Chapter 7

ENVIRONMENTAL MAGNETIC STUDIES

ENVIRONMENTAL MAGNETIC PARAMETERS

Environmental magnetism (EM), also known as mineral magnetism measures the inherent magnetic properties such as concentration of magnetic minerals, mineralogy and granulometry in natural samples (Thompson and Oldfield, 1986; Maher and Thompson, 1999; Evan and Heller, 2003). The EM methods are inexpensive, fast proxies that require relatively less preparation time and also allow measurement of large number of samples in lesser time (Peters and Dekkers, 2003; Phartiyal et al., 2003; Warrier et al., 2011; Walden et al., 1999; Dearing, 1999). Magnetic susceptibility (χlf) is one of the widely used parameters for paleoclimate/paleoenvironmental studies from variety of archives ranging from terrestrial to marine, and lacustrine environments on broader scales (Banerjee et al., 1981; Maher and Thompson, 1992; Nawrocki et al., 1996; Geiss and Banerjee, 1997; Langereis et al., 1997; Chlachula et al., 1998; Evans and Heller, 2001; Anderson et al., 2002; Zhnag and Yu, 2003; Demory et al., 2005; Maher, 2011; Zhnag et al., 2012). Rock magnetic/EM properties of deep-sea sediments from world oceans are also found to correlate with the major climatic variability on shorter and longer time scales (Colin et al., 1998; Lean and McCave, 1998; Bloemendal, 1989). Similarly, changes in aeolian fluxes, fluvial inputs, shifts in ocean currents have also been tracked successfully using mineral magnetic studies (Bloemendal et al., 1992, Oldfield, 1977; Thouveny et al., 1994; Robinson and McCave, 1994; Robinson et al., 1995). The loess sediments from Chinese Plateau, during late Quaternary showed good correlation of low field magnetic susceptibility with the paleoclimatic variability (Chen et al., 1997) that further correlates with the δ^{18}O record from Arabian Sea (Kukla et al., 1988). The mineral magnetic measurements can also be used for determining sediment provenance, transport pathways as a supportive proxy along with geochemical proxies and particle size data (Oldfield and Yu, 1994; Lepland and Stevens, 1996; Bonnett et al., 1988; Oldfield et al., 1993; Hutchinson and Prandle, 1994; Clifton et al., 1997, 1999; Xie et al., 1999, 2000; Zhang et al., 2001; Booth et al., 2005).

In addition to the magnetic properties of natural sediments, the grain size parameters provide one of the basic and equally important datasets about the depositional environments and their variability through time (Joshep et al., 1998). The correlation between these two helps to reconstruct the palaeoenvironmental condititions through time, for e.g. mineral magnetic parameters have been widely used to infer climatic signals in marine and deltaic sediments (Basavaiah and Khadkikar, 2004; Sangode et al., 2007). Attempts have been made for paleoenvironmental reconstructions and even to assess the sea level fluctuations using magnetic parameters from variety of archives (Ouyang et al. 2014; Basavaiah et al., 2015). A study from arid region of Thar desert interpreted paleoclimate based on mineral magnetic studies done on sediments from Bap Malad and Kanod playas (Deotare et al., 2004). Magnetic susceptibility (χ_{lf}) of the sediment gives concentration of magnetic minerals in particular sample. Similarly, ARM, IRM and SIRM also reflect the magnetic mineral concentrations (Thompson and Oldfield, 1986). The sediment magnetic properties found to co-vary with the particle size of the magnetic mineral grains (Thompson and Morton, 1979; Thompson and Oldfield, 1986, Gale and Hoare, 1991; Yim et al., 2004; Maher, 1988; Boar and Harper, 2002). The magnetic susceptibility and grain-size of the sediments are generally related to the depositional environments and may be linked with the climatic variability (Bloemendal et al., 1992; Oldfield and Robinson, 1985, David et al., 2001). Many studies evaluated the magnetic susceptibility as a rainfall proxy and advocate its usage in paleomonsoonal reconstructions (Sandeep et al., 2017; Basavaiah and Kadhkikar, 2004; Prasad et al., 2014: Heller et al., 1993; Maher et al., 1994). The magnetic grain size analysis along with median grain size and sorting of sediments was carried out to delineate the environmental deposition conditions (Joseph et al., 1998). Basically, the response acquired through magnetic measurements under varied environmental conditions can help to reconstruct the paleomoonsoon/paleoenvironmental conditions of an area (Shankar et al., 2006; Jelinowska et al., 1995).

Environmental magnetic analysis was carried out at Paleomagnetic laboratory in Birbal Shani Institute of Paleoscience (BSIP), Lucknow, India. The general characteristics of the magnetic parameters are mentioned in Table 2. ~10 g of air-dried sample was filled in non-magnetic sample holders for analysis. Magnetic susceptibility (χlf) at low frequency (0.47 kHz) was determined on Bartington Susceptibility Meter (Model MS2) (noise level ~3x10x^{-9}m^{3} kg-1 for a 10 g sample). Anhysteric remanent magnetization (ARM) was induced in the samples using a Molspin AF demagnetizer (with an ARM attachment) in a constant biasing field of 0.1 mT superimposed on a decaying alternating field (a.f.) with a peak of 100mT at the decay rate of 0.001 mT xspecific ARM by size of the biasing field (0.1mT= 79.6A/m; Walden, 1999b). Isothermal remnant magnetization (IRM) was induced in the samples at different field strengths of 20, 50, 70, 100, 200, 300 up to 800 mT and back fields up to -300 mT using ASC Scientific IM 10-30 Impulse Magnetizer. The remenance were measured in a Minispin magnetometer of Molspin Ltd. (sensitivity ~10x - 7Am2 kg-1 for a 10 g sample). The interparametric ratios that were used are S-ratio, SIRM/χlf and χARM /SIRM, ARM/ χlf, Soft IRM and Hard IRM. The isothermal remenance induced at 800mT was considered as the saturation isothermal remanent magnetization (SIRM). S-ratio was calculated by the expression (-IRM-300mT/SIRM2500mT). χARM/SIRM, SIRM/χlf were calculated to determine magnetic grain size. For magnetic mineralogy, the IRM acquisition was performed on all samples (Maher et al., 1999; Walden, 1999; Evans and Heller, 2003).

The major environmental magnetic parameters are classified based on their dependence on the magnetic mineral concentration, grain size and mineralogy.

Concentration parameters

The low and high-frequency susceptibilities (χlf, χhf), Susceptibility of Anhysteretic Remanent Magnetization (χARM) and Saturated Isothermal Remanent Magnetization (SIRM) are proportional to the amount of magnetic minerals present in the sediments.

Grain size parameters

IRM is a measure of the grain size of magnetic minerals of stable single domain size range (Thompson and Oldfield, 1986; Oldfield, 1991). The ratios of χARM /χlf, χARM/SIRM, and χSIRM/χlf are also indicators of the grain size of magnetic minerals. The higher values of χARM /χlf, χARM/SIRM indicate a fine magnetic grain size while a higher value of SIRM/χlf indicates a coarse grain size (Thompson and Oldfield, 1986; Oldfield, 1991; Walden, 1999).

Mineralogy of magnetic minerals

IRM is a function of the magnetic mineralogy and grain size (Oldfield et al., 1999). Hard isothermal remanent magnetization (HIRM) is an indicator of the concentration of remanence carrying imperfect antiferromagnets such as hematite and goethite while soft isothermal remanent magnetization (Soft IRM) are used for the calculation of total concentration of remanence carrying ferrimagnets such as Magnetite (Dekkers, 2007).

These parameters as a part of environmental magnetism is taken into account to delineate the palaeoenvironmental implication from the GRK basin two sedimentary cores was recovered from central basin and southern margin of the basin. The variation and response of sediments to the environmental magnetic parameters from both the cores are mentioned below.

DHORDO CORE

The Dhordo core is divided into three segments based on magnetic minerals concentration, magnetic grain size and magnetic mineralogy which are further explained based on chronological division.

Concentration parameters

In the Greenlandian Stage high but steady contribution from the low susceptibility magnetic mineral (χlf) ($10^8 m^3 kg^{-1}$), is noted. The χlf chart shows transition towards low magnetic mineral concentration where the value noted is 17 ($10^8 m^3 kg^{-1}$) (Figure 7.1). The bivariant chart of χlf and χARM shows the cluster of magnetic minerals between 25 – 20 ($10^8 m^3 kg^{-1}$) for χlf and between 40 – 80 ($10^8 m^3 kg^{-1}$) for χARM (Figure 7.1). The higher input of magnetic minerals shows high influx of sediments during Greenlandian Stage (Thompson and Oldfield, 1986; Oldfield, 1991). The SIRM value shows fluctuating yet steady input of magnetic minerals where the value reaches highest at the bottom of the core in Greenlandian Stage (Figure 7.).

During Northgrippian Stage the χlf shows the highest value in comparison with the entire core, this highest peak marked by χlf is also noted from the χARM and SIRM values at the same depth. Thereafter, decrease in the value of χlf and χARM is noted. Whereas the SIRM shows bell shaped chart towards the top of the Northgrippian Stage which denotes low to high magnetic minerals concertation. The Northgrippian Stage in the core ends with a marked feature where all the graphs of all the three magnetic mineral concentration parameter shows an abrupt dip in their values. This abrupt fall in the values of the magnetic mineral concentration parameters marks the end of this stage in the core.

The Meghalayan Stage in the core denotes from the lowest values noted from χlf, χARM and SIRM parameters where the values are lowest in comparison with the entire core of Dhordo. The value noted from the χlf and χARM bivariant plot shows the low concentration of magnetic minerals. This same phenomenon is noted for the SIRM parameter as well where it fluctuates towards the lower value of the concentration minerals. This transition towards the lowest value by all the three magnetic concentration parameters significantly point towards lowest occurrence of magnetic minerals. The low values of concentration parameters show low sediments influx during this stage. This is also in agreement with the establishment of aridity in the area which is also noted on global prospect (Enzel et al., 1999; Gupta et al., 2004).

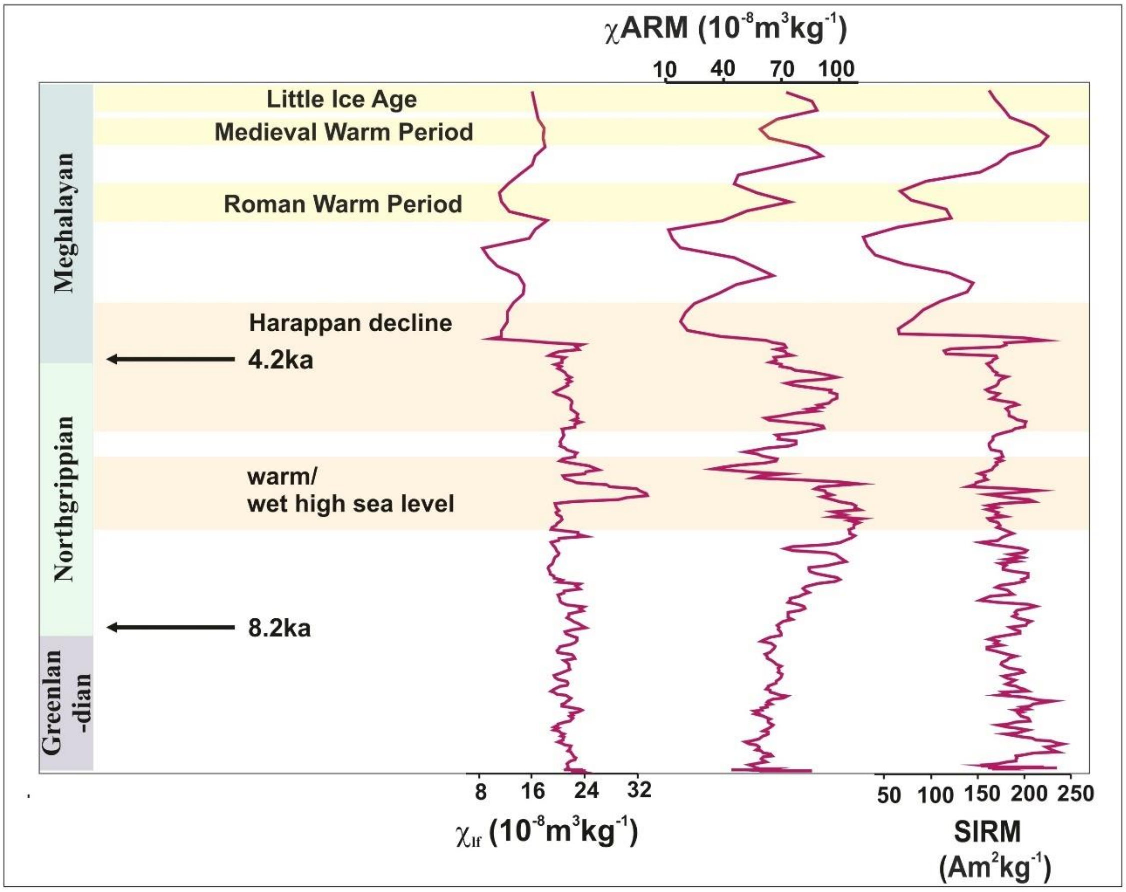

Figure 7.1. Temporal scale variability in concentration environmental magnetic parameters in Dhordo core, western India.

Grain size parameters

The Greenlandian Stage marks the transition of χARM/ χlf, χARM/ SIRM towards the high value mark donating high input of fine-grained sediments during this stage. The low value denoted from SIRM/χlf also mimics in accordance with the other magnetic grain size parameters of contributing finer size sediments during this stage.

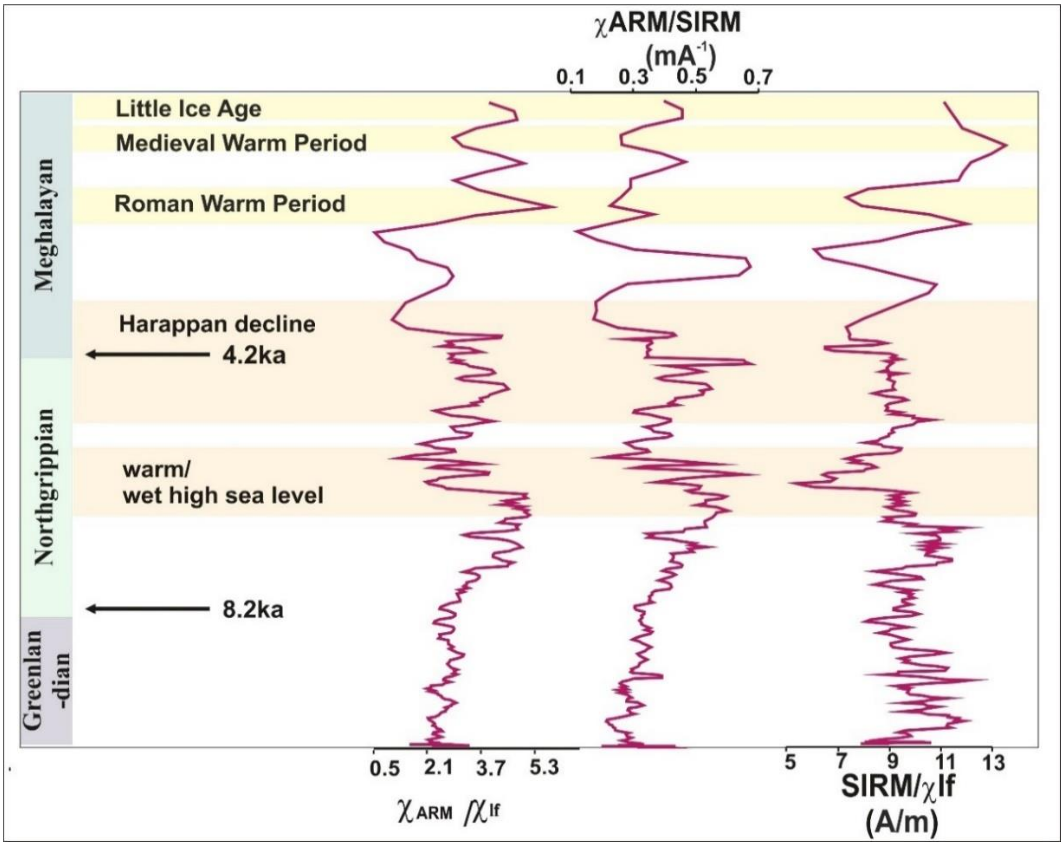

Figure 7.2. Temporal scale variability in grain size environmental magnetic parameters in Dhordo core, western India.

The Northgrippian Stage is recognised as the stage of highest fine grained sediment deposition. The χARM/ χlf, χARM/ SIRM marks the highest value, which is remarked as the highest from the entire core (Figure 7.2). The SIRM/χlf value shows opposite values in comparison to other parameter suggestive of higher input of finer grained magnetic minerals. The transition from high value to low value is also one of the marked features noted from this stage.

The lowest value of χARM/ χlf, χARM/ SIRM is noted from the Meghalayan Stage which suggests the coarser or comparative coarser grained sediments input in the area. These sediments are the result of aridity setup during this stage which is concluded from the other parameters as well during this stage. However, input of finer grained magnetic sediments is noted from the high value of χARM/ χlf, χARM/ SIRM towards the top of the core pointing occurrence of short spell of wet stage (Figure 7.2).

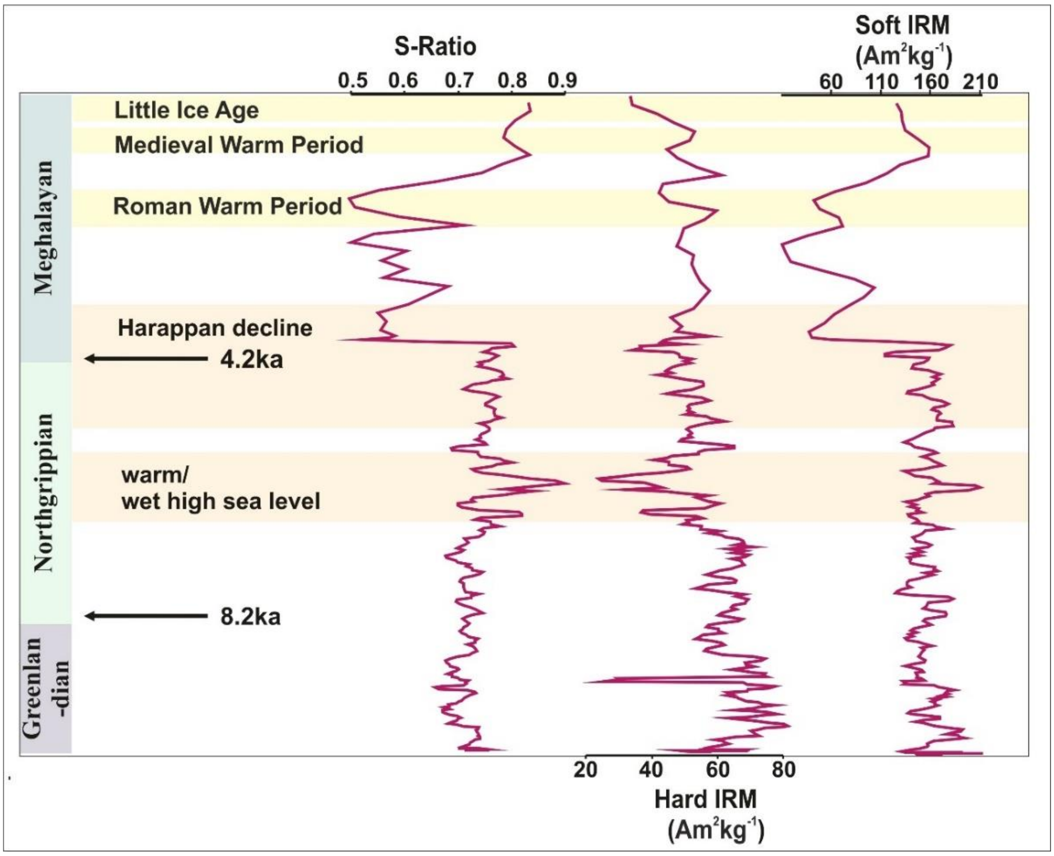

Figure 7.3. Temporal scale variability in mineralogical environmental magnetic parameters in Dhordo core, western India.

Mineralogy of magnetic minerals

The S-ratio is a parameter which denotes the mineralogical distinction based on its value, high value approaching 1.0 denotes the presence of magnetite mineral whereas value less than 0.5 denotes the presence of Hematite mineral. The S- ratio remain below 0.9 in the Greenlandian Stage denoting the presence of Magnetite minerals which is confirmed by the soft IRM ratio shows high value at the same time the Hard IRM shows low value (Figure 7.3).

The Northgrippian Stage shows absolute presence of magnetite mineral which shows high energy of deposition during this stage (Blaha et al., 2011; King et al., 1982). This core shows larger fluctuation during this stage as the highest S-ratio reading is noted from this stage at the same time the Hard IRM shows the lowest reading.

The lowest reading of s-ratio is noted from Meghalayan Stage where it plunges to the lowest point reading from the entire core (Figure 7.3). This reading of s ratio denotes the presence of Hematite minerals from this stage. This conformation of presence of Hematite is also confirmed by the reading of Hard IRM. The Meghalayan Stage is known for the establishment of aridity in the area where the presence of anhydrite like gypsum and salt crystal is quite evident. However, the reading of s ratio reaches to 0.8 from the top of the core where it denotes the presence of magnetite minerals from the Dhordo core.

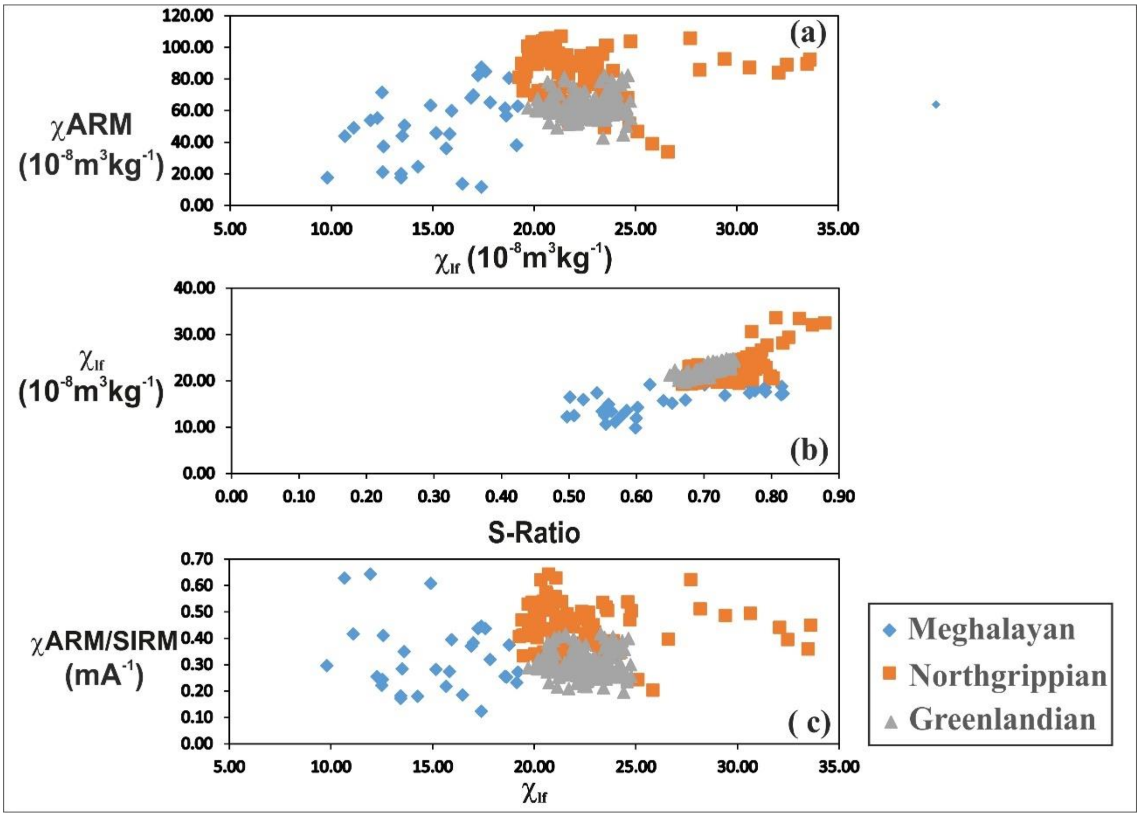

Figure 7.4. Scatter plots between a) χARM vs χlf, b) χlf vs S-ratio and c) χARM /SIRM vs χlf showing a distinction based on Dhordo chronological division.

PALAEOENVIRONMENTAL IMPLICATIONS IN DHORDO CORE

Greenlandian Stage

The Dhordo core shows a transition towards the average line mark in susceptibility with value of ~23 ($10^{-8}m^3kg^{-1}$) from ~60 - ~50 m (~10 - ~9.5 kyr BP) which coincides with the presence of thinly laminated silt present at these depths (Maurya et al., 2013, Khonde, 2013). The presence of these lamination shows the evolution of the basin under moderate energy of deposition along with persistent increasing sediment flux into the basin. The χlf values coupled with the S-ratio marks increase in the average values from ~9.5 – 9.2 kyr BP. The readings of χlf and S-ratio continues to hover around the average value mark. The cyclic relations ships between these two parameters can be noted from this stage. This stage is mainly dominated by muddy sediments texturally classified as clayey silt to silty clay (Figure. 7.4). The transition from silty clay to clayey silt shows gradually (Figure. 7.4) shift in the energy of deposition (Maurya et al., 2013). The relative increase in finer sediment flux indicated by increasing trend of χARM/SIRM (Figure. 7.4), which shows the gradual strengthening of monsoonal conditions, the S-ratio and χlf indicating a decrease in the reading pointing toward the presence of Hematite/Goethite at ~50 m which inferring lowering of the precipitation (Evans, M., & Heller, F., 2003; Basavaiah et al., 2014). χARM/SIRM and χARM/χlf shows coarse sediment input at ~58- 57 m depth indicative of the high coercivity mineral formation which is developed in the sediments during relatively dry conditions (Maher and Thompson, 1995). χARM/SIRM and χARM/χlf shows less than the average value pointing towards the coarser sediment input develop under oxidation conditions.

The increasing trend from 45 – 43 m along with increased in percentage of fine sand sediment influx is encountered upto 43 m, this marks a small spell of relatively higher energy conditions with enhancement of monsoonal conditions. (Figure. 7.5) (Evans, M., & Heller, F., 2003). The paleoclimatic record during the early Holocene reported from Lunkaransar dry lake of Thar desert reports a fluctuating monsoon during this early Holocene period (Enzel el al., 1999). A few paleoclimate records from the Arabian Sea advocated about an increase in the southwestem monsoon activity 10,000 to 9,500 years ago (Overpeak et al., 1996). Sirocko, et al., (1993) inferred that the strengthening in the monsoon winds was noted during 7500 to 8850 calendar years B.P. The record from our data shows an overall stage marking a fluctuating climate with gradual building monsoonal conditions.

Northgrippian Stage

The coupled reading of χlf and S-ratio shows a fairly constant reading which hovers around the average line (~8.3- ~7.5 kyr BP). However, the χlf and S-ratio shows peak dip in the reading which infers low value at ~8.2 kyr BP. χARM/SIRM and χARM/χlf granulometric parameter also shows lower values suggesting the coarsening of the sediments at ~8.2 kyr BP. The stage is marked by low value of χlf with an average value of ~20 ($10^8 m^3 kg^{-1}$) from ~7.5 kyr BP - ~6.5 kyr BP m, the decrease in values can also be noted in S-ratio from 30-28 which is in cyclic correlation with Hard IRM where it denotes high value from the same depth. The high value of Hard IRM reflects the dominance of anti-ferromagnetic minerals which develop due to weak monsoonal conditions during ~7.5 kyr BP. The magnetic parameter (χlf, S-ratio, Soft IRM) shows increasing trend from ~6.3 - ~6.1 kyr BP which suggests the dominant of lower coercivity magnetic minerals (magnetite), moreover the grain size parameter also shows an increase in fine sand percentage from this depth suggestive of high sediment influx (23-22 m). This depth from our core shows a rise in the energy of the depositional conditions which points an abrupt paleoclimatic/ paleoenvironmental change from ~6.1 kyr BP.

The high value of χARM/χlf indicates the finer grain size of the magnetic minerals which develop during high monsoonal conditions (Maher and Thompson, 1996). The signature of this is noted globally as high sea level and warm-wet conditions. The decrease values of S- ratios also denotes the peak downfall along with other magnetic parameters. The particle size reading suggests the depositions of sediments under low energy conditions. This stage is reported as Mature Harrapan civilisation Era, which is also reflected in our core from the same stage. Moreover, this points towards the declining of monsoonal conditions lowering of humid conditions during this stage. This stage in our data is recorded as fluctuating climatic conditions from stronger monsoonal conditions ~6 kyr BP to reducing monsoonal conditions during ~4.5 kyr BP. Our data collaborates well with pollen evidence from Himalayan region which predicts strong monsoon during mid Holocene (Phadtare, 2000). The data also synthesises with Enzel et al., (1999) suggesting the occurrence of an abrupt event around 6.3 kyr BP from Lunkaransar dry lake of Thar desert which was followed by drying up of lake at around ~4.2kyr BP. The study from Arabian sea, Gupta et al., (2003) suggested development of dry event <~5.5 kyr BP which matches well with the data from this stage.

Meghalayan Stage

The sharp decline in concentration dependent parameter χlf marks the stage of aridity. This reading of S-ratio from ~3.4 kyr BP to 2.5 kyr BP declines to the lowest (average 0.5) in comparison with entire core data reflecting the transitions from low coercivity magnetic mineral (Magnetite) to high coercivity magnetic mineral (Hematite/ Goethite). The Hard IRM and Soft IRM possesses out of phase relationship reflecting the aridity for this stage. The sediments show decrease in chemical weathering which implies the sediments to have deposited in oxidising condition (Khonde et al., 2017). The sudden increase in χlf and S-ratios is noted from 2.5 kyr BP to 1.8 kyr BP this transition from low to high values in magnetic parameter is also reflected in the partial size parameter where the increased in the fine sand percentage is noted. This section marks the Roman warm period. The fine grain magnetic parameter χARM/χlf infers the input of fine grain SD magnetic minerals confirming the input of high sediment flux in response to warm conditions. The stage Medieval warm stage and Little Ice Age (LIA) in our core covers from depth 0- 2 m is not well reflect from the magnetic parameter however the enhance in the χlf and S-ratios shows the gradual build-up of warm stage prevailed. The magnetic grain size parameter has high χARM/SIRM values (average $0.3x10^8m^3kg^{-1}$) reflecting fining of the magnetic grain size which reflect the stage of moderate humid period. Moreover, the presence of Gypsum from the top part of the core reflects the deposition of the core under dry conditions. The fluctuations in the topmost sections correlate well with the dry event, recorded globally and in the Indian subcontinent (Gupta et al., 2003; Dixit et al., 2014). The pollen analysis from the Himalayan region also suggests a gradual decrease in the monsoon strength from 4.5 kyr BP to 4 kyr BP which corelates well with the data showing aridity.

BERADA CORE

The Berada core is divided into three segments based on magnetic minerals concentration, magnetic grain size and magnetic mineralogy which are further explained based on chronological division.

Concentration parameters

In the Greenlandian Stage high to low contribution from the low susceptibility magnetic mineral (χlf) ($10^8m^3kg^{-1}$), is noted. The χlf chart shows transition towards low magnetic mineral concentration where the value noted is 17 ($10^8m^3kg^{-1}$) (Figure 7.5). The bivariant chart of χlf and χARM shows the cluster of magnetic minerals between 25 – 8 ($10^8m^3kg^{-1}$) for χlf and between 0 – 100 ($10^8m^3kg^{-1}$) for χARM (Figure 7.5). The higher input of magnetic minerals shows high influx of sediments during Greenlandian Stage. The SIRM value shows fluctuating yet steady input of magnetic minerals where the value reaches highest at the bottom of the core in Greenlandian Stage (Figure 7.5).

During Northgrippian Stage the χlf shows high value at the initiation of this stage, this high peak is also noted from the χARM and SIRM values at the same depth. Thereafter decrease in the value of χlf and χARM is recorded from the core. Whereas the SIRM reflects slow yet fluctuating minor peak towards the top of the Northgrippian Stage which denotes low to high magnetic minerals concertation (Figure 7.5).

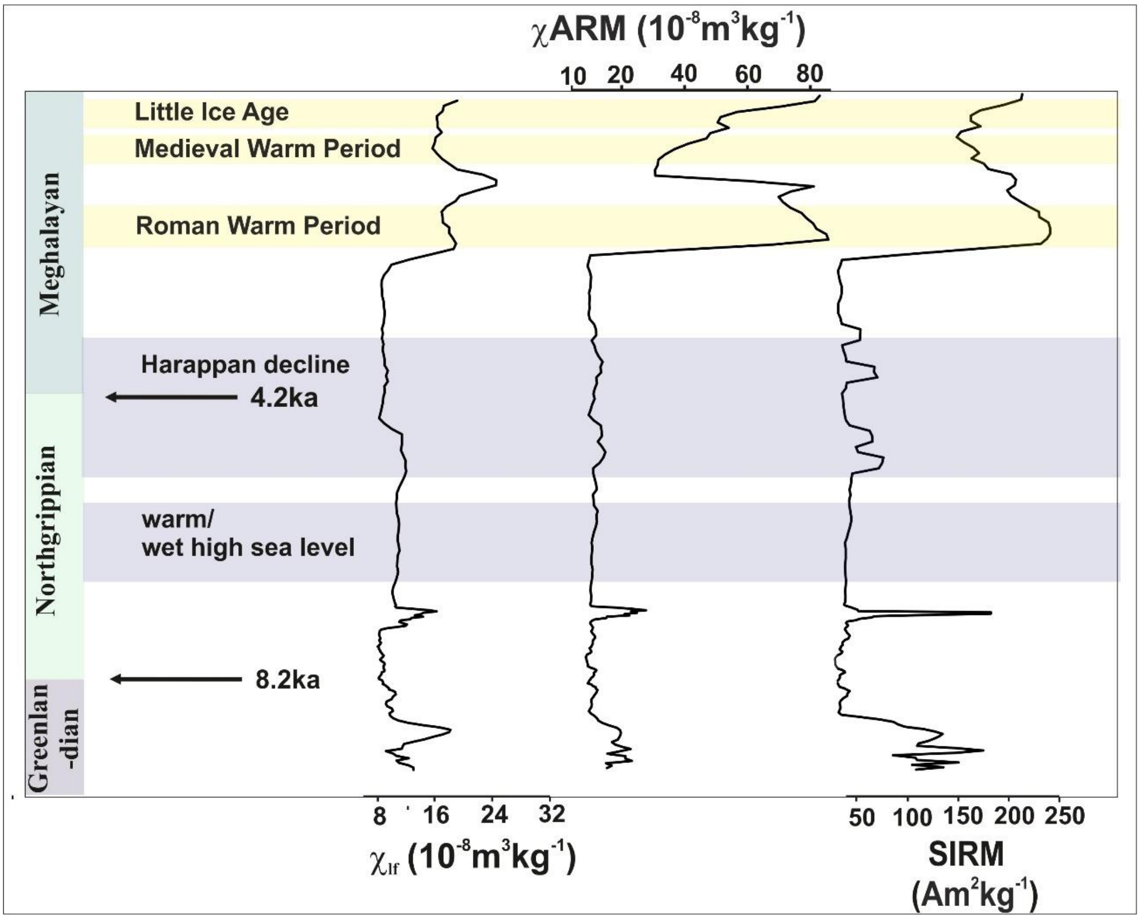

Figure 7.5. Temporal scale variability in concentration environmental magnetic parameters in Berada core, western India.

The Meghalayan Stage in the core denotes the highest values for χlf, χARM and SIRM parameters where the values notes are highest from the entire core of Berada. The value of χlf and χARM bivariant plot shows the high concentration of magnetic minerals. This same phenomenon is noted for the SIRM parameter as well, where it fluctuates towards the high value of the concentration minerals (Figure 7.5). This transition recorded from the values by all the three magnetic concentration parameter is significant in pointing towards lowest occurrence of magnetic minerals. This concludes the arguments of high sediments influx during this stage. The Meghalayan Stage in the core has a marked feature where all the graphs of all the three magnetic mineral concentration parameter shows an abrupt high peak in their values. This abrupt rise in the values of the magnetic mineral concentration parameters marks the end of this stage in the core (Figure 7.5).

Grain size parameters

The Greenlandian Stage marks the transition of χARM/ χlf, χARM/ SIRM towards the high value mark donating high input of fine-grained sediments during this stage (Figure

7.6). The low value denoted from SIRM/χlf also mimics the in accordance with the other magnetic grain size parameters contributing finer size sediments during this stage.

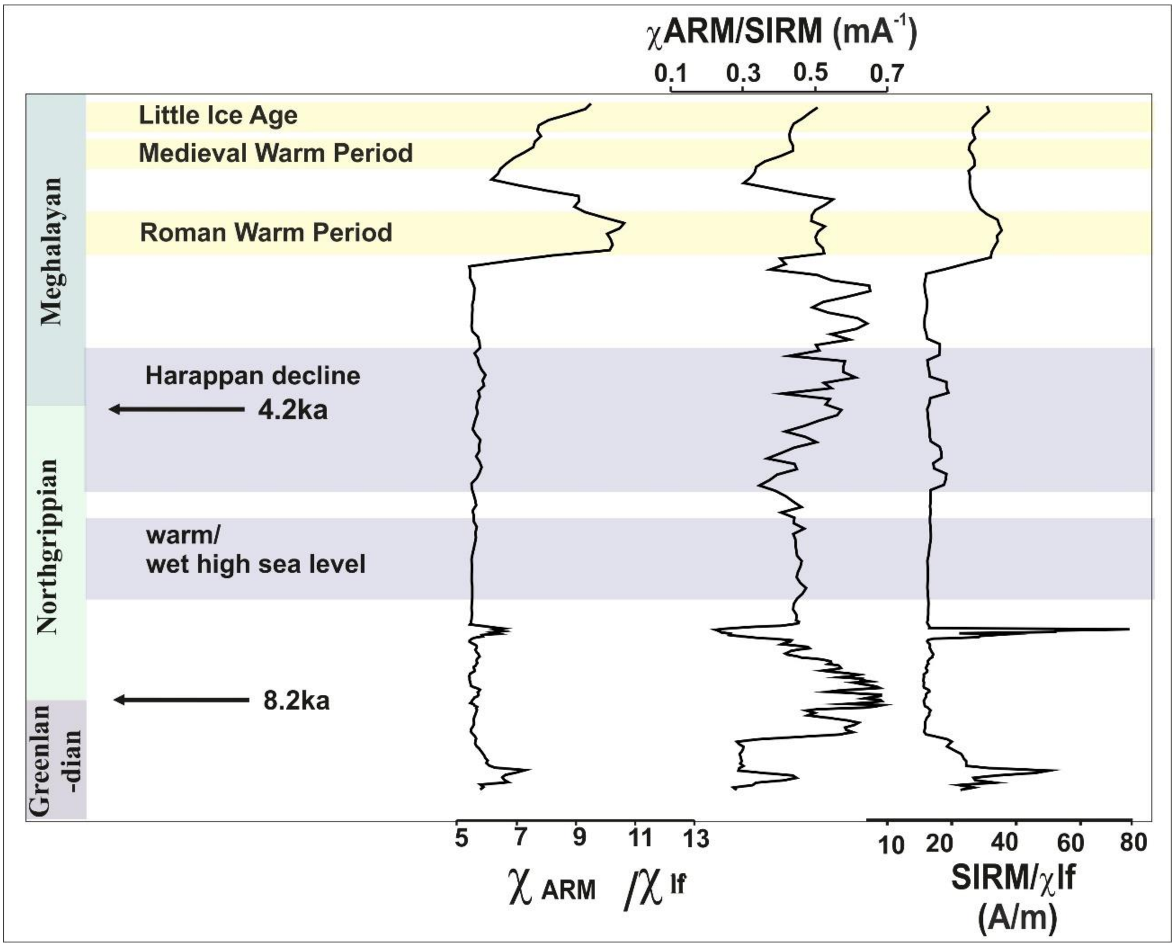

Figure 7.6. Temporal scale variability in grain size environmental magnetic parameters in Berada core, western India.

The Northgrippian Stage is recognised as the stage of highest fine grained sediment deposition. The χARM/ SIRM shows the highest value, which marks highest from the entire core. The SIRM/χlf value shows in opposite to other parameter which also suggests the higher input of finer grained magnetic minerals (Figure 7.6). The transition from high value to low value is also one of the marked features noted from this stage.

The lowest value of χARM/ χlf, χARM/ SIRM is noted from the Meghalayan Stage which suggests the coarse or comparative coarse grained sediments input in the area (Figure 7.6). These sediments are the result of high sedimentation flux during this stage concluded from the magnetic grain size parameters. However, input of finer grained magnetic sediments is noted from the high value of χARM/ χlf, χARM/ SIRM towards the top of the core.

Mineralogy of magnetic minerals

The S-ratio is a parameter which denotes the mineralogical distinction based on its value, high value approaching 1.0 denotes the presence of magnetite mineral whereas value less than 0.5 denotes the presence of Hematite mineral. The s- ratio remain below 0.9 in the Greenlandian Stage denoting the presence of Magnetite minerals which is confirmed by the soft IRM ratio which shows high value at the same time the Hard IRM shows low value (Figure 7.7).

The Northgrippian Stage shows absolute presence of magnetite mineral which shows high energy of deposition during this stage (Blaha et al., 2011; King et al., 1982). This core shows larger fluctuation during this stage as the highest S-ratio reading is noted from this stage at the same time the Hard IRM shows the lowest reading.

The low reading of S-ratio is noted from Meghalayan Stage, where it plunges to the lowest point reading from this stage (Figure 7.7). This reading of S- ratio denotes the presence of Hematite minerals from this stage. The presence of Hematite is also confirmed from the reading of Hard IRM. The Meghalayan Stage is known for the establishment of aridity in the area where the presence of anhydrite like gypsum and salt crystal is quite evident. However, the reading of S-ratio reaches to 0.8 from the top of the core where it denotes the presence of magnetite minerals from the Berada core.

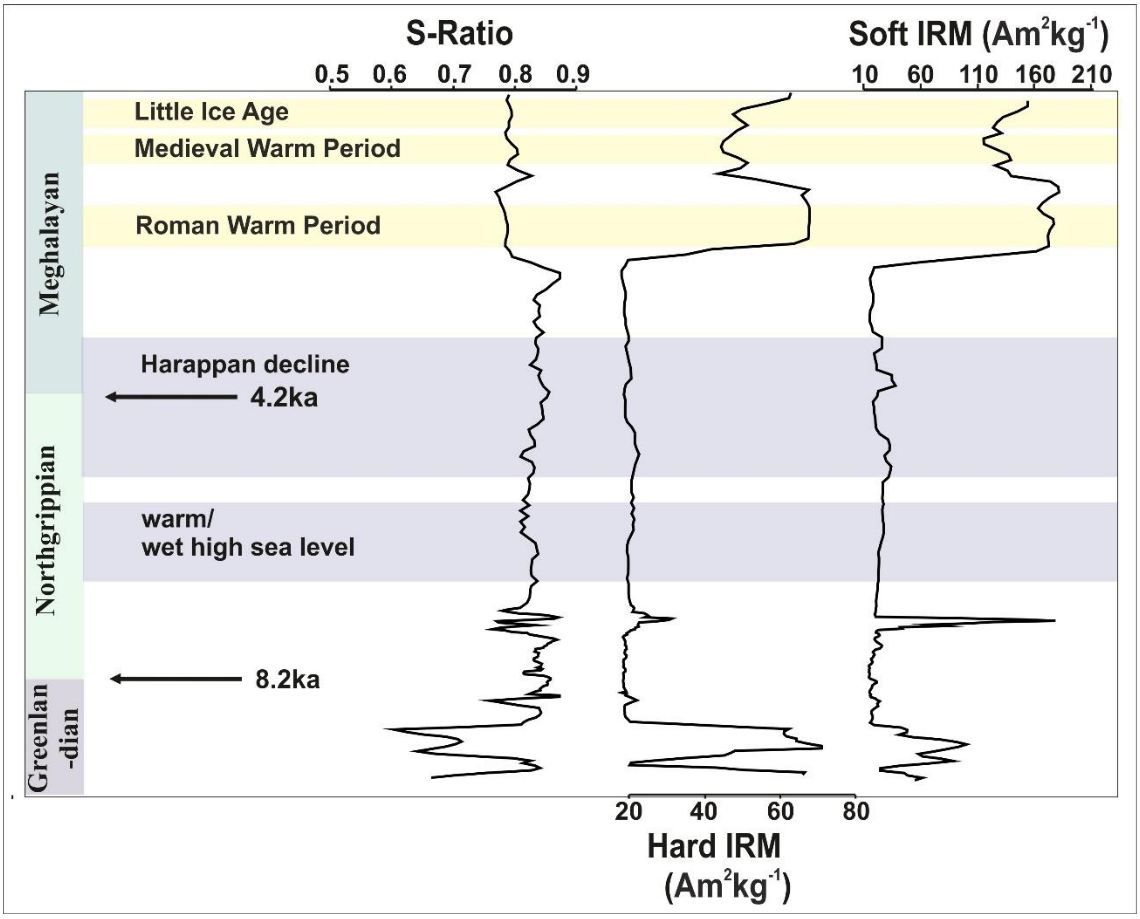

Figure 7.7. Temporal scale variability in mineralogical environmental magnetic parameters in Berada core, western India.

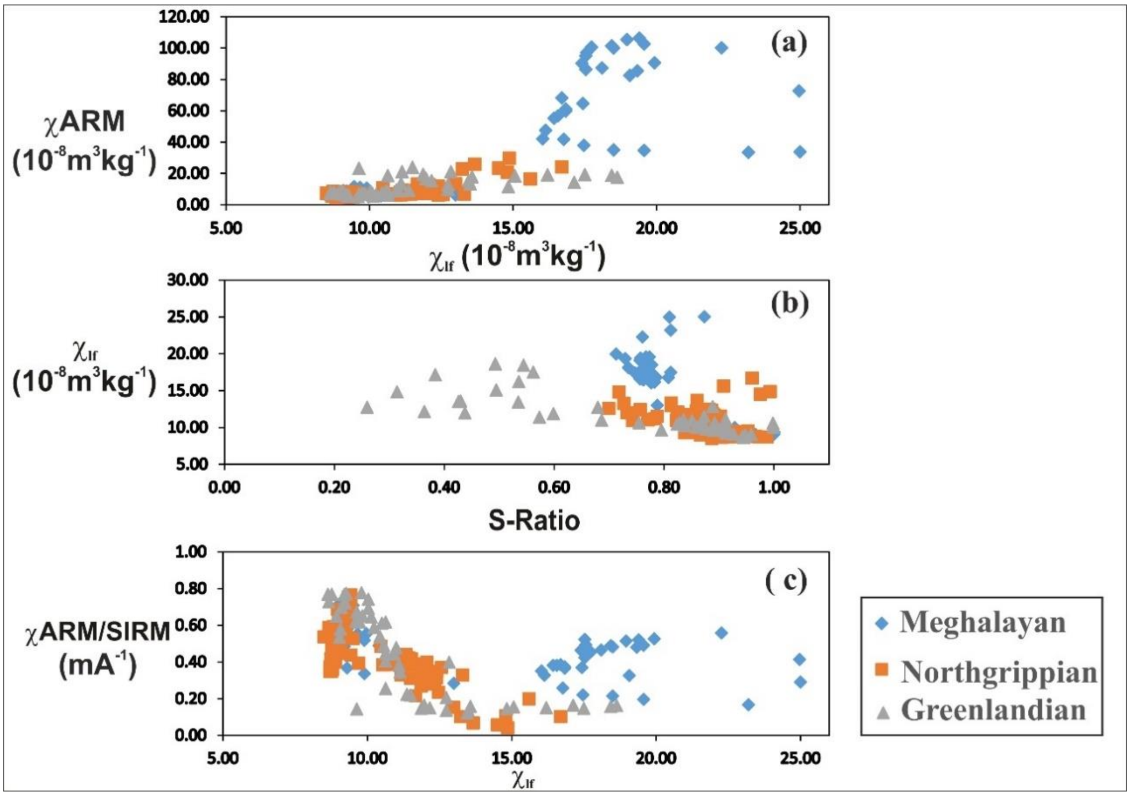

Figure 7.8. Scatter plots between a) χARM vs χlf, b) χlf vs S-ratio and c) χARM /SIRM vs χlf showing a distinction based on Berada chronological division.

PALAEOENVIRONMENTAL IMPLICATIONS IN BERADA CORE

Greenlandian Stage

The core during this stage (~9.7 - ~8.8 kyr BP) from 40 to 35m marks moderate to lower values of S-ratio <0.7, however the χlf values are in contrast with the S-ratio values. This contradiction could further be explained upon the trend of hard IRM which has a peak in the reading confirming the presence of hematite/goethite magnetic minerals (Thompson and Oldfield, 1986). This interpretation is reinforced by the presence of a heterogeneous magnetic granulometric state (from smaller to coarser ferrimagnetic particles) and increase of the hard fraction, likely due to the presence of hematite. The presence of high coercivity hard minerals advocated the input of terrigenous against biogenic element which marks the core location to be more towards the landward part of the estuarine/marshy land during this stage and experienced high tide influence reaching beyond the study area.

Peak at around ~7.5 kyr BP, noted in χlf and S-ratio reflects the input of ferrimagnetic minerals. Furthermore, highest peak noted from soft IRM coupled with high peak in χARM advocates the input of finer ferrimagnetic mineral grains. The sedimentation in the core (40 to 30 m) experienced fluctuating yet consistent monsoonal condition. The Greenlandian is considered as a stage of stronger monsoon (Gupta et al., 2003). Overall, the stage marks a fluctuating climate but gradual building monsoonal conditions and input of finer sediments. The values of S-ratio are between 0.8 and 0.9 suggesting the moderate influx of finer sand sediments, this may be in response to gradual build-up of monsoon during 8.5 to 7.5 kyr BP (Sanker et al., 2006; Warrier et al., 2011). The paleoclimatic record during the Greenlandian Stage reported from Lunkaransar dry lake of Thar Desert reports fluctuating monsoon (Enzel et. al., 1999). Paleomonsoonal records from the eastern Arabian Sea (Off Makran margin) also showed increase in the southwestern monsoon activity - 10 000 to - 9,000 years ago (Overpeck et al., 1996; Thamban et al., 2002; Khonde et al., 2017a). Sirocko et al (1993) inferred that the strengthening in the monsoon winds was noted during 7500-8850 calendar years BP. The record from our data shows wetter spell during the 10.6 to 10 kyr BP followed by a dry spell during 10-9 kyr BP. Whereas the strengthening monsoonal conditions initiated after 9-8 kyr BP where our records mark the mineralogical changes occurred due to the wetter climate.

Northgrippian Stage

The mineral magnetic concentration (χ_{lf}) shows consistent yet transition towards the average value line coupled with S-ratio, SIRM, χARM and SIRM/χlf data which also marks above average value mark from 27- 20 m indicating enrichment in weathering and high sediment flux (Evan and Heller, 2003). The magnetic signature in this stage indicated high and strong monsoonal condition. The granulometric parameter χARM/SIRM shows transition towards higher value demonstrating the input of finer magnetic minerals in an enhanced monsoonal condition. The Northgrippian Stage is known for high increase in precipitation. Other reported palaeoclimatic studies from the Banni plain also marks the stage to be affected by increase in the monsoonal conditions (Juyal et al., 2006). The strong monsoon precipitation during early mid Holocene is noted from the Thar desert (Singh et al.,1990; Roy and Singhvi., 2016). Our data also collaborates pollen evidence from Himalayan region which predicts strong monsoon during mid Holocene (Phadtare, 2000).

Meghalayan Stage

The S-ratio shows decreasing trend along with χARM/SIRM and with the increment in hard IRM pointing towards the input of hematite/goethite of coarser nature. The presence of gypsum from the top core of Berada evident of deposition under arid condition. The sediments show decrease in chemical weathering which implies the sediments to have deposited in oxidising condition (Khonde et al., 2016). The particle size shows the coarsening towards the top part of the core in response to the regressive phase of the sea. The fluctuations in the topmost sections correlate well with the dry event, recorded globally and in the Indian subcontinent (Gupta et al., 2003; Dixit et al., 2014). This change correlates with the drying up of lakes reported from the Thar Desert (Dixit et al., 2014) and mainland Gujarat (Prasad et al., 2014a) at around - 4.2 kyr BP, whereas slightly it differs with Enzel et al. (1999). Moreover, 4.2 kyr BP event is well established arid event that is observed throughout the globe (Staubwasser et al., 2003; Railsback et al., 2018; Bini et al., 2019).