed 13% to the total variance and has high positive loading by % organic carbon and % organic nitrogen. It is interpreted to be related to "food quality". Correlation analysis between PC1, PC2, PC3 and PC4 showed that the density of the amphipods had high correlation only with PC4, which has positive loading with NO_3 and silt %.

Because of the unique structure of the amphipod assemblage in the canyon, PCA was carried out for just the canyon's environmental parameters to find out if the same environmental parameters accounted for the within-canyon variance. The first three components accounted for 93% of the total variance in the canyon's data (Table 3.10, 3.11). PC1 accounted for 54% of the variance and had high positive loading with % clay, metals (Fe, Cr, Sn, Be) and near-bottom POC. It had high negative loading with sand, which is interpreted to be characteristic of organic carbon flux. PC2 accounted for 25% of the variance and it had high positive loading with organic nitrogen % and high negative loading with C/N ratio, which are interpreted to be related to food quality. PC3 accounted for 14% of the variance and had high positive loading with near-bottom suspended materials. A high correlation was found between the abundance of amphipods and the PC3 in the canyon ($R^2=0.94$, $P<0.001$) and consequently we rejected the fourth hypothesis (H_{04}).

A regression model (R^2= 0.8, P= 0.029) was used to predict the amphipod abundance in the northern Gulf of Mexico using PC1, PC2 , PC3 and PC4 as predictors.

Amphipods (Ind. m^{-2}) = 1465-1778.PC1-2322PC2+1237 PC3 +12367 PC4

Amphipod abundance was significantly correlated with the chlorophyll flux to deep water (R^2 =7.3, P<0.01) (Fig. 3.18). A model for predicting the amphipod abundance based on the carbon flux to the deep water was:

Amphipods = 4594 * chl a flux - 502.854 (R^2 = 0.7, p<0.001). However adding the total suspended matter (TSPM) to the model enhanced its power (R^2= 0.97, P<0.001), and the predicted abundance of amphipods can be calculated as

Amphipods (Ind.m^{-2}) = 5824* Chl a flux- 19257 TSPM -2830

where Chl a flux is the amount of chlorophyll settling to deep water sediment and TSPM is the near-bottom suspended materials.

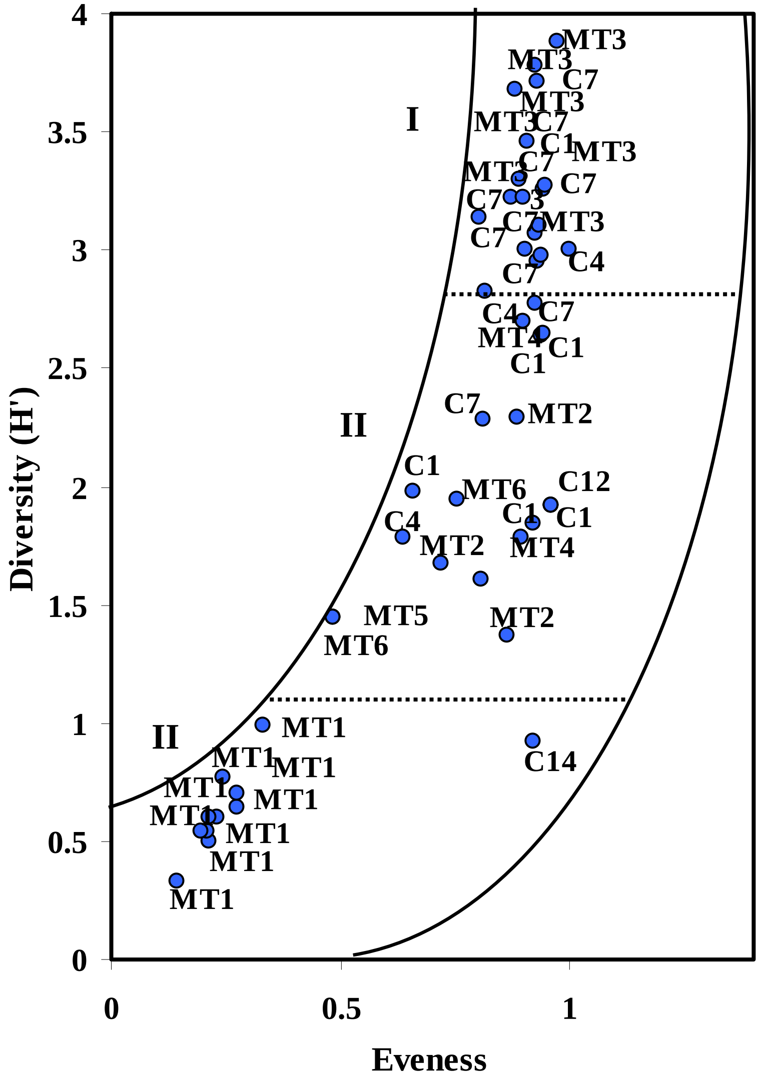


Fig. 3.16. Amphipod diversity index and evenness for the replicates from different cruises (2000-2002) to assess the quality of the different locations.

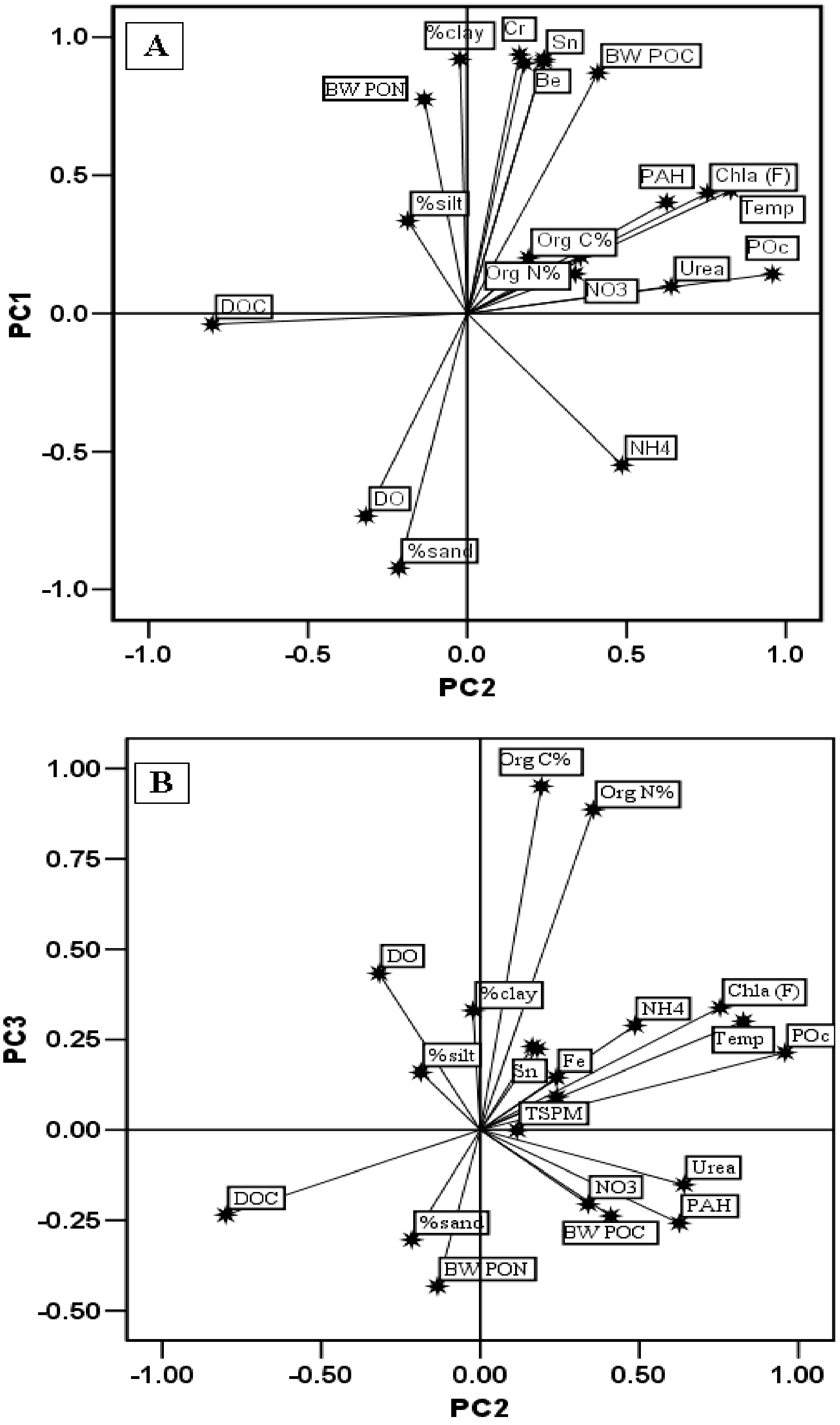


Fig. 3.17. Principal components analysis of 21 environmental variables; Variable loading scores for PC1 vs. PC2 (A), and PC2 vs. PC3 (B).

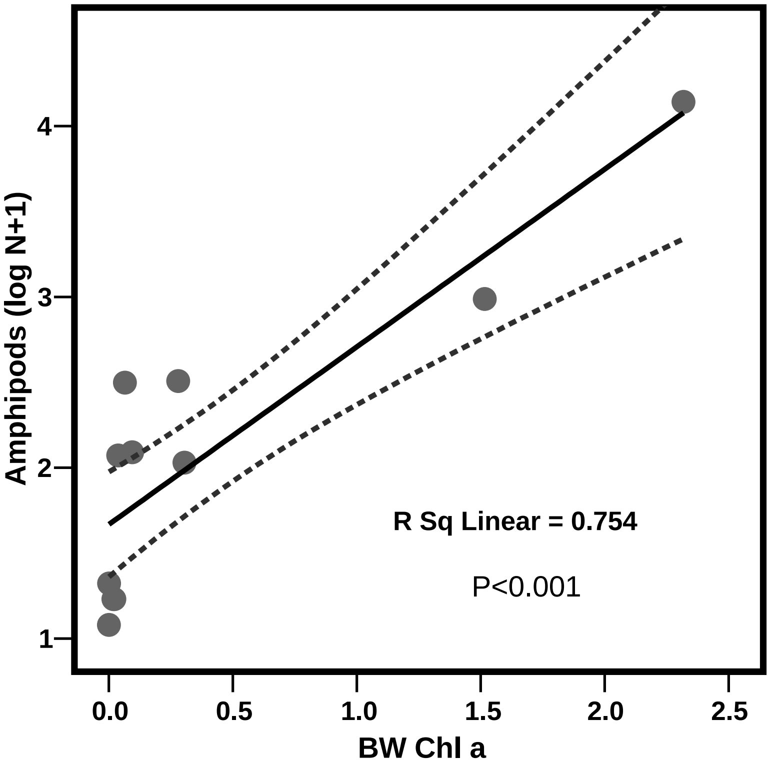


Fig. 3.18. Regression of amphipod abundance as Log (N+1) as a function of the adjusted chlorophyll as proxy to the flux to the sediment (Bw Chl a).

Table 3.5. The average measurements for 22 environmental factors measured in the sediment and near bottom water in the 11 locations of the study area during the period 2000-2002.

Station	**C1**	**C4**	**C7**	**C12**	**C14**	**MT1**	**MT2**	**MT3**	**MT4**	**MT5**	**MT6**
Depth (km)	0.336	1.463	1.072	2.921	2.487	0.481	0.678	0.987	1.401	2.275	2.745
Temperature	11.4	4.2	4.7	4.0	4.0	8.3	6.1	4.9	4.1	4.0	4.0
DO (mg/L)	2.4	4.2	3.7	4.5	4.4	2.5	3.1		4.3	5.5	4.4
Chla (mg/m3)	0.500	0.220	0.280	0.180	0.190	2.470	2.130	0.760	0.410	0.023	0.019
PAH (µg/g)	561.6	15.2	158.9	83.8	31.3	526.5		524.8	173.3	47.5	65.2
Be	1.8	1.6	1.8	1.1	1.6	2.1	2.0	2.0	1.7	0.9	1.1
Sn (µg/L)	2.2	1.4	1.9	0.9	1.5	2.5	2.5	2.5	1.7	0.6	0.7
Fe (µg/L)	32700	26900	32250	20700	29900	37650	35400	37200	29900	15800	25950
Cr (µg/L)	63.5	54.2	59.6	44.2	61.2	70.5	68.2	67.4	57.3	30.4	49.6
DOC (mM)	2.178	1.919	1.340	1.923	3.188	0.953	1.803	2.234	2.718	2.374	3.063
POC (µM)	4.80	4.40	3.40	2.85	2.40	6.10	3.20	3.20	2.60	3.30	2.40
NO3 (µM)		18.90	19.80	21.75	12.40	20.40	17.40	23.80	19.10	14.50	10.90
NH4 (µM)	15.00	20.40	21.50	18.30	8.90	27.50	26.80	10.30	24.50	33.10	10.20
UREA (µM)	3.20	3.30	3.60	3.80	3.50	4.40	2.70	3.80	2.60	3.30	3.50
Org-C%	0.998	0.735	0.815	0.544	0.648	1.135	0.899	0.025	0.938	0.217	
Org-N%	0.129	0.096	0.118	0.079	0.089	0.161	0.125	0.013	0.091	0.038	
% Sand	4.3	10.8	8.0	24.6	4.8	2.0	2.7	4.1	9.0	64.3	29.7
% Silt	35.0	36.3	40.6	40.7	22.9	33.0	40.1	40.7	45.5	15.3	26.9
% Clay	60.7	52.9	51.5	34.7	72.4	65.0	57.1	55.2	45.5	20.4	43.5
POC_µg/L	48.9	18.6	22.5	8.8	25.7	38.3	28.5	43.8	8.2	5.4	12.9
PON_µg/L	5.480		3.930	1.790	3.990	2.550	4.430	5.105	1.990	2.290	3.450
TSPM_mg/L	0.245	0.152	0.116	0.276		0.164	0.697	0.209	0.158	0.202	0.143

Table 3.6. Eigenvalues for the correlation matrix for the metals PCA .

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	18.238	67.547	67.547
2	3.305	12.242	79.789
3	1.946	7.207	86.996
4	1.459	5.404	92.400
5	.685	2.539	94.939
6	.551	2.040	96.978
7	.399	1.480	98.458
8	.286	1.059	99.517
9	.098	.363	99.880
10	.033	.120	100.000

Table 3.7. Variable loads for the rotated (varimax) factor for the metals PCA.

Metals	PC1	PC2	PC3	PC4
Ag	.029	.661	.713	-.025
Al	.967	.201	.001	-.104
As	.800	-.452	-.084	.042
Ba	.560	-.442	.093	.512
Be	.992	.021	.022	-.054
Ca	-.973	.220	-.019	.056
Cd	.496	.248	.476	-.359
Co	.800	.240	-.522	.031
Cr	.976	.034	-.154	-.030
Cu	-.102	.814	-.544	.053
Fe	.991	-.001	-.072	-.038
K	.971	.126	-.001	-.136
Mg	.833	.368	-.296	.161
Mn	.847	-.473	-.145	.081
Na	.895	.104	.217	.327
Ni	.740	.575	-.286	.037
P	.763	.283	.159	-.116
Pb	.936	-.129	.230	.119
S	.855	-.017	.234	.439
Sb	.831	-.312	.080	.102
Si	.485	-.222	.002	-.739
Sn	.980	-.131	.063	-.035
Sr	-.903	.371	-.106	.167
Ti	.946	-.046	-.215	-.120
Tl	.545	.667	.367	.178
V	.973	.173	-.136	-.042
Zn	.925	.044	.069	-.175

Table 3.8. Eigenvalues for the correlation matrix for the environmental PCA .

Component	Eigenvalues		
	Total	% of Variance	Cumulative %
1	10.064	47.923	47.923
2	4.011	19.101	67.023
3	2.682	12.771	79.795
4	1.780	8.476	88.271

Table 3.9. Principal Component Analysis matrix containing variable loads for the rotated (varimax) component of the environmental parameters.

	PC1	PC2	PC3	PC4
Temperature	.445	.827	.301	-.032
DO (mg/L)	-.734	-.318	.434	-.403
PAH (µg/g)	.402	.626	-.258	.367
DOC (mM)	-.039	-.800	-.235	-.353
POC (µM)	.143	.958	.214	-.024
NO3 (µM)	.144	.339	-.205	.905
NH4 (µM)	-.549	.486	.289	-.173
Urea (µM)	.099	.641	-.151	.094
Org-C%	.200	.192	.952	.014
Org-N%	.205	.355	.887	-.058
%sand	-.923	-.215	-.304	-.056
% Silt	.335	-.187	.160	.905
% Clay	.920	-.023	.331	.042
POC_µg/L	.870	.410	-.238	.043
PON_µg/L	.776	-.135	-.432	-.082
TSPM_mg/L	.120	.116	-.001	.103
Chl a at bottom	.436	.754	.339	-.103
Fe	.911	.239	.145	.215
Cr	.937	.164	.231	.183
Sn	.920	.241	.092	.191
Be	.904	.179	.224	.263

Table 3.10. Eigenvalues for the correlation matrix for the environmental PCA for the canyon transect.

Component	Eigenvalues		
	Total	% of Variance	Cumulative %
1	11.78	53.56	53.56
2	5.56	25.28	78.85
3	3.17	14.16	93.02
4	1.56	6.98	100.0

Table 3.11. Principal Component Analysis matrix containing variable loads for the component of the environmental parameters for the canyon transect.

	PC1	PC2	PC3	PC4
TEMP	.725	.670	-.071	-.146
DO (mg/L)	-.837	.457	.261	.148
PAH (µg/g)	.682	-.074	-.692	.226
DOC (µM)	-.635	-.696	.181	.282
POC (µM)	.491	.745	-.449	-.049
NO3 (µM)	.793	-.456	-.319	.245
NH4 (µM)	-.577	.784	.218	-.074
UREA (µM)	.465	.303	-.821	-.134
Org-C%	.334	.696	.489	.406
Org-N%	.401	.822	.362	.178
%sand	-.965	-.118	-.221	-.082
% Silt	.676	-.496	.349	.419
% Clay	.963	.014	.215	.163
POC_µg/L	.912	-.120	-.261	-.293
PON_µg/L	.546	-.590	.094	-.587
C/N	.489	-.814	.311	-.039
TSPM_mg/L	.171	.021	.775	-.608
Chl a at bottom	.681	.699	.101	-.193
Fe	.983	-.080	.139	.086
Cr	.971	-.033	.218	.095
Sn	.975	-.062	.206	-.061
Be	.981	-.020	.163	.104

III.5. Discussion

III.5.1. The canyon habitat

The high abundance of tubicolous ampeliscid amphipods at the canyon's head is evidence for organic enrichment. It is a consistent theme that the high densities of benthic organisms are associated with high input of labile organic carbon (Vetter, 1994; Boetius et al., 2000; Vetter and Dayton, 1998; Brown et al., 2001; Aller et al, 2002). Canyons have complex structure that funnel and concentrate the organic debris, and thus they can be sites of enhanced secondary production if not hotspots for benthic communities (Rowe et al., 1982; Gage and Tyler, 1991; McHugh et al., 1992; Gage et al., 1995; Vetter, 1998; Vetter and Dayton, 1998, Metaxas and Giffin, 2004). Our values of amphipod abundances in the canyon were high in comparison with comparable depths in the Mediterranean Sea (Cartes and Sorbe, 1999), but similar to densities of benthic organisms on comparable depths in southern California (about 12,900 ind.m^{-2}) (Vetter and Dayton, 1998, Vetter, 1998). Some canyons however show no signs of enhanced densities (Houston and Haedrich, 1984; Marquiegui and Sorbe, 1999). Low abundance can be due geological instability "activity" of the canyon where the continuous flushing of sediment prevents recruitment (Rowe et al., 1982).)

The peculiar combination of conditions at the canyon head allows the dominant *A. mississippiana* to out-compete other small invertebrates for food and space. However, there is no explanation for why only *A. mississippiana* is dominant among two closely related tube dwellers. Several studies have found distinctive fauna in canyons (Rowe, 1971; Ohata, 1983; Buscail et al., 1990; Marquiegui and Sorbe, 1999) with numerically dominant species, presumably associated with the canyon's organic enrichment.

Although sediment organic carbon in the head of the Mississippi Canyon was not particularly high (Table 3.5), organic detritus may enter the bottom water as a flow and stay suspended due to physical mechanisms. The current in the bottom water of the Mississippi Canyon is about 0.25 m/sec (Burden, 1999) and may re-suspended the organic materials and carry them to the tubes of the benthic amphipods. Ampeliscids and ischyrocerid amphipods characteristic of the canyon's head are known to be weakly motile if not sedentary and feed on particulate matter suspended from the water column or advected materials (Mills, 1967; Gili and Coma, 1998; Nyssen et al 2002).

The organic flux in the Mississippi Canyon appears to be coming from combination of vertical flux and horizontal flux of particulate suspended matter. The calculated chlorophyll flux from the surface water was highly correlated with the faunal abundance and may be contributing to such high faunal abundance at the canyon's head. However, there may be a significant lateral transport of organic matter from the continental shelf. Lateral transport of low salinity and high chlorophyll water to the slope has been attributed to eddies of the Loop Current (Qian et al, 2003). The flow from the Mississippi River may interact with the canyon's topography to enhance POM flux over the canyon's head leading to buildup of suspended matter in the trough which creates a hotspot for secondary production (Baguley et al, 2006 a,b).

III.5.2. Zonation pattern in amphipods

The apparent zonation in families of the amphipods in our study may reflect their feeding guilds. Tube building Ampeliscidae, which are suspension feeders, exhibited very limited bathymetric range at the canyon's head, while deposit feeding ampeliscids were abundant at the deeper depths of the canyon and in the slope adjacent to the canyon. The Melitidae and Aoridae, which are deposit feeders, were mainly abundant at intermediate depths. The Eusiridae, Pardaliscidae are suprabenthic amphipods which have high to intermediate mobility (Cartes and Sorbe, 1999) and are mostly predators (Nyssen et al, 2002), were only abundant at the lower slope depths in the non-canyon transect.

III.5.3. Diversity pattern in amphipods

Competitive exclusion could be at its highest at the head of the Mississippi canyon due to the enhanced food availability, which leads to the dominance by a few species. On the other hand, the food availability decreases with depth, enhancing biological diversity (Dayton and Hessler, 1972). Levin et al (2001) found that diversity within a functional group increases from regions of low to moderate productivity, and then declines toward regions of higher productivity. The high input of POC at the canyon's head may accelerate competitive exclusion (Huston, 1979), while the low flux of organic carbon in the lower slope depths support low population densities that depress biodiversity (Rex 1973). The depth of maximum richness was comparable to that reported by Cartes and Sorbe (1999) for the Mediterranean amphipods. However this depth has been much shallower than what is observed by Rex (1983) for other faunal groups.

Water current of about 25 cm/sec in the bottom water of the Mississippi Canyon may be behind the reduced diversity. Levin et al. (2001) stated that a near-bottom current exceeding 20–25 cm/sec, can depress diversity either by eroding epifaunal species or by smoothing out and reducing physical heterogeneity. A highly energetic environment promotes dominance and depresses biodiversity (Paterson and Lambshead, 1995; Gage, 1997). The observed diversity pattern was reported for other faunal groups (Rex, 1981, 1983, Rex et al, 1997; Allen and Sanders, 1996).

According to the stress predictability model (Alcolado, 1992), the head of the canyon is a stressful environment having the least diversity and evenness. Although a deep water station (C14) is represented in the third group with MT1, it can be differentiated by having high species evenness (Fig.3.16).

III.5.4. Assessment of the “health” of the canyon

Several faunal parameters imply that the canyon is highly stressed. These included high dominance, low diversity and species indicators for the stressed environment. In addition PAHs are bioenhanced by dominant ampeliscids (Soliman and Wade, In press). *Ampelisca abdita* is listed among the few tolerant species (capitillids and spinoid polychates) that can survive in organically enriched environments. Dense ampeliscid mats are found to be associated with chronic anthropogenic disturbance (Rhoads et al., 1978). The tubes enable them to obtain oxygen above the water-sediment interface (Gallagher & Keay, 1998). Aller (1982) found that the tubes of the ampeliscids are not only defensive against predators, but they also protect the ampeliscids against the inward diffusion of toxic anions. He considered the ampeliscids as early colonists that aerate and detoxify organically enriched sediments. In this study, the highest concentrations of PAHs as well as several anthropogenic trace metals were found at the head of the canyon coincident with the high abundance of ampeliscids (Soliman and Wade, in press). Constant physical disturbance of the sediment ensures that the benthic fauna remains in an early successional state favoring dominancy of opportunists (Levin et al, 2001). The ampeliscid bed is apparently an indicator for a stressed environment. Future research is needed to monitor changes in the structure and pollution level in such an unpredictable spot at the canyon's head.

CHAPTER IV

SECONDARY PRODUCTION OF *AMPELISCA MISSISSIPPIANA* (SOLIMAN AND WICKSTEN 2007), (AMPHIPODA, CRUSTACEA) IN THE HEAD OF THE MISSISSIPPI CANYON, NORTHERN GULF OF MEXICO*

Annual production was calculated for the ampeliscid amphipod *Ampelisca mississippiana* (Soliman and Wicksten, 2007) that dominates the benthic c^{3}ommunity at the head of the Mississippi Canyon at a depth of approximately 450 to 500 m, in the northern Gulf of Mexico. Average densities were 12,094 ± 2,499 Ind m^{-2}, with secondary production of 6.93 g dry wt m^{-2} (corresponding to estimated univoltine generation based on a regression model), based on the Hynes-Hamilton and Coleman (1968) method modified by Menzies (1980). The production/biomass ratio (P/B) was in the range of 3.11. Growth rates of this magnitude are comparable to available data for freshwater and shallow marine ampeliscids, but are unexpectedly high for deep ocean habitats, especially the depauperate northern Gulf of Mexico.

IV.1. Introduction

Secondary production is the rate at which energy or organic carbon is incorporated into living mass by heterotrophic organisms per unit area over time. It is an important measure for demodulating the functioning of any ecosystem because it quantifies the transmission of energy from one trophic level to the next in food webs

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* Submitted to Deep-Sea research II. Yousria Soliman and Gilbert Rowe, 2007.

(Waters 1977, Downing 1984, Benke 1984 & Benke 1993). It can be one of the most comprehensive assessments of ecosystem integrity (Buffagni & Comin 2000, Dolbeth et al, 2005), and is thus a valuable tool in evaluating the effects of man-induced stress.

A surprising finding in recent DGOMB surveys (Rowe et al., 2007) was a mat of a previously undescribed ampeliscid amphipod crustacean which dominated the fauna at the head of the Mississippi Canyon. The new ampeliscid (*Ampelisca mississippiana* Soliman and Wicksten 2006) can constitute over 90% of the macrofauna, with densities exceeding 26,000 ind m^{-2} in some boxcores. Because of their dominance, their secondary production could account for most of the macrofaunal production. Growth rates are rarely measured in deep benthic food webs because replication is difficult and the sparse fauna is usually highly diverse (Gage, 1992). The high densities of this single species have provided a rare opportunity to quantify this important variable at this unique site.

Secondary production of marine invertebrates is calculated either by measuring growth and mortality of identifiable cohorts (Benke, 1984) or by measuring the loss of biomass by size–frequency classes (Hynes-Hamilton and Coleman 1968; Hamilton, 1969; Benke, 1979; Menzies, 1980). Due to the difficulties of sampling deep water sediments, monthly and even seasonal sampling is rarely possible. The size –frequency method is preferable when cohorts can not be followed over time. Empirical models (Morin and Bourassa 1992, Tumbiolo and Downing 1994, Brey et al. 2001, Cartes et al. 2002, and others) based on relationships between population and environmental parameters have also been used alternatively to estimate the secondary production.

The objectives of this study were to estimate secondary production of the dominant benthic invertebrate population, *A. mississippiana*, using size frequency analysis, as well as multiple linear regression (MLR) models, and to compare these measures to other macrofaunal populations from different habitats. The resulting estimates can then be used in community food web budgets (Rowe et al., this volume) and analysis of potential contaminant concentration and transfer up the food web (Soliman and Wade, this volume).

IV.2. Study area

The Mississippi Canyon, located in the Northern Gulf of Mexico (28º 32' N, 89º 49' W, Fig. 4.1), is a prominent morphological feature directly adjacent to the Mississippi River delta (Balsam and Beeson, 2003). The trough-like feature is a conduit for sediment and organic materials transported by the Mississippi River and the surrounding coastal zone, by-passing the continental shelf, which is truncated in this location. Offshore oil and gas operations in and near the Mississippi Canyon may be a source of PAHs from drilling mud and produced water, or oil seepage may be present, in addition to river-borne, land-derived materials.

IV.3. Material and methods

The sampling station is located at the head of the Mississippi Canyon (480m depth). Amphipods were sampled annually or biannually from 2000-2004 from the head of the canyon (MT1) (Fig. 4.1) using a 0.2 m^{-2} version of the GOMEX or Gray-O‘Hara boxcore (Boland and Rowe, 1991) deployed from the R.V. Gyre. Up to five replicates were taken on each visit, for a total of 14 total cores over the course of the study.

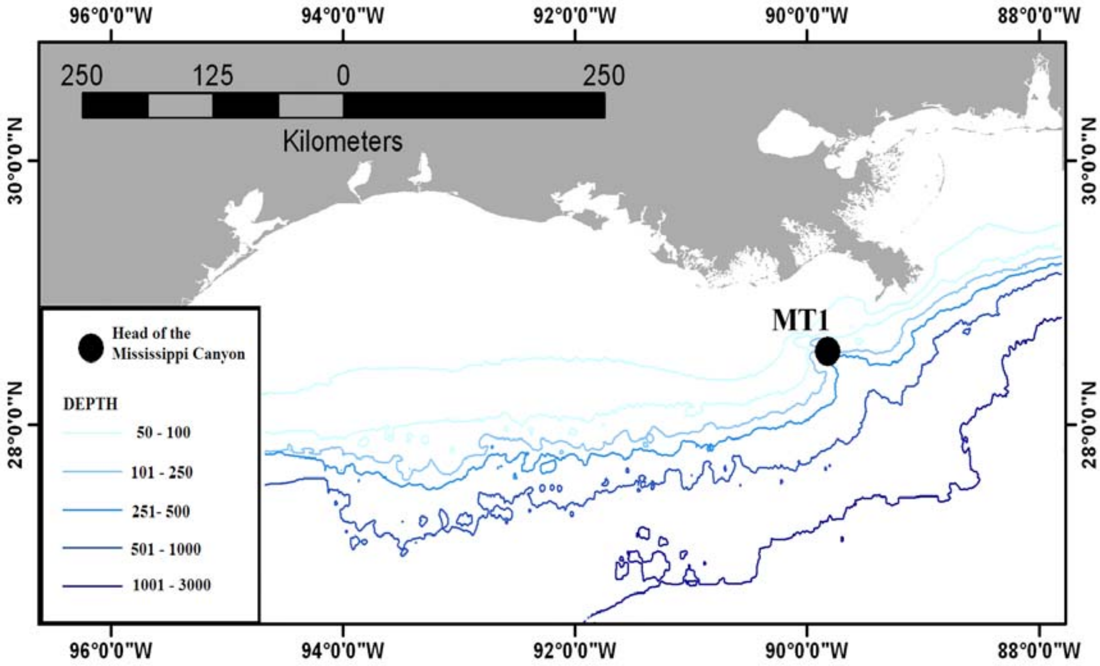

Fig. 4.1. Map showing the location of the head of the Mississippi Canyon, Northern Gulf of Mexico.

The overlying water and the top 15 cm of the surface sediment of each box core were sieved through 300 micrometer sieves. The samples were fixed in 10% formalin with filtered sea water. Rose Bengal was used to stain living material, followed by sorting in the lab using a dissecting microscope. Following separation from the remaining mud, the specimens were permanently preserved in 70 % ethyl alcohol.

Subsamples were taken from each sample (ca. 450 individuals) for length measurements using a calibrated ocular micrometer. The length of each individual ampeliscid was measured from the tip of the rostrum to the base of the telson (Bousfield, 1973). The individuals were separated into nine presumed "age" groups, based on length. Sub-samples from the frozen samples (not alcohol preserved) were used for wet weight measurements. The wet weights of only four of the nine age groups were determined and then dried at 60 ºC for four hours or to a constant weight to determine dry weight biomass per individual. A regression model is then developed and used to predict the weight of the other length groups.

Annual secondary production was estimated by several different complementing methods:

1.1. The "size frequency" method (the average cohort method, SFM) or Hynes method (Hynes-Hamilton and Coleman 1968; Menzies, 1980). This calculation of production involves measuring the loss of biomass between the successive size intervals. This method is based on dividing the population into size classes. It assumes that the sample contains an 'average cohort', which represents the mean size distribution of animals over a year, and production is estimated as the sum of losses between successive size classes (Waters, 1979). This method does not require the discrimination of cohorts over time and can thus be used whenever the cohorts cannot be monitored over time.

$$P = \mathrm{a}\ [\ \textstyle\sum_{\mathrm{i}} (N_j - N_{j+1})\ (w_j w_{j+1})^{0.5}]\ 12/\mathrm{CPI}$$

where i is the number of size classes, dj is the mean density in the j size class (ind./m^2), wj the mean individual weight in j size class (dry weight, mg), and j and j + 1 the consecutive size classes (j = 1, 2,…, a), and CPI the cohort production interval (mean life span in months). Because in deep water studies, monthly or even seasonal sampling is difficult and costly, we constructed a regression model for the temperatures and the average number of generations per year for ampeliscids from different geographic locations (See table 4.5). Biomass of age groups of *A. mississippiana* was measured directly and from the relationship between the body weight as mg dry wt and the body length (mm) which was cubic $W = 0.0078L^{2.4238}$, $R^2 = 0.99$, $P<0.05$. The estimates from the size frequency method are compared with multiple linear regression models commonly used in the calculation of secondary production.

1.2. Seven empirical models were used to calculate the production and P/B ratio, two for marine invertebrates (Brey, 2001; Tumbiolo and Downing, 1994), three for marine benthic/suprabenthic crustaceans (Cartes et al, 2002), and Four for fresh water species (Plante and Downing 1989; Morin and Bourassa 1992). The results of these models were compared with result of size frequency method.

a) Brey's P/B-Model (Brey, 1999; 2001):

$$\text{Log (P/B)} = 7.947 - 2.294 \log(M) - 2409.856 * 1/(T+273) + 0.168 * 1/Z + 0.194(\text{Subt}) + 0.180(\text{In-Epi}) + 0.277(\text{ME}) + 0.174(\text{Taxon1}) - 0.188(\text{Taxon2}) + 0.330(\text{Taxon3}) - 0.062(\text{H}) + 582.851 * \log(M) * 1/(T+273)$$

Where, M is Body mass (KJ), T is water temperature °C, Z is water depth and the other variables are qualitative(0,1): Subt, subtidal species; In-Epi, infaunal–epifaunal species; ME,motile fauna; Taxon1, Polychaeta or Crustacea; Taxon2, Echinodermata; Taxon3, Insecta; H, lake habitat. Conversion from mg dry weight to KJ is performed assuming 16.775 Joule/mg DW (mean Ampelisca caloric equivalent using data bank conversion in Brey (2001) electronic book that was comparable to value of Dauvin and Joncourt, (1989).

b) Cartes et al models (2002):

Two models are used to predict the P/B ratio (MLR1, MLR2), and one model predicts secondary production for benthic crustaceans (MLR3).

i. $\log P/B = 0.103 + 0.036T - 0.186 \log M$

ii. $\log P/B = 0.349 - 0.203 \log M + 0.020T + 0.362Scap - 0.119 \log Z$

iii. $\log P = 0.155 + 0.985 \log B - 0.269 \log M + 0.028T$

where B = mean annual biomass, M = mean individual mass (= B/D), D = mean annual density; T is the water temperature °C; and Scap, swimming capacity, is a qualitative evaluation (0,1).

c) Tumbiolo and Downing (1994) model:

$\log P\ (\text{g dry wt m}^{-2}\ \text{y}^{-1}) = 0.240 + 0.960\ \log B -0.21 \log M_{max} +0.030T - 0.160 \log (Z + 1)$

where, B is the ampeliscid biomass in g dry.m^{-2}; and M_{max} is the maximum mean ampeliscid weight (mg dry wt); T is average water temperature in ºC; and Z is depth in meters.

d) Morin and Bourassa model (1992):

$$\log_{10} P= -0.75+ 1.01 \log_{10} B - 0.34 \log_{10} M + 0.037T$$

where, B = mean annual biomass, M = mean individual mass (= B/D), D = mean annual density, and T is the water temperature °C.

e) Plante & Downing (1989) model:

$$\log P\ (\text{g dry wt m}^{-2}\ \text{y}^{-1}) = 0.06 + 0.79\ \log(B) - 0.16\ \log(M_{max}) + 0.005\ T$$

where; B is the ampeliscid biomass in g dry wt m^{-2}; M_{max} is the maximum ampeliscid weight (mg dry wt); and T is average water temperature in ºC.

IV.4. Results

Among 18 taxa recorded from the head of the Mississippi Canyon (Fig 4.1, MT1), amphipods were the dominant faunal group, representing about 75% of the total recorded macro- invertebrates (Fig. 4.2). Among the amphipods, *A. mississippiana* was the dominant (>90 %). The surface of the sediment was carpeted by its soft membranous tubes that were evident on the surface of most box cores and throughout numerous bottom photographs taken at the site. The substrate is mostly muddy (65% Clay) and the average temperature is 8.3 C, (see table 4.1 for other environmental parameters at MT1). The average density (Table 4.2) was 12,094±2,499 ind. m^{-2}, which was higher than any other group at any continental slope site sampled from Mexico to Florida (Wei et al., 2007). The average number was highest in 2000 (avg. 15,571 $ind.m^{-2}$) and decreased to an apparent minimum in 2002 (9,614 $ind.m^{-2}$) (Fig. 4.3), although these differences were not statistically significant. The biomass followed the same pattern (Table 4.2), with the means ranging from 3.04 g dry wt m^{-2} on the first survey down to 1.84 g dry wt m^{-2} on the 3rd set of samples. The mean biomass was 2.32 (±0.44) g dry wt m^{-2}, providing a mean mass of 0.19 mg dry wt per individual. This would be equivalent to 0.073 mg C per individual, assuming that organic matter is 40% carbon (Rowe 1983).

A. mississippiana is univoltine based on a linear regression model between the temperatures and the ampeliscids' number of generation ($R^2 = 0.425$, d.f= 13, P=0.008) (Fig.4.4). For a cohort production interval (CPI) of 12 months (corresponding to the estimated one generation per year), the annual production is estimated to be 6.93 g dry wt $m^{-2}.y^{-1}$ (Table 4.3). This would be equivalent to approximately 7.595 mg carbon m^{-2} day^{-1}, assuming that the dry weight is 40% carbon (Rowe 1983). Thus the ratio of the annual production to the average biomass (*P/B* ratio) was 3.11 (Table 4.4). The rate of annual secondary production based on the regressions of biological and environmental information (Fig. 4.5) ranged from just less than 5 to about 15 g dry wt m^{-2}, with a mean of 7.98 (±3.29, n=7) g dry wt m^{-2}. The P/B ranged from 2.22 to 6.7, with a mean of 3.61 (±1.45, n=7) (Table 4.4). There is no statistical evidence that the regression methods we utilized for our population at the MT1 site are different as a whole from the SFM method.

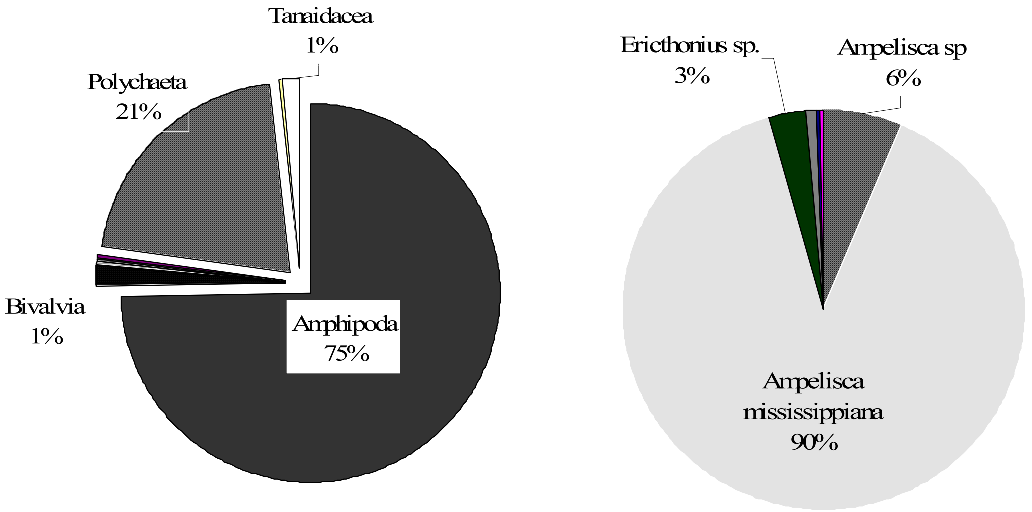

Fig. 4.2. Percentage composition of the total macrofauna and gammaridian amphipods at MT1 (480 m).

Table 4.1. Average values for eighteen environmental parameters measured at the head of the Mississippi canyon at which this study is based (2000-2002).

Parameter	**MT1**	**Parameter**	**MT1**
Depth (km)	0.481	Org-C%	1.135
Temperature	8.3	Org-N%	0.161
DO (mg/L)	2.5	% Sand	2.0
Chla (mg/m3)	2.470	% Silt	33.0
PAH (µg/g)	526.5	% Clay	65.0
DOC (mM)	0.953	POC_µg/L	38.3
POC (µM)	6.10	PON_µg/L	2.550
NO3 (µM	12.40	TSPM_mg/L	0.164
NH4 (µM)	27.50	UREA (µM)	4.40

Table 4.2. Cruise, site and faunal data on which this study is based.

Year	**Locations**	**Depth**	**No of ampeliscid amphipods**	**Average ind.m^{-2}**	**Biomass Dry wt g.m^{-2}**
Cruise-1 2000	MT1-1	480	1650	15571	3.04
	MT1-2	482	791		
	MT1-3	482	3985		
	MT1-4	481	4076		
	MT1-5	481	2968		
Cruise-2 2001	MT1-2	490	1806	11577	2.20
	MT1-3	485	2174		
	MT1-4	480	1506		
	MT1-5	478	2512		
Cruise-3 2002	MT1-2	465	767	9614	1.84
	MT1-4	465	2550		
Cruise-4 2004	MT1-1	485		11613	2.21
	MT1-2				
	MT1-3				

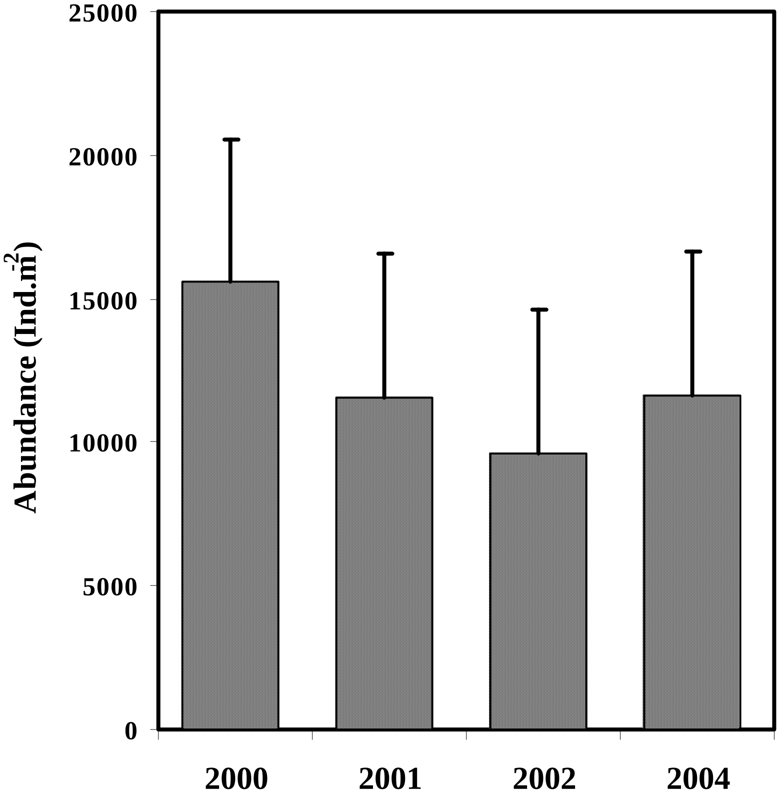

Fig. 4.3. Mean annual abundance and production of *Ampelisca mississippiana* Soliman and Wicksten 2006 in the head of Mississippi Canyon based on four summer cruises from June 2000 to August 2004. Error bars represent standard deviation around the mean of five replicate 0.17 m^{-2} box cores.

Table 4.3. Secondary production for a population of the ampeliscid amphipod *A. mississippiana* at the head of Mississippi Canyon (480m) from June 2000 through August 2004. Negative values dropped.

Size Intervals (mm)	Ind m^{-2}	Dry wt/ind (mg)	standing stock (mg ww.m-2)	standing stock (mg m^{-2})	Number lost	Wt loss	Total wt lost	Number of size classes	Production (mg dry wt m^{-2}-$year^{-1}$)
2.00	962	0.04	307.2	38.5					
2.50	2861	0.07	1544.9	200.3	-1899.0	0.1	-104.4	9.0	-940.0
3.00	1613	0.12	1747.4	193.6	1248.0	0.1	118.6	9.0	1067.0
3.50	1899	0.14	2307.3	265.9	-286.0	0.1	-37.2	9.0	-334.6
4.00	1040	0.24	1549.6	249.6	859.0	0.2	163.2	9.0	1468.9
4.50	1795	0.27	3006.6	484.7	-755.0	0.3	-192.5	9.0	-1732.7
5.00	1118	0.36	2515.5	402.5	677.0	0.3	213.3	9.0	1919.3
5.50	702	0.46	1625.1	322.9	416.0	0.4	170.6	9.0	1535.0
6.00	104	0.56	256.9	58.2	598.0	0.5	305.0	9.0	2744.8
	0	0.00	0.0	0.0	104.0	0.3	29.1	9.0	262.1
∑	12,094		14,860.96	2,216					6.93

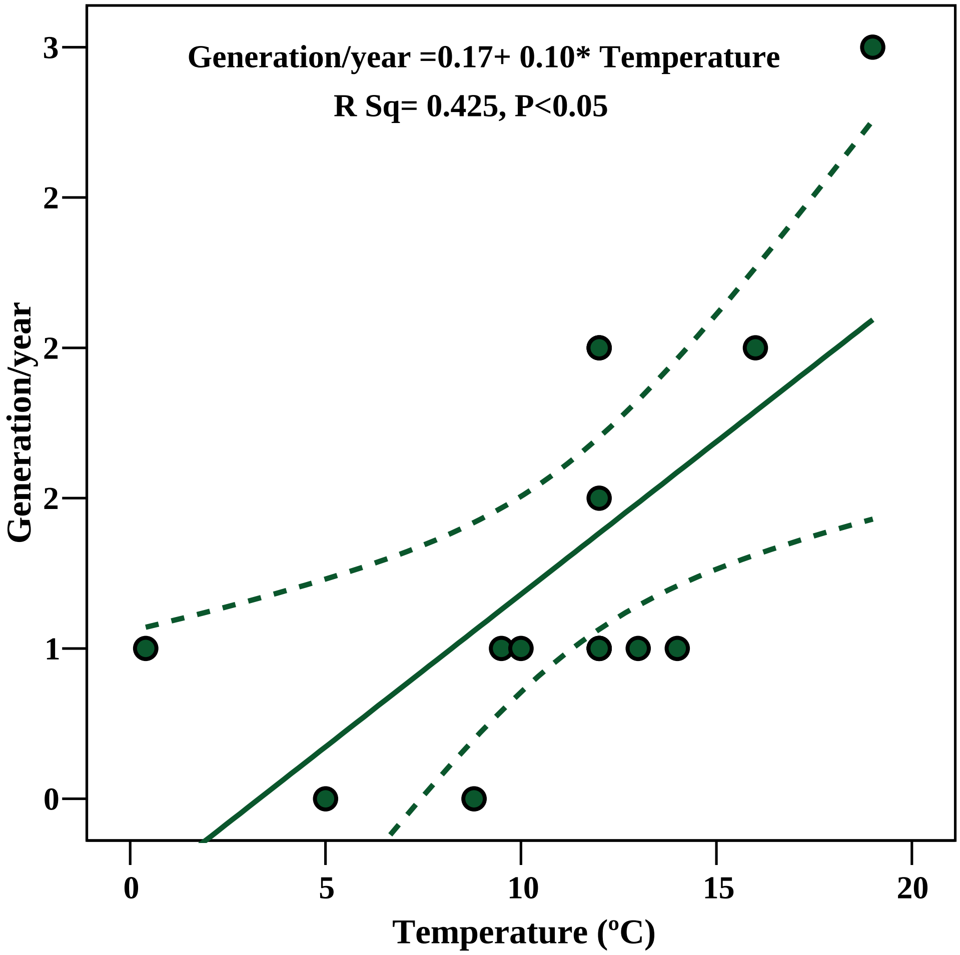

Fig. 4.4. Generations /year vs. the temperature of ampeliscid amphipods. The fitted equation explains 41% of the variability in number of generations.

Table 4.4. Secondary production and P/B ratio based on the size frequency method and different linear regression models.

Method	P	P/B
Size Frequency (based on univoltine assumption)	6.93	3.13
Brey (2001)	6.78	3.06
Cartes et al, 2002 –LRM1	7.42	3.46
Cartes et al, 2002 –LRM2	4.88	2.22
Cartes et al, 2002 –LRM3	8.44	3.80
Tumbiolo and Downing (1994)	7.16	3.23
Morin and Bourassa (1992)	15.028	6.7
Plante & Downing (1989)	6.14	2.77

IV.5. Discussion

The ampeliscid bed at the canyon head is one of the densest Ampelisca beds reported from different geographic areas. It is the first record for dense ampeliscid population from deep water. The average annual density of 12,904 ind.m^{-2} was comparable to densities of shallow water ampeliscid populations such as *A. armoricana*, and *A. araucana* (12,121& 11,280 ind.m^{-2}, respectively) (Dauvin, 1989; Carrasco & Arcos, 1984). The size frequency method (SFM) of estimating secondary production is presumed to be a reasonable substitute for the cohort method (Cartes et al. 2002) but requires independent knowledge of the cohort production interval (CPI). Our sampling was not frequent enough to define the growth of cohorts in time. However, Generations/year-temperature regression model could predict the number of generations per year to be 1 generation (corresponds to CPI=12 month). In ampeliscids, the life span

(3 to 36 months) and the number of generations per year (0.5 to 2) are variable, mostly associated with water temperature (Sainte-Marie, 1991). Our samples were taken from a depth of 480 m with about stable temperature of 8.3 ºC. Cold water ampeliscids (2-8 ºC) used to have longer life (24-30 months) and fewer generations (0.5-1) (Wildish, 1984). Sainte-Marie, (1991) suggested that deep-sea amphipods would be similar to high latitude species in having univoltinism, the same reproductive strategy. Our samples were always taken in late spring, or early summer; however, we make the assumption that the estimates of the mean biomass are reasonable (Morin et al., 1987), because samples were characterized by both adults and juveniles. Generally, it has been assumed that inter-annual variations in biomass and production can be more pronounced in shallow-water populations (Rachor et al., 1982).

The SFM estimates of both production and P/B fell in the middle of the estimates based on population and environmental regressions, as has been demonstrated previously for the macrofauna (Cartes et al. 2002). This supports the validity of our estimates, although the validity of these two different approaches in this case needs to be confirmed using the more widely accepted “cohort (CPI) interval” method.

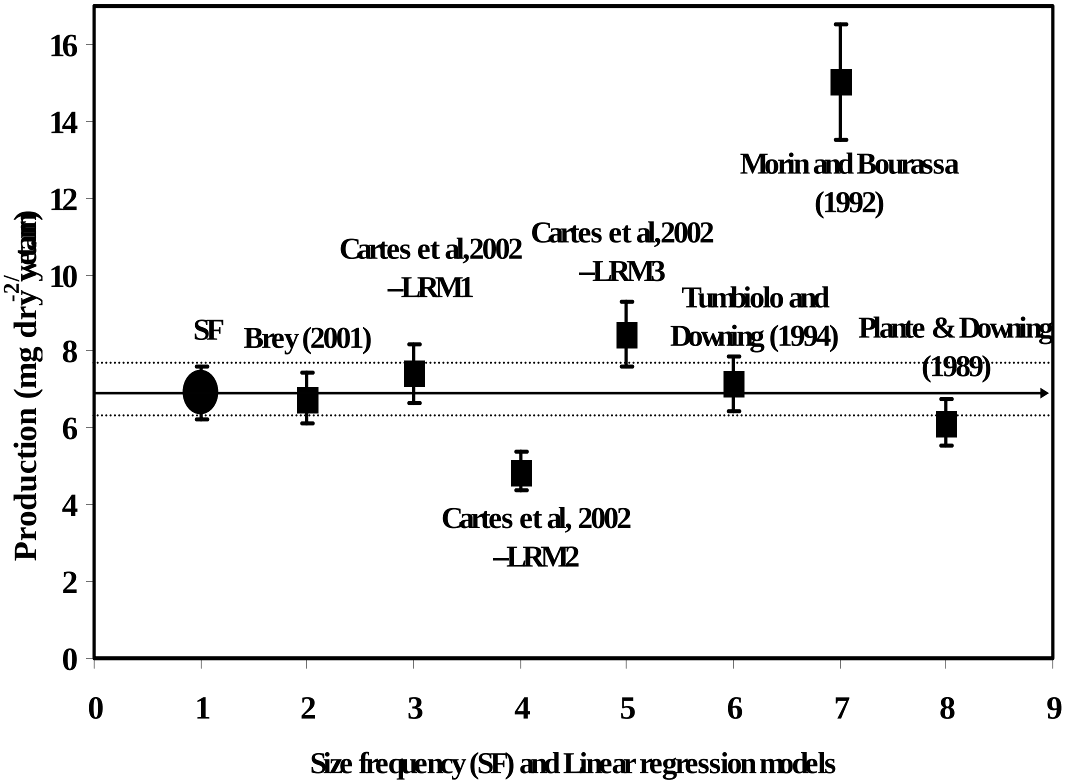

Fig. 4.5. Comparison between the production estimates (a) and P/B ratio (b) using the size frequency method and different empirical models.

Submarine canyons are intermittent, sometimes deep indentations into most ocean margins. Some are known to trap organic detritus and thus can be sites of enhanced secondary production by the benthic macrofauna (Rowe et al., 1982; Gage and Tyler, 1991; McHugh et al., 1992; Gage et al., 1995; Vetter, 1998; Vetter and Dayton, 1998, Metaxas and Giffin, 2004). The production estimate, along with the *P/B*, at the head of the Mississippi Canyon suggest that this environment is a highly productive system, compared to other locations in the Gulf of Mexico. However, this rate is not particularly high compared with some canyons elsewhere. For example, a southern California submarine canyon dominated by dense populations of leptostracan crustaceans ($3.5 * 10^6$ m^{-2}) was characterized by substantially higher production (at least 881 g dry wt m^{-2}. yr^{-1} and P/B=6.1; Vetter, 1998). This production is approximately 100 times the MT1 value we derived. On the other hand, our value was not substantially different from that at comparable depths in the Mediterranean Sea (range 0.13 to 9.0 mg dry wt m^{-2}. yr^{-1}), with a P/B ratio of 1.6-12.6 (Cartes and Sorbe, 1999). Our estimate of 6.9 g dry wt. m^{-2} y^{-1} (equivalent to approximately 2.76 g C $m^{-2}.y^{-1}$) is comparable to that at equivalent depths off Chile (range 0.83- 6.8 g C.$m^{-2}.y^{-1}$)(Quiroga et al, 2005). The regression method illustrates that the variation in the life histories and the mean body masses between the benthic groups are sometimes more important than environmental variability in explaining differences in production and P/B ratios (Cusson & Bourget, 2005).

The population under study exhibits a production that is higher than many other ampeliscid amphipods documented in the literature (Table 4.5). On the other hand, Table 5 illustrates that the P/B ratio is not different from other species. The reason for this disparity lies in the differences in population densities: the greater the density and biomass, the greater the production, given similar population turnover rates.

Table 4.5. Comparison between the secondary production of *A. mississippiana* and other ampeliscid populations.

Species	**Source**	**Location**	**Depth**	**G (Y^{-1})**	**Production**	**P/B**
Ampelisca abdita	Franz and Tanacredi, 1992	Jamaica Bay, USA	1-10	2	10-26	3.53-4.16
Ampelisca agassizi	Collie, 1985	Goerges Bank	69-84	0.5	2.2	1.5
Ampelisca araucana	Carasco and Arcos, 1984	Chile	65	2	8.03-12.43	3.65-4.45
Ampelisca armoricana	Dauvin 1988c	English Channel	17	1	10.376-0.12*	1.76-2.74
Ampelisca brevicornis	Dauvin 1988a	English Channel	4-17	1.5	0.043-0.491	2.15-2.8
Ampelisca brevicornis	Klein et al. 1975	North Sea	28	1	0.122-0.253[a]	3.14-4.8
Ampelisca brevicornis	Hasting, 1981	Isle of Man		1	1.31-1.68	2.49-3.21
Ampelisca macrocephala	Highsmith and Coyle 1990	Bering Sea	30-35		30-40	1.0
Ampelisca sarsi	Dauvin 1989	English Channel	17	1	0.016-1.029	1.93-2.99
Ampelisca tenuicornis	Dauvin 1988	English Channel	4-17	2	0.699-1.683	3.12-4.20
Ampelisca typica	Dauvin 1988b	English Channel	17	2	0.073 – 0.160	4.06-4.36
Byblis japonicus	Sudo and Azeta 1996	Shijiki Bay, Japan	10	3	7.53	10.83
A. mississippiana	Present Study	N.Gulf of Mexico	480	0.5-1	7.5 – 3.3	3.24 – 1.43

* values recorded 7 years after *Caldiz* oil spill.

a: Values based on wet weight

The *A. mississippiana* population production is high because it dominates the community so overwhelmingly. We presume that the peculiar combination of conditions allows it to out-compete other small invertebrates for food and space, while at the same time somehow being somewhat protected from competitors. It has been suggested, for example, that the tubes of ampeliscids provide protection against predation, especially the juveniles, as well as increase the physical stability of soft fine-grained sediment (Woodin, 1976; Gage and Tyler, 1991). The sediment organic carbon in the head of the Mississippi Canyon is not particularly high (TOC <1%, Morse and Beazley, this volume). However, the rate at which detritus enters the near-bottom suspended matter load may be important, even if the concentration of organics is modest. It has been demonstrated elsewhere that physical mechanisms resuspend particulate matter in abrupt topography of submarine canyons due to focusing of tidal flow (Gardner, 1989). Detritus available to the canyon benthos may arrive as flow along the floor. Ampeliscid amphipods are known to be suspension-deposit feeders (Mills, 1967), that can capture suspended particulates by developing dense, three-dimensional communities whose structural complexity depends on flow speed (Gili and Coma, 1998). This trough, swept with high suspensions of detritus of low organic content, may be a poor environment for all but these ampeliscids.

The rate of carbon cycling by the entire community at this same location (MT1) has been estimated by measuring oxygen uptake by the bottom sediment community using incubations of whole sediments and the overlying water. The sediment community oxygen consumption (SCOC) has been estimated to result in the recycling of 36.5 mg C m^{-2} day^{-1}, $\sigma(n)=15.1$, (Rowe et al., this volume). Thus the estimate of macrofauna secondary production, on a daily basis (7.59 mg C m^{-2} day^{-1}), is approximately 1/4 of the estimated carbon turnover by the respiration of the entire community (bacteria, meiofauna and macrofauna). Estimates of secondary production have rarely if ever been conducted at the same site where SCOC has been measured, and the data here might imply either the SCOC measurement is underestimated or the production estimate is too high. This apparent disparity will only be resolved with further sampling that allows cohort growth to be defined over time or improved SCOC measurements.

A more comprehensive characterization of the population dynamics of *A. mississippiana* is the following equation:

d[N]/dt = food ingestion – loss to feces – loss to respiration – gonad production – mortality(= predation) – emigration (or + immigration),

where N is some unit of population size in terms of organic mass. Mortality is usually assumed to be a function of predation. The elements of this equation can be used in a comparison of the secondary production of *A. mississippiana* calculated in this paper. The comparison can also be extended to what is known, or at least inferred, about other aspects of the entire benthic community located in the head of the Mississippi Canyon. An important component of such equations is respiration. We did not conduct respiration rate measurements on *A. mississippiana*, but sediment community incubations conducted at the site (Rowe et al., this issue) indicated that community oxygen consumption (SCOC) was 36.5 mg C m^{-2} day^{-1} (std. dev.=15.1, n = 4). The fraction of this total attributed to *A. mississippiana* can be estimated using an allometric model for the rate of similar taxa, based on size and temperature (Mahaut et al. 1995). At ca. 10 ºC, with a biomass of ca. 912 mg C m^{-2}, the mean respiration for the population, based on respiration constants in Mahaut et al.1995, would be ca. 12.5 mg C $m^{-2}day^{-1}$, or 1/3 of the total for the community (macroauna, meiofauna and bacteria). This compares reasonably well with our estimate of secondary production. With a P/B ratio of ca. 3.5, the production expected from a stock size of 912 mg C m^{-2} would be 3192 mg C m^{-2} $year^{-1}$, or ca. 9 mg C m^{-2} day^{-1} (Fig. 4.6). This suggests that the growth efficiency of *A. mississippiana* is approximately [9/ (9 + 12.5)] x 100 = 41% (=secondary production in carbon/total assimilated carbon). The production of 9 is assumed to be balanced at steady state with a combination of mortality (=predation, or transfer to a higher level in the food web) and gonad production that is transferred to new cohorts. Although brooding eggs were observed occasionally in the population, we were not able to differentiate this component of the budget from other losses. We assume, in this over-simplified budget, that emigration and immigration are zero. This analysis suggests that our estimate of secondary production is not unreasonable. It is probably not higher than our estimate, but on the other hand it probably is not more than a factor of two lower than our estimate. This indirect estimate of possible error is about the same as that using the different generation time estimates.

Ampeliscids transfer carbon and energy to higher-level consumers (Mills, 1967; Sudo and Azeta, 1996; Dauvin, 1988, 1989), including demersal fishes (Collei, 1985, 1987; Franz and Tanacredi, 1992; Carlson et al, 1997; González and Oyarzún, 2004), and gray whales (Nerini & Oliver, 1983; Kaiser and Spencer, 1994, Dunham and Duffus, 2002, Highsmith et al, 2005). For example, *A. abdita* represented 88% of the food of the winter flounder in Jamaica Bay. The disappearance of amphipods may reduce bottom-feeding fish populations (Franz and Tanacredi, 1992). We have no direct evidence so far that the dense population of ampeliscid amphipods in the Mississippi Canyon plays an important role in the food chain; however, Powell et al. (2003) found the demersal fish were most abundant in the Mississippi and the Desoto Canyons in a survey over the entire northern continental slope.

Although there now are a number of estimates for the secondary production for some deep-sea macrofaunal groups on continental slopes, up to depths of several km’s (Quiroga et al. 2005, Cartes et al. 2000, 2002; Cartes and Sorbe 1999, Brey and Gerdes, 1998), there is still scant information on growth rates and secondary production in general among deep-sea organisms (Rowe 1983, Gage 1992).

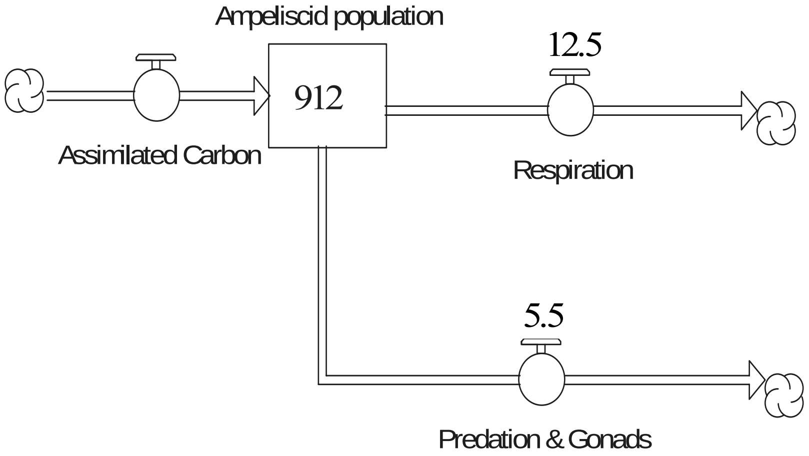

Fig. 4.6. Flow chart showing the carbon flow in the *A. mississippiana* population.

CHAPTER V

ESTIMATES OF PAHS BURDENS IN A POPULATION OF AMPELISCID AMPHIPODS CARPETING THE HEAD OF THE MISSISSIPPI CANYON (N. GULF OF MEXICO)*

The bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) by a dense population of ampeliscid amphipods (12,094±2,499)carpeting the head of the Mississippi Canyon at a depth of 480 m is estimated and compared with estimation for amphipods from the shallow water, Houston Ship Channel. The distribution of individual PAH in sediments is different from the distribution in the organisms both in deep and shallow water, suggesting preferential uptake/depuration or uptake from pore or bottom waters. The average bioaccumulation factor (4.36 ± 2.55) and the biota sediment accumulation factor (0.24±0.13) for the total PAHs by the ampeliscid at the canyon's head were within the range reported for other benthic invertebrates. The average bioaccumulation factors were highest for dibenzothiophenes (up to 132 for C1-dibenzothiophenes) and alkylated PAHs and lowest for parent high molecular weight[4] PAHs (HPAHs). Shallow water amphipods were similar to the ampeliscids in showing high preference to bioaccumulate alkylated PAHs and low preference to bioaccumulate parent HPAHs.

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* Submitted to Deep-Sea Research II, Yousria Soliman and Terry Wade, 2007.

V.1. Introduction

The northern Gulf of Mexico is a major production area for US subsurface gas and oil (Sassen et al., 2001). Drilling platforms represent a source of PAHs either through the drilling mud, produced water or direct oil seepage. PAHs are hydrophobic organic contaminants that tend to accumulate in sediment. The concentrations of PAHs in sediment were measured during the DGOMB study (Wade et al., 2007). The concentration of polynuclear aromatic hydrocarbons (PAHs) at the head of the canyon had a mean of 446.0±115 ng/gm dry wt. Benthic organisms are exposed to organic contaminants and are known to accumulate aromatic hydrocarbons (Landrum and Robbins, 1990), with a potential transfer through the food webs. Elevated concentrations of PAH in aquatic organisms are correlated to areas receiving chronic hydrocarbon discharges (Neff, 1995). Bioaccumulation integrates the bioavailabitity of contaminants in all the environmental media around the organism.

During the same DGOMB study, a mat of a new ampeliscid amphipod, *Ampelisca mississippiana* (Soliman and Wicksten, 2007), was recorded at depth of about 480 m at the head of the Mississippi Canyon. Ampeliscid amphipods densely inhabited many soft bottom habitats (Steimle, 1982; Collei, 1985; Franz, and Tanacredi, 1992; Occhipinti-Ambrogi et al, 2005). They are suspension-deposit feeders consuming detrital materials and transferring them to higher-level organisms in the benthic food webs (Mills, 1967). Ampeliscids are largely used as toxicity test organism in sediment quality assessment (Ho et al., 1997 and Carr et al., 1996) and as indicators for contamination (Gallagher and Keay, 1998; Botton, 1979) especially for aromatic hydrocarbons.

Amphipods in general and ampeliscids specifically are good indicator of oil polluted sites. They are so useful as primary environmental monitor for oil pollution (Grosse et al. 1986) that U.S. Governmental agencies now require their identification to species level in permitting operations such as oil leases (Thomas, 1993). With the exception of mollusks, very little work has been done on the PAHs associated with invertebrates that form the base of the benthic food web especially amphipods. Also there are limited reports of bioaccumulation of PAHs in deep waters.

Because of the abundant presence of the ampeliscid amphipods at the head of the Mississippi Canyon, assessment of bioaccumulation of PAHs was undertaken. Two approaches are used to determine bioaccumulation factors; field and laboratory. The field approach was used in the present study as it provides the most realistic measure of PAHs bioavailability and is essential for determining the extent of bioaccumulation in natural field systems (Lee, 1992).

The objectives of this study were to determine bioaccumulation of PAHs in an important and dominant benthic amphipod population, the population of *A. mississippiana*. Bioaccumulation factors of PAHs for a shallow water amphipod from Houston Ship Channel are estimated to compare factors in shallow water with those in deep water.

V.2. Study area

The Mississippi Canyon, located in the northern Gulf of Mexico (28º 32' N, 89º 49' W) is prominent morphological feature. Sediment and detrital materials transported by the Mississippi River extend its domination to the Deep Sea through that Canyon

(Balsam and Beeson, 2003). This Canyon, which is a conduit for sediment and organic material could also be a pathway for anthropogenic materials that are transported by the Mississippi River into the surrounding coastal zone. There are large-scale offshore oil and gas operations in the Mississippi canyon that may be potential source of PAHs from drilling mud, produced water or oil seepage, which may impact benthic assemblages.

A shallow water location in the Houston ship channel was sampled to determine the bioaccumulation factor of PAHs and the individual PAHs by the amphipods and compare these with those of the canyon's head.

V.3. Material and methods

Two approaches provide direct measures for bioaccumulation: the field and the bioassay approach. Both approaches involve measuring tissue residues in either field-collected or laboratory exposed organisms. In the present study, the field approach was used. Five grab samples were collected in June of 2002 and August of 2004 from the head of the Mississippi canyon (MT1-b) for the analysis of the PAHs bioaccumulation factors by the ampeliscid sp (Fig. 5.1). Another sample was collected from the Houston Ship Channel to determine the bioaccumulation of PAHs by amphipods. The amphipods were sieved and collected in combusted glass jars with teflon-lined lids and stored frozen (-20°C) until analysis. Sediment and amphipods samples were analyzed for polynuclear aromatic hydrocarbons (PAHs) using NOAA National Status and Trends Methods (Denoux et al. 1998; Qian et al. 1998). Deuterated PAH are added before the extraction and are used to calculate analyte concentrations. Sediment samples are oven dried at 40^0C, while amphipod samples were freeze dried and then they are both mixed with anhydrous sodium sulfate and extracted with methylene chloride in a Dionex 200 Automated Solvent Extractor (ASE). The extracts are then separated from possible interfering compounds by silica/alumina columns. An aliquot of the amphipod extracts are used to measure the % lipid. The purified extracts are analyzed on a HP 5890/5970 gas chromatograph with a mass selective detector (GC/MS) using a selected ion detection technique. The GC/MS is calibrated with known concentrations of analytes at five different concentration levels and the average response factors of the analytes are used for PAH concentration determination. Concentrations of PAHs are reported as ng/g on a dry weight basis for sediment samples. Parent low molecular weight PAHs, (PLPAHs), parent high molecular weight PAHs (PHPAHs), alkylated PAHs and dibenzothiophenes are all reported. The results of these two cruises are compared with the results of other DGOMB cruises to the same location (MT1) as well as to the deeper locations (MT3, MT4, MT5, MT6 at 480, 987, 1400, 2275, and 2750 m respectively) in the Mississippi canyon. Each sample batch includes a procedural blank, a matrix spike, a matrix spike duplicate and a standard reference material. These quality assurance samples ensured that the analytical results for each batch are valid and of acceptable accuracy and precision.

Sediments were also analyzed for total organic carbon (TOC) using Leco elemental analyzer. Sediment samples were first dried at 1000 ºC and then combusted at 1,380 ºC to produce CO_2, which was measured using an infrared detector. Inorganic carbon was removed by acidification with H_3PO_4.

Bioaccumulation factor (BAF) and biota sediment accumulation factor (BSAF) were measured for the total PAHs, PLPAHs, PHPAHs, alkylated PAHs, dibenzothiophenes and individual PAHs in deep water as well as shallow water amphipods for comparison.

BAF has been defined as the concentration of contaminant in tissue divided by the concentration in sediment (Lee, 1992), and it is considered as a direct measure of the bioavailability of the contaminants in the environment.

$$BAF_S = C_t/C_s$$

Where C_t is the concentration of PAHs in tissue and C_s is the concentration in sediment.

The equilibrium-partitioning model is used to calculate the biota sediment accumulation factor (BSAF). This model assumes that organic carbon is the only sink for neutral organics in the sediment and that lipids are the only sink in the organism and that organic contaminants are only partitioned between the lipid of the organism and the organic carbon in sediment until equilibrium is obtained. BSAFs are defined as the ratio of a substance's lipid-normalized concentration in tissue of an aquatic organism to its organic carbon-normalized concentration in surface sediment (USEPA, 1995) and it could be used to predict the biota burden of organic contaminants. BSAF is calculated as:

$$BSAF = (C_t/L)/(C_s / TOC)$$

where: BSAF = biota-sediment accumulation factor (g carbon/g lipid)

C_t = tissue concentration at steady-state (ng/g)

L = lipid content (g/g)

C_s = sediment concentration (ng/g)

TOC = total organic carbon in sediment (g/g)

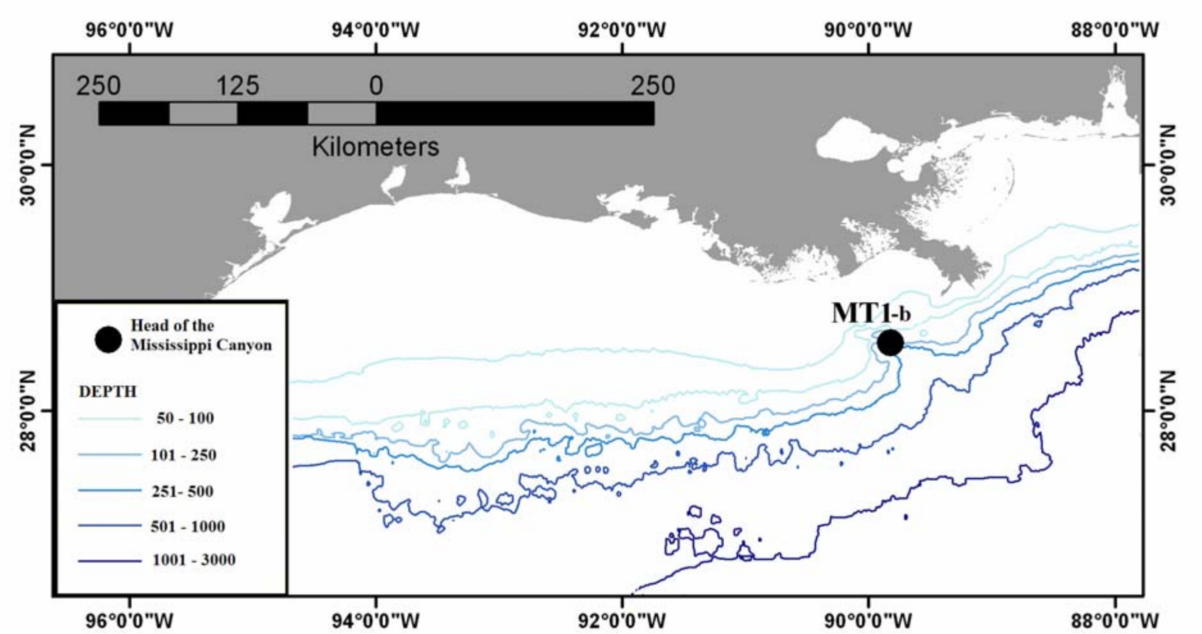

Fig. 5.1. Map showing the location of MT1-b at the head of the Mississippi Canyon, Northern Gulf of Mexico.

V.4. Results and discussion

The average PAHs concentration at the head of the Mississippi Canyon (MT1-b) (550.32±77.92) was comparable to the average reported by Wade et al (2006) (446.0±115 ng/g) with a mean of 498.16±52.16 ng/g (Table 5.1). Total PAHs concentrations in the sediment of the canyon's head were higher than back ground level

(200 ng/g) of the Gulf deeper water (Fig. 5.2) and comparable to PAHs concentration in some shallow areas of Mississippi Delta and Galveston Bay (Santschi et al, 2001). The PAHs concentrations in Canyon's sediment increased exponentially with the increasing % of clay in sediment (R^2= 0.61) and exponentially decreased with increasing the % of sand (R^2= 0.66) (Fig. 5.3). The organic carbon percent in sediment (POC%) did not show high correlation with the PAHs concentration (R^2= 0.34), while, the dissolved organic carbon was negatively correlated (R^2 = -0.48) with the total PAHs in the sediment. The PAHs concentration in the canyon is positively correlated to barium concentration in sediment (R^2= 0.73), (Fig. 5.4) indicating that drilling mud is probably a potential source of some of the PAHs detected (Wade et,al., 2005; Wade et al, 2006).

Table 5.1. Total PAHs, lipid % and TOC% at deep water and shallow water locations.

Samples description		Total PAHs	Mean PAHs (ng/g dry wt)		Lipid (g/gm)	TOC%
Sediment	Cruise of 06-2002	628.2	550.32±77.9	498.16 ±52.16	--	0.6
	Cruise of 08-2004	472.4				0.32
	DGOMB Cruise 1	733.0	446.0±115		--	1.135
	DGOMB Cruise 2	350.3				
	Shallow water	144.1	144.1		--	1.41
Ampelisca	Cruise of 06-2002	5010.7	2680.25±2330		0.11	--
	Cruise of 08-2004	349.8			0.054	--
amphipod	Shallow Water	324.5	324.5		0.13	--

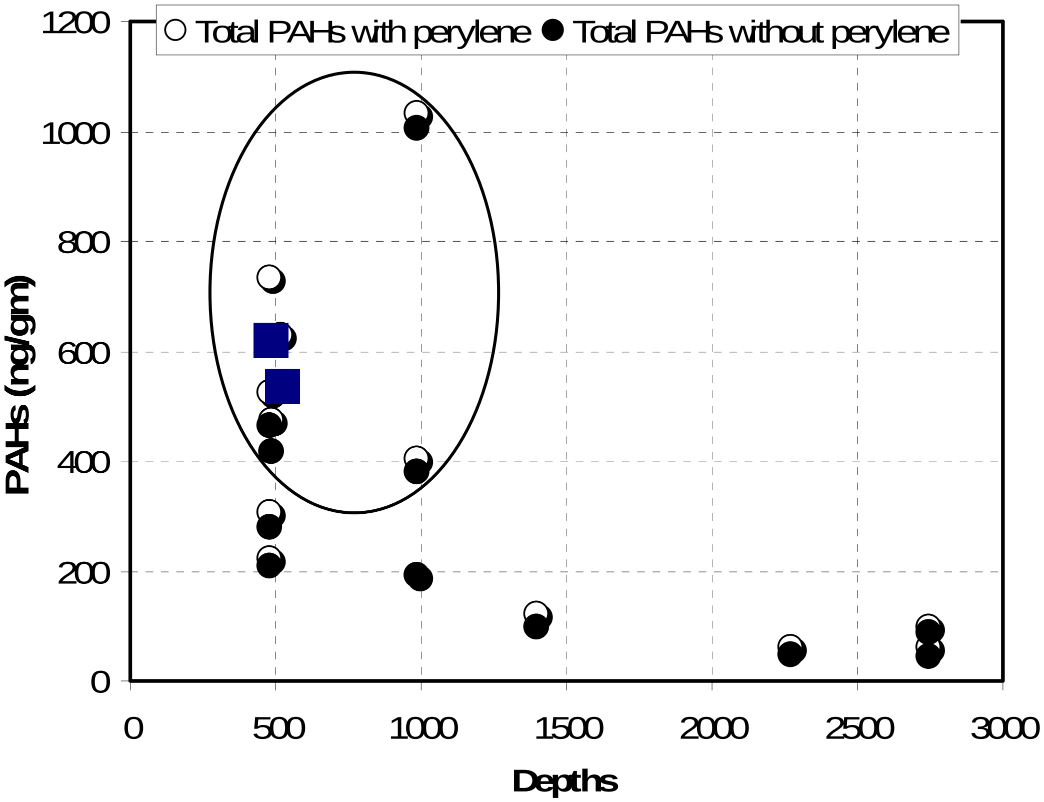

Fig. 5.2. Concentration of PAHs at the canyon head from DGOMB study (•, ○) as well as other two cruises (■) through 2000-2004 comparing with other depths at the canyon.

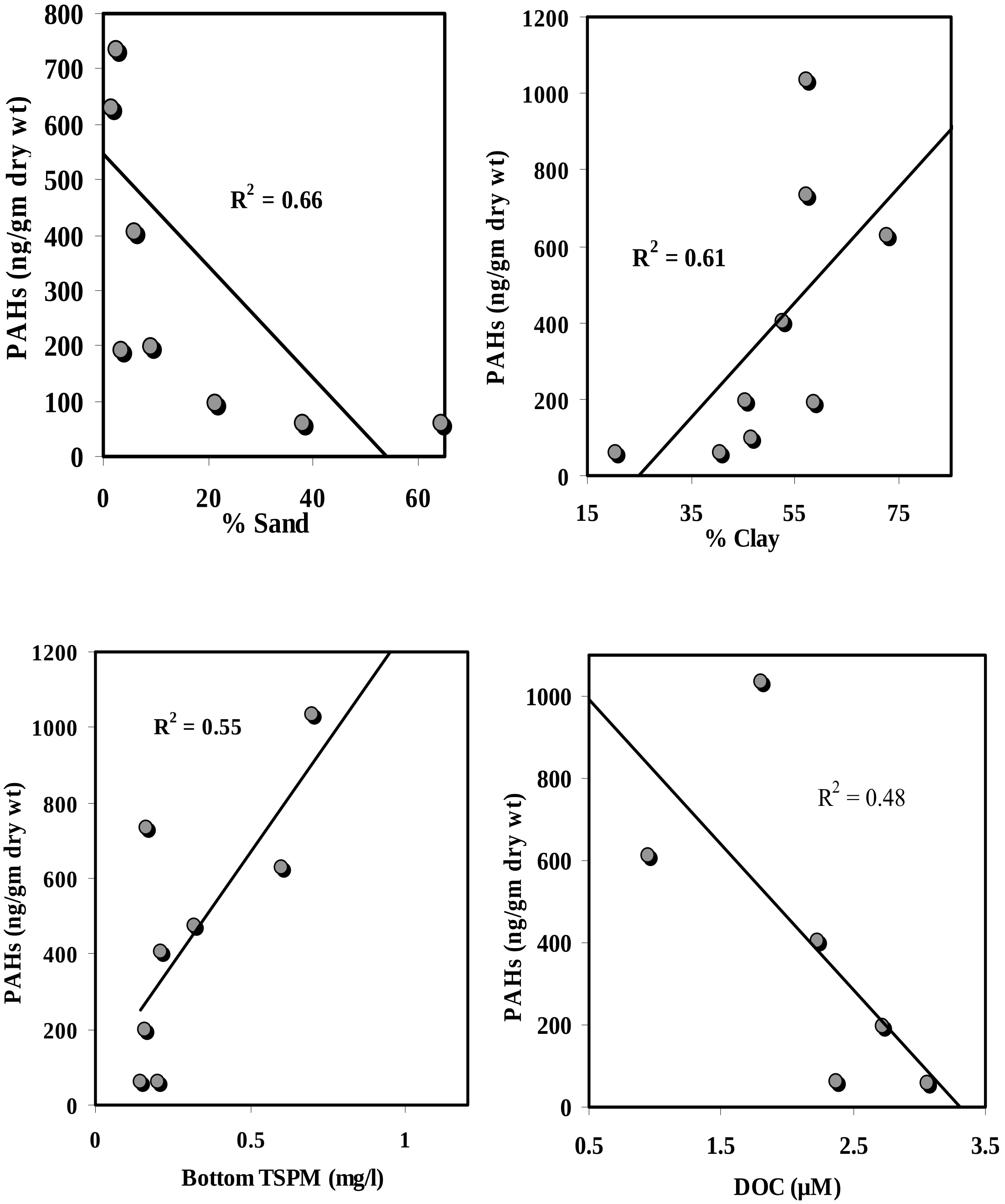

Fig. 5.3. Relation between total PAHs at the sediment of the canyon at different depths and Total suspended matter (TPSM), Dissolved organic carbon (DOC), % sand and % caly.

Low molecular weight PAHs compounds (LPAHs) which includes naphthalene, acenaphthene, fluorene, phenanthrene and anthracene (Table 5.6) showed lower contribution to the total sediment PAHs at the head of the Canyon (average 77.92±17.33 ng/gm dry wt) compared to HPAHs (Avg.= 304.10±36.90) and alkylated PAHs(249.89±31.23). Perylene was the major contributor to the HPAHs measured at the canyon's head where it constituted about 13% of the total PAHs (Fig 5.5). Other HPAHs such as benzo(b)fluoranthene as well as pyrene were considerably abundant constituted 6.14% and 5.07% of total PAHs respectively (Fig. 5.5). Alkylated naphthalenes were highly abundant and they together constituted about 19% of total PAHs.

Comparing PAHs at the canyon's head (MT1, MT1-b) with PAHs at deeper locations in the canyon showed that the profile of the PAHs was mostly the same at the different depths with dominancy of HPAHs in the form of perylene, and the alkylated PAHs including C1-naphthalene, C2 naphthalene (Fig. 5.5,5.6). Dibenzothiophenes showed the lowest contribution to the concentration of the total PAHs down the canyon's sediment.

High levels of total PAHs is observed in the *A. mississippiana* reaching 5000 ng/g dw. This high concentration was found in samples of adult collected during June. However this concentration was as low as 343 ng/g dry wt in samples that are dominated with juveniles in August (Table 5.5). The lipid content in the ampeliscids (Table 5.1) ranged between 5.4 % dry wt to 11 % dry wt (average of 8.3±3.82 % dry wt for all reproductive stages), which is comparable to the lipid content of other ampeliscids such as *Ampelisca abdita* (10.4% dry wt) (Fay et al, 2000). The PAHs concentrations in the amphipods showed big variation that could be due to the age of the amphipods.

Table 5.2. Comparison between the concentrations of parent low molecular weight PAHs (LPAHs), parent high molecular weight PAHs (HPAHs), alkylated PAHs and dibenzothiophenes in the sediment of present study locations, DGOMB locations and the amphipods.

	Parent LPAHs		Parent HPAHs		Alkylated PAHs		Dibenzothiophenes	
MT1-b	60.59	77.92± 17.33	267.20	304.10± 36.90	218.67	249.89± 31.23	12.13	12.12± 0.004
MT1	95.25		341.00		281.11		12.12	
MT3	136.08		137.12		437.54		6.72	
MT4	28.47		76.17		84.52		7.64	
MT5	7.57		33.20		32.81		1.23	
MT6	7.74		33.89		33.55		1.52	
Ampelisca	194.30		32.95		1988.60		460.40	
Shallow water-sediment	10.90		80.10		44.60		3.00	
shallow water-amphipod	48.30		84.40		181.90		4.70	

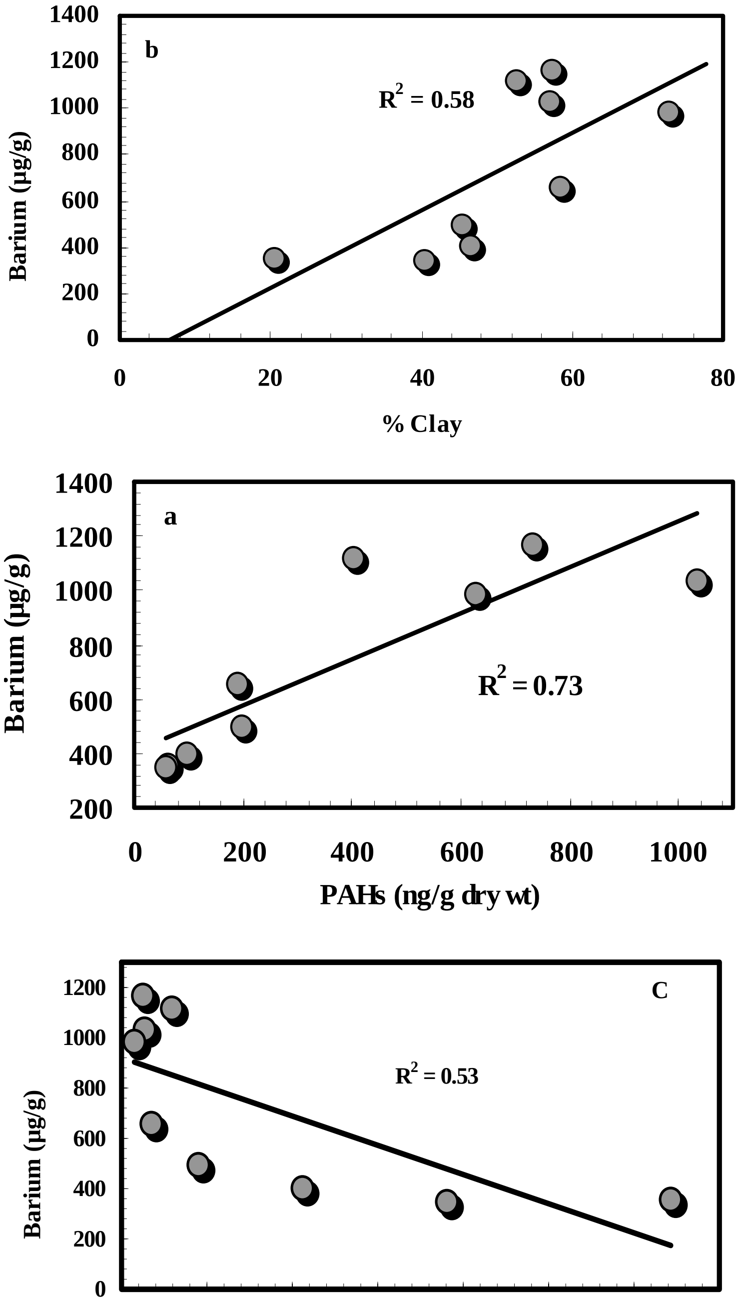

Fig. 5.4. Total barium at the sediment of the canyon and concentration of PAHs (a) and the % caly in the sediment (b) and % sand (c).

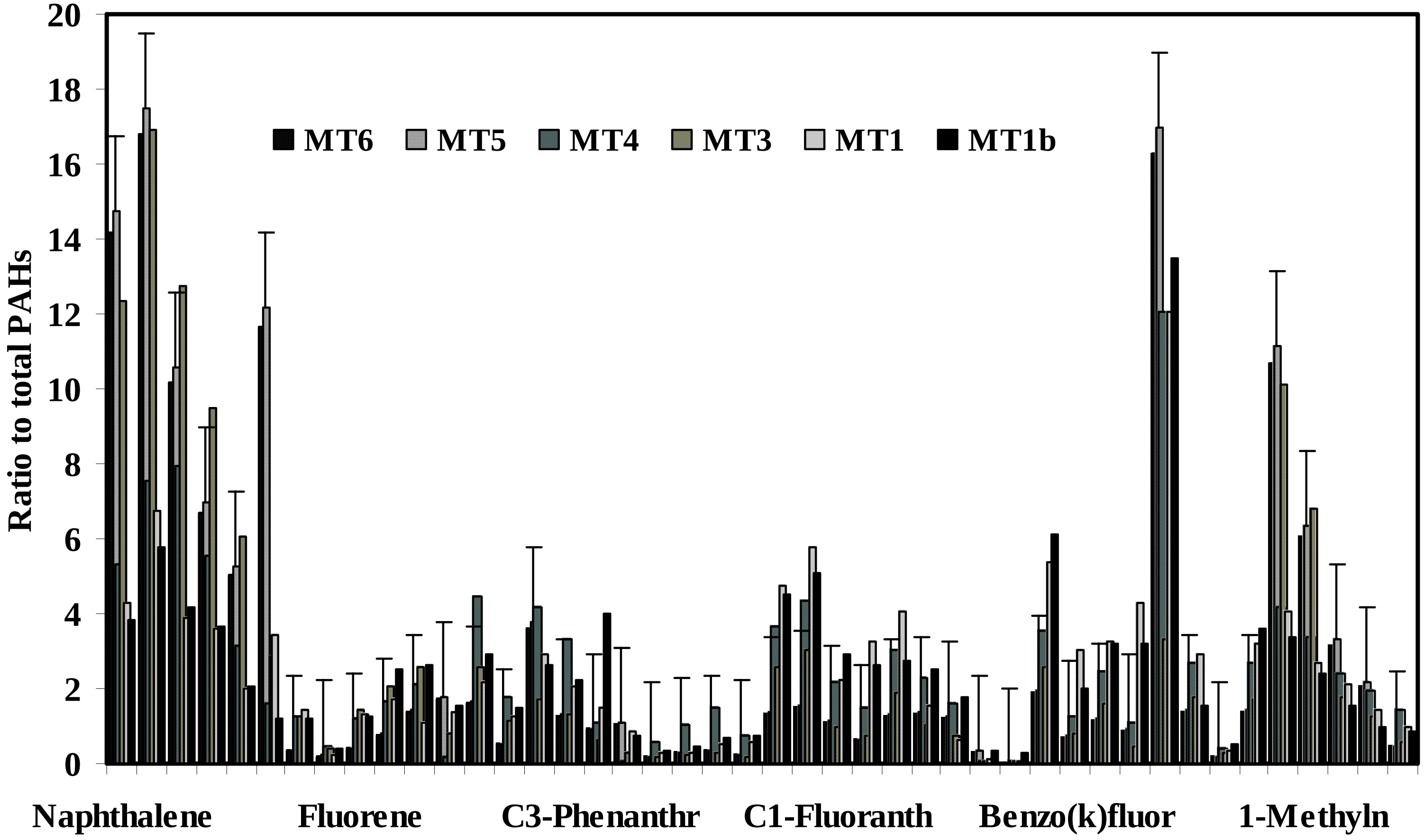

Fig. 5.5. The distribution of individual PAHs at MT1(b), MT1, MT3, MT4, MT5 and MT6 at the Mississippi Canyon.

Eriksson Wiklund, et al (2003) found seasonal variation and age variation in the bioaccumulation of the PCBs in the amphipods where the adult female had higher concentrations than juvenile. The total consumption and pseudofeces production of organic materials are found to be function of the size frequency distribution of benthic population filter feeders (Young et al, 1996) which will affect the accuracy of the assessment of the impacts of an organism on transferring organic carbon. The high concentration in the amphipods indicates high uptake as well as slow release. Lower respiration rate at deep cold water may cause higher concentration of organic contaminants in the amphipods (Eriksson Wiklund, et al, 2003).

The distribution of individual PAHs in the ampeliscid amphipod was not completely similar to those in the sediments (Fig.5.7). Ampeliscids had very low concentrations of parent HPAHs (32.95 ng/g dry wt) and very high concentrations for both, the alkylated PAHs (1988.60 ng /g dry wt), and dibenzothiophenes (460 ng/g dry wt) (Fig. 5.8). Looking at the individual PAHs in the ampeliscids, the highest were alkyl fluorenes (C1-fluorene, C2-fluorene, C3-fluorene) which accounted for 32%, alkyl dibenzothiophenes (17%), alkyl phenanthrenes (16.9 %) alkyl naphthalenes (13%), and alkyl chrysenes. The ampeliscid extracts exhibited apparently the discriminate abundance of alkyl-substituted species of naphthalene, flourene, phenanthrene and dibenzothiophene suggesting the oil as a probable source of PAHs (Fig 9). The high concentration of alkylated PAHs in benthic organisms is documented by NOAA's Mussel Watch program (NOAA 1998), showing very high percentages of alkylated PAHs in bivalves at some sites around the USA.

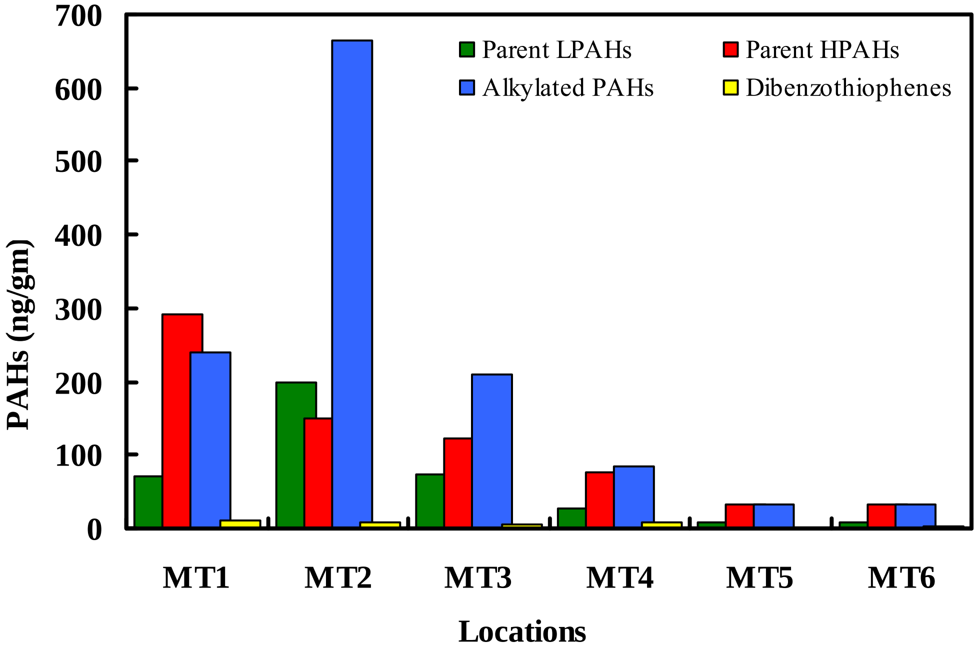

Fig. 5.6. The distribution of parent LPAHs, parent HPAHs, alkylated PAHs and dibenzothiophenes at MT1, MT1(b), MT3, MT4, MT5 and MT6 at the Mississippi Canyon.

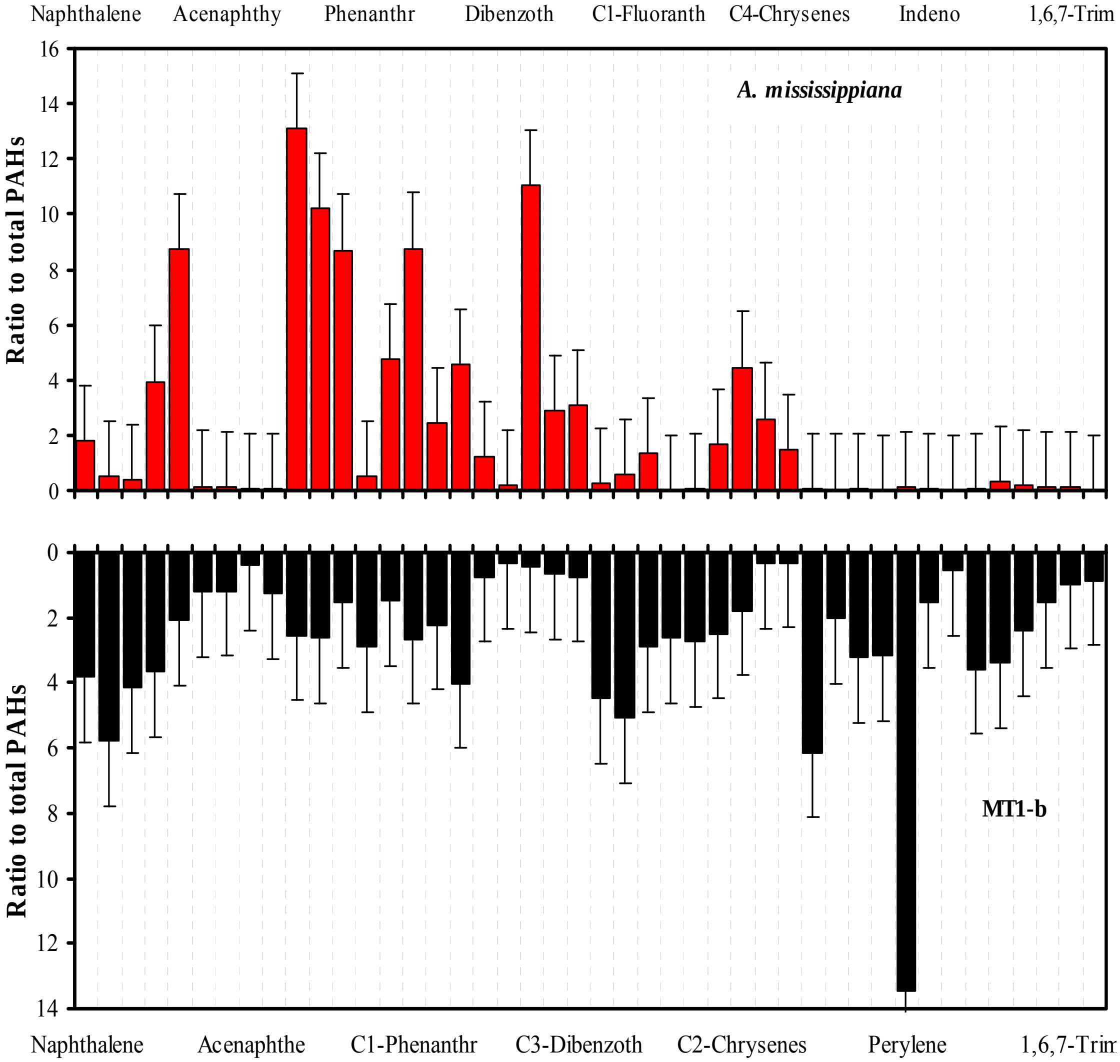

Fig. 5.7. Average ratios of PAHs individual for the ampeliscids and sediment at MT1-b.

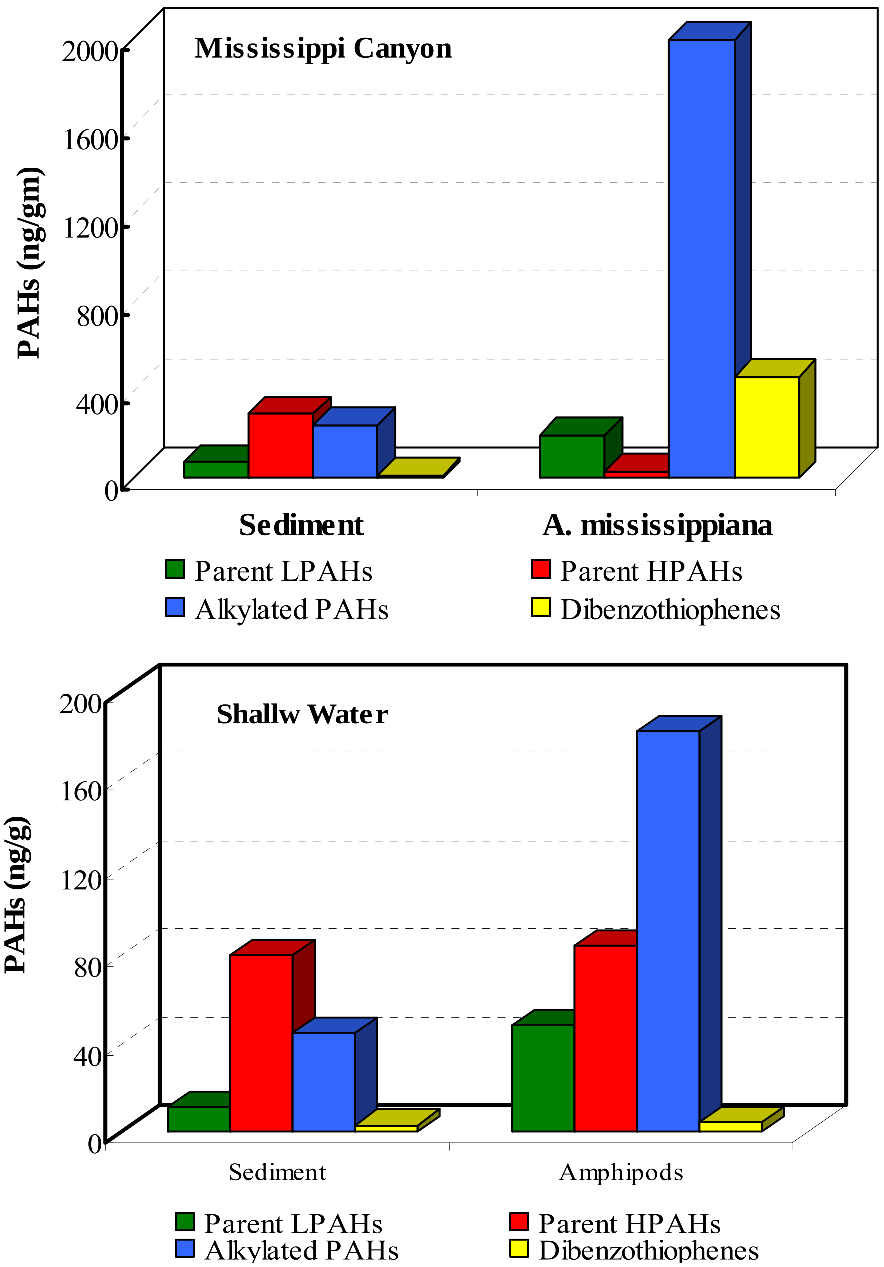

Fig. 5.8. Comparison between the concentrations of parent LPAHs, parent HPAHs, alkylated PAHs and dibenzothiophenes in amphipods and sediment of deep (MT1) and shallow water.

The variation between the PAHs profiles in sediment and ampeliscid amphipods might reflect the interaction of the ampeliscids with the overlying water (Meador, 2003). For shallow water sediment from Houston ship channel, the total PAHs concentration was much lower than that recorded from the deep water (144 ng/gm). Although the high molecular weight PAHs (benzo(b)fluoranthene, pyrene, benzo(a)Pyrene, C1-chrysenes, benzo(e)pyrene, benzo(a)anthracene) were the major contributors to the total PAHs of the shallow water sediment, shallow water amphipods also had high concentrations of alkylated PAHs (181.9 ng/g dry wt) comparing with the low concentration observed in sediment (44.60 ng/gm dry wt) (Table 5.5). The individual PAHs in the amphipods were still dominated by the low molecular weight PAHs (LPAHs) as well as alkylated PAHs such as C1-fluorene (14%), C2-fluorene (12%), naphthalene (11%), C4-naphthalene (8%), (Fig. 10). The distribution of parent PAHs and alkyl homolog provide useful information on determining the sources of PAHs. Parent compounds are usually formed under high temperature indicating pyrogenic sources while PAHs dominated by alkyl constituents are indicative of petroleum sources (Sporstol et al. 1983, Berthou and Vignier 1986, Stienhauer and Boehm, 1992).

The bioaccumulation factors for PAHs are calculated as the ratios of PAH in ampelisca to PAH in sediment. The average bioaccumulation factor for the total PAHs was 4.36 (Table 5.3). However the bioaccumulation factor for the individual PAHs behaved differently where the bioaccumulation factors for the alkylated PAHs were higher than that for the parents and this was a common pattern for the deep-water ampeliscids as well as for the shallow water amphipods (fig. 9&10). Alkylation of PAHs increases the molecular weight of PAHs which lowers their rate of degradation (Hellou et al, 1999). Alkylated PAHs probably take a longer time to be metabolized because of their higher molecular weight and higher octanol water partition coefficient (log K_{ow}) (Hellou et al, 1999). The bioaccumulation factor showed a significant linear relation with the log K_{ow}., ($R^2 > 0.56$, $P<0.05$) for the two sampling years of 2002 and 2004, respectively , (Fig.11). The average bioaccumulation factor for the individual PAHs in the canyon's ampeliscids were highest for C1-dibenzothiophene (132), C2-dibenzothiophene (23.9) C3-dibenzothiophene (22.8), C3-chrysenes (46), C4-chrysenes (30), C3-fluorene (32.7), C2-fluorene (18) and C1-fluorene (20). Parents PAHs such as chrysenes, fluorene and fluoranthene showed the lowest bioaccumulation factors (0.08, 0.24 and 0.25 respectively) (Table 5.3). Similar to the deep water amphipod, the bioaccumulation factors for the individual PAHs for the Ship channel amphipods were highest for dibenzothiophene (23), followed by alkyl fluorene (C2-fluorene and C1-fluorene; 22.8 and 19 respectively). Generally both deep water and shallow water amphipods had high bioaccumulation factor for LPAHs and alkylated PAHs, however deep-water ampeliscid had high bioaccumulation factor for dibenzothiophenes (Table 5. 4).

Biota sediment accumulation factor for the ampeliscids at the head of the canyon ranged between 7.24 for C1-dibenzothiophene to less than 1×10^{-2} for benzo(a) pyrene, benzo(a)anthracene and chrysene (Table 5.3). Alkyl PAHs tended to bioaccumulate to a greater degree than parent compound PAHs and this is probably because the parent PAHs degrade faster than their alkylated homologs (Volkman et al, 1984). The heterocycles, dibenzothiophenes, had the highest bioaccumulation in deep-water ampeliscids, although it was not abundant in the sediment, suggesting another source of uptake such as suspended materials which is common at canyons. Dibenzothiophene is abundantly found in areas with high organic suspended materials and run off as it has a high particulate affinity as well as low microbial degradation rate (Yanga et al, 1998; Yang and Zhang, 1997). PAH accumulation from resuspended sediment may be substantial in dynamically bioturbated environments (McElroy et al, 1990, Ciarelli et al, 1999) such as canyon environments where sediment-bound PAHs, could be resuspended from bottom sediments into the water column by tidal currents events (Axelman and Broman , 1999), and this might facilitate incorporating the PAHs into the suspension feeder ampeliscids. Ventilated water is also another possible route for the uptake of more soluble forms of PAHs ($K_{ow} \leq 5.5$) (Meador, 2003). The lipid content, reproductive status (adult vs juvenile), organism size, may all affect the bioaccumulation of PAHs in the ampeliscids. Braumard et al. (1998) found elevated BSAFs for mussels from the Baltic in March compared to those in August and October and he attributed that to the seasonal variation in filtration rate or a probable variation in the digestive enzymes due to seasonal cycles.

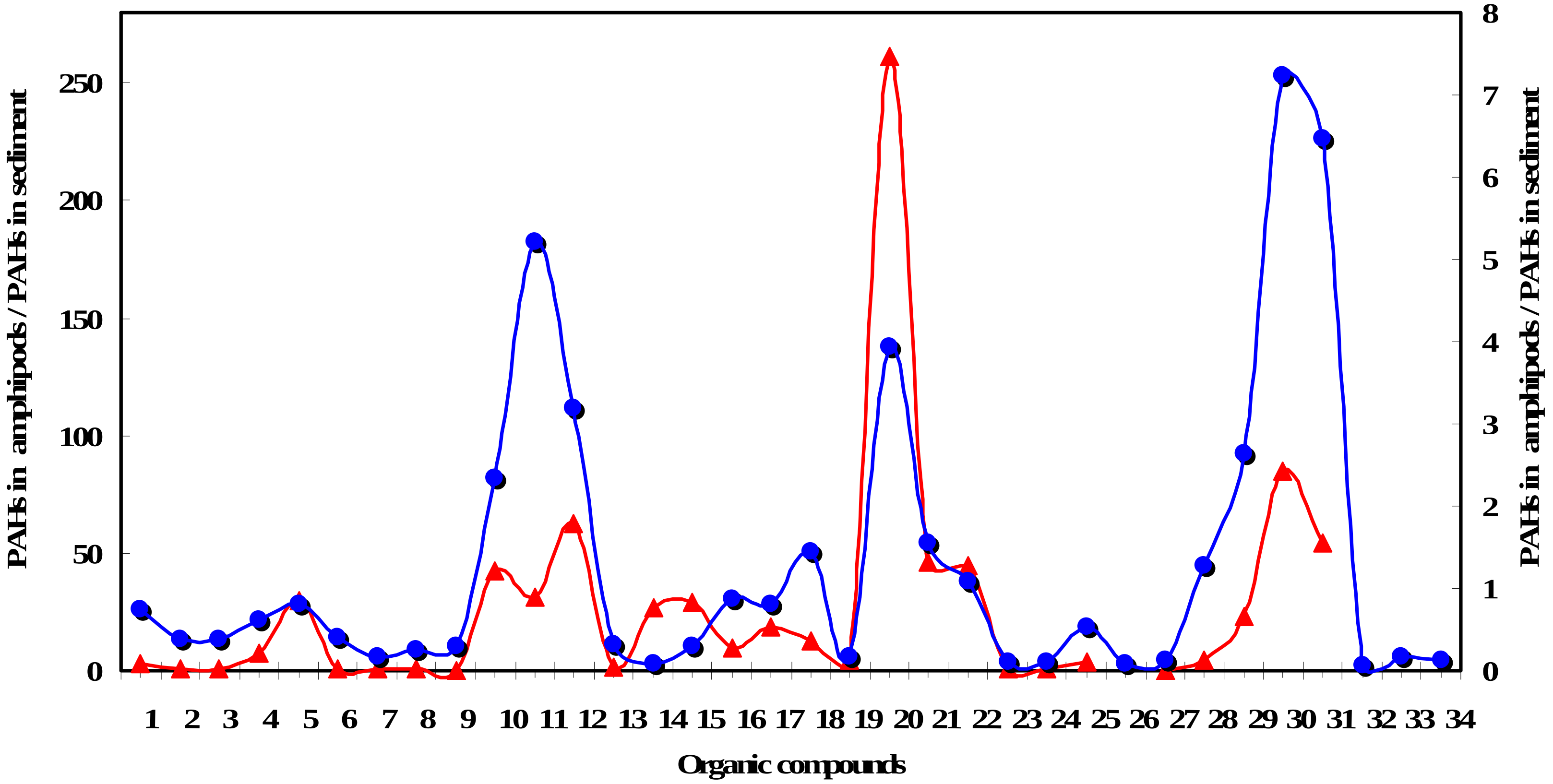

Fig. 5.9. Ratio of individual concentration of PAHs in *A. mississippiana* to those in sediment.
(▲2002 samples ● 2004 samples).

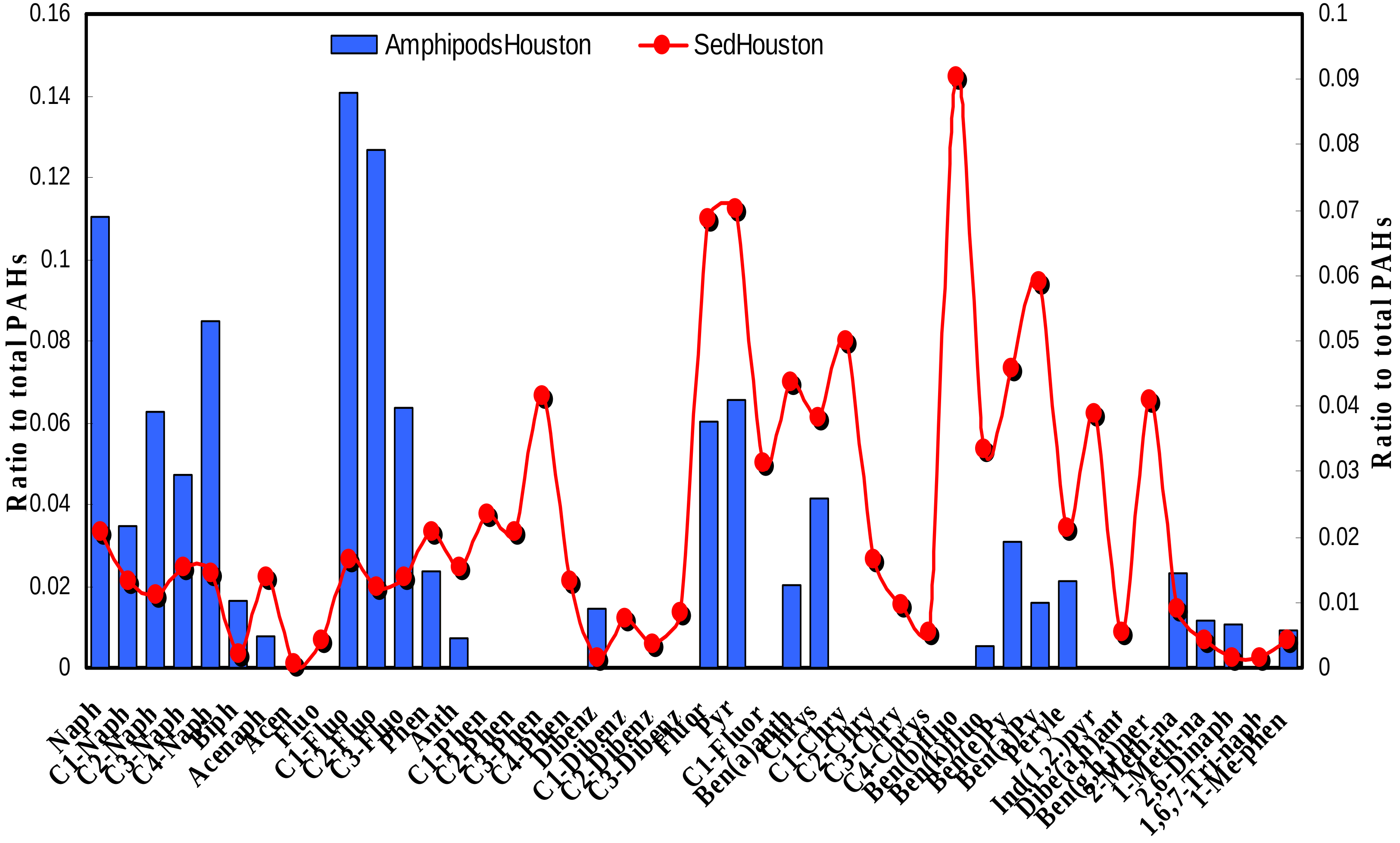

Fig. 5.10. Ratios of PAHs individual for the amphipoda and sediment at shallow water location (Houston Ship Channel).

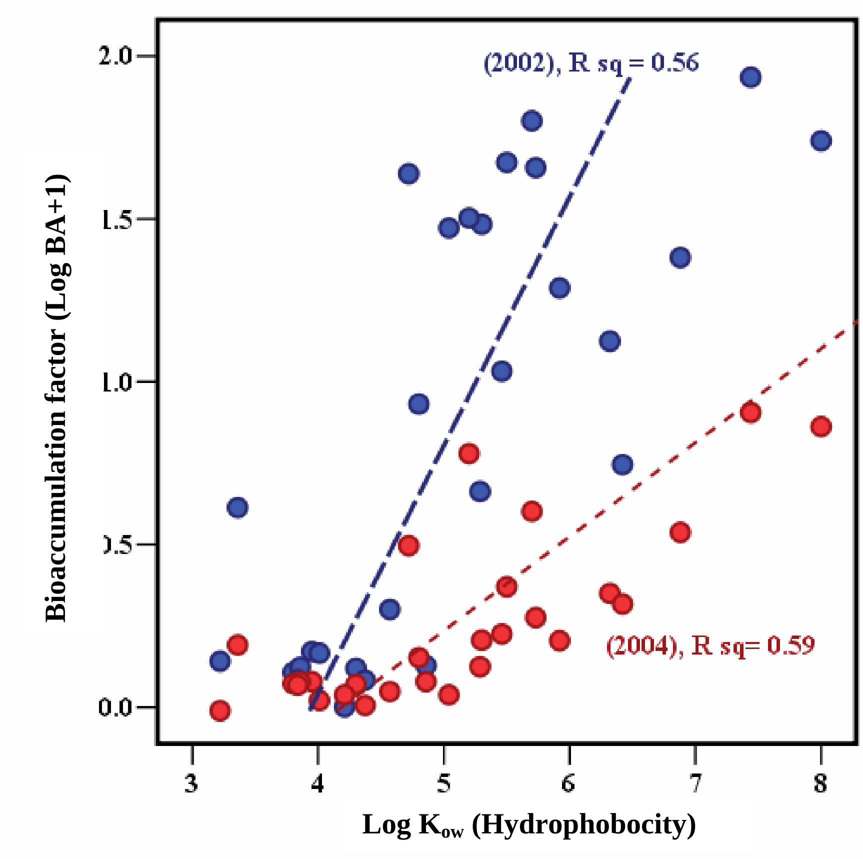

Fig. 5.11. Correlation between log bioaccumulation factor (BA) and log K_{ow} for different PAHs.

The PAHs at the canyons head as well as other canyon locations is probably petrogenic in the origin based on several diagnostic ratios for the PAHs (Table 5.6). However the presence of high Perylene indicates that there is a combination of sources including continental inputs as well as petroleum sources. The dominance of perylene might be explained by the large continental inputs, in conjunction with a reducing medium (Venkatesan, 1988) while relatively abundant naphthalene and its alkyl-substituted homologues coupled with low concentrations of the 4-5 ringed parent PAHs, could be indicative for unweathered petroleum (Robertson, 1998; Yunker and Macdonald 1995).

The equilibrium-partitioning model does not sufficiently distinguish between the diversity of feeding strategies (Morrison *et al.* 1996), which might affect the significance of the results for benthic organisms that probably have multi-feeding strategies (e.g. suspension-deposit feeders). The model also does not account for metabolism and life stages. However measuring the bioaccumulation factor estimated the cumulative effect for the PAHs that is in the deep Gulf and showed that the bioaccumulation factor is comparable or sometimes higher than estimations from shallow water habitats.

Table 5.3. Average accumulation factor and biota sediment accumulation factor for individual PAHs by the undescribed ampeliscid amphipods and shallow water amphipod.

	Log K_{ow}	Deep Water ampeliscids		Shallow water amphipods	
		BAF	BSAF	BAF	BSAF
Naphthalene	3.37	2.03±0.90	0.1124± 0.04	11.93	1.29
C1-Naphthalenes	3.87	0.43±0.03	0.024± 0.001	5.95	0.65
C2-Naphthalenes	4.37	0.45±0.04	0.025± 0.002	12.75	1.38
C3-Naphthalenes	5	4.18±2.5	0.23± 0.13	6.95	0.75
C4-Naphthalenes	5.55	15.20±10.18	0.83± 0.55	13.10	1.42
Biphenyl	-	0.541±0.10	0.03± 0.004	17.67	1.92
Acenaphthylene	4.07	0.38±0.14	0.02± 0.007	1.25	0.14
Acenaphthene	3.92	0.46±0.15	0.026±0.007	0.00	0.00
Fluorene	4.18	0.25±0.03	0.014 ±0.002	0.00	0.00
C1-Fluorene	4.97	22.52±14.27	1.23±0.77	19.04	2.07
C2-Fluorene	5.2	18.12 ± 9.12	1.00±0.480	22.83	2.48
C3-Fluorene	5.5	32.79 ± 20.92	1.79±1.13	10.30	1.12
Phenanthrene	4.57	0.76 ± 0.31	0.042±0.01	2.57	0.28
Anthracene	4.54	13.26 ± 9.32	0.72±0.50	1.05	0.11
C1-Phenanthrenes/Anthracenes	5.14	14.56 ±10.09	0.79±0.54	0.00	0.00
C2-Phenanthrenes/Anthracenes	5.51	5.42 ± 3.21	0.30±0.17	0.00	0.00
C3-Phenanthrenes/Anthracenes	6	9.70 ± 6.29	0.53±0.31	0.00	0.00
C4-Phenanthrenes/Anthracenes	6.51	6.98 ± 3.92	0.38±0.21	0.00	0.00
Dibenzothiophene	4.49	2.17 ± 1.41	0.12±0.07	23.50	2.55
C1-Dibenzothiophene	4.48	132.58 ± 90.9	7.24±4.95	0.00	0.00
C2-Dibenzothiophene	5.5	23.91 ± 15.81	1.30±0.86	0.00	0.00
C3-Dibenzothiophene	5.73	22.84 ± 15.38	1.24±0.83	0.00	0.00
Fluoranthene	5.22	0.25 ± 0.11	0.014±0.005	1.97	0.21
Pyrene	5.18	0.52 ± 0.29	0.03±0.015	2.10	0.23
C1-Fluoranthene/pyrenes	5.72	2.17 ± 1.16	0.12±0.06	0.00	0.00
Benzo(a)anthracene	5.91	5.86 ± 0.03	0.003 ± 0.001	1.03	0.11
Chrysenes	5.86	0.08 ±0.03	0.005±0.001	2.45	0.27
C1-Chrysenes	6.42	3.02 ± 1.23	0.17±0.06	0.00	0.00
C2-Chrysenes	6.88	12.95 ±7.28	0.71±0.39	0.00	0.00
C3-Chrysenes	7.44	46.22 ± 27.56	2.54±1.49	0.00	0.00
C4-Chrysenes	8	30.27 ± 16.83	1.67±0.90	0.00	0.00
Benzo(b)fluoranthene	5.8	0.08	0.0018	0.00	0.00
Benzo(k)fluoranthene	6	0.015	0.0048	0.35	0.04
Benzo(e)Pyrene	-	1.58	0.0040	1.52	0.16
Benzo(a)Pyrene	6.04	0.23	0.0006	0.60	0.07
Perylene	-	0.26	0.0026	2.23	0.24
Indeno(1,2,3-c,d)pyrene	7	0.46	0.0663	0.00	0.00
Dibenzo(a,h)anthracene	6.7	0.39	0.0000	0.00	0.00
Benzo(g,h,i)perylene	6.5	0.53	0.0027	0.00	0.00
2-Methylnaphthalene	3.86	0.46± 0.05	0.03±0.001	5.77	0.63
1-Methylnaphthalene	3.87	0.39 ± 0.02	0.02±0.0002	6.33	0.69
2,6-Dimethylnaphthalene	4.26	0.31 ± 0.07	0.018±0.003	17.50	1.90
1,6,7-Trimethylnaphthalene	4.89	0.47 ± 0.05	0.027±0.002	0.00	0.00
∑ PAHs	- -	4.36 ± 2.55	0.24±0.13		

Table 5.4. Average bioaccumulation factor for LPAHs, HPAHs, alkylated PAHs and Dibenzothiophenes at deep and shallow water

	Parent LPAHs	Parent HPAHs	Alkylated PAHs	Dibenzothiophenes
Ampeliscids	3.21	0.12	9.09	37.96
Shallow water amphipods	4.43	1.05	4.08	1.57

Table 5.5. Comparison between the head of the canyon environmental parameters with the other deeper water from the first *RV* cruise.

	MT1	MT2	Mt3	Mt4	Mt5	MT6
Org. carbon %	1.135	0.89	0.025	0.94	0.22	0.14
% sand	2.5	2.7	5.9	9	64.3	38.1
% Silt	40.3	40.1	41.5	45.5	15.3	21.5
% Clay	57.2	57.1	52.6	45.5	20.4	40.4
Total PAHs with perylene	446.0	-	542.6	121.0	60.1	77.9
Total PAHs without perylene	392.2	-	524.8	97.31	47.5	65.2
Org-N%	0.161	0.125	0.013	0.091	0.038	-
DOC (mM)	0.953	1.803	2.234	2.718	2.374	3.063
Bottom POC (µg/L)	38.3	28.5	19.31	8.22	5.43	12.85
C/N ratio	11.4	7.74	8.715	7.2	5.35	3.705
Bottom Suspended matter (mg/L)	0.164	0.697	0.285	0.158	0.202	0.134

Table. 5.6. Diagnostic ratios used to identify the sources of PAHs in the study area.

	Naph/Phen ratio	**MP/P**	**Fluoranthene/Pyrene**
MT1	1.21	1.7	0.92
MT2	8.32	1.9	0.82
MT3	2.77	2.1	0.86
MT4	1.20	1.4	0.85
MT5	1.21	2.1	0.96
MT6	1.20	2.5	0.88
MT1-2002	1.38	2.1	0.87
MT1- 2004	1.21	4.0	0.90
Sed. Of Houston	1	0.9 (pyro)	0.98
	>>1 for petroleum, 0.2-1 for clean sediment	MP/P ≈ 2 – 6 for unburned fossil PAH & <1 for pyrogenic	FLT/PYR < 1 For Petrogenic sources
Source	Stienhauer and Boehm, 1992	Garrigues et al., 1995	

Table 5.7. List of polycyclic aromatic hydrocarbons groups and their compounds.

Polycyclic Aromatic Hydrocarbons (PAHs)

Parent LPAHs

Naphthalene
Acenaphthylene
Acenaphthene
Fluorene
Phenanthrene

Parent HPAHs

Fluoranthene
Pyrene
Benz[a]anthracene
Chrysene
Benzo(b)fluoranthene
Benzo(k)fluoranthene
Benzo[e]pyrene
Benzo[a]pyrene
Perylene
Indeno[1,2,3-cd]pyrene
Dibenz[ah]anthracene
Benzo[ghi]perylene

Dibenzothiophenes

Dibenzothiophene
C1-Dibenzothiophene
C3-Dibenzothiophene
C2-Dibenzothiophene

Alkylated PAHs

C1-Naphthalenes
C2-Naphthalenes
C3-Naphthalenes
C4-Naphthalenes
C1-Fluorene
C2-Fluorene
C3-Fluorene
C1-Phenanthrenes/Anthracenes
C2-Phenanthrenes/Anthracenes
C3-Phenanthrenes/Anthracenes
C4-Phenanthrenes/Anthracenes
C1-Fluoranthene/pyrenes
C1-Chrysenes
C2-Chrysenes
C3-Chrysenes
C4-Chrysenes
2-Methylnaphthalene
1-Methylnaphthalene
2,6-Dimethylnaphthalene
1,6,7-Trimethylnaphthalene
1-Methylphenanthrene

CHAPTER VI

GENERAL SUMMARY

Deepwater amphipods were important components of the macrofauna of the slope of the Mississippi Canyon. The numerical abundance of amphipods showed negative exponential decrease with depth. The amphipods were found to be more abundant and richer in species than in the non-canyon transect with exceptionally high abundance at the canyon's head at depth of 480 m. A new amphipod species, *Ampelisca mississippiana* was the major contributor to this high abundance at the canyon's head. This species is a tube dwelling amphipod and is commonly found in organically enriched shallow habitats.

The high faunal abundances at the head of the canyon are consistent with findings of other studies in other canyons systems, and are largely attributed to the enhanced organic carbon flux in these abrupt topographic features. The species composition in the canyon's head was different from other depths in the canyon as well as in the non-canyon transect. Several species could be used as canyon indicator species. The canyon's head is characterized by the abundance of tube dwelling species that flourish only in organically enriched environments. Excluding the head of the Mississippi Canyon, the study area in the northern Gulf of Mexico constituted three depth related amphipod zones. The first is in the upper slope 600-1000 m, the second is in the middle slope (1000-1500 m) and the third is deeper than 1500 m.

The diversity is depressed at the head of the canyon probably due to competitive exclusion by the dominant species, *A. mississippiana*. It dominates organically enriched areas in association with pronounced currents that probably bring more potential food for almost sessile, filter feeding bioengineers, who create their own refuge. Higher species richness is found in the canyon (61 species) than in the non-canyon (38 species), probably due to the complexity of the canyon transect and the high heterogeneity. Highest diversity was found at mid-depth in the canyon and non-canyon transects where intermediate carbon flux as well as low physical disturbances could be found. Some species were found in the deeper locations of the canyon were found in shallower stations in the non-canyon transect while others appeared only in the non-canyon transect. The effects of the canyon and depth were found to be the most important factors determining the structure of benthic amphipods in the study area. Environmental factors such as organic carbon flux or the amount of near bottom suspended matter (TSPM) are depth correlated and are consequently found to be correlated with the abundance of the amphipods.

Secondary production based on the size frequency method is found to be high (6.9 g dry wt.$m^{-2}.y^{-1}$) and comparable to secondary production for different shallow water ampeliscid beds. The production estimates using linear regression models were very close to the size frequency method except for one shallow water model. The production/biomass ratio (P/B) was within the range reported for deep water crustaceans and shallow water ampeliscids.

The distribution of individual PAHs in sediment was different from their distribution in the *A. mississippiana* suggesting preferential uptake/depuration or uptake from pore or bottom waters. High concentration of PAHs in *Ampelisca* is probably attributed to the high uptake and low release due to the low temperature (8 ºC) that might slow down the metabolism of these high molecular weight compounds. *A. mississippiana* exhibited selective bioaccumulation of alkyl-substituted PAHs which has been also documented for other invertebrates. The bioaccumulation factor for the total PAHs by *A. mississippiana* was within the known range for benthic invertebrates (4.3), but the bioaccumulation factors for the individual PAHs were very high, reaching 132 for dibenzothiophenes. The lowest bioaccumulation factors were found for parent PAHs, probably because they have faster degradation rate.

The integrated study for the Mississippi canyon indicated that the head of the canyon has a degraded benthic habitat quality which is attributed to the cumulative effects of organic enrichment, pollution by PAHs, physical disturbance, and probably other factors. The dominancy of *A. mississippiana* was an indicator for this degradation. The high bioaccumulation factor for the PAHs was another vector for this degradation of environmental quality. More studies are needed to understand the ampeliscid bed at the canyon's head and to measure the secondary production of the amphipods using the cohort method, which is more accurate than the size frequency method. Models other than the known equilibrium-partitioning model are required to determine the biota–sediment-water accumulation factor. The previous model does not account for different feeding habits and uptake from overlying water. My results for PAHs bioaccumulation could be enhanced by measurements for PAHs in the near bottom suspended materials.

REFERENCES

Alcolado, M. P., 1992. Sobre la interpretación del ambiente marino mediante el empleo de los índices de diversidad y equitatividad. Cienias Biólógicas 24, 124–127.

Allen, J. A., Sanders, H. L., 1996. The zoogeography, diversity and origin of the deep-sea protobranch bivalves of the Atlantic: the epilogue. Progress in Oceanography 38, 95–153.

Aller, J. Y., Aller, R. C. and Green M. A., 2002. Benthic faunal assemblages and carbon supply along the continental shelf/shelf break-slope off Cape Hatteras, North Carolina. Deep-Sea Research II 49, 4599–4625

Aller, R. C., 1982. The effects of macrobenthos on chemical properties of marine sediment and overlying water. In McCall, P. L. and Tevesz, M. J. S. (Eds.), Animal-sediment Relations. Plenum Press, New York, Pp. 53-102

Axelman J., Broman D., 1999. Inventories and fluxes of polychlorinated biphenyles from a contaminated industrial site. Environmental Toxicology and Chemistry 18 (9), 1871–1881.

Baguley J. G., Montagna P. A., Woncheol, L., Hyde L. J., Rowe G. T., 2006a. Spatial and bathymetric trends in Harpacticoida (Copepoda) community structure in the Northern Gulf of Mexico deep-sea. Journal of Experimental Marine Biology and Ecology 330, 327–341.

Baguley, J. G., Montagna, P. A. Hyde, L. J., Kalke, R. D., Rowe, G. T., 2006b. Metazoan meiofauna abundance in relation to environmental variables in the northern Gulf of Mexico deep sea. Deep Sea Research Part I: Oceanographic Research Papers 53, 1344-1362.

Balsam W. L., Beeson J. P., 2003. Sea-floor sediment distribution in the Gulf of Mexico. Deep-Sea Research 50, 1421-1444.

Barnard, J. L., Thomas, J. D., 1989. A new species, *Ampelisca burkei*, (Crustacea: Amphipoda) from Florida. Proceedings of the Biological Society of Washington (Journal) 102, 375-384.

Barnard, J. L., 1954a. Amphipoda of the family Ampeliscidae collected by the *Velero III* in the Caribbean Sea. Allan Hancock Atlantic Expedition Report, 7, 1-13.

Barnard, J. L., 1954b. Amphipoda of the family Ampeliscidae collected in the eastern Pacific Ocean by the Velero III and Velero IV. Allan Hancock Pacific Expedition Report, 18, 1-137.

Barnard, J. L. 1960a. New bathyal and sublittoral ampeliscid amphipods from California, with an illustrated key to *Ampelisca*. Pacific Naturalist 1, 1-36.

Barnard, J.L. 1960b. The amphipod family Phoxocephalidae in the eastern Pacific Ocean, with analyses of other species and notes for a revision of the family. *Allan Hancock Pacific Expedition 18*: 175-368, 75 pls

Barnard, J. L.,1962. Benthic marine Amphipoda of southern California: families Aoridae, Photidae, Ischyroceridae, Corophiidae, Podoceridae. Pacific Naturalist 3, 1 - 72.

Barnard, J. L., 1964. Deep-sea Amphipoda (Crustacea) collected by the *R.V. Vema* in the eastern Pacific Ocean and the Caribbean and Mediterranean seas. Bulletin American Museum Natural History 127(1), 1- 46.

Barnard, J. L., 1961. Gammaridean Amphipoda from depths of 400 to 6000 metres. Galathea Report 5: 23-128.

Barnard, J. L., 1966. Submarine canyons of southern California. Part V, systematics: Amphipoda. Allan Hancock Pacific Expeditions, 27, pp. 1 - 166.

Barnard, J. L., 1969. The families and genera of marine gammaridean Amphipoda. United States National Museum Bulletin 271, pp. 1 - 535.

Barnard, J. L., 1971. Gammaridean amphipods from a deep-sea transect off Oregon. Smithsonian Contributions to Zoology, 61, 1-86.

Benke, A. C., 1979. A modification of the Hynes method for estimating secondary production with particular signifi-cance for multivoltine populations. Limnology and Oceanography 24, 168-171.

Benke, A. C., 1984. Secondary production of aquatic insects. In: Resh, V.H., Rosenberg, D.M. (Eds.), Ecology of Aquatic Insects. Praeger, New York, pp. 289–322.

Benke, A. C., 1993. Concepts and patters of invertebrate production in running waters. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie 25, 15–38.

Berger, W. H., Fischer, K., Lai, C., Wu, G., 1988. Ocean carbon flux: maps of primary production and export production. In: Agegian, C.R. (Ed.), Biogeochemical Cycling and Fluxes Between the Deep Euphotic Zone and other Oceanic Realms. NOAA, Washington, DC, pp. 131–176.

Berthou, F., Vignier V., 1986. Analysis and fate of dibenzothiophene derivatives in the marine environment. International Journal of Environmental Analytical Chemistry 27, 81-96.

Betzer, P. R., Showers, W. J., Laws, E. A., Winn, C. D., Di Tullio, G. R., Kroopnick, P. M., 1984. Primary productivity and particle fluxes on a transect of the equator at 153EW in the Pacific Ocean. Deep-Sea Research 31, 1–11.

Biggs, D. C., Hu, C., Műller-Karger, F .E., 2007. Remotely sensed sea surface chlorophyll and POC flux at Deep Gulf of Mexico Benthos sampling stations. Deep-Sea Research II, In press.

Blankenship, L. E., Yayanos, A. A., Cadien D.B., Levin, L. A., 2006. Vertical zonation patterns of scavenging amphipods from the Hadal zone of the Tonga and Kermadec Trenches .Deep Sea Research Part I: Oceanographic Research Paper 53, 48-61.

Bluhm, B.A., Brey, T., Klages, M., 2001. The autofluorescent age pigment lipofuscin: key to age, growth and productivity of the Antarctic amphipod *Waldeckia obesa* (Chevreux, 1905). Journal of Experimental Marine Biology and Ecology 258, 215-235.

Boetius A, Ferdelman T, Lochte K, 2000. Bacterial activity in sediments of the deep Arabian Sea in relation to vertical flux. Deep-Sea Research II 47, 2835-2875.

Boland, G., Rowe, G., 1991. Deep-sea benthic sampling with the GOMEX box corer. Limnology and Oceanography 35, 1015-1020.

Borja, A. Franco J., Perez, V., 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European Estuarine and Coastal Environments: Marine Pollution Bulletin 40, pp. 1100–1114.

Bosley K. L., Lavelle J. L. Brodeur, R. D., Wakefield W. W., Emmett R. L., Baker E. T., Rehmke K. M., 2004. Biological and physical processes in and around Astoria submarine Canyon, Oregon, USA. Journal of Marine Systems 50 21– 37

Botton, M.L., 1979. Effects of sewage sludge on the benthic invertebrate community of the inshore New York Bight. Estuarine and Coastal Marine Science 8, 169-180.

Bousfield, E. L., 1973. Shallow-water Gammaridean Amphipoda of New England. Cornell University Press, Ithaca, NY, 312 pp.

Brey, T., 2001. Population dynamics in benthic invertebrates. A Virtual Handbook.Version 01.2. http://www.awi-brebremerhaven.de/benthic/Ecosystem /FoodWeb/Handbook.

Brey, T., 1999. Growth performance and mortality in aquatic macrobenthic invertebrates. Advances in Marine Biology 35, 153–223.

Brey, T., Gerdes D., 1998. High Antarctic macrobenthic community production. Journal of Experimental Marine Biology and Ecology 231, 191-200.

Brown, C. J., Lambshead, P.J.D., Smith, C.R., Hawkins, L.E., Farley, R., 2001. Phytodetritus and the abundance and biomass of abyssal nematodes in the central, equatorial Pacific. Deep Sea Research, Part I 48,555–565

Brown, S.S., G.R. Gaston, C.F. Rakocinski, R.W. Heard, J.K. Summers, 2000. Effects of sediment contaminants and environmental gradients on macrobenthic community trophic structure in Gulf of Mexico estuaries. Estuaries 23, 411-424.

Browsky, B., Mezey, E., Hoffman, B. J., 1993. Two glycine transporter variants with distinct localization in the CNS and peripheral tissues are encoded by a common gene. Neuron 10, 851-863.

Buffagni, A., Comin, E., 2000. Secondary production of benthic communities at the habitat scale as a tool to assess ecological integrity in mountain streams Hydrobiologia 422/423, 183–195.

Burden, C.A., 1999. Sediment transport in the Mississippi Canyon: the role of currents and storm events on optical variability. M.S. Thesis. Texas A&M University, College Station, 120pp.

Burnham, K. P., Overton, W. S., 1979. Robust estimation of population size when capture probabilities vary among animals. Ecology 60, 927-936.

Buscail, R., Pocklington, R., Daumas, R. and Guidi, L., 1990. Fluxes and budget of organic matter in the Benthic Boundary Layer over the north-western Mediterranean. Continental Shelf Research 10, 1089- 1122.

Carlson, J. K., Randall, T. A., Mroczka, M. E., 1997. Feeding habits of winter flounder (*Pleuronectes americanus*) in a habitat exposed to anthropogenic disturbance. Journal of Northwest Atlantic Fishery Science 21, 65–73.

Carr, R. S., Long, E. R., Herbert, L. W., Chapman, D. C., Thursby, G., Sloane, G. M and Wolfe, A. W., 1996. Sediment quality assessment studies of Tampa Bay. Florida Environmental Toxicology and Chemistry 15, 1218–1231.

Carrasco F. D., Arcos D. F., 1984. Life history and production of a cold-temperate population of the sublittoral amphipod *Ampelisca araucana*. Marine Marine Ecology Progress Series 14, 245-252.

Cartes J. E., Sorbe J. C., 1999. Estimating secondary production in bathyal suprabenthic peracarid crustaceans from the Catalan Sea slope (western Mediterranean; 391–1255 m). Journal of Experimental Marine Biology and Ecology 239, 195-210.

Cartes, J. E., Brey, T., Sorbe, J. C., Maynou, F., 2002. Comparing production–biomass ratios of benthos and suprabenthos in macrofaunal marine crustaceans. NRC Canadian Journal of Fisheries and Aquatic Sciences 59, 1616–1625.

Cartes, J. E., Elizalde, M., Sorbe, J. C., 2000. Contrasting life-histories and secondary production of populations of *Munnopsurus atlanticus* (Isopoda Asellota) from two bathyal areas of the NE Atlantic and the NW Mediterranean. Marine Biology 136, 881–890.

Chao, A., 1987. Estimating the population size for capture-recapture data with unequal catchability. Biometrics 43, 783-791

Chevreux, E., 1887. Crustacés amphipods nouveaux, drogués par l'Hirondelle, pendant la campagne de 1886. Bulletin de la Société Zoologique de France 12, 566-580.

Chevreux, E., 1900. Amphipodes provenant des campagnes de l'Hirondelle (1885-1888). Résultats des Campagnes Scientifique accomplies Par le Prince Albert 1er de Monaco 16, 1-195.

Ciarelli, S., Straalen, N. M., Klap V. A., Wezel A. P., 1999. Effect of sediment bioturbation by the estuarine amphipod *Corophium volutator* on Fluoranthene resuspension and transfer into the mussel (*Mytilus edulis*). Environmental Toxicology and Chemistry 18(2), 318–328.

Collie, J. S., 1985. Life history and production of three amphipod species on Georges Bank. Marine Ecology Progress Series 22, 229–238.

Collie, J. S., 1987. Food consumption by yellowtail flounder in relation to production of its benthic prey. Marine Ecology Progress Series 36, 205–213.

Cruz-Escalona, V. H., Arreguín-Sánchez, F., Zetina-Rejón M., 2007. Analysis of the ecosystem structure of Laguna Alvarado, western Gulf of Mexico, by means of a mass balance model. Estuarine, Coastal and Shelf Science. In press.

Cusson, M., Bourget, E., 2005. Global patterns of macroinvertebrate production in marine benthic habitats. Marine Ecology Progress Series 297, 1–14.

Dauer, D. M., 1993. Biological criteria, environmental health and estuarine macrobenthic community structure. Marine Pollution Bulletin 26, 249–257.

Dauvin J. C, Joncourt, M., 1989. Energy values of marine benthic invertebrates from the western English Channel. Journal of the Marine Biological Association of the United Kingdom 69, 589-595.

Dauvin J. C., Bellan-Santini, D., 1988. Illustrated key to *Ampelisca* species from the north-eastern Atlantic. Journal of the Marine Biological Association of the United Kingdom, 68, 659-676.

Dauvin, J. C., 1988. Biologie, dynamique, et production de populations de crustacés amphipodes de la Manche occidentale. *Ampelisca tenuicornis* (Liljeborg). Journal of Experimental Marine Biology and Ecology 118, (1), 55-84.

Dauvin, J. C., 1988a. Biologie, dynamique, et production de populations de crustacés amphipodes de la Manche occidentale. *Ampelisca brevicomis* (Costa). Journal of Experimental Marine Biology and Ecology 119, 213-233.

Dauvin, J. C., 1988b. Biologie, dynamique, et production de populations de crustacés amphipodes de la Manche occidentale. *Ampelisca typica* (Bate). Journal of Experimental Marine Biology and Ecology 121, 1-22.

Dauvin, J. C., 1988c. Life cycle, dynamics, and productivity of Crustacea-Amphipoda from the western English Channel. 4. *Ampeliscu urmoricanu* Bellan-Santini et Dauvin. Journal of Experimental Marine Biology and Ecology 123, 235-252.

Dauvin, J. C., 1989. Life cycle, dynamics and productivity of Crustacea-Amphipoda from the western English Channel. 5. *Ampelisca sarsi* Chevreux. Journal of Experimental Marine Biology and Ecology 128, 31-56.

Dayton, P. K., Hessler, R. R., 1972. Role of biological disturbance in maintaining diversity in the deep sea. Deep Sea Research I 19:199-208.

Deegan, J. W., Day, Jr., Gosselink, J.G., Yantiez-Arancibia, A., Chavez, G. S. Sanchez-Gil, P., 1986. Relationships among physical characteristics, vegetation distribution, and fisheries yield in Gulf of Mexico estuaries. In: Wolfe, D. A., (Ed.), Estuarine Variability. Academic Press, New York, pp. 83–100.

Denoux, G., Gardinali, P., Wade, T.L., 1998. Quantitative determination of polynuclear aromatic hydrocarbons by gas chromatography/mass spectrometry—selected ion monitoring (SIM) mode. In: Sampling and Analytical Methods of the National Status and Trends Program, Mussel Watch Project: 1993–1996 Update. NOAA Technical Memorandum NOS ORCA 130, pp. 129–139.

Díaz-Uribe, J. G., Arreguín-Sánchez, F., Cisneros-Mata, M. A., 2007. Multispecies perspective for small-scale fisheries management: A trophic analysis of La Paz Bay in the Gulf of California, Mexico. Ecological Modeling 201, 205-222.

Dickinson, J. J, A.G. Carey, J. R., 1978. Distribution of gammarid Amphipoda (Crustacea) on Cascadia Abyssal Plain (Oregon), Deep-Sea Research I 25, 97-106.

Dickinson, J. J., 1982. The systematics and distributional ecology of the family Ampeliscidae (Amphipoda: Gammaridea) in the northeastern Pacific region. 1. The genus *Ampelisca*. Publications in Biological Oceanography, National Museum of Canada 10, 1–39.

Dolbeth M., Lillebø, A. I., Cardoso, P. G., Ferreira, S. M., Pardal, M. A., 2005. Annual production of estuarine fauna in different environmental conditions: An evaluation of the estimation methods. Journal of Experimental Marine Biology and Ecology 326, 115- 127.

Dolbeth, M., Cardoso, P. G., Ferreira, S. M., Verdelhos, T., Raffaelli D., Pardal M. A., 2007. Anthropogenic and natural disturbance effects on a macrobenthic estuarine community over a 10-year period. Marine Pollution Bulletin, In press.

Downing, J. A., 1984. Assesment of secondary production: the first step: In Downing J. A., Rigler, F. H., (Eds). A Manual on Methods for the Assesment of Secondary Productivity in Fresh Waters. 2nd edition. Blackwell Scientific Publication, Oxford, UK. Pp 1-12.

Dunham, J. S., Duffus, D. A., 2002. Diet of gray whales (*Eschrichtius robustus*) in Clayoquot Sound, British Columbia, Canada. Marine Mammal Science 18, 419-437.

Ellwood B. B., Balsam W. L., Roberts, H. H., 2006. Gulf of Mexico sediment sources and sediment transport trends from magnetic susceptibility measurements of surface samples. Marine Geology 230 (3-4) 237-248.

Eriksson Wiklund, A-K., Wiklund, S.J., Axelman, J., Sundelin, B., 2003. Dynamics of lipids and polychlorinated biphenyls in a Baltic amphipod (*Monoporeia affinis*): a field study. Environmental Toxicology and Chemistry 22 (10), 2499–2507.

Escobar-Briones, E., Winfield, I., 2003. Checklist of the Benthic Gammaridea and Caprellidea (Crustacea: Peracarida: Amphipoda) from the Gulf of Mexico Continental Shelf and Slope. Belgian Journal of Zoology 133, 37-44.

Etter R. J., Grassle J. F., 1992. Patterns of species diversity in the deep sea as a function of sediment particle size diversity. Nature 360, 576–578

Fay A.A., Brownawell B.J., Elskus A.A., McElroy A.E., 2000. Critical body residues in *Ampelisca abdita*: sediment exposures to organic contaminants. Environmental Toxicology and Chemistry 19, 1028-1343.

Folk, R. L., 1974. Petrology of Sedimentary Rocks. Austin, Texas, Hemphill Publ. Co., Austin, Texas.

Franz, D. R., Tanacredi, J. T., 1992. Secondary production of the Amphipod *Ampelisca abdita* Mills and its importance in the diet of juvenile Winter Flounder (*Pleuronectes americanus*) in Jamaica Bay, New York. Estuaries 15, 193–203.

French L. S., Richardson, G., Kazanis, E. G., Montgomery, T. M., Bohannon, C. M., Gravois, M. P., 2006. Deepwater Gulf of Mexico 2006: America's Expanding Frontier. OCS Study MMS 2006-022. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, Louisiana. 148 pp.

Gage, J. D., 1992. Benthic secondary production in the deep sea. In: Rowe, G.T. and Pariente, V. (Eds.), 1992. Deep-sea Food Chains and the Global Carbon Cycle Kluwer Academic Publishers, Dordrecht, The Netherlands. Pp. 199–216.

Gage, J. D., 1997. High benthic species diversity in deep-sea sediments: the importance of hydrodynamics. In: Ormond, R.F.G., Gage, J.D., Angel, M.V., (Eds), Marine Biodiversity. Cambridge University Press, Cambridge. UK. pp 148-177.

Gage, J. D., Lamont, P. A., Tyler, P. A., 1995. Deep-sea macrobenthic community at contrasting sites off Portugal, preliminary results: I. Introduction and diversity comparisons. Internationale Revue der gesamten. Hydrobiologie 80, 235–250.

Gage, J. D., Tyler, P. A., 1991. Deep Sea Biology: A Natural History of Organisms at the Deep-sea Floor. Cambridge University Press, Cambridge, UK 504pp.

Gallagher, E. D., Keay, K. K., 1998. Organism-sediment-contaminant interactions in Boston Harbor. In Stolzenbach, K. D. and Adams, E. E. (Eds.). Contaminated Sediments in Boston Harbor. MIT Sea Grant Press. Pp. 89-132.

Gallaway, B. J., J. G. Cole, R. G. Fechhelm, 2003. Selected aspects of the ecology of the Continental Slope Fauna of the Gulf of Mexico: A Synopsis of the Northern Gulf of Mexico Continental Slope Study, 1983-1988. OCS Study MMS 2003-072. New Orleans, LA: USDOI/MMS, Gulf of Mexico OCS Region. 44 p

Gardner, W. D., 1989. Periodic resuspension in Baltimore Canyon by focusing of internal waves. Journal of Geophysical Research 94, 18185-18194.

Garrigues, P. H. Budzinski, Manitz, M. P., Wise, S. A.,1995. Pyrolytic and petrogenic inputs in recent sediments: a definitive signature through phenanthrene and chrysene compounds distribution. Polycyclic Aromatic Compounds 7 275–284.

Gaston, G. R., Vittor, B. A., Barrett., B., 1998. Benthic communities of Louisiana coastal waters. Louisiana Department of Wildlife and Fisheries Bulletin Number 45. 183 Pp.

Gili J.M., Coma R., 1998. Benthic suspension feeders: their paramount role in littoral marine food webs. Trends in Ecology & Evolution 13:316–321

Goeke, G. D., Heard, R. W. Jr., 1983. Amphipods of the family Ampeliscidae (Gammaridea). I. *Ampelisca bicarinata*, a new species of amphipod from the Gulf of Mexico. Gulf Research Report, 7, 217-223.

Gómez-Gesteira, J.L., Dauvin, J.-C. , 2000. Amphipods are good bioindicators of the impact of oil spills on soft-bottom macrobenthic communities. Marine Pollution Bulletin 40, 1017–1027.

González, P., Oyarzún, C., 2004. Diet of the Chilean sandperch, *Pinguipes chilensis* (Perciformes, Pinguipedidae) in southern Chile. Journal of Applied Ichthyology, 19, 371-375.

Grosse, D. J., Pauley, G. B., Moran., D., 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--amphipods. U.S. Fish Wildlife Service Biological Report 82(11.69). U.S. Army Corps of Engineers, TR EL-82-4.

Hamilton, A. L., 1969. On estimating annual production. Limnology and Oceanography 14: 771–782.

Hatch A. C.,. Burton, G. A Jr., 1999. Photo-induced toxicity of PAHs to *Hyalella azteca* and *Chironomus tentans*: effects of mixtures and behavior. Environmental Pollution 106, 157-167.

Hermsen, J. M., Collie, J. S., Valentine, P. C. 2003. Mobile fishing gear reduces benthic megafauna production on Georges Bank. Marine Ecology Progress Series 260:97-108.

Highsmith R. C., Coyle, K., Bluhm B., Konar, B., 2005. Amphipod prey of gray whales in the northern Bering Sea: changes in abundance and distribution. May 16-20, 2005, at the Victoria Conference Centre in Victoria, British Columbia, Canada.

Highsmith, R. C., Coyle, K. O., 1990. High productivity of northern Bering Sea benthic amphipods. Nature 344, 862–864

Ho, K. T., Mckinney, R. A., Khun, A., Pelletier, M. C. and Burgess, R. M., 1997. Identification of acute toxicants in New Bedford Harbor Sediments. Environmental Toxicology and Chemistry 16, 551–557.

Hobson, K. A., Fisk, A., Karnovsky, N., Holst, M., Gagnon, J.-M., Fortier, M., 2002. A stable isotopic (d13C, d15N) model for the North Water food web: implications for evaluating trophodynamics and the flow of energy and contaminants. Deep-Sea Research II 49, 5131- 5150.

Holmes, S. J., 1908. The Amphipoda collected by the U.S. Bureau of Fisheries steamer "Albatross" off the west coast of North America, in 1903 and 1904, with description of a new family and several new genera and species. Proceeding of the United Sates National Museum, 35, 489-543, 46 text figs.

Houston, K. A., Haedrich, R. L., 1984. Abundance and biomass of macrobenthos in the vicinity of Carson Canyon, northwest Atlantic ocean. Marine Biology, 82, 301-305

Hurlbert, S. H., 1971. The non-concept of species diversity: a critique and alternative parameters. Ecology 52, 577–586.

Huston, M., 1979. A general hypothesis of species diversity. American Naturalist 113: 81–101.

Hynes-Hamilton, H. B. N.,Coleman, M. 1968. A simple method for assessing the annual production of stream benthos. Limnology and Oceanography 13, 569–573.

Kaim-Malka, R. A., 2000. Elevation of two eastern Atlantic varieties of *Ampelisca brevicornis* (Costa, 1853) (Crustacea: Amphipoda) to full specific rank with redescription of the species. Journal of Natural History 34, 1939-1966.

Kaiser, M. J., Spencer, B. E., 1994. Fish scavenging behaviour in recently trawled areas. Marine Ecology Progress Series 112, 41–49.

Kaiser, M. J., Pulsipher, A. G, 2004. A binary choice severance selection model for the removal of offshore structures in the Gulf of Mexico. Marine Policy, 28 97-115.

Kennicutt, M. C. II , J. L. Sericano, T. L. Wade, F. Alcazar, Brooks, J. M., 1987. High molecular weight hydrocarbons in Gulf of Mexico continental slope sediments Deep Sea Research Part A. Oceanographic Research Papers 34, 403-424.

Klein, G., Rachor, E., and Gerlach, S. A. 1975. Dynamics and production of two populations of the benthic tube-dwelling Amphipod *Ampelisca brevicornis* (Costa) in Helgoland Bight. Ophelia 14, 139–159.

Kropp, R. K., 2004. Review of Deep-Sea Ecology and Monitoring as They Relate to Deep-Sea Oil and Gas Operations. PNNL-14540, Pacific Northwest National Laboratory, Richland, WA.

Lambshead, P. J. D., Platt, H. M., Shaw, K. M., 1983. The detection of differences among assemblages of marine benthic species beased on an assessment of dominance and diversity. Journal of Natural History 17, 859-874

Landrum P. F., Tigue, E. A., Driscoll, S. K., Gossiaux, D. C., Van Hoof1, P. L., Gedeon, M. L., Adler, M., 2001. Bioaccumulation of PCB Congeners by *Diporeia* spp.

kinetics and factors affecting bioavailability. Journal of Great Lakes Research. 27(2), 117–133

Landrum, P. F., Robbins, J. A., 1990. Bioavailability of sediment associated contaminants: A review and simulation model. In Sediments: Chemistry and Toxicity of In-Place Pollutants. Baudo, R., Giesy, J. P., Muntau, H., Eds. pp. 237–263. Lewis Publishers, Chelsea, MI.

Lee H., 1992. Models, muddles, and mud: Predicting bioaccumulation of sediment-associated pollutants. In: Burton A.G., (Ed.), Sediment Toxicity Assessment. CRC, Boca Raton, FL, 267–293.

Levin, L. A., Etter, R. J., Rex, M. A., Gooday, A. J., Smith, C. R., Pineda, J., Stuart, C. T., Hessler,R. R., Pawson, D., 2001. Environmental influences on regional deep-sea species diversity. Ann. Rev. Ecol. Syst. 132: 51-93.

Levin, L. A., Gage, J. D., Martin, C., Lamont, P. A., 2000. Macrobenthic community structure within and beneath the oxygen minimum zone, NW Arabian Sea. Deep-Sea Research Special Volume: Benthic Processes in the Arabian Sea. Deep-Sea Research Part II 47, 189-226.

Lincoln R., 1979. British Marine Amphipoda: Gammaridea, British Museum (Natural History), London, 657 pp

Mahaut, M.L., Sibuet, M., Shirayama, Y., 1995. Weight-dependent respiration rates in deep-sea organisms. Deep Sea Research 42:1575-1582.

Marquiegui, M. A., Sorbe, J. C., 1999. Influence of near-bottom environmental conditions on the structure of bathyal macrobenthic crustacean assemblages from the Capbreton canyon (Bay of Biscay, NE Atlantic). Acta Oecologica 20, 353-362.

Mayer-Pinto, M., Junqueira, A. O. R., 2003. Effects of organic pollution on the initial development of fouling communities in a tropical bay, Brazil. Marine Pollution Bulletin 46, 1495-1503.

McAleece, N., Lambshead, P. J. D., Paterson, G. L. J., Gage, J. D., 1996. Biodiversity Pro. A program for analyzing ecological data, http://www.nrmc.demon.co.uk.

McElroy, A.E., Farrington, J.W., Teal, J. M., 1990. Influence of mode of exposure and the presence of a tubiculous polychaete on the fate of benzo(a)anthracene in the benthos. Environmental Science& Technology 24, 1648–1655.

McHugh, C. M., Ryan, W. B. F., Hecker, B., 1992. Contemporary sedimentary processes in the Monterey Canyon-fan system. Marine Geology 107, 35-50.

Mclusky, D. S., 1989. The Estuarine Ecosystem, 2nd Ed. Chapman and Hall, London. 215 pp.

Meador, J. P., 2003. Bioaccumulation of PAHs in marine invertebrates. In: PAHs: An Ecological Perspective. Douben P.E.T. (Ed.), John Wiley and Sons, Pubs., Chichester, Uk, Chapter 9, pp. 147-171.

Menzies, C.A., 1980. A note on the Hynes–Hamilton method of estimating secondary production. Limnology and Oceanography 25 (4), 770-773.

Metaxas, A., Giffin, B., 2004. Dense beds of the ophiuroid *Ophiacantha abyssicola* on the the continental slope off Nova Scotia, Canada. Deep-Sea Research Part I: Oceanographic Research Papers 51 (10), 1307-1317.

Mills, E., 1963. A new species of *Ampelisca* (Crustacea: Amphipoda) from eastern North America, with notes on other species in the genus. Canadian Journal of Zoology 41, 971-989.

Mills, E. 1964. *Ampelisca abdita*, a new amphipod crustacean from eastern North America. Canadian Journal of Zoology 42, 559-575.

Mills, E. 1965. The zoogeography of North Atlantic and North Pacific ampeliscid amphipod crustaceans. Systematic Zoology 14(2), 119-130.

Mills, E. 1967a. The biology of an amphipod ampeliscid crustacean sibling species pair. Journal of Fisheries Research Board of Canada 24, 305-355.

Mills, E. 1967b. A reexamination of some species of *Ampelisca* (Crustacea: Amphipoda) from the east coast of North America. Canadian Journal of Zoology 45, 635-652.

Mills, E. 1971. Deep-sea Amphipoda from the western North Atlantic Ocean. The family Ampeliscidae. Limnology and Oceanography 16 (2), 357-386.

Mitra, S., Bianchi, T. S., 2003. A preliminary assessment of polycyclic aromatic hydrocarbon distributions in the lower Mississippi River and Gulf of Mexico, Marine Chemistry 82, 273-288.

Morin, A., Bourassa, N., 1992. Mode`les empiriques de la production annuelle et du rapport P/B d'inverte´bre´s benthiques d'eau courante. Canadian Journal of Fisheries and Aquatic Sciences 49, 532– 539.

Morin, A., Mousseau T. A., Roff, D. A., 1987. Accuracy and precision of secondary production estimates. Limnology and Oceanography 32, 1342-1352.

Morrison, H.A., Gobas, F.A.P.C., Lazar, R., Haffner, G.D., 1996. Development and verification of a bioaccumulation model for organic contaminants in benthic invertebrates. Environmental Science and Technology 30(11), 3377-3384.

Morse, J., Beazley, 2006. Organic matter in deep-water sediments of the northern Gulf of Mexico and its relationship to the distirbution of benthic organisms. This volume.

Neff, J.M., 1995. Polycyclic aromatic hydrocarbons. In: B.L. Donley and M. Dorfman (Eds.), Fundamantals of Aquatic Toxicology: Methods and Applications. Hemisphere Publishing Corporation, pp. 416–454.

Nerini M. K., Oliver J. S., 1983. Gray whales and the structure of the Bering Sea benthos. Oecologia 59, 224-225.

National Oceanic and Atmospheric Administration (NOAA). 1998 (on-line). "Monitoring the Coastal Environment" by Robertson, A., Orlando, P., Turgeon, D. NOAA's State of the Coast Report. Silver Spring, MD: NOAA. URL: http://state_of_coast.noaa.gov/bulletins/html/mcwq_12/mcwq.html

Nyssen, F., Brey, T., Lepoint, G., Bouquegneau, J., De Broyer, C., Dauby, P., 2002. A stable isotope approach to the eastern Weddell Sea trophic web: focus on benthic amphipods. Polar Biology 25, 280 - 287.

Occhipinti-Ambrogi, A. O., Savini, D., Forni, G., 2005. Macrobenthos community structural changes off Cesenatico coast (*Emilia Romagna*, Northern Adriatic), a six-year monitoring programme. Science of The Total Environment 15, 353(1-3), 317-28.

Odum, E.P., 1985. Trends expected in stressed ecosystems. BioScience 35(7): 419-422.

Ohta, S., 1983. Photographic census of large-sized benthic organisms in the bathyal zone of Suruga Bay, central Japan. Bulletin of the Ocean Research Institute 15, 244pp.

Paterson G.L.J., Lambshead, P.J.D., 1995. Bathymetric patterns of polychaete diversity in the Rockall Trough, north-east Atlantic. Deep-Sea Research 42:1199–1214

Pearson, T. H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanographic Marine Biology Annual Review. 16: 229-311.

Pequegnat, W.E., 1983. The ecological communities of the continental slope and adjacent regimes of the northern Gulf of Mexico. Final report to the U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, La. Contract No. AA851-CT1-12.

Peterson, C.H., Kennicutt II, M.C., Green, R.H., Montagna, P., Harper Jr., D.E., Powell, E.N. and Rosigno, P.F., 1996. Ecological consequences of environmental perturbations associated with offshore hydrocarbon production: a perspective on long-term exposures in the Gulf of Mexico. Canadian Journal of Fisheries and Aquatic Sciences 53, pp. 2637–2654.

Plante, C., Downing, J. A., 1989. Production of freshwater invertebrate populations in lakes. Canadian Journal of Fisheries and Aquatic Sciences 46, 1489-1498.

Powell, S. M., Haedrich R. L., McEachran, J. D., 2003. The deep-sea fish fauna of the northern Gulf of Mexico. Journal of Northwest Atlantic Fishery Science 31, 19-33.

Qian, Y., Jochens, A.E., Kennicutt II, M.C., Biggs, D.C., 2003. Spatial and temporal variability of phytoplankton blooms and community structure over the continental margin of the northeast Gulf of Mexico based on pigment analysis. Continental Shelf Research 23, 1–17.

Qian, Y., Sericano, J.L., Wade, T.L., 1998. Extraction and Clean-up of Sediments for Trace Organic Analysis. In: Sampling and Analytical Methods of the National Status and Trends Program, Mussel Watch Project: 1993-1996 Update. NOAA Technical Memorandum NOS ORCA 130, 94-97.

Quiroga, E., Quiñones, R.A., Palma, M., Sellanes, J., Gallardo, V.A., Gerdes, D., Rowe, G., 2005. Biomass size-spectra of macrobenthic communities in the oxygen minimum zone off Chile. Estuarine, Coastal and Shelf Science 62, 217-231.

Rachor, E, Arntz, W. E., Rumohr, H., Mantau , K.H., 1982. Seasonal and long-term population fluctuations in Diastylis rathkei (Crustacea: Cumacea) of Kiel Bay and German Bight. Neth J Sea Res 16:141–150

Reid, D. M., 1951. Report on the Amphipoda (Gammaridea and Caprellidea) of the coast of tropical West Africa. Atlantide Report 2, 189-291.

Reish, D.J., and Barnard, J.L. 1979. "Amphipods." Pages 345 to 370. In: C.W. Hart and S.L.H. Fuller, Jr., eds. Pollution Ecology of Estuarine Invertebrates. Academic Press. New York.

Rex, M.A., Etter, R.J., Stuart, C.T., 1997. Large-scale patterns of species diversity in the deep-sea benthos. In: Ormond RFG, Gage JD, Angel MV (Eds.). Marine biodiversity. Cambridge University Press, Cambridge, p 94–121

Rex, M.A., 1973. Deep-sea species diversity: decreased gastropod diversity at abyssal depths. Science 181, 1051–1053.

Rex, M.A., 1981. Community structure in the deep-sea benthos. Annual Review of Ecology and Systematics 12, 331–353.

Rex, M.A., 1983. Geographic patterns of species diversity in the deep-sea benthos. In: Rowe, G.T. (Ed.), The Sea, vol. 8. Wiley, New York, pp. 453–472.

Rhoads, D. C., P. L. McCall, and J. L. Yingst. 1978. Disturbance and production on the estuarine seafloor. American Scientist 66 577-586.

Robertson, A. 1998. Petroleum hydrocarbons. In: AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 661–716.

Rogers, A., D., Billett, W., Berger, E., Flach, A., Freiwald, J., Gage, D., Hebbeln, C., Heip, O., Pfannkuche, E., Ramirez-Llodra, L., Medlin, M., Sibuet, K., Soetaert, O., Tendal, A., Vanreusel, M., Wlodarska-Kowalczuk, 2003. Life at the edge: Achieving prediction from environmental variability and biological variety. In: Wefer, G., Billett, D. S. M., Hebbeln, D., Jørgensen, B. B., Schlüter, M., Van Weering, T. C. E. (Eds.), Ocean Margin Systems, Springer-Verlag, Berlin. Pp. 387-404.

Rowe, G.T., 1971. Benthic biomass and surface productivity. In: Fertility of the Sea. Vol. 2. Costlow Jr., J.D. (Ed.), Gordon and Breach, New York, p. 441-454.

Rowe, G.T., Sibuet, M., Deming, J., Khripounoff, A., Tietjen, J., 1991. ‘Total’ sediment biomass and preliminary estimates of organic carbon residence time in deep-sea benthos. Marine Ecology Progress Series 79, 99-114.

Rowe, G. T. 1983. Biomass and production of the deep-sea benthos. In G. T. Rowe (Ed.), The Sea. Vol. 8 Wiley and Sons, New York.

Rowe, G. T., Menzel, D. W., 1971. Quantitative benthic samples from the deep Gulf of Mexico with some comments on the measurement of deep-sea biomass. Bulletin of Marine Science 21:556-566.

Rowe, G. T., Polloni, P. T., Haedrich R. L., 1982.The deep-sea macrobenthos on the continental margin of the northwest Atlantic Ocean. Deep Sea Research Part A. Oceanographic Research Papers 29 (2), 257-278.

Rowe, G.T., Kennicutt II, M.C., 2002. Deepwater program: Northern Gulf of Mexico continental slope habitats and benthic ecology; Year 2: Interim report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2002-063

Sainte-Marie, B., 1992. Foraging of scavenging deep-sea lysianassoid amphipods. In: Rowe, G. T., Pariente, V., (Eds.) Deep-sea Food Chains and the Global Carbon Cycle. Kluwer, London, pp 105-124

Sainte-Marie, B., 1991. A review of reproductive bionomics of aquatic gammaridean amphipods: variation of life history traits with latitude, depth, salinity and superfamily. Hydrobiologica. 223, 189-227.

Sanders, H.L., 1968. Marine benthic diversity; a comparative study. American Naturalist 102(905), 243-282.

Santschi, P.H., Presley, B.J., Wade, T.L., Garcia-Romero, B., and Baskaran, M. 2001. Historical contamination of PAHs, PCBs, DDTs, and heavy metals in Mississippi River Delta, Galveston Bay and Tampa Bay sediment cores. Marine Environmental Research 52, (1), 51-79.

Sassen, R., Losh, S. L., Cathles, III, L., Roberts, H. H , Whelan, J. K., Milkov, A. V. Sweet, S. T., and DeFreitas, D. A., 2001. Massive vein-filling gas hydrate: relation to ongoing gas migration from the deep subsurface in the Gulf of Mexico. Marine and Petroleum Geology 18 (5), 551-560.

Serejo, C. S., Wakabara, Y. & Valério- Berardo, M.T. (2000) Taxonomy and geography distribution of *Ampelisca* (Amphipoda : Gammaridea) from the Brazilian coast. *Polskie Archiwum Hydrobiologii*, 47 (3–4), 495–510.

Shepard, F. P., Dill, R. F., 1966. Summary characteristics and dimensions of submarine canyons. In: Shepard, F. P.; Dill, R. F. (Eds.), Submarine Canyons and Other Sea Valleys. Rand McNally, Chicago, pp. 223- 231.

Sibuet, M., Lambert, C.E., Chesselet, R., Laubier, L., 1989. Density of the major size groups of benthic fauna and trophic input in deep basins of the Atlantic Ocean. Journal of Marine Research 47, 851-867.

Sokal, R. S., Rholf, F. S, 1979. Biometría. Blume, Barcelona. 832 p.

Soliman Y. S., Wade, T. L., 2007. Estimates of PAHs burdens in a population of ampeliscid amphipod carpeted the head of the Mississippi Canyon (N. Gulf of Mexico). Deep Sea Research II (submitted).

Soliman Y., Wicksten, M., 2007. *Ampelisca mississippiana,* a new species (Amphipoda: Gammaridea) from the Mississippi Canyon (northern Gulf of Mexico), Zootaxa 1389, 45-54.

Sporstol, S., Gjos, N., Lichtenthaler, R.G., Gustavsen, K.O.,Urdal, K., Oreld, F., Skel, J., 1983. Source identification of aromatic hydrocarbons in sediments using GC-MS. Environmental Science and Technology 17, 5. 282–286.

Statzner B., Moss B., 2004. Linking ecological function, biodiversity and habitat: a mini-review focusing on older ecological literature. Basic and Applied Ecology, 5, 97-106.

Steimle, F. W., 1982. The benthic macroinvertebrates of the Block Island Sound. Estuarine, Coastal and Shelf Science 15, 1-16.

Stienhauer, M. S., Boehm, P. D., 1992. The composition and distribution of saturated and aromatic hydrocarbons in near shore sediments, river sediments, and coastal peat of the Alaskan Beaufort Sea: Implications for detecting anthropogenic inputs. Marine Environmental Research 33, 223-253.

Stimpson, W., 1864. Synopsis of the marine Invertebrata collected by the late Arctic Expedition, under Dr. J. J. Hayes. Proceedings of the Academy of Natural Sciences, Philadelphia,15, 138-142.

Sudo, H., Azeta, M. 1996. Life history and production of the amphipod *Byblis juponicus* Dahl (Gammaridea: Ampeliscidae) in a warm temperate zone habitat, Shijiki Bay, Japan. Journal of Experimental Marine Biology and Ecology 198, 203-222.

Swartz, R. C., Cole, F. A., Schultz, D. W. and W. A. DeBen. 1986. "Ecological Changes on the Palos Verdes Shelf Near a Large Sewage Outfall: 1980-1983." Marine Ecology: Progress Series. 31, 1-13.

Thomas, J. D, 1993. Biological monitoring and tropical biodiversity in marine environments: a critique with recommendations, and comments on the use of amphipods as bioindicators. Journal of Natural History 27, 795-806.

Thurston, M., 1979. Scavenging abyssal amphipods f rom the North-east Atlantic Ocean, Marine Biology 51, 55- 68.

Tumbiolo, M.L., Downing, J.A., 1994. An empirical model for the prediction of the secondary production of marine benthic invertebrates. Marine Ecology Progress Series 114, 165-174.

United States Environmental Protection Agency (USEPA). 1995. CRITFC exposure study. Water Quality Criteria and Standards Newsletter. USEPA, Washington, DC.

Venkatesan, M. I., 1988. Occurrence and possible sources of perylene in marine sediments - a review. Marine Chemistry 25, 1-27.

Vetter E. W., Dayton P. K., 1998. Macrofaunal communities within and adjacent to a detritus-rich submarine canyon system. Deep-Sea Research Part II: Topical Studies in Oceanography, 45(1-3), 25-54.

Vetter E.W.,1998. Population dynamics of a dense assemblage of marine detritivores. Journal of Experimental Marine Biology and Ecology 226(1), 131-161.

Vetter, E. W. 1994. Hotspots of benthic production. Nature 372- 47.

Volkman, J.K., Alexander, R., Kagi, R.I., Rowland, S.J., and Sheppard, P.N., 1984. Biodegradation or aromatic hydrocarbons in crude oils from the Barrow Sub-basin of Western Australia. Organic Geochemistry 6, 619-632.

Wade, T.L, Wolff, G.A. and Presley B.J., 2005. Contaminant Chemistry: Polycyclic Aromatic Hydrocarbons (PAH) and Trace Elements (TE) Northern Gulf of Mexico Continental Slope Habitat and Benthic Ecology Study Results. McKay, M. and J. Nides, (Eds.), 2005. In: Proceedings 23ed. Gulf of Mexico information transfer meeting, January 2005. U.S. Dept. of the Interior, Mineral Management Service, Gulf of Mexico OCS Region, New Orleans, La. OCS Study MMS 2005-006. 44-4

Wade, T.L., Soliman Y. S., Sweet S. T., Wolff G. A., Presley B. J., 2007. DGoMB Trace elements and polycyclic aromatic hydrocarbons (PAH). Deep-Sea Research II (Submitted)

Warwick, R.M., Clarke, K.R., 1991. A comparison of some methods for analyzing changes in benthic community structure. Journal of the Marine Biological Association of the United Kingdom 71, 225–244.

Waters, T.F., 1977. Secondary production in inland waters. Advances in Ecological Research 10, 91-164.

Waters, T.F., 1979. Influence of benthic life history upon the estimation of secondary production. Journal Fisheries Research Board of Canada 36, 1425-1430.

Watling, L., 1995. Chapter 3. The Families Ampeliscidae, Amphilochidae, Liljeborgiidae, and Pleustidae. In: Taxonomic Atlas of the Benthic Fauna of the Santa Maria Basin and Western Santa Barbara Channel. Vol. 12, pp. 137-176. Special Publications of the Santa Barbara Museum of Natural History, Santa Barbara , California.

Weaver, P. E. , Billett D. S. M., Boetius A. , Danovaro, R., Freiwald A., Sibuet, M.,2004. Hotspot ecosystem research on Europe's Deep-Ocean Margins. Oceanography 17, 132-143.

Wei, C.L., Rowe, G.T., Hubbard, F., Scheltema, A. H., Wilson, G.D., Petrescu, I, Forster, J., Wicksten, M.K., Davenport, R., Chen, M., Soliman, Y., Wang, Y., 2007. The Bathymetric Zonation and Community Structure of Deep-Sea Macrobenthos in the Northern Gulf of Mexico. Deep-sea Reasearch II (Submitted).

Wildish, D. J., 1984. Secondary production of four sublitoral amphipod populations in the Bay of Fundyzdult-larval interactions in dense infaunal assemblages: patterns of abundance. Journal of Marine Research 34, 25-41.

Yang G.P.; Zhang Z.B, 1997. Adsorption of Dibenzothiophene on marine sediments treated by a sequential procedure. Journal of Colloid and Interface Science 192(2), 398-407.

Yanga, G. P., Liu, X.L., Zhang J.W., 1998. Distribution of dibenzothiophene in the sediments of the South China Sea. Environmental Pollution 101, 405-414.

Young, B.L., Padilla, D.K., Schneider, D.W., and Hewett, S.W., 1996. "The importance of size-frequency relationships for predicting ecological impact of zebra mussel populations,". Hydrobiologia 332, 151-158.

Yunker, M.B., Macdonald, R.W., 1995. Composition and origins of polycyclic aromatic hydrocarbons in the Mackenzie River and on the Beaufort Sea shelf. Arctic 48(2), 118-129.

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PUBLICATIONS:

1.1. Y. S. Soliman and M. K. Wicksten, 2007. *Ampelisca mississippiana*; A new species (Amphipoda, Gammaridae) from the Mississippi Canyon (N. Gulf of Mexico). Zootaxa 1389, 45-54.

1.2. Y. S. Soliman, and G.T. Rowe, 2007. Secondary Production of *Ampelisca mississippiana* Soliman and Wicksten 2007 (Amphipoda, Crustacea) in the Head of the Mississippi Canyon, Northern Gulf of Mexico. Deep Sea Research (In press).

1.3. Y. S. Soliman and T. L. Wade, 2007. Estimates of PAHs burdens in a population of ampeliscid amphipod carpeted the head of the Mississippi Canyon (N. Gulf of Mexico). Deep Sea Research (Submitted).

1.4. Y. S. Soliman and G. T. Rowe, 2007. Deep water amphipods down transects within and adjacent to the Mississippi Canyon (N. Gulf of Mexico). Deep Sea Research (In correction).

1.5. T. L. Wade, Y.S. Soliman, S. T. Sweet, G. A. Wolff and B. J. Presley. DeGoMB Trace Elements and Polycyclic Aromatic Hydrocarbons (PAHs). Deep Sea Research (In press).

1.6. Gilbert T. Rowe, Chihlin Wei, Clif Nunnally, Richard Haedrich, Paul Montagna, Jeff Baguley, Joan Bernhard, Mary Wicksten, Archie Ammons, Elva G. Escobar Briones, Yousra Soliman, Jody Deming, 2007. Food Web Analysis in the Deep Gulf of Mexico. Deep Sea Research (submitted).

1.7. Chih-Lin Wei, Gilbert T. Rowe, G. Fain Hubbard, Amélie H. Scheltema, George D. F. Wilson, Iorgu Petrescu, John M. Forster, Mary K. Wicksten, Roe Davenport Min Chen, Yousria Soliman, Yuning Wang, 2007. The Bathymetric Zonation and Community Structure of Deep-Sea Macrobenthos in the Northern Gulf of Mexico.