STUDY OF TAPHONOMIC ATTRIBUTES AND MAJOR MECHANICAL PROPERTIES OF MOLLUSCAN SHELLS FROM CHILIKA LAKE, ODISHA, INDIA

SUBMITTED BY,

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DEDICATION

This thesis is dedicated to my parents R.K Subba and Panna Subba for their love and support who has always been an inspiration for me.

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ABSTRACT

It is the natural selection over millions of years, which make mollusc shells to develop their unique shell structure and mechanical properties to protect themselves from attack by predators. The mechanical function of shell depends upon its ability to resist deformation and failure under imposed environmental stresses. The shell is predominantly made up of $CaCO_3$. The effect of shell microstructure, bonding strength of calcite crystals and intercalations with organic portion,on overall mechanical behaviour is significant towards its adaptation with time. These were contemplated and investigated by researchers in recent past but still the understanding is modest.

In the present investigation an attempt has been made to study the variation of mechanical characteristics of predominant bivalve shells collected from the Eastern fringe of Chilika Lake, Odisha, India, namely *Anadara granosa*, *Meretrix meretrix* and *Sunetta meroe*. Different taphonomic attributes like abrasion, fragmentation, bioerosion and dissolution along with disparity of mechanical properties were studied. Variations of Spatial thickness and density of shells were estimated and correlated with specific ecological niches.

Investigations regarding the same shows interesting trends and correlations from a taphonomic study and with tested mechanical behaviours. This study may be related to the causes for unique behaviour of molluscs and possible functional significance of the shell structures.

CERTIFICATE FROM THE SUPERVISOR

This is to certify that Mr. Rohan Subba has worked under the supervision of Dr. Anupam Ghosh and Dr. Susanta Chaudhuri, Assistant Professors in the Department of Geological Sciences, Jadavpur University and completed his thesis entitled "**Study of taphonomic attributes and major mechanical properties of molluscan shells from Chilika lake, Odisha, India**" which is being submitted towards the partial fulfilment of his M.Sc. Final Examination in Applied Geology of Jadavpur University in 2019.

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CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Introduction

Shells protect the soft anatomy of molluscs from abiotic and biotic stresses, and vary dramatically within species in response to spatial and temporal environmental variation (Vermeij 1978). Molluscan shells evolved initially during the Paleozoic, probably as antipredator structures in response to the diversification of highly efficient and mobile metazoan predators. Both structure and composition determine how effective a shell is in reducing predation. In addition the shell also plays an important role in the burrowing and boring processes. Even after the death of molluscs, the taphonomic processes acts differently on it.

Shell strength can also be influenced by its microstructure, since the ability to resist breaking forces varies among microstructural types (Vermeij & Currey 1980, Currey 1988). Shells can be reinforced against predation by altering their orientation, composition, or number of microstructural layers (Currey & Kohn 1976, West & Cohen 1996).Thus there is a need to investigate the mechanical properties of the shell materials in relation to their possible functional significance and shell strength to resist stress conditions.

Chilika, Odisha on the east coast of India inhabits diverse molluscan communities. So, sampling of the bivalvian shells from Chilika and measurement of taphonomic attributes mechanical tests such a microhardness tests, area, density and thickness were performed and its correlation with the environmental conditions was the main aim of this dissertation.

1.2 Objectives

- To study the various taphonomic attributes that acts on the bivalvian shell after its death.
- To construct taphograms based on the degree to which the taphonomic attributes affects the shells
- To determine the major mechanical characteristics of a bivalvian shell and representing the variation of the properties such as density, thickness, microhardness and area of a shell in a systematic way along the centre line of the shells from the commissure line to the umbo
- To estimate the degree of importance that the mechanical properties have in determining which species of bivalves and the particular zone of bivalvian shell that is prone to predation

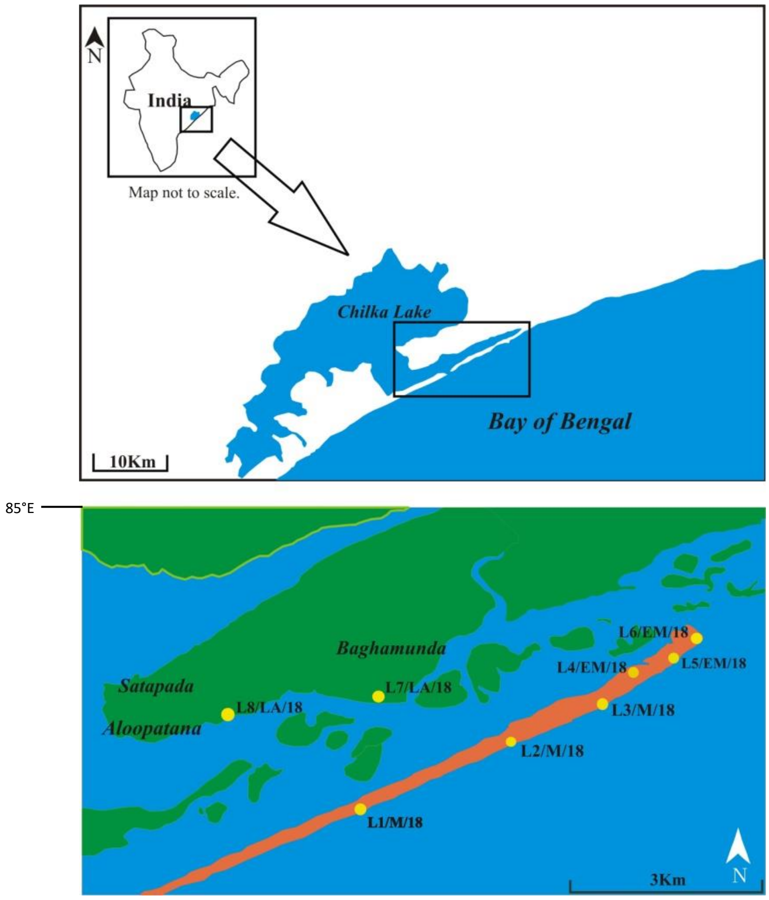
CHAPTER 2

STUDY OF THE FIELD AREA

Chilika Lake (eastern fringe), Odisha was the field area for the dissertation work. It is rich in molluscan shells which facilitated easy collection of samples.

2.1 Location

Chilika Lake (Figure 1a)is a brackish water lagoon, spread over the Puri, Khurda and Ganjam districts of Odisha state on the east coast of India, at the mouth of the Daya River, flowing into the Bay of Bengal, covering an area of over 1,100 km^2. It is located at 19^0 43'N & 85^0 19'E. It is the largest coastal lagoon in India and the second largest coastal lagoon in the world.



Legend: (L1 –L8) Location no. M – Marine, EM – Estuary Mouth, LA – Lake.

Fig 2.1 Location Map and sampling stations of Chilika lake, Odisha, India.

2.2 Accessibility

The lake is well connected by road to Kolkata and Chennai through National Highway No.5. Satpada town towards the eastern bank of the lake is about 50 kms by road southwest of the city of Puri and at a distance of 100 km from Bhubaneswar, the capital of Odisha, which is also the nearest airport. A broad gauge railway line of the South Eastern Railway from Kolkata flanks along the western bank of the lake passing through Chilka, Balugaon and Rambha stations.

2.3 Climate

A tropical monsoon climate prevails over the basinal area of the lake. It experiences South-west and North – east monsoons during the month of June to September and November to December respectively with about 72 rainy days and an average annual rainfall of 1,238.8mm. The maximum temperature of 39.9 C and minimum temperature of 14 C have been recorded. The variation in wind speed is from 5.3 to 16 meters/ hour with southerly and southwesterly direction due to the influence of South west monsoon and from north and north easterly direction during the rest of the months.

2.4 Flora and Fauna

Chilika Lake was designated the first Indian wetland of international importance under the Ramsar Convention in 1981, due to its rich biodiversity. Recent surveys revealed an overall 726 species of flowering plants belonging to 496 genera and 120 families. Fabaceae is the most dominant plant family followed by Poaceae and Cyperaceae. It is also the largest wintering ground for migratory birds, on the Indian sub-continent. Species listed in the IUCN Red List of Threatened Species inhabit the lake for at least part of their lifecycle. Large flocks of greater flamingos, Goliath herons, egrets, spoonbills, storks , white bellied sea eagle, pariah kite, marsh harriers, peregrine falcon are some of the birds seen in the Lake. The Irrawaddy dolphin (*Orcaella brevirostris*) is the flagship species of Chilika lake.As for molluscs a total of 324 species : 170 species of gastropods, one species of scaphopod, 147 species of bivalves and six species of Cephalopods were reported in the paper (Fauna of Orissa, Zoological Society of India)

2.5 Physiography and Drainage

Chilika Lake, water varies from 0.3 m to 0.8 m in the dry season to 1.8 m to 4.2 m in the rainy season. The lake has a maximum length of 64.3 km with a mean width of 20.1 km.It has a maximum depth of 4.2 m and a water volume of 4 km^3. A 32 km long outer channel connects the lake with the Bay of Bengal at Arakhuda village.

2.6 Population and Occupation

The main settlements are Puri and Satpada.. Fishing serves as an important resource within the the regional economy besides providing a source of high quality of protein for local consumption. Chilika fish are exported to markets (largely in Kolkata) providing a significant source of revenue for numerous participants in the fishery. Due to current export potentiality and high price obtained from landed prawns, they continue to maintain an important position in the commercial fishery within the lagoon. Other occupation for the people of Chilika includes tourism due to its rich biodiversity.

2.7 Geological Settings of Chilika

The lake is estuarine in character in an ephemeral environment. Geological study has indicated that the coastline extended along the western shores of the lake in the Pleistocene era with its northeastern region lying under the sea. That the coastline has moved eastward over the ages is supported by the fact that the nearby Konarak Sun Temple, built originally on the seashore a few hundred years ago, is now about 3 Km away from the coast. The catchment area of Chilika Lake has a rock, sand and mud substratum. It contains a wide range of sedimentary particles such as clay, silt, sand, gravel and shell banks but the major part of the catchment area is silt. Around 1.6 metric tons per year of sediment is deposited in Chilika lake by rivers Daya and several streams. White bands of coral in the southern sector, at a height of 8m, above the present water level, shows that the area was once marine and that the water was much deeper than present.

CHAPTER 3

BRIEF LITERATURE REVIEW

3.1 Taphonomy

Taphonomy is the ‘‘science of the laws of burial’’ (Efremov 1940); it involves the transition of animal remains from the biosphere to the lithosphere. Ternary diagram has long been used as an analytical and graphical tool to classify sedimentary rocks (e.g., Krumbein and Sloss, 1963) and to characterize their provenance (e.g., Dickinson and Suczek, 1979). Ternary diagrams have also been used in paleoecology to depict the substrate relationships and trophic composition of paleocommunities (Scott, 1974, 1976).

3.2 Study of Mechanical Properties

It has been revealed from the literature survey that the investigation on mechanical characterizations of bivalve shells received an immense acceleration internationally after 1960s and it shows a direct relation to configure and predict prey-predator relationships both for the recent time and for the geological past.

The bivalve shell, like bone (Currey 1964) may be considered as a material consisting of two phases retaining their separate identities (Wainwright 1969). The phases are crystalline calcium carbonate in the form of calcite or aragonite and an organic matrix consisting largely of fibrous protein.The phases are arranged into various distinct fabrics which are recurrent throughout the Bivalvia and other molluscan classes.

The components of biological shells calcium carbonate, which is in general about 95 wt.% and less than 5 wt.% organic materials (Currey, J.D.,1977). X-ray diffraction (XRD) is usually used to detect the detailed structure of these minerals.In 1960, Lutt et al. identified the calcium carbonate phases for 19 mollusc shells.It was in 1963, Wilbur and Watabe studied the regeneration process with some mollusc species and found that the crystalline phase in some species was not changed during regeneration. Calcium carbonate changed from the amorphous state to aragonite during the growth of the shells. Calcite traces were only detected in some organisms (Medakovié et.al. 1997) Investigators analyzed the $CaCO_3$ polymorphs in different kinds of shells with different treatments (Su, X.W., 2002 et. al., Ren, F.Z., 2007 et. al.). Most of the shells contain aragonite. The external shell strength of bivalves were thoroughly been investigated by several workers i.e. Currey, J.D.,1977, Taylor, J.D., 2002 et. al., and Barthelat, F., 2007 et. al. The high strength and good toughness of shells were first identified by Currey and Taylor (1974). They reported that the strongest shells had nearly twice the compressive strength of bone. Although the flexure strength of shells with some structures, such as homogeneous structure, is not as high as that of bone, the compression strengths of shells can be much higher than bone (Taylor, J.D., 1972 et. al.). Paula and Silveira, (2009) summarized the analytical methods including XRD method. The different $CaCO_3$polymorphs can form different types of morphologies, such as sheet nacreous structure, prismatic structure, , foliated structure, cross-lamellar, lenticular nacreous structure, complex cross lamellar structure and homogeneous structure (Taylor, J.D., 1972, et.al., Currey, J.D., 1976). These structures, with simple components, can result in outstanding properties, such as flexure strength and toughness. The compression strengths of a significant number of shell species have already analyzed the results by Weibull statistics. They showed that the quasi-static compression strength (measured as failure probability of 50% [P(V)=0.5]) of abalone and conch are 540 MPa and 166 MPa respectively for loading perpendicular to the shell surfaces; and 235 MPa and 310 MPa respectively for loading parallel to the shell surfaces. Lin et al. (2006) later investigated the mechanical properties of a clam called *Tridacna gigas* and compared the results with those obtained by Menig et al. (2000, 2001). They found that the compression strength of red abalone (*Haliotis rufescens*) is about twice as that of clam (*Tridacna gigas*) and four times as that of conch (*Strombus gigas*).

In Indian context, recent study on the shell parameters and other related mechanical properties of bivalve has been reported from only a dissertation work of Ritabrata Mukherjee. He made a study of the major mechanical properties of dominant bivalve shells (*Mactra turgida, Donax scortum, Meretrix meretrix*) collected from the Chandipur sea coast, Odisha, India. His work was well appreciated of which the abstract publication can be found in GEOCON 2017, Calcutta University.

Here in the present study an effort has been made to study the major mechanical properties of dominant bivalve shells as collected from Chilika, Odisha, India. Data on various mechanical properties and their variation along the centreline has been reported from the adult species of *Anadara granosa, Meretrix meretrix, Sunetta meroe.* It is to be noted here, value of all the examined characteristics were measured perpendicularly to the growth lines of the shells.

CHAPTER 4

SYSTEMATICS & TAXONOMY

4.1 Systematics

Systematics is the study of the units of biodiversity. Systematics differs from ecology in that the latter is concerned with the interactions of individuals (and therefore species) in a particular time, while the former is concerned with the diversification of lineages through time. Systematics includes the discovery of the basic units of biodiversity (species), reconstructing the patterns of relationships of species at successively higher levels, building classifications based on these patterns and naming appropriate taxa (taxonomy), and the application of this pattern knowledge to studying changes in features of organisms through time. It also includes the building and maintenance of biodiversity collections, upon which all the products of systematic studies are based. These are museum collections of preserved specimens of all kinds.

4.2 Taxonomy

Taxonomy (from Ancient Greek: *taxis*, "arrangement", and "*nomia*, "method") is the science of defining and naming groups of biological organisms on the basis of shared characteristics. Organisms are grouped together into taxa (singular: taxon) and these groups are given a taxonomic rank; groups of a given rank can be aggregated to form a super group of higher rank, thus creating a taxonomic hierarchy. Swedish botanist **Carl Linnaeus** is regarded as the "Father of Taxonomy", as he developed a system known as Linnaean classification for categorization of organisms and binomial nomenclature for naming organisms.

4.3 Taxonomy of the observed species:

a) Anadara granosa

Kingdom: Animalia

Phylum: Mollusca

Class: Bivalvia

Order: Arcida

Family: Arcidae

Genus: *Anadara*

Species: *granosa* (Linnaeus 1758)

Measurement: The average shell length is 5.64 cm and shell height is 5.25 cm (Plate 1a, 1b).

Morphology: Shell equivalve, thick and solid, ovate, strongly inflated, slightly longer than high and feebly inequilateral (Poutiers, 1998). Umbones strongly protruding, cardinal area rather large. About 22 radial ribs (23 - 25) with wide interstices at each valve. Ribs stout and distinctly rugose, bearing regular,often rectangular nodules. Periostracum rather thin and smooth. Internal margins with strong crenulations corresponding with the external radial ribs. No byssal gape. Outside of shell white under the yellowish brown periostracum. Inner side white, often tinged light yellow towards the umbonal cavity. *Anadara granosa* is infaunal and lives in an area of silty bottom with relatively low salinity. It is a shallow burrower.filter feeder. Their feeding habit is related to the bottom feed where they live. Their important nutrient components are organic detritus, phytoplankton and unicellular algae.

Remarks: *Anadara granosa* is abundanty found in Chilika - marine, lake and estuarine environment under investigation.

b) *Meretrix meretrix*

Kingdom: Animalia

Phylum: Mollusca

Class: Bivalvia

Order: Veneroida

Family: Veneridae

Genus: *Meretrix* (Lamarck, 1799)

Species: *meretrix* (Linnaeus)

Measurements: The average shell length is 4.58 cm and shell height is 4.02 cm (Plate 2a, 2b).

Morphology: Valves are light brownish in colour, equivalved, sub triangular in shape and considerably thicker. Shell surface is smooth, concentric growth lines present. Beak is prosogyral, acute umbonal angle. Anterior end is less rounded rounded compared to the posterior. Lunule is smaller and more depressed in comparison with the escutcheon . Ligament is external (opisthodetic). Dentition is heterodont . Muscle scars are weakly anisomyarian and joined by an entire pallial line. A shallow pallial sinus is present. Pallial line and ventral commissural line is parallel to each other. And, Hinge is broad and curved. *Meretrix meretrix* is semi infaunal in nature. In its live position Meretrix always have its escutcheon part raised above the substrate, usually sand, in which it burrows.

Remarks: *Meretrix meretrix* is abundantly found in lake and marine environmentsin the Chilika area. A shallow burrower in habit, it mostly prefers wet sands as its substrate for burrowing. The dark coloured escutcheon, raised above the substrate serves as an effective camouflage so that it is not easily noticed by its predators.

c) *Sunetta meroe*

Kingdom: Animalia

Phylum: Mollusca

Class: Bivalvia

Order: Venerida

Family: Veneridae

Genus: *Sunetta*

Species: *meroe* (Linnaeus, 1758)

Measurement: The average shell length is 4.76 cm and shell height is 3.32 cm (Plate 3a, 3b).

Morphology: Surface of the shell smooth. Surface of the shell sculptured (light brownish) with concentric ribs either entire or part. Shell elongately ovate; more inequilateral in shape.Sculptured partly anterior part being smooth; escutcheon deep. Ribs flat, narrow; postero-ventral margin angulate. Dentition is heterodont.

Sunettameroe is a shallow-water, infaunal, filter-feeding, marine or estuarine bivalves.

Remarks: *Sunetta meroe* is abundantly found in Chilika - marine and estuarine environment but it is absent in the lake environment.

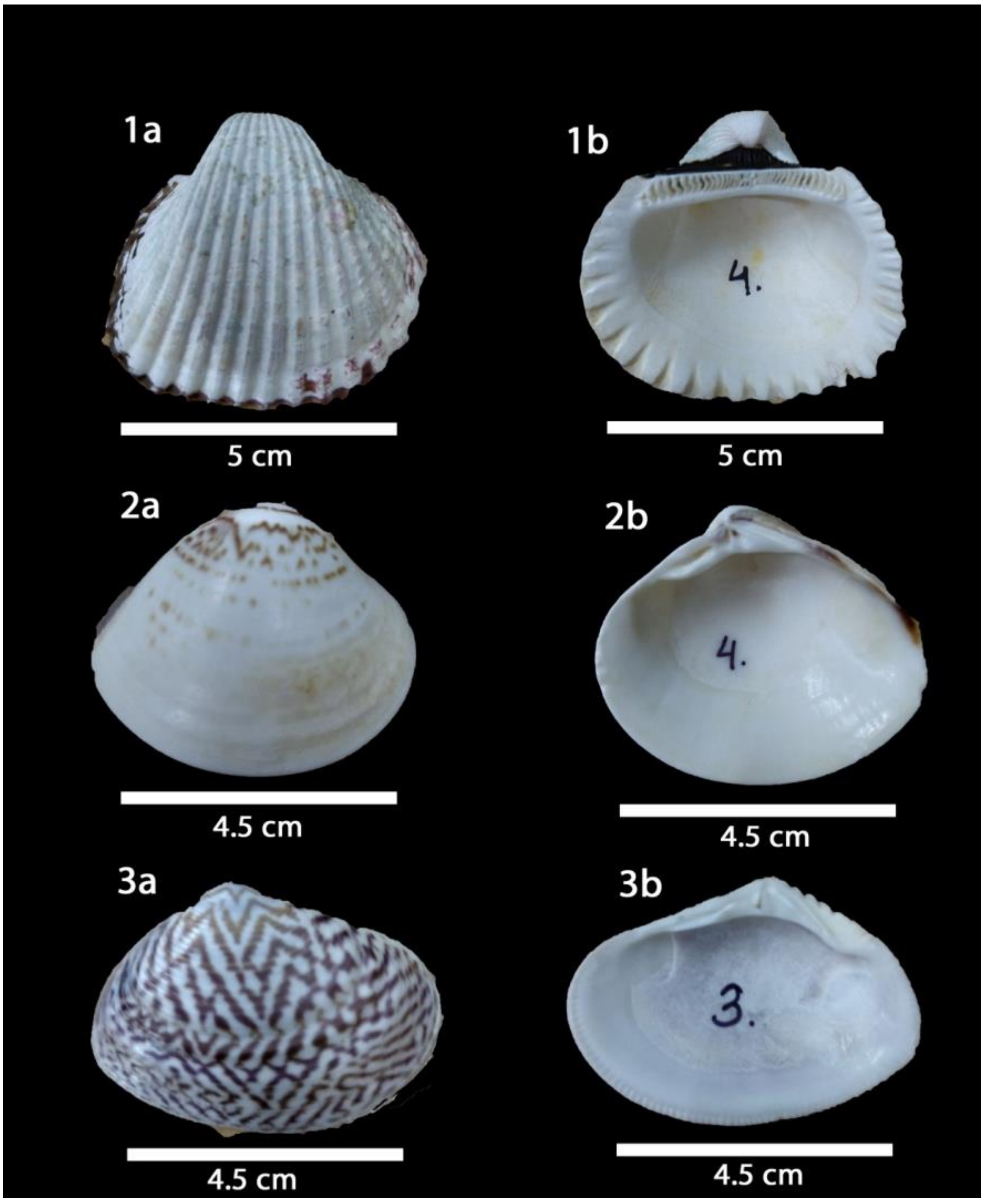


Plate 1: (1a) *Anadara granosa* (E.L.V); (1b) *Anadara granosa* (I.L.V)
(2a) *Meretrix meretrix* (E.L.V); (2b) *Meretrix meretrix* (I.L.V)
(3a) *Sunetta meroe* (E.L.V); (3b) *Sunetta meroe* (I.L.V)

Legends: (E.L.V): External Lateral View (I.L.V): Internal Lateral View

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CHAPTER 5

TAPHONOMY & TAPHOGRAMS

5.1 Taphonomy and Its Attributes

Taphonomy, introduced to paleontology in 1940 by a Russian scientist Ivan Efremov (a Greek word 'taphos' meaning burial and 'nomos'meaning law). Taphonomy is the study of a remains of an organism in relation to a post –mortem (after death) transformation which occur at the site of burial. In a broader sense, it includes the study of the processes which leads to fossilization as well as the stages of transformation. There are five main stages of taphonomy: disarticulation, dispersal, accumulation, fossilization, and mechanical alteration of a remains of an organism through the action of environmental factors.

5.2 Significance of Taphonomy

In a sedimentary rocks, fossils are found plentifully and for an accurate and satisfactory, scientific-conclusion of an ecological niche of a fossilized organism, the study of the processes of fossilization plays a very crucial part. For example, if a fossil assemblage contains more of one type of fossil than another, one can infer either that the organism was present in greater numbers, or that its remains were more resistant to decomposition.The biasness of a fossil record could be evident as revealed by Taphonomy and it also dictates the processes and the rates of deposition.A preservation is caused by a very selective processes (biasness) and not all organisms are preserved in the same exact way as the other. A factor affecting a likelihood of an organism getting preserved as a fossil is a source of a potential bias. So, to identify the scope of such biasness is the most important goal of a taphonomy which is useful for the interpretation of the abundance of an organisms which make up a fossil biota.

Some of the taphonomic biases in fossil records:

- Consistency over preservation in geologic time
- Physical attributes of the organism itself
- Human biases
- Gaps in time series
- Characteristics of the Habitat

- Temporal resolution
- Mixing of fossils from different areas

Taphonomic processes allow researchers to identify the prevalent condition of paleoenvironment. The variable taphonomic characteristics between fossils reflects to a changes in the environment of their post mortem habitats often, these findings can relate environmental shifts within the present day.

5.3 Taphonomic Processes : Broadly the taphonomic processes involves 2 main stages i.e. biostratinomy followed by diagenesis

- **Biostratinomy :**

  Biostratinomy (Weigelt, 1927) is a part of taphonomy that deals with processes that act on organisms after their death until final burial (Seilacher, 1973, Kidwell and Bosence, 1991). These processes are largely destructive, and include physical, chemical and biologica effects: Physical effects non-exhaustively include transport, breakage and exhumation. Chemical effects include early changes in mineralogy and oxidation.Biological effects include decay, scavenging, bioturbation, encrustation and boring. The processes of biostratinomy are often dominated by sedimentological factors, analysis of the biostratinomy of a fossil can reveal important features about the physical environment it once lived in.

- **Diagenesis :**

  The term diagenesis, literally meaning "across generation"**.** The process describes the changes and alterations that take place on skeletal (biological) material once it gets buried into the sediment. Alteration occurs at all scales from molecular loss and substitution, through crystallite reorganization, porosity and microstructural changes, and in many cases, to disintegration of the complete unit and change of shape of shells.

5.4 Taphonomic Grades:

Different degrees of transport and reworking imparts different physical characteristics to fossiliferous assemblages (different "taphonomic grades') and reflect different time scales of accumulation and deposition.

Well-preserved fossil assemblages (high taphonomic grade) generally reflect accumulation over short time spans; as taphonomic grade decreases, the time represented by the accumulation of the fossiliferous assemblage increases. The taphonomic grade of a fossil assemblage changes in one direction (high to low) with time, and provides a measure against which we can evaluate the aspects of the 'fossiliferous assemblage' that may fluctuate through time.

The grades are assigned as 0,1 and 2 as illustrated by the figure 1(a) below;

- ❖ (Good), condition of the species with respect to that attribute – 0 (**minimal or no development of a Taphonomic attribute**).
- ❖ (Fair), condition of the species with respect to that attribute -1 (**moderate development of a Taphonomic attribute**).
- ❖ (Poor), condition of the species with respect to that attribute-2 (**high development of a Taphonomic attribute**).

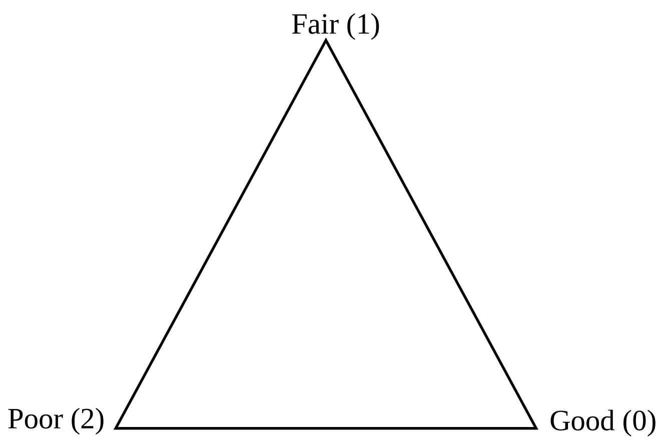


Fig 5.1 Ternary Taphogram

5.5 Significance of Taphonomic Attributes:

It defines the nature of a concentration of fossils through the investigation of a taphonomic attributes (preservational features). So, different taphonomic attributes are analysed according to different taphonomic grades for each sample of a target species. Some of the commonly considered taphonomic attributes are as follows:

- **Fragmentation :** It is defined by the rate of breakage of shells and serves as a proxy for environmental energy. The degree to which a rate of fragmented shells is highest, in environment with high water turbulence and coarse substrates such as beaches and tidal channels resulting from the impact of other shells, rocks and waves and could also be possible by ecological interactions such as, shell breaking predation or bioturbation. Higher rates of fragmentation (shell breakage) indicates the environmental condition like energy of the currents and a wave action.

- **Abrasion :** When the bivalve shells are exposed to moving particles (corrosive materials) or when the shells themselves are moved relative to other particles. It is a result of near-shore waves, currents or tidal action and one of the most easily observable characteristics is the loss of surface ornamentation. It is also important to analyse the degree of surface alteration, which is generally related to abrasion.

- **Bioerosion :** It is defined as the alteration of shells caused by the activity of organisms usually in search of food or shelter which takes the form of boring, etching, rasping, breakage and abrasion of the shell surface. So, a mollusc shell or a bivalvian shell to be exact, loses its information and the process of bioerosion is evident as identifiable traces made by organisms on hard parts or surfaces. An intensity and rate of bioerosion as evident in fossils yield an idea about its depositional environment, burial and the nature of its preservation.

- **Dissolution :** Different molluscan skeletons are made of either calcium carbonate or silicic skeletons. So, it displays different solubility in acidic solution. The fluctuation in temperature (therefore ocean depth and latitude), pH and pCo_2 conditions of the water are the governing factors which enhances or degrades the dissolution process. Also, it depends upon the relative solubility of the particular crystal form of the biomineral used by a given species. Calcitic hard part with high magnesium carbonate are the most soluble, followed by aragonitic and low magnesium calcitic hard parts. The solubility decreases from high magnesium carbonate to aragonite to low magnesium carbonate hard parts.

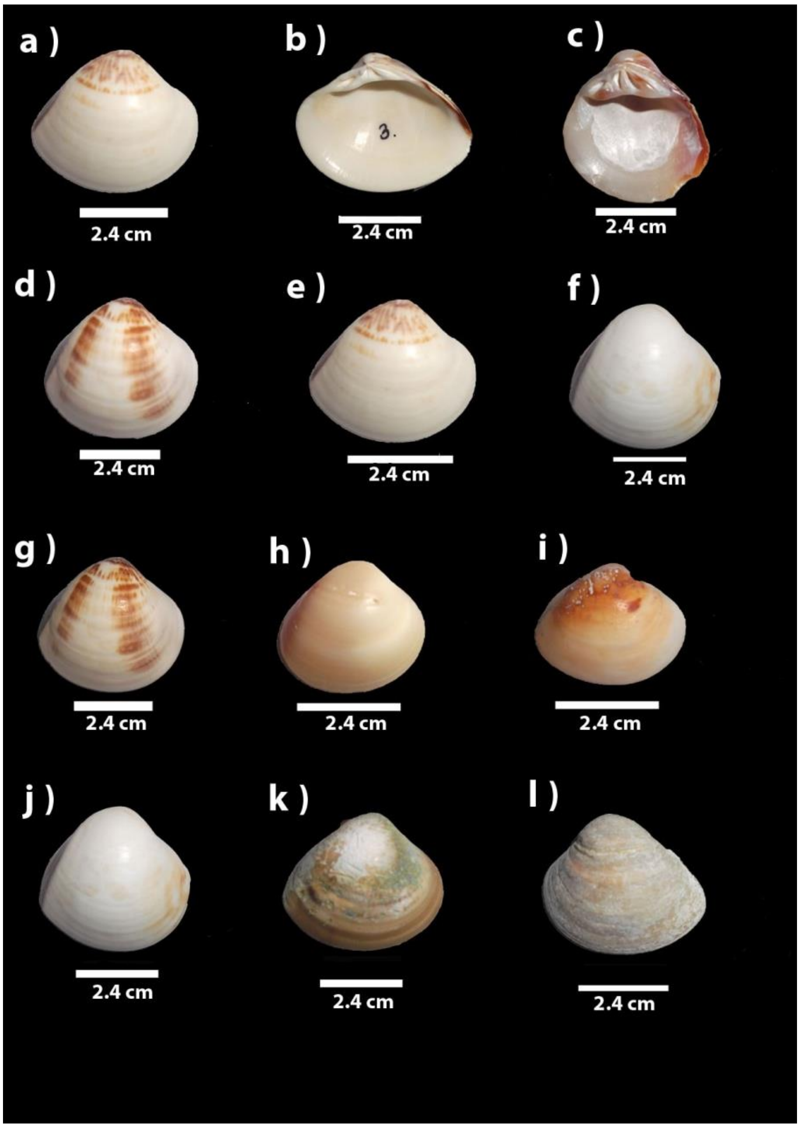


Fig 5.2 Different grades of Plate 2: *Meretrix meretrix* shell (Good - left shell, Fair – middle and Poor – right shell)

Table 5.1 Detailed explanation of Plate 2:

Fragmentation	a.)Unbroken shell	**Abrasion**	d.)Shell with ornamented surface, not abraded
	b.)Broken shell		e.)Shell with abraded surface
	c.)Fragmented shell		f.)Shell with complete loss of ornamentation, abraded
Bioerosion	g.)Unbroken shell	**Dissolution**	j.)Undissolved whole shell
	h.)Fairly bioeroded		k.)Fairly dissolved shell
	i.)Shell with incomplete drill holes and marks		l.)High rate of surface dissolution

5.6 Taphograms

These are simple ternary diagrams which provide a graphical approach and can be applied to comparative taphonomy if the degree of alteration lead itself to a three fold classification scheme. Ternary diagrams play a useful role in taphonomic analysis. When the quality of preservation of a hard part can be expressed in a three fold scheme, a single point on a triangular diagram characterizes the frequency distribution of taphonomic alteration within a sample. Comparison of samples with such a ternary taphogram is an efficient way to explore variation in the preservation of the hard parts. (Kowalewski et al. 1995)

5.7 Results and Discussion

Four attributes – Abrasion, Bioerosion, Dissolution and Fragmentation are plotted as taphograms for (M) Marine, (EM) Estuarine or Estuary Mouth and (LA) Lake environment. The plots are shown and discussed.

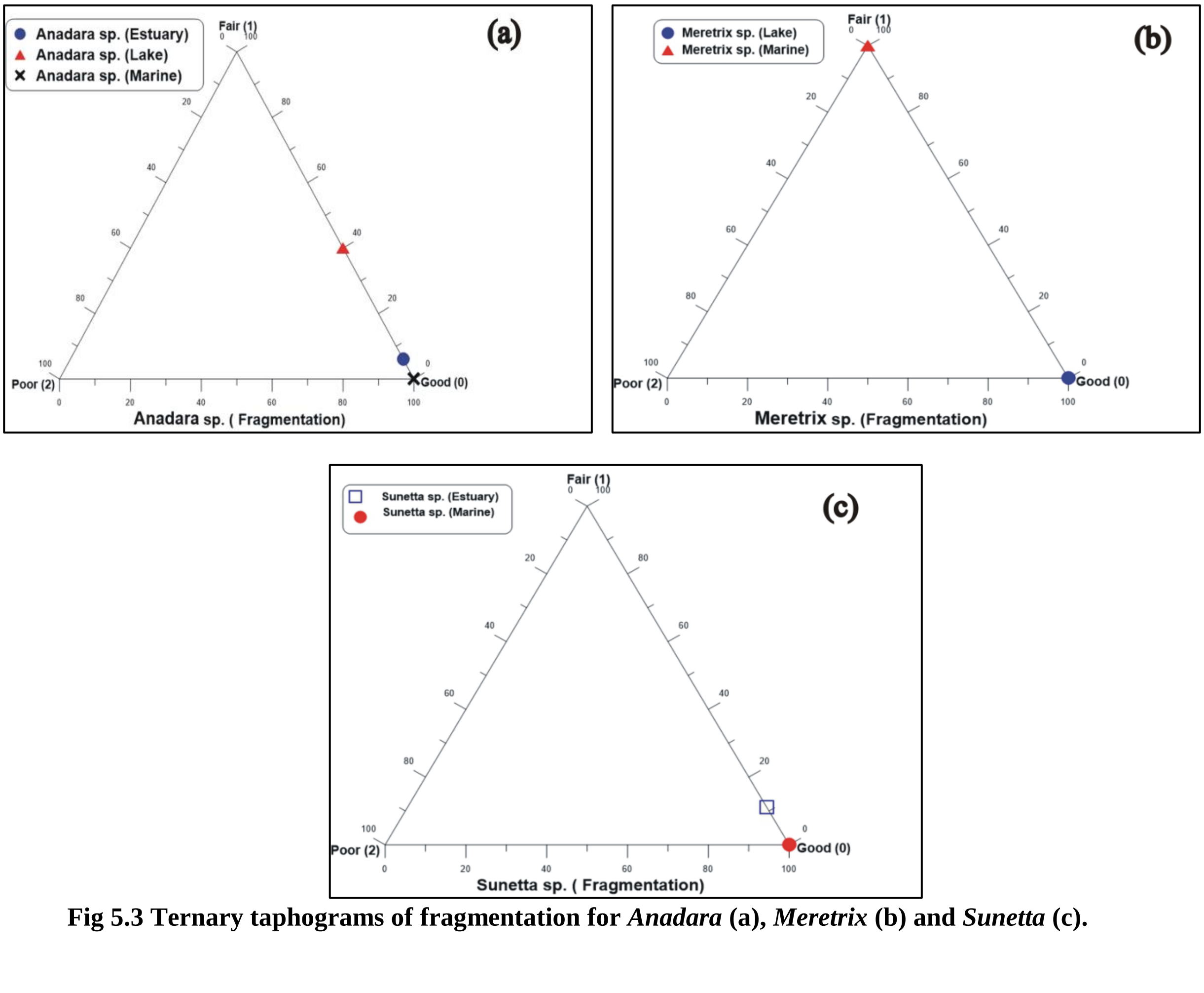


Fig 5.3 Ternary taphograms of fragmentation for *Anadara* (a), *Meretrix* (b) and *Sunetta* (c).

Based on the plots of ternary taphograms, only at the lake or lagoonal environment *Anadara granosa* (**Figure a**) show some effects of fragmentation (observed: chipped edges of the shell) compared to the othe two environments i.e marine and estuarine. Even though, the mechanical action of waves, currents and tides in the marine and mixing dynamics of estuarine environment is significantly higher but, the effects of fragmentation is almost negligable and the shells are well preserved. It could be attributed to the fact that the shells of *Anadara granosa* has a high thickness as an intrinsic property which provides durability and resistance to the shell hence, attribute of fragmentation is not prominent at the marine or estuarine environment. In the Lake or lagoonal environment anthropogenic activities predominate thereby showing higher effect of fragmentation.

Meretrix meretrix (**Figure b**) shows a fair amount of fragmentation at the marine environment which is evident from the mechanical actions of wave, tide, wind and current present in the studied area. In Lake or lagoonal environment the mechanical action of waves and tides are subsequentially, reduced so, the samples has been well preserved. The thickness and density as an intrinsic property of the carbonate shells of *Meretrix* is significantly higher as compared to the species *Sunetta*. Thus, provides durability to the shell.

In case of *Sunetta meroe* (**Figure c**), observed attribute is absent in marine environment and the shells are well preserved. But, in the estuarine environment slight fragmentation towards the commissural lines of few samples were observed.The shells of *Sunetta* are relatively thinner so lesser density compared to the other observed species so, it must have been transported in ‘suspension’ mostly, than being transported by ‘saltation’ with regards to other thicker and higher density shells. Other possible reason could be the higher energy dynamics at the estuarine environment.

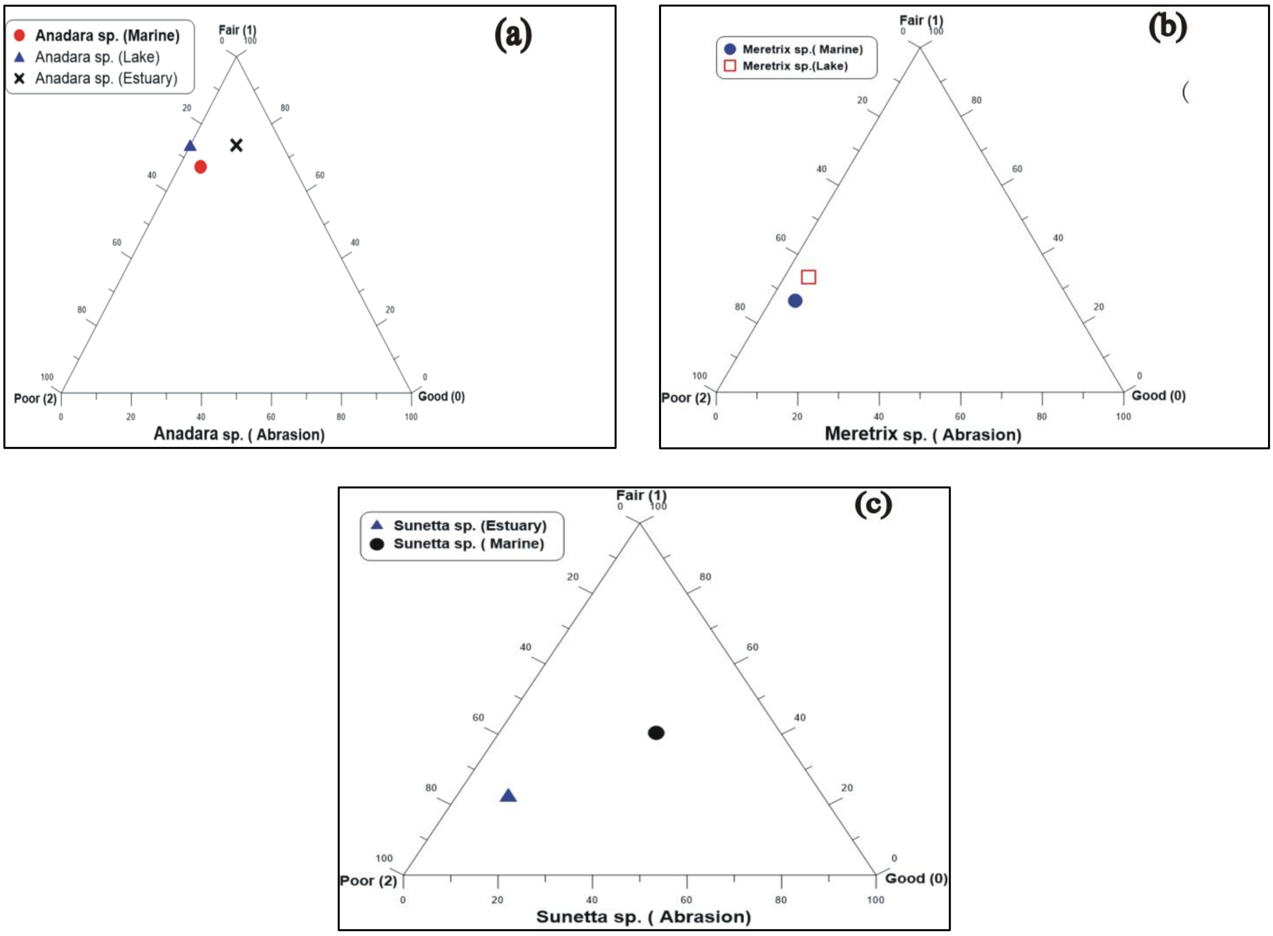


Fig 5.4 Ternary taphograms of abrasion for *Anadara* (a), *Meretrix* (b) and *Sunetta* (c).

Based on the plots of ternary taphograms, for *Anadara granosa* (**Figure a**) effects of abrasion is fairly moderate at the estuarine environment so, fairly well preserved compared to marine environment with slightly higher effects of abrasion than esturine environment:

Some of the observable characteristics are: The ornamented ridges at the exterior surface of the studied species has been significantly smoothened, lusture of the shell 'periostracum' faded and worn out. At the marine environment wave, tide and current action are the major mechanical processes which enhances abrasion. Estuarine environment consist of mixing dynamics of water and sediments which caused significant abrasion of the shells of *Anadara*. Anthropogenic activities and wind carried sediments dominate the lagoonal environment whereas, other effects of wave, tide and current action is comparatively reduced. A slight higher effects at the marine could be related to a higher density of the carbonate shells which correlates with the 'saltation' means of transportation at the lower or middle column of water, consisting of medium to larger sized sediments.

Meretrix meretrix (**Figure b**) shows a prominent attribute of abrasion in a marine environment and slightly lower at the lake or lagoonal environment . The exterior carbonate shells of the species *Meretrix* shows a well defined attribute of abrasion; it has a dull appearance whereby the lusture has been worn off and lost. Significant sandblasting features from sediment includes scratch marks over the ornamentated shell surface and minute dents are also observed. *Meretrix* has quite a high thickness so, has a higher density. Waves, currents and tides are the factors associated in the marine environment. In case of lake or lagoon; mechanical processes are significantly reduced but, human activities could be the other artificial means which could have acted upon the observed samples.

In case of *Sunetta meroe* (**Figure c**) prominent attribute of abrasion are observed in estuarine environment compared to the marine. Estuarine environment show more mixing dynamics of both water and sediments (surface runoff by channels and streams). The intensity of physical abrasion is enhanced at the estuary with frequent storms and floods coupled with waves and tides. Sandblasting of sediments increased due to the increase of sediments at the estuary as an effect, more abrasion on the shells of *Sunetta meroe*.

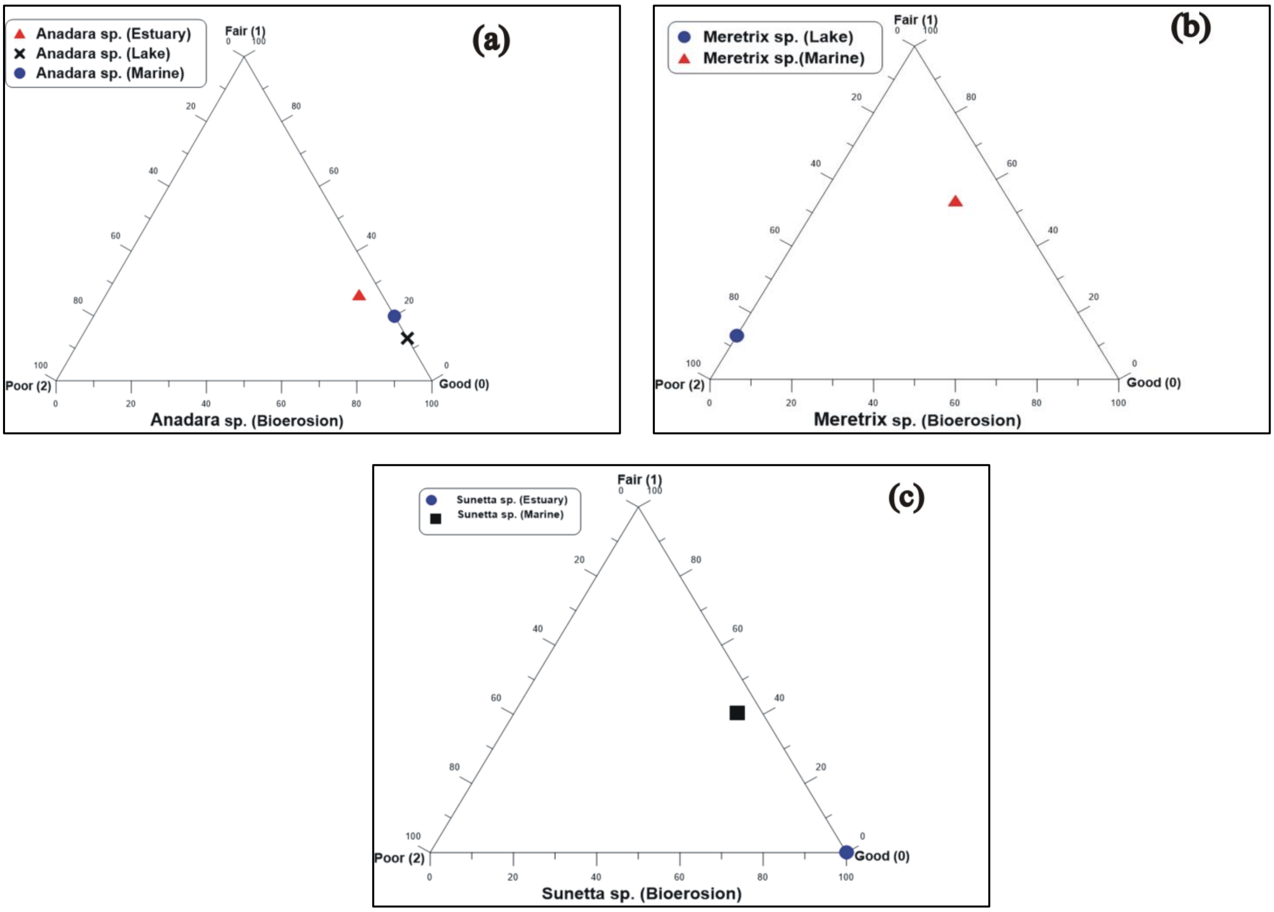


Fig 5.5 Ternary taphograms of bioerosion for *Anadara* (a), *Meretrix* (b) and *Sunetta* (c).

Anadara granosa (**Figure a**) at the estuarine environment displays a well preservation; at the marine environment shows much better preservation potential compared to the estuarine; at the Lake or lagoonal environment very well preserved compared to the other two formerly mentioned. At the estuarine environment slightly higher effect of the process of bioerosion due to the presence of freshwater organisms and predators which would graze upon the studied species.

For *Meretrix meretrix,* (**Figure b**) the observed attribute of bioerosion is largely prominent for the studied species, at the Lake or lagoonal environment and moderate effects at the marine environment. The observed characteristics show: At the lagoonal environment algal growth observed over the shell surfaces whereas, at the marine environment minute grazing, rasping and growth of minute barnacles (symbiotic) observed over the studied species. An attribute of bioerosion is significantly higher in lagoonal areas due to the stagnant water which has been affected by anthropogenic activities which adds up nitrogen content in the water so, algal growth is enhanced. Whereas, in the marine environment there is a continuous mixing of alkaline water and presence of marine predators causes bioerosional effect as mentioned above.

In case of *Sunetta meroe (***Figure c***),* more attribute of bioerosion observed at the marine environment and absent at the estuarine environment so, the shells are well preserved at the latter. The species *Sunetta* from estuarine environment lacks any attribute and has no evidence of features like grazing or biting as observed in the marine environment. From the observed samples marine environment seems to be dominated by more saltwater organisms and plants compared to the estuarine environment.

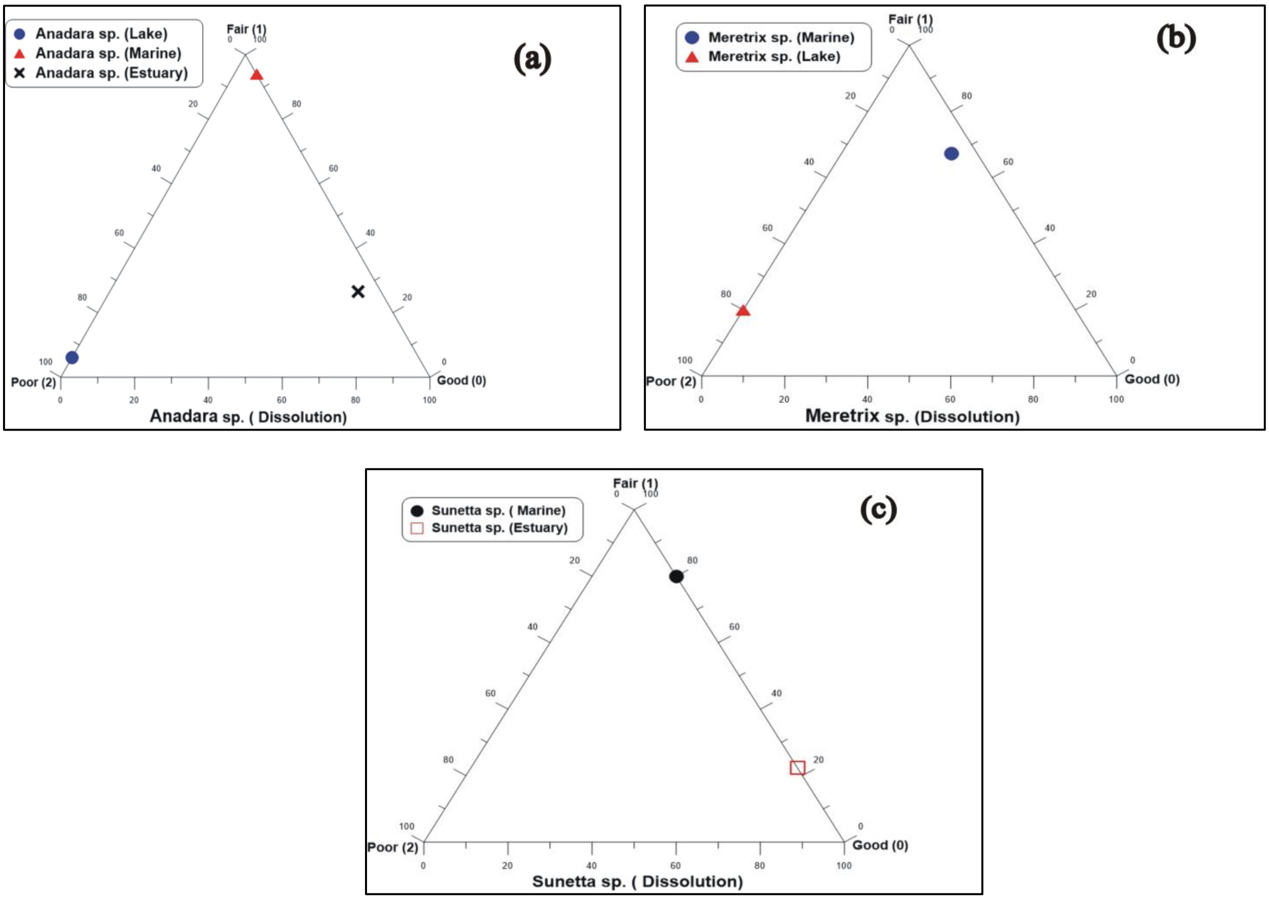


Fig 5.6 Ternary taphograms of dissolution for *Anadara* (a), *Meretrix* (b) and *Sunetta* (c).

Anadara granosa (**Figure a**) are well preserved at the estuarine environment so, no prominent effects were observed compared to the moderate effects at the marine environment and the most prominence at the Lake or lagoonal environment. The effects of dissolution is very prominent at the lagoonal area for the studied species which is evident from the ternary plot as the water chemistry at the lagoonal area is acidic in nature.the marine environment effects are fairly moderate due to the alkalinity of the marine water system. The studied species are well preserved at the estuarine area due to the mixing of fresh river water which decreases the alkalinity of marine water during mixing.

For *Meretrix meretrix (***Figure b***)*, a prominent attribute is observed at the Lake or lagoonal environment and moderate effects at the marine environment. The reason is same as stated for the former species in the lagoonal environment. Moreover, in the marine environment, repeated wave action drives the shell to and fro from a particular place to the other whereas, in a lagoonal areas a carbonate shell could be exposed and restricted to a particular area for a longer period as the wave and current action is significantly reduced. Hence, the rate of dissolution is enhanced and remains undisturbed if a shell is restricted to a lagoonal water for a longer period of time.

In case of *Sunetta meroe (***Figure c***)* moderate effects of dissolution is observed at the marine environment and the shells of the same species are more preserved at the estuarine environment. The species observed at the marine environment shows moderate level of corrugation at the commissural edges. Fading of exterior shell colour hence, shows colour variation from the umbonal to commissural edges as recorded in case of abrasion. In an estuarine environment salinity from marine influences decrease due to the dynamic influx of freshwater from rivers so the process of dissolution also decreases. It is evident from the above ternary plot for the observed samples.

It is to be noted that some of the species are restricted only to their particular ecological niches hence, not found in all of the studied environment.

5.8 Conclusions

The taphonomic processes have acted differently in the bivalve community.

- ❖ Fragmentation effects are responsible due the resistance imparted by the inherent properties of the shell structure and also on the energy dynamics of a particular environment.
- ❖ Abrasion effects depend upon the length of the transportation from its death till its burial (Biostratinomy) and better effects are observed on the species with smooth shelled surfaces.
- ❖ Bioerosion (biological activities) is least due to high depositional rates and thus less sub-aerial exposure.
- ❖ Dissolution effects are a result of the pH condition of a particluar environment and from the above studies it was observed to be higher in lagoonal environment due to the acidification from anthropogenic impact.

CHAPTER 6

CHARACTERIZATION OF MAJOR MECHANICAL PROPERTIES OF BIVALVIAN SHELLS

6.1 Introduction

It is the natural selection over hundreds of millions of years, which make mollusk shells to develop their unique shell structure and mechanical properties to protect themselves from attack by a variety of marine predators, which try to break the shell by using compressive force, prying attack or nipping attempt. The mechanical function of the shell depends upon its ability to resist deformation and failure under environmental stresses; and those two main factors in shell architecture, shape and construction materials are involved in determining the shell strength. Thus there is a need to investigate the mechanical properties of the shell materials in relation to their possible functional significance and shell strength to resist stress conditions. The components of biological shells are mostly calcium carbonate which is in general about 95 wt% and less than 5 wt% organic materials [1–3].

The Eastern coast of India houses a huge number of marine invertebrates especially bivalves and gastropod communities. In the present investigation an attempt has been made to study the variation of three major mechanical characteristics of the predominant bivalve shell as collected from the Chilika, Odisha, India. The examined bivalves are namely *Anadara granosa, Meretrix meretrix* and *Sunetta meroe.* Variation of compressive strength of the constituting shell material; thickness, density and area are the major properties which were measured along the centerline of the shell normal to the growth lines for all the three species following the standard scientific processes. Out of the numbers of mechanical parameters the tested three are seemed to be the most significant regarding the impulsive compressive force. As indentation is the most commonly attributed predating processes, compressive strength of the shell material was measured following the standardized experimental method of nano-indentation and Vickers hardness was measured. All these major mechanical properties showed significant spatial variations for an individual species and values for different species also reveal a substantial range of variance. In this chapter an attempt has been made to present a comparative analysis on studied mechanical parameters, collectively for all three molluscan shell and interrelations between those properties for an individual species. For all the studied parameters measurements were done on fully matured samples, those were collected from the Chilika, Odisha.

6.2 Methodology

Estimation of three major mechanical properties i.e centerline thickness; compressive strength as deflected by Vickers hardness values and density variations along centerline for collected bivalve mollusc shell were done on fully matured recent samples, those are collected from Chilika, Odisha. The three most abundant bivalve species were *Anadara granosa*, *Meretrix meretrix* and *Sunetta meroe* as shown in the Fig 6.1 and tests related to measuring the mentioned properties were carried out on those.

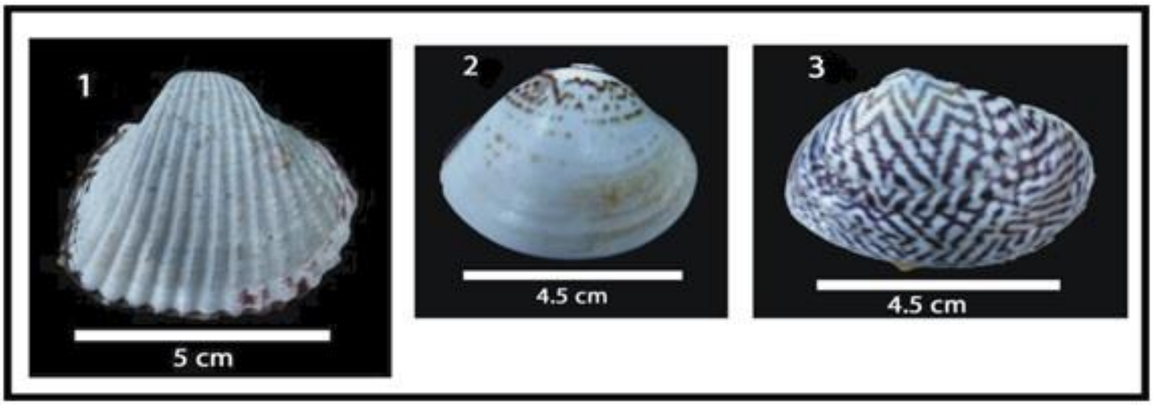


Fig 6.1 Photographs of the species, chosen for the Characterization of Major Mechanical Properties

(1-*Anadara granosa*, 2- *Meretrix meretrix*, 3 *Sunetta meroe*)

6.2.1 Centerline thickness

Variation of thickness along the centerline were measured normal to the growth line for all the three species. For an individual species measurement of shell thickness were done on the equidistant points from the margin i.e. commissure line of the shell. Initially three fully matured samples of individual species were chosen and cleaned carefully by running water to wash out the surficial foreign materials then dried up at room temperature. Centerline of individual shell was drawn by joining the midpoint of the commissure line with the hinge point at umbo and then the specimens were cut with a water cooled low-speed diamond saw. Fig 6.2 (a-c) reveals the preparation of samples for measuring the centerline thickness.

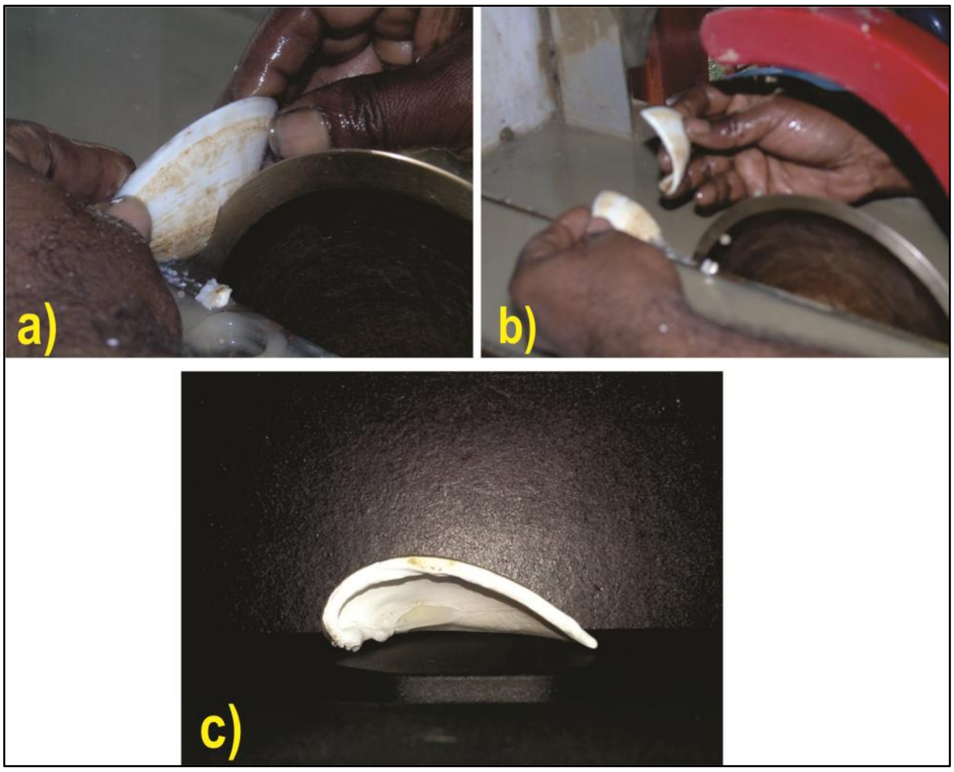


Fig 6.2 (a-c) Preparation of samples for measuring the centerline thickness

For all the bisected samples thickness were measured normal to the growth lines at the equidistant points on the centerline and the locational distance of the point of measurement were normalized by the actual length of the centerline i.e l/L where l is the distance of the measuring point from the commissure line and L is the actual measured length of the centerline. The points were chosen with and equal intervals from the commissure line on which thickness measurement was carried out.

Fig 6.3 (a-c) Measuring the variation of centerline thickness

A minimum of six points were measured to check the variations of thickness for all the samples. The numbers and locations of the point of measurement were exactly identical for all the three cuts chosen to measure the thickness variations for the same species.Thickness at the points was measured carefully by using a 'Mitutoyo' made digital vernier calipers with accuracy of ± 0.0001mm. Steps as followed to measure the variation of shell thickness is presented by Figs 6.3 (a-c). The measured thickness on identical points were then averaged to get an overall mean thickness of the point located on the centerline of the shell and that estimated mean values were taken to study and compare the variation of thickness for individual species and collectively for all the three species respectively. Table 6.1 presents the ranges of thickness value (averaged) as measured on the different normalized location points on the centerline of all the three species: *Anadara granosa, Meretrix meretrix* and *Sunetta meroe.*

Table 6.1 Centerline thickness as measured from commissure line

Normalised Distance	Centreline Thickness (mm)		
	Anadara	***Meretrix***	***Sunetta***
0	2.41	1.44	1.27
0.2	3.48	1.84	1.32
0.4	3.05	2.06	
0.5			1.35
0.6	2.77	2.2	
0.7			1.36
0.8	3.49	1.79	
1	3.37	2.38	2.68

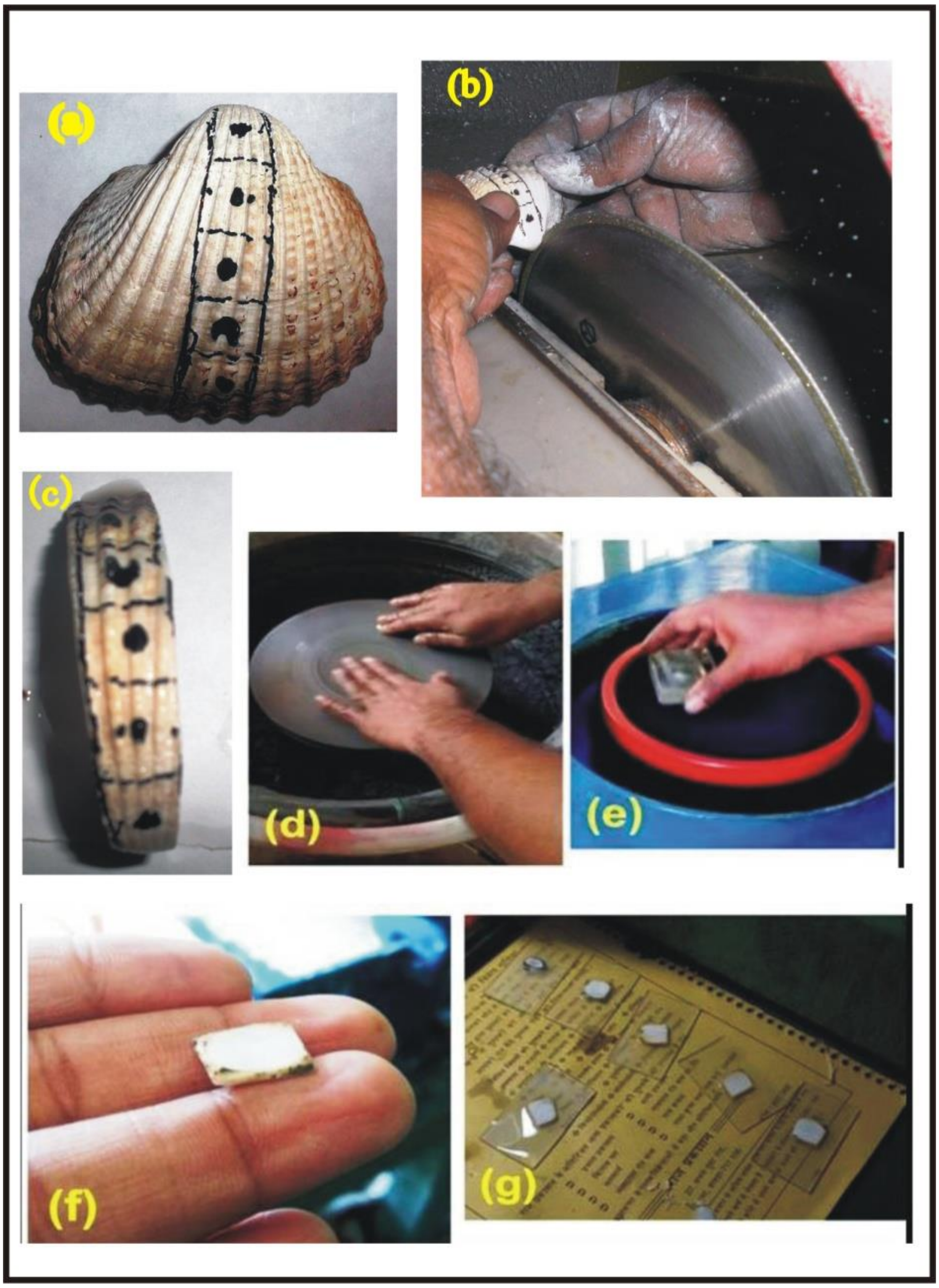
6.2.2 Vickers hardness

The Vickers hardness test, also referred to as microhardness test was developed in 1921 by Robert L. Smith and George E. Sandland at Vickers Ltd. The Vickers test is often easier to use than other hardness tests since the required calculations are independent of the size of the indenter, and the indenter can be used for all materials irrespective of hardness. The basic principle, as with all common measures of hardness, is to observe the questioned material's ability to resist plastic deformation from a standard source.

The Vickers test can be used for all fine sheets of metals or non-metals and has one of the widest scales among hardness tests. The unit of hardness given by the test is known as the Vickers Pyramid Number (VH) or Diamond Pyramid Hardness (DPH). The hardness number is determined by the load over the surface area of the indentation and not the area normal to the force, and is therefore not pressure.

Here VH values were estimated on the same locational points of thickness measurement and micro indentation testing were carried out at the center of cuts of 1 cm^2. These individual 1 cm^2 samples were made serially one by one from a 1cm widen slice cut out following the centerline of the shell maintaining an equal distance form that. The locational distance (l) of the central point of the drawn out samples normalized with the total length (L) of the centerline of the shell. Surface of all the cut out samples made diamond polished to get a clear view under ‘Vickers Hardness Meter’. The final values of VH of each cuts were estimated following the standard procedure. Fig 6.4(a-g) show the steps those are followed to prepare a sample of 1 $cm^2$for testing VH values for the species.

The Vickers test can be used for all metals and has one of the widest scales among hardness tests. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV) or Diamond Pyramid Hardness (DPH). The hardness number can be converted into units of pascals, but should not be confused with pressure, which also has units of pascals. The hardness number is determined by the load over the surface area of the indentation and not the area normal to the force, and is therefore not pressure.

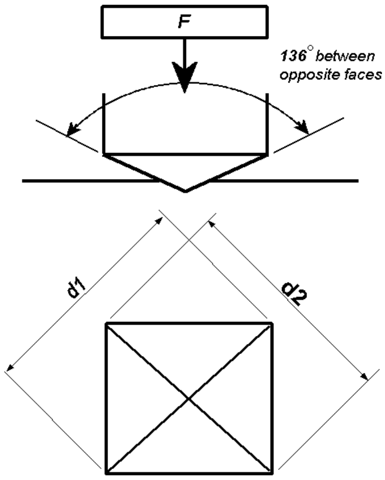


Figs 6.4(a-g) Steps those are followed to prepare a sample of 1 cm^2 for testing VH values for the species.

The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is very much expensive.

6.2.2.1 Testing methods and formulas

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is obtained by dividing the load (in kgf) by the surface area of indentation(A) in square mm.



Figs 6.5 Required observed dimensions for estimating VH values (not to scale)

F= Load in kgf

d = Arithmetic mean of the two diagonals, d_1 and d_2 in mm

HV = Vickers hardness

A can be determined by the formula.

$$A = \frac{d^2}{2\sin(\frac{136}{2})}$$

which can be approximated by evaluating the sine term to give $A \approx \frac{d^2}{1.8544}$

HV $= \frac{F}{A} \approx \frac{1.8544\,F}{d^2}$ [kgf/mm^2]

where, *F* is in kgf and *d* is in millimeters.

6.2.2.2 Estimating VH values

The corresponding units of HV are then kilograms-force per square millimeter (kgf/mm²). To calculate Vickers hardness number using SI units one needs to convert the force applied from newtons to kilogram-force by dividing by 9.80665 (standard gravity).

This leads to the following equation

$\mathrm{VH} \approx 0.1891 \frac{\mathrm{F}}{\mathrm{d}^2}$ [kgf/mm^2]

Where, *F* is in N and *d* is in millimeters. A common error is that the above formula to calculate the VH number does not result in a number with the unit Newton per square millimeter (N/mm^2), but results directly in the Vickers hardness number (usually given without units), which is in fact kilograms-force per square millimeter (kgf/mm²).

To convert the Vickers hardness number to SI units the hardness number in kilograms-force per square millimeter (kgf/mm²) has to be multiplied with the standard gravity (9.80665) to get the hardness in MPa (N/mm²) and furthermore divided by 1000 to get the hardness in GPa.

When the mean diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but is more convenient to use conversion tables.

Here in present study, VH values for the species *Anadara* were estimated under two different load implied as 50 gram force (gf) and 100 gram force (gf) respectively. Estimated Vickers Hardness Number (VHN) values of the samples of different species under different implied load are presented serially in the Table 6.2 respectively.

All the measurement of VH were done using the Vickers hardness testing instrument kept at *M.L. Dastur School of Material Science, Indian Institute of Engineering Science and Technology, Shibur, Howrah, WB, India* .Figs 6.6 (a-c) shows the photographs as taken in the laboratory during estimating VH values using the instrument.

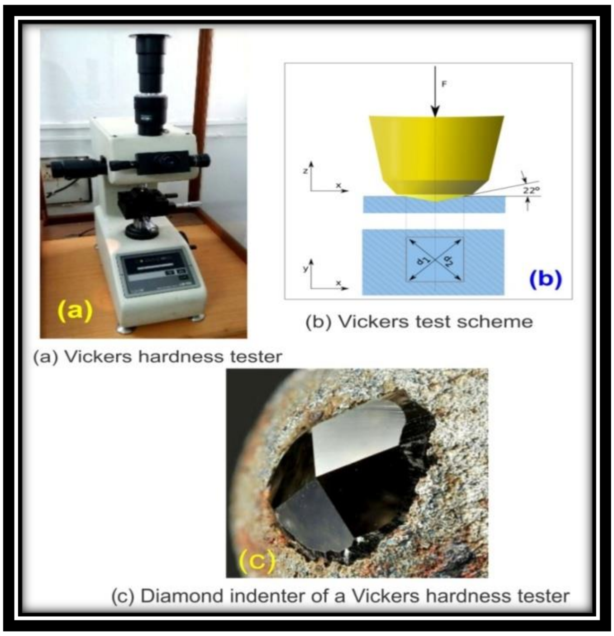


Fig 6.6 (a-c) Photographs in the laboratory during estimating VH values

Table 6.2 VH values as measured normal to the growth lines for *Anadara* under 50 gf and 100gf.

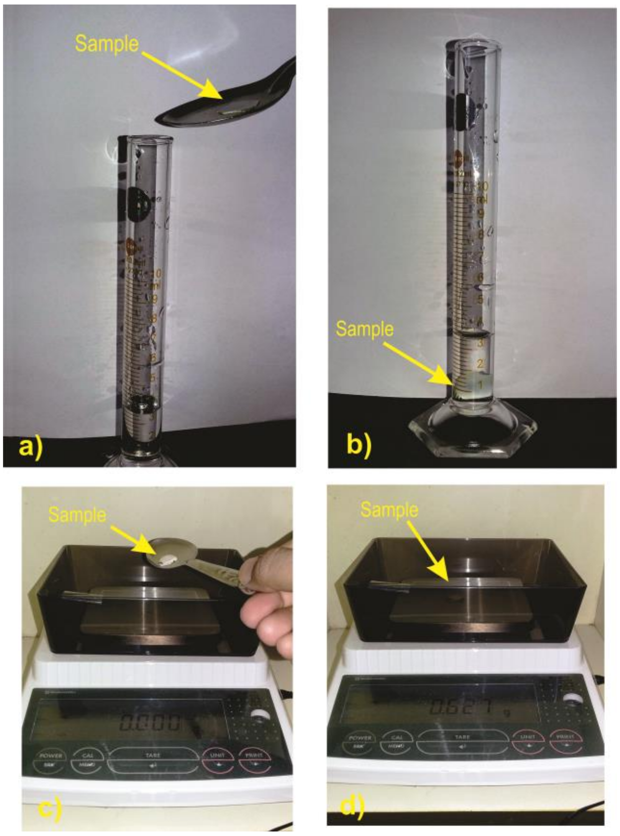
Normalised Distance from Commissure line	Vickers Hardness (MPa)	
	at 100 gf	at 50 gf
0.0	12.65	190.06
0.2	102.10	166.72
0.4	82.50	146.96
0.6	76.60	102.82
0.8	73.80	89.50
1.0	81.70	121.26

6.2.3 Density variation

From the estimated results of centerline thickness and VH values it seems to be obvious that density of the costing shell materials varies substantially from the commissure line towards umbo, which seems to be a protuberant resultant of the orientation and arrangement of the consisting crystals (chiefly aragonites) , by which the shell is made-up of.

6.2.3.1 Measurement of density

For all the three species samples were cut out of the same dimensions (i.e. 1cm^2), as it was done to determine the VH value,to determine the variation of the density of the molluscan shells along the centerline from the commisure line to the umbo. In order to estimate the density variations, each of the samples were weighed out first in a weighing machine of least count (0.1mg).Figs 6.7 (a – d) show the steps followed to measure the variations of density along centerline.



Figures 6.7 (a – d) Steps followed to measure the density

Hence the mass of the zones for each of the three species i.e., *Anadara granosa*, *Meretrix meretrix* and *Sunetta meroe* were serially obtained from the commissure line to their umbonal region. Next, the volume of the same samples were estimated by dipping them in a 10 ml measuring cylinder and noticing the rise in the water level each time the samples were put inside the cylinder. The volumes were estimated for all the weighted samples

The values of the mass and volumes of each of the zones for the three species were noted separately in a tabular form and the densities were estimated by simply dividing the mass of each of the zones by their volume [using the simple formula Density (d) = mass (m)/ volume (v)].

Table 6.3 Density variations along the centerline for different normalized position

Species name	Normalized distance from commissure line	Mass (gm)	Volume (cc)	Density (gm/cc)
Anadara granosa	0.00	1.07	0.60	**1.78**
	0.20	1.51	0.70	**2.15**
	0.50	1.44	0.60	**2.40**
	0.70	1.25	0.60	**2.08**
	1.00	1.49	0.80	**1.86**
Meretrix meretrix	0.00	1.09	0.60	**1.81**
	0.30	1.45	0.60	**2.41**
	0.60	1.54	0.80	**1.92**
	1.00	1.67	0.70	**2.38**
Sunetta meroe	0.00	0.38	0.20	**1.90**
	0.50	0.41	0.30	**1.36**
	1.00	0.39	0.30	**1.30**

Table 6.3 reveals the density variation results along the centerline for different normalized position for all the three species. A notable variation in the density values were clearly noted from the commisure line to the umbonal region and respective plots were obtained which shows an almost similar trend for density variations against the normalized positions on the centerline.

6.2.4 Variation in the area of the shell

Table 6.4 Area variations for 3 of the studied species

Species	Total Average Area (cm^2)
Anadara granosa	**29.61**
Meretrix meretrix	**18.44**
Sunetta meroe	**15.61**

Variation of area amongst 3 of the studied species were studied with the highest surface area of Anadara followed by Meretrix and Sunetta as tabulated in the Table 787

6.3 Results and Discussion

6.3.1 Study on variation of centerline thickness

Variation of centreline thickness as measured along the centreline of the shell, perpendicular to its growth lines in all the cases are represented by Table 6.1 for *Anadara* , *Meretrix* and *Sunetta*.

From Table 6.1, it was noted the overall thickness for *Anadara* ranges between 2.41 cms to a maximum of 3.37 cms. The minimum thickness was noted at the tip of commissure line whereas maximum thickness 3.49 was noted just before the hinge point i.e. near to umbo.

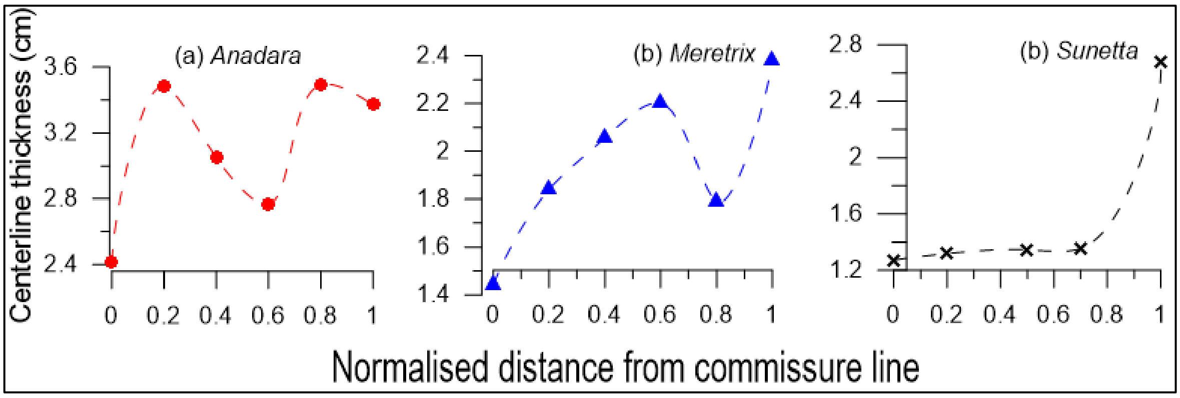
For the studied species *Meretrix* the overall thickness was much lesser than the species *Anadara* and the limits ranges from 1.44 cms to 2.38 cms. Here, similarly the minimum thickness was noted on commissure line whereas, the maximum thickness of 2.38 cms was noted at the end point of umbo.

The point to be mentioned here is, the umbilical curvature of the species was comparatively much acute than that of *Anadara* and radial ribs perpendicular to growth lines were completely absent. Overall size of the species was comparatively lesser than that of *Anadara.*

Thickness of the species *Sunetta* was overall much thinner than the previous two species of *Anadra* and *Meretrix.* Here range of thickness limited between 1.27 cms at commissure line to a maximum of 2.68 cms at the hinge point.

And a drastic enhancement of thickness was observed between a normalised distance of 0.7 – 1 and became almost double from 1.36 cms – 2.68 cms which were not the cases for the previous species of *Anadara* and *Meretrix.*

Fig 6.8 (a-c) reveal the plots of centreline variation of the studied species as, it changes with the propagation from commissure line towards the end point of umbo. Here to get a comparative relationship between the thickness variation of the studied species the centreline measurement points were made dimensionless by reciprocating the distance of measurement from the commissure line to the length of the centreline of that particular species.



Figs. 6.8 (a-c) Variations of thickness along centerline of the mollusk shells

From the plots it is evident that for all the species minimum thickness were noted at the tip of the commissure line then, it increases gradually. This increase of thickness was quite rapid and acute for the species *Anadara* and it reaches a thickness of 3.6 cms at a distance of 0.2 whereas for the species *Meretrix* this initial increase of thickness continue with a well – slopped gradient and reaches a thickness maximum of 2.2 cms at a distance of 0.6 whereas in case of *Sunetta* the enhancement of the thickness from the commissure line upto a distance of 0.65 was negligible and reaches a thickness of 1.35 cms at a distance of 0.65.

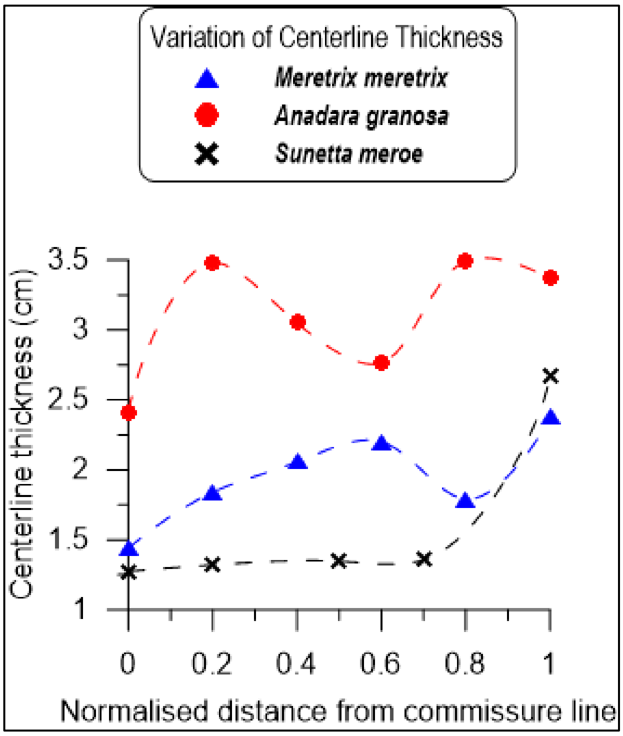


Fig 6.9 Combined Variations of thickness along centerline of the mollusk shells

For all the three studied species substantial lessening of thickness were noted in between a distance of 0.6 to 0.8. And again it increases towards the umbilical point. This increases towards the umbilical point. This increase of thickness near to umbo i.e. from a distance of 0.8 -1 were most acute steepened for *Sunetta* followed by *Meretrix* and *Anadara.*

From the plots it is quite clear that near to umbo portion were thickened maximum for *Anadara granosa* and thickness varies from 3.49 cms at 0.8 to 3.37 cms at 1, for *Meretrix meretrix* 1.79 cms at 0.8 to 2.38 cms at 1 and for *Sunetta* 1.52 cms at 0.8 to 2.68 cms at 1.

6.3.2 Study on Vickers hardness (VH)

The variation of VH value for the species *Anadara* were estimated following scientific protocol using the ‘Vickers Hardness Testing Instrument. For measuring the VH value for the samples, the same locations were chosen as it was for the thickness measurement. VH value were measured perpendicular to the orientation of the growth lines i.e. implying stress, normal to the orientations of the growth lines. The hardness values for *Anadara* under 50 gf load and 100 gf load is shown in Table 6.2

Fig 6.10 reveals the plots of VH values for the species *Anadara* as it varies gradually from commissure line to umbo under the applied force of 50 gf. It's noted from the plots that *Anadara* has minimum hardness at normalized location of about 0.8 where the hardness value is 89.50 kgf. The maximum hardness (190.06 kgf/mm^2) is encountered at the peripheral zone nearest to the commissure line while the minimum hardness at the region just near to the umbonal region .And, shows the similar trend for 100kgf as well.

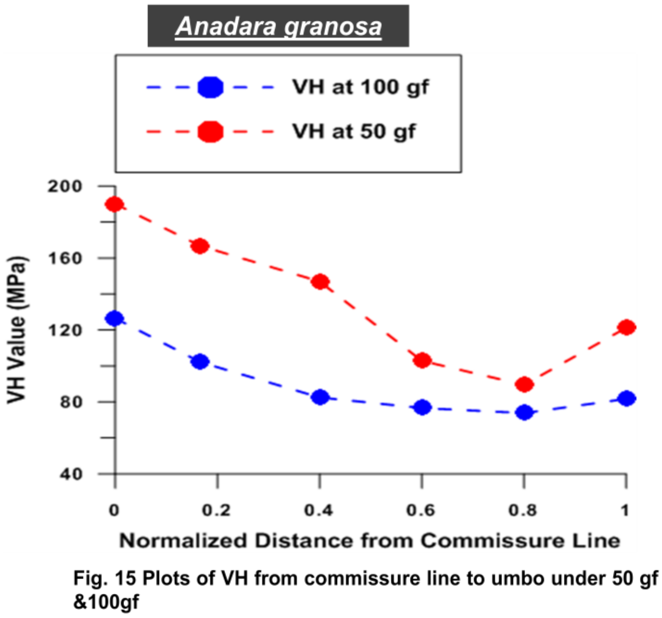


Fig 6.10 Variation of hardness for 50 gf and 100gf for the species *Anadara*.

6.3.3 Study on density variations

Fig 6.11 reveal the plots of density variation for the samples that were obtained along the centre line from commissure line to the umbo for the individual species as shown. From the plots it is clear that *Anadara* has highest density of ~2.4 gm/cc for its normalized position of 0.5. After that it shows a downward trend and the lowest density is prevailing for the umbonal region (1.86gm/cc). A somewhat similar trend follows for *Meretrix* where the highest (~2.38gm/cc) and lowest density (~ 1.92 gm/cc) is found for normalized positions of 0.6 (which corresponds to the same location for *Anadara*) and near the umbonal region respectively.

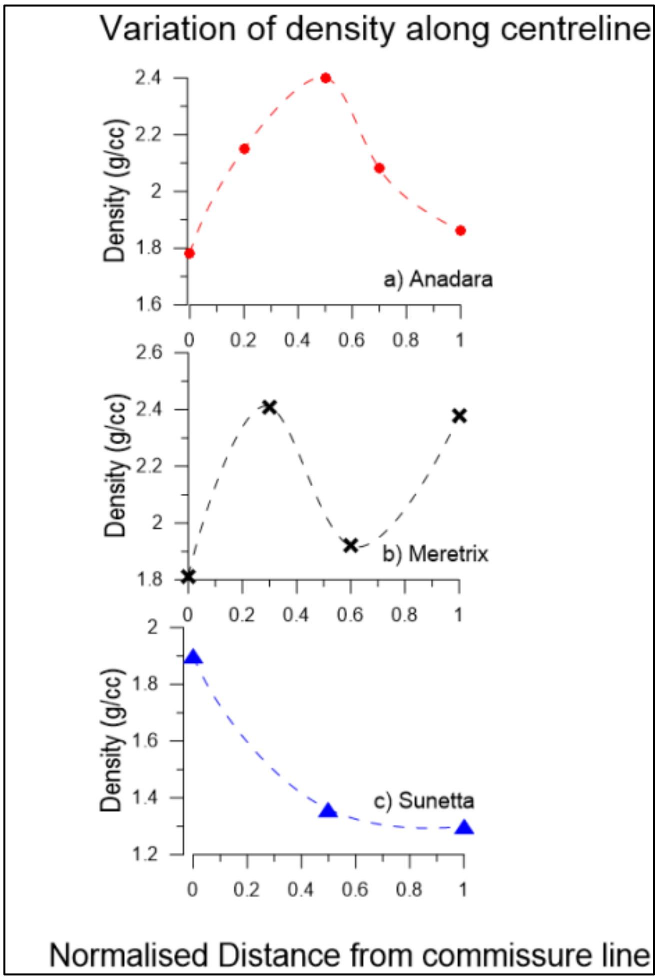
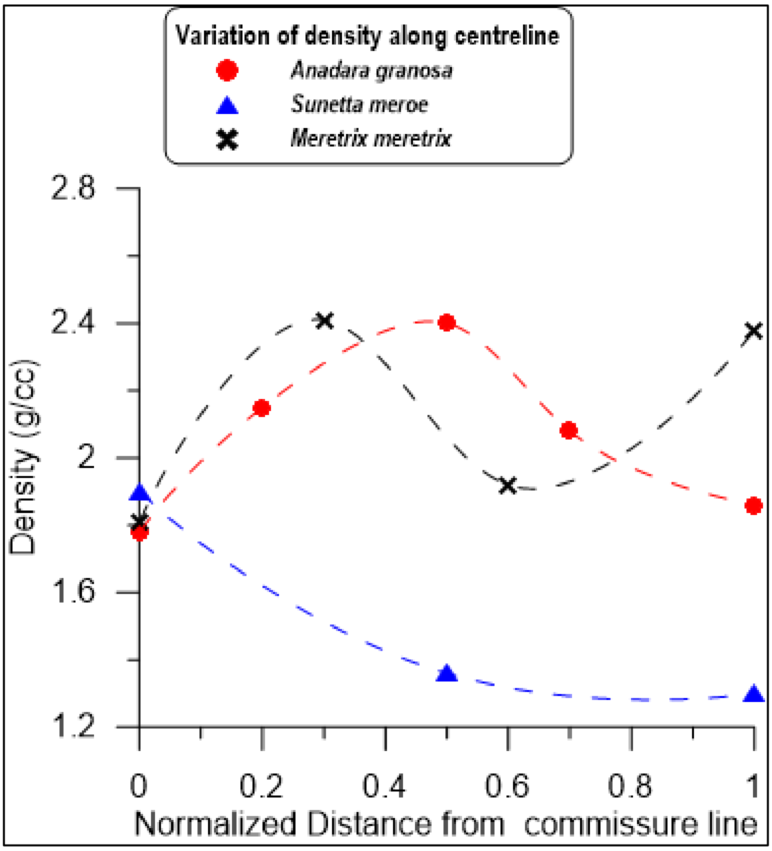


Fig 6.11 Comparison of shell densities , for individual species

The bivalve *Sunetta* shows a different trend of variation of density. Here though highest density (~1.90 gm/cc) is obtained from normalized position of around 0 (commissural zone) the least density (~1.30 gm/cc) is obtained from the normalized position of 1 which represents the zone corresponding to the zone just before the umbonal region. This trend in density variation in case of *Sunetta* is exactly in accordance with that of the variation of its thickness whereas the other two species i.e. *Anadara* and *Meretrix* has nearly similar trend of varying density and comply with the other two parameters i.e. thickness and hardness. A comparative analysis of density variation values has been presented by the Fig 6.12



Figs 6.12 Comparison of shell densities (Combined Plots)

It is observed from the plots that *Anadara* and *Meretrix* has almost similar values and a more or less similar trend of varying density too, while Sunetta has lower density overall compared to the other two species. Both *Anadara* and *Meretrix* shows a rise in density values from their first normalized position to the second normalized positions though this increment is steeper for *Meretrix* and gentler for *Anadara*. From here both shows a decrease in density to their next normalized position and here again the decrease is much sharper for *Meretrix* than *Anadara*. Then a slight decrease in density follows for both the species which grades to minimum near the umbonal regions. As stated earlier, *Sunetta* follows a different trend in variation of density where the minimum value of density is encountered in the zone at the umbonal region represented by the normalized position of 0.8-1. From the comparative study it is also evident that the normalized position of 0.4-0.8 is the zone of overall low density considering all the 3 species which is in par with the overall low thickness zones and hardness zones (complying with the evidences of predation). Thus it can be concluded that the answer to this observations may well lie within the internal structure and arrangement (stacking patterns of the aragonite crystals) of the molluscan shells.

6.3.4 Study of shell area:

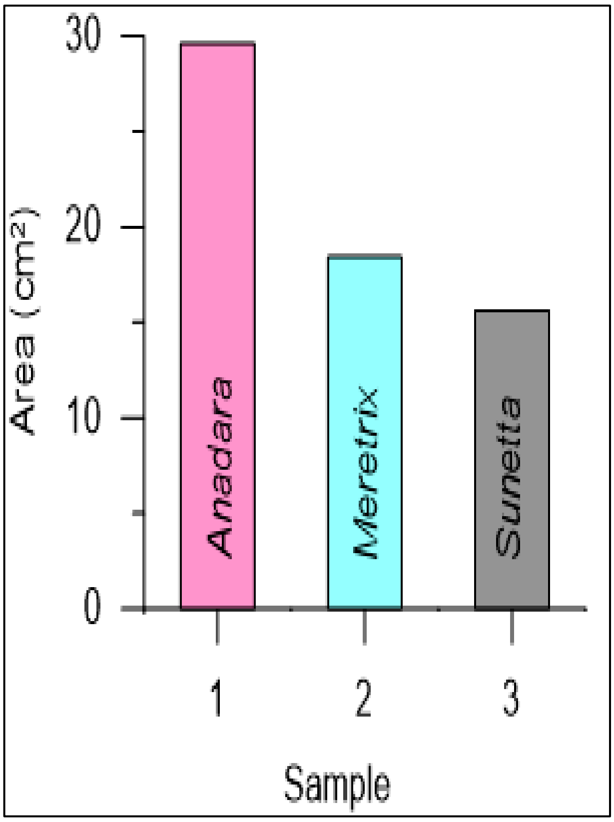


Fig 6.13 Comparison of shell area for the studied species

From the Fig. 11 Anadara was found to have a higher shell area (29.61 cm^2) with a decreasing value towards Meretrix (18.44 cm^2) and least for Sunetta (15.61 cm^2) as shown in the Table 6.4

Well, the shell area of the species has a strong correlation with the mechanical properties of a mollusc and also with its ecological niches.

6.4 Ecological niches of the studied species:

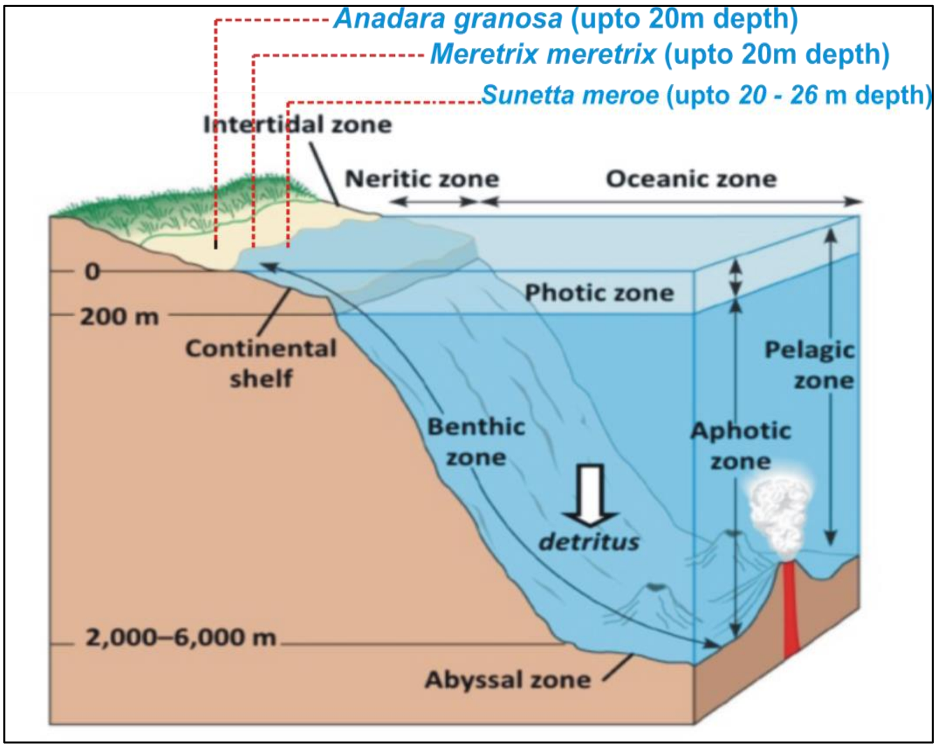


Fig 6.14 Ecological niches of all the 3 studied species

Even though all three of the studied species of *Anadara, Meretrix* and *Sunetta* inhabits the intertidal zone but the depth to which it dwells differs as indicated in the Figure 6.14 So, the rate of taphonomic attributes and mechanical properties differ by its structural design as well as composition for various different species. Anadara is a shallow dweller at the intertidal zone about a depth (upto 20m) so it evolved in a way with its architectural structure consisting of ribs and furrows and its thickness is significantly higher compared to the species which dwell at much higher depth. As, for Meretrix (upto 20m and more) being a burrower it inhabits quite a greater depth at the intertidal zone compared to Anadara, it has smooth surface and lesser thickness as to facilitate its activities of burrowing and boring on the sediments - water interface. Sunetta is an infaunal species which inhabits the greatest depth (upto 20m to 26m) amongst the other two and has smooth, elongately ovate shaped shell surface and has the least thickness and density. With the process of evolution its shell was built to be an efficient energy conserver during it burrowing process.

6.5 Conclusions

In the present investigations a new data set were presented on the major mechanical properties of the most dominant recent bivalve shells from Chilika, Odisha. *Anadara granosa, Meretrix meretrix* and *Sunetta meroe* are the bivalve species on which estimation of major mechanical properties were done following standard scientific methods. From the obtained results on thickness variation it is evident that for all the bivalves, peripheral part is thicker as well as umbo whereas the thinnest zone in all the cases is located around ~0.4-0.8 locations. These may be attributed to the arrangement of calcite/aragonite crystals within the shell of the mollusks which can only be studied through imagery under a high magnification microscopy such as SEM. Out of all the three species *Sunetta* is the thinnest one where as overall centerline thickness was highest for the species *Anadara*.

Compressive strength of the species *Anadara* as estimated through VH values reveals a systematic trends and it was revealed that under 50 gf hardness value of Anadara is maximum (~190 kgf/mm^2) at position near to the commissure line while the minimum value (~89 kgf/mm^2) observed at the zone prior to the umbonal area.

Under 100 gf the VH values shows an increase in magnitude for all the tested samples but the trends were almost similar with that of the trends of plots as obtained under 50 gf. Also the majority of the hardness values for the corresponding zones of the tested species did not differ significantly from one another. For 100 gf maximum value (~102 kgf/mm^2) is observed near the commissural zone and minimum value (~73 kgf/mm^2) observed just near the umbonal zone which correspond with the trend of 50 gf.

From the study of density variations along the centerline it is evident that the normalized position of 0.4-0.8 is the zone of overall low density considering all the 3 species which is in par with the overall low thickness and hardness zones (complying with the evidences of predation).Thus it can be concluded that the answer to this observations may well lie within the internal structure and arrangement (stacking patterns of the aragonite crystals) of the molluscan shells.

CHAPTER 7

CONCLUSIONS & FUTURE SCOPE

7.1 Conclusions

1. Dissolution effects are more prominent in Lake or lagoonal environment due to the acidification by anthropogenic impacts compared to other environments.
2. Abrasion effects depends on the length of the transportation from its death to till its burial
3. From the obtained results on thickness variation it is evident that for all the bivalves, peripheral part is thicker as well as umbo whereas the thinnest zone in all the cases is located around ~0.4-0.8 locations.
4. Under a loading force of 50 gf hardness value is of *Anadara* is maximum at position near to the commissure line while the minimum value observed at the zone prior to the umbonal area.
5. Under 100 gf the VH values shows an increase in magnitude for all the tested samples but the trends were almost similar with that of the trends of plots as obtained under 50 gf.
6. From the study of density variations along the centerline it is evident that the normalized position of 0.4-0.8 is the zone of overall low density considering all the 3 species which is in par with the overall low hardness and thickness zones (complying with the evidences of predation).
7. The answer to this observations may well lie within the internal structure and arrangement (stacking patterns of the aragonite crystals) of the molluscan shells.

7.2 Future Scope

The obtained conclusions from the present investigation need substantial explanations of internal arrangement of constituent crystals of the bivalve shells. It is clear from the preliminary observations that there is a sharp variation in the mechanical properties as studied for all the three species which surely attributed because of the internal configuration of constituent crystals. This needs a detailed study on spatial arrangement of crystals in both along and perpendicular to the growth lines preferably through Scanning Electron Microscope (SEM).

REFERENCES

Avery, R., Etter, R.J., 2006, Microstructural differences in the reinforcement of a gastropod shell against predation, Marine Ecology Progress Series, Vol. 323: 159-170

Barthelat, F., Rim, Jee E., Espinosa, Horacio D., 2009,A Review on the Structure and Mechanical Properties of Mollusk Shells – Perspectives on Synthetic Biomimetic Materials, Springer publication

Chen, P.Y., Lin, A.Y.M., Lin, Y.S., Seki, Y., Stokes, A.G., Peyras, J., Olevsky, E.A., Meyers, M.A., McKittrick, J., 2008, Structure and mechanical properties of selected biological materials, Journal Of The Mechanical Behavior Of Biomedical Materials I (208-226), Elsevier.

Clarkson, E.N.K., 1998, Invertebrate Palaeontology and Evolution, 452 p.

Currey, J.D.,1964, Biorheology Vol.2, p.1

Currey, J.D.,1977, Mechanical properties of mother of pearl in tension, Proceedings of the Royal Society of London.Series B, Biological Sciences,Vol. 196, No. 1125 pp. 443-463.

Currey, J.D., 1999,The Design Of Mineralized Hard Tissues For Their Mechanical Functions, The Journal of Experimental Biology 202, 3285–3294.

Dickinson, W.R., Suczek, C.A., 1979, Plate Tectonics and Sandstone Composition, The AAPG Bulletin V. 63 No. 12, P. 2164-2182.

Hechenberger, C., 2014, Structure, mechanics and function of the mollusc shells, SE Marine Biology, Vol. 124, (980-987).

Jinbo, Z., Tong, Jin., Li, C., Ma, Y., Di, X., 2011, The Study on Toughening Mechanism and Mechanical Properties of Stacked Microstructure of Shell, CISME (Communications in Information Science and Management Engineering, Vol.1 No.9 pp.39-43

Kamat, S., Su, X., Ballarini, R., Heuer, A.H., 2000, Structural basis for the fracture toughness of the shell of the conch *Strombus gigas*, Nature, Vol. 405, 1036-1039.

Kowalewski, M., Flessa, K.W., Hallman, D.P., 1995, Ternary Taphograms: Triangular Diagrams Applied to Taphonomic Analysis, Palaios, Vol. 10, p. 478-483.

Krumbein, W.L., Sloss, L.L., 1963, Stratigraphy and sedimentation, W.H. Freeman publications, 660 p.

Lutt, A., Grandjean, J., Grégorie, C., 1963 Arch. Int. Physiol. Biochem. Vol.68 p 829

Maria de Paula, S., Silveira, M.,2009, Studies on molluscan shells: Contributions from microscopic and analytical methods, Micron, Vol. 40, p. 669–690.

Medakovié, D., Popovié, S., Grzeta.B., Plazonié, M., Brenko, M.H., 1997, Mar. Biol. Vol.129, p 129.

Menig, R., Meyers, M.A., Meyers, M.H., Vecchio, K.S., 2000, Acta Mater.Vol. 48, p.2383.

Menig, R., Meyers, M.A., Meyers, M.H., Vecchio, K.S.,2001, Material Science & Engineering A Vol.297 p. 203

Raup, D.M., Stanley, S.M., 1971, Principles of Palaeontology, 388 p.

Ren, F.Z., Wan, X.D., Ma, Z.H., Su, J.H., 2009, Mater. Chem. Phys. Vol. 114, p. 367

Scott, R.W., 1974, Fossils in the Making-Vertebrate Taphonomy and Paleoecology, The University of Chicago Press, 338 p.

Scott, R.W., 1976, Biotic Interactions in Recent and Fossil Benthic Communities, Plenum Press Publictions, 836 p.

Su, X.W., Belcher, A.M., Zaremba, C.M., Morse, D.E., Stucky, G.D., Heuer, A.H., 2002 Chem. Mater. Vol.14, p. 3106

Taylor, J.D., Layman, M., 1972, The Mechanical Properties Of Bivalve (Mollusca) Shell Structures, Palaeontology, Vol.15, Part 1, pp.73-87.

Wilbur, K.M., Watabe, N., 1963 Ann. NY Acad. Sci. Vol.109, p. 82.

Yang, W., Kashani, N,. Li, X.W., Zhang, G.P., Meyers, M.A., 2010, Structural characterization and mechanical behavior of a bivalve shell (*Saxidomus purpuratus*),Materials Science and Engineering, Article in Press, MSC-02948; No. of Pages 6, Elsevier.

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Pulak Sengupta

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