CHAPTER 6

Abrupt weakening of the Indian summer monsoon ~4.3 kyr BP: Collapse of the Indus Valley civilization

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6.1 Introduction

Climatic variability has been regarded as a major driving factor in the growth and decline of societies in the historical past. Numerous civilizations achieved peak of their socio-economic, cultural and technological advancements during persistent moist and climatically conducive intervals (Weiss et al., 1993; Matthews et al. 1999; Cullen et al., 2000; deMenocal, 2001; Staubwasser et al., 2003; Zhang et al., 2008; Buckley et al., 2010; Day et al., 2012; Lachniet et al., 2012; Ziegler et al., 2013). Abrupt climatic variability and long dry spells caused widespread famines that devastated agriculture, inducing cultural adaptations, migrations or even collapse of civilizations (Weiss et al., 1993; Enzel et al., 1999; Dixit et al., 2014). The Holocene interval has witnessed repeated occurrences of abrupt centennial to millennial scale climatic variability which were aligned with changes in solar insolation (Bond et al., 1997; Agnihotri et al., 2002; Wang et al., 2005), sea surface temperatures (Kumar et al., 2006; Mohtadi et al., 2014), atmospheric circulations (Fleitmann et al., 2003; Gupta et al., 2003), volcanism (Bay et al., 2004; Miller et al., 2012), and concentration of atmospheric CO_2 (Manabe et al., 1990; IndermuÈhle et al., 1999).

The late Holocene is marked by one of the widely recorded 4.2 ka event that coincides with a long arid phase in the Indian subcontinent. The abrupt weakening of global monsoon at 4.2 kyr BP caused prolonged droughts all over the world coinciding with the downfall of the Akkadian Empire in Mesopotamia (Weiss et al., 1993; Cullen et al., 2000), Old kingdom in Egypt (Drysdale et al. 2006), the early Bronze Age civilizations in Greece (Drake, 2012), early civilization in North America (Booth et al., 2005), Yangtze civilization in China (Yasuda et al., 2004) and Indus-Harappan civilization in the Indian subcontinent (Staubwasser et al., 2003; Dixit et al., 2014).

The Harappan also known as Indus-Sarasvati civilization was the most extensive and developed among the ancient civilizations that exhibited well planned architecture, water storage, urban sewage system, scripture, agriculture and marine trade (Possehl et al., 1997; McIntosh, 2008; Giosan et al., 2012). The mysterious demise of such an advance culture is generally attributed to socio-economic strife (Possehl et al., 1997; Madella and Fuller, 2006; Vahia and Yadav, 2011) and climatic deterioration in south Asia beginning around 4.2 ka B.P. (Staubwasser et al., 2003; Berkelhammer et al., 2012; Dixit et al., 2014). The proxy records suggest a sudden weakening of the ISM strength around 4.2-4.0 ka BP that lasted for two centuries (Berkelhammer et al., 2012; Dixit et al., 2014), contemporaneous with increased aridification in western India (Singh et al., 1990; Enzel et al., 1999), lowering of sea level and reduction in the Indus River discharge, as well as increased salinity in the Arabian Sea (Staubwasser et al., 2003; Giosan et al., 2012). However, the available palaeoclimatic records from the western Himalaya which controlled the hydrological budget of the region of Harappan settlements do not demonstrate any such substantial climatic variability at that time (Fontes et al. 1996; Wünnemann et al., 2010; Leipe et al., 2014; Rawat et al., 2015).

Also, the demise of such widespread culture because of an arid phase of 200 yrs (time span less than the LIA) is questioned by several workers (Possehl, 1997; Madella and Fuller, 2006; MacDonald, 2011). In this study, I have investigated changes in the strength of the ISM in the western Himalaya during the last 4,500 yrs using geochemical, stable isotopic and grain size proxy records from the Tso Moriri Lake, Ladakh Himalaya. Our record shows a severe arid phase in the western Himalaya between 4,350 and 3,450 ysr BP that coincides with the fall of Harappan civilization.

The Harappan civilization was the most extensive among ancient civilizations, covering about 1.5 million km^2 area in India, Pakistan and Afghanistan (Figure 6.1). Its advanced architecture, well stratified society, water management system, uniform trade weights, scriptures, seals and marine trade privilege this culture in much advance to other contemporary civilizations. The origins of Harappan civilization can be traced to Mehargarh around 7,000 BC, with the beginning of animal domestication and agricultural practices during early Holocene warm phase and strengthened ISM associated with it (Possehl, 2002; Gupta, 2004; Vahia and Yadav, 2011). A large number of village and urban settlements originated in the Early Harappan phase between ~5,000 and 2,500 BC along the Indus and Ghaggar-Hakra river systems (Possehl, 2002; Madella and Fuller, 2006; Vahia and Yadav 2011). The civilization attained its utmost development from 2,500 to 2,000 BC (Mature Harappan phase) (McIntosh 2008; Giosan et al., 2012). Several mega urban settlements developed in this period.

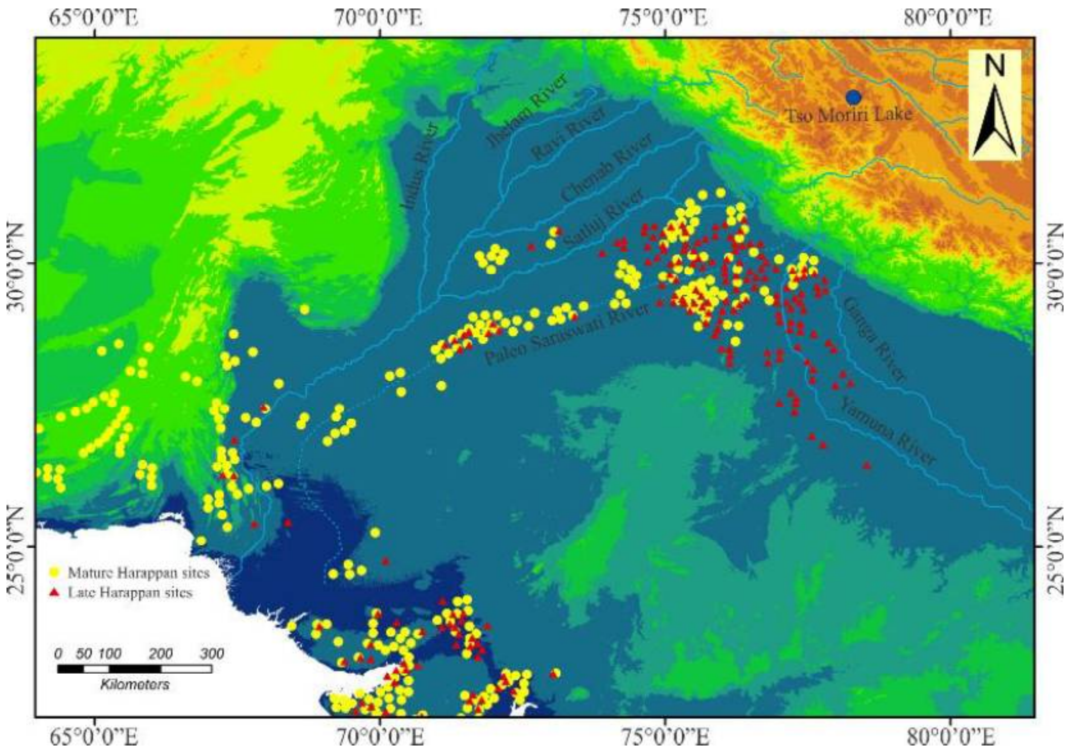

Figure 6.1 Location of sites of the Harappan civilization in India, Pakistan and Afghanistan in yellow circle and red triangle (Madella and Fuller, 2006). Also shown are the location of the Tso Moriri Lake, NW Himalaya in blue circle.

The frequency of settlements during the Mature Harappan phase was maximum along the Ghaggar-Hakra Rivers which indicate enough water availability for agriculture in this region (Mughal, 1990; Madella and Fuller, 2006; Vahia and Yadav, 2011). However, after 1,900 BC, the civilization began to decline and most of the urban settlements were abandoned. During the Late Harappan period (1,900-1,000 BC), several village like settlements grew along the Yamuna and Ganga rivers that suggest a southward and eastward migration of population (Possehl, 1997; Madella and Fuller, 2006; Giosan et al., 2012; Dixit et al., 2014). Around 1,000 BC, the urban Harappan civilization completely perished and transformed into rural communities scattered over a large area (Possehl, 1997; Madella and Fuller, 2006).

The Harappan civilization was primarily agrarian based and the agriculture was of inundation type which was dependent on river discharge (Fuller and Madella, 2001; MacDonald, 2011; Giosan et al., 2012). The river's discharge in turn was regulated by precipitation and the snowmelt in the western Himalayan region. In the present day, the region of Harappan culture is influenced by two different moisture sources: the ISM during summers and the Mid-Latitude Westerlies (MLW) in winters (MacDonald, 2011; Dixit et al., 2014; Leipe et al., 2014). A marked precipitation gradient can be observed in the region from the southeast to the northwest with decreasing influence of the ISM. As mentioned earlier, the ISM supplies around 80% of the annual precipitation in the southeast margin of the Harappan region and 10% in the northwestern part (MacDonald, 2011). So changes in ISM precipitation might have played a major role in the rise and fall of the Harappan civilization.

6.2 Results

6.2.1 Grain size measurements

The particle size distribution in these lakes reveals the changes in hydrological energy of rivulets joining the lake (Mishra et al., 2015). During the warm and wet climate, the stream discharge enhances due to more precipitation and snowmelt that leads to increase of suspended load and coarse fraction at coring site TMC-1 of the Tso Moriri Lake while lake level is of minor importance due to

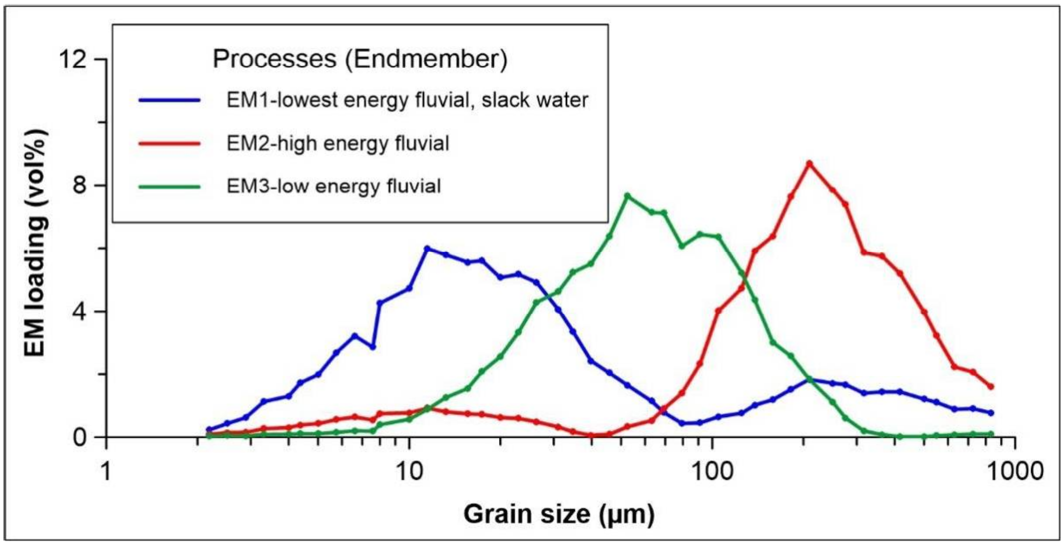

Figure 6.2 Optimal end-member modelling (EM1-EM-3) using grain size data of core TMC-1 from the Tso Moriri Lake, Ladakh, NW Himalaya. End-member loadings represent sedimentologically interpretable unmixed grain-size distributions of three end members; EM1(lacustrine deposition of clay under slack water conditions near the river mouth, indicating very low or even temporary absence of river discharge, EM2 (high energy fluvial flow, and EM2(low energy fluvial flow).

contemporary outflow conditions. Under colder and drier climatic conditions the inflow intensity is significantly reduced and only provides low energy transported suspended load of finer fractions deposited as silt and clay at the study core. The extracted end members from the grain size changes (EM1-EM3; Figure. 6.2) are attributed to three different processes: i) lacustrine deposition of clay under slack water conditions near the river mouth, indicating very low or even temporary absence of river discharge (EM1), ii) high energy flow, indicated by the major deposition of sand components (EM2), and iii) low energy flow and deposition of silt fractions (EM3). The grain size profile indicates the high EM2, and low EM3 and EM1 from 4,500 to 4,350 cal yrs BP. After 4,350 cal yrs BP, EM3 abruptly increased and remained high until 3,450 cal yrs BP while EM2 decreased. The EM3 values decreased between 2,800 and 650 cal yrs BP coinciding with increased EM2 values. But the EM1 values increased after 650 cal yrs BP.

6.2.2 Elemental abundances

Al and Rb show parallel variations, indicating detrital influx to the lake from the catchment. The abundance of these elements in the monsoon marginal regions increase in the cold intervals as a result of enhanced physical weathering in lake surroundings (Morill et al., 2006; Shen et al., 2013; Mishra et al., 2015). During the warm and humid climatic conditions, the growth of monsoon induced vegetation in the lake catchment limits the physical weathering and transport of these elements to the lake (Morill et al., 2006; Shen et al., 2013). In warm and humid intervals, the intensity of chemical weathering increases in the lake catchment that in turn supplies more Sr and Ca to the lake; chemical weathering decreases in arid and cold intervals. The Rb/Sr and Al/Ca ratios in the lake sediments thus can be used as an unequivocal proxy for ISM behavior. From 4,500 to 4,350 cal yrs BP, the values of Al/Ca and Rb/Sr ratios remain very low. Around 4,350 cal yrs BP, their values show an abrupt increase which persists till 3,450 cal yrs BP. After 3,450 cal yrs BP, the Al/Ca and Rb/Sr ratio again decreased until present with two phases of slight enrichment between 3,100-2,700 and 650-200 cal yrs BP. (Figure 6.3).

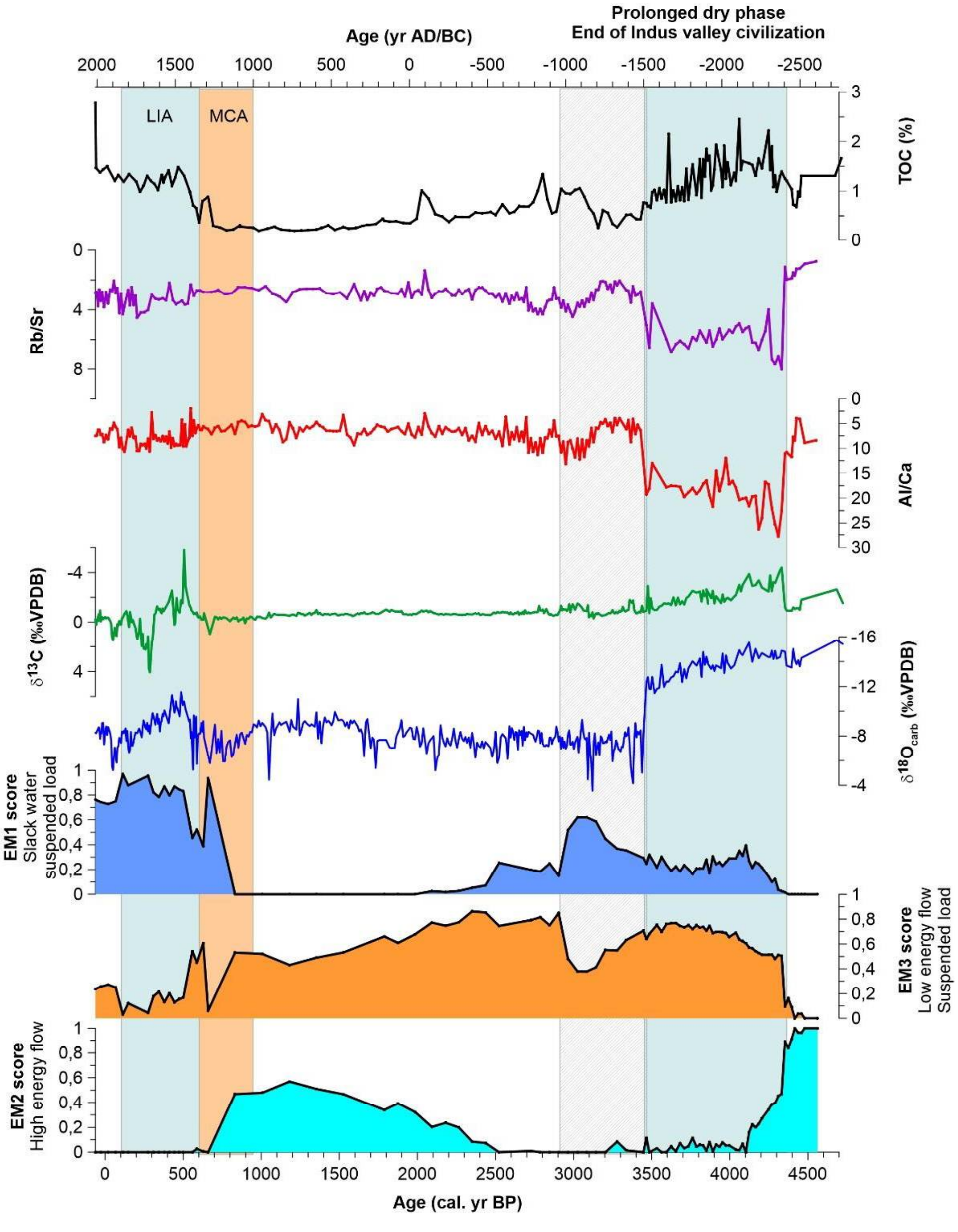

Figure 6.3 Indian summer monsoon proxy records of extracted end members from grain size variations (EM1: fluvial-lacustrine deposition of clay under slack water conditions, EM2: fluvial high energy flow, and EM3: fluvial low energy flow), $\delta^{18}O$ and $\delta^{13}C$ ratios in bulk carbonate, elemental ratios of Al/Ca and Rb/Sr and TOC

(Wt. %) in core TMC-1 from the Tso Moriri Lake, Ladakh, NW Himalaya. Light green-grey bars indicate prolonged arid phase during ~4,350-3,450 cal yrs BP and the Little Ice Age (LIA). A potential commencement of the arid phase until 2,800 cal yrs BP is marked by the shaded bar. Medieval Climate Anomaly (MCA) is marked in light orange.

6.2.3 The δ^{18}O and δ^{13}C ratios in lake carbonate

The δ^{18}O values of authigenic carbonate in high altitude lakes from the NW Himalaya reflect the changes in isotopic signature of lake water, the moisture source (ISM/MLW), temperature during carbonate deposition and evaporation (Fontes et al., 1996; Wünnemann et al., 2010; Mishra et al., 2015). The δ^{13}C ratio is controlled by the changes in the isotopic composition of dissolved inorganic carbon, productivity inside as well as outside the lake, vegetation and photosynthesis. The δ^{18}O values of bulk carbonate in the Tso Moriri core (TMC 1) varies from -15.7 to -3.5 ‰. The values remain very light from 4,500 to 3,450 yrs BP. After 3,450 yrs BP, a sudden increase in the values has been observed which persists until 650 cal yrs BP. Between 650 and 400 cal yrs BP, the values are slightly decreased and enriched again thereafter. The δ^{13}C values vary between -5.8 ‰ and 4.5 ‰, showing abrupt increase around 4,350 cal yrs BP and then gradually decreased. The δ^{13}C ratio does not show much fluctuation from 3,450 to 650 yrs BP, but showing very high fluctuations thereafter. The large amplitude variability in isotopic values in the Tso Moriri Lake cannot be explained by a single factor, but more likely by a combination of several factors for the time span under consideration, of which the sources of water supply to the hydrologically open lake played a dominant role.

6.2.4 The δ^{13}Corg and total organic carbon (TOC) in organic carbon

The $\delta^{13}C_{org}$ signatures of the lake carbon extensively used to understand the types of vegetation (C_3 and C_4 plants) in the lake catchment as well as inside the lake (Teeri and Stowe, 1976; Quade and Cerling, 1995; Huang et al., 2000). The TOC (Wt %) indicates the high organic content and hence high organic productivity (Talbot and Livingstone, 1989; Matzinger et al., 2007) inside and outside in lake catchment area. The δ^{13}C of bulk organic carbon in core TMC-1 varies from -24.9 ‰ to -15.4 ‰ (Figure 6.3). The δ^{13}C values remain low between 4,500 and 650 cal yrs BP except the period between 3,000 and 2000 cal yrs BP when an increase in the values observed. After 650 cal yrs BP, the δ^{13}C ratio shows sudden increase and consistently higher values till the present. The TOC (wt. %) values are very low between 4,500 and 4,350 cal yrs BP followed by a sudden increase from 4,350 to 3,000 cal yrs BP. Since 3,000 cal yrs BP, the values again decreased and remained low until 650 cal yrs BP. From 650 cal yrs BP to the Present, the values again increased. The large variations in δ^{13}C in TMC-1 reflect the contribution of aquatic phytoplanktic algae along with the terrestrial vegetation and soil organic matter. The higher δ^{13}C values in the top samples result from the enhanced productivity of phytoplanktic algae in the lake which contributed major part to the sedimentary organic matter.

6.2.5 Spectral analysis:

Spectral analysis of Al/Ca time series from the Tso Moriri Lake for the period 4,500 to -62 cal yrs BP indicates the strong periodicities of 140 yrs, 80 yrs, 63 yrs, 58 yrs and 45 yrs (Figure 6.4).

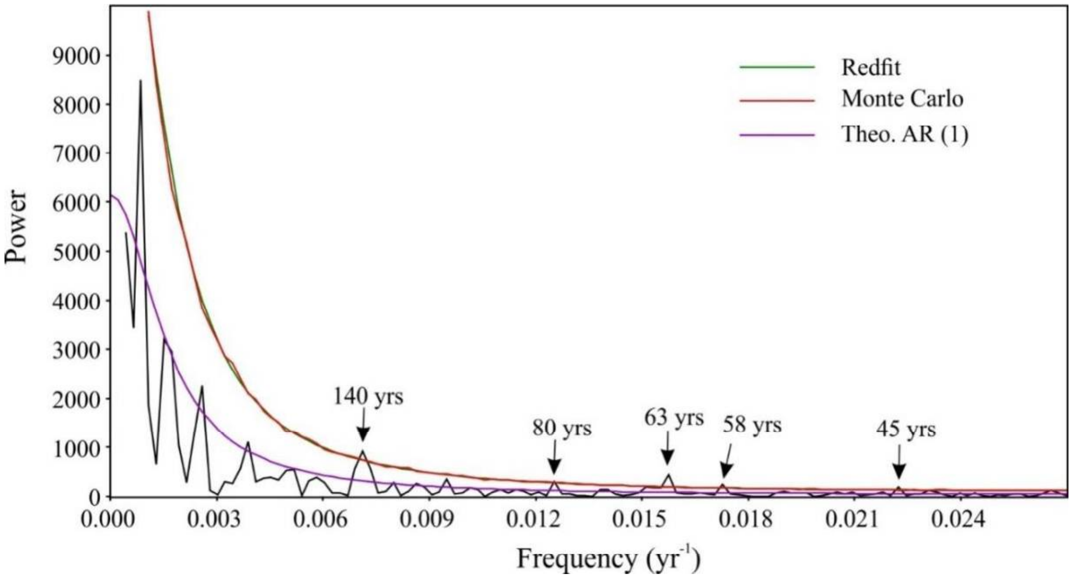

Figure 6.4 Spectral analysis of Al/Ca time series from core TMC-1, Tso Moriri Lake, Ladakh, NW Himalaya for the period 4,500 to -62 cal. yr BP showing the strongest periodicity at 140, 80, 63, 58 and 45 yrs (90%) using PAST Red Fit and Monte Carlo methods.

6.3 Discussion

Based on variability of elemental abundance and grain size, TMC-1 profile can be categorized in five different subdivisions:

(i) 4,500 to 4,350 cal yrs BP

Low values of Al/Ca and Rb/Sr ratios suggest warm and wet climate in the western Himalaya from 4,500 cal yrs BP to 4,350 cal yrs BP (Figure 5.3). High EM2 shows high sand fraction and in turn the high hydrological energy of the streams (Figure 6.2, 6.3). This warm interval in the western Himalaya is also evidenced in high A/C ratio in the Tso Kar Lake (Wünnemann et al., 2010) and Chandra valley peat bog records (Rawat et al., 2015). This phase is contemporaneous with the enhanced ISM intensity recorded in low $\delta^{18}O$ values in the Kotla Dhar Lake, Haryana (Dixit et al., 2014), low $\delta^{13}C$ values in the Lonar Lake, central India (Sarkar et al., 2015), low $\delta^{18}O$ values in the Mawmluh cave, eastern Himalaya (Berkelhammer et al., 2012) and the Qunf cave, Oman (Fleitmann et al., 2003) and higher abundances of Globigerina *bulloides (*G. *bulloides)* and low salinity in the Arabian sea (Gupta et al., 2003, Staubwasser et al., 2003). Due to atmospheric warming during this time period, the ITCZ migrated farther north to the Tso Moriri Lake site leading to abundant ISM precipitation (Fleitmann et al., 2003; 2007).

(ii) 4,350 to 3,450 cal yrs BP

The Al/Ca and Rb/Sr values abruptly rose at ~4,350 cal yrs BP suggesting a sudden onset of cold and dry climate in the NW Himalaya that continued till 3,450 cal yrs BP (Figure 6.3). The decrease in EM2 and increase in EM3 also suggest the reduction in high energy flow. Highly negative $\delta^{18}O$ values also indicate influence of increased glacial melt during this time span. The grain size data indicates the presence of this arid phase until 2,800 cal yrs BP which is not indicated by elemental proxies possibly due to absence of weathered material in stream tracks. This rapid onset of prolonged arid phase in the western Himalaya can be attributed to the weakening of the ISM at ~4.2 ka BP. The continental records of lake desiccation in western India (Enzel et al.1999), high $\delta^{18}O$ values in Kotla Dahar Lake, Haryana (Dixit et al., 2014), high $\delta^{13}C$ values in Lonar Lake, central India (Sarkar et al., 2015), low A/C ration in Tso Kar Lake (Wünnemann et al., 2010) and Tso Moriri Lake (Leipe et al., 2014), high $\delta^{18}O$ values in Mawmluh cave, eastern Himalaya (Berkelhammer et al., 2012) as well as the marine records of lower G. *bulloides* production, reduced discharge of Indus River and high salinity in the Arabian Sea (Gupta et al., 2003; Staubwasser et al., 2003), all indicate reduction in ISM intensity at ~4.3 kyr BP. The weakening of the ISM at 4.3 kyr BP was perhaps driven by enhanced El Niño Southern Oscillation (ENSO) activity (Figure 6.5). The enhanced ENSO activity shortened the summer monsoon season by delaying the onset and early withdrawal timings that diminish the moisture output in the NW Himalaya (Sinha et al., 2011; Berkelhammer et al., 2012). The reduced solar output (Perry and Hsu, 2000), decreased PDO (McDonald, 2011) and negative IOD (Abram et al., 2009) were additional forcing factors for a prolonged weak ISM period.

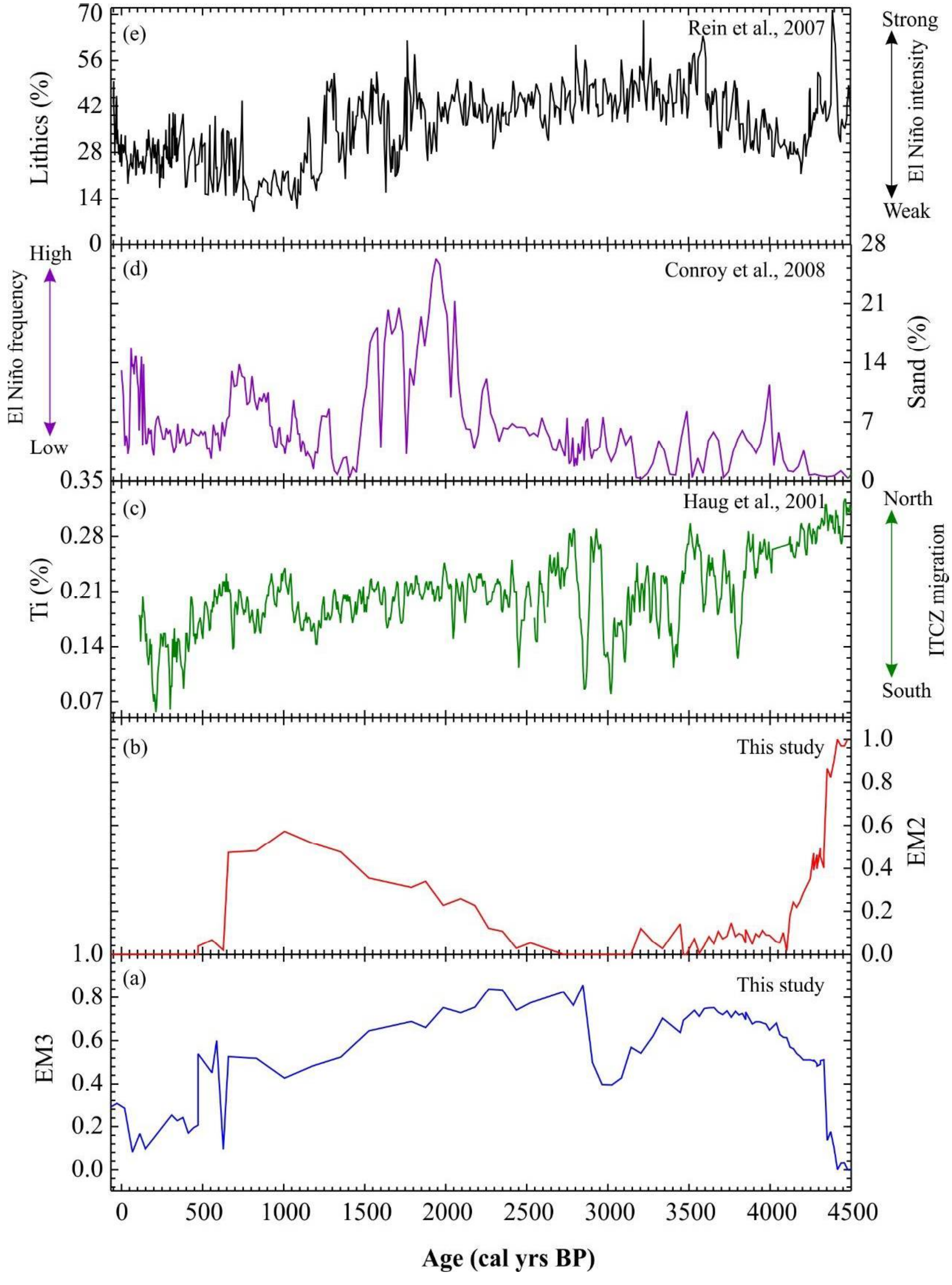

Figure 6.5 Indian summer monsoon proxy records from the Tso Moriri Lake, Ladakh compared with lake record from eastern tropical Pacific Ocean region, and

marine records from the eastern Pacific Ocean and Cariaco Basin. (a) EM3 (low energy fluvial) from the Tso Moriri Lake, NW Himalaya (present study), (b)EM2 (high energy fluvial) from the Tso Moriri Lake, NW Himalaya (present study), (c)percent Ti from the ODP site 1002, Cariaco Basin (Haug et al., 2001), (d) percent sand in sediment core from the El Junko Lake, Galapagos, eastern tropical Pacific (Conroy et al., 2008) and (e) 10 years running mean of lithics percentage from marine core SO147-106KL, eastern Pacific Ocean (Rein, 2007).

(iii) 2,800 to 950 cal yrs BP

The interval between 2,800 and 950 cal yrs BP experienced abundant ISM precipitation with a general increasing trend of enhanced discharge. After 2,300 cal yrs BP, slack water deposits (EM1) are lacking indicating the dominance of EM3 with a general decreasing trend while EM2 increases as a result of increasing high energy flow in the lake (Figure 6.2, 6.3). Low Al/Ca and Rb/Sr ratios also indicate increased precipitation in the region (Figure 6.3). This is also supported by enhanced $\delta^{18}O$ values due to increased precipitation accompanied by increased evaporation (Figure 6.3).

(iv) 950 to 600 cal yrs BP

From 950 to 600 cal yrs BP, the ISM remained strong with the commencement of the MWP. This is indicated by more positive oxygen isotopic values, decreased EM2 and increased EM1 (Figure 6.2, 6.3). The enhanced ISM strength during the MWP is also observed in numerous palaeoclimatic records of ISM variability (Thompson et al. 2000; Agnihotri et al., 2002; Anderson et al., 2002; Gupta et al., 2003; Fleitmann et al., 2003; Buckley et al., 2010; Cook et al., 2010; Sinha et al., 2011).

(v) 600 to 200 cal yrs BP:

Between 600 and 200 cal years BP, the NW Himalaya experienced the onset of cold and arid conditions coinciding with the LIA. The oxygen isotopic values significantly depleted with the decreased strength of the ISM. Grain size data shows the highest amount of slack water deposits (EM1), indicating very low or even temporary absence of inflow to the Tso Moriri Lake during the LIA. This phase of atmospheric cooling and weak monsoon is visible in several other palaeoclimatic records from Asia (Thompson et al., 2000; Zhang et al., 2008; Berkelhammer et al., 2010; Buckley et al., 2010; Yadav, 2013).

The strong periodicities of 140 yrs, 80 yrs, 63 yrs, 58 yrs and 45 yrs in Al/Ca ratio time series from the Tso Moriri Lake are also reported from the cave records of ISM variability from Oman and China, indicating the solar influence on the strength of the ISM (Fleitmann et al., 2003; Wang et al., 2005).

6.4 Weakening of the ISM ~4.3 kyr BP and collapse of the Indus valley civilization:

Proxy records from the Tso Moriri Lake indicate an abrupt decrease in the intensity of the ISM ~4,350 cal yrs BP which persisted until 3,450 cal yrs BP. The snow deposition in the western Himalaya perhaps decreased during a weak ISM. Less precipitation and snowmelt in turn reduced the discharge of Indus and Gagghar- Hakra rivers (Giosan et al., 2012). This decreased the frequency and intensity of floods in these river systems that decreased the fertility of soil in Harappan culture (Giosan et al., 2012). At about 4,200-3,900 yrs BP, the population began to migrate towards Ghaggar-Hakra (Possehl et al., 1997; Fuller and Madella, 2006; Giosan et al., 2012; Dixit et al., 2014). Therefore, the sites of the Late Harappan period are concentrated near the Ghaggar-Hakra river system. But, the continued failure of agriculture practices because of a weak ISM and reduced river discharge could not support the large population of Harappan civilization with high living standards, and finally the culture disintegrated around 3,000 cal yrs BP.

Our multiproxy record from the Tso Moriri Lake documents the presence of 4.2 ka event in the western Himalaya with sharp boundaries. Earlier, it was thought that the influence of the 4.2 ka event was not so prominent in the western Himalaya. This is the first record showing the prolonged drought of ~900 yrs beginning around 4,350 cal years BP. The discharge of the Indus River and its tributaries decreased due to less precipitation and snow availability in the western Himalaya. The drainage pattern of Ghaggar-Hakra river system also changed from perennial to seasonal. This record suggests the weakening of the ISM as the major contributing factor for the rise and fall of the Harappan civilization. The water scarcity for prolonged time adversely affected the agricultural practices that led to the fall of Harappan settlements.