JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.93, January 2019, pp.37-45

Time Resolution of the Phanerozoic Rock Records: Challenges of High-Resolution Palaeobiological and Geochemical Proxy-Based Interpretations

Pratul Kumar Saraswati
Department of Earth Sciences, IIT Bombay, Mumbai - 400 076, India
E-mail: *pratul@iitb.ac.in*

ABSTRACT

The understanding of the Earth's processes in the geologic past has advanced due to the ability to resolve geologic time in the rock records at progressively higher levels of time resolution. The rock records are now being probed to decipher short-term processes of palaeobiological and palaeoclimatic interests operating at a few tens of kyr to centennial and decadal scales. How good are the stratigraphic records to answer such questions? The fragmentary nature of the stratigraphic records is well recognized, and it is best summed up by the catchphrase "more gaps than record" or "a set of frozen accidents" of some leading stratigraphers. Quantitative analysis of sedimentary records in the 1980s and taphonomic studies supported by radiometric dating of shells in 1990s gave insight into an estimation of temporal resolutions of rock records. Two distinct types of resolutions are recognized, stratigraphic resolution (among strata) and palaeontological resolution (within stratum). The stratigraphic resolutions in 10^6-years scale can be achieved by biostratigraphy alone in the Cenozoic, and it can be raised to 10^5 to 10^4-years scale when integrated with as many means as magnetostratigraphy, radiometric dating, and cyclostratigraphy. Taphonomic processes deteriorate the palaeontological resolutions, and it is of major concern in bridging the gap between 10^4-years scale resolutions in the geological records and the human-life observations. The palaeobiological and palaeoclimatic processes at this scale may require exceptional records and rigorous approach to demonstrate that the requisite time-resolution is achievable in the investigated rock record.

INTRODUCTION

The first question in the interpretation of geological events is, where are they placed in the Geologic Time? The temporal relationship between the two spatially separated events is the next key question. Time and stratigraphic correlation are thus fundamental to the interpretation of rock records. Time is resolved primarily by the radiometric method in the Precambrian and by biostratigraphy and radiometric method in the Phanerozoic. Magnetostratigraphy, chemostratigraphy and orbital cyclicity are often the tools that aid in building a chronostratigraphic scale of the Phanerozoic sedimentary successions. The suitability of a stratigraphic record to answer a particular geological question depends upon the level of achievable time resolution (that is the ability to resolve the events which are closely-spaced in time). The biostratigraphers and geochronologists are continuously making efforts to improve the time scale such that the palaeobiologic and palaeoenvironmental processes are deciphered at progressively better time resolutions. It is a pertinent question as to how good are the stratigraphic records to have captured the short-term events of the past? The improvements in analytical techniques in the past decades have led to phenomenal growth in the use of geochemical proxies in palaeoclimate interpretation. A single shell of a planktic foraminifer may be enough to give oxygen isotope composition and, laser ablated single chambers of a foraminifer may provide Mg / Ca ratios to interpret ocean water temperatures. But has the ability to analyze single specimens translated into high-resolution palaeoclimate interpretation? Answers to these questions lie in a sound understanding of the nature of the stratigraphic records.

Lyellian uniformitarianism views sedimentation as continuous, slow, day to day process. Dott (1983), among others, believed that sedimentary record is mostly a record of episodic events in which gaps represent more time than the preserved strata. Quantitative studies on sedimentation rates (Schindel, 1980; Sadler, 1981) supported it and were also in agreement with the most persuasive work of Ager (1993, the first edition in 1973) who described the stratigraphic records as follows: "*there are gaps within the gaps, and the record is permeated with them, at every scale. The frozen accidents that the gaps enclose can still tell us a great deal, but only if we get the time scale right.*"

The fragmentary nature of the rock records did not discourage researchers from asking the core questions on the evolution of life and climate on this planet. Today, more subtle questions are asked about ecological and community level processes of life, as well as amplitudes of carbon isotope excursions for possible estimation of greenhouse gas emissions in deep time. Interpretations at millennial and sub-millennial time scales are becoming common. Understanding about the completeness of rock records and their attainable temporal resolutions are of critical importance in answering these questions and in reading the rock records at high time resolutions. Unfortunately, many contributions on high-resolution interpretations either do not recognize its importance or fail to provide insight to the readers whether the examined record was suitable for the levels of resolution at which the interpretations were made. This paper reviews the development in conceptual understanding in stratigraphy and their impacts on resolving palaeobiological and palaeoclimatic questions at higher temporal resolutions.

SEDIMENTATION AND ROCK RECORDS

The understanding of the nature of sedimentation is of prime importance in the evaluation of temporal resolutions of rock records. Two schools of thought, uniformitarianism, and catastrophism, prevailed in the early nineteenth century when the science of stratigraphy was in its formative period. Charles Lyell (1797-1875) advocated the doctrine of uniformitarianism, according to which the present day processes acting over long time scales are sufficient to explain the past succession of strata. Georges Cuvier (1769-1832) invoked intermittent and catastrophic processes in the geologic history. The slow, continuous and day-to-day sedimentation versus intermittent

0016-7622/2019-93-1-37/$ 1.00 © GEOL. SOC. INDIA | DOI: 10.1007/s12594-019-1118-8

and catastrophic deposition essentially determines if rock records are continuous or with gaps. Uniformitarianism has had a strong influence on our assumptions and interpretations of the geological records. Contrary to continuous sedimentation, discontinuity in sedimentary records, however, was also recognized very early in North American successions (Blackwelder, 1909; Barrell, 1917). One of the most authoritative works on the nature of sedimentation is by Ager (1993) who concluded that "sedimentation in the past has often been very rapid indeed and very spasmodic." He used the term "catastrophic uniformitarianism" to indicate that periodic catastrophic events may have more effect on stratigraphic records than vast periods of gradual evolution. Dott (1983) also passionately argues against the doctrine of uniformitarianism and holds that it casts subtle constraints upon our thinking. He refrains from using the word "catastrophic or catastrophism" and suggests the use of "episodic" in context of sedimentation. He provides several examples in support of episodic sedimentation and illustrates it with facies models of a prograding shoreline and a subsea fan (Fig. 1).

As stated before, by the early twentieth century, geologists had well recognized that stratigraphic gaps (unconformity) of different magnitudes separate the sedimentary successions (see Blackwelder, 1909 for the then concepts of different types of unconformities). Not only the long duration discordant contacts were recognized but also the parallel beds separated by the periods of non-deposition and erosion. Barrell (1917) noted that "diastems range of all values from seasonal cessations of sedimentation to those which approach geologic epochs in duration." Although conceptual knowledge existed about the presence of stratigraphic gaps of varying magnitudes, it was backed by quantitative research in the 1980s on sedimentation rates by Schindel (1980) and Sadler (1981). Sadler (1981) attempted to resolve the completeness (or the incompleteness) of the rock records by compiling 25,000 data on sediment accumulation rates in various environments and for different time spans. He concluded that accumulation rates are environment specific and are inversely proportional to the length of the interval over which they are measured (Fig. 2). The inverse relationship between the net rate and the duration of accumulation is due to unsteady accumulation. As the duration of observation increases, more and longer gaps contribute to reducing the estimated rate of sedimentation. Several quantitative stratigraphic studies followed the pioneering work of Sadler (1981) that supported the incompleteness of the stratigraphic records at different time scales. It also revealed fractal-like property (in being self-similar across different scales) of gaps and sedimentation rate at geologically relevant time scales (Plotnick, 1986; Schlager, 2004 and references therein). Miall (2016a)

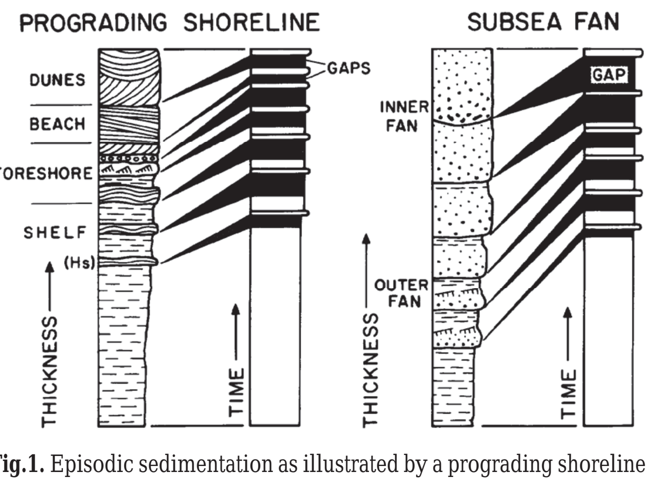

Fig.1. Episodic sedimentation as illustrated by a prograding shoreline and a subsea fan. Note the inequality of time represented by different types of strata and the gaps accounting for more time than the deposition of strata (after, Dott, 1983).

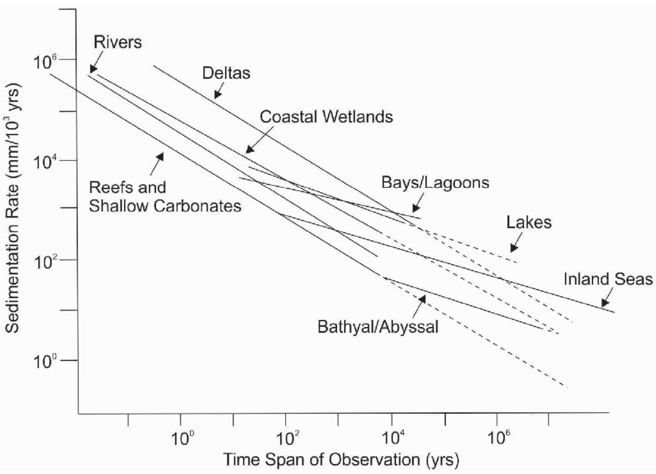

Fig.2. Relationship between sedimentation rates and time span of observation for different sedimentary environments (after Sadler, 1981).

suggested that missing time in the rock record is distributed through multiple sedimentary breaks and classified them into four broad groups, ranging from major breaks of 10^6 – 10^7 years to minor breaks spanning 10^{-6} – 10^{-1} year duration. He attributed the formation of each of the scale-specific unconformities to the geological processes operating at the corresponding temporal scales. Ager's (1993) catchphrase "more gaps than record" and Miall's (2015) "a set of frozen accidents" best sum up the nature of the rock records.

LINKING TIME AND ROCK RECORDS

Time and rock records are unified by chronostratigraphy. Chronostratigraphy deals with the relative time relations and ages of rock bodies. A chronostratigraphic unit consists of rocks formed during a specified interval of geologic time, and such units are grouped in a hierarchical scale to subdivide the geological record (Table 1). This scale was established from a combination of regional lithologic units and of unique, non-recurring events provided by biological evolution (Gradstein et al., 2004, p.20). "Stage" is the basic working unit of chronostratigraphy and each stage was delimited at a "stratotype" (mostly marginal marine to pelagic successions located in Europe) that serve to characterize its limits and fossil content. A geochronologic unit is an abstract unit, unlike material chronostratigraphic unit, that is measured from the rock record by radioactive decay and other means (Table 1). The Phanerozoic stratigraphic successions are provided relative age by fossils (biostratigraphy) and absolute age by radiometric methods (geo-chronology). All the other stratigraphic methods, including magneto-stratigraphy, cyclostratigraphy, and chemostratigraphy, are required to be calibrated either by biostratigraphy or radiometric dating.

***Biostratigraphy*:** Biostratigraphy is based on an orderly course of evolution of life and its irreversibility in time. It is because of this robust basis that fossils are the best means of determining the relative

Table 1. Hierarchy of chronostratigraphic and geochronologic units as per the International Stratigraphic Guide (Murphy and Salvador, 1999)

Chronostratigraphic Units	Geochronologic Units
Eonothem	Eon
Erathem	Era
System	Period
Series	Epoch
Stage	Age
Substage	Sub-age or Age

Table 2. Duration of the foraminiferal and calcareous nannofossil zones during the Cenozoic. Calculation based on Wade et al. (2011) for foraminifera and Berggren et al., (1995) for calcareous nannoplanktons. Values are rounded off to one decimal figures

Period / Epoch	Max. duration (myr)		Min. duration (myr)		Av. duration (myr)	
	Foram.	Nanno.	Foram.	Nanno.	Foram.	Nanno.
Quaternary	1.3	1.5	0.6	0.2	-	-
Pliocene	1.1	0.6	0.1	0.1	0.5	0.5
Miocene	2.5	4.2	0.1	0.1	1.0	0.8
Oligocene	2.2	3.6	0.9	0.5	1.4	2.0
Eocene	2.6	3.4	0.5	0.7	1.4	1.6
Palaeocene	2.7	2.5	0.2	0.2	0.9	1.1

age of stratigraphic successions and their correlation. Fossils assign local stratigraphic sections to global chronostratigraphic units. Different groups of fossils are useful in defining different intervals of geological time. Trilobites and brachiopods are good guide-fossils in the Palaeozoic era while ammonites in the Mesozoic and microfossils in the Cenozoic are known for their exceptional stratigraphic values. Deep sea drilling in the 1960s made major advancements in taxonomy and phylogenetic relationship of oceanic microfossils including foraminifera, calcareous nannofossils, and radiolaria. It assisted in planktic microfossil biostratigraphy of the Cenozoic and lead to an unprecedented refinement in time resolution. Sixty-two planktic foraminiferal zones (of different durations) are recognized in the tropical Cenozoic, with an average duration of ~ 1 myr (Table 2). A more or less similar resolution is provided by calcareous nannofossils, and enhanced resolutions can be obtained by integrating multiple microfossil zonations where boundaries of the zones do not coincide. For example, the resolution of the Oligocene epoch, having the longest average duration of both foraminiferal and calcareous nannofossil zones, can be increased by integrating the two schemes of zonations

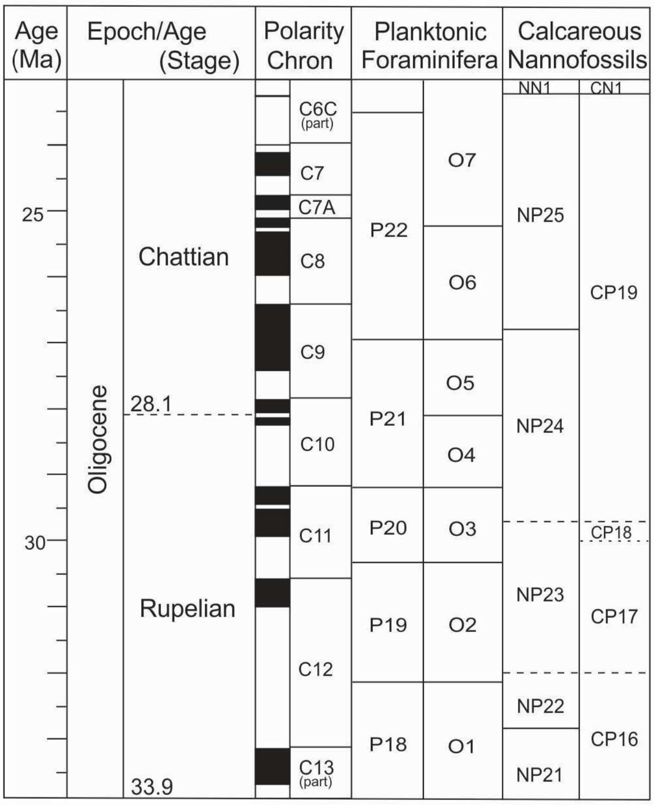

Fig.3. Integration of planktic foraminiferal and calcareous nanno-plankton zones of the Oligocene epoch (after Gradstein et al., 2012).

(Fig. 3). It may be noted that due to provinciality of the microfossils, the same zonal scheme is not applicable to all latitudes.

The stratigraphers, however, are aware of the problems in achieving high levels of temporal resolutions. The lowest occurrence (LO) and the highest occurrence (HO) of a taxon are used for biostratigraphic zonation. The LO and HO may correspond to two evolutionary events of a species, the First Appearance Datum (FAD) and the Last Appearance Datum (LAD) respectively. The biozone is converted into a chronozone whose boundaries record the FAD and LAD of the nominate taxon/taxa (Berggren and Pearson, 2005). However, it may not be true due to various reasons including the incompleteness of the record and diachroneity in the two evolutionary datum levels. In the Neogene marine microfossils, the two events are diachronous by 50 to 880 kyr. The diachrony is attributed to change in environmental gradients through time, the evolutionary adaptation of populations, migration due to water mass changes and investigator biases (Miller et al., 1994; Spencer-Cervato et al., 1994). The susceptibility of certain planktic microfossils to dissolution in deep sea can either modify the stratigraphic range of the species or may cause the disappearance of marker species (Parker, 1967; Srinivasan and Kennett, 1981). Parker (1967) noted that dissolution is prevalent in the Pacific Ocean than in the Atlantic Ocean and also discussed the pitfalls of condensed sections leading to mixing of zonal boundaries and elimination of short-lived zones.

The ranges of taxa may also be truncated and incomplete due to sampling bias (*Signor-Lipps effect*) and facies change (*Lazarus taxa*). Quantitative methods are proposed for confidence intervals on the ends of observed ranges in local sections and recommended to be calculated when absolute rates of molecular or morphological evolution are to be estimated (Strauss and Sadler, 1989; Marshall, 1990). Sequence stratigraphy has provided a new scope to understand the spatial and temporal distribution of fossils in stratigraphic records. The first and the last occurrences are clustered at flooding surfaces and sequence boundaries, rather than being randomly distributed (Holland, 1995). The first and the last occurrences of taxa in a section, therefore, may not truly represent the times of origination and extinction. The magnitude of differences in age between the first occurrence and FAD or the last occurrence and the LAD, known as range offset, varies systematically within sequences. Holland (2000) simulated the range offset of last occurrences in several depositional sequences and found that it reaches > 1 myr in up-dip parts of shelves and transgressive systems tract of the deep basin. It also tends to increase near the shelf-slope break of late highstand to early lowstand systems tract. These zones are particularly risky for the assumption that the first and the last occurrences correspond to FAD and LAD respectively. Although estimating range offset may be difficult, models predict that temporal resolution of the fossil record typically may be in the order of 1 myr due to this effect (Holland and Patzkowsky, 2002). It is stated that due to the various problems discussed above, resolution finer than 1 to 2 myr may not be possible by biostratigraphy alone in the Cenozoic (Miller and Kent, 1987).

***Radiometric dating*:** The absolute age of stratigraphic successions is estimated by different techniques of radiometric dating. Many techniques are available for dating igneous and metamorphic rocks, but there are fewer techniques to date sedimentary rocks. Uranium-lead (U-Pb) and argon-argon (Ar-Ar) are the two widely used decay series for absolute dating of rocks. The materials for dating include zircon crystals from volcanic ash falls and lavas for U-Pb dating, and biotite, sanidine and hornblende from volcanic rocks for Ar-Ar dating. Direct dating of sedimentary rocks is limited, and instead the associated igneous or metamorphic rocks are dated to bracket the age of the sedimentary rocks. Dating of associated ash beds (tephrochronology) is most helpful in determining the absolute age of sedimentary rocks although the limitation is their absence in many basins. Biostratigraphy, and not the radiometric dating, therefore remains the primary basis of the chronology of Phanerozoic sedimentary successions. Glauconite, a sedimentary diagenetic mineral, was widely used in the 1980s for obtaining the direct age of sedimentary rocks but it was noted that glauconite gives systematically younger ages and therefore it is no more used in modern geologic time scales (Gradstein et al., 2012). Moreover, glauconite and other such diagenetic minerals give diagenetic age rather than the depositional age of the sediments. In comparison to the dating of deep time sedimentary records, there are many tools for dating Quaternary sediments. Radiocarbon dating is the most widely used radiometric technique for the Quaternary. The upper age limit of the measurement is ~ 50,000 years. A range of materials can be used for radiocarbon dating including wood, charcoal, shell, and pottery. The accelerator mass spectrometry (AMS) technique developed in the 1980s was a major advancement to analyze small sample size for radiocarbon dating. The Uranium-series and cosmogenic nuclide are effective for dating few hundreds to few tens of thousands of years, and ^{210}Pb is applicable for few tens of years. Luminescence dating and fission-track dating are the other radiometric methods used in the Quaternary. The annually banded records including tree rings and growth bands in coral can provide exceptional temporal resolution, but they need to be calibrated for age by radiometric dating. Although geochronology has commendably advanced to address analytical uncertainties, the availability of datable materials, the requirement of a closed-system and the rigor of the laboratory analysis remain critical issues (Erwin, 2006).

***Raising resolution by integrative stratigraphy*:** The modern stratigraphy integrates biostratigraphy and radiometric dating with magnetostratigraphy, chemostratigraphy, and cyclostratigraphy to enhance the resolution of the stratigraphic records. The stratigraphic units defined by these latter kinds of stratigraphy are isochronous and correlatable over a wide extent, but they are recurrent in geological history. Their age cannot be decided without the aid of biostratigraphy or radiometric dating. When calibrated biostratigraphically or geochronologically, they provide highest possible stratigraphic resolutions especially in the Neogene and Quaternary times. The integration of these different stratigraphic inputs has made it possible to achieve temporal resolutions of the order of a few tens to hundreds kyr in Cenozoic and Mesozoic marine successions (Table 3).

The record of the reversals of the Earth's magnetic polarity in lava flows and deep marine sediments has become an important tool in stratigraphic correlation and dating. The rock's magnetism is either normal (the present day polarity) or reversed, and it is illustrated as black and white bar codes respectively. The black and white bar codes cannot tell time independently unless calibrated by biostratigraphy or geochronology. It should be noted that if the time-span between the palaeomagnetic reversals is less than the time-span resolvable by biostratigraphy or radiometric dating, then the identity of the palaeomagnetic event cannot be determined (Eicher, 1976, p.83). The reversals recorded in a stratigraphic section are compared with the standard polarity scale to date the section (see Fig. 3 for the Oligocene polarity chrons). Some reversals lasted for less than 10,000 yrs while two major reversals in Jurassic and Cretaceous lasted for more than 15 myrs. Berggren et al. (1995) gave numerical ages to the evolutionary datum levels (FAD & LAD) of planktic foraminifera and the biozones by integrating them with magnetostratigraphy and radiometric dating.

Table 3. Resolutions achievable by integrated stratigraphy in marine successions (after Miall, 1997)

Periods	Resolution
Quaternary	< 1 – 3 kyr
Late Cenozoic	5 – 10 kyr
Early Cenozoic	10 kyr – 1 myr
Late Cretaceous	100 kyr – 1 myr
Early Cretaceous	10 myr
Jurassic	50 – 150 kyr
Triassic	225 kyr – 2 myr

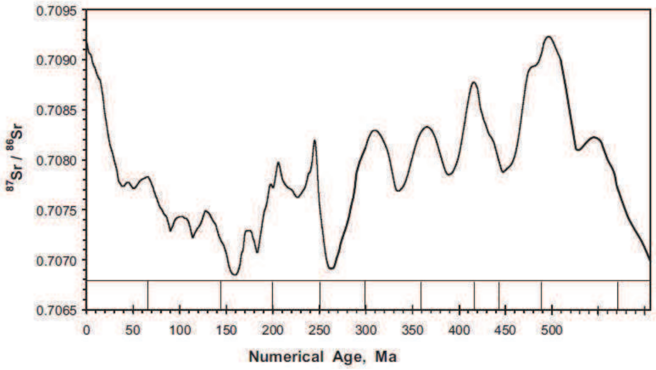

Fig.4. $^{87}Sr/^{86}Sr$ variation in the Phanerozoic Eon (after McArthur, 2010).

The changes in ocean water chemistry leave their imprint in the depositing sediments. The pattern of changes through time as preserved in the rock records is the basis of chemostratigraphy. The stable isotopes of strontium and oxygen are most widely used chemostratigraphic tools in the correlation of Cenozoic marine sediments. The value of strontium isotope ratios (^{87}Sr / ^{86}Sr) in marine carbonates has varied through time, making the strontium isotope stratigraphy (SIS) a potential tool to date and correlate the sedimentary successions. A numerical age of the sample is given by measuring its ^{87}Sr / ^{86}Sr ratio and comparing it with the calibration curve (Fig. 4; McArthur, 2010). For certain time intervals, due to the sinuosity of the calibration curve, the same strontium isotope ratios may give more than one numerical age. The technique has limited value unless multiple ages are discarded independently by biostratigraphy or other dating techniques. It is also well established that the oxygen-isotopic composition of the ocean water underwent cyclic variation in the Quaternary due to formation and melting of continental ice sheets. Emiliani (1955) for the first time attributed the cyclical variation in oxygen isotopic composition of foraminiferal carbonates to glacial – interglacial periods and recognized climatic stages in the Pleistocene. Shackleton and Opdyke (1973) applied it to stratigraphy and defined Marine Isotope Stages (MIS) where the stage boundaries are defined by times of rapid isotopic change in the oceans. The odd-numbered stages are interglacial intervals characterized by lighter oxygen-isotope values, and even numbered stages are glacial intervals recognized by heavier oxygen-isotope values. The MIS integrated with magnetostratigraphy and biostratigraphy provides one of the finest stratigraphic resolutions for the Quaternary marine successions (Fig. 5).

Cyclostratigraphy is a relatively new tool and an active area of research due to its potential in a high-resolution calibration of the Geologic Time Scale (GTS; Gradstein et al., 2004, 2012). Cyclic variation in stratigraphic record is supposedly linked to orbitally induced climatic changes (Milankovich theory) and thus capable of providing resolution at 10^4 to 10^5 years scale. Hays et al. (1976) were the pioneers to test the orbital hypothesis in stratigraphic record of the southern Indian Ocean and conclude that changes in earth's orbital geometry are the main cause of the succession of Quaternary ice ages. Their study on oxygen isotope composition of the planktic foraminifera, complemented by the radiolarian records showed periodicities of 23 ky, 42 ky and 100 ky respectively in the last 450 ky. These studies motivated stratigraphers to use the orbital record for cyclostratigraphy and develop a high-resolution time scale, particularly in the Quaternary. Cyclostratigraphy plays an important role in

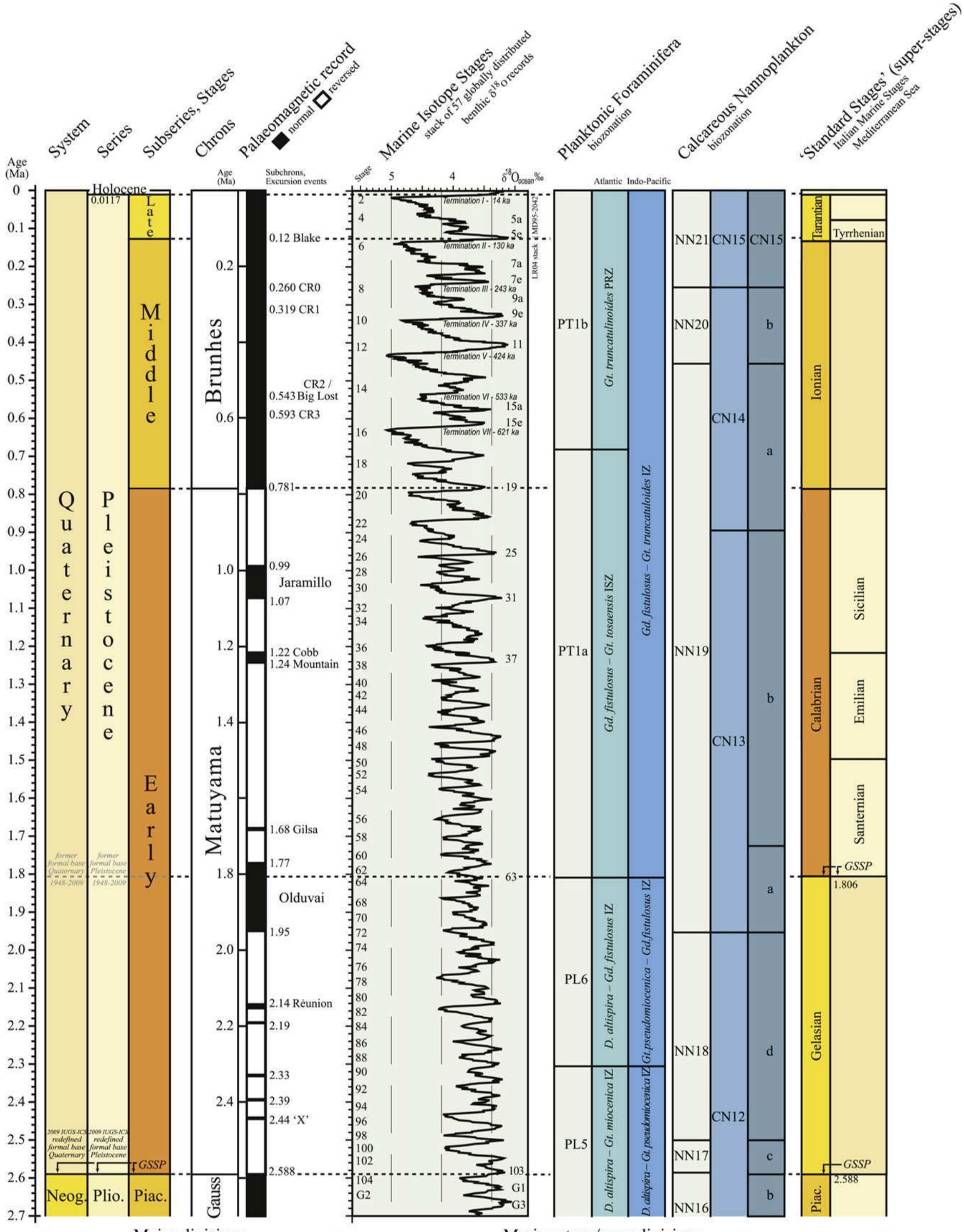

Fig.5. Marine Isotope Stages integrated with polarity chrons and planktonic microfossil biozones for the Quaternary Period (reproduced with permission, Pillans and Gibbard, 2012)

defining Global Boundary Stratotype Section and Point (GSSP) and in estimating their astrochronological ages. The success of astronomical tuning in Neogene stratotypes has led to argue for choosing continuous, deep marine and cyclic sections for stratotypes where such cyclicity are more likely to be preserved (Hilgen et al., 2006). Further, Hilgen et al. (2015) advocate its application in older successions and even in continental facies. But there are also equally strong reservations about this approach because of several assumptions in this technique and as Miall (2016b) observes the preservation of such a section complete at the 10^4 to 10^5 –year scale is likely to be very unusual.

TAPHONOMY AND TIME

The taphonomic aspect of fossil assemblages is generally ignored in most stratigraphic analysis as it may not have a marked effect on low-resolution interpretations. The time-averaging of fossil assemblages and stratigraphic disorders due to benthic mixing, however, are likely to have a serious impact on high-resolution stratigraphic interpretations. In fossiliferous beds, shells are "time-averaged" due to the pooling of successive populations and communities into a single assemblage of remains (Kidwell and Flessa, 1995). Consequently, the fossils occurring in the same bed are not contemporaneous with one another. It is observed that the grab samples of the upper 5 to 20 cm of the seabed can contain bivalve shells that may be thousands to tens of thousands of years old (Kidwell, 2013). Time-averaged assemblages coarsen temporal resolution, and the population-level information is lost although they are representative of long-term environmental conditions. The magnitude of time-averaging may vary from days to millions of years (Fig. 6). The snapshots (census assemblage), having fossils contemporaneous with one another, are neither recorded in subfossil deposits nor observed in present-day depositional settings (Kowalewski and Bambach, 2008). Modern dating tools including AMS and amino acid racemization helped estimate the duration of time-averaging in recent fossil assemblages (Table 4). Time-averaging of about 2 kyr is estimated for the foraminiferal assemblage on beaches of Jamaica and Hawaii (Martin et al., 1996; Resig, 2004). The fresh, un-cemented specimen of late Pleistocene foraminifer *Marginopora vertebralis* co-exist with recent specimens of the species, recording a time-averaging of 125 kyr (Murray-Wallace and Belperio, 1995). Unlike in the Pleistocene – Holocene assemblages, the radiometric dating is not useful in estimating the duration of time-averaging in older samples.

Table 4. Duration of time-averaging in recent foraminiferal assemblages as estimated by AMS and amino acid racemization methods

Foraminifera	Time-averaging	Dating method	Reference
Archaias, Amphistegina	2 kyr	AMS ^{14}C	Martin et al. (1996)
Marginopora	125 kyr	Amino Acid Racemization	Murray Wallace and Balperio (1995)
Amphistegina	>1.5 kyr	AMS ^{14}C	Resig (2004)

Stratigraphic and taphonomic evidence together with the sedimentary and biological processes in the modern environments are used to estimate the durations in older successions (see Kidwell, 1993, for details). The fossiliferous strata, therefore, have two distinct types of resolution: first, among-strata *stratigraphic resolution* and second, within-stratum *palaeontological resolution* (Kowalewski and Bambach, 2008). It is important to note that the two kinds of resolutions although related may not be the same. As discussed before, stratigraphic record is more of gaps such that the sediments deposited in successive depositional events are separated by longer periods of non-deposition (diastems). The stratigraphic resolution is decided by the age of the depositional events and the duration of the diastems. A bed, however, may contain shells of organisms that existed during the depositional event as well as those pre-dating and post-dating it (during the diastems), making the paleontological resolution poorer than the stratigraphic resolution.

The smearing of stratigraphic signals due to bioturbation is of concern in deep-sea records. It is cautioned that given the recent trends towards high-resolution stratigraphy, an understanding of the process of benthic mixing is essential for correct interpretation of the signals (Schiffelbein, 1984). Bioturbation and dissolution modify the radiocarbon age profile of sediments in the deep sea. The un-bioturbated section shows a linear age-depth relationship while bioturbated mixed layer has a constant older age. Further, differential dissolution impacts the radiocarbon age of the mixed layer (DuBois and Prell 1988). The mean core top ages from above and below the lysocline in Atlantic are found to differ by ~700 years. It is explained that below the lysocline dissolution removes carbonates from the mixed layer and in the process older material is removed relative to young materials of the sedimentation flux. The radiocarbon age of the mixed layer, therefore, becomes younger with increased dissolution.

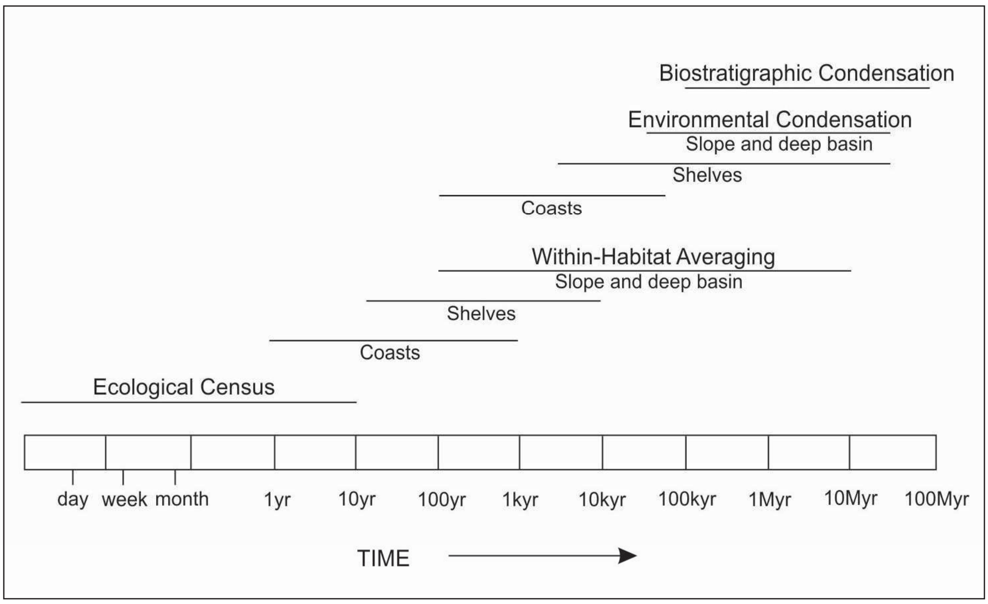

Fig.6: Estimated time-averaging for different types of fossil assemblages (after Kidwell and Bosence, 1991).

DISCUSSION

The gaps of varying magnitudes are all pervasive in stratigraphic records. How seriously it impacts interpretations depends upon the status of knowledge and the nature of the investigation. While standard biostratigraphic zonations may suffice most routine stratigraphic studies, high-resolution palaeoclimate interpretations, calibrations of transient geochemical signals and certain palaeobiological inferences are highly challenging to deduce from stratigraphic records. Not only the correct chronology of the events is required, but the contemporaneity of the recognized events need to be established regionally or globally.

Biostratigraphy has made a significant contribution in raising the time resolution of the Phanerozoic stratigraphic successions. Its potential can be recognized in the Cenozoic where planktic microfossils can provide a resolution of <1 myr. An intensive stratigraphic study for hydrocarbon exploration by the ONGC in the past decades has led to establish regional Stages that are well-dated by multiple biostratigraphic zonations (Raju, 2013, 2017). The planktic foraminifera and nannoplankton datums are established in different basins enabling better stratigraphic resolutions. Due to diachroneity of the biostratigraphic datum events and preservational issues, however, it is reasonable to expect a resolution of 1-2 myr based on biostratigraphy alone. Resolutions of ~ 10 kyr for certain intervals can be expected when integrated with the other means of stratigraphy. Similarly, a high resolution of a few hundreds of kyr is also achievable in the Mesozoic by ammonite zones integrated with other means of stratigraphy. There are over 40 ammonoid Zones recognized in the Jurassic sequence of the Indian subcontinent (Krishna et al., 2011), implying a resolution of <1 myr, that can be further raised by integrating them with magnetostratigraphy and chemostratigraphy. It is not a coincidence that planktic foraminifera and ammonites that provided high temporal resolutions in the Cenozoic and Mesozoic respectively are also the most thoroughly studied fossils for their taxonomy and phylogeny. It emphasizes the importance of taxonomy and phylogeny in raising time resolution in stratigraphy. The declining interest in this core area of palaeontology and discouraging response of funding agencies to support this "routine" research will not help raise the resolution of the stratigraphic records any further.

There are limited means of direct dating of sedimentary rocks. The most widely used glauconite dates provide the age of diagenesis and not the depositional age. The laser-probe Ar-Ar dating of glauconite grains from the same populations has shown a wide range of ages, suggesting a genesis time of ~ 5 myr for the mineral (Smith et al., 1998) and implying its severe limitation in obtaining high-resolution stratigraphic records. The indirect dating through tephrochronology dates the inter-bedded ash and thus brackets the age of the sedimentary rocks. The chronostratigraphic boundaries, biozones, and events are similarly given absolute ages by extrapolating the age of the ash beds, assuming a continuous and constant rate of sedimentation. The assumption may not be of much consequence at coarse resolution, but it is questionable at high temporal resolutions. Moreover, not all sedimentary successions have ash beds to date. The radiometric dating alone is therefore of little practical value in high-resolution studies, except for the Quaternary. The biostratigraphy and radiometric dating, integrated with magnetostratigraphy, oxygen or strontium isotope stratigraphy and cyclic stratigraphy are capable of providing finest resolution of the stratigraphic records. A resolution of few tens to hundreds of kyr is achievable in the Mesozoic and Cenozoic and 1 to 3 kyr in the Quaternary.

The short-term palaeoclimate changes such as the hyperthermal events of the Eocene are precisely constrained by integrative stratigraphy involving magnetostratigraphy, tephrochronology, and cyclostratigraphy (Westerhold et al., 2009 and references therein). The biostratigraphy alone may not be successful for these short-lived, successive warming events that require a time resolution of the order of ~ 100 ky or less. Caution should be exercised while interpreting the transient geochemical signals (carbon isotope excursions, for example) for their duration and amplitude. The inherent discontinuity and cryptic gaps in the rock records may change the true amplitude and slope of the signals.

Besides the stratigraphic resolution discussed above the palaeontological resolution further limits the time resolutions of the rock records. The radiometrically dated shells in the modern environments reveal time-averaging varying over nine orders of magnitude but typically in the range of 100s to 1000s of years (Kowalweski and Bambach, 2008). The implications are clear – unsuitability of the rock records for inferring colonization, population dynamics and such palaeobiological processes that operate at this time scale. The palaeoclimate interpretations based either directly on fossils or geochemical proxies derived from them are also subject to the same constraints. The geochemical proxies are routinely employed in palaeoceanographic and palaeoclimate studies. It is now possible to determine $\delta^{18}O$, $\delta^{13}C$ and Mg / Ca ratios in single shells of foraminifera, but whether it translated into high-resolution interpretation is debatable due to the complexity of the stratigraphic records. The monsoon reconstructions at millennial and centennial scales have the same serious issues in their reproducibility. The exceptions are the interpretations based on annually banded archives such as tree-rings, speleothems, varves, corals, and ice-cores. The limitations of both stratigraphic and palaeontologic resolutions may make the rock records extremely difficult to decipher palaeobiological and palaeoclimatic events at 10^3 - 10^4 year or finer scale.

The stratigraphic records are interpreted today at increasingly higher time scales. It is imperative that such studies are based on rigorous stratigraphic observations, and use multiple means to constrain the chronology and ensure the viability of the desired temporal resolution in the examined record. A good example to set such a protocol is by INQUA Palaeoclimate Commission for establishing marine event-based chronostratigraphy in North Atlantic (Lowe et al., 2008; Austin and Hibbert, 2012). All high-resolution studies should endeavour to adopt such protocols that essentially recommends independent and preferably quantified proxy data, radiocarbon dates, comparison with independent regional stratotypes and validation of correlations by Marine Isotope Stages, tephrochronology, dendrochronology and annually laminated lacustrine and marine sediments. Following the strong debate on phyletic gradualism vs. punctuated equilibria (Eldredge and Gould, 1972), a set of procedures, termed "resolution analysis," was proposed to address palaeobiological questions that rely particularly on the completeness of the stratigraphic records. It includes *temporal scope, microstratigraphic acuity*, and *stratigraphic completeness*. A temporal scope is the total span of geologic time encompassed in a sampled sequence; microstratigraphic acuity is the amount of time represented in each fossiliferous sample; stratigraphic completeness is the proportion of the temporal scope represented by actual strata, as opposed to the gaps (see Schindel, 1982 for detailed procedure). Several other researchers proposed methods to estimate temporal resolution of the sedimentary records so that they are assessed for their suitability to document processes at that scale of observation. Some of these are discussed below, and they should form an essential part of research in high-resolution analysis.

It was realized at the beginning of the deep sea research that benthic mixing and waves and currents smear the short-term signals in stratigraphic records. Berger and Heath (1968) quantitatively modeled the vertical mixing of the particles and calculated the proportions of the original concentration of a tracer (microfossil, for example) in the sediment above its true level of occurrence. By specifying the mixed layer thickness and an acceptable level of contamination (the reworked

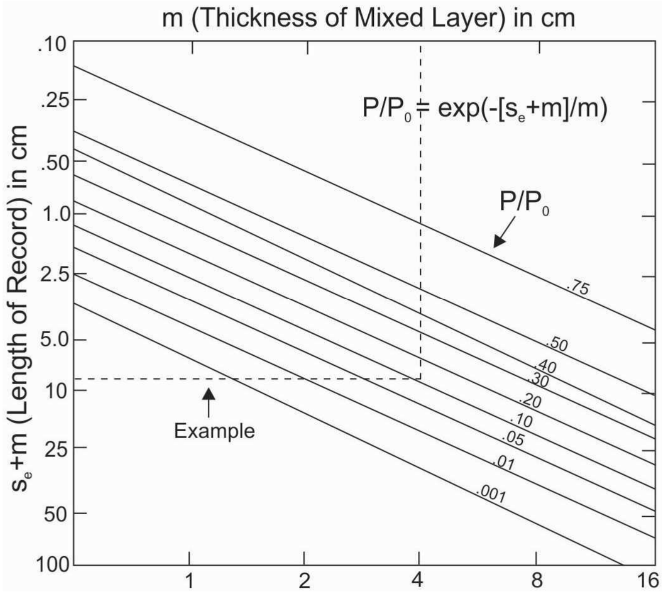

Fig.7. Vertical mixing in pelagic sediments and its effect on stratigraphic resolution as illustrated by Berger and Heath (1968). The example in the figure shows that if mixed layer thickness is 4 cm, 10% mixing of the original concentration of the species (P/P_0) occur at 9 cm above the true level of extinction. If the rate of sedimentation is 1 cm / ky, resolution is 9000 years.

microfossil proportion), it is possible to estimate the stratigraphic resolution of the given record (Fig. 7).

Sadler (1981) expressed completeness as the ratios of long- to short-term accumulation rates, at the time-scale of the short-term rate. The following equation is used to estimate the completeness of the section for a particular span of time:

$$\text{Completeness} = (t / T)^{-m}$$

where, t is the desired short time span, T is the time span of the whole section and m is the slope of the trend line of sediment accumulation rate and time span for the particular depositional environment (plots provided by Sadler (1981) and Schindel (1982) for the major sedimentary environments).

Schifflebein (1984) found sedimentation rate as primary control and limiting factor on a signal resolution in deep-sea cores. He proposed the following equation to find the minimum sedimentation rate required to ensure that a signal of a particular period could be recovered:

$$\nu \text{ (cm /kyr)} = 20.0 / \text{period (kyr)}$$

where, ν is the rate of sedimentation and “period” is the time of an event (or time resolution) expected to recover from the core. It implies that a minimum sedimentation rate of 20 cm/kyr is required for the 1000 year resolution.

Quantitative stratigraphy has contributed significantly to our conceptual understanding of the formation of gaps and the so-called “frozen accidents.” The efforts to derive short-term palaeobiological and palaeoclimatic processes from such records would require researchers to be more rigorous in approach. It should be a norm than an exception to formulate and follow standard procedures specific to broader themes of research. Notwithstanding the gaps, the sedimentary records have preserved evidence to answer core questions in the history of the Earth. We are reminded of Van Andel (1981) who do not consider the gaps in sedimentary records as a serious problem and asserts that “if the history of the Earth is mainly shaped by rare but major events, we need not greatly regret our inability to track the trivial day to day happenings.”

CONCLUSIONS

The all-pervasive gaps in stratigraphic records are well-reported in literature since the early parts of the twentieth century. Quantitative documentation of sedimentation and gaps have led to a better appreciation of the incompleteness of the rock records. High-resolution interpretations should take cognizance of the developments in stratigraphy that have given insight to the completeness of the stratigraphic records.

Biostratigraphy alone can provide a resolution of 10^6 years and above but integrated with magnetostratigraphy, and radiometric dating can practically raise the resolution to 10^5 years for the Mesozoic and the Palaeogene. A still higher resolution of 10^4 years is possible in the Neogene.

While biostratigraphy may provide adequate support in routine stratigraphic studies ($10^6 - 10^7$ years scale) higher temporal resolution should necessarily include as many means as biostratigraphy, magnetostratigraphy, radiometric dating, isotope stratigraphy and cyclic stratigraphy to constrain the chronology of the examined sections.

Time-averaging and bioturbation are the serious constraints in bridging the gap between 10^4-year scale and the human-life observations. The palaeobiological and palaeoclimatic processes at this scale may require rigorous approach and exceptional records. The annual banded archives are the best bets though long-term continuous records may not be apparent.

The geochemical proxies derived from fossils are biased by palaeontological resolution, in addition to the stratigraphic resolutions. The geochemical signals of palaeoclimatic importance may be attenuated, and their slopes may be modified due to cryptic gaps and time-averaged assemblages. Such records need to be evaluated most scrupulously.

Acknowledgement: I am extremely grateful to Professors M.S. Srinivasan, P.K. Bose, R.S. Sharma and Kanchan Pande for their constructive reviews that immensely improved the manuscript.

References

Ager, D.V. (1993) The Nature of the Stratigraphical Record. III Edition, John Wiley & Sons, Chichester, p.151.

Austin, W.E.N. and Hibbert, F.D. (2012) Tracing time in the ocean: a brief review of chronological constraints (60-8 kyr) on North Atlantic marine event-based stratigraphies. Quaternary Sci. Rev., v.36, pp.28-37.

Barrell, J. (1917) Rhythms and the measurement of geologic time. Geol. Soc. Amer. Bull., v.28, pp.745-904.

Berger, W.H. and Heath, G.R. (1968) Vertical mixing in pelagic sediments. Jour. Marine Res., v.26(2), pp.134-143

Berggren, W.A., Kent, D.V., Swisher, C.C. and Aubry, M.A. (1995) A revised Paleogene geochronology and chronostratigraphy. *In:* Berggren, W.A., Kent, D.V. and Hardenbol, J. (eds): Geochronology, Time Scales and Global Stratigraphic Correlation: Unified Temporal Framework for an Historical Geology. Soc. Econ. Geol. Paleont., Spec. Publ. No.54, pp.129-212.

Berggren, W.A. and Pearson, P.N. (2005) A revised tropical to sub-tropical Paleogene planktonic foraminiferal zonation. Jour. Foraminiferal Res., v.35, pp.279-298.

Blackwelder, E. (1909) The valuation of unconformities. Jour. Geol., v.17, pp.289-299.

Dott, R.H. Jr. (1983) 1982 SEPM Presidential Address: Episodic sedimentation – how normal is average? How rare is rare? Does it matter? Jour. Sediment. Petrol., v.53, pp.5-23.

DuBois, L.G. and Prell, W.L. (1988) Effects of carbonate dissolution on the radiocarbon age structure of sediment mixed layers. Deep-Sea Res., v.35, pp.1875-1885.

Eicher, D.L. (1976) Geologic Time. II Ed., Prentice Hall, New Jersey, 150p.

Eldredge, N. and Gould, S. J. (1972) Punctuated equilibria: an alternative to phyletic gradualism. *In:* Schopf, T.J.M. (Ed.), Models in Paleobiology, Freeman Cooper and Company, San Francisco, pp.82-115.

Emiliani, C. (1955) Pleistocene temperatures. Jour. Geol., v.63, pp.538-578.

Erwin, D.H. (2006) Dates and rates: temporal resolution in the deep time

stratigraphic record. Ann. Rev. Earth Planet. Sci., v.34, pp.569-590.
Gradstein, F.M., Ogg, J.G. and Smith, A.G. (Eds.) (2004). A Geologic Time Scale 2004. Cambridge University Press, Cambridge, p.589.
Gradstein, F.M., Ogg, J.G., Schmitz, M.D. and Ogg, G.M. (Eds.) (2012) The Geologic Time Scale 2012. Elsevier, Amsterdam, v.1, p.435.
Hays, J.D., Imbrie, J. and Shackleton, N.J. (1976) Variations in the earth's orbit: Pacemaker of the ice ages. Science, v.194, pp.1121-1132.
Hilgen, F., Brinkhuis, H. and Zachariasse, W. (2006) Unit stratotypes for global stages: The Neogene perspective. Earth Sci. Rev., v.74, pp.113-125.
Hilgen, F.J., Hinnov, L.A., Aziz, H.A., Abels, H.A and others (2015) Stratigraphic continuity and fragmentary sedimentation: the success of cyclostratigraphy as part of integrated stratigraphy. *In:* Smith, D.G., Bailey, R.J., Burgess, P.M. and Fraser, A.J. (eds) Strata and Time – Probing the Gaps in our Understanding. Geol. Soc. London Spec. Publ., no.404, pp.157-198.
Holland, S.M. (1995) The stratigraphic distribution of fossils. Paleobiology, v.21, pp.92-109.
Holland, S.M. (2000) The quality of the fossil record: a sequence stratigraphic perspective. Paleobiology, v.26, pp.148-168.
Holland, S.M. and Patzkowsky, M.E. (2002) Stratigraphic variation in the timing of first and last occurrences. Palaios, v.17, pp.134-146.
Kidwell, S.M. (1993) Patterns of time-averaging in shallow marine fossil record. *In:* S.M. Kidwell and A.K. Behrensmeyer (Eds.), Taphonomic Approaches to Time Resolution in Fossil Assemblages, The Paleontological Society, Pittsburgh, pp.275-300.
Kidwell, SM. (2013) Time-averaging and fidelity of modern death assemblages: building a taphonomic foundation for conservation palaeobiology. Palaeontology, v.56, pp.487-522.
Kidwell, S.M. and Bosence, D.W.J. (1991) Taphonomy and time averaging of marine shelly faunas. *In:* P.A. Allison and D.E.G. Briggs (Eds.), Taphonomy: Releasing the Data Locked in the Fossil Record, Plenum Press, New York, pp.116-209.
Kidwell, S.M. and Flessa, K.W. (1995) The quality of the fossil record: Populations, species and communities. Annual Review of Ecological Systematics, v.26, pp.269-299.
Kowalewski, M. and Bambach, R.K. (2008) The limits of palaeontological resolution. *In:* P.J. Harries (Ed.), High-Resolution Approaches in Stratigraphic Paleontology, Springer, pp.1-48.
Krishna, J., Pandey, B. and Pathak, D.B. (2011) Current status of the Jurassic ammonoid stratigraphic framework in the Indian subcontinent with focus on the tectonically controlled regional transgressive-regressive couplets. *In:* Bhargave, O.N. (Ed.), Facets of the Phanerozoic. Mem. Geol. Soc. India, v.78, pp.140-176.
Lowe, J.J., Rasmussen, S.O., Bjorck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C. and the INTIMATE group (2008) Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. Quaternary Sci. Rev., v.27, pp.6-17.
Marshall, C.R. (1990) Confidence intervals on stratigraphic ranges. Paleobiology, v.16, pp.1-10.
Martin, R.E., Wehmiller, J.F., Harris, M.S and Liddell, W.D. (1996) Comparative taphonomy of foraminifera and bivalves in Holocene shallow water carbonate and siliciclastic regimes: taphonomic grades and temporal resolution: Paleobiology, v.22, pp.80-90.
McArthur, J.M. (2010) Strontium isotope stratigraphy. *In* Application of Modern Stratigraphic Techniques: Theory and Case Histories. SEPM Spec. Publ. No. 94, pp.129-142.
Miall, A.D. (1997) The Geology of Stratigraphic Sequences. Springer, Heidelberg, p.433.
Miall, A.D. (2015) Updating uniformitarianism: stratigraphy as just a set of "frozen accidents." *In:* Smith, D.G., Bailey, R.J., Burgess, P.M. and Fraser, A.J. (Eds.), Strata and Time: Probing the Gaps in our Understanding. The Geological Society, London, pp. 11-36.
Miall, A.D. (2016a) The valuation of unconformities. Earth Sci. Rev., v.163, pp.22-71.
Miall, A.D. (2016b) Stratigraphy – A Modern Synthesis. Springer International, Switzerland, p.454.
Miller, K.G. and Kent, D.V. (1987) Testing Cenozoic eustatic changes: The critical role of stratigraphic resolution. *In:* Ross, C.A. and Haman, D. (Eds.), Timing and depositional history of eustatic sequences: Constraints on seismic stratigraphy: Cushman Foundation for Foraminiferal Research, Spec. Publ., no.24, pp.51-56.
Miller, K.G., Wright, J.D., van Fossen, M.C. and Kent, D.V. (1994) Miocene stable isotopic stratigraphy and magnetostratigraphy of Buff Bay, Jamaica. Geol. Soc. Amer. Bull., v.106, pp.1605-1620.
Murphy, M.A. and Salvador, A. (1999) International stratigraphic guide – An abridged version. Episodes, v.22, pp.255-271.
Murray-Wallace, C.V. and Belperio, A.P. (1995) Identification of remanie fossils using amino acid racemization. Alcheringa, v.18, pp.219-227.
Parker, F.L. (1967) Late Tertiary biostratigraphy (planktonic foraminifera) of tropical Indo-Pacific deep-sea cores. Bull. Amer. Paleont., v.52, pp.115-208.
Pillans, B. and Gibbard, P. (2012) The Quaternary Period. *In:* Gradstein, F.M., Ogg, J.G., Schmitz, M.D. and Ogg, G.M. (Eds.), The Geologic Time Scale 2012. Elsevier, Amsterdam, pp.979-1010.
Plotnick, R.E. (1986) A fractal model for the distribution of stratigraphic hiatuses. The Journal of Geology, Vol. 94, pp. 885-890.
Raju, D.S. N. (2013) Regional and standard stratigraphic classifications and correlation in India. *In:* Malarkodi, N., Keller, G., Reddy, A.N. and Jaiprakash, B.C. (Eds.), Proceedings of XXIII Indian Colloquium on Micropaleontology and Stratigraphy and International Symposium on Global Bioevents in Earth's History. Geol. Soc. India Spec. Publ., no.1, pp.98-124.
Raju, D.S.N. (2017) Phanerozoic stratigraphy of India through charts and notes. Bull. ONGC, v.52(3), pp.1-68.
Resig, J.M. (2004) Age and preservation of *Amphistegina* (Foraminifera) in Hawaiian beach sand: implications for sand turnover rate and resource renewal. Marine Micropaleontology, v.50, pp.225-236.
Sadler, P.M. (1981) sediment accumulation rates and the completeness of stratigraphic sections. Jour. Geol., v.89, pp.569-584.
Schiffelbein, P. (1984) Effect of benthic mixing on the information content of deep-sea stratigraphical signals. Nature, v.311, pp.651-653.
Schindel, D.E. (1980) Microstratigraphic sampling and the limits of paleontologic resolution. Paleobiology, v.6, pp.408-426.
Schindel, D.E. (1982) Resolution analysis: a new approach to gaps in the fossil record. Paleobiology, v.8, pp.340-353.
Schlager, W. (2004) Fractal nature of stratigraphic sequences. Geology, v.34, pp.185-188.
Shackleton, N.J. and Opdyke, N.D., 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Paciûc core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6-year scale. Quaternary Res., v.3, pp.39–55.
Smith, P.E., Evensen, N.M., York, D. and Odin, G.S. (1998) Single-grain ^{40}Ar-^{39}Ar ages of glauconites: Implications for the Geologic Time Scale and global sea level variations. Science, v.279(5356), pp.1517-1519.
Spencer-Cervato, C., Thierstein, H.R., Lazarus, D.B. and Beckmann, J. (1994) How synchronous are Neogene marine plankton events? Paleoceanography, v.9, pp.739-763.
Srinivasan, M.S. and Kennett, J.P. (1981) A review of Neogene planktonic foraminiferal biostratigraphy: Applications in the equatorial and south Pacific. SEPM Spec. Publ., v.32, pp.395-432.
Strauss, D. and Sadler, P.M. (1989) Classical confidence intervals and Bayesian probability estimates for ends of local taxon ranges. Mathematical Geol., v.21, pp.411-427.
Van Andel, T.H. (1981) Consider the incompleteness of the geological record. Nature, v.294, pp.397-398.
Wade, B.S., Pearson, P.N., Berggren, W.A. and Palike, H. (2011) Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. Earth Sci. Rev., v.104, pp.111-142.
Westerhold, T., Rohl, U., McCarren, H.K. and Zachos, J.C. (2009) Latest on the absolute age of the Paleocene-Eocene Thermal Maximum (PETM): new insights from exact stratigraphic position of key ash layers +19 and -17. Earth Planet. Sci. Lett., v.287, pp.412-419.

(Received: 3 May 2018; Revised form accepted: 21 August 2018)