CHANDIPUR MUD BALLS: AN ENIGMA

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by

Ankan Koley
Examination Roll No: **MGEO194022**

Under the supervision of
Dr. Soumik Mukhopadhyay

DEPARTMENT OF GEOLOGICAL SCIENCES
JADAVPUR UNIVERSITY
KOLKATA-700032
MAY, 2019

DEDICATED TO
MY GRANDFATHER

LATE MR. RAGHUPATI MONDAL

যাদবপুর বিশ্ববিদ্যালয়
কলকাতা-৭০০০৩২, ভারত

JADAVPUR UNIVERSITY
KOLKATA-700032, INDIA

FACULTY OF SCIENCE : DEPARTMENT OF GEOLOGICAL SCIENCES

CERTIFICATE

This is to certify that **Mr. ANKAN KOLEY** of M.Sc. Final Year, 2019, bearing Exam Roll Number **MGEO194022** and Registration Number **128257** of **2014-15**, has worked under my guidance in the Department of Geological Sciences and completed his M.Sc. Thesis Dissertation entitled **"CHANDIPUR MUD BALLS: AN ENIGMA"** which is being submitted towards the partial fulfillment of his M.Sc. Final examination in Applied Geology in Jadavpur University.

30/05/19

Signature

Prof. Sanjay Sanyal

HOD

Department of Geological Sciences

Jadavpur University, Kol-32

Head
Department of Geological Sciences
Jadavpur University
Kolkata-700032

30/5/19

Signature

Dr. Soumik Mukhopadhyay

Supervisor

Department of Geological Sciences

Jadavpur University, Kol-32

Dr. SOUMIK MUKHOPADHYAY
Assistant Professor
Dept. of Geological Sciences
Jadavpur University

দূরভাষ : ২৪১৪-৬৬৬৬/প্রসারণ : ২২৬৮
Website : www.jadavpur.edu
E-mail : hod_geological@jdvu.ac.in
Phone : 2414 6666/Extn. 2268

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Author

Ankan Koley

“Exact science and its practical movements are no checks on the greatest poet, but always his encouragement and support … The sailor and traveller, the anatomist, chemist, astronomer, geologist, phrenologist, spiritualist, mathematician, historian and lexicographer are not poets, but they are the lawgivers of poets and their construction underlies the structure of every perfect poem”

— Walt Whitman

In Walt Whitman and William Michael Rossetti (ed.), 'Preface to the First Edition of Leaves of Grass',Poems By Walt Whitman (1868),46.

Abstract

Mud balls, commonly referred to as discrete, near spherical masses of soft but cohesive sediment that have been eroded and transported intact from their original site of formation. They are reported from a wide range of depositional environments, both in modern settings as well as in ancient records. Although different models are proposed for generation as well as orientation of mud balls in different depositional settings, some common prerequisite conditions can be surmised, which are- (a) generation of mud balls must require erosion of formerly buried and slightly compacted thick mud layer by some high energy flows, strong enough to excavate the buried mud layer, and (b) subsequent transportation and depositional mechanisms control the distribution and orientation of the mud balls.

The studied area in Chandipur coast is characterized by the presence of a vast, gently dipping (<2^0 dip) tidal flat (almost 3.5 km wide) and a narrow beach (slope 4-9^0) (100-120 m wide), with an estuary at the north-eastern side. Overall, it represents a very low energy environment with low tidal intensity, unable to cut any distinct tidal channel and disrupted occasionally by some storm channels only. Mud balls, both armoured and unarmoured, of different sizes and shapes (majority of them are ellipsoidal, ovoid, triangular, square, rectangular, trapezoidal and spherical) are encountered within the studied stretch, preferably along the junction between the beach and the tidal flat as well as on the seaward side of the larger barrier bars. River borne sediments, dispersed through formation of riverine spits, eventually get modified to form shore parallel barrier bars and merge with the coast line after migrating over the vast tidal flat, under tidal influence mainly. These local barrier bars isolate some portion of the tidal flat to produce a temporary low energy, calm and quite environment which is demarcated as ‘Swamp’ on their landward side. In response to the invading transgression, the barrier bars migrate over the thick swampy mud deposited on their landward side, which being thixotropic, remains almost static and gets compacted. Eventually the inactive, previously buried, swampy mud gets exposed on the seaward side of the migrated bar and becomes prone to desiccation and erosion. These desiccated mud acts as the source of the mud balls in the area. During sub-aerial exposure, as in case of low tide periods, this thick mud unit gets desiccated. The next high tide easily separates the desiccated mud chunks and carried them towards shoreline. Various shapes among mud balls may be attributed to the initial irregular shape of desiccated mud chunks. Hence, the formation of mud balls, in this setting does not require any high energy flows to erode out formerly buried mud as proposed in most of the earlier works as a necessary prerequisite.

During transportation over the tidal flat, these mud balls get rounded as well as armoured with readily available organic shells. Under the low energy setting of this area, these heavy, elongated mud balls should be transported as bed load or rolling load and accordingly long axes of these mud balls should be oriented shore parallel after final deposition. Chandipur mud balls contradict this general consensus too, as a large number of mud balls used to show shore perpendicular orientations of long axes, as generally expected in case of sediment gravity flows due to transportation as suspension load. But, in a low energy coast like Chandipur, frequent presence of such high energy sediment gravity flows are hard to apprehend. Critical analysis has revealed a distinct relationship between the shape of the mud balls and its ultimate orientation, where purely ellipsoidal mud balls showed mostly shore parallel orientation of their long axes, a vast number of mud balls with tapered ellipsoidal (ovoid) shape were found lying with their long axes at high angle or perpendicular

to shore line. This peculiar orientation of Chandipur mud balls can be attributed to the asymmetric mass distribution along the long axis in case of tapered mud balls and the couple of forces imposed on them by consecutive swash and backwash. Their behaviour, on the sloping shore is almost similar to that of an egg rolling along a lowly inclined ($<10^{o}$ dip) plane. Sometimes surface irregularity also influences the final orientation of mud balls.

Preserved mud balls were found within some trenches in the foreshore of Chandipur beach, which showed both shore parallel as well as shore perpendicular orientations of the long axis. Therefore, it can be stated that the Chandipur mud balls, clearly stand apart from mud balls reported from other areas, both in genesis as well as final orientation of long axes. Critical investigation of the interrelationship among the slope, shape and orientation is required to avoid misleading interpretations for environments as well as paleo-geography.

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CHAPTER-1: INTRODUCTION

1.1. INTRODUCTION:

Mud balls, commonly referred to as discrete, near spherical masses of soft but cohesive sediment that have been eroded and transported intact from their original site of formation, are reported from a wide range of depositional environments, both in modern settings as well as in ancient records from alluvial and fluvial settings, lacustrine systems, tidal coasts, wave-dominated coasts, continental slopes and submarine fans. Mud balls, both armoured and unarmoured of different sizes and shapes (majority of reported varieties are ellipsoidal, ovoid, triangular, square, rectangular, trapezoidal and spherical) have been encountered. Mud balls developed in various environments, generally show distinct morphological and compositional features. Under various names mud balls have received brief and infrequent mention in the Geological literatures of the past hundred years and have been termed differently in different literature through time, such as rip-up clasts (Allen, 1982), mud balls (Bell, 1940), clay pebbles (Trefethen and Dow, 1960; Nossin, 1961), clay galls (Pettijohn, 1957), clay balls (Haas, 1927), and intraformational clasts (Smith, 1972). In general they are termed as mud balls for their near spherical shape and rounded to subrounded body geometry.

Classification of mud balls are based on four aspects including volumetric abundance of balls, sorting, roundness and grain size, which are closely related to transport distance, flow viscosity and sedimentary slope gradients. The three parameters are matrix, sorting and roundness which are used to classify nine types of mud balls (Li et al., 2017). Sorting is indicated by the standard deviation from a normal distribution. With increased transport distance or repeated agitation of sediment, different sizes tend to become separated.

Roundness can be calculated from the cross-sectional shape of a clast. It is given by the ratio of the radius of corner to the radius of the maximum size circle that can be inscribed within the outline of the grain in the plain of measurement (Stanley, 1969; Li et al., 2017). During the transportation, sharp edges tend to be chipped off and then the abrasion smoothes the surface.

Mud balls could be formed by multiple ways including failure of soft sediments, erosion of muddy sediment, and bioturbation/faecal pellets. Failure and erosion, which are dominant genetic mechanisms, generally involve interaction between physical processes of flow and sediments. Bioturbation only occurs in sediments with organisms. Although different models are proposed for generation as well as orientation of mud balls in different depositional settings, some common prerequisite conditions can be surmised, which are, (a) generation of mud balls must require erosion of formerly buried and slightly compacted, thick mud layer by some high energy flows, strong enough to excavate the buried mud layer, and (b) subsequent transportation and depositional mechanisms control the distribution and orientation of the mud balls. Brittle mud balls are commonly generated in sub-aerial conditions like alluvial, tidal, and fluvial environments by dehydration and cracking of muddy sediments. In subaqueous conditions, failure of muddy sediments that normally show plastic characteristics are triggered by mass movements during sliding and slumping through physical parameter changes including cohesion, effective pressure and shear strength. Study of different mud balls may help for identifying specific depositional processes and preservative conditions.

1.2. <u>LOCATION</u>:

The studied area for the dissertation is Chandipur (Latitude: 21.4399°N , Longitude:87.0149° E). It is situated in the Balasore district of Odisha, in the eastern coast of India and in the north western corner of the Bay of Bengal. The study area is actually a stretch of around 4km along the coastal plain, from the PWD bungalow of Chandipur at the south to the Buddhabalam River towards the north.

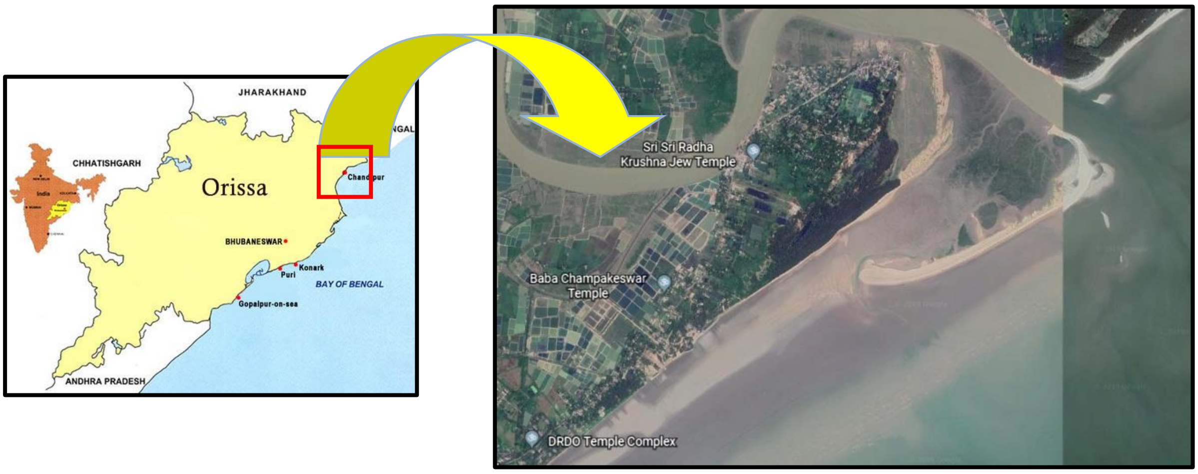


Fig 1.1: Geographic location of CHANDIPUR, the field area

1.3. <u>SCOPE OF WORK</u>:

Chandipur is a place which is a canvas of modern shallow marine and coastal environments. Here we get different types of environments like beach environment, tidal environment, bar-barrier environment, swamp environment, eolian environment all at a stretch of around 8 km^2. The beach, though not a true beach, has all the aspects of a beach like burrows, foreshore, backshore etc. The tidal flat covers an area of about 5km stretch. The ripples forming and destroying everyday helps us to clear our conception a lot. There are many problems that are yet to be solved in Chandipur. The peculiar orientation and genesis of mud balls here is one of those problems. Thus it gives us a chance to think on our own on "What can be the reason behind this?" Thus there is a huge scope of work in "THE DYNAMIC CHANDIPUR".

Studied area in Chandipur is primarily a marginal marine setting, comprising six distinct milieus:

- The tidal flat
- The beach
- The barrier bar
- The marshy swamps at interbar area
- The estuary at the confluence of river Buddhabalam
- The beach-dune complex

Chandipur-on-sea thus provides an excellent scope of work, not only because it is a treasure house of a large variety of organisms and sedimentary as well as biogenic structures, but also because of the very fact that such an ever changing complex sheds light on certain interesting arenas of the sedimentology-stratigraphy-palaeontology related study, like the one in this study regarding the formation and orientation of mud balls found here.

1.4. GOAL:

The study area of the coastal province of Chandipur is a complex setup of eolian dune-field–beach–tidal flat and barrier bar which presents a unique scope of study of a vast range of sedimentary processes and products in a modern setting. The goal of overall work included:

- Document the process of genesis of Chandipur mud balls; its uniqueness, if any
- Study the pattern and peculiarities, if any, in the orientation of Chandipur mud balls; unravel the mystery behind it.
- Extraction of the controlling factors behind such orientation.
- Investigation of preservation potential of Chandipur mud balls.

The field of geology has a common saying "The present is the key to past", which is religiously followed as the theory of Uniformitarianism. Thus, our main purpose of visit to the Chandipur-on-sea includes a thorough understanding of the present day modern conditions and processes, as well as the imprints left behind by them, so that this knowledge can be extrapolated to investigate the processes and the products as obtained in the ancient rock records.

CHAPTER-2: OVERVIEW OF MUDBALL

2.1. GENERAL VIEW:

Mud balls, commonly referred to as discrete, near spherical masses of soft but cohesive sediment that have been eroded and transported intact from their original site of formation. Mud clasts, also termed as rip-up clasts (Allen, 1982), mud balls (Bell, 1940), clay pebbles (Trefethen and Dow, 1960; Nossin, 1961), clay galls (Pettijohn, 1957), clay balls (Haas, 1927), and intra-formational clasts (Smith, 1972), are commonly distributed in marine to non-marine settings. They are reported from a wide range of depositional environments, both in modern settings as well as in ancient records from alluvial/fluvial, lacustrine systems, tidal coasts, wave-dominated coasts, continental slopes and submarine fans. Mud balls, both armoured and unarmoured, of different sizes and shapes (majority of them are ellipsoidal, ovoid, triangular, square, rectangular, trapezoidal and spherical) are encountered in nature. Mud balls are widely developed in various environments, generally showing distinct sedimentary features.

2.2. FORMATION, TRANSPORTATION AND DESTRUCTION MECHANISMS:

In the past decades, mud clasts have been studied widely in individual systems including their origin, properties, and transportation (Bell, 1940; Nossin, 1961; Williams, 1966; Fagerstrom, 1967; Dickas and Lunking, 1968; Stanley, 1969; Knight, 2005; Mather et al., 2008).

The occurrence of the mud balls, in Minas Basin area of Nova Scotia, coincides with areas in which high tides undercut cliffs of glacially-derived cohesive clay (Stanley, 1969; Tanner, 1996; Fig 2.1). The resulting slumps are broken into blocks by wave action and subsequently rounded. The compact form of irregularly shaped mud balls (Tanner, 1996) suggests an origin as equant blocks prior to undergoing significant rounding. Transport across the pebbly beach causes the armouring by the adherence of coarse sediment that covers the upper intertidal zone.

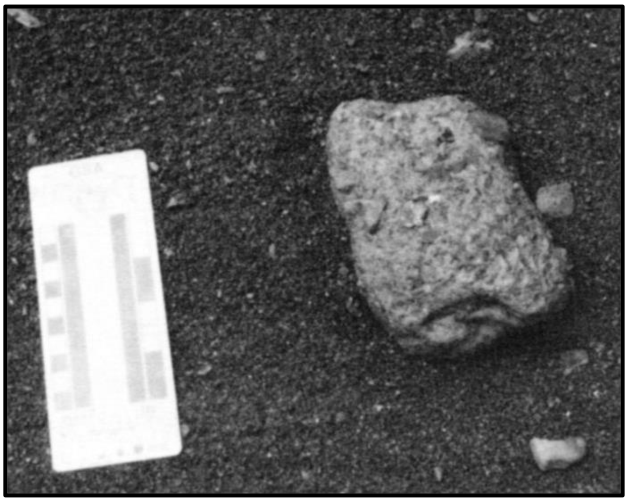


Fig 2.1: Equant block of mud prior to undergoing significant reworking (Tanner, 1996).

The clay which is deposited in intertidal mud flat is eroded due to wave undercutting when the unit becomes exposed in the emergent runnels during the early summer. Soft-sediment clasts are formed as the clay unit is broken up (Knight, 2005).

Knight (2005) has mentioned two processes of mud clast generation from crack bearing clay unit.

i) Detachment of desiccated mud polygons due to wave action generates mud clasts as well (Fig 2.2). These cracks usually link together, forming 4 to 6-sided polygons. The cracks are usually straight, are the same thickness throughout their length and form a V-shaped wedge in section that terminates or changes in thickness and direction at laminae boundaries. The crack-defined polygons can be classified as joined and non-orthogonal (Allen, 1987) and remain across the exposed sediment surface (Knight, 2005).
ii) Tension cracks are also developed in some places along the margins and seaward-facing front of the clay unit where soft-sediment clasts are being detached from the main sediment body. These cracks, developed parallel to the erosional front of the clay unit, are sometimes infilled with or overlain by beach sand (Knight, 2005).

Fig 2.2: Exposure of buried mud layer due to excavation through high energy waves and mud chunks after desiccation (Knight, 2005)

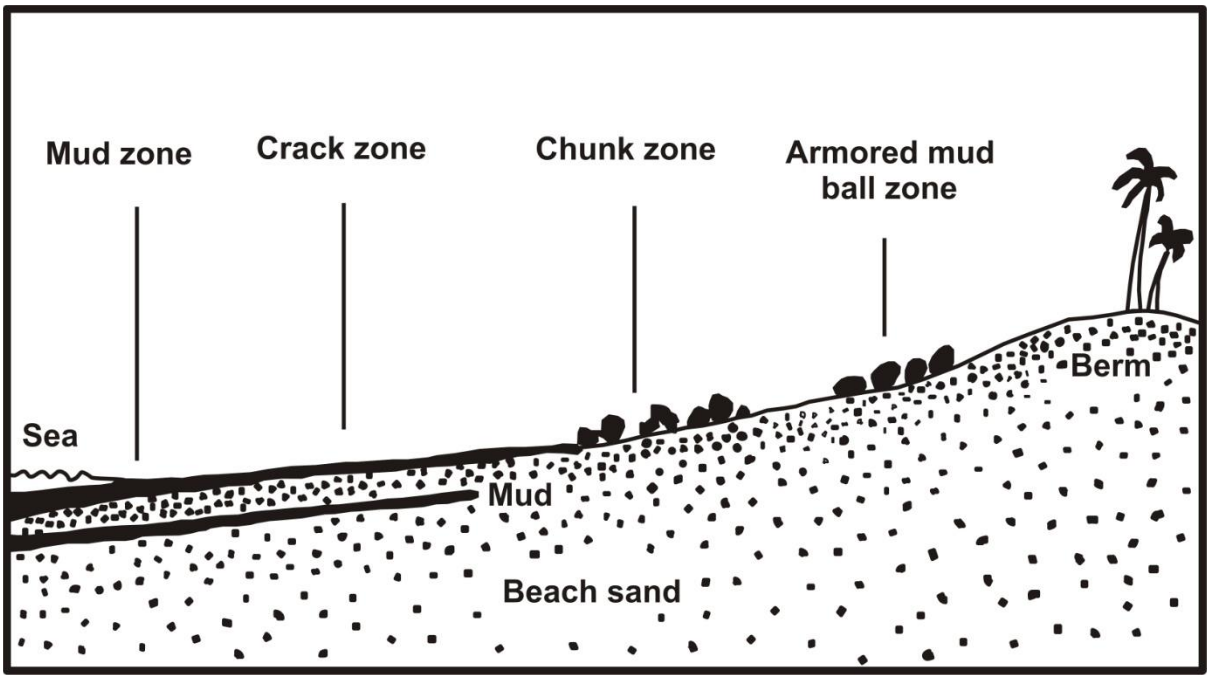


Fig 2.3: Schematic model showing formation of mud chunks due to wave activities (Kale, 1993)

Even two groups of clasts were identified in his study. Attached clasts are defined as those clasts that are located immediately adjacent to (<30cm distance) that part of the sediment unit from which they were derived. Detached clasts are defined as those located more than 30 cm away from the sediment unit.

The high spring tide can undercut sediments from intertidal zone. Stanley mentioned in his paper (Stanley, 1969) that this kind of erosion from a nearby cliff in his study area can result in slumping and derivation of mud and gravel onto the upper tidal-flat platform, a wave-cut bench that is alternatively exposed and submerged twice each day. Derived blocks of soft plastic silty clay moved from the undercut strata of clay, silt, sand and gravel and were rolled about on the beach by waves. This material becomes an important source of armoured mud balls. He also suggested that within 36 hours after high tide and slumping, armoured mud balls had not been transported more than 100-200m away from their point of origin.

The processes of mud ball generation and armouring have been studied along the shore of Lake Superior by Dickas and Lunking (1968), which are a bit different as they are not in any intertidal or high energy coastal environment. In their observation of the lake-ward tilt of tree trunks along the Lake Superior shoreline indicates that's soil creep together with slumping are dominant features of mud-bank erosion. In the summer months during periods of storm activity, the mud banks are undercut and large blocks of mud collapse onto the beach. Smaller masses of this mud are reworked into tri-axial ellipsoids by the storm waves which carry the embryonic, clayey, plastic-like masses into the tidal zone of the lake. The range of tides is small, but due to the gentle gradient of the lake shelf zone, tidal activity is noted some distance offshore. So, storm waves are the major reason behind erosion of mud and shaping them, where tidal activity being less, contributes in late phase slow reworking near offshore.

In order to determine where the armouring process takes place, a sampling method was adopted by the authors. Along a beach zone where armoured mud balls were found, samples of lake-bottom sediments were taken along a traverse line at right angles to the shore. These were taken at 0,10, 20, and 30 ft depths. Histograms of the sediments from each of these stations were plotted (Dickas and Lunking, 1968). A comparison of the composite histogram of the mud ball armour (Dickas and Lunking, 1968) with the histogram constructed from the sediment size distribution of the samples taken on the traverse line, indicates that a majority of the armouring takes place in the normal tidal zone. This tidal or beach station was the only station sampled whose particles contained elastic material within the granule and pebble range.

According to authors, after the collapse of the mud-bank, smaller masses of mud are transported to the normal tidal zone, where they acquire a veneer of sand, granules, and pebbles. During the next storm cycle, those mud balls which have undergone armouring and have been protected from physical destruction within the surf zone are cast high up on the beach area. There they are deposited beyond the reach of normal tidal action and any further "armouring."

Dickas and Lunking (1968) have also mentioned three patterns of destructions of mud balls in the Lake Superior beach area. In the warm summer temperatures, the inner mud core begins to desiccate within a matter of days. The mud core shrinks and cracks (Dickas and Lunking, 1968) and the veneer of 'armour' begins to spall off. The entire ball is eventually destroyed.

During the winter months, mud ball destruction proceeds in a slightly different manner. The lower winter temperatures retard the desiccation of these balls, but cause the interstitial water to freeze and fix the mud balls in place. Prior to the spring thaws, desiccation and frost heaving combine to destroy the remaining specimens. Although frost heaving is the dominant form of destruction during the winter months, desiccation continues on a small scale as the interstitial water evaporates. With the onset of the spring thaws, the general direction of melt waters is toward the lake. As the snow cover melts, the mud balls that have survived are carried by melt waters into the lake and destroyed.

Thus, regardless of the season, within a matter of months all armoured mud balls are destroyed. This explains the absolute lack of fossil forms in the recent sediments of Lake Superior.

Li et al. (2017) have stated three major processes of mud clast formation including failure of soft sediments (Nossin, 1961; Karcz, 1969), erosion of muddy sediments (Allen, 1982, 1985; Migniot, 1968) and bioturbation/faecal pellets (Seilacher, 1967; Frey and Wheatcroft, 1989). Failure and erosion, which are dominant genetic mechanisms, generally involve interaction between physical processes of flow and sediments. Bioturbation only occurs in sediments with organisms and influences the water content and thus density/cohesion of the mud (Potter et al., 2005).

2.3. DEPOSITIONAL SETTING:

Armoured mud balls that consist of rounded, pebble-encrusted masses of clay are unusual clastic sedimentary structures observed primarily in fluvial and tidal settings. Tanner (1996) has mentioned that their origin in fluvial environments, in which down stream transport of clay masses produces a nearly spherical shape (Haas, 1927; Bell, 1940; Pettijohn and Potter, 1964). Additionally, he has referred that their origin has been documented on shorelines of lacustrine (Haas, 1927) and marine environments (Grabau, 1932; Kugler and Saunders, 1959; Hall and Fritz, 1984) where oscillatory motion from wave action produces more elongate shapes. The occurrence of armoured mud balls in the intertidal zone of mega-tidal coasts has been reported by Thompson (1968) and Stanley (1969).

Li et al. (2017) also has documented that mud clasts are widely found both in marine and non-marine environments and in modern and ancient records from alluvial/fluvial systems (Haas, 1927; Bell, 1940; Little, 1982; Mather et al., 2008), lacustrine systems (Dickas and Lunking 1968), tidal coasts (Stanley, 1969; Kale, 1993; Tanner, 1996; Knight, 2005), wave-dominated coasts (Hall, 1984; Bhattacharya, 1993; Ghandour et al., 2013), continental slopes (Goldschmidt, 1994), and submarine fans (Chun et al., 2002).

Armoured mud balls have been described from modern alluvial and coastal environments and, in a few instances, have also been recognized in recent and ancient intertidal deposits (Richter, 1926; Stanley, 1969).Though lacustrine mud balls are rare in documentation, recent armoured mud balls were mentioned to be collected along the south shore of Lake Superior, wherever mud-banks are found adjacent to the lake shore (Dickas and Lunking, 1968).

Fig 2.4: Lake Superior armoured mud balls shown on a 1 square centimetre grid-(a) Photograph showing mud balls in various stages of disintegration, (b) and (c) close-up photographs of typical mud balls(Dickas and Lunking, 1968).

2.4. OCCURRENCE, SIZE, SHAPE / GEOMETRY:

The relationship between forces of cohesion and impact is a key factor in determining the fairly uniform size of the mud balls and structural strength, for instance, determines the maximum size of ellipsoids (Stanley, 1969) (i.e., "Forces tending to hold a ball together are opposed to those tending to destroy it. Cohesion is called upon to resist the distinctive forces of impact, and the power to resist it is quite obviously proportional to the area under stress" (Bell, 1940).

The compressibility and plasticity should also be taken under consideration regarding the size of mud ball and the size of their armouring (Stanley, 1969). Through soil-test examinations, plastic limit, liquid limit and plasticity index of mud can be measured. The size and shape of mud balls and the size distribution of their armour tend to approach geometrical similarity (Stanley, 1969). Sphericity and form can also be related to other properties of the original material being moved, such as hardness and bedding as discussed by Sneed and Folk (1958), Pittman and Overshine (1968).

However, the elliptical form and uneven armour can be best explained by the particular mode of transport processes inherent to the tidal environment, that is alternating current directions and variable current velocities (Stanley, 1969).

Stanley (1969) has also mentioned that armoured mud balls examined in the Las Posas region by Bell, in other alluvial environments by Gardner (1908), Haas (1927), and Cartwright (1928), in glacial outwash deposits by Leney and Leney (1957), and in deep marine environments (Osborne, 1953; Stanley, 1964), display a considerably greater degree of sphericity and more uniform pebble coating than do those in the beach and intertidal flat of Island View locality. On the other hand, the tri-axial ellipsoidal shape of intertidal mud balls more closely resembles that of armoured mud balls formed in marine beaches (Grabau, 1932; Kindle, 1937; Kugler and Saun-ders, 1959) and lacustrine coastal environments (Haas, 1927; Dickas and Lunking, 1968).Field studies in the fluvial environment have shown that angular, non-armoured clay blocks are shaped into highly spherical armoured mud balls in less than 15 minutes (Bell, 1940).

Blocks transported predominantly forward by water with movement in many directions along the bottom result in rapid rounding by wearing away of projecting parts and build up of a heavy coat of granules and pebbles eliminates further growth and probably retards corrosion. Thus, balls that are allowed to roll and bounce freely for considerable distances, such as on flood plains or in submarine valleys, tend to develop high sphericity and a fairly even pebble armour; on the other hand mud balls in beach, intertidal flats and other coastal environments are more ellipsoid, elongated or platy and develop less sphericity (Stanley, 1969).

Dickas and Lunking (1968) have concluded that in a freshwater lacustrine environment, tri-axial ellipsoids rather than spherical forms are more common to be found. The quantity of armour accumulated is a power function of the surface area of the ball (Stanley, 1969).

Dickas and Lunking (1968) found that the Lake Superior armoured mud balls had their armour extending to a maximum depth of 6 cm (2.4 in.) into the mud ball and occupying a mass equaling, by weight, 11 to 36 percent of the total weight of the specimen.

The armour included fragments of quartzite, agates, jaspers, basalts, gneisses, sandstones and other igneous rock and metamorphosed rocks, all related to nearby provenances. These fragments were well-rounded; only the more resistant types displayed any degree of angularity. The amount and maximum size of armour increase directly with size (Stanley, 1969; Fig 2.5).

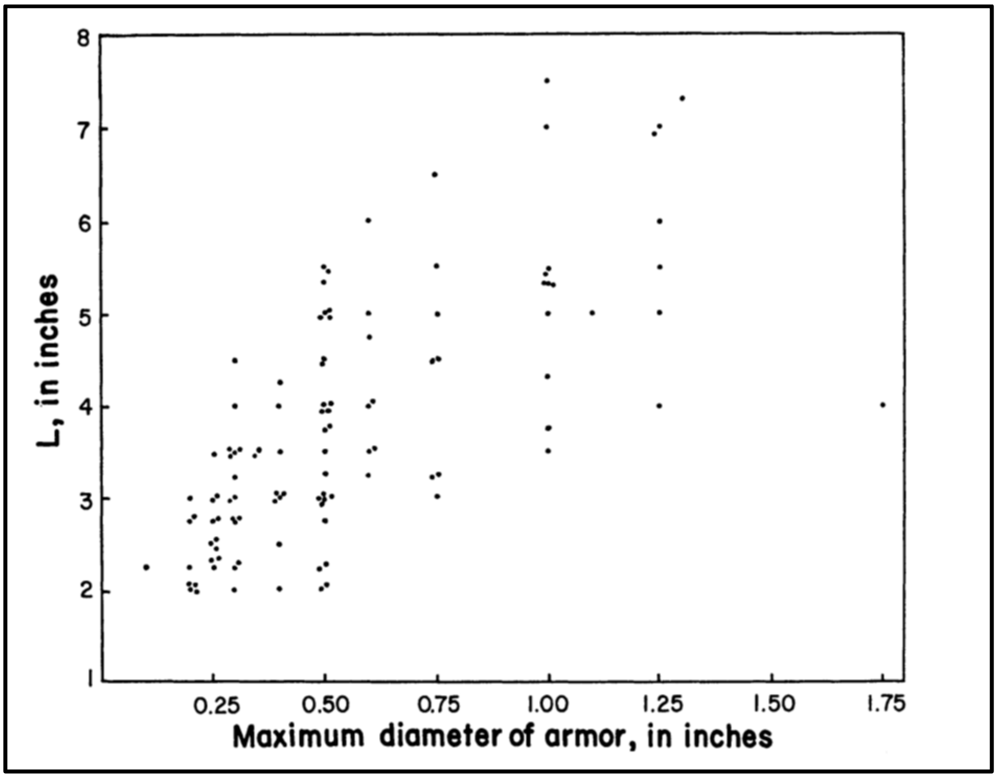


Fig 2.5: Diagram showing relation between size (L axis) of mud balls and maximum diameter of their granule and pebble armouring.

The shape of each armoured mud ball can be determined (Stanley, 1969) by plotting size data on a sphericity form diagram (Sneed and Folk 1958). To obtain shape, S/L, and (L - I) / (L - S) are computed and plotted (where L, long axis; I, intermediate axis; S,short axis) on the triangular diagram (Fig 2.6) used for analyzing a tri-variant system. Sphericity (Ψ_ρ), a quantitative value illustrating departure of a body from equi-dimensionality, is provided directly on the Sneed and Folk form diagram. The formulation for Ψ_ρ, maximum projection sphericity is [$\sqrt[3]{(S^2/LI)}$].

The three end points of the triangle define: (a) a sphere with all axes equal (compact end point), (b) an oblate spheroid with two long axes and one short one (platy end point) and (c) a prolate spheroid with one long axis and two short ones (elongate end point).

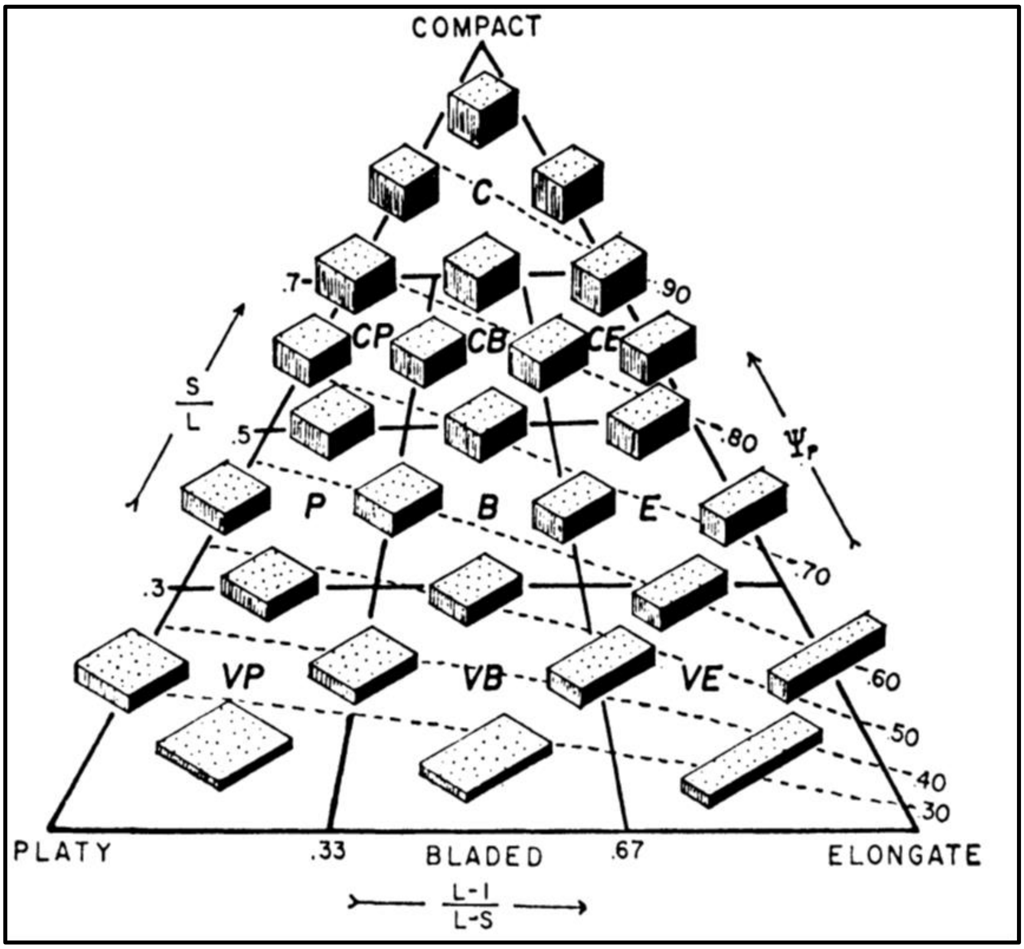


Fig 2.6: Sphericity-form diagram after Sneed and Folk (1958). L, long axis; I, intermediate axis; S, short axis; Ip, maximum projection sphericity [$\sqrt[3]{(S^2/LI)}$] (Stanley, 1969).

Tanner (1996), based on his 50 measurements, stated that mud balls range in size from 2 to 20 cm in diameter (long axis, L) with a mean diameter of 9 cm. The shapes of these objects are variable and include nearly spherical (compact by the method of Sneed and Folk, 1958), prolate spheroid (platy of Sneed and Folk; Fig 2.7 a), and oblate spheroid shapes (elongate of Sneed and Folk; Fig2.7 b), the last being the most abundant.

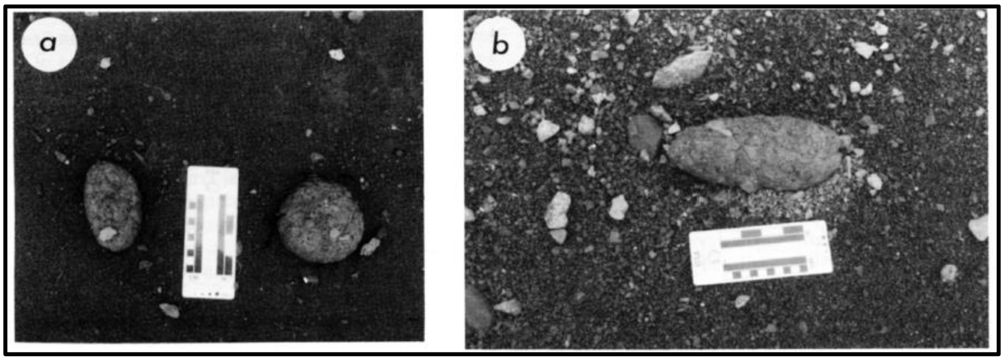


Fig 2.7: a) Prolate spheroid (left) and b) Oblate spheroid (right) mud balls

The mud balls studied along the shore of Lake Superior by Dickas and Lunking (1968) occur as tri-axial ellipsoids (Dickas and Lunking, 1968). The dimensions of these ellipsoids range from 6.2 cm (2.5in.) to 15.4 cm (6.1 in.) along the major / long axis (L), from 3.8 cm (1.5 in.) to 9.1 cm (3.6 in.) along the intermediate axis (I) ; and from 2.1 cm (1.1 in.) to 7.1 cm (2.6 in.) along the minor / short axis (S).

Roundness values of armoured mud balls can be obtained, as mentioned by Stanley (1969), by visually comparing the silhouette of balls with diagrams on a chart for estimation of roundness (Pettijohn 1957; Stanley, 1969). Roundness is independent of ball size but is distinctly related to position of the balls and their final position from their origin, i.e., how much they have transported and reworked before their final settlement (Stanley, 1969).

2.5. CLASSIFICATION:

Li et al. (2017) have proposed a triangular chart (Fig 2.8) of classification of mud clasts based on physical properties of volumetric abundance of clasts, sorting, and roundness. Li et al. (2017) also shows grain size of the mud clasts are mainly controlled by transport distance, viscosity and sedimentary slope gradients.

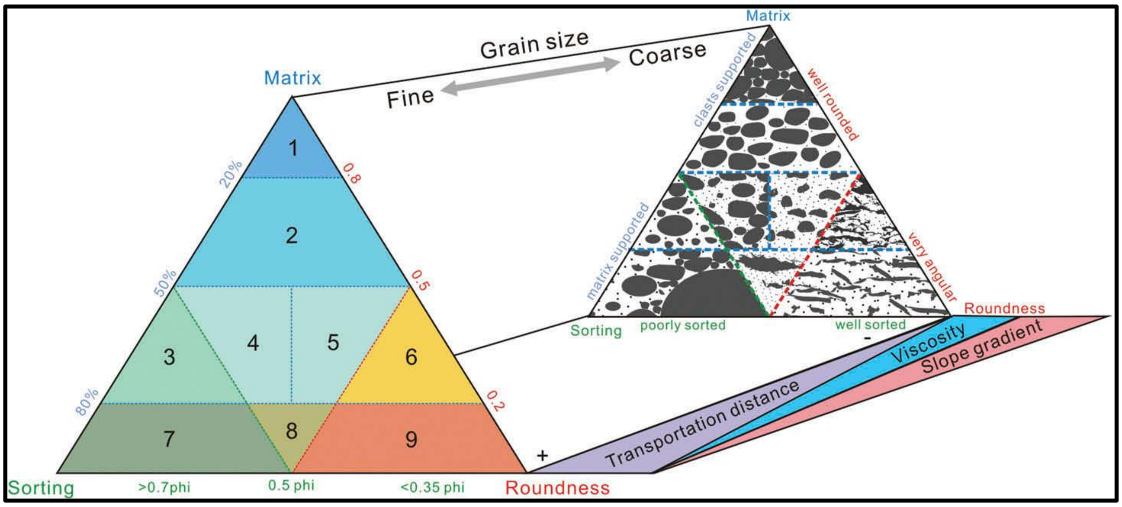


Fig 2.8: Triangular chart of classification of mud clasts based on physical properties of volumetric abundance of clasts, sorting and roundness, showing grain size of the mud clasts are mainly controlled by transport distance, viscosity and sedimentary slope gradients. Note that 1) Clast-supported, well-sorted, well-rounded; 2) Clast/matrix-supported, moderately sorted, well-rounded; 3) Matrix-supported, poorly sorted, well-rounded; 4) Matrix-supported, moderate sorted, moderately rounded; 5) Matrix-supported, well-sorted, moderately rounded; 6) Matrix-supported, well-sorted, very-angular; 7) Matrix-supported, poorly sorted, rounded; 8) Matrix-supported, poorly sorted, poorly rounded; 9) Matrix-supported, moderately sorted, very angular (Li et al., 2017).

In the mentioned study, for the classification of mud clasts, at first, the rocks are separated in to matrix and clasts (grain size, larger than 2 mm). The clasts are then characterized by textures (sorting and roundness). Finally, the three parameters of matrix, sorting and roundness are used to classify nine types of mud clasts. Each end member in the triangular chart represents one typical product under a certain sedimentary environment also. It is also proposed that grain size is influenced by the gradient, channel pattern, deformation and sedimentation of deposits. Grain size provides useful pointers concerning the transportation history of mud clasts and the processes and environments of deposition.

2.5.1. <u>VOLUMETRIC ABUNDANCE OF CLASTS IN THE DEPOSIT</u>:

A distinction has been made between the clasts and the matrix. Between gravel-size mud clasts, finer sands, silts and/or mud are commonly present. These finer sediments between mud clasts have been referred to as the matrix of the deposit. Matrix-supported has been defined where the amount of matrix is more than 50%. Clast supported deposits fall in the group when the matrix is less than 20%. When the matrix is between 20% and 50%, these deposits represent the transition between matrix-supported and clast-supported (Li et al., 2017, Table 1).

2.5.2. **SORTING**:

Sorting, in this study, has been indicated by the standard deviation from a normal distribution. With increased transport distance or repeated agitation of sediment, different sizes tend to become separated (Nichols 2009). Here Phi(Φ) scale has been used for subdivision of mud clasts, which includes well-sorted (Φ <0.5), moderately sorted (0.5 <Φ < 1.0), and poorly sorted (Φ >1.0) proposed by Folk and Ward (1957).

Matrix Content	<20 % Clast supported	20-50% Clast / matrix supported	>50% Matrix supported	>50% Matrix supported	>50% Matrix-supported	>50% Matrix-supported	>80% Matrix-supported	>80% Matrix-supported	>80% Matrix-supported
Sorting	<0.5 Well sorted	0.5-1 Moderately sorted	>1 Poorly sorted	0.5-1 Moderately sorted	<0.5 Well-sorted	<0.5 Well-sorted	>1 Poorly sorted	0.5-1 Moderately sorted	<0.5 Well-sorted
Roundness	>0.8 Well rounded	>0.5, <0.8 Rounded	>0.8 Well rounded	>0.5, <0.8 Rounded	>0.5; <0.8 Rounded	>0.2; <0.5 Angular	>0.5; <0.8 Rounded	>0.2; <0.5 Angular	<0.2 Very-angular

Table-1: Criteria for characterizing classification of mud clasts.

2.5.3. ROUNDNESS:

They have also proposed that roundness can be calculated from the cross-sectional shape of a mud clast. It is given by the ratio of the radius of corner to the radius of the maximum size circle that can be inscribed within the outline of the grain in the plain of measurement (Wentworth, 1919; Wadell, 1932; Boggs 2009). During the transportation, sharp edges tend to be chipped off and then the abrasion smoothens the surface (Tucker, 2009).

Armoured mud balls in the intertidal zone of the Minas Basin (near Lower Five Islands) have been described by Stanley (1969) who observed the following:

1) A tendency toward bladed and elongate shapes for the mud balls and
2) A tendency for roundness of the mud balls to increase with distance from the high tide mark, from backshore portion of beach towards lower areas at intertidal zone.

But no clear correlation of distance from the high tide mark with size or shape or number of mud balls was observed in the same Minas Basin, close to Stanley's study area, by Tanner (1996).

On the contrary, the frequency of occurrence of mud balls along the beach zone of Lake Superior (Dickas and Lunking, 1968)varies inversely with increasing distance from the outcropping mud banks to the surf zone. Where the beach zone is widest, the population of mud balls over a unit area was found to be smallest; in areas which had a narrow beach zone, the population of mud balls per unit area was found to be greatest.

According to Stanley (1969), the absence of armoured mud balls smaller than 2 inches (5.1 cm) after a high spring tide in the beach area with a tidal flat and intertidal zone at the seaward side, suggests that this may be the critical size below which total destruction occurs rapidly during high tidal energy. This destruction may well be related, in part, to a smaller surface area that is coated with a proportionately smaller amount of protective armour.

2.6. ORIENTATION:

The back and forth movement of mud blocks caused by waves as the tide floods and ebbs across an inclined plane results in rotation about the blocks' major axes. The effectiveness of this almost continuous rolling-pin effect is indicated by the tendency of the long axes of mud balls to align parallel to the strike of the slope and shoreline (Stanley, 1969).

Stanley, in his statistical observation (Stanley, 1969) on a beach near Lower Five Islands, Nova Scotia, on the north shore of the Minas Basin, southeast Canada, stated that more than 50 percent, of the armoured mud balls found on the lower stretch are oriented parallel or nearly parallel to the strike of the beach, that is, parallel to the shoreline; the remaining pebbles are oriented subparallel (angular divergence $>30^0$ with shoreline) or at random in reference to the shoreline. Proceeding up slope to the middle part of the beach there is a decrease in number of pebbles oriented parallel to the shoreline (thirteen are sub-parallel or randomly oriented, ten are parallel, and nine are perpendicular to the shoreline out of total 32 samples). On the upper most beach only one of measured thirteen mud balls (nearly 8%) was oriented parallel to the shore line.

Tanner (1996), in the same Minas Basin area, observed that elongate mud balls were observed lying in orientations both parallel to the strike direction of the beach as well as parallel to the dip direction (Fig 2.9) of 33 elongate mud balls, 15 were dip-oriented, 11 were strike-oriented, and 7 were intermediate. Mud balls with a strike-parallel orientation were observed adjacent to those with a dip-parallel orientation.

Fig 2.9: Mud balls oriented along dip, along strike and along intermediate directions. Black arrows note the dip direction in several adjacent locations (Tanner, 1996).

2.7. PRESERVATON POTENTIAL:

The preservation potential of mud balls within strata is relatively low, though many studies record their preservation in rock record. Though It is generally assumed that armoured mud balls have a transitory existence; however, fossil forms have been reported. Dickas and Lunking (1968) have mentioned that various authors make references to Pleistocene mud balls in Michigan glacial till (Leney and Leney, 1957), Pliocene balls in the Pico Formation of southern California (Cartwright, 1928), Miocene forms in Trinidad (Kugler and Saunders, 1959), Cretaceous forms in the Patuxent Formation of the east coast of the United States, and Jurassic forms from the coast of Spitzbergen (Frass, 1932), armoured mud balls of Jurassic age have been described in alluvial fan deposits of the Deerfield basin (Little, 1982).

Excellent armored mud balls were first discovered in blocks of Turners Falls Sandstone (Little, 1982; Fig 2.10) that formed the foundation of a dismantled bridge. Turners Falls Sandstone is a formation of variable thickness, up to 300 m. It is interpreted by Wessel (1969) and Handy (1976) to be the distal portions of three alluvial fans (the Mt. Toby

Conglomerate) which were deposited in a Mesozoic graben. Here thirteen sandstone blocks were found to contain a total of 25 armored mud balls and all the structures are easily seen.

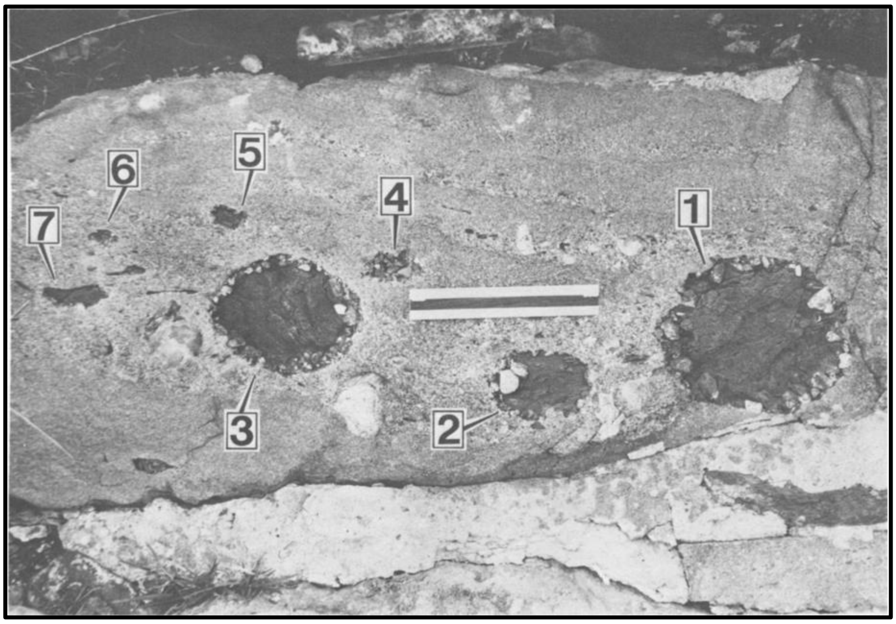


Fig 2.10: Well preserved armoured mud balls within a sandstone of Turner Falls Sandstone formation

According to Little (1982), the first examples of lithified fluvial armoured mud balls have been found in this Lower Jurassic Turners Falls Sandstone. Although their sizes are similar to modern armored mud balls, their ellipsoidal shape differs from the modern spheres (Haas, 1927; Bell, 1940), suggesting formation by stream abrasion modification of disc-shaped mud clasts. It is also mentioned that these armored mud balls formed due to quick deposition, from nearby mud deposits in a distal alluvial fan environment (Little, 1982).

Preservation of mud balls in alluvial, fluvial and glacial environment has been cited less than that within coastal and tidal environments, because drying and spalling of balls in intertidal environment are not as important as a cause of destruction of the structures as they are on floodplains or lakeshores (Stanley, 1969). More probably, ellipsoids in intertidal flats are eventually worn down and broken up by continuous impact with less mobile crystalline pebbles on the inclined surface. High tides combined with storm waves also destroy many of the partially buried mud balls.

A number of partially buried armoured mud balls were found in the studied beach area of Island View locality (Stanley, 1969). The preservation of armoured ellipsoids in other coastal environments (Kugler and Saunders, 1959) and in tidal environments (Richter, 1926) has been cited and it is also likely that a few of those described in this study are buried and occasionally preserved.

Whereas fossil mud balls from glacial and marine environments have been reported in the literature, fossilized mud-balls of fresh water lacustrine origin should not be expected to be found according to Dickas and Lunking (1968).

In their work in Lake Superior vicinity, they have concluded that almost all the mud balls found in the beach area and lake shore are subject to their ultimate fate to be destroyed by the interaction of climatic elements, desiccation, periglacialivation (freeze-thaw cycle) and heavy snow cover which occurs in the Lake Superior Region. Armoured mud ball residuals that have persisted are ultimately removed by melt-waters of the spring thaws and carried into the lake to final destruction.

2.8. GEOLOGICAL IMPLICATIONS:

The preservation of soft-sediment clasts in the geological record has implications for clast provenance and paleo-geography, and direction and strength of paleo-currents (Little, 1982; Diffendal,1984; Hall and Fritz, 1984). As preservation of mud balls in coastal environments (Kugler and Saunders, 1959) and in tidal environments (Richter, 1926) has been cited, the size, shape, composition of armour and orientation of such structures can be used in paleo-geographic interpretations of ancient intertidal deposits (Stanley, 1969).

Soft-sediment clasts found in modern fluvial, marine, coastal and glacial environments can also provide information on sediment source area, erosional processes and the mode, rate and direction of clast transport (Knight, 1999, 2005).These sedimentary structures, the end product of specific erosional and transport mechanisms are of petrologic interest and thus have been of concern to geographers and geologists during the past century (Jones and King, 1875; Bell, 1940).

Study of the different mud clasts may help for identifying specific depositional processes and preservative conditions in turn (Li et al., 2017).

CHAPTER-3 : MUD BALLS IN CHANDIPUR

The studied area in Chandipur coast is characterized by the presence of a vast, gently dipping (<2^0 dip) tidal flat (almost 3.5 km wide) and a narrow beach (100-120m wide) (Slope: 4-9^0), with an estuary, at the north-eastern side. Overall, it represents a very calm and quiet low energy environment, with low tidal intensity probably micro to meso-tidal in nature, unable to cut any distinct tidal channel, and disrupted occasionally by some storm activities only. Mud balls, both armoured and unarmoured, of different sizes and shapes (majority of them are ellipsoidal, ovoid, triangular, square, rectangular, trapezoidal and spherical) are encountered within the studied stretch, preferably along the junction between the beach and the tidal flat as well as on the seaward side of the barrier bars. The existing mud balls show diversity in their orientations as the tapered or ovoid shaped mud balls show high angle to the shoreline trend while that of the ellipsoidal mud balls show parallelism with the shoreline trend. On the basis of formation and bearings, here lies the uniqueness of genesis and orientation of mud balls in Chandipur.

3.1. FORMATION, TRANSPORTATION AND DESTRUCTION MECHANISMS OF MUDBALLS:

River borne sediments get dispersed through formation of riverine spits. Eventually these spits get modified to form shore parallel barrier bars and merge with the coast line after migrating over the vast tidal flat through time, under tidal influence mainly. These local barriers form local lowlands, with low energy environment behind them, termed as ‘Swamp’. These areas are mainly characterized by recent mud deposition. During the migration of these barrier bars towards the shoreline they gradually cover up the swampy mud, deposited behind and eventually cross it. Older mud deposited on those swamps gets exposed along the seaward side of the migrating bar and can be termed as older ‘Inactive swamps’ (Fig 3.1).

Fig 3.1: Inactive swamp exposed at the seaward side of the larger barrier bar

These formerly buried mud layers are much more thixotropic in nature as they are compacted by the overburden pressure of the migrating bars. Recent mud of swamps may show compactness in some places but those muds of older inactive-swamps exhibit darker mud layer in the core with thin sand linings all over it. During dry sunny periods, these exposed formerly buried mud layers get dried and desiccated due to the scorching heat of the sun. Also, when the inactive-swamps are sub-aerially exposed, that is, in times of low-tides, these mud layers get easily desiccated. These desiccated mud chunks (Fig 3.2) are the main source of the mud balls, as they are prone to erosion and subsequent transportation, even under the feeble wave action of Chandipur area, during the next high tide. During this transportation, towards the shoreline over the tidal flat, these mud balls get rigorously reworked and ultimately acquire their near spherical, rounded to subrounded shapes as well as the armouring of coarser sand and shell fragments.

Fig 3.2: Exposed inactive swamp and desiccated mud chunks covering the outcrop

Fig 3.3: Transported ellipsoidal mud balls deposited at the foreshore

The mud balls sometimes suffer prolonged transportation and as a result they become more and more rounded. During this transportation (Fig 3.3) over the large tidal flat these mud balls get covered up by the shells lying on the vast tidal and take the form of armoured mud balls. Owing to their mass and size under the backdrop of low energy conditions of Chandipur area, the mud balls are most likely to be transported as bedload or rolling load . It is evident from the long axis shore parallel orientations of most of the mud ball varieties, except the tapered ellipsoidal (or ovoid) ones. This variety used to show a shore perpendicular distribution of the long axes of the mud balls, which can only be expected to form if the material is carried as a suspension load. Considering the size and mass of these mud balls, only some very high energy fluid gravity flows or sediment gravity flows are capable to carry them in suspension, which are hard to conceive in a low energy environment like Chandipur. Here lies the uniqueness regarding the orientation of a variety of Chandipur mud balls.

These heterogenic mud balls of Chandipur are not only formed or transported but also get destructed by several processes, operating within the low-lying vast intertidal-flat. The main mechanisms which have been observed during the field visit are-

i. Some portion of the exposed formerly buried mud layers, as well as, already developed mud balls, got disintegrated into the water during the high water stage.
ii. If the tidal intensity is very much high, then the desiccated mud chunks often get flattened, even broken while colliding with some obstacles.
iii. During summer the sub-aerially exposed mud balls or the mud balls in backshore totally get dried up and get fragmented.
iv. Due to anthropogenic activity often the mud balls of beach part totally get diminished.
v. If the mud chunks readily convert to the armoured ones due to the presence of huge amount of shells on the tidal flat then they lose the chance of getting proper shape and as a consequence become stationary. A puddle of stationary mud balls can be observed in many low lying places affecting the orientation and final disposition of mud balls accumulated there.

3.2. OCCURRENCE, SIZE AND SHAPE/GEOMETRY:

After being eroded out from the mud layers the mud chunks are carried to the foreshore and backshore of the barrier bars, foreshore and backshore of the beach and even near to the strand line owing to exceptionally high tides or occasional storm activities. Most of the mud balls are found to be distributed along the seaward side of both barrier bar and beach. In the beach, mud balls are generally concentrated along the junction of foreshore and tidal flat, but partially buried mud balls are also found within the tidal flat itself. Mud balls are also found to be strewn all across the beach back shore, but in lesser quantity. Mud balls, positioned near the strandline, or even within the backshore, are comparatively larger in size and found to be partially buried within the sand owing to wind activity, as well as, anthropogenic impact. During the pre-storm field visit the accumulation of mud ball in a 6x2m grid, near the junction between foreshore and tidal flat, was less than 100 but during the post-storm visit (after the storm 'Titli' in October, 2018) it had been found to be 250 and 380 within two different grids.

The occurrences of older inactive-swamps play a major role in this whole scenario. A number of inactive-swamps are observed within the studied stretch, some are exposed along the foreshore tidal flat boundary, while others on the seaward side of the larger barrier bars (Fig 3.1). Multiple generations of inactive swamps are identified (Fig 3.4). Older layers are comprised of thick, compact (due to overburden pressure and consequent dewatering) mud, dark in colour, while the younger ones are less compact and lighter in colour (Figs 3.5 & 3.6).

Fig 3.4: Showing multiple generations of inactive swamp mud layers

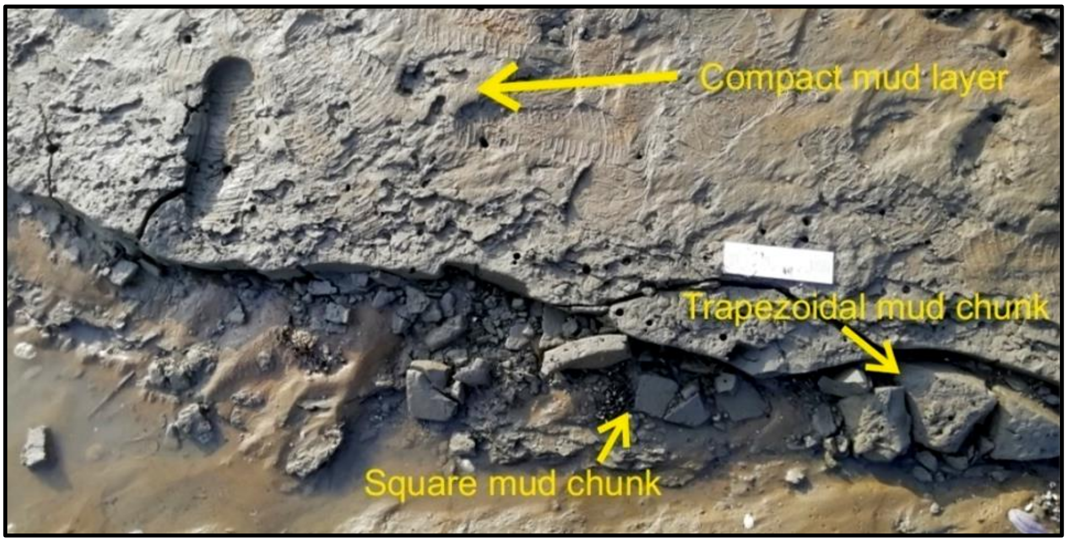


Fig 3.5: Close up showing compact and thick swamp mud and desiccated mud chunks on it

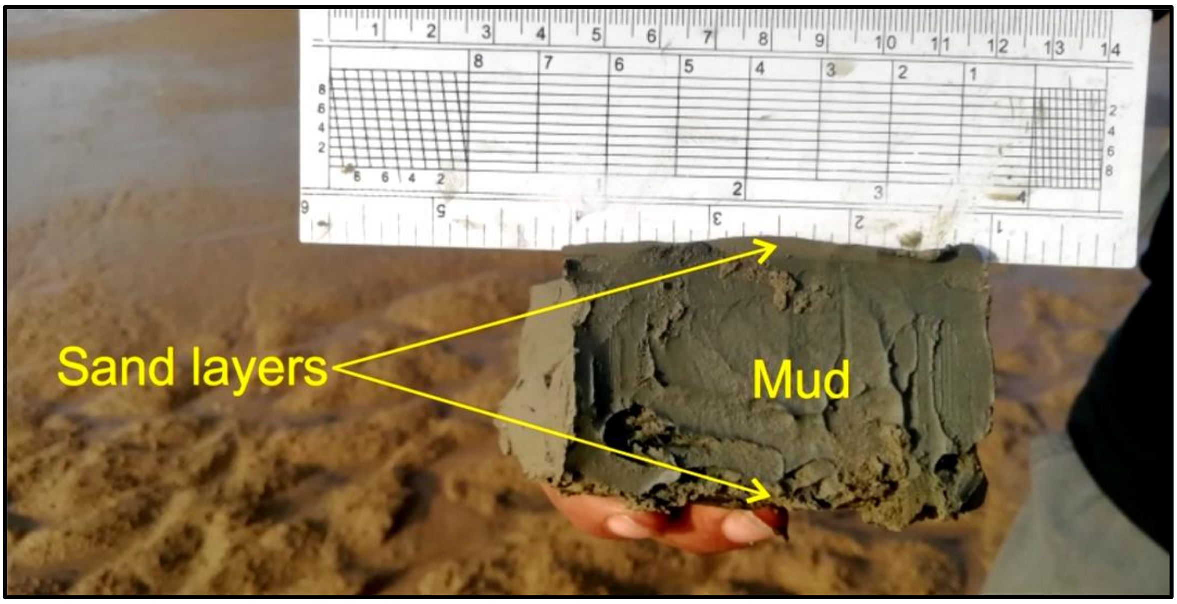


Fig 3.6: Cross-section showing inactive swamp mud sandwiched between sand layers

The sizes of mud balls in Chandipur have shown large variations. The range of size in beach is for long axis 2.6-17.3 cm, for short axis 0.6-6.7cm, for intermediate axis 0.8-15 cm whereas that of bar is quite different when compared to the previous one; for long axis 4.5-28.2 cm, for short axis 1.1-8.9 cm, for intermediate axis 2.8-19.4 cm. Now most of the large sized mud balls are mainly seen near the inactive-swamps for both beach and bar. During the storm event 'Titli' some large scale mud balls are also found just near to the strand line. It is a rare case and the size varies for long axis 4.5-16 cm, for short axis 1.2-8.1 cm and for intermediate axis 1.8-11 cm.

The mud balls of Chandipur exhibit various kinds of shapes in the span of their existence. The shape variation ranges among ellipsoidal, ovoid(tapered ellipsoidal), flat triangular, trapezoidal, nearly spherical and rectangular. The mud chunks, when eroded, used to show lesser roundness, and are mostly polygonal, square, rectangular and/or triangular in shape (Figs 3.7 & 3.8). During transportation they underwent rounding, that resulted in their ellipsoidal to ovoid shapes. These are the most common varieties of mud balls found in this area. The amount of armouring also varies, generally the more rounded ones show more armouring (Fig 3.9).

Fig 3.7: Armoured nearly spherical mud ball (left) and Armoured ellipsoidal mud ball (right)

Fig 3.8: Trapezoidal mud ball (left) and Armoured tapered mud ball (right)

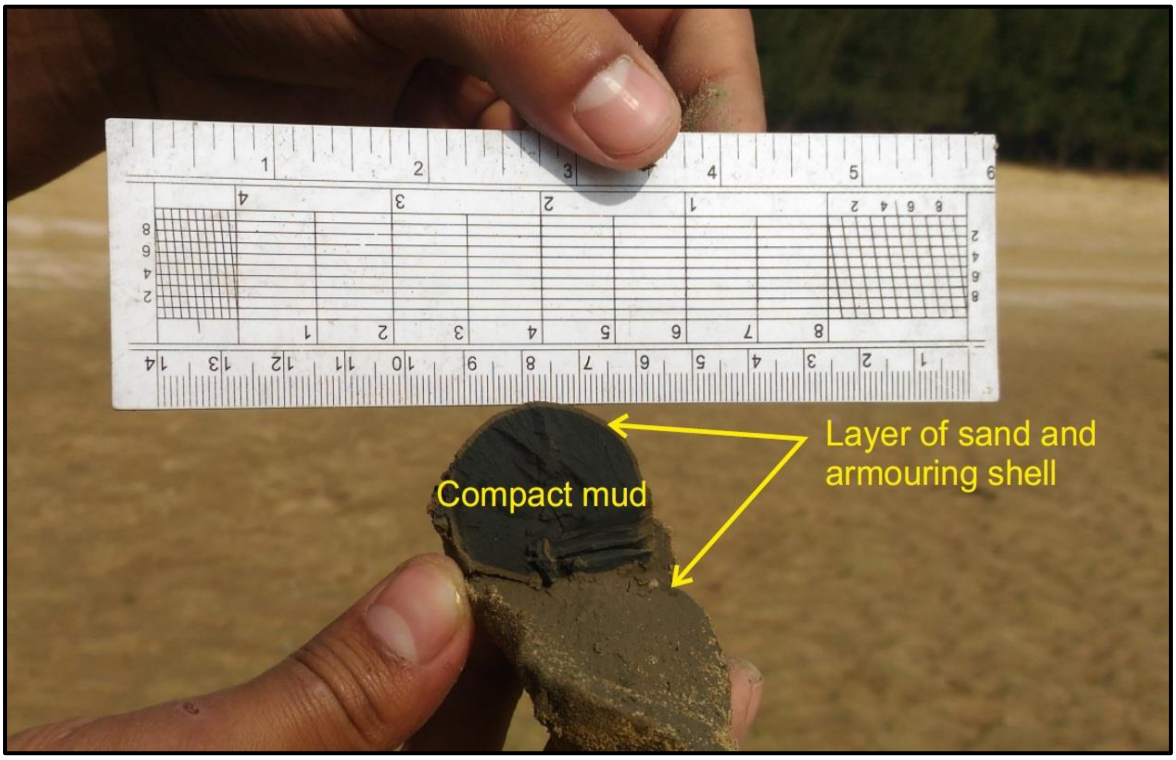
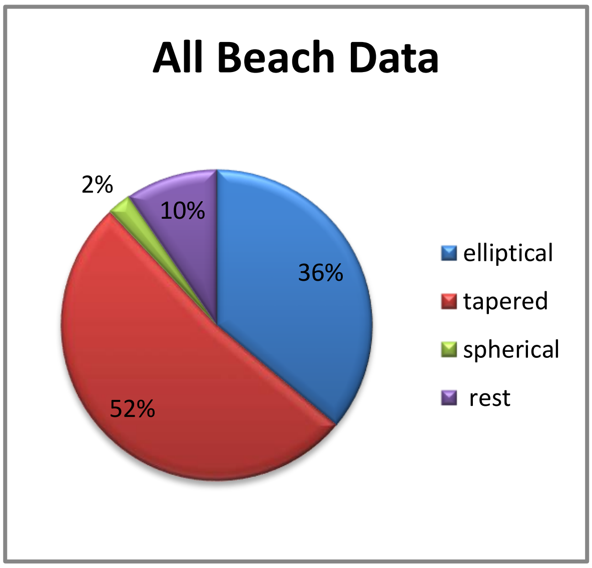


Fig 3.9: Cross-section of armoured mud ball of Chandipur coastal area



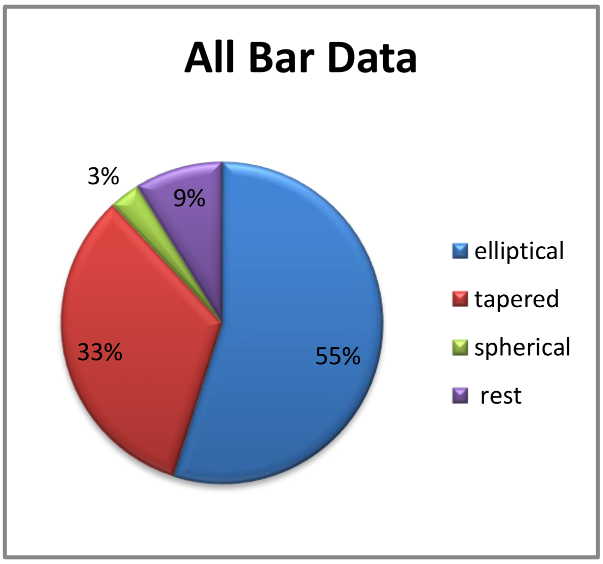


Fig 3.10: The above pie chart shows the dominance of corresponding mud balls in both beach and bar

3.3. ORIENTATION :

In previous literatures specific orientation of mud balls has not been given much importance for inferring their mode of transportation or implying their depositional environments, except in few cases, either in rock records or in preserved event beds, imbrication of major and minor axes of mud clasts has been referred to their sediment gravity flow or very high energy turbidity flow origin (Southern et al., 2015). Even both shore parallel and shore perpendicular long axis orientation were observed in the works of Stanley (1969) and Tanner (1996); but no strong inference were established based on systematic and statistical data collection and analysis.

In this study, orientation of Chandipur mud balls has been given the center of interest. They exhibit a different and unique orientation pattern compared to the mud balls reported previously from other places. Distinctly different trends can be observed in case of the two major varieties of mud balls, i.e., for the ellipsoidal and tapered ellipsoidal (ovoid) varieties. The orientation of their long axis, shore line trend for corresponding data sets in different places both at beach and bar and the acute angle difference between shore line and their long axis (as shown in Fig 3.14) were measured meticulously. The given rose diagrams (Fig 3.11) indicate that the ellipsoidal mud balls are residing certainly in low angle ($\leq 10^0$) with the shoreline trend whereas, the tapered or ovoid mud balls are residing at a quite high angle (≥30^0) with the shoreline trend.

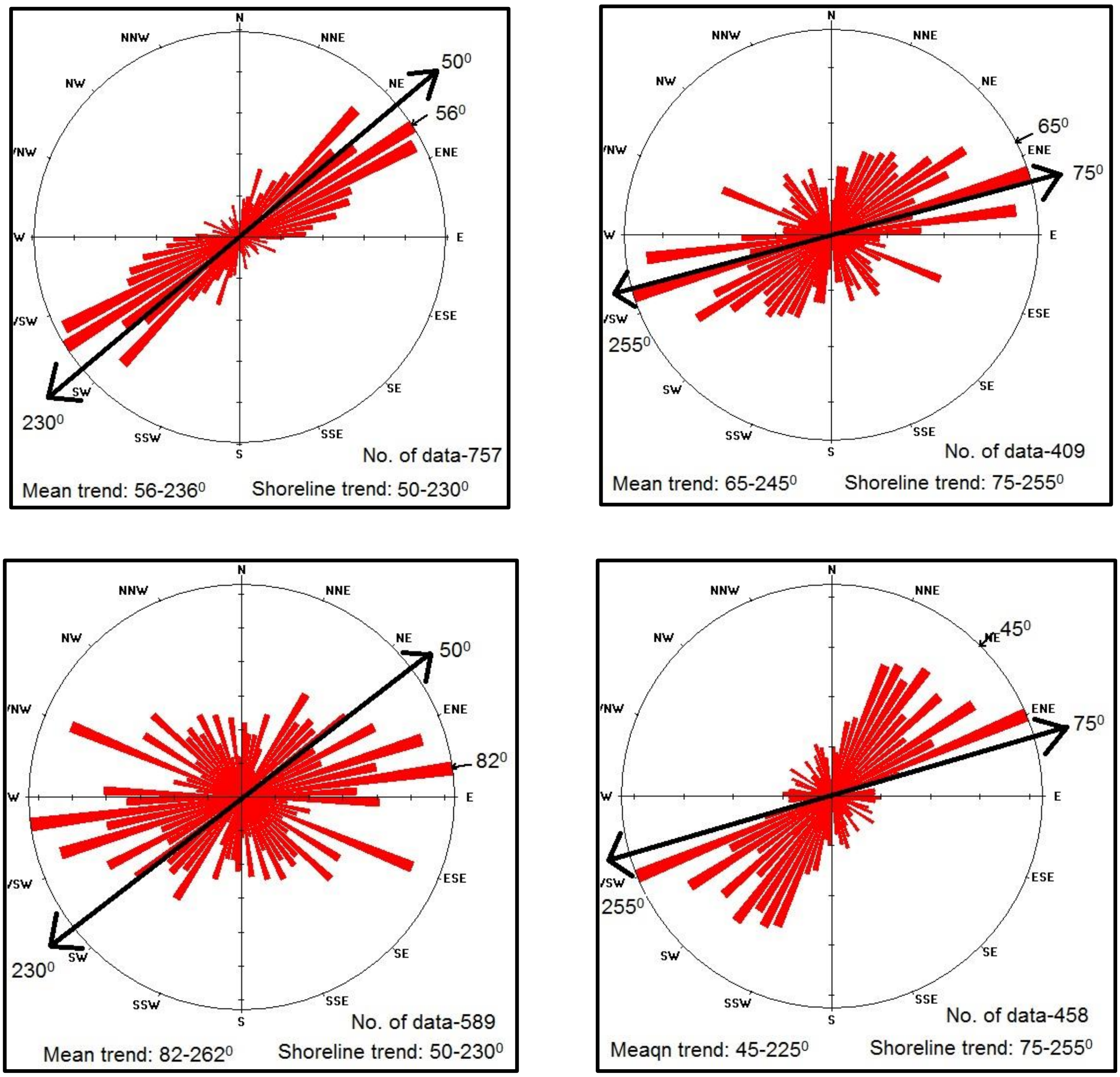
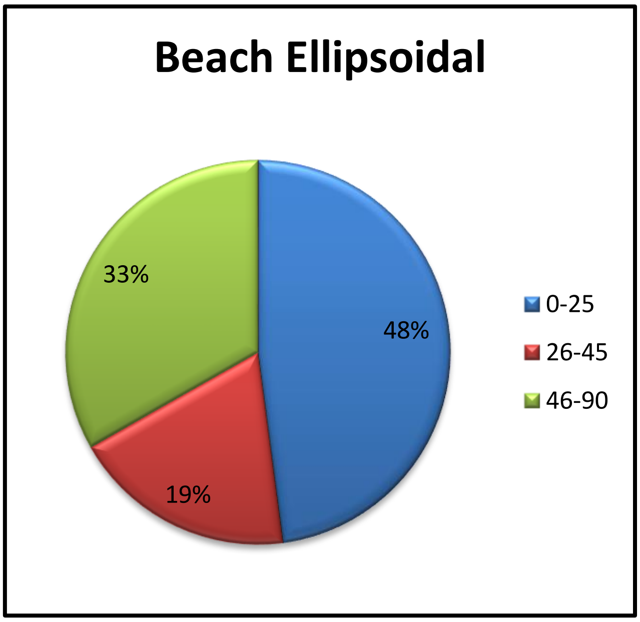


Fig 3.11: The above rose diagrams show the orientations of Beach Ellipsoidal (top left), Bar Ellipsoidal (top right), Beach Tapered (bottom left) and Bar Tapered (bottom right) mud balls with their shoreline trend of both beach and bar

The ellipsoidal ones show a shore parallel orientation or a low angle of 0-25^0 to the shoreline whereas the tapered ones exhibit high angle of 46-90^0 or perpendicular orientation to the coastline (Figs 3.12 & 3.13).



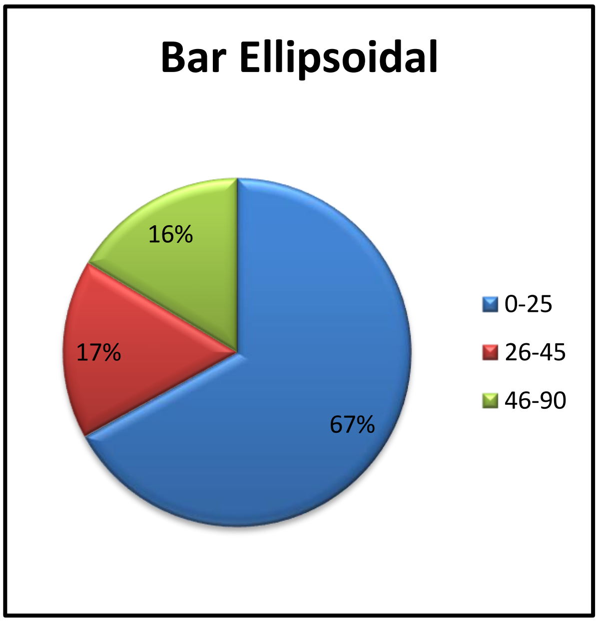
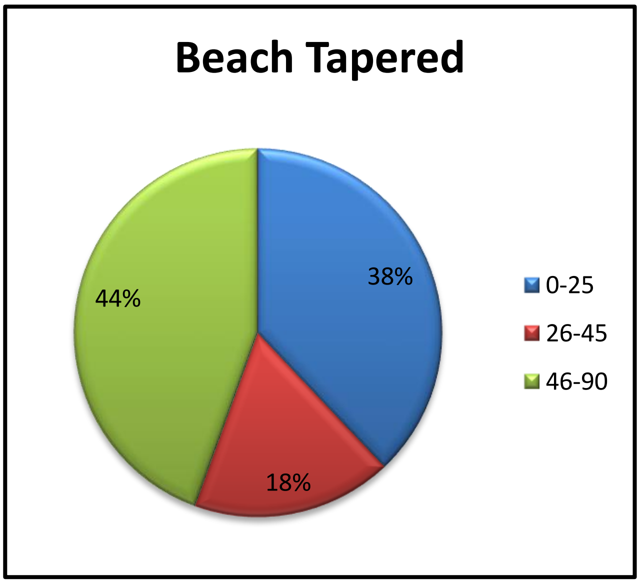


Fig 3.12: The above pie charts represent the angle of deviation of elliptical mud balls with the shoreline of both beach and bar



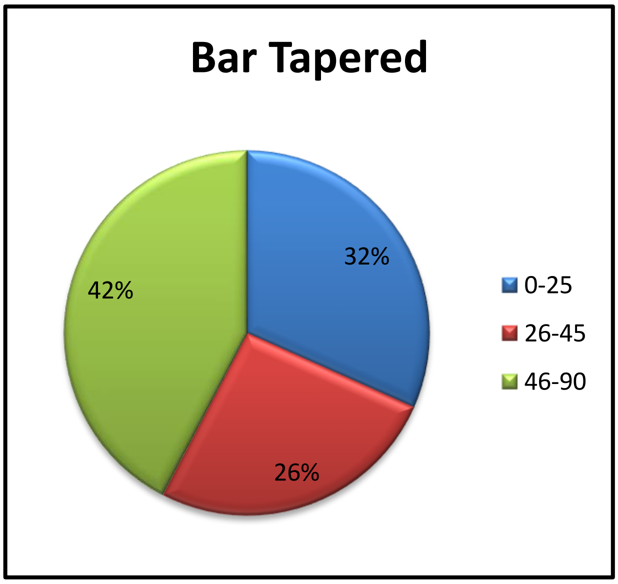


Fig 3.13: The above pie charts represent the angle of deviation of tapered mud balls with the shoreline of both beach and bar

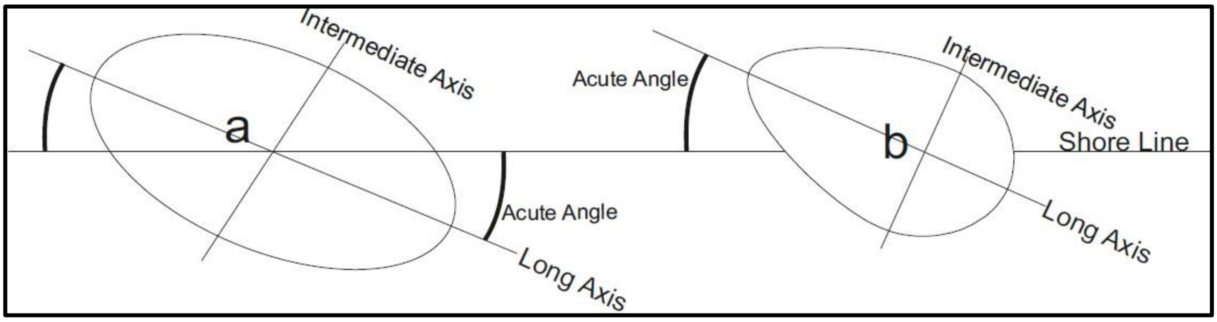
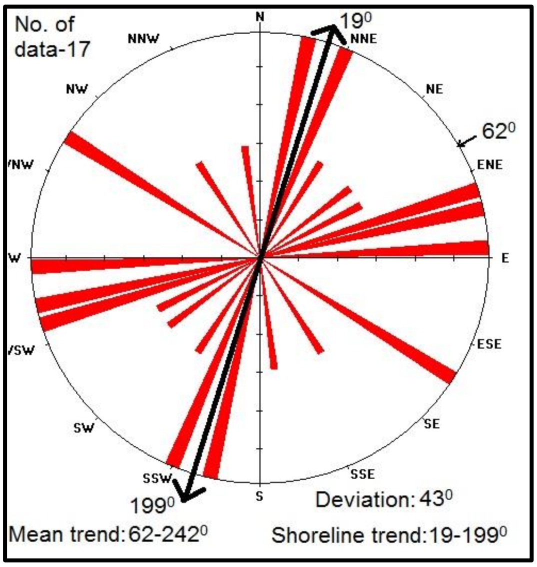
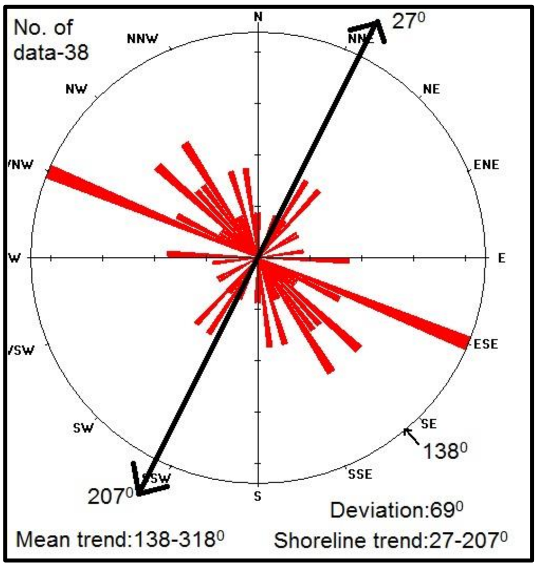
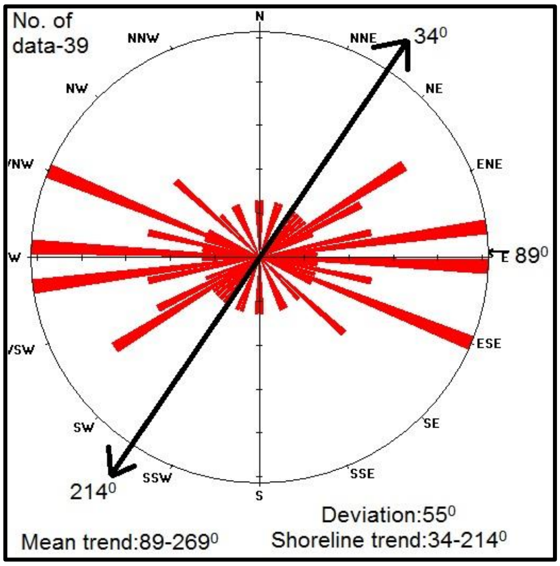


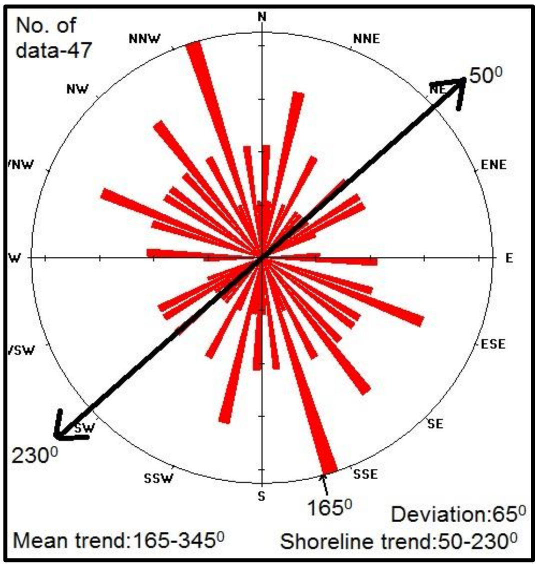
Fig 3.14: Schematic representation of orientation of a) purely ellipsoidal and b) tapered(ovoid) mudballs with respect to shore line

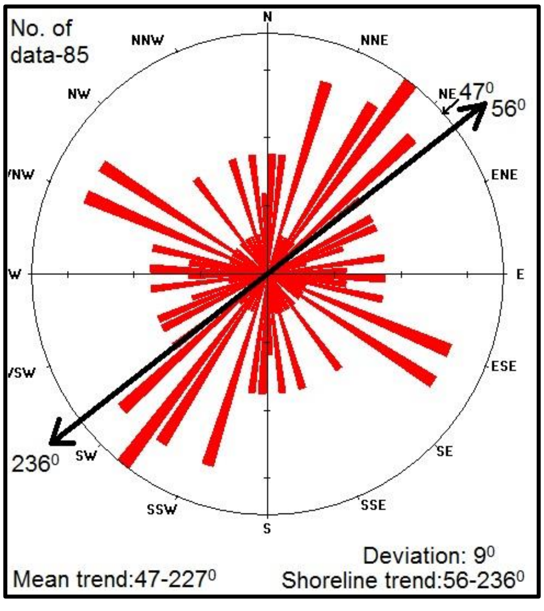
Due to the effect of different tidal currents and changing trend of shoreline the tapered mud balls show different deviation of angles according to corresponding shoreline trend. The data are as follows:

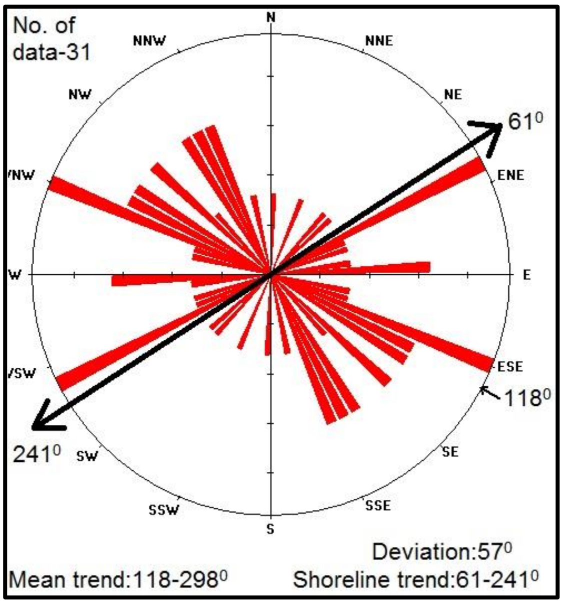












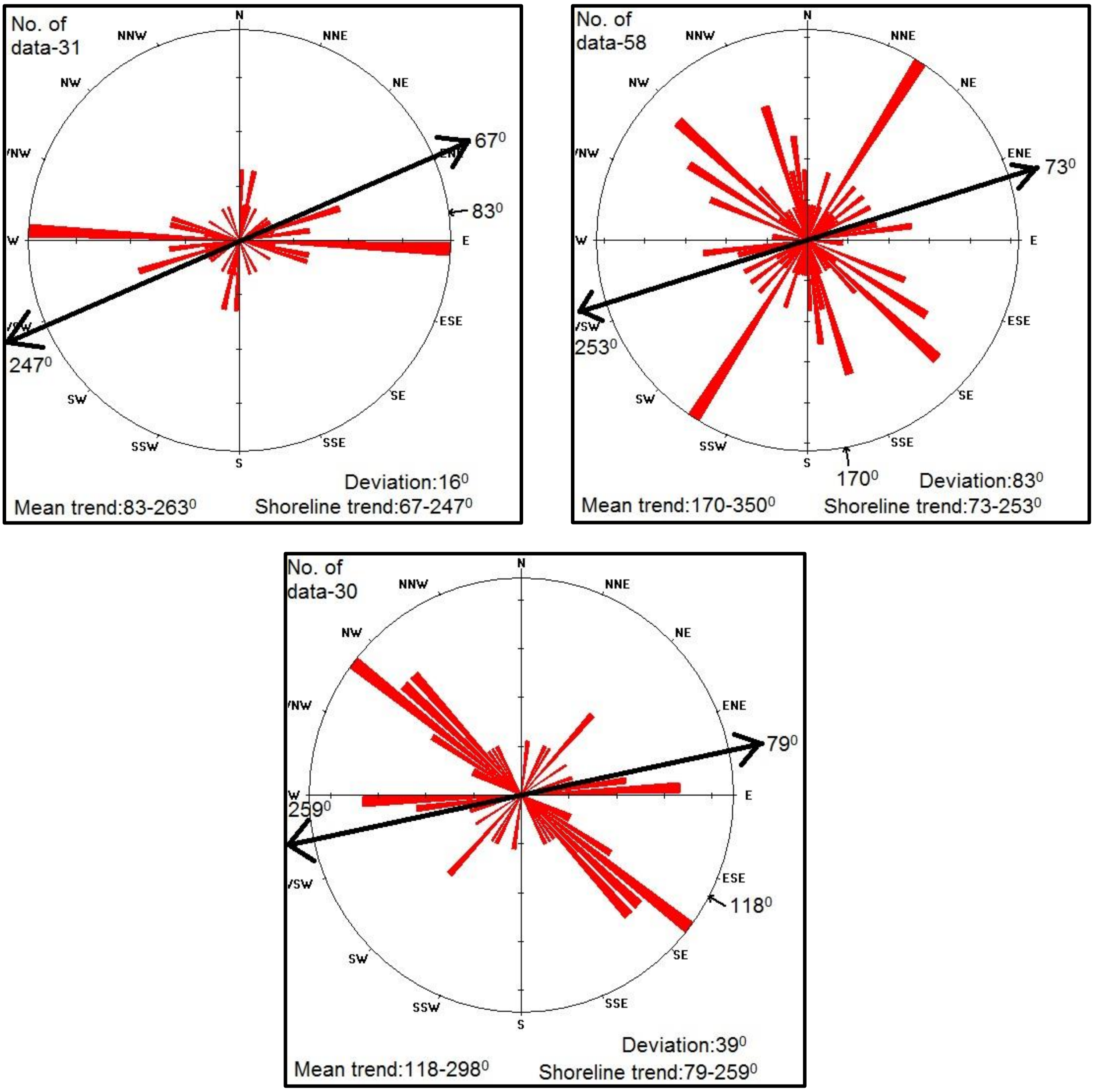
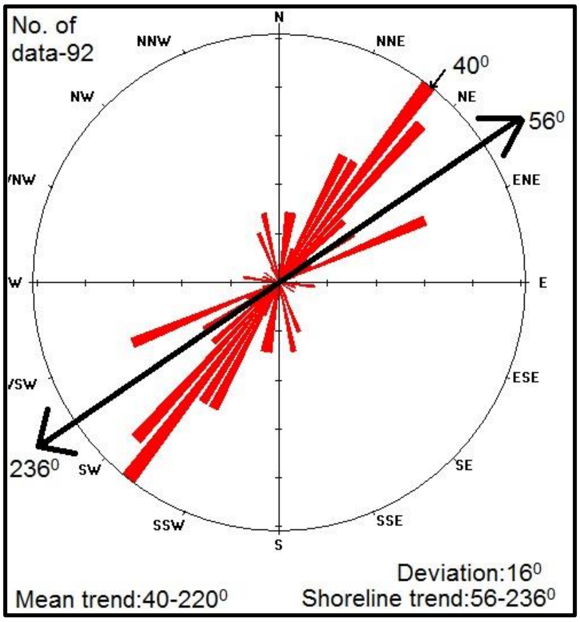


Fig 3.15: The above rose diagrams indicate the low to high angle deviation of the tapered mud balls to the corresponding shoreline trend of beach

Here, in the above represented rose diagrams (Fig 3.15) it has been clearly represented that the tapered mud balls in beach show various kinds of orientations from low angle to high angle of deviation to the shoreline. It can also be observed that as per the uniqueness of Chandipur mud balls, most of the tapered mud balls show high angle of deviation (39^0 to 83^0). As the range of change of shoreline trend varies widely from 19-79^0 so, the role of different components of tidal currents are quite dominant here.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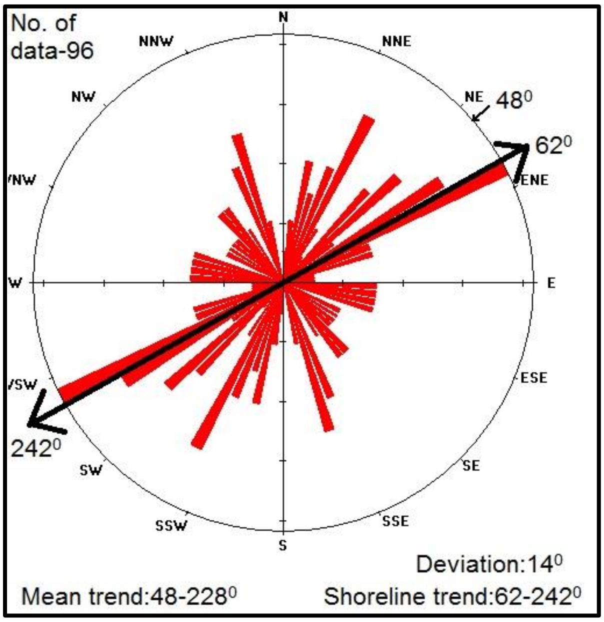
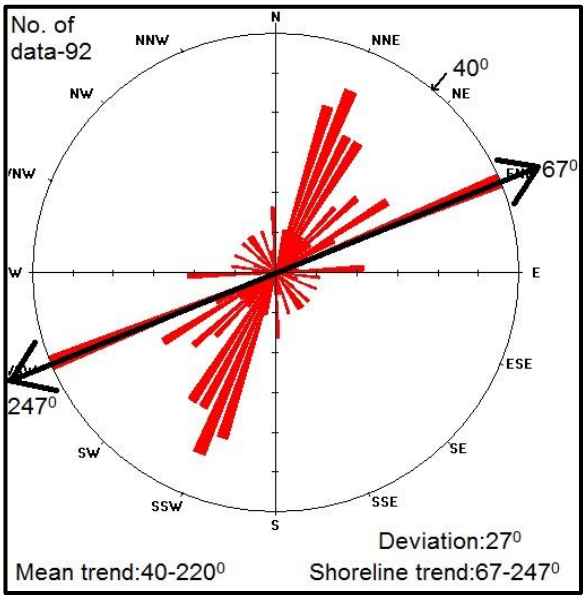
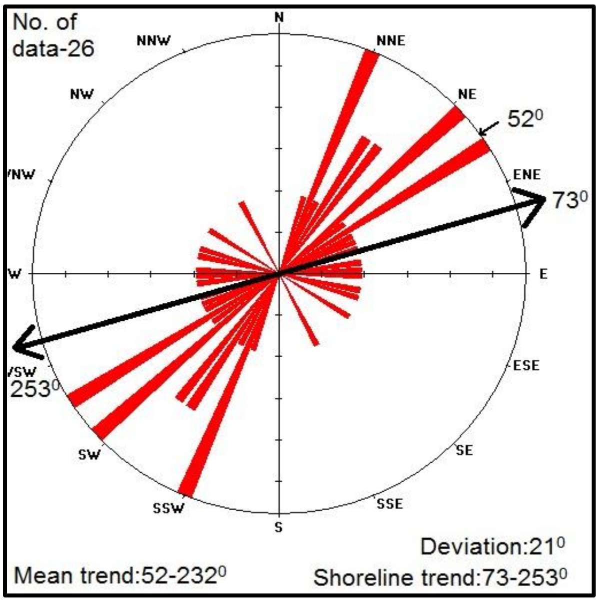
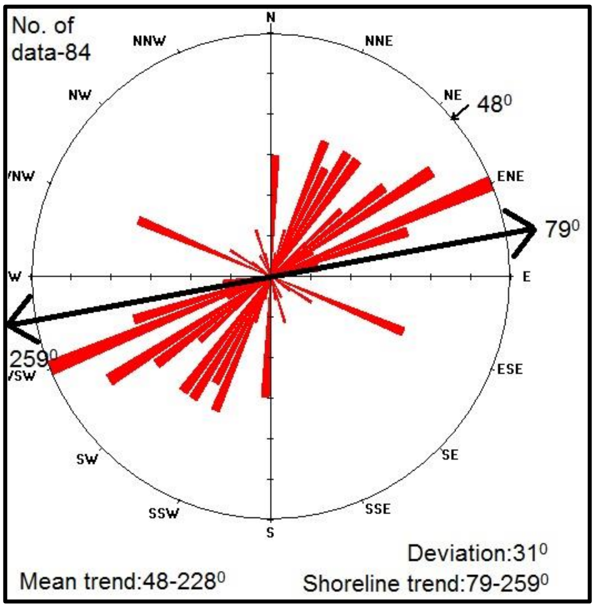
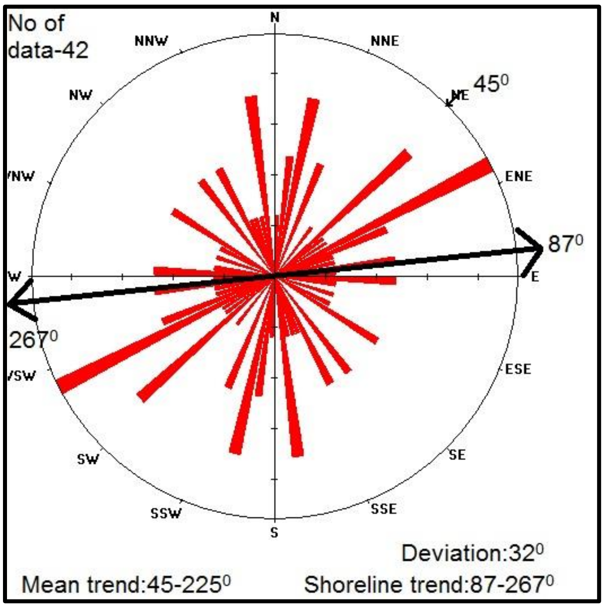
Deviation:16^{0}
Mean trend:40-220^{0}
Shoreline trend:56-236^{0}


No. of data-96
48^{0}
62^{0}
242^{0}
Deviation:14^{0}
Mean trend:48-228^{0}
Shoreline trend:62-242^{0}


No. of data-92
40^{0}
67^{0}
247^{0}
Deviation:27^{0}
Mean trend:40-220^{0}
Shoreline trend:67-247^{0}


No. of data-26
52^{0}
73^{0}
253^{0}
Deviation:21^{0}
Mean trend:52-232^{0}
Shoreline trend:73-253^{0}


No. of data-84
48^{0}
79^{0}
259^{0}
Deviation:31^{0}
Mean trend:48-228^{0}
Shoreline trend:79-259^{0}


No of data-42
45^{0}
87^{0}
267^{0}
Deviation:32^{0}
Mean trend:45-225^{0}
Shoreline trend:87-267^{0}

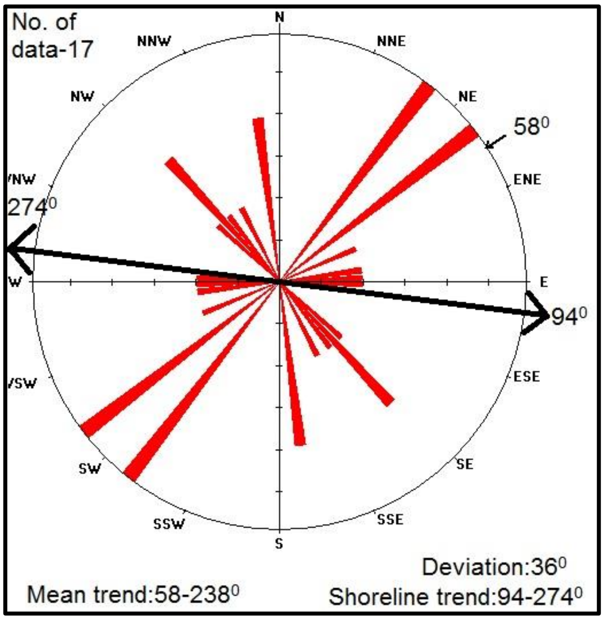


Fig 3.16: The above rose diagrams indicate the low to medium angle deviation of the tapered mud balls to the corresponding shoreline trend of bar

Here, in the above represented rose diagrams (Fig 3.16) it can be seen that the tapered mud balls in bar are showing orientation of low to intermediate angle of deviation to the shoreline trend. As the range of change of shoreline trend is comparatively low in this region, the major dominance of different tidal components is quite submissive. So, the outcome is tapered mud balls showing more or less intermediate angle of deviation to the shoreline caused by these reasons.

3.4. PRESERVATION POTENTIAL:

Previous studies (Cartwright, 1928; Leney and Leney,1957; Kugler and Saunders, 1959; Dickas and Lunking, 1968; Little, 1982) revealed that the preservation potential of mud balls are very low within strata, though many studies record their preservation in rock record. The mud balls are basically soft- sedimentary clasts so, during any high energy flow there is a possibility of getting disintegrated. During the dry sunny periods sub aerially exposed mud balls may also get desiccated. Bioturbating activities have a profound effect on the environment and are thought to be a primary driver of biodiversity. Due to this bioturbation or some biogenic activities and due to anthropogenic activities the preservation of mud balls are very much agitated. Sometimes the storm events or any high energy flow may also dispossess the partially buried mud balls (Fig 3.17).

Fig 3.17: Association of partially buried mud balls and mud clasts between the foreshore and tidal flat at Chandipur coastal area

In Chandipur the scenarios are quite different. Despite of low potential it has been observed that the mud balls were preserved within the trench (Fig 3.18). The storm events or high energy flows not only lower the preservation potential but also support in preserving mud balls. The preserved mud balls are found at quite a greater depth within the trench and enveloped by thick layer of sediments and shale hash deposits. This phenomenon depicts the influence of high energy flows. Within the trench it has been seen that the preserved mud balls are oriented at high angle (Fig 3.19) or rather perpendicular to the direction of shoreline. Though the recovered mud ball doesn't possess any profound shape so, initially it has been quite difficult to interpret its orientation but still the long axis is representing a high angle orientation regarding whether it is ellipsoidal or tapered.

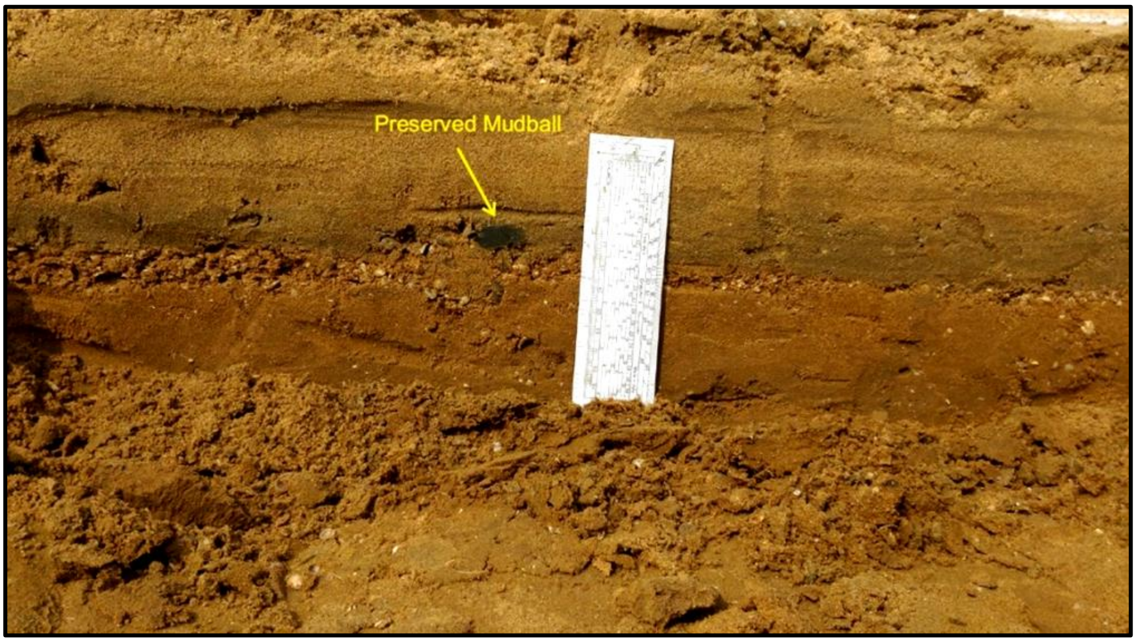


Fig 3.18: Preservation of mud balls within the trench

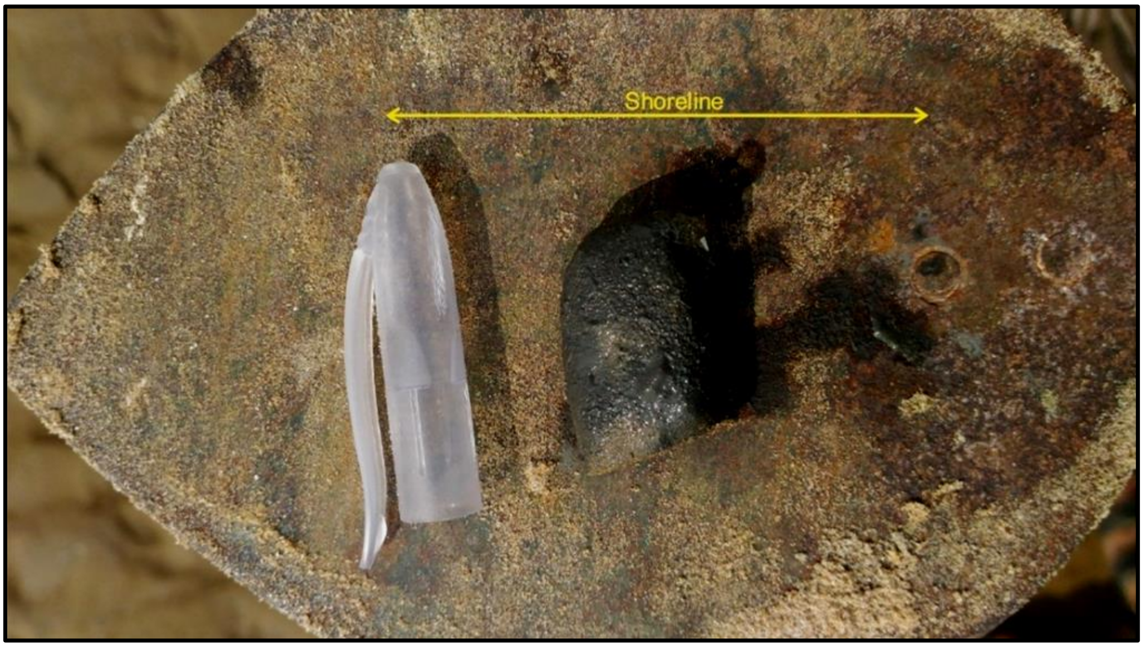


Fig 3.19: Recovered mud ball from trench, showing almost shore perpendicular orientation

Several partially buried mud balls have been found (Fig 3.20) at the junction of beach and tidal and that of bar and tidal flat. These are the pathways or indicator to the future preservation potential of mud balls and it seems to be quite high.

Fig 3.20: The partially buried mud balls indicating the future preservation potential

From this point of view again it has been observed that the long axis of preserved mud balls oriented themselves in such a manner that it occurs to be the suspension load transportation method, whereas, the actual scenario belongs to the bedload movement and created this havoc unique entity.

CHAPTER-4 : THE REASONS BEHIND THE UNIQUENESS

It has been described in the previous chapters that the uniqueness of Chandipur mud balls lie mainly on their genesis, transportation method and orientation when compared to the general characteristics of mud balls worldwide. Mud balls of this area clearly owe their origin to the dynamic nature of the Chandipur coast.

In the case of formation of mud balls in general the pre-requisite conditions are-

1. Exposure of formerly buried compact mud layers due to excavation through high energy flow
2. Erosion of mud chunks
3. Subsequent transportation
4. Deposition mechanisms control the distribution and orientation

But the scenario in Chandipur is totally different from that. In concordance with the general low energy environmental conditions of Chandipur, high energy flows, in order to excavate the buried mud layers, are hard to conceive. Mud layers, supplying the mud chunks, later to be transformed into mud balls, are exposed on the surface of Chandipur tidal flat. Usually, muds exposed to the surface do not possess enough cohesion, to be eroded as chunks. The dynamic nature of the Chandipur coast accounts for the cohesiveness of the mud layers exposed over the tidal flat of the area. The process is as following -

1. Development of low energy swampy environments, leading to the deposition of thick mud layers, on the landward side of the migrating barrier bars.
2. Landward migration of the bars, under tidal and/or eolian action over the previously deposited swampy muds.
3. As the migration rate of sandy bars are much more than that of the cohesive mud layers, soon the barrier bar crosses over the swamp, exposing it on the seaward side.

4. The seaward exposed swampy mud, become much more cohesive by the dewatering caused during the overburden pressure produce by the migrating bars. Such thick mud layers are identified as inactive swamps.
5. Desiccation of such inactive swampy mud layers, during low tide.
6. Erosion of such slightly compacted and thick mud layers by tidal currents as well as low energy waves. As the mud chunks are already cracked, even low energy waves can dislodge them easily.
7. Subsequent landward transportation of these mud chunks over the vast tidal flat.
8. Acquisition of shell armour, abundantly available at the tidal flat, during transportation.
9. Final deposition of these mud balls at or near the beach and seaward side of the barrier bar.
10. Depositional mechanisms control the ultimate distribution and orientation of mud balls along the foreshore of both beach and barrier bar.

During the field visit before and after the storm event 'Titli' it has been viewed that the presence of high energy flows like storms, can aggravate the generation, as well as deposition of the mud balls in Chandipur coast, but they are not the primary prerequisite for the distribution of mud balls in the area. Chandipur consists of a wide and vast tidal flat where a low energy environment prevails. The main driving force here is the presence of tidal flat as well as wave generated currents, though weak in nature. As it is a calm and quiet environment so the tidal intensity is less and as a result the main transporting method is bedload movement, rolling, sliding or toppling based on the size, shape, and surface irregularities of the mud balls, along with the surface slope. Sometimes the mud balls got stuck in the tidal flat or near to foreshore and in that case the sizes of the stuck mud balls determine whether they will remain static or reorient themselves by the effect of swash and backwash. As high energy flows are rare, reorientation of larger mud balls itself is a rare phenomenon.

In concordance with the general characteristics of a bedload transportation, the Chandipur mud balls must show shore parallel orientation of their long axes. But the astonishing thing is that the ovoid shaped mud balls show perpendicular or high angle orientation to the shoreline despite of being carried away by bedload movement. Such orientations, if preserved in rock record, clearly depict deposition from suspension load, and hence demand emplacement through sediment gravity flows, owing to the pebble-grade sizes of the mud balls. The assumption is surely erroneous, and may lead to severe misconceptions regarding the depositional environment. To explain such deviations in orientation pattern of Chandipur mud balls minute and detailed studies regarding the size and shape of these mud balls are taken into account, along with the ground slope and irregularities of the sites of deposition. The four parameters apparently control the final dispositions and orientations of the Chandipur mud balls and are discussed in details in the next section.

The four parameters are-

1. Size of mud balls
2. Shape of mud balls
3. Surface irregularity
4. Intensity of swash and backwash

1. <u>Size of mud balls</u>:

The size of mud balls plays a vital role in determining the final disposition and orientation of the settled mud balls. First of all, a critical size is needed to withstand the friction and abrasion during reworking and transportation of the soft, plastic mud chunks. Both in beach and bar region the minimum size of long axis is > 2.5 cm, where intermediate and short axes are always > 0.5 cm. The critical length of long axis to prevent disintegration in turbulent water may lie between 2.5-2.6 cm as revealed from the taken data as no record of any measured mud ball or mud chunk shows long axis length smaller than the mentioned limiting value. The size of mud balls directly influences their final orientations as size is proportional to mass and larger mud balls with greater mass, once deposited on the foreshore-tidal flat junction, are hard to rework and reorient. Moreover, large tapered mud balls have a stable disposition on a sloping surface with their broader end facing downward under the action of gravity. This is due to their asymmetric mass distribution along their long axis. Where larger mud balls retain their stable position under the action of swash and backwash, smaller ones get displaced and reoriented by the action of swash and backwash even after their deposition on sloping foreshore. In most of the cases for larger mud balls the tapered end being lighter are forced to spin down the slope due to back wash where the broader ends spin being stationary at a point acting as a pivot. This leads them to settle in an instable orientation having their tapered ends facing downward.

Size also marks its importance indirectly. Larger mud balls are less effected by small scale undulations of ripple matted tidal flat. On the other hand the smaller ones get trapped within undulated troughs of ripples and their orientation lacks the preference of any physical and/or motile stability.

2. **Shape of mud balls:**

The shape of mud balls plays a crucial role in their orientation. Desiccated dry mud chunks are fragmented into several shapes which have been discussed earlier. The final shapes are totally dependent on their initial shape. For example, elliptical mud balls are mainly derived from rectangular shaped mud chunks whereas, the tapered mud balls are formed from irregular polygonal or trapezoidal mud chunks. Spherical mud balls are mainly generated from square shaped mud chunks as a result of prolonged transportation. In response to different tidal components the desiccated mud chunks are mainly of irregular polygonal or trapezoidal shaped and the outcome is the huge abundance of tapered mud balls at or near the beach and comparatively lesser abundance at or near the large barrier bar. The elliptical ones show parallelism to the shoreline because of their even mass distribution at both the ends whereas, the tapered mud balls show their long axis oriented at high angle to the shore line for having asymmetric mass distribution along length. So, when the rotation occurs to those mud balls they basically try to maintain their stability and resulted in their rotation hinged upon the tapered end. The whole body of mud ball rolls in a manner like a hard-boiled egg rolling over an inclined surface (sloping $<7^0$). Due to the center of mass being shifted towards the broader end, the egg stabilizes in vertical position or at high angle while rotating across the inclined plane (Fig 4.1) instead of rotating along the inclined plane and stops. The similar thing occurs for tapered mud balls, as during their movement along the sloping plane, for same number of rotational turns the broader end covers more translational distance than the narrower end due to their difference in circumference, and to compensate this path difference the entire body introduces another rotation across the plane of motion along an axis perpendicular to the plane and passing through the tapered end (Fig 4.3). In this way they take their most stable disposition and orientation with their broader end facing downward and tapered end facing upward, i.e., with long axis at high angle to the strike of the plane (in this case the trend of the shore line), to overcome the gravitational instability generated by their asymmetric mass distribution and shape under the couple of forces imposed on them by consecutive swash and backwash. If the slope of the surface is too high (> 10^0), then sliding will occur in the place of rolling and above mentioned phenomenon will be flawed. This peculiar rotational movement can even occur at a very low sloping or almost horizontal plane of motion, mimicking the behavior of any conical object rotating on a horizontal plane (Fig 4.2). In that case only the gravitational instability would not work and the ovoid body can rest with either end of it facing the seaward side without any preference for orienting the heavier (broader) end and thus high angular deviation from shore line trend along the long axis can again be gained spontaneously.

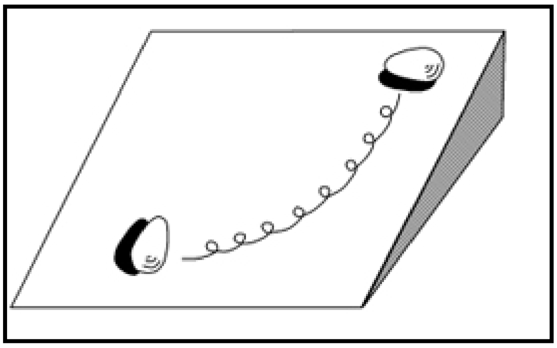


Fig 4.1: Motion of hard-boiled egg on an inclined surface

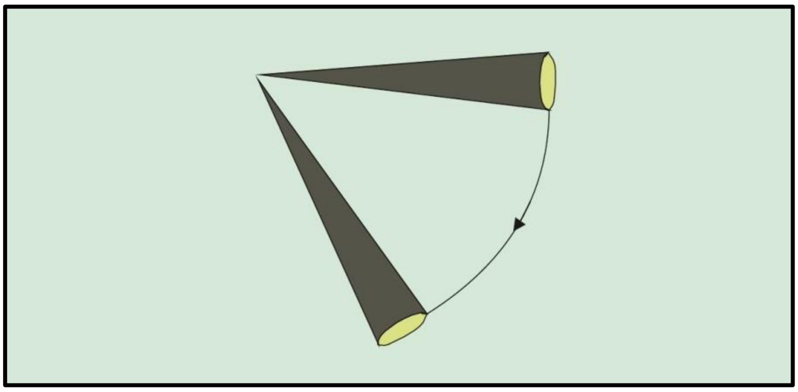


Fig 4.2: The similar motion can be seen in case of conical objects

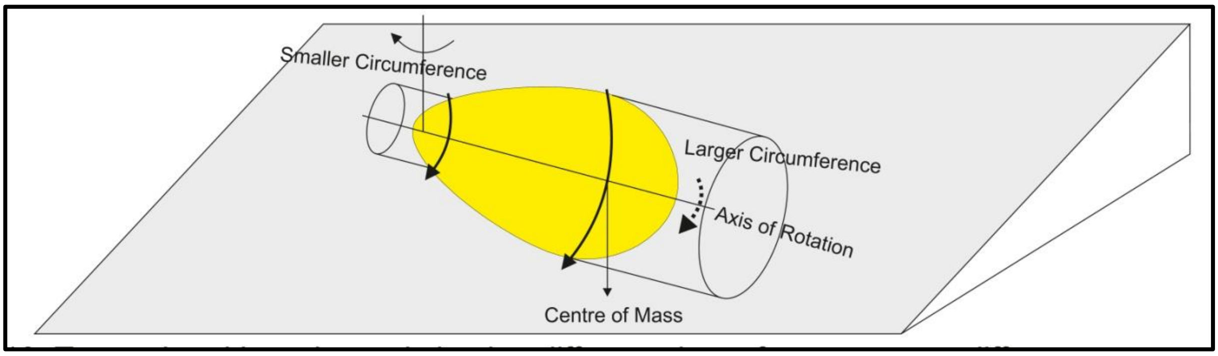


Fig 4.3: Tapered and broader ends having different circumference, cover different amount of path after a single rotation. Hence rotation across the inclined plane along an axis normal to the plane is introduced.

3. Surface irregularity:

Sometimes the surface irregularities play vital role in the final orientation of the mud balls. If any large mud ball somehow got stationary at the junction of tidal flat and beach foreshore, then it creates a depression at its landward side and some smaller mud balls got stuck with that during their movement during backwash. It has also been viewed that if large mud ball gets hindered by any obstacle then the re-orientation of those are very much tough and a rare phenomenon.

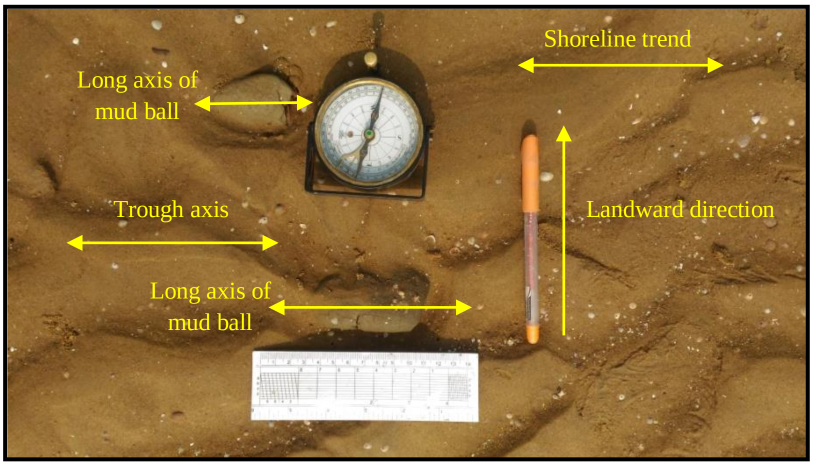


Fig 4.4: Due to the effect of surface irregularity the long axis of mud ball is oriented parallel to the trough axis and at low angle to the shore line trend.

4. Intensity of swash and backwash:

The intensity of swash and backwash also imply very much important effect on the final orientation of mud balls. Initially the force of swash disturbs the orientation of already settled mud balls and during the backwash it again gets its orientation. Sometimes the backwash do not possess the threshold force to rotate the mud balls entirely and it only succeeds in rotating the lighter, tapered end instead of the broader and heavier end. As a result, tapered mud balls aligning their tapered end facing both seaward and landward sides have been observed during this study.

Besides these four parameters during the minute and detailed field investigation another condition has been taken into account and that is the surface slope. It inevitably facilitates the rotational motion and preferential disposition due to gravitational instability, and also influences the intensity of swash and backwash. But whether it is directly affecting the orientation of mud balls or not, the conclusion may be drawn at the end of this discussion. Chandipur has a vast tidal flat, having a gentle slope of 2-3^0 along with the slope of 4-9^0 of beach and bar environment. Indifferent of slope the preference of tapered mud balls, orienting their long axes at high angle to the shoreline has been reported. At the junction of tidal flat and foreshore where the slope is $\leq 2^0$ and at the foreshore and backshore of both beach and bar where the slope is 4-9^0, in all these places the tapered ones are exhibiting their highly deviated angle bearings. The supporting data are attached as follows:

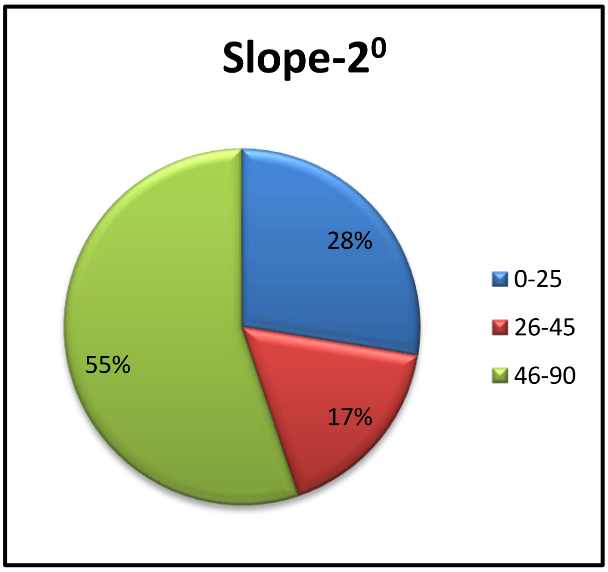
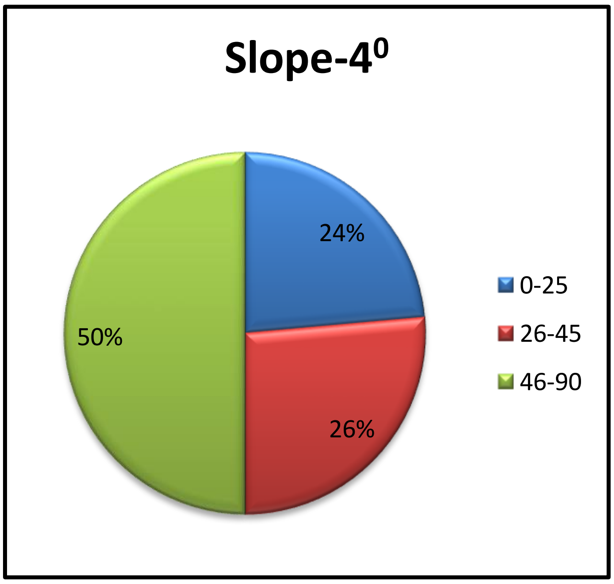
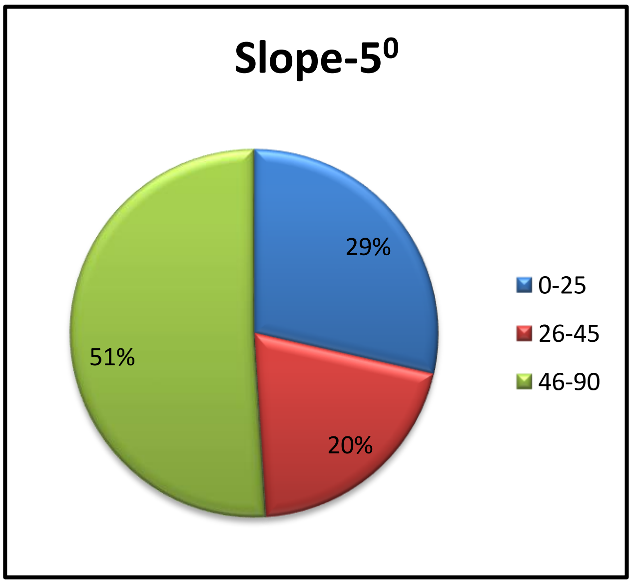
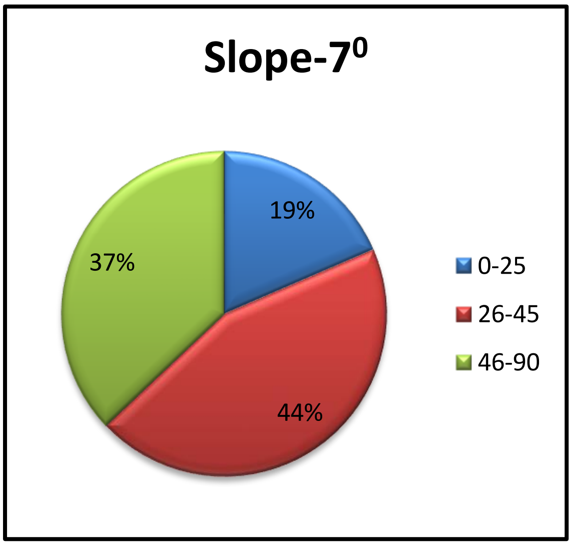


Fig 4.5: The pie chart shows the preferred high angle orientation of tapered mud balls at the junction of tidal flat and foreshore







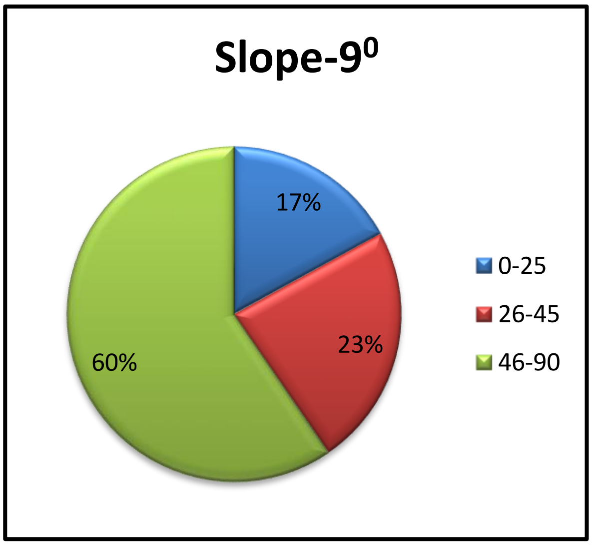


Fig 4.6: The above pie charts represent the preferred high angle orientation of tapered mud balls at foreshore and backshore of both beach and bar environment.

In the above represented pie charts (Fig 4.6) it has been clearly viewed that the tapered mud balls do not much change the intensity of their high angle of deviation with the corresponding slope change. Whatever the slope is, the dominance of highly deviated angle remain consistent. Thus, it can be inferred that the surface slope does not affect or help in the final orientation directly but it is very much helpful in introducing and influencing the rotational motion of the tapered mud balls under the effects of swash and backwash and also in immobilizing the final stabilization of Chandipur mud balls.

CHAPTER-5: CONCLUSIONS

Occurrence of a vast population of mud balls in a low energy environment regime like Chandipur coastal area has inspired awe in the mind of several workers through last few decades. Being a micro- to meso-tidal flat, the area offers low energy tidal currents which are too feeble to excavate older, thicker mud layers underlying centimeter scale cover of very recent sediments. Though meso-scale scours have been reported (Sarkar et al., 1991) in the tidal flat, especially in the immediate seaward side of the junction of beach foreshore and tidal flat, immediate seaward and landward sides of bars and large dunes within the tidal flat and explained as products of roller eddies formed due to instantly induced hydraulic jumps that are caused when waves or tidal currents hit a positive relief in the topography and flow back. But again, lack of tensional cracks and large scours within the inactive older swamp mud horizons suggest the inability of roller eddies in eroding the compact and thicker older mud. Rather they only erode recent mud and sandy sediments which are not eligible for forming mud balls due to lesser compaction and cohesion. On the other hand, multiple exposures of polygonal cracks found in older swamp mud and scattered mud chunks around them (Figs 3.2 & 3.5) support the supply of mud ball forming mud from already sub-aerially exposed, dried up older swamps through desiccation, subsequent transportation and erosion. These evidences clarify that even under low energy condition, gradual migration of bars under tidal currents, unveiling the older swamp mud beneath them is the driving factor behind the finding of this huge population of mud balls. This is undoubtedly a unique scenario of formation which contradicts with the general, established prerequisites regarding high energy flows, wave actions or role of sediment gravity flows for excavating and supplying buried and compact mud to form mud balls and mud clasts, till date.

The enigmatic orientation pattern of ovoid mud balls and difference in patterns showed by two major shape-varieties of mud balls found here corroborate many possible insights of some previous geological conundrums. There is a “sensu-stricto” in geology which states that long axis imbrication or orientation of long axis parallel to the flow direction implies transportation through suspension load. But here in Chandipur, it is clearly understood that body geometry and mass distribution, influenced by topography, slope and local variations in the intensities of swash and backwash, give rise to orientations even under deposition through pure bed load and/or rolling load movement which are similar to that of generated under movement through suspension load within a high energy depositional milieu, which is definitely not the case here under fair weather conditions. During the field visits, both under fair weather and storm affected conditions, it has been found that preservation potential of Chandipur mud balls is not vague, rather they are preserved intact in much more concentration after tidal high flow and storm events. Finding of flattened mud balls retaining their shoreline perpendicular or flow parallel orientation of long axis within trenches, under few inches' thick sediment pile portrays an abnormal intuition foreshadowing the possibilities for wrongly explaining this kind of finding in future rock records as the product of sediment gravity flows or high energy turbulent flows which are totally out of the scene for this kind of depositional environment. Even this finding questions some previous mysteries regarding the finding of imbricated, intraformational mud clasts in shallow marine and tidal environments reported earlier.

Hence, present study infers that sometimes what is seen and understood in a firsthand encounter, can be puzzling and misleading without detailed investigation of all the constraining parameters under all possible and logically feasible combinations. Even conventional law of parsimony can lead to misconception, as stated by Prof. Charles Lapworth,-

"Nothing perhaps has so retarded the reception of the higher conclusions of Geology among men in general, as ... [the] instinctive parsimony of the human mind in matters where time is concerned."

Ancient records are sometimes hard to explain or very easy to mislead without investigating any modern analogy.

References

1. Allen, J.R.L., 1982, Sedimentary structures: their character and physical basis: Amsterdam, Elsevier. 663.
2. Allen, J.R.L., 1985, Principles of physical sedimentology: Allen & Unwin, London.
3. Bagnold, R.A., 1954, Experiments on a gravity-free dispersion of large solid spheres in a Newtonian liquid under shear: Proceedings of the Royal Society A, Vol. 225, 49–63.
4. Bell, H.S., 1940, Armored Mud Balls: their origin, properties, and role in sedimentation: Journal of Geology, Vol. 48, 1–31.
5. Bhattacharya, A., 1993, Backwash-and-swash-oriented current crescents: Indicators of beach slope, current direction and environment: Sedimentary Geology, Vol. 84, 139–148.
6. Bhattacharya, J.P., and Giosan, L., 2003, Wave-influenced deltas: Geomorphological implications for facies reconstruction [J]: Sedimentology, Vol. 50(1), 187–210.
7. Blatt, H., Middleton, G., and Murray, R., 1973, Origin of Sedimentary Rocks: Englewood Cliffs (NJ), Prentice-Hall Inc.; 45–102.
8. Boggs, S., 2006, Principles of sedimentology and stratigraphy: Upper Saddle River (NJ), Prentice Hall; 21-48.
9. Boggs, S., 2009, Petrology of sedimentary rocks: New York (NY), Cambridge University Press; 610.
10. Bridge, J., and Demicco, R., 2008, Earth surface processes landforms and sediment deposits: Cambridge, Cambridge University Press; 810.
11. Bridge, J.S., 2009, Rivers and floodplains: Forms, processes, and sedimentary record: New York (NY), John Wiley & Sons; 491
12. Chun, S.S., Choe, M.Y., and Chough, S.K., 2002, Armored mudstone boulders in submarine debris-flow deposits, the hung-hae formation, pohang basin: an evidence for the large scale
13. slumping of adjacent area of a submarine channel or scar wall: Geosciences Journal, Vol. 6, 215–225.
14. Collinson, J., Mountney, N., and Thompson, D., 2006, Sedimentary structures: Harpenden, Terra Publishing; 292.
15. Dickas, A.B., and Lunking,W., 1968, The origin and destruction of armored mud balls in a fresh-water lacustrine environment: Lake Superior, Journal of Sedimentary Research, p. 1366–1370.
16. Fagerstrom, J.A., 1967, Development flotation and transportation of mud crusts – neglected factors in sedimentology: Journal of Sedimentary Petrology, Vol. 37, 73–79.
17. Folk, R.L., and Ward, W.C., 1957, Brazos River bar: A study in the significance of grain size parameters: Journal of Sedimentary Research, Vol. 27.
18. Frey, R.W., and Wheatcroft, R.A., 1989, Organism-substrate relations and their impact on sedimentary petrology: Journal of Geological Education, Vol. 37, 261–279.
19. Ghandour, I.M., Al-Washmi, H.A., and Haredy, R.A., 2013, Gravel-sized mud clasts on an arid microtidal sandy beach: example from the Northeastern Red Sea, South Al-Wajh, Saudi Arabia: Journal of Coastal Research, Vol. 291,. 110–117.
20. Goldschmidt, P.M., 1994, Armoured and unarmoured till balls from the Greenland Sea floor: Marine Geology, Vol. 121, 121–128.

21. Haas, W.H., 1927, Formation of Clay Balls: Journal of Geology, Vol. 35, 150–157.
22. Hall, A.M., 1984, Armored mud balls from cabretta and sapelo barrier islands, Georgia: Journal of Sedimentary Petrology, Vol. 54, 831–835.
23. Haughton, P., Davis, C., McCaffrey, W., and Barker, S., 2009, Hybrid sediment gravity flow deposits–classification, origin and significance: Marine and Petroleum Geology, Vol. 26, 1900–1918.
24. Holthuijsen, L.H., 2007, Waves in oceanic and coastal waters: Cambridge, Cambridge University Press; 404.
25. Kale, A.A.V.S., 1993, Morphology and formation of armoured mud balls on revadanda beach, Western India: Journal of Sedimentary Research, Vol. 63, 809–813.
26. Karcz, I., 1969, Mud Pebbles in a Flash Floods Environment: Journal of Sedimentary Research, Vol. 39, 333–337.
27. Knight, J., 2005, Processes of soft-sediment clast formation in the intertidal zone: Sedimentary Geology, Vol. 181, 207–214.
28. Kugler, H.G., and Saunders, J.B., 1959, Occurrence of armoured mud balls in Trinidad, West Indies: The Journal of Geology, Vol. 67, 563–565.
29. Li S., Li S., Shan X., Gong C. and Yu X., 2017. Classification, formation, and transport mechanisms of mud clasts, International Geology Review, Vol. 59:12, 1609-1620.
30. Little, R.D., 1982, Lithified Armored Mud Balls of the lower Jurassic turners falls sandstone, North-Central Massachusetts: Journal of Geology, Vol. 90, 203–207.
31. Macquaker, J.H., Bentley, S.J., and Bohacs, K.M., 2010, Wave enhanced sediment gravity flows and mud dispersal across continental shelves: Reappraising sediment transport processes operating in ancient mudstone successions: Geology, Vol. 38:10, 947–950.
32. Mather, A., Stokes, M., Pirrie, D., and Hartley, R., 2008, Generation, transport and preservation of armoured mud balls in an ephemeral gully system: Geomorphology, Vol. 100, 104–119.
33. McKay, J.L., Longstaffe, F.J., and Plint, A.G., 1995, Early diagenesis and its relationship to depositional environment and relative sea-level fluctuations (Upper cretaceous marshy bank
34. formation, alberta and british Columbia): Sedimentology, Vol. 42:1, 161–190.
35. Nichols, G., 2009, Sedimentology and stratigraphy: West Sussex: John Wiley & Sons; 44-68.
36. Nishiyama, Y., 1986, Tamagowa naze Tamago kataka [Why are eggs eggshaped?], Tokyo: Nihon Hyoronsha, 11-26.11
37. Nossin, J.J., 1961, Occurrence and origin of clay pebbles on the East Coast of Johore, Malaya: Journal of Sedimentary Research, Vol. 3, 437–447.
38. Olariu, C., and Bhattacharya, J.P., 2006, Terminal distributary channels and delta front architecture of river-dominated delta systems[J]: Journal of Sedimentary Research, Vol. 76:2, 212–233.
39. Pettijohn, F.J., 1957, Sedimentary rocks Second Edition: New York, Harper and Bros. 718.
40. Pettijohn, F.J., Potter, P.E., and Siever, R., 1987, Sand and sandstone: New York, Springer Science & Business Media.
41. Plint, A.G., Macquaker, J.H., and Varban, B.L., 2012, Bedload transport of mud across a wide, storm-influenced ramp: cenomanian–turonian kaskapau Formation, western Canada foreland basin: Journal of Sedimentary Research, Vol. 82:11, 801–822.

42. Potter, P.E., Maynard, J.B., and Depetris, P.J., 2005, Mud and mudstone: Berlin, Springer. 297.
43. Powers, M.C., 1953, A new roundness scale for sedimentary particles: Journal of Sedimentary Research, Vol. 23.
44. Sarkar, S., Bose, P. K., Bandhopadhayay, S., 1991, Intertidal occurrence of mesoscale scours in the Bay of Bengal, India, and their implications: Sedimentary Geology, Vol. 75, 29-37.
45. Schieber, J., Southard, J.B., and Schimmelmann, A., 2010, Lenticular shale fabrics resulting from intermittent erosion of water-rich muds—Interpreting the rock record in the light of recent flume experiments: Journal of Sedimentary Research, Vol. 80:1, 119–128.
46. Seilacher, A., 1967, Bathymetry of trace fossils: Marine Geology, Vol. 5, 413–428.
47. Sen, A., Koley, A., Samanta, P., Mukhopadhyay, S., 2019, Genesis and orientation of Chandipur mud balls- A unique phenomenon, Abstract Vol., 35th Convention of Indian Association of Sedimentologists, 2019.
48. Smith, N.D., 1972, Flume experiments on the durability of mud clasts: Journal of Sedimentary Research, Vol. 42, 378–383.
49. Stanley, D.J., 1969, Armored mud balls in an intertidal environment, minas basin, Southeast Canada: Journal of Geology, Vol. 77, 683–693.
50. Tanner, L.H., 1996, Armoured mud balls revisited: Atlantic Geology, Vol. 32, 123–125.
51. Trefethen, J.M., and Dow, R.L., 1960, Some features of modern beach sediments: Journal of Sedimentary Research, Vol. 30, 589–602.
52. Tucker, M.E., 2009, Sedimentary petrology an introduction to the origin of sedimentary rocks: West Sussex, John Wiley & Sons; 260.
53. Wadell, H., 1932, Volume, shape, and roundness of rock particles: Journal of Geology, Vol. 40, 443–451.
54. Wentworth, C.K., 1919, A laboratory and field study of cobble abrasion: Journal of Geology, Vol. 27, 507–521.
55. Williams, G.D., 1966, Origin of shale-pebble conglomerate: AAPG Bulletin, Vol. 3, 573–577.