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Sedimentological and carbonate data evidence for lake level variations during the past 3700 years from a southern Indian lake

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ABSTRACT

Over the years, several proxies have been developed to reconstruct rainfall variability. However, most rely on indirect approaches to provide qualitative paleorainfall estimate. In an attempt to obtain a more direct measure of paleorainfall, Shankar et al. (2006) explored the rock magnetic properties of lake sediments from Thimmannanayakanakere (TK) in tropical southern India. They proposed the use of magnetic susceptibility as a proxy for rainfall in the tropics. Warrier and Shankar (2009) provided geochemical evidence in support of this proposition. Here, sedimentological and carbonate data is provided as further evidence to bolster Shankar et al.'s (2006) proposition.

High (low) values of χ_{lf} indicate high (low) rainfall in the region of TK during the past 3700 years. Particle size variations suggest that the sand % was high (low) during arid (humid) periods, when the TK lake level was low (high). Hence, a negative correlation is documented between sand % and χ_{lf} along with other rock magnetic parameters. HIRM (an indicator of magnetically “hard” minerals like haematite and goethite) is suggestive of a relatively arid climate; the high (low) HIRM values in TK sediments indicate arid (humid) conditions. For this reason, sand % is positively correlated with HIRM. By contrast, fine silt and clay contents are low during low-rainfall periods and vice versa. Thus, both fine silt and clay contents are positively correlated with χ_{lf} and other rock magnetic parameters, but negatively correlated with HIRM. Magnetic minerals reside principally in the fine silt fraction of TK sediments as evidenced from the positive correlation between fine silt content and magnetic susceptibility. Carbonate content too is indicative of paleorainfall conditions, being high (low) during arid (humid) climatic conditions. Based on the χ_{lf}, sand % and carbonate % data, we have inferred lake level variations in TK during the past 3700 years.

1. Introduction

Determining the periodicity and amplitude of climatic variations in the past is important for projecting the future climate scenario. Of the several parameters that constitute climate, rainfall is perhaps the most important, as it impacts the agriculture, economy and well-being of the people of a region. Over the past few decades, several archives like marine (Trauth et al., 2003; Zheng et al., 2010) and lacustrine (Holzhauser et al., 2005; Cherapanova et al., 2007; Dearing et al., 2008; Stansell et al., 2010) sediments, tree-rings (Raspopov et al., 2004; D'Arrigo et al., 2008), speleothems (Denniston et al., 2000; Burns et al., 2002; Lachniet et al., 2004) and ice-cores (Jouzel et al., 1993) were investigated to decipher paleoclimate/paleoenvironment. They used proxies such as stable isotopes of oxygen and carbon, clay mineralogy, diatoms and pollen, all of which give only indirect estimate of rainfall.

In this regard, we investigated the rock magnetic parameters of sediments from Thimmannanayakanakere (TK) — a small lake in southern India, and proposed magnetic susceptibility as a proxy for paleorainfall variations in the tropics (Shankar et al., 2006). We based our proposition on the positive correlation documented between magnetic susceptibility of TK sediments and instrumental rainfall data for the past 130 years. This proposition was bolstered by historical records of a drought and a high-rainfall period, besides proxy records from geographically distant locations. Subsequently, Warrier and Shankar (2009) provided geochemical evidence for the use of magnetic susceptibility as a rainfall proxy in the tropics. They found a high percentage of pedogenic magnetite during high rainfall periods (and vice versa), with metal/Al ratios also exhibiting a good correlation with magnetic susceptibility. Here, we test the hypothesis that sedimentological and $CaCO_3$ data can provide additional proof for the proposition that magnetic susceptibility may be used as a proxy for rainfall in the tropics.

Our rationale for the hypothesis is as follows: Particle size of lake sediments must be related to lake level, which, in turn is coupled to

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rainfall. Thus, there is a rainfall-particle size linkage. Similarly, there is a carbonate content-rainfall linkage because of carbonate precipitation in lakes under arid (low rainfall) but not humid (high rainfall) conditions.

One of the basic physical properties of sediments is their particle size. Variations of particle size in sediment records suggest the changing transport energy, lake levels and paleoenvironmental zones of deposition (Conroy et al., 2008). The transport and deposition of clastic materials from the watershed to a depositional basin are principally controlled by hydraulic conditions (Sly, 1978; Håkanson and Jansson, 1983). Particle size distribution was widely used by researchers to determine paleoclimate because it is sensitive to climatic changes, not disturbed by biological activities (Chen et al., 2004) and also because the methodology is simple, fast and inexpensive.

A survey of literature shows two diametrically opposite climatic interpretations of particle size data:

a) Down-core variations in the particle size of lake sediments reflect fluctuations in lake level as well as general trends of warming versus cooling. A high content of coarse particles is generally considered an indicator of warm and dry climate, whereas a high content of fine particles usually indicates a cool and wet climate (Wang et al., 2001; Chen et al., 2004; Yanhong et al., 2006; Xiao et al., 2009; Burnett et al., 2010). During dry periods, there is a drop in lake level with a reduction in the lake area. This results in the sampling location being closer to shore line where coarse particles are easily deposited but fine particles are still kept in suspension because of the strong hydrodynamic disturbance at low lake level. Thus, a high content of coarse particles is noted (Finney and Johnson, 1991; Shuman et al., 2001). During periods of high rainfall, however, the rise in lake level enlarges the lake area and as a consequence, the sampling location shifts far from the shore line. Hence, due to the weak hydrodynamic conditions, fine particles get deposited in the centre of the lake, whereas coarse particles are deposited near the shore (Menking, 1997; Chen and Wan, 1999). In a few studies of lake sediments, clastic materials like gravel, sand, silt and clay were found to occur, in that order, from the lake shore to the centre, signifying a decreasing particle size with increasing water-depth and decreasing hydrodynamic power (Sarmiento and Kirby, 1962; Sly, 1978; Picard and High, 1981; Sun et al., 2001).
b) Another interpretation is that during periods of high rainfall, coarse particles are transported to the centre of the lake due to high runoff, increased erosive power and large transport capacity. During low-rainfall periods, on the other hand, only fine particles are transported to deep water regions due to the low runoff, decreased erosive power and decreased transport capacity (Kashiwaya et al., 1987; Chen et al., 2004; Peng et al., 2005; Conroy et al., 2008). Hence, a coarse particle size reflects high rainfall conditions and vice versa. Percentage of carbonate in lake sediments, especially those of closed basins, is another useful proxy for lake-level variations (Bischoff et al., 1997) and an important indicator of temperature and humidity variations (Wetzel, 2001). Temperature plays an important role in enhancing the productivity of a lake which, in turn, favours the production of autochthonous carbonate within the lake. High temperature leads to an increase in algal productivity, which depletes the dissolved CO_2 content of lake water. This process favours the formation of dissolved inorganic carbon. During periods of high evaporation (warm and dry conditions), inorganic carbonates are precipitated in situ and deposited on the lake floor (Wetzel, 2001). Hence, a rise (drop) in the carbonate % of lacustrine sediments indicates a low (high) lake level and an arid (humid) climate.

2. Site settings

Thimmannanayakanakere (TK) – a small lake covering an area of 0.17 km^2 – is located at the foothills of the Chitradurga Fort, Karnataka State (Fig. 1). Chitradurga is located in the southern part of the Deccan Plateau. The TK Lake is situated in a mountainous belt and the adjoining hills are mostly bare, stony and aligned SSE–NNW. A few streams that drain them transport water and sediment to TK. Barring these hill ranges, the area is open and plain. Geologically, TK is situated in the Chitradurga Basin of the Chitradurga group. The area is predominantly covered with porphyritic and coarse grained granitic gneiss. Other rock types belonging to this group are greywacke, chert, phyllite, banded ferruginous chert, volcanics, Fe–Mn formations, limestone, dolomite and phyllite (Radhakrishna and Vaidyanadhan, 1997). The average annual rainfall in the area is ~64 cm, received mostly during the SW monsoon (Fig. 2). The lake-level rises by ~2–3 m during the monsoon season; however, during the peak of summer, the water evaporates, leaving the lake-bed dry. This is evidenced by the markings of paleo-lake-level on the rocks near the lake (~5.5 m; Plate 1). It also indicates that the lake level was much higher earlier as it rarely rises to the height of the markings at present. The temperature is 16.6–27.9 °C during November–February and 36.2–41 °C during March–May. The relative humidity is high during June–November, but decreases to ~30% during the other months. Strong winds blow mostly from SW or west during the SW monsoon. During the rest of the year they blow from NE and SE (Gazetteer of India, 1985). The slopes of the hills in the study area are covered with patches of acacia, bamboos and other timber species. Previous records indicate the presence of good timber trees, suggesting that the soil was fertile. However, such vegetation is rarely seen at present due to recurring droughts and deforestation (Gazetteer of India, 1985).

3. Materials and methods

3.1. Thimmannanayakanakere sediments and chronology

Sedimentological and inorganic carbonate studies were carried out on samples collected (at 2-cm interval) from a 3.7-m pit dug in the distal end of TK. The chronology of the TK sediment profile was established using ^{14}C dates obtained on the organic matter in sediment samples by liquid scintillation counting (Gupta and Polach, 1985). The ages were calibrated using the software CALIB, version 4.3 (Stuiver et al., 1998). The age–depth model obtained with the help of the two ^{14}C dates suggests a mean sedimentation rate of 0.99 mm/year and each of the 2-cm thick samples represents a duration of ~22 years. Further details of sampling, ^{14}C analysis and age–depth model are given by Shankar et al. (2006).

3.2. Particle size analysis

Based on the magnetic susceptibility data (Shankar et al., 2006), 31 sediment samples representing periods of high and low rainfall were selected to study their particle size distribution (Carver, 1971). Approximately 10 g of the sediment sample was taken in a pre-weighed glass beaker and 50 ml of 10% glacial acetic acid and 20 ml of 30% hydrogen peroxide (H_2O_2) were added to eliminate carbonate material and organic matter. The sample was washed thoroughly with double distilled water (Millipore). Ten millimetre of 5% sodium hexametaphosphate (calgon) solution was added to the sediment sample to deflocculate the clay particles. The sample was then wet-sieved through an ASTM sieve (mesh no. 230) to separate the sand (>63 μm) and silt + clay (<63 μm) fractions. The >63 μm fraction was transferred to a pre-weighed beaker and oven-dried at 100 °C. Later 10 ml of calgon solution was added to the silt + clay fraction and the solution was stirred and poured into a 1000 ml measuring cylinder. The cylinder was filled with double distilled water up to the 1000 ml mark. The sample was stirred and, according to Stokes' law, coarse silt (CS), medium silt (MS), fine silt (FS) and clay (<2 μm) fractions were withdrawn from the cylinder with the help of a 20-ml pipette. The 20-ml sample solutions were transferred to pre-weighed beakers and dried in an oven at 100 °C. Once dried, the weight was noted down. The weight of the