**Early Holocene to Present Paleoenvironmental Shifts and Short Climate
Events Inferred from Tropical Wetland and Lake sediments, Kukkal
Lake, Southern India: Geochemistry and Palynology**

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Early Holocene to Present Paleoenvironmental Shifts and Short Climate Events Inferred from Tropical Wetland and Lake sediments, Kukkal Lake, Southern India: Geochemistry and Palynology

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Abstract

The Kukkal basin, Tamil Nadu, India, receives most of its rain from the southwest monsoon. A sediment core from Kukkal Lake, preserves a continuous sediment record from the Early Holocene to present (9000 yr BP to present). The present lake is artificial, situated at an elevation of ~1887 m a.s.l., in a small basin that appears to have alternated between a and wetland depositional environment. Climate proxies, including sediment texture, TOC, Total Nitrogen (TN), C/N, pollen and geochemical composition indicate a steady progression to wetter conditions, with two stepwise changes at about 8000, and between 3200 and 1800 yr BP. The change at 8000 yr BP appears to correspond to a brief (100-150 yr) dry spell recorded elsewhere in India. The change at 3200-1800 yr BP consisted in a rapid intensification of the southwest monsoon, and may correlate with the initiation of the Roman Warm Period. There is no clear evidence of changes at the times of the Medieval Warm Period and the Little Ice Age. A warm period (1150-850 yr BP) and Little Ice Age (LIA) (550-150 yr BP) of wetter

conditions events are observed in the Kukkal lake. The C/N ratio of the sediments ranges from 14.02 to 8.31 indicating that the organic matter originated from a mixture of lacustrine algae and vascular plants. Chemical weathering indices (CIA, CIW and PIA) are consistent with extreme silicate weathering. Pollen data show a development from savanna vegetation prior to about 8000 yr BP, followed by grassland with palms, the appearance of ferns just prior to 3200 yr BP, and the establishment of forest between 3200 and about 1800 yr BP.

Key words: Tropical lake, tropical wetland, Holocene, monsoonal intensity, pollen, radiocarbon dating, climate change

INTRODUCTION

During the last two decades scientific interest in the reconstruction of the Asian monsoon variations particularly the South West Monsoon (SWM) since the Late Quaternary to Holocene period has increased significantly. In particular, in the Indian subcontinent many types of natural archives such as lake and marine sediment cores, palynology, tree rings and corals (Mayewski et al., 2004) have been used to restructure late Quaternary-Holocene paleoclimatic shifts. Such records include fluvial archives of the Gujarat region (Chamyal et al., 2002), deep marine sediment cores studied from the Arabian Sea, and the Bay of Bengal (Gupta et al., 2003, 2005; Chauhan et al., 2010; Nagasundaram 2014; Achyuthan et al., 2015), aeolian sediments from the Thar desert (Achyuthan et al., 2007a, b), lacustrine sediments from Kerala (Farooqui and Sekhar 2011; Farooqui et al., 2010; Kumaran et al., 2008; Veena et al., 2014), peat deposits from the foreland basin of the Himalyas (Sharma et al., 2006; Rawat et al., 2015), glacial moraines and proglacial deposits of the Ladakh region (Sant et al., 2011), speleothems (Narayana et al., 2011) and tree rings (Esper et al., 2002 a, b, 2003; Yadav and Singh 2002; Shah and Bhattacharya, 2009).

The Indian subcontinent is one of the largest monsoon-dominated regions of the world and the climate is controlled primarily by the SWM. Lakes and wetlands in this region function as repositories of sediment deposited in a closed system, and may act as major sinks for organic carbon. Therefore, sediment cores from such sites in the area affected by the SWM can provide a continuous, high-resolution of paleoenvironmental record of the evolution of the SWM (Verschuren, 2003; Verschuren et al., 2000).

It is important to reconstruct past climate and to study paleoclimate records with high resolution because the past performance of the monsoon may provide vital input for projecting future climate change. Furthermore, an understanding of climate change in the Indian subcontinent from the early Holocene to the present potentially has profound implications for an understanding of human

development, because rain-fed agriculture and river valley civilisation were established during this time interval (Possehl 1996; Allchin 1997; Gupta 2004, Ponjtoon et al., 2014).

In the Asian region, paleoclimate records based on lake sediments indicate that both southwest summer and northeast winter rains were stronger in the early Holocene period (10,000 –7000 yr BP) than today, resulting in a wetter and cooler climate over the Asian continent. But the Holocene Megathermal was a much warmer phase in areas that received East Asian monsoon (An et al., 2000; Wang et al., 2005; Sun and Li, 2011). Warming started around 8000 yr BP and the Holocene Megathermal Maximum (HMM), occurred between 7200 and 6000 yr BP. After 3000 yr BP, climate in China area returned to a cold and dry state (Sun and Li, 2011). These conclusions are based on a wide variety of proxies, including pollen and diatoms (Prell and Kutzbach, 1987; Van Campo et al., 1996), oxygen isotopes from marine sediments (Sirocko et al., 1993, 1996), and Arabian Sea upwelling intensities (Prell and Van Campo, 1986; Overpeck et al., 1996). Staubwasser et al., (2002, 2003) provided some insight in the climate variability in the SWM region since the mid Holocene.

A history of flow volume of the Indus River over the past 5000 yr has been reconstructed by von Rad et al. (1999 a, b). The Indus has a large catchment in a region that is now partly semi-arid. Being fed by melting Himalayan ice as well as precipitation in the semi-arid hinterland, its discharge is governed by a complex interplay of phenomena. Information obtained to date shows a stronger SWM since about 1500 yr BP.

Temperature indicators are less clear, except around the Medieval Warm Period (MWP) () and the Little Ice Age (LIA) (Crowley and Lowery 2000). Chauhan and Vogelsang (2006) reported that the LIA had a large temporal and spatial variability due to the variations in the intensity of SWM and had its impact across the globe. A period of warming in Oman coeval with that in China, was observed from the index fossil *Globigerinoides bulloides*, which indicates wind-

induced upwelling of ocean water, during the interval 1200 yr BP to 600 yr BP (Gupta et al., 2003). However, in the northern hemisphere, the LIA was a mild cooling event (Crowley and Lowery 2000; Crowley, 2000; Anderson et al., 2002; Singhvi and Kale, 2008). Summarizing these studies, it is evident that a significant variation of the SWM, encompassing several cycles of fluctuations, occurred during the Holocene.

To date, the marine record from the Arabian Sea has proved to be the most consistent and continuous record of the SWM fluctuations (Sirocko et al., 1993, 1996, 2000; Kudrass et al., 2001; Lückge et al., 2001; Thamban et al., 2002; Tiwari et al., 2005, 2006), whereas limited studies have been carried out in the Bay of Bengal (Duplessy, 1982; Chauhan et al., 2004; Chauhan and Vogelsang, 2006; Achyuthan et al., 2015). However, lakes of peninsular India preserve a great wealth of paleoenvironmental and paleoclimate data spanning the last 6000 yr as described by Limaye et al., (2010) and Veena et al., (2014). The lake and wetland archives of Tamil Nadu have received so far little attention. Kukkal Lake, in the Palani Hills, Dindigul District, Tamil Nadu State, lies in a basin affected by both the SWM and NEM rains. Hence, the main objectives of the present study are to reconstruct the Holocene paleomonsoon and paleoenvironmental shifts using the Kukkal lake sediments.

STUDY AREA

Kukkal Lake (Figure 1) (lat and long) is a small, irregular, fresh water body covering an area of 18 ha, and situated at an altitude of 1887 m above sea level. The present lake is impounded by a low dam at the northern end, and floods an area that appears to have been a wetland similar to one about 300 m south of the lake. Both features may have been lakes at times in the past. Presently, the lake has an catchment area of 2 to 3 km², that is forested and relatively undisturbed by human activities; some abandoned paddies on the east side of the lake are the only evidence of agriculture in the catchment. Sediment in the basin beneath the lake is therefore suitable for carrying out paleoenvironment research. Bedrock underlying the catchment is Precambrian charnockite associated with hornblende-biotite gneiss, granite and quartzite, and is covered by a thin veneer of red vertisol and lateritic soil

(Bagyaraj and Gurugnanam, 2011). The geology and geomorphic observations in and around the lakes reveal that the Kukkal Lake basin is structurally controlled by faults and lineaments, as are the main tributary watercourses within the basin. The catchment receives rainfall from both the SWM and NEM, the NEM being dominant (Meher-Homji and Gupta 1999). The mean annual rainfall for Kodaikanal over a four-year period (2001-2004) was 1690 mm (Bagyaraj and Gurugnanam, 2011). The dry season is from December through March, and there is also a short dry period in July. The climate is salubrious for most of the year with summer temperatures reaching 19.8°C (max) and 11.3°C (min) and winter temperatures between 17.3°C (max) and 8.3°C (min). Meher-Homji and Gupta (1999) state that Kodaikanal experiences a bixeric climate regime receiving high rainfall from October to December (ie. NEM). The lake is surrounded by the 'Shola' forests (the word 'Shola' derived from the Tamil language word 'cōlai' meaning grove or thick vegetation cover (Meher-Homji 1967). The Sholas are patches of stunted tropical montane forest found in the valleys in the midst of rolling grassland in the higher montane regions of the Nilgiri Hills, South India. The soil texture varies from clay to silty clay; soils are acidic in nature and contain a high percentage of iron oxide and alumina. In the 'Shola' forests, accumulation of humus in the top layers of the soil renders it a black color (Meher-Homji, 1967; Bera and Farooqui, 2000). The dominant trees in the shola forest are represented by *Michelia nilagirica*, *Bischofia javanica* (bishop wood), *Calophyllum tomentosa*, *Cedrela toona* (Indian mahogany), *Eugenia* (myrtle) spp., *Ficus glomerata* and *Mallotus* spp. and small trees such as *Pygeum gardneri*, *Schefflera racemosa*, *Linociera ramiflora*, *Syzygium* spp., *Rhododendron nilgircum*, *Mahonia nepalensis*, *Elaeocarpus recurvatus*, *Ilex denticulata*, *Michelia nilagirica*, *Actinodaphne bourdellonii*, and *Litsea wightiana*. These forests are interspersed with grasslands, characterized by frost and fire-resistant grass species like the *Chrysopogon zeylanicus*, *Cymbopogon flexuosus*, *Arundinella ciliata*, *Arundinella mesophylla*, *Arundinella tuberculata*, *Themeda tremula*, and *Sehima nervosum*.

MATERIALS AND METHODS

Field methods

The field map was prepared using Survey of India toposheets, a Google Earth map, and Satellite imagery data products IRS LISS III for delineating faults, lineaments and channels draining into the lake. Faults and the rock types exposed around the lake surroundings were also noted. An acid-washed 6.4 cm diameter and of nearly 94 cm in length PVC pipe sediment core was raised from the lake floor. The sediment core sampled location was marked using a Garmin III Global Positioning System (GPS) (Fig.1), subsampled at 2cm interval, stored in clean zip locked polythene bag, marked and stored for further analyses.

Chemical and Physical analyses

For the sediment texture analyses, about of 5 g of the dried sediment was washed following Carver (1971) through a 230 American standard testing machine (ASTM) sieve mesh opening of 0.063 mm until the water passing through was clear (Tables 1, 2). This separated the sand from the silt and clay content. The sediments collected in the 230 sieve mesh was calculated as sand content. Silt and clay percentage were determined using the measuring jar and settling velocity experiment following Carver (1971). Procedures of Loring and Rantala (1992) and Piper (1947) were adopted for the determination of calcium carbonate content. The organic matter (OM) in the sediment sample was determined following the procedure of Gaudette et al., (1974). The Total Organic Carbon (TOC) and Total Nitrogen (TN) were determined using about 1 g of sediment sample, decarbonated with a 1M solution of hydrochloric acid, washed three times with deionized water, freeze-dried and then analyzed in a Thermo Scientific FLASH 2000 CHNS-O Organic Elemental Analyzer (OEA) at the Department of Geology, Anna University, Chennai (Table 3). Major oxide and trace element analyses were carried out at the Central Instrumentation Facility (CIF) at Pondicherry University, Pondicherry using a WD-XRF Spectrometer with samples in powder form. The samples were analysed for SiO₂, Al₂O₃, Na₂O, CaO, Fe₂O₃, K₂O, TiO₂, P₂O₅, MnO, MgO and Sr, Cr, Cu, Ni, Co, Pb, Zn, V, Ba, and Zr (Tables 4 and 5, Figure 4). Results were normalized to Al (Figure 4).

Calculation of chemical indices

The degree of rock alteration and weathering can be estimated quantitatively using several geochemical indices (e.g., Duzgoren-Aydin et al., 2002; Maslov et al., 2003; Price and Velbel, 2003; Yudovich and Ketris, 2011). However, for the charnockite and gneisses exposed around the study area weathering indices till date have not been calculated. Most of these indices are expressed in terms of molecular or weight percentages of various oxides or groups of oxides. During chemical weathering, more labile minerals, such as feldspar and plagioclase, are depleted in Ca^{2+} , K^+ and Na^+ and transformed into minerals that are more stable under surface conditions. As the intensity of weathering increases, rocks and sediments become enriched in Al, Ti, Fe, and Mn (Minyuk et al., 2014).

Chemical Index of Alteration (CIA): The CIA was defined as follows by Nesbitt and Young (1982) using molecular proportions:

$$\text{CIA} = [\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{NaO} + \text{K}_2\text{O})] \times 100$$

with CaO being the amount of CaO incorporated in the silicate fraction of the rock. The CIA measures the proportion of Al_2O_3 versus more labile oxides, and reflects the relative amount of feldspars and clay minerals in a sample. A CIA value of 50 corresponds to unaltered albite, anorthite, and potassic feldspar. Typical values of the CIA are 30 to 40 for basalt, 45 to 55 for granites and granodiorites, 75 to 85 for illite, 75 for muscovite, and close to 100 for kaolinite and chlorite (Nesbitt and Young, 1982).

Chemical Index of Weathering (CIW) This index was proposed by Harnois (1988) and is calculated using the equation:

$$\text{CIW} = [\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O})] \times 100$$

with Al_2O_3 treated as an immobile component and CaO and Na_2O as mobile elements. K, in contrast, is not included in this index, because it may be leached and/or accumulated in the residual weathering products. Fedo et al., (1995)

suggested that Al in this index be used without any correction for its occurrence in K-feldspar, and therefore, generally K-feldspar- rich rocks yield very high CIW values. Potassic granite, for example, has a CIW value of 80 and fresh K-feldspar has an index of 100, values that are similar to those of the residual products of chemical weathering e.g., 80 for smectite, and 100 for kaolinite, illite and gibbsite.

Plagioclase Index of Alteration (PIA): This index (Fedo et al., (1995) estimates the weathering intensity of plagioclase feldspar and is calculated as follows :

$$PIA = [(Al_2O_3 - K_2O) / (Al_2O_3 + CaO + Na_2O + K_2O)] \times 100$$

Chemical Weathering Intensity (CWI): Oxides such as CaO, MgO, and Na₂O are considered more soluble and mobile, while Al₂O₃, SiO₂, and TiO₂ are considered to be more insoluble and resistant (Mackereth, 1966a, b, Engstrom and Wright, 1984). Sun et al., (2010) proposed the CWI as an alternative to the CIA in order to understand the intensity of weathering and apparently wet or dry conditions. The CWI was calculated as follows, using molecular proportions:

$$CWI = [(CaO + MgO + Na_2O) / Al_2O_3] \times 100$$

Palynology

Forty eight sediment samples (taken at 2 cm intervals) were analysed. Ten grams of each sample was treated with warm 10% potassium hydroxide and later sieved through 150 ASTM mesh (105 µm). The sieved fraction was allowed to settle overnight and the supernatant was drained. The residue was treated with 40% hydrofluoric acid. The sample was then acetolysed, following Faegri and Iversen (1989). The 650 mesh (10 µm) fraction was collected and mounted on a glass slide in glycerine jelly for palynological study under a light microscope (Olympus BX-52).

Radiocarbon dating

Four organic carbon rich samples from the core were subjected to acid-base-acid pre-treatment, and dated by liquid scintillation counting on benzene at the Department of Geosciences, University of Arizona, Tucson, USA. The radiocarbon ages were then calibrated using Calib 6.0 (Stuiver et al., 2010) following Stuiver and Reimer (1993) method.

RESULTS

Lithology

Based on the colour and texture, three litho units were recognized in the core. Litho unit I (100-47 cm) is represented by black coloured (10 Y 2/1) Munsell color scale codes, fine sandy silt, clayey silt and silty sand, peaty layers, overlain by lithological unit II (47-28 cm) which is brownish black (10 Y 2/3) in colour, moderately sorted, sandy silt and silty sand, peat laminae, with sub angular to angular grains. Lithological unit III (28-0 cm) is brownish black (10 Y 3/1) in colour, and consists of sandy silt and silty sand laminae, peat with well rounded sand grains. It contains coarse organic carbon pellets and abundant roots and root pores (Table 1, Figures 2 and 3).

Chronology

Radiocarbon dates (Figure 2), (Table 2) range from 9105 yr BP (99 cm depth, ~ 9255 BC) to near modern (99.7 pMC at 17 cm depth, or ~ AD 1650-1955). The plot of depth versus age indicates that the sedimentation rate from the early Holocene to recent was low (0.11 mm/yr) throughout the time interval from 14 to 100 cm, with small variations as follows: 0.19 mm/yr from 9105 yr BP to 7640 yr BP; 0.06 mm/yr from 7640 yr BP to 3215 yr BP (71-43 cm depth) and 0.08 mm/yr from 3215 yr BP to about 150 yr BP. Above 14 cm, the deposition rate is higher, with a minimum value, calculated by attributing an age of 300 yyr BP at 14 cm, of 0.4 mm/a.

Stable Carbon Isotopes

Values of $\delta^{13}\text{C}$ of organic carbon in the sediment show a general upward decrease from near -16‰ at 98-100 cm (9105 yr BP) to near -23‰ at present (Table 2). The transition can best be explained as the result of a decreasing proportion of organic matter derived from C₄ plants over time. Both C₃ and C₄ sedges grow at present in a peat bog in a similar tropical montane environment in the Nilgiri Hills, Tamil Nadu State, India (Rajagopalan et al., 1999).

Sediment texture

Textural analysis of clastic fraction of the Kukkal sediment core is shown in Figure 3. The sand percentage ranges from 12.5% (depth 70 cm) to 92% (depth 50 cm). The silt percentage ranges from 8% (depth 50 cm) to 75% (depth 70 cm), while the clay ranges from 0.5% (depth 50 cm) to 17% (depth 85 cm). Three main zones are apparent: below about 65 cm, with silt > sand and clay > 10%; from about 60 to 40 cm, sand predominant, clay < 5%; above 40 cm, sand and silt about equal, and clay < 5%. Most of the sediment core contains >25% organic matter consistent with a lacustrine or wetland environment. Recurring peaty sediment suggests that a wetland environment may have prevailed over much or all of the interval represented by the sediment core, prior to construction of the dam.

Sediment chemistry

TOC content increases steadily up the section from about 3.5% at 85-100 cm to 15.8% at 1 cm (Figure 3, Table 3). Similarly, TN content increases gradually from 0.4% (depth 85-100 cm) to 1.0-1.3% (depth 0-30 cm) and the C/N ratio increases gradually from about 8% (depth 85-100 cm) to 14% (depth 1 cm). A C/N ratio 13-14 suggests a sub-equal mixture of algal and vascular plant contributions (Meyers and Lallier-Vergès 1999). Intervals of low C/N ratio (< 9) occur at 12-14, 22-24, 30-34, 40-44 and 76-100 cm core depth (Figure 3). The sample at 2-4 cm probably represents the present artificial lacustrine environment, and has a C/N ratio of 14, indicating that vascular and algal plant material is deposited in shallow standing water in this environment. At the depth 40 to 35 cm a concurrent

decrease in OM, TOC, and TN is immediately followed by a sharp decrease in sand deposition.

The vertical profile of the major oxides versus depth (Table 4, Figure 4 and 5) shows that the lake sediments have SiO₂ varying from 31 (depth 70 cm) to 47% (depth 35 cm), with Al₂O₃ from 13% (depth 20 cm) to 22% (depth 80 cm), and Fe₂O₃ from 5 (depth 50cm) to 9% (depth 75 cm). TiO₂ varies from 0.9% (depth 10 cm) to 1.3% (depth 40 cm). K₂O, CaO, MgO, MnO and Na₂O are present in small (<2%) amounts. The relative concentrations of the major oxides in the sediment core can be summarized as SiO₂>Al₂O₃>Fe₂O₃>TiO₂>MgO>CaO>K₂O>P₂O₅>MnO>Na₂O. Most of the oxide trends show two prominent features: decreases in SiO₂, Al₂O₃, Fe₂O₃ and TiO₂ at 30-35 cm, accompanied by increases in P₂O₅, MnO and CaO; and at 70-80 cm, decreases in SiO₂, Al₂O₃, P₂O₅ and K₂O (Figure 5). Discriminant plots of major oxides point towards intense weathering of exposed rocks around the catchment area (Figures 6, 7, 8a, b) accompanied by an increase in Fe₂O₃. There is an overall significant decrease of Al₂O₃ (about 10%) since 9105 yr BP (Figure 4).

In the sediment sequence of the Kukkal lake core, the values of the CWI increase from 4-6 (characteristic of depths below 40 cm) to 8-10 (characteristic of depths above 30 cm) (Figure 9). Generally, higher values of CWI indicate stronger weathering and presumably wetter conditions and a strong monsoon (Sun et al., 2010). Concurrent decreases occur in the values of the CIA, PIA and CIW between 40 and 30 cm (Figure 9). The shifts in all four indices reflect an increase in CaO concurrent with a decrease in Al₂O₃ between 40 and 30 cm.

Palynology

The pollen spectra are shown in Figure 10, and pollen types are illustrated in Fig. 11. The best preservation of pollen is in the upper layer (0-27 cm). Arboreal taxa appear above 27 cm and below 87 cm core depth, while grasses and palms are prominent between 27 and 87 cm and sedges are most prominent above 27 cm. Monolete and trilete fern spores are abundant above 28 cm.

Pollen is poorly preserved between 27 and 87 cm core depth, but grass pollen is abundant. Grasses are also represented by phytoliths. On the basis of palynological analysis four phases could be recognised. Phases I to III in general correspond to a fluvial depositional environment (Figure 10, 11). However, phase-I (87-100 depth cm) can be identified with low energy deposition and as a result, sparse deposition and preservation of arboreal pollen such as *Elaeocarpus*, *Hopea* and the non-arboreal taxa like the Euphorbiaceae, Lamiaceae, and Apiaceae. Asteraceae along with Cyperaceae and Poaceae pollen were recorded. Phases II (41-87 depth cm) and III (27-41 depth cm) are represented by dominance of the *Artemisia*, Poaceae and Cyperaceae along with the pollen grains of Palmae. Overall, the pollen counts in Phases 1-3 are low and reach maximally 40 to 50 per 10 g of sediment (Figure 10, 11). Dumbbell shaped grass phytoliths and other forms of phytoliths such as bulliform and spiny are quite common. Phase IV, shows assemblage of both arboreal and non-arboreal pollen assemblage in (Figure 10, 11).

Discussion

Sedimentary environment

The chronology of the core, and inferred measurements of sedimentation rate, indicates a sedimentary environment that has been continuous and close to stable in this small basin for the past 9000 yr. However, high proportion of sand deposited between 60 to 45 cm interval indicate a faster accumulation rates. Peat-like deposits of organic matter are consistent with a wetland environment like those present elsewhere in montane valleys of the tropical Western Ghats. Variations in the C/N ratio of organic matter may indicate changes in the abundance of algae in the basin flora, and, by implication, changes in the amount of standing water in the basin (Figure 3). The basin may have been lacustrine for relatively brief intervals corresponding to 12-14, 22-24, 30-34, and 40-44 cm, in addition to a longer interval corresponding to 76-100, cm in the core (Figures 4, 5). The present-day lacustrine environment is due to damming. Superimposed on this sedimentary system are

changes revealed by our climate proxy measurements – both unidirectional steady changes, and abrupt events.

Unidirectional changes

The chemistry of the OM in the core has evolved steadily over the past 9000 yr. TOC, TN and C/N all show an upward increase in the core (Figure 3). The values of $\delta^{13}\text{C}$ also suggest an increase. A progression from mainly C_4 to mainly C_3 species in the basin is indicated, and this is in support with an increasingly wet climate. Increasing rainfall may also be responsible for the increasing amount of organic matter over time, preservation being more likely when the basin sediments remain wet for long periods. The CaO/MgO ratio in the silicate fraction also increases towards the top of the core section, and Al_2O_3 decreases.

Step-wise changes

Several proxies show step-wise changes in the range 30-40 cm. Major oxide measurements change in such a way that all four chemical weathering indices calculated for this study shift to new values corresponding to more intense weathering over that depth interval. Fe_2O_3 , MnO and P_2O_5 also show shifts. The changes in chemical indices are concurrent with increases in Ca/Al and Si/Al (Figure 5), but there is no change in the relative abundance of clay (Figure 3). Proportions of Asteraceae, Poaceae and palmae or Arecaceae decrease markedly in the record over this depth interval (Figures 10, 11). These changes immediately follow a change in the character of clastic sedimentation from sand-dominant to sand and silt in approximately equal proportions. They are succeeded rapidly by a further change in the pollen record, namely enhanced preservation of arboreal Ferns increase in abundance earlier, at depths of 46 to 40 cm in the core. This change is at ca 3000 yr BP (at 40 cm) to 1800 yr BP (at 30 cm). A step-wise change similar to that reflected in enhanced preservation of pollen and the appearance of diatoms just above 30 cm in the Kukkal core and occurred at 1500 yr BP in Pookode Lake, Kerala, at an altitude of 770 m.a.s.l (Veena et al., 2014).

As noted before, the shifts in the chemical indices appear to relate to increased deposition of CaO as silicate minerals, and concurrent increase in Si/Al. A change in clay mineralogy, with deposition of Ca-smectite above 30 cm, is a possible way of accounting for the change. The increase in CWI indicates a greater intensity of weathering, but deposition of sediment bearing this signature is likely to have lagged behind the climate stimulus responsible for the change. Together, most of the observations suggest a period of increasing rainfall. The changes may even have begun as early as 6000 yr BP, when sand began to dominate the clastic sediment, and have led to more abundant fern vegetation by 3500 yr BP, and forest vegetation largely replacing grasslands with palms by 1700 yr BP. This change might account for the decrease in sand deposition at about 1700 yr BP, if the change to forest vegetation led to less energetic runoff.

The increase in sand deposition near 6000 yr BP could be a separate step-wise event, independent of the events beginning around 3500 yr BP. A further step-wise event is indicated at 90 cm in the core, (about 8700 yr BP), prior to which some arboreal pollen and fern spores were preserved. Above this horizon, the relative abundances of sand, silt and clay change abruptly in the sediment core towards the top. Major oxide trends show inflections at about 80 cm, possibly resulting from the same event, with a lag reflecting the time required for weathering chemistry to respond.

Human effects

The higher sediment deposition rate between 0 and 14 cm in the core corresponds to events of the last 350 yr or less, and is the only evidence consistent with human-caused changes in the lake catchment. As noted above, abandoned paddy terraces are present along the east side of the catchment. Agriculture may have become established in this montane site since the early 17th century. Cutting of trees in the forested part of the catchment may also have contributed to the increased sedimentation rate.

Regional and Global Correlations

The Kukkal lacustrine/wetland basin has responded to hydrological changes, principally changes in the amount of precipitation from the SWM, over the 9000 year record presented here. Several other proxy records of similar length are available for comparison in the region of the SWM and the East Asian Monsoon (EAM). Oxygen isotope records from radiometrically-dated speleothems (Cheng et al., 2009; Liu et al., 2013; Fleitmann et al., 2003, 2004, 2007; Morrill et al., 2013a, 2013b) show a general unidirectional decrease in $\delta^{18}\text{O}$ since about 8000 yr BP (Fig. 12). The trend is interpreted by the authors, on the basis of the isotope amount effect, as evidence for a gradual increase in intensity of the SWM and EAM, and is consistent with the unidirectional changes at Kukkal, also interpreted as evidence of an increase in monsoon intensity. Similar unidirectional changes occur in another proxy, the abundance of *Globigerina bulloides* in seafloor sediment in the Arabian Gulf near Oman (reference). The general increase in SWM rainfall is consistent with the results of Yadava and Ramesh (2005), who interpreted a speleothem record as indicating the highest rainfall around AD 1666 (LIA).

The speleothem records also show a trough in the $\delta^{18}\text{O}$ between 8500 and 8000 yr BP., interpreted in part as a decrease in monsoon intensity beginning at 8200 yr BP and lasting 100 to 150 yr. An event close to this time is present in the Kukkal sediments at an interpolated age of 8700 yr BP, where it is marked by the replacement of savanna vegetation by grassland assemblage, and inflections in the curves of major oxide abundances. Given the uncertainties of the age interpolation, the proxy records may all be recording the same event.

At Kukkal, the more pronounced stepwise event between stepwise event between 3000 and 1800 yr BP has no clear counterpart in the speleothem or *G. bulloides* records. Possible counterpart events in climate records from the Indian subcontinent include the pollen-preservation event at 1500 yr BP at Pookode Lake, Kerala (Veena et al., 2014) (discussed above) and a change of slope in a speleothem $\delta^{18}\text{O}$ record from Orissa, India (Yadava and Ramesh, 2005). In the case of the latter, the authors interpret the record as indicating increasing rainfall up until 1500 yr BP, followed by a period of decreasing rainfall that is not evident at Kukkal. A high-rainfall phase at 3000–2300 yr BP is recorded in the discharge of the Indus River (von Rad et al., 1999 a, b). However, this is at variance with a long drought in the Thar Desert, India, between 3600 and 2000 yr BP (Swain et al., 1983; Bryson and Bryson, 1996) or aridity and weakening of the summer monsoon between 4500 and 2000 yr BP in the continental records (Swain et al., 1983).

Climatic events of global scale during the last 3000 yr include the Roman Warm Period (RWP) (2500-1600 yr BP (Wang et al., 2012; Wang et al., 2013), the Medieval Warm Period (MWP, 790-620 yr BP) and the (LIA, 330-80 yr BP) (Bianchi and McCave, 1999). These phenomena have been proposed on the basis of multi-proxy studies in records from higher latitudes, e.g. (Liu et al., 2007, 2013; Zhou et al., 1991, 2011 ; Sukumar et al., 1993, Mazari et al., 1996; Lehmkuhl 1997; von Rad et al., 1999 a, b; Denniston et al., 2000). Crowley and Lowery (2000) described the LIA as a mild cooling event in the Northern Hemisphere. Hu et al., (2001, 2008) determined that the LIA led to $\sim 1.7^\circ\text{C}$ of cooling around Alaska (Keigwin, 1996). The LIA, therefore, has a large temporal and spatial variability

across the globe (IPCC report 2001,). The stepwise event at 3000 to 1800 yr BP in the Kukkal proxies appear to anticipate the RWP by a few hundred years (Figs. 5 and 9), but the interpolated dates are only approximate; the inflections in the curves may in fact correspond with the initiation of the RWP. There are no events at Kukkal that correspond convincingly to the MWP and the LIA. Even though Zonneveld et al., (1997) suggested a rapid teleconnection between the climates of high latitude and the SWM, the only evidence of such relationships in the Kukkal core is the stepwise event that may correspond to the beginning of the RWM.

A possible scenario for Kukkal

When comparing and contrasting climatic proxy records from different environments, it must be borne in mind that each environment will have its own set of responses to a particular climatic forcing. Terrestrial records involving plant associations, in particular, may have much longer response times than caves and marine sediments. In the case of the Kukkal record, it is possible to conceive of the evolution of the basin as the protracted response to a century or two of dry climate at about 8000 yr BP, followed by increasing rainfall. Savanna is initially replaced by grassland with palms, sedges and ferns appear later, and all are eventually succeeded by forest in a process that lasts several thousand yr. Evolving vegetation and rainfall amount control weathering, and the character and availability of clastic sediment. Eventual establishment of mature shola forest limits the energy of runoff and the availability of coarser clastics. Pollen preservation is poor following the period of dry climate, and recovers only when the SWM intensity increases more rapidly, augmenting the amount of standing water in the wetland/lake basin.

The conclusions that emerge from this study are:

- i) The Kukkal sediment core contains lacustrine or wetland sediments representing deposition from the Early Holocene (9000 yr BP) to the present. Four radiocarbon ages indicate a slow average sedimentation rate of 0.11 mm/a, except in the upper 14 cm of core, where the rate was 0.4 mm/a or greater. The rate increase may reflect human activity.
- ii) Steady unidirectional climate change is indicated by the degree of preservation of organic matter, and by evolution of its composition. Superimposed on this trend are two stepwise changes, at about 8000 and between about 3000 and 1800 yr BP. The former change appears to correspond to a dry spell of 100-150 yr recorded elsewhere in India. The latter corresponds to a local rapid intensification of the SWM, and may correlate with the initiation of the Roman Warm Period. The Medieval Warm Period and the Little Ice Age are not clearly represented in the record.
- iii) The C/N ratio of Kukkal lake sediments ranges from 14.02 to 8.31 indicating that the organic carbon originates from a mixture of lacustrine algae and vascular plants. Stable carbon isotope data suggest early dominance of C₄ plants such as sedges, and a progressive increase in the ratio of C₃ to C₄ in deposited organic matter.
- iv. Chemical weathering indices indicate extreme silicate weathering over the past 9000 yr, with a step-wise increase in intensity beginning about 3000 yr BP. Palynological results reveal a succession of vegetation types, beginning with savanna prior to about 8000 yr BP, succeeded by grassland with palms and Asteraceae species. Spore-bearing plants became abundant just prior to 3200 yr BP and forest was established between 3200 and 1800 yr BP.

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Figure 1 Location map of Kukkal Lake and the coring site.

Figure 2. Sediment core texture, radiocarbon ages, sedimentation rate, CaO/MgO and CWI variation with depth.

Figure 3. Down sediment core variations of texture, OM, TOC, TN percentage and C/N ratio.

Figure 4 Depth versus major oxide variation observed in the sediment core

Figure 10. Pollen spectrum of sediment core. Note that there is a significant shift in the abundance of Poaceae, Cyperaceae and Palmae

Figure 11 Pollen forms identified in palynological assemblage.

1.Syzygium; 2 Eugenia; 3 Euphorbiaceae; 4 Artemisia; 5 Bignoniceae; 6 Umbellifera; 7 Terminalia; 8 and 9 Asteraceae; 10 Eurya; 11 Moraceae; 12 Hopea; 13 Lemna; 14 Myriophyllum; 15 Pinus; 16-17 Cyperaceae; 18-19 Poaceae; 20 Palmae; 21 Monolete; 22-25 Trilete spores; 26 Pseudoschizae; 27 Bulliform Phytolith; 28-29 Dumbell shaped phytolith; 30 Phytolith; 31-32 Spiny phytolith of grass; 33 phytolith.

Figure 5. Down sediment core variations of major elements normalized by Al and CWI values.

Figure 6 Ternary diagram showing weathering trend of sediment using $\text{Al}_2\text{O}_3 - (\text{CaO} + \text{Na}_2\text{O}) - \text{K}_2\text{O}$ diagram

Figure 8 a, b Scatter plots of CIA vs. CIW and PIA of sediment core

Figure 7. Paleoenvironment discrimination of sediment core exhibiting deposition of highly weathered sediments in arid and dry conditions.

Figure 9. Down sediment core variations showing CIA, CIW , PIA and CWI values

Since the last 9200 yr BP.

Figure 12 A comparison of various proxies and geochemical data patterns as observed from various sites such as ODP site 723A (*G. bulloides* %) Arabian Sea, Hematite% (in MC52-VM29-191) from North Atlantic site, $\delta^{18}\text{O}\text{‰}$ (Dongge Cave), $\delta^{18}\text{O}\text{‰}$ (Hongyuan site), Qunf cave site, Berijam and Kukkal parameters (after Bond et al., 2001 and Gupta et al., 2003). Vertical grey bars indicate periods of weak SWM.

Table 1. Lithology of the Kukkal lake sediment core

Litho unit (Depth cm)	Description	Munsells color
III (28-0)	Brownish black (10 Y 3/1) in colour and the sediment type was sandy silt and silty sand laminae, with the coarse organic carbon pellets with rootlets and root pores.	Brownish black 10 YR 3/1
II (47-28)	brownish black (10 Y 2/3) in colour moderately sorted sandy silt and silty sand quartz, fine clear coarse quartz, angular to sub angular with ferruginous nodules, and peat 3.5 mm in length	Brownish black 10 YR/2/3
I (100-47)	Peaty layer, dark black, clay with few roots, organic rich layer, fine sandy silt, clayey silt and silty sand layers	Black 10YR 2/1

Table 2. Radiocarbon dates of the lake sediment core collected from the Kukkal lake

S.No	Lab ID	Depth (cm)	¹⁴ C age (yr BP)	Calibrated date	δ ¹³C‰
1					-22.6
2	A16345	16-18	99.7 ± 1.1 pMC	AD 1650 - 1955	-23.3
3					-22.8
4	A16346	42-44	3215 ± 120	1862 - 1131 BC	-20.6
5	A16347	70-72	7640 ± 165	7028 – 6110 BC	-17.7
6	A16311	98-100	9105 ± 345/-330	9255 – 7526 BC	-16.1

Table 3. Sediment texture, OM, TOC, TN content, C/N ratio and age of Kukkal sediment core

S.No	Depth (cm)	Age	Sand %	Silt %	Clay %	CaCO ₃ %	OM %	TOC %	TN %	C/N	Sediment type
1	2-4	17.58	45.75	50.72	3.53	2.25	42.34	15.79	1.13	14.02	Sandy silt
2	4-6	29.30	40.11	55.61	4.27	0.48	40.86	12.13	1.04	11.62	Sandy silt
3	6-8	41.02	50.61	45.49	3.90	1.32	47.02	12.34	1.09	11.32	Silty sand
4	8-10	52.74	41.98	53.57	4.46	1.10	32.70	12.54	1.14	11.01	Sandy silt
5	10-12	64.46	42.23	53.39	4.39	1.17	34.77	10.29	1.19	8.73	Sandy silt
6	12-14	76.18	36.98	58.00	5.02	0.93	34.89	8.05	1.25	6.45	Sandy silt
7	14-16	87.90	41.00	54.50	4.50	0.90	36.64	13.19	1.18	11.15	Sandy silt
8	16-18	99.70	40.83	53.99	5.17	1.40	35.11	13.20	1.09	12.21	Sandy silt
9	18-20	339.34	40.87	54.33	4.81	1.25	36.30	13.21	1.00	13.28	Sandy silt
10	20-22	578.98	44.20	51.30	4.50	1.16	36.17	10.53	1.04	10.25	Sandy silt
11	22-24	818.62	39.02	56.40	4.58	1.19	35.38	7.85	1.09	7.22	Sandy silt
12	24-26	1058.25	39.88	55.26	4.86	1.29	37.15	12.54	1.12	11.19	Sandy silt
13	26-28	1297.89	42.66	53.02	4.31	1.59	36.45	13.49	1.18	11.39	Sandy silt
14	28-30	1537.53	51.73	44.26	4.01	1.38	38.93	14.45	1.25	11.59	Silty sand
15	30-32	1777.17	46.24	49.67	4.09	0.76	32.95	8.60	0.93	8.02	Sandy silt
16	32-34	2016.81	39.73	56.40	3.87	1.16	22.48	2.76	0.62	4.45	Sandy silt
17	34-36	2256.45	40.75	55.42	3.83	1.57	23.97	5.35	0.51	10.52	Sandy silt
18	36-38	2496.08	41.26	55.47	3.27	0.19	24.58	7.83	0.63	12.12	Sandy silt
19	38-40	2735.72	39.49	57.15	3.36	0.57	26.81	10.30	0.75	13.72	Sandy silt
20	40-42	2975.36	50.66	46.01	3.33	0.53	30.97	7.94	0.89	9.56	Silty sand
21	42-44	3215.00	64.97	32.41	2.62	0.55	34.74	5.58	1.03	5.41	Silty sand
22	44-46	3531.07	78.47	19.55	1.98	0.72	37.81	11.50	0.97	11.86	Sand
23	46-48	3847.14	91.92	7.56	0.52	0.63	40.04	9.86	0.88	11.13	Sand
24	48-50	4163.21	91.29	7.97	0.74	0.36	41.56	8.22	0.79	10.40	Sand
25	50-52	4479.29	82.66	14.65	2.69	0.57	42.72	8.57	0.71	12.23	Sand
26	52-54	4795.36	77.90	18.83	3.27	0.59	42.18	8.92	0.63	14.07	Sand
27	54-56	5111.43	78.02	18.76	3.22	0.36	41.68	8.61	0.69	12.43	Sand

Table 3. (Continued)

S.No	Depth (cm)	Age	Sand %	Silt %	Clay %	CaCO ₃ %	OM %	TOC %	TN %	C/N	Sediment type
28	56-58	5427.50	78.91	17.91	3.18	1.00	42.20	8.13	0.63	12.84	Sand
29	58-60	5743.57	81.84	14.80	3.36	0.78	42.02	7.64	0.58	13.25	Sand
30	60-62	6059.64	82.38	13.63	4.00	0.76	40.65	7.57	0.55	13.66	Sand
31	62-64	6375.71	57.92	34.06	8.02	0.77	38.85	7.50	0.53	14.07	Silty sand
32	64-66	6691.79	35.73	54.99	9.28	1.48	37.55	6.96	0.73	9.50	Sandy silt
33	66-68	7007.86	21.26	67.64	11.10	0.98	36.20	6.39	0.60	11.10	Sandy silt
34	68-70	7323.93	12.25	74.56	13.20	1.00	36.25	5.82	0.46	12.70	Clayey silt
35	70-72	7640.00	17.91	69.41	12.68	1.67	31.80	5.49	0.47	11.61	Sandy silt
36	72-74	7744.64	20.52	67.08	12.40	1.00	31.67	5.16	0.49	10.52	Sandy silt
37	74-76	7849.29	19.68	68.12	12.20	1.64	30.06	4.25	0.47	9.03	Sandy silt
38	76-78	7953.93	24.78	61.25	13.96	2.44	30.96	4.38	0.51	8.69	Sandy silt
39	78-80	8058.57	36.44	50.75	12.81	2.28	30.71	4.51	0.54	8.34	Sandy silt
40	80-82	8163.21	23.12	60.79	16.09	2.38	32.14	4.51	0.55	8.28	Sandy silt
41	82-84	8267.86	22.61	63.39	14.01	2.79	32.27	4.52	0.55	8.21	Sandy silt
42	84-86	8372.50	18.41	64.90	16.69	3.19	28.69	3.58	0.40	8.89	Sandy silt
43	86-88	8477.14	14.97	69.91	15.12	2.79	29.74	3.86	0.42	9.10	Clayey silt
44	88-90	8581.79	20.99	63.20	15.81	2.40	30.80	4.15	0.45	9.30	Sandy silt
45	90-92	8686.43	24.33	61.45	14.22	2.46	32.17	4.91	0.56	8.77	Sandy silt
46	92-94	8791.07	23.57	61.10	15.33	3.16	31.62	4.90	0.56	8.76	Sandy silt
47	94-96	8895.71	19.65	64.20	16.15	4.08	30.10	4.90	0.56	8.75	Sandy silt
48	98-100	9105.00	27.50	57.93	14.57	0.92	30.28	4.42	0.53	8.31	Sandy silt
Average			43.87	48.77	7.36	1.37	34.87	8.07	0.77	10.44	
Minimum			12.25	7.56	0.52	0.19	22.48	2.76	0.40	4.45	
Maximum			91.92	74.56	16.69	4.08	47.02	15.79	1.25	14.07	

Ages: **measured** interpolatedCompositions: Maximum **bold**, minimum *bold*

Table 4. Major Oxides (%) and weathering index of the sediments from the Kukkal sediment core

S.No	Depth (cm)	Age	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MgO	K ₂ O	P ₂ O ₅	CaO	MnO	Na ₂ O	CIA	CIW	PIA	CWI
1	2-4	17.58	41.01	14.06	6.29	0.94	0.57	0.55	0.59	0.68	0.08	0.01	91.88	91.96	95.13	8.99
2	4-6	29.30	40.06	14.02	6.71	0.94	0.58	0.54	0.57	0.68	0.08	0.01	91.88	91.96	95.08	9.14
3	8-10	52.74	40.52	14.73	6.46	0.93	0.58	0.55	0.58	0.69	0.07	0.01	92.17	92.25	95.27	8.73
4	14-16	87.90	41.50	13.39	6.13	0.95	0.56	0.56	0.60	0.67	0.08	0.01	91.56	91.65	94.97	9.26
5	18-20	339.34	39.59	13.31	6.95	0.95	0.59	0.54	0.56	0.68	0.09	0.01	91.56	91.65	94.87	9.59
6	24-26	1058.25	40.18	14.14	6.47	1.01	0.71	0.55	0.57	0.68	0.07	0.01	91.96	92.05	95.17	9.90
7	28-30	1537.53	39.35	13.77	5.38	0.94	0.60	0.58	0.61	0.65	0.06	0.01	91.67	91.75	95.19	9.21
8	34-36	2256.45	46.65	16.77	7.75	1.13	0.63	0.57	0.50	0.43	0.05	0.01	94.29	94.37	97.34	6.42
9	38-40	2735.72	36.65	18.73	7.38	1.25	0.66	0.61	0.46	0.30	0.04	0.01	95.31	95.38	98.31	5.19
10	44-46	3531.07	31.66	17.73	6.87	1.13	0.71	0.52	0.47	0.27	0.03	0.02	95.65	95.73	98.34	5.66
11	48-50	4163.21	32.30	19.01	5.09	1.12	0.60	0.53	0.47	0.25	0.02	0.01	96.03	96.10	98.61	4.50
12	54-56	5111.43	32.16	19.16	6.01	1.09	0.64	0.53	0.42	0.23	0.02	0.01	96.11	96.18	98.70	4.64
13	58-60	5743.57	32.01	19.31	6.93	1.06	0.69	0.53	0.37	0.22	0.01	0.01	96.20	96.26	98.79	4.77
14	64-66	6691.79	31.68	19.30	8.03	1.07	0.79	0.52	0.38	0.21	0.01	0.01	96.26	96.33	98.80	5.26
15	68-70	7323.93	31.35	19.28	9.14	1.08	0.89	0.51	0.38	0.21	0.01	0.01	96.33	96.39	98.82	5.75
16	74-76	7849.29	34.11	21.00	9.30	1.13	0.73	0.58	0.39	0.15	0.01	0.01	96.58	96.64	99.22	4.22
17	78-80	8058.57	37.63	22.21	7.50	1.19	0.88	0.64	0.46	0.18	0.02	0.01	96.38	96.44	99.10	4.85
18	84-86	8372.50	37.65	22.05	7.63	1.18	0.90	0.65	0.47	0.18	0.02	0.01	96.31	96.37	99.09	4.99
19	88-90	8581.79	37.67	21.89	7.76	1.18	0.92	0.65	0.47	0.19	0.02	0.01	96.25	96.31	99.07	5.13
20	92-94	8791.07	37.49	21.48	7.37	1.12	0.89	0.64	0.45	0.18	0.02	0.02	96.22	96.29	99.05	5.06
21	98-100	9105.00	37.31	21.06	6.98	1.07	0.85	0.63	0.43	0.18	0.01	0.02	96.20	96.27	99.04	5.00
Average			37.07	17.92	7.05	1.07	0.71	0.57	0.49	0.38	0.04	0.01	94.61	94.68	97.52	6.49
Minimum			31.35	13.31	5.09	0.93	0.56	0.51	0.37	0.15	0.01	0.01	91.56	91.65	94.87	4.22
Maximum			46.65	22.21	9.30	1.25	0.92	0.65	0.61	0.69	0.09	0.02	96.58	96.64	99.22	9.90

Maximum **bold** minimum *italic*

Table 5. Trace elements content of the sediments from the Kukkal sediment core

S.No	Depth (cm)	Age	Sr	Y	Zr	V	Cr	Ni	Cu	Zn	Rb	Nb	Pb	Th	U	Ba
1	2-4	17.58	78.75	15.75	222.95	66.50	69.65	54.95	33.35	78.75	38.80	8.90	40.75	20.25	0.60	498.50
2	4-6	29.30	79.35	15.50	236.25	72.00	70.25	55.80	33.40	79.95	41.30	9.40	37.95	20.10	0.65	516.50
3	8-10	52.74	76.70	16.10	209.20	76.00	72.40	54.50	33.40	75.50	37.80	8.70	40.00	20.80	0.30	468.00
4	14-16	87.90	80.80	15.40	236.70	57.00	66.90	55.40	33.30	82.00	39.80	9.10	41.50	19.70	0.90	529.00
5	18-20	339.34	82.00	14.90	263.30	68.00	68.10	57.10	33.40	84.40	44.80	10.10	35.90	19.40	1.00	565.00
6	24-26	1058.25	74.30	15.20	257.50	79.00	69.00	54.70	31.90	80.50	46.30	8.40	36.10	19.90	0.90	464.00
7	28-30	1537.53	79.30	15.30	277.60	92.00	61.40	59.60	33.20	84.30	46.90	8.90	42.70	20.90	0.80	483.00
8	34-36	2256.45	59.70	16.20	297.10	100.00	70.60	62.60	35.10	74.70	41.70	11.70	27.30	22.10	1.00	350.00
9	38-40	2735.72	61.40	17.90	325.90	95.00	97.80	67.70	50.50	90.40	45.90	12.70	42.80	29.10	1.40	331.00
10	44-46	3531.07	53.40	20.10	226.40	106.00	103.20	60.80	48.20	74.60	36.80	13.30	36.40	30.00	1.50	283.00
11	48-50	4163.21	51.70	24.30	277.20	92.00	96.00	62.70	54.60	72.90	36.00	12.90	38.60	34.00	1.60	277.00
12	54-56	5111.43	50.85	26.35	246.65	94.00	92.15	65.80	51.90	70.80	37.80	11.85	34.10	35.35	1.90	272.00
13	58-60	5743.57	50.00	28.40	216.10	96.00	88.30	68.90	49.20	68.70	39.60	10.80	29.60	36.70	2.20	267.00
14	64-66	6691.79	48.60	28.65	223.20	121.00	94.00	71.55	47.25	71.90	42.90	12.00	29.40	33.80	1.60	283.50
15	68-70	7323.93	47.20	28.90	230.30	146.00	99.70	74.20	45.30	75.10	46.20	13.20	29.20	30.90	1.00	300.00
16	74-76	7849.29	51.10	30.20	257.60	174.00	103.90	83.20	44.40	78.20	51.50	13.00	37.70	33.10	1.00	303.00
17	78-80	8058.57	52.40	31.80	234.60	93.00	105.10	89.50	50.00	93.20	55.10	14.30	36.20	35.00	1.20	314.00
18	84-86	8372.50	52.00	31.10	249.10	120.50	107.80	91.55	50.40	98.95	59.50	14.45	37.55	32.45	1.10	319.50
19	88-90	8581.79	51.60	30.40	263.60	148.00	110.50	93.60	50.80	104.70	63.90	14.60	38.90	29.90	1.00	325.00
20	92-94	8791.07	50.15	31.40	235.55	119.50	108.95	89.95	50.10	103.05	64.55	13.70	35.25	27.05	1.35	322.50
21	98-100	9105.00	48.70	32.40	207.50	91.00	107.40	86.30	49.40	101.40	65.20	12.80	31.60	24.20	1.70	320.00
Average			60.95	23.15	247.35	100.31	88.72	69.54	43.29	83.05	46.78	11.66	36.17	27.37	1.18	371.02
Minimum			47.20	14.90	207.50	57.00	61.40	54.50	31.90	68.70	36.00	8.40	27.30	19.40	0.30	267.00
Maximum			82.00	32.40	325.90	174.00	110.50	93.60	54.60	104.70	65.20	14.60	42.80	36.70	2.20	565.00

Maximum **bold**, minimum **bold italic**.