CHAPTER 6

SOLAR FORCING OF LATE HOLOCENE CLIMATIC RECORDS FROM ACTIVE MUDFLATS OF SAURASHTRA

6.1 Sun and Climate

Sun being the primary source of energy drives the Earth's climate. Role of Sun in climatic variability was first speculated by (Herschel, 1800). Detailed study dealing with the comparison of solar activity inferred from sunspots and earth's climatic history on centennial time scale during last millennia indicated good correlation and resulted in the famous hypothesis of sun-climate relationship (Eddy, 1976). A striking similarity between the solar activity and globally averaged sea surface temperature over the past 120 yr (SST) was identified (Reid, 1987) and it was suggested that any alteration in the solar radiation can potentially cause climate change (Frohlich and Lean, 1998). The association between sunspot cycles, occurrence of aurorae, geomagnetic storms and weather pattern led to the establishment of sun-climate relationship in the latter part of 19th century (Hoyt and Schatten, 1997). The high solar activity results in enhanced solar irradiance, lower cosmic ray fluxes, increased geomagnetic activity, higher incidence of lower-latitude aurorae and vice versa (Gray et al., 2010).

Various studies investigated the inter-relationship between the solar activity and climate (Agnihotri et al., 2002; Velasco and Mendoza, 2008; Feulner, 2012). It has been suggested that a small variation in solar activity on centennial or multi decadal time scales coupled with various feedback mechanisms, such as variations in water vapour budget, ice cover, albedo etc. can have cumulative effect, thereby resulting in significant changes in regional climate (Mehta and Lau, 1997; Beer et al., 2000).

6.2 Total Solar Irradiance (TSI)

Prior to the launch of satellites, it was thought that the solar energy received by the top of earth's atmosphere was constant (Solar Constant), and small variations in incoming radiation were difficult to detect due to the presence of atmosphere. However, since 1978 the radiometers sent in space revealed that there exist variations in the solar constant values (Ramesh, 2007). The Total Solar Irradiance (TSI) also known as the Solar Constant (SC) is defined as the total radiant power passing through a unit area at Earth's mean orbital distance of 1 astronomical unit and is represented as Watts per square meter (W/m^2). The solar irradiance is also expressed in calories per square centimetre per minute. The present day TSI is about 1367 W/m^2, with an uncertainty of about 4 W/m^2 (Hoyt and Schatten, 1997). An increase of 1.3 W/m^2 (0.1%) in the total irradiance levels has been recorded by the Space-based solar monitoring system during the 1980 and 1990 maxima of the Sun's 11-year activity cycle relative to activity minima of 1986 and 1996 (Willson and Hudson, 1991; Lean, 1997).

The historical records of solar activity complement the instrumental records of TSI variability. The sunspot records date back to 1610 AD and the combination of the 11-year Schwabe cycle along with the longer cyclic patterns in solar activity such as the Gleissberg cycle of ~80–90 years can be seen in the historic records (Engels and van Geel, 2012). Other than this, proxy records also revealed Suess cycle of 208 years and longer cycle of 2300 year known as Hallstatt cycle (Mayewski et al., 1997). Several periods of low solar activity such as the Oort Minimum (980–1120 AD), Wolf Minimum (1282–1342 AD), Sporer Minimum (1416–1534 AD), Maunder Minimum (1645– 1715 AD) and Dalton Minimum (1795–1820 AD) resulted due to the combined effect of various cycles mentioned above. It is interesting to note that the Sporer and Maunder Minimum period of reduced solar activity coincided with the colder climate of the northern hemisphere which is known as LIA (Engels and van Geel, 2012).

6.3 Past climatic proxies and solar forcing

There exists a correlation between the solar cycle and related activity with the Earth's global climate and temperature (Friis-Christensen and Lassen, 1991; Parker, 1999; Lean and Rind, 2001; Tan et al., 2004). It has been established that changes in solar activity were responsible for the variability in the Holocene sub-tropical monsoon on decadal and centennial timescales (Knudsen et al., 2011). However, the strength and nature of the sun-climate link still remains to be assessed. During the Holocene, the influence of solar activity on surface hydrographic conditions of North Atlantic was observed by Bond et al. (2001). The synchronous variation of Total Solar Irradiance (TSI) with monsoonal records helps in assessing the role of solar forcing on climate (Agnihotri et al., 2002). The records of $\delta^{13}C$ of peat used as humidity and precipitation proxy from the north eastern China for the last 6000 yr BP revealed significant climate shifts with severe droughts that coincided with the solar maxima (Hong et al., 2001). Spleothems have been effectively used as a continental archive capable of providing long spanning high resolution climatic records. Study based on subtropical speleothems indicate that the spectral density distributions of stable oxygen isotope in speleothem exhibit a significant ~210 yr cyclicity which coincides with the three Suess solar-cycle bursts viz. 1850–3200 BP, 4500–5700 BP and 7750–8850 BP when particularly ~210 yr solar cycle was strong (Knudsen et al., 2009; Knudsen et al., 2011). As it is difficult to get an undisturbed continental archive, usually coastal and off shore marine cores are studied. The off shore marine sediment cores are considered to be undisturbed and can provide a continuous records of climate. The coastal core off Sri Lanka coast suggests presence of TSI periodicities of ~20 ~28–32, ~64, ~100, ~128, ~192, ~256 yr based on wavelet analysis of the detrended multiproxy records and it was concluded that similar forcing mechanism affects both Indian Summer and winter monsoon, as their variability is statistically similar (Ranasinghe et al., 2013).

Research shows that the climate over the Indian subcontinent is largely influenced by the changes in the solar irradiance (Gupta et al., 2005). Paleoclimatic reconstruction based on the productivity proxies for last millennia from the south eastern Arabian Sea indicated existence of a strong coupling between surface productivity, TSI and monsoon intensity (Agnihotri et al., 2002). A multiproxy study on the marine sediment core raised from the south-eastern Arabian Sea indicated that both the Indian summer monsoon precipitation and the solar activity has declined since the mid-Holocene (Tiwari et al., 2015). To ascertain recent climatic perturbations, instrumental records of rainfall have been frequently used in addition to the proxy based studies. Studies based on the instrumental records of the Indian monsoon rainfall and the sunspot activity suggest that there exists significant positive correlations between the sun spot activity during the period between 1871–2000 AD. Moreover, the FFT (Fast Fourier Transform) and wavelet analysis of the southwest monsoon variability also showed the periods 2.7, 16 and 22 years, similar to the period found in the sunspot occurrence data (Hiremath and Mandi, 2004).

6.4 Solar forcing on the Climatic Records from the Saurashtra Mudflats

As Sun plays a vital role in monitoring the global climatic variability, the tropical region is expected to be significantly influenced by the variations in the solar irradiance. Though, there are several paleoclimatic studies indicating the sun-climate relationship, there remains a paucity for the response of mudflats towards the changing TSI. The present study provides an opportunity to ascertain the response of climatic signatures embedded in the mudflat with the variations in the solar irradiance during the past few thousand years. In view of this, the paleoclimatic records from various proxies of the mudflats have been analysed, processed and compared with the TSI records for the last 2 ka to obtain respective periodicities.

6.4.1 Influence of Solar Forcing during last 2 ka

Enhanced TSI results in warm and humid conditions along with increased monsoonal activity, which in turn enhances insitu productivity (Agnihotri et al., 2003) and weathering (Warrier and Shankar, 2009). The sediment core raised from the active mudflats of Rohisa (RH) provides a climatic history of last 2000 yr BP. The region is drained by ephemeral rivers that may induce significant variability (enhancement/ decline) in any of the proxies and thereby reflecting change in the monsoonal activity. The only ephemeral river draining this region is the Malan River which gets activated during the southwest monsoon.

The sample resolution of Rohisa core is ~50 yr. In order to study the response of mudflat towards the solar forcing, the annually averaged TSI data (50 point running average) (Steinhilber et al., 2009) was compared with productivity, weathering and detrital proxies (Fig. 6–1). Any marginal fluctuation in the TSI results in alteration of the monsoonal variability (Agnihotri et al., 2011), which in turn will affect the detrital flux in the study area and is expected to reflect in respective climatic proxies.

In the present study, the productivity and weathering proxies in Rohisa follow similar trend to that of TSI (Fig.6–1). As mentioned in the previous chapter (Chapter-5), based on the proxy data it was observed that warm and humid conditions persisted in the region with enhanced productivity and weathering proxies during 1969–1546 cal yr BP and 1546–503 cal yr BP, corresponding to RWP and MWP respectively. During last 200 yr BP, however, warm condition persisted with enhanced productivity but with reduced detrital and weathering proxy and the period is known as MW period.

The climatic proxies when compared with the TSI data (50 pt. running average) shows evidence of high productivity and weathering with enhanced TSI, but with a decreasing trend from 1969–1546 cal yr BP (Fig. 6–1). This was followed by a marginal increase with a simultaneous enhancement in the TSI between 1546–503 cal yr BP. However, after 800 cal yr BP, a gradual decrease in the proxies and the TSI has been observed. The period between 1546 and 503 cal yr BP corresponds to MWP. It has been suggested that the global MWP persisted due to the enhanced TSI during 1142–1201 AD (Jirikowic and Damon, 1994; Velasco Herrera et al., 2015). Therefore, the warm and humid conditions during the MWP probably resulted due to the solar forcing as indicated by the TSI records. After 503 cal yr BP a gradual increase in the TSI has been evidenced which correlates well with the detrital proxy with a decline in the weathering and productivity (Fig. 6–1). This period corresponds to LIA and as indicated by the detrital proxy enhanced monsoon persisted with reduced weathering and productivity proxy suggests absence of warming conditions. Therefore, during LIA cool and humid conditions persisted in the region. A similar cool and humid climatic conditions during LIA has also been observed at Pinder valley, Kumaon, higher Himalaya (Rühland et al., 2006).

During LIA, though, there was gradual increase in the TSI, the western disturbance might have been dominant resulting in enhanced winter precipitation in the region. Such enhanced winter precipitation due to increased western disturbances has been assessed by stable isotope based study of stalagmite from Kumaun Lesser Himalaya (Kotlia et al., 2012).

A paleoproductivity reconstruction for the last millennia using Arabian Sea core suggests significant role of TSI in monitoring the overhead productivity in the region (Agnihotri et al., 2002). Based on synchronous trend being followed by the proxies and the TSI, it may be deduced that TSI might have played a significant role in monitoring the monsoon activity and in–situ productivity of the region. During LIA, the western disturbances were more prominent due to the southward shift of ITCZ (discussed in chapter-5).

6.4.2 Spectral Analysis

Paleoclimatic time series records are unevenly spaced and to obtain the periodicities embedded in these records, spectral analyses are carried out to decipher information on the role of solar forcing in the paleoclimatic processes.

In the present study, the spectral analysis was performed using the package called SPECTRUM (Schulz and Stattegger, 1997), which provides the power spectrum in unevenly spaced time series using Lomb-Scargle algorithm. The dominant periodicities in the time series can be determined by this algorithm. However, as the spectral powers in smaller periodicities are less and are masked by the higher periodicities. In order to extract the smaller periodicities that are central to this study, the higher (cut off periods for DV and RH were >1500 yr and >800 yr respectively) periodic components in the output power spectra are removed using FFT filtering method and time-domain reconstruction is done. The reconstructed time series are again subjected to spectral analyses. By adopting this method, the lower periodicities can be brought out by suppressing the spectral powers in the higher periodic components.

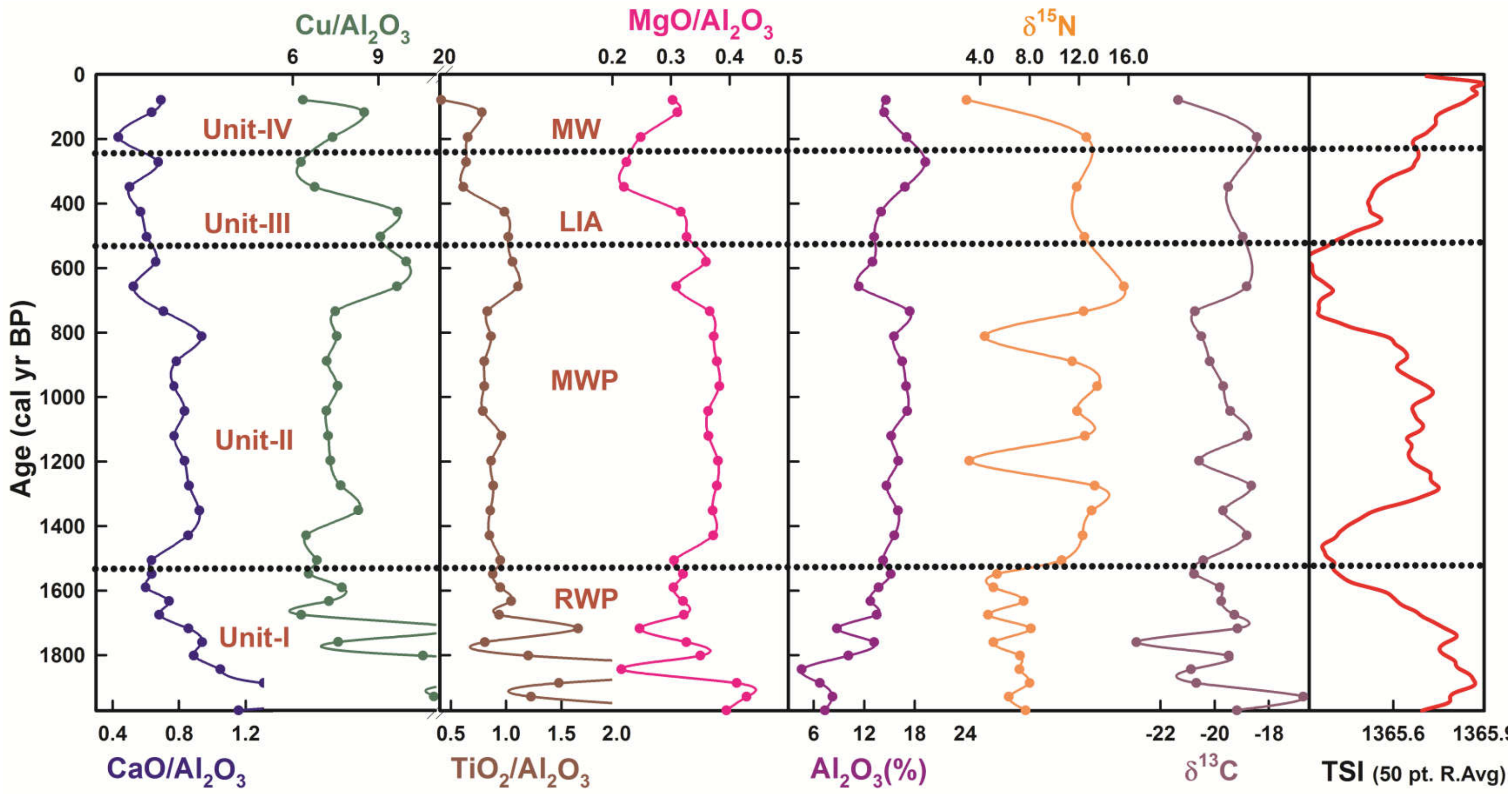

Figure 6-1.Comparison of detrital, productivity and weathering proxies with TSI (50 yr running average) for the Rohisa active mudflat sediment core (RH) during last 2000 yr BP.

The spectral analysis of time series of detrital, weathering and productivity proxies for both the active mudflats were performed on raw data (unsplined data) which was further detrended using Table Curve 2D v5.

I. Diu Active Mudflat

The Diu active mudflat recorded a climatic history of last 4000 yr BP. The sample resolution between 0–41 cm is ~140 yr/sample and between 41–70 cm is 43 yr/sample. The spectral analysis of productivity and weathering proxy of Diu active mudflat mainly show two periodicities viz. 1037 yr and 2075 yr respectively (Fig. 6–2). Other periodicities were not significant due to the masking. Therefore, detrending of the proxy data was carried out with the help of Table curve so that lower periodicities can be resolved. The periods >1500 yr were considered as cut off.

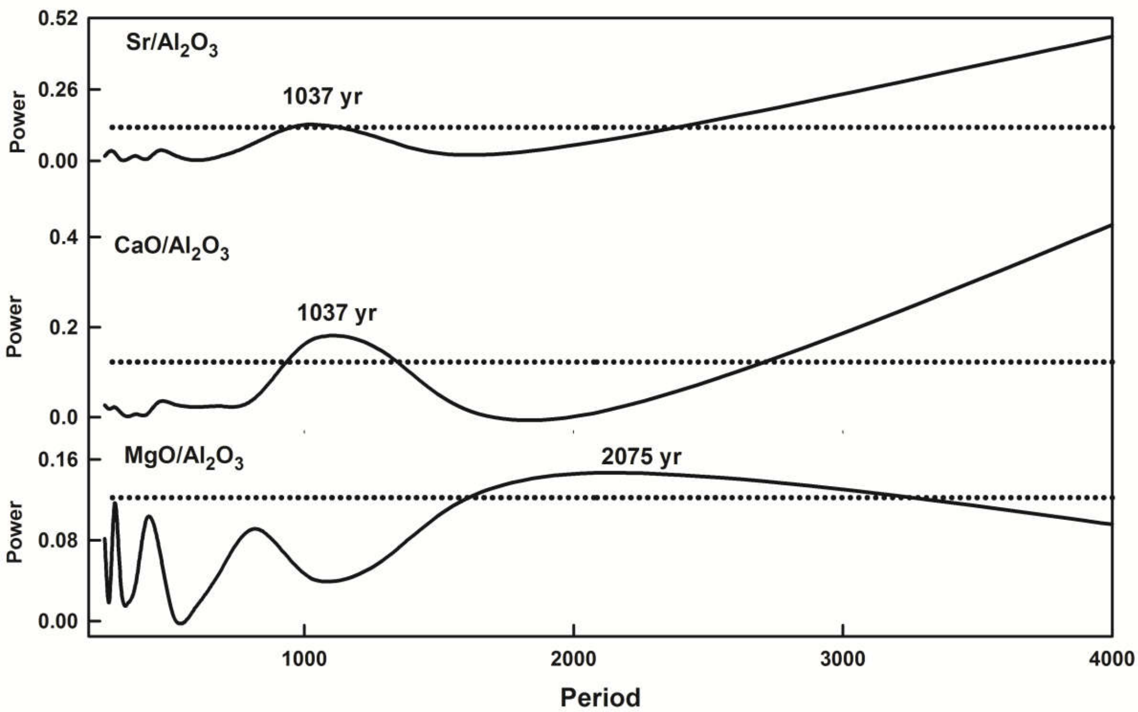

Figure 6-2. Spectral analysis of non–detrended productivity and weathering proxy of partially active Diu mudflat (DV).

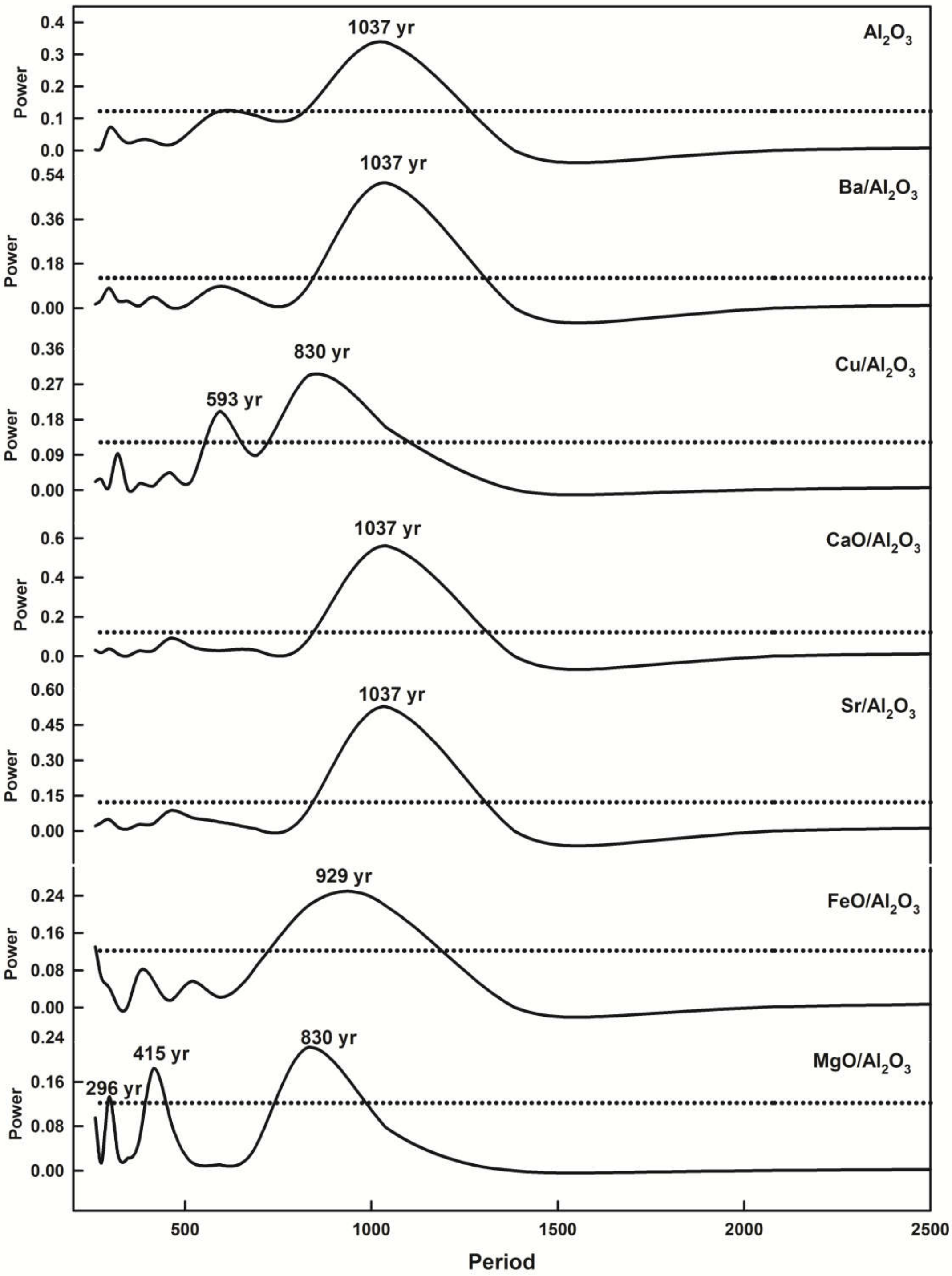

Figure 6-3. Major periodicities after detrending the detrital, productivity and weathering proxy data for the sediment core DV from partially active mudflat of Diu.

After detrending various paleoclimatic proxies of the Diu active mudflat (detrital, weathering and productivity), 1037 yr periodicities became significant in CaO/Al_2O_3, Sr/Al_2O_3, Ba/Al_2O_3 and Al_2O_3 (Fig. 6–3). The 830 yr periodicities have been displayed by both MgO/Al_2O_3 and Cu/Al_2O_3 (Fig. 6–3) while 593 yr and 415 yr periodicities are found in Cu/Al_2O_3 and MgO/Al_2O_3 respectively. Moreover, the lowest periodicity of 296 yr is indicated by MgO/ Al_2O_3.

II. Rohisa Active Mudflat

The Rohisa active mudflat has archived a climatic history of last 2000 yr BP. The sample resolution of the Rohisa sediment core is between 0–39 cm is ~75 yr/sample and between 39–60 cm is ~43 yr/sample.

The spectral analysis of the detrital, productivity and weathering proxies were carried out for the Rohisa sediment core. The spectral analysis of Al_2O_3, Al_2O_3 normalised Ba and MgO indicated a prominent periodicity of 651 yr, while 162 yr periodicity is shown by TOC/TN. Likewise, 875 yr periodicity has been indicated by CaO/ Al_2O_3 (Fig. 6–4). In order to resolve the lower frequencies (age^{-1}), the detrending of the proxy data was carried out.

The period >800 yr was considered as cut off periods. After detrending, periodicities of 651 yr, 177 yr and 370 yr became significant in the TOC/TN spectrum (Fig. 6–5).

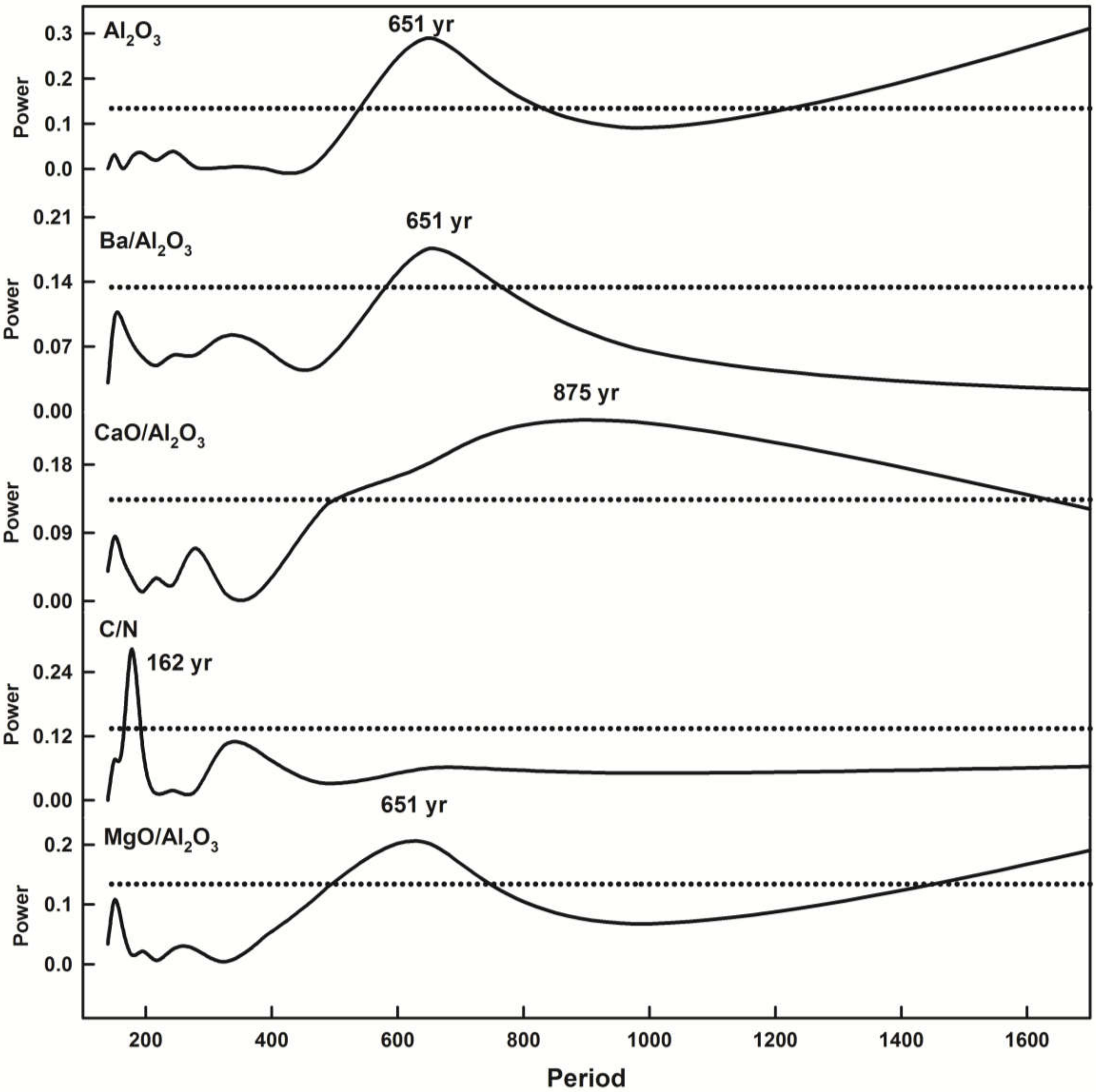

Figure 6-4. Spectral analysis of detrital, productivity and weathering proxies for Rohisa sediment core during last 2000 yr.

6.5 Evidences of solar forcing from active mudflats of southern Saurashtra

Sun playing a vital role in monitoring global temperature and climate, is amply suggested by previous studies showing strong interlinking between monsoon and TSI with the help of various proxies (Hong et al., 2001; Gupta et al., 2005; Agnihotri et al., 2011; Ranasinghe et al., 2013). However, the present study is an attempt to ascertain the response of tropical mudflat towards the TSI variation. The climatic history of last 2000 yr BP of Rohisa mudflat has shown that the productivity and weathering in the region has responded in accordance with the changes in the TSI. The warm and humid conditions during RWP and MWP in the region resulted due to increased TSI.

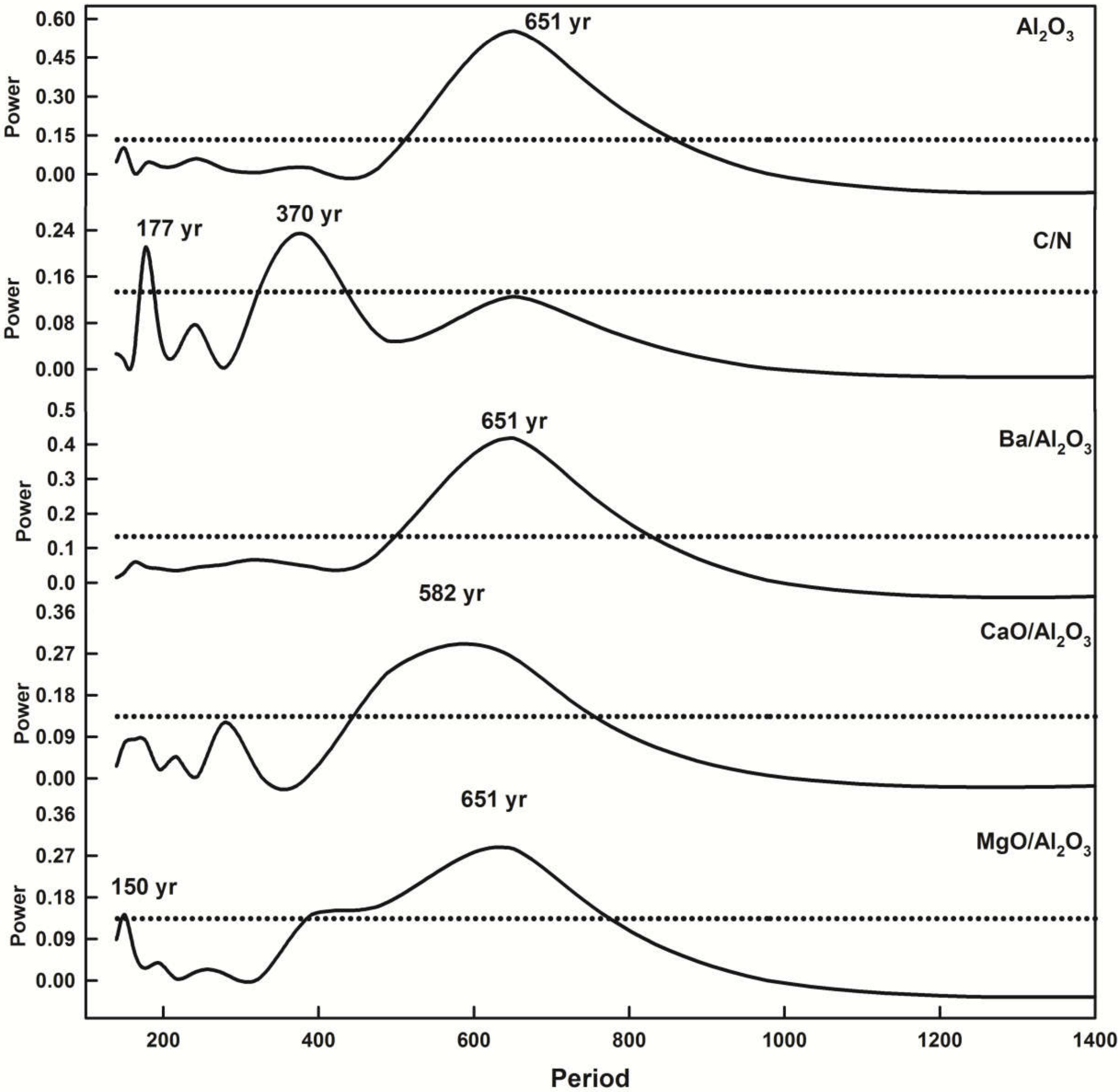

Figure 6-5. Spectral analysis of the de–trended terrestrial, productivity and weathering proxies for the Rohisa sediment core during last 2000 yr.

However, increased influence of western disturbance during LIA masked the gradual increasing trend of TSI and hence resulted in to winter precipitation in the region. Solar forcing during the MWP has been observed by various studies (Agnihotri et al., 2002).

Table 6-1. Solar Periodicities obtained from non-detrended and detrended climatic proxies for active mudflats of southern Saurashtra coast (RH and DV).

Sr No.	Proxy	Periodicities (yr)
Rohisa sediment core-RH		
1.	Al_2O_3	651
2.	TOC/TN	162, 177, 370
3.	Ba/Al_2O_3	651
4.	CaO/Al_2O_3	582, 871
5.	MgO/Al_2O_3	150, 651
Diu sediment core-DV		
6.	Al_2O_3	1037
7.	Ba/Al_2O_3	1037
8.	CaO/Al_2O_3	1037
9.	MgO/Al_2O_3	296, 415,830, 2075
10.	Cu/Al_2O_3	593, 830
11.	FeO/Al_2O_3	929
12.	Sr/Al_2O_3	1037

The spectral analysis of two of the active mudflat from Rohisa and Diu revealed prominent solar periodicities of 162 yr, 296 yr, 370 yr, 415 yr, 651 yr and 1037 yr. Periodicities of ~ 250 yr and 125 yr are comparable to those of the present study and have been identified from the varved sediment off Karachi coast which indicate that the solar variability played a significant role in controlling the monsoonal activity in the region (Von Rad et al., 1999). Likewise, the $\delta^{13}C$ of peat from northeastern China showed various solar periodicities similar to the presence study such as 162 yr, 278 yr, 389 yr, 467 yr, 834 yr and 1060 yr (Hong et al., 2001). Therefore, it may be concluded that the mudflats of southern Saurashtra have responded well towards the changing solar irradiance.