MINERAL MAGNETIC STUDIES OF THE TANK SEDIMENTS

4.1 Introduction:

Magnetic susceptibility is a measure of the presence of iron-bearing minerals within the sediments and is widely used as a proxy indicator for changes in sediment composition that are linked to climate-controlled depositional processes. In scientific terms, magnetic susceptibility is the degree to which a material can be magnetized in an external magnetic field. Magnetizable minerals include the strongly magnetizable minerals (ferromagnetic minerals) and moderately magnetizable minerals (paramagnetic minerals). The ferromagnetic minerals include magnetite, hematite, goethite, etc., and the paramagnetic minerals may include clay minerals (chlorite, smectite and glauconite), iron and manganese carbonates, ferromagnesian silicates (olivine, amphiboles and pyroxenes) etc. as well as a variety of ferric-oxyhydroxide mineraloids (Thompson and Oldfield, 1986; Maher and Taylor, 1988; Basavaiah and Khadkikar, 2004; Shankar et al., 2006). In simple words, magnetic susceptibility is a measure of the ease with which particular sediments are magnetized when subjected to a magnetic field. The ease of magnetization is related to the concentration and composition (size and mineralogy) of magnetizable material present in the sediment sample.

Environmental magnetism investigates the mineral magnetic properties of naturally occurring minerals. The changes in the mineral magnetic properties of the sediments depend on the different environmental and geomorphic processes. Magnetic susceptibility gives idea about the concentration of magnetic minerals while frequency dependent susceptibility provides an estimate of the ultra-fine ferrimagnetic or super-paramagnetic particles (Maher and Taylor, 1988; Pant et al., 2005b). The magnetic susceptibility is a very useful environmental magnetic parameter in the studies of marine and lake sediments because it is a very sensitive indicator of temporal changes in the concentration of magnetic minerals in the terrigenous material deposited on the sea floors and lake bottoms (Verosub and Roberts, 1995).

The rocks of the lithosphere are the only significant source for all the magnetic minerals present in the atmosphere and hydrosphere. The process of weathering and
erosion changes iron compounds in such a way that which reflect the mineralogy of the parent material. The biogeochemical processes in the regolith under prevailing present and past conditions affect the mineral magnetic properties of the sediments. With the help of magnetic susceptibility we can infer about sediment sources and erosive processes on timescales ranging from months to millennia (Thompson and Oldfield, 1986; Oldfield, 1991; Evans and Heller, 2003).

During the last few decades, environmental magnetism has emerged as an important method for studying past global climatic and environmental changes. The mineral magnetic properties of the different deposits can be used to reconstruct palaeoclimatic and palaeoenvironmental changes (Verosub and Roberts, 1995). The major sources of magnetic minerals into the lake are detrital input from the catchment area of the lake, diagenetic process, biogenic process and dissolution of detrital magnetic minerals in the lake (Evans and Heller, 2003). The magnetic properties of different lakes may vary with respect to the local climate and environmental change. Some lakes may record global change while others may provide information about regional or local climate change. The palaeoclimatic records of closed lakes in arid and semi-arid regions are less affected by external factors (Shouyun et al., 2002).

Magnetic measurement of the lake sediments reflects the types and amount of magnetic grains transported into the lake from its catchment area and the variation in the magnetic susceptibility indicates the changes in the concentration of magnetic minerals (Dearing and Flower, 1982; Yu and Oldfield, 1993; Juyal et al., 2009). The mineral magnetic properties of the natural materials are dependent on various environmental and geomorphic processes such as formation, transportation, and deposition of magnetic minerals. When rocks are broken down due to different weathering processes, the concentration, size and mineralogy of magnetic grains eroded from the rocks are affected by prevailing environmental conditions (Verosub and Roberts, 1995).

The importance of magnetic susceptibility to understand and reconstruct past global climatic and environmental changes has been given by many researchers from India and other parts of the world (Thompson et al., 1975; Dearing et al., 1981; Dearing and Flower, 1982; Thompson and Oldfield, 1986; Maher and Taylor, 1988; Oldfield, 1991; Yu and Oldfield, 1993; Maher et al., 1994; Verosub and Roberts, 1995; Guerrero et
Magnetic susceptibility measurements of various deposits (lake, aeolian, playa, loess, proglacial) from different regions of the India to reconstruct the palaeoclimatic (palaeomonsoon) and palaeoenvironmental conditions were carried out by numerous workers such as Kusumgar et al., 1992 (Manasbal Lake, Kashmir); Ghosh and Bhattacharya, 2003 (Lake Goting, Garhwal); Phartiyal et al., 2003 (Pithoragarh palaeolake, Kumaun Himalaya); Basavaiah et al., 2004 (Proglacial Lake, Central Himalaya); Khadkikar and Basavaiah, 2004 (aeolian deposits, Saurashtra); Deotare et al., 2004 (Bap-Malar and Kanod playa, Thar Desert); Pant et al., 2005b (Central Himalayan loess deposits); Shankar et al., 2006 (Tropical Tank); Juyal et al., 2009 (Goting Lake, Uttarakhand); Kotlia et al., 2008 (Dulam Lake, Uttarakhand Himalaya); Kotlia et al., 2010 (Phulara Lake, Kumaun Himalaya); Wunnemann et al., 2010 (Tsokar Lake, Ladakh), etc.

Shankar et al. (2006) have given the rationale for using standard range of magnetic parameters, such as magnetic susceptibility ($\chi_{lf}$) and percentage of frequency dependent susceptibility ($\chi_{fd\%}$) for the reconstruction of palaeoclimatic conditions in the catchment area of small tanks in semi-arid parts of Chitradurg, Karnataka. They found a good positive relationship between low-frequency magnetic susceptibility ($\chi_{lf}$) and monsoonal rainfall. Thus, they had proposed that magnetic susceptibility may be used as a proxy for studying past monsoon rainfall variations. According to them, the link between $\chi_{lf}$ and rainfall in the catchment is as follows:

a) During high-rainfall events, the proportion of silt and sand fractions will be high thus increasing the fluxes of terrigenous material and magnetic minerals into the tank.

b) During low-rainfall events, the proportion of clay fraction will be higher but the fluxes of terrigenous material and magnetic minerals into the tanks will be low.

In the present study, the above link forms the basis of interpretation of magnetic susceptibility ($\chi_{lf}$) and percentage frequency dependent susceptibility ($\chi_{fd\%}$). The magnetic susceptibility ($\chi_{lf}$) is a measure of concentration of magnetic minerals and
percentage of frequency dependent susceptibility ($\chi_{fd\%}$) is a measure of concentration of Super Paramagnetic (SP) particles.

Warrier and Shankar (2009) have shown that pedogenic $\chi_{lf}$ and pedogenic $\chi_{fd\%}$ are positively correlated with monsoon rainfall data for Chitradurga station and Peninsular India, suggesting that the content of pedogenic magnetite is controlled by monsoon rainfall in the catchment. They also have shown that Metal/Al (indicators of chemical weathering intensity) ratios are positively correlated with $\chi_{lf}$, suggesting a terrigenous source for magnetic minerals. Thus, they have provided the geochemical evidence for the proposition that $\chi_{lf}$ may be used as proxy for past monsoonal rainfall.

4.2 Methodology:

The methodology of mineral magnetic measurements involves preparation of samples and measurement of samples with the help of magnetic susceptibility sensors. It should be noted here that only one pit from each tank with relatively longer record was selected for mineral magnetic measurements due to limited time available for analysis at IIG. The mineral magnetic measurements were not carried out for Pashan Tank sediments because the depth of Pashan Tank pit was very small.

Preparation of samples:

A 25-30 gm of oven dried sediment sample was taken into the mortar. Care was taken to clean the mortar and pestle with the ethanol and tissue paper. The sediment samples were ground with the help of mortar and pestle until the material has become homogeneous (fine one). The plastic film (paper) has been kept into the 10 cm$^3$ non-magnetic plastic bottles to wrap sediments and weighing of empty bottles was carried out. The fine sediments were placed into the plastic bottles and tamped down with the flat end of a fiber rod until sediments were packed tightly. The weighing of bottles with sediment sample were done and then the weight of empty bottles were subtracted from the weight of bottles with sediment sample to obtain exact weight of the sediment samples used for magnetic susceptibility measurements. While processing samples, the use of iron implements was avoided because of the risk of contamination. The implements built from
the stainless steel, aluminum and plastic were used for the preparation of samples, because they provide a much reduced risk of contamination.

**Measurements of samples:**

Magnetic susceptibility measurements were performed on the bulk sediment samples of all tanks using Bartington MS2B magnetic susceptibility meter with a dual-frequency sensor operating at low and high frequency magnetic susceptibility (0.47 kHz and 4.7 kHz), and an AGICO’s KLY-2 Kappabridge susceptibility meter. After starting the susceptibility meter, it was allowed to warm up for 15-20 minutes. Then the sensor was calibrated using the ferrite bead/Fe$_2$O$_3$ provided by the manufacturer. The plastic bottles containing sediment samples were placed into the sensor of susceptibility meter and magnetic measurements were made. Each sample was measured for three times with both frequencies and the average value of these three measurements were taken into consideration for further analysis. Two air measurements were made before and after the measurement of the samples. The average value of two air measurements was deducted from the actual value of sample measurement. The metal objects (such as screws, nails, coins, rings, jewellery, metal buttons etc.) were kept away from the instrument because they can affect on the magnetic measurements. The rock magnetic parameters, such as low-frequency mass specific magnetic susceptibility ($\chi_{lf}$) and its frequency dependent component ($\chi_{fd}{\%}$), were calculated from low-frequency and high-frequency measurements to get some idea about the concentration and grain size distribution of magnetic minerals. Following Basavaiah and Khadkikar (2004) and Foster et al. (2008) the calculations of Magnetic Susceptibility ($\chi_{lf}$) and Percentage Frequency Dependent Susceptibility ($\chi_{fd}{\%}$):

$$\chi_{lf} = \chi_{LF} \times 10^{-5} \times 10^{-5} m^3 / (g \times 10^{-3} kg) \quad (Eq. 1)$$

Where, ‘$\chi_{lf}$’ represents mass specific magnetic susceptibility, ‘$\chi_{LF}$’ represents susceptibility values measured at 0.47 kHz and ‘g’ shows the weight of sediment sample in grams.

$$\chi_{fd}{\%} = ((\chi_{LF} - \chi_{HF}) / \chi_{LF}) \times 100 \quad (Eq. 2)$$
Where, $\chi_{fd\%}$ represents percentage frequency dependent susceptibility. $\chi_{LF}$ and $\chi_{HF}$ represent susceptibility values measured at 0.47 and 4.7 kHz, respectively.

The Anhysteretic Remanent Magnetisation (ARM) and Isothermal Remanent Magnetisation (IRM) measurements were carried out for sediments of Sarola Tank only because the result of ARM and IRM measurements were not promising and secondly, due to limited laboratory time slot availability for analysis. The ARM was measured using Frequency Alternating Field (AF) demagnetizer with ARM attachment and Molspin spinner magnetometer. First, the samples were subjected to the 100 MilliTesla (mT) and 0.05 mT fields and then ARM intensity was measured on Molspin spinner magnetometer. With the help of ARM intensity, the ARM and $\chi_{ARM}$ (susceptibility of ARM) were calculated using following formulae (Basavaiah and Khadkikar, 2004; Shankar et al., 2006).

$$\text{ARM} = \text{ARM intensity} \times 10^{-5} \text{Am}^2/(g \times 10^{-3} \text{kg}) \quad \text{Eq. 3}$$

$$\chi_{ARM} = \text{ARM} \times 10^{-5} \text{m}^3 \text{kg}^{-1}/39.79 \quad \text{Eq. 4}$$

where, 39.79 represents the size of the biasing field at 0.05 mT = 39.79 A m$^{-1}$

The IRM was measured at fields starting from 20 mT up to 300 mT using a Molspin pulse magnetizer. The isothermal remanence obtained at the highest field of 300 mT was considered as Saturation Isothermal Remanent Magnetisation (SIRM).

$$\text{IRM} = \text{IRM} \times 10^{-5} \text{Am}^2 \text{kg}^{-1} \quad \text{Eq. 5}$$

$$\text{SIRM} = \text{IRM} \times 10^{-5} \text{Am}^2 \text{kg}^{-1} \quad \text{Eq. 6}$$

By using ARM, IRM and SIRM, following mineral magnetic parameters were calculated.

$$\text{ARM/}\chi (10^2 \text{Am}^{-1}) \quad \text{Eq. 7}$$

$$\text{ARM/SIRM} \quad \text{Eq. 8}$$

$$\text{Soft-IRM} = (\text{SIRM} - \text{IRM}_{30\text{mT}}) (10^{-5} \text{Am}^2 \text{kg}^{-1}) \quad \text{Eq. 9}$$

$$\text{Hard-IRM} = (\text{SIRM} - \text{IRM}_{300\text{mT}}) (10^{-5} \text{Am}^2 \text{kg}^{-1}) \quad \text{Eq. 10}$$

$$\text{S-Ratio} = (\text{IRM}_{300\text{mT}} / \text{SIRM}) \quad \text{Eq. 11}$$

The meaning and interpretation of the above mentioned mineral magnetic parameters is given in Table 4.1.
Table 4.1 Mineral magnetic parameters and their interpretation.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\chi_{lf}$</td>
<td>Proportional to the concentration of magnetic minerals</td>
</tr>
<tr>
<td>2.</td>
<td>$\chi_{fd}$ (%)</td>
<td>Proportional to the concentration of super paramagnetic magnetic minerals</td>
</tr>
<tr>
<td>3.</td>
<td>ARM</td>
<td>It allows estimation of concentration and presence of finer ferromagnetic minerals</td>
</tr>
<tr>
<td>4.</td>
<td>$\chi_{ARM}$</td>
<td>Proportional to the concentration of magnetic minerals of stable single domain size range</td>
</tr>
<tr>
<td>5.</td>
<td>IRM, SIRM</td>
<td>Relates to both mineral types and concentration</td>
</tr>
<tr>
<td>6.</td>
<td>ARM/$\chi$, ARM/SIRM</td>
<td>High values denote significant stable single domain (SSD) (magnetite) grains</td>
</tr>
<tr>
<td>7.</td>
<td>ARM/SIRM</td>
<td>Low values indicate a large multi domain (MD) (magnetite) grains</td>
</tr>
<tr>
<td>8.</td>
<td>Hard-IRM</td>
<td>Proportional to the concentration of magnetically ‘hard’ minerals like hematite and goethite</td>
</tr>
<tr>
<td>9.</td>
<td>S-Ratio</td>
<td>Relative proportions of ferrimagnetic and anti-ferromagnetic minerals (high ratio = relatively high proportion of magnetite)</td>
</tr>
</tbody>
</table>


4.3 Mineral magnetic properties of the tank deposits:

The sample-wise results of all the tanks are given in Appendix I. The salient features of each tank are discussed below.

4.3.1 Bhatodi Tank Pit-II

The results of mineral magnetic properties for Pit-II of Bhatodi Tank are given in Table 4.2. From the table it is observed that the percentage frequency dependent susceptibility of the samples varies between 0.52 and 1.95%. The average is 1.44%. The magnetic susceptibility ranges from 40.7 to 104.77$\times$10$^{-7}$m$^3$kg$^{-1}$ and the average of magnetic susceptibility is 71.54$\times$10$^{-7}$m$^3$kg$^{-1}$. 
Table 4.2 Mineral magnetic properties of tanks deposit.

<table>
<thead>
<tr>
<th>Tank and Pit</th>
<th>Magnetic properties</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\chi_{fd}%$</td>
<td>1.44</td>
<td>0.52</td>
<td>1.95</td>
</tr>
<tr>
<td>Bhatodi Pit-II</td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>71.54</td>
<td>40.70</td>
<td>104.77</td>
</tr>
<tr>
<td></td>
<td>$\chi_{fd}%$</td>
<td>1.50</td>
<td>1.15</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>102.08</td>
<td>73.97</td>
<td>124.73</td>
</tr>
<tr>
<td>Sarola Pit-II</td>
<td>$\chi_{fd}%$</td>
<td>4.13</td>
<td>3.09</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>38.05</td>
<td>22.82</td>
<td>56.56</td>
</tr>
<tr>
<td>Kapurwadi Pit-I</td>
<td>$\chi_{fd}%$</td>
<td>1.71</td>
<td>0.81</td>
<td>2.47</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>81.86</td>
<td>57.34</td>
<td>111.54</td>
</tr>
<tr>
<td>Mastani Pit-I</td>
<td>$\chi_{fd}%$</td>
<td>2.60</td>
<td>1.36</td>
<td>3.62</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>172.78</td>
<td>38.89</td>
<td>403.15</td>
</tr>
<tr>
<td>Supa Pit-I</td>
<td>$\chi_{fd}%$</td>
<td>3.61</td>
<td>1.59</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>59.25</td>
<td>24.81</td>
<td>124.45</td>
</tr>
<tr>
<td>Pushkar Pit-I</td>
<td>$\chi_{fd}%$</td>
<td>3.37</td>
<td>0.45</td>
<td>5.59</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>7.97</td>
<td>4.32</td>
<td>37.54</td>
</tr>
<tr>
<td>Vaghad Pit-I</td>
<td>$\chi_{fd}%$</td>
<td>3.37</td>
<td>0.45</td>
<td>5.59</td>
</tr>
<tr>
<td></td>
<td>$\chi_f$ (10^{-7} m^3/kg)</td>
<td>7.97</td>
<td>4.32</td>
<td>37.54</td>
</tr>
</tbody>
</table>

The plot for Bhatodi Tank Pit II (Fig. 4.1) shows two major changes in the $\chi_f$ and $\chi_{fd}\%$ variation separated at ~250 cm. The lower part shows large fluctuations in $\chi_f$ as well as $\chi_{fd}\%$. There is a clear inverse relation between the two as can be seen by the inter correlation of the major peaks in the $\chi_f$ corresponding to drop in $\chi_{fd}\%$. This overall trend depicts a clear detrital control of $\chi_f$ indicating major sediment flux at ~460, ~335 and 280 cm levels, perhaps due to the increase in the rainfall. This follows the major change over at 250 cm with drop in $\chi_f$ and corresponding high $\chi_{fd}\%$. The upper part after this interval shows low variation in both the parameters although the inverse relation is still maintained. This part is therefore, suitable to derive proxy climatic signatures. The vertical variation, thus indicates a detrital control for the lower part followed by low variability in the upper part (Fig. 4.1). The interval at ~250 cm, therefore, suggests a shift in the tank sedimentation system in response to climatic variability.

The plot of magnetic susceptibility ($\chi_f$) against percentage frequency dependent susceptibility ($\chi_{fd}\%$), given in Fig. 4.2, reveals a negative but very weak statistical relationship between $\chi_f$ and $\chi_{fd}\%$.

4.3.2 Sarola Tank Pit-II

The mineral magnetic data of Sarola Tank, Pit-II is presented in Table 4.2. It is evident that the percentage frequency dependent susceptibility of the samples varies between 1.15 and 1.95%. The magnetic susceptibility ranges from 73.97 to 124.77*10^{-7}
Fig. 4.1 Vertical variation in the % frequency dependent susceptibility ($\chi_{fd}$%) and magnetic susceptibility ($\chi_{lf}$) in ($10^{-7} \text{ m}^3\text{kg}^{-1}$) for Bhatodi Tank, Pit-II.
Fig. 4.2 Bivariate plots of magnetic susceptibility ($\chi_{lf}$) and percentage frequency dependent susceptibility ($\chi_{fd\%}$) values.
m³kg⁻¹. The average values of χ₇fd% and χ₇lf are 1.50% and 102.08×10⁻⁷m³kg⁻¹ respectively.

Unlike Bhatodi Tank, the vertical variation in the values of χ₇fd% and χ₇lf shows a general decrease in the magnetic susceptibility towards the top (Fig. 4.3). By and large, depth-wise slight cyclic variations are seen in the distribution of χ₇fd%. The lowest value (1.15%) of χ₇fd% and highest value (124.73×10⁻⁷m³kg⁻¹) of χ₇lf is noticed at the depth of ~250 cm from the top. The highest magnetic susceptibility value at of ~250 cm indicates high concentration of mineral magnetic particles, most likely due to increased sediment flux. The lithosection can be divided into two parts (Part-I, 0 to ~250 cm and Part-II, ~250 to 425 cm) on the basis of variation in the concentration of magnetic minerals in the sediments. From the depth of ~250 cm, the χ₇lf decreases towards top and bottom of the profile. The lowermost unit (~350 to 425 cm) indicates high variation in the amount of χ₇fd% (Fig. 4.3).

The plot of magnetic susceptibility (χ₇lf) versus percentage frequency dependent susceptibility (χ₇fd%) given in Fig. 4.2, indicates a poor relationship between χ₇lf and χ₇fd%.

Figs. 4.4 and 4.5 show vertical variation in the different mineral magnetic parameters of Sarola Tank, Pit-II sediments. A χ₇lf trough at 360 cm corresponds to low ARM, χ₇ARM, χ₇fd%, soft-IRM and higher S-ratio and decreasing clay content (Figs. 4.4 and 4.5). This indicates higher detrital influx controlled by a mixture of multi-domain (MD) and super-paramagnetic (SP) grains. The entire scenario of gradual trend from base with peak at 360 cm, therefore, could be assigned to change in sedimentation regime. The lower part initially received the catchment soils to fill the tank which was followed by an episode of relatively prolonged higher precipitation bringing the detrital MD grains along with SP fraction. Such conditions can favorably occur during prolonged summer (drought) followed by the precipitation as in arid condition. Hence, this interval (base to 360 cm) may indicate semi-arid to arid transition and the event at 360 cm may be related to a drought event.

Further from 350 to 250 cm, the χ₇lf is almost steady along with ARM, χ₇ARM and soft-IRM. However there is a gradual decrease in χ₇fd% along with clay content. This steady state of climatic condition is followed by a zone (at the depth of 250 cm) of anomalous high susceptibility and soft-IRM and lowest χ₇fd%, ARM/SIRM and clay
Fig. 4.3 The % frequency dependent susceptibility ($\chi_{fd} \%$) and magnetic susceptibility ($\chi_{lf} * 10^{-7} m^3 kg^{-1}$) plots for Sarola Tank, Pit-II.
Fig. 4.4 Plot showing the vertical variations in the clay %, $\chi_{lf}$ ($10^{-7}$ m$^3$ kg$^{-1}$), $\chi_{fd}$%, ARM ($10^{-5}$ Am$^2$ kg$^{-1}$), $\chi_{ARM}$ ($10^{-5}$ m$^3$ kg$^{-1}$) and ARM/$\chi$ ($10^{2}$ Am$^{-1}$) for Sarola Tank, Pit-II.
Fig. 4.5 Plot showing the depth-wise variations in the ARM/SIRM, Soft-IRM ($10^{-5}$ Am$^2$ kg$^{-1}$), Hard-IRM ($10^{-5}$ Am$^2$ kg$^{-1}$), S-Ratio-100mT and S-Ratio-300mT for Sarola Tank, Pit-II.
content (Figs. 4.4 and 4.5). The combination of low $\chi_{fd}\%$, high $\chi_{lf}$ and higher soft and hard IRM indicates majority of MD fraction due to higher precipitation unlike the precious event (at 360 cm) where the precipitation occurred during drought condition.

The interval from ~230 to ~100 cm is further marked by steady state climatic condition because no major variation is observed in the mineral magnetic parameters. The interval from ~100 cm to top show steady decrease in $\chi_{lf}$ along with clay but higher ARM content indicates overall decrease in the rainfall as well as seasonality.

### 4.3.3 Kapurwadi Tank Pit-I

The mineral magnetic analysis of Kapurwadi Tank sediments reveals that the percentage frequency dependent susceptibility ($\chi_{fd}\%$) varies between 3.09 and 5.86% and average is about 4.13%. The magnetic susceptibility constitutes about $38.05 \times 10^{-7} \text{m}^3\text{kg}^{-1}$ and it ranges between 22.82 and $56.56 \times 10^{-7} \text{m}^3\text{kg}^{-1}$ (Table 4.2).

The plots of mineral magnetic properties indicate that, by and large, the $\chi_{fd}\%$ has clear inverse relationship with $\chi_{lf}$ (Fig. 4.6). The $\chi_{fd}\%$ gradually increases from bottom to top of the profile. Variation in the $\chi_{lf}$ reflects gross changes in the relative concentration of magnetic minerals. The highest concentration of magnetic minerals observed at the depth of 35 cm from the top (Fig. 4.6). Overall profile shows high variability in both the parameters. The plot (Fig. 4.6) of vertical variation in the amount of concentration of mineral magnetic particles in the sediments generally shows cyclic changes. The major peaks of magnetic susceptibility at 35, 120, 160, 190, 270 and 325 cm indicate increased amount of mineral magnetic fraction due to major sediment flux into the tank. This indicates increase in the runoff perhaps in response to higher monsoon rainfall.

Fig. 4.2 shows the variation in the magnetic susceptibility ($\chi_{lf}$) and percentage frequency dependent susceptibility ($\chi_{fd}\%$), for sediment samples. From the figure it is evident that as the $\chi_{lf}$ increases, the $\chi_{fd}\%$ decreases, indicating a good negative correlation between the two.

### 4.3.4 Mastani Tank Pit-I

The mineral magnetic properties for Mastani Tank, Pit-I are shown in Table 4.2. From the data it is apparent that the percentage frequency dependent susceptibility of the
Fig. 4.6 Magnetic properties measured for samples taken from a deep lithoprofile of Kapurwadi Tank, Pit-I.
samples varies between 0.81 and 2.47% and the magnetic susceptibility ranges from 57.34 to 111.54*10^{-7} m^3 kg^{-1}. The average values of $\chi_{fd\%}$ and $\chi_{lf}$ are 1.71% and 81.86*10^{-7} m^3 kg^{-1} respectively.

Trend analysis reveals that the magnetic susceptibility values decrease toward the top but the values of percentage frequency dependent susceptibility increases towards the top. Like Bhatodi and Sarola Tank, the lithosection of this tank is also divided into two major parts from the depth of ~250 cm on the basis of vertical variation in the $\chi_{lf}$ and $\chi_{fd\%}$ (Fig. 4.7). The upper part (0 to 250 cm) shows low variation whereas lower part (250 to 440 cm) indicates higher variation in both the parameters. The highest concentration of magnetic particles is noticed at 310 cm level. This increase in the sedimentation into the tank suggests enhanced rainfall in the catchment. The bivariate plot (Fig. 4.2) of $\chi_{lf}$ and $\chi_{fd\%}$ shows that they are negatively correlated, but the correlation is weak.

### 4.3.5 Supa Tank Pit-I

The results of magnetic properties (Table 4.2) suggest that the percentage frequency dependent susceptibility varies between 1.36 and 3.62% while magnetic susceptibility ranges between 38.89 and 403.15*10^{-7} m^3 kg^{-1}. The Supa Tank sediments show more variation in the values of $\chi_{lf}$ as compared to $\chi_{lf}$ values of any other tank sediments. The average of $\chi_{fd\%}$ is 2.60% and $\chi_{lf}$ is 172.78*10^{-7} m^3 kg^{-1}.

From the plots of vertical variation in the percentage frequency dependent susceptibility ($\chi_{fd\%}$) and magnetic susceptibility($\chi_{lf}$) (Fig. 4.8) it is evident that the $\chi_{fd\%}$ decreases while $\chi_{lf}$ increases in the upward direction. A perfect opposite trend is noticed in the plots of magnetic properties (Fig. 4.8). This lithoprofile also shows two major changes like Bhatodi and Mastani Tanks in the vertical variation of $\chi_{lf}$ and $\chi_{fd\%}$ separated at ~130 cm. The lower part shows small fluctuations and the upper part reveals large fluctuations in the distribution of $\chi_{lf}$ and $\chi_{fd\%}$. If the entire profile is considered, the uppermost unit is characterized by high concentration of magnetic minerals and lowermost unit constitutes low amount of mineral magnetic particles in the sediments.
Fig. 4.7 Mineral magnetic variations for Mastani Tank, Pit-I.
Fig. 4.8 The % frequency dependent susceptibility ($\chi_{fd}$%) and magnetic susceptibility ($\chi_{lf}$) versus depth for Supa Tank, Pit-I.
(Fig. 4.8). This most likely suggests that in recent years the rainfall of the catchment area of the Supa Tank has been increased as compared to the earlier period.

4.3.6 Pushkar Tank Pit-I

The mineral magnetic analysis of Pushkar Tank sediments indicates that the percentage frequency dependent susceptibility ($\chi_{fd\%}$) varies between 1.59 and 4.23% and average is about 3.61%. The mean of magnetic susceptibility is about $59.25 \times 10^{-7} \text{m}^3\text{kg}^{-1}$ and it ranges between 24.81 and $124.45 \times 10^{-7} \text{m}^3\text{kg}^{-1}$ (Table 4.2).

Fig. 4.9 illustrates the vertical variation in the mineral magnetic properties of the Pit-I of Pushkar Tank. The plots do not reveal any distinct co-variation in the percentage frequency dependent susceptibility and magnetic susceptibility (Fig. 4.9). The plot of $\chi_{fd\%}$ shows random vertical variations. The distribution of $\chi_{lf\%}$ remains, more or less, identical from 0 to 45 cm, 90 to 115 cm and from 145 to 190 cm. In general, increased amount of super paramagnetic particles ($\chi_{fd\%}$) is observed from 45 to 90 cm and 115 to 145 cm. The lowermost unit (190 to 240 cm) is characterized by cyclic variations in the $\chi_{fd\%}$ (Fig. 4.9). As far as the depthwise variation of $\chi_{lf}$ is concerned, the upper portion (0 to 80 cm) of the lithosection shows large fluctuations whereas the lower unit (80 to 240 cm) indicates low variability in $\chi_{lf}$. High peaks of $\chi_{lf}$ are identified at the depths of 65, 155 and 235 cm, indicating high concentration of fractions of magnetic minerals (Fig. 4.9).

Fig. 4.2 shows the nature of variation in the magnetic susceptibility ($\chi_{lf}$) with the variation in the percentage frequency dependent susceptibility ($\chi_{fd\%}$). The plot indicates that, by and large, as $\chi_{lf}$ increases there is decrease in $\chi_{fd\%}$.

4.3.7 Vaghad Tank Pit-I

From the mineral magnetic data (Table 4.2) it is evident that the average of percentage frequency dependent susceptibility of the samples is 3.37% and it varies between 0.45 and 5.59%. The magnetic susceptibility ranges from $4.32 \times 10^{-7} \text{m}^3\text{kg}^{-1}$ to $37.54 \times 10^{-7} \text{m}^3\text{kg}^{-1}$ and the mean is $9.97 \times 10^{-7} \text{m}^3\text{kg}^{-1}$.

Inverse trend is observed for both the parameters (Fig. 4.10). Whereas the magnetic susceptibility shows an increase towards the top, the values of percentage
Fig. 4.9 Depth-wise variation in the mineral magnetic properties for Pushkar Tank, Pit-I.
Fig. 4.10 Plot of % frequency dependent susceptibility ($\chi_{fd}$%) and magnetic susceptibility values ($\chi_{lf}$) for Vaghad Tank, Pit-I.
frequency dependent susceptibility shows a decline. Another important feature of the pit is a sudden increase in the $\chi_{lf}$ at a depth of 55 cm from the top, suggesting more concentration of magnetic minerals due to increased sediment flux into the tank (Fig. 4.10). The upper portion of the profile is characterized by more variation (increased monsoon variability), whereas lower portion shows less variation in the magnetic properties (low monsoon variability).

The plot given in Fig. 4.2 illustrates a negative but weak relationship between magnetic susceptibility and percentage frequency dependent susceptibility.

4.3.8 Vertical variation in the magnetic susceptibility ($\chi_{lf}$) of sediments of all tanks:

From the combined plot of magnetic susceptibility ($\chi_{lf}$) (Fig. 4.11), it can be concluded that the magnetic susceptibility generally increases from bottom to top for Bhatodi Tank, Supa Tank, Pushkar Tank and Vaghad Tank sediments. But a decreasing trend is noticed for Sarola Tank and Mastani Tank sediments. The Kapurwadi Tank sediments do not show any particular trend in the $\chi_{lf}$ but random variations (Fig. 4.11). The interval at ~250 cm for Bhatodi, Sarola and Mastani Tanks and interval at ~130 cm for Supa, Pushkar and Vaghad Tanks divide the lithosections into two major parts. The upper portion of the Supa, Pushkar and Vaghad Tanks lithosections and lower part of the Bhatodi and Mastani Tanks lithosections show high fluctuations in $\chi_{lf}$ and $\chi_{fd}\%$, indicating high variability in the sediment flux. The intervals at ~250 and ~130 cm suggest a major shift in the tank sedimentation system in response to change in the monsoon strength (Fig. 4.11).

By and large, inverse relationship is noticed in the vertical variation of percentage of clay and magnetic susceptibility (Figs. 4.12 and 4.13). A perfect negative trend is observed at the lithoprofile of Kapurwadi Tank (Fig. 4.12). From the plots (Figs. 4.12 and 4.13), it can be concluded that, as the percentage of clay increases, the concentration of magnetic minerals decreases.
Fig. 4.11 A combined plot showing the vertical variation in the magnetic susceptibility ($\chi_l$) in ($10^{-7}$ m$^3$kg$^{-1}$) for Pit-II of Bhatodi and Sarola Tanks sediment and Pit-I of Kapurwadi, Mastani, Supa, Pushkar and Vaghad Tanks sediment.
Fig. 4.12 Relationship between percentage of clay and the magnetic susceptibility ($\chi_{lf}$) in ($10^{-7} \text{m}^3\text{kg}^{-1}$) for Bhatodi Tank (Pit-II), Sarola Tank (Pit-II), Kapurwadi Tank (Pit-I) and Mastani Tank (Pit-I) deposits.
Fig. 4.13 Plot showing the relationship between the percentage of clay and the magnetic susceptibility ($\chi_{lf}$) in ($10^{-7} m^3 kg^{-1}$) for Supa Tank (Pit-I), Pushkar Tank (Pit-I) and Vaghad Tank (Pit-I) deposits.
4.3.9 Relationship between textural classes and magnetic susceptibility ($\chi_{lf}$):

Figs. 4.14 and 4.15 show the correlation between textural classes and magnetic susceptibility. The plots given in Fig. 4.14 indicate positive relationship between sand-silt% and magnetic susceptibility. The magnetic susceptibility increases with increase in the percentage of sand and silt.

The plots shown in the Fig. 4.15 indicates negative relationship between percentage of clay and magnetic susceptibility, as expected. Generally, as percentage of clay increases, there is decrease in the magnetic susceptibility. This means that the particles of magnetic minerals are less concentrated in the clay and more concentrated in the sand and silt sized particles. The plots of Kapurwadi and Supa Tanks show a good inverse relationship between clay % and $\chi_{lf}$ (Fig. 4.15).

4.4 Summary of the results:

The following table gives the salient features of the mineral magnetic analysis for all the eight tanks.

<table>
<thead>
<tr>
<th>Parameter Tank and Pit</th>
<th>Average $\chi_{ld}$%</th>
<th>Average $\chi_{lf}$ ($10^{-7}$ m$^3$ kg$^{-1}$)</th>
<th>Correlation (r) between $\chi_{lf}$ and $\chi_{ld}$%</th>
<th>Correlation (r) between sand silt % and $\chi_{lf}$</th>
<th>Correlation (r) between clay % and $\chi_{lf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bhatodi Pit-II</td>
<td>1.44</td>
<td>71.54</td>
<td>-0.12*</td>
<td>0.33*</td>
<td>-0.32*</td>
</tr>
<tr>
<td>Sarola Pit-II</td>
<td>1.50</td>
<td>102.08</td>
<td>-0.24*</td>
<td>0.45*</td>
<td>-0.45*</td>
</tr>
<tr>
<td>Kapurwadi Pit-I</td>
<td>4.13</td>
<td>38.08</td>
<td>-0.63*</td>
<td>0.74*</td>
<td>-0.74*</td>
</tr>
<tr>
<td>Mastani Pit-I</td>
<td>1.71</td>
<td>81.86</td>
<td>-0.40^</td>
<td>0.62*</td>
<td>-0.60*</td>
</tr>
<tr>
<td>Supa Pit-I</td>
<td>2.60</td>
<td>172.78</td>
<td>-0.86*</td>
<td>0.79*</td>
<td>-0.79*</td>
</tr>
<tr>
<td>Pushkar Pit-I</td>
<td>3.61</td>
<td>59.25</td>
<td>-0.45*</td>
<td>0.42^</td>
<td>-0.42^</td>
</tr>
<tr>
<td>Vaghad Pit-I</td>
<td>3.37</td>
<td>7.97</td>
<td>-0.26*</td>
<td>0.66*</td>
<td>-0.67*</td>
</tr>
<tr>
<td>*Correlations significant at 0.001 level; ^Correlations significant at 0.01 level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlations significant at 0.05 level; xInsignificant correlation.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Relatively high average $\chi_{ld}$% (4.13) is observed (Table 4.3) in the deposits of Kapurwadi Tank, indicating high concentration of super paramagnetic minerals in the sediments. The highest average value (172.78) of magnetic susceptibility is noticed in the Supa Tank sediments and relatively more average susceptibility (Table 4.3) observed in the deposits of Sarola and Mastani Tanks. The high magnetic susceptibility values of
Fig. 4.14 Bivariate plots of sand-silt % against magnetic susceptibility (\(\chi_{lf} \times 10^{-7} \text{m}^3\text{kg}^{-1}\)).
Fig. 4.15 Plots showing relationship between clay % and magnetic susceptibility ($\chi_{lf}$) in ($10^{-7}$ m$^3$kg$^{-1}$).
these tanks indicate high sediment flux into the tank may be due to the increased monsoon rainfall. The Supa, Sarola and Mastani Tanks are located in the semi-arid climatic region and in the foothill zone. The lowest average value of magnetic susceptibility is occurred in the Vaghad Tank deposits indicate low sediment flux into the tank and dominance of fines. This tank is located in sub-humid climatic region.

A strong positive relationship is observed in the magnetic susceptibility and sand silt % for all tanks (Table 4.3).

4.5 Key points from this chapter:

There are several conclusions to be drawn from the data presented in this section. Only the most salient ones are listed below

1. Magnetic susceptibility values increase towards the top at Bhatodi, Supa, Pushkar and Vaghad Tanks, but decrease towards the top at Sarola and Mastani Tanks.

2. The $\chi_{fd} \%$ ranges between 1.44 and 4.13% whereas $\chi_{lf}$ varies between 7.97 and $172.78 \times 10^{-7} \text{m}^3\text{kg}^{-1}$

3. The high mineral magnetic concentration (average $\chi_{lf}$ is $172.78 \times 10^{-7} \text{m}^3\text{kg}^{-1}$) is observed in the Supa Tank sediments which correspond to the high silt and sand content of the tank.

4. The low mineral magnetic concentration (average $\chi_{lf}$ is $7.97 \times 10^{-7} \text{m}^3\text{kg}^{-1}$) is noticed in the Vaghad Tank sediments which correspond to the low percentage of silt and sand. This tank’s sediments constitute a very high percentage of clay.

5. By and large, all tank deposits have inverse relationship between magnetic susceptibility ($\chi_{lf}$) and percentage frequency dependent susceptibility ($\chi_{fd} \%$). This means that as the $\chi_{lf}$ increases, the values of $\chi_{fd} \%$ decrease.

6. All profiles show a statistically significant positive trend between sand-silt % and $\chi_{lf}$. This means that as the percentage of sand and silt increases, there is an increase in the values of magnetic susceptibility (Shankar et al., 2006, observed identical trend).

7. All profiles show a statistically significant negative trend between clay % and $\chi_{lf}$ implying that as the percentage of clay increases, values of $\chi_{lf}$ decrease (Shankar et al., 2006, suggested same trend).
8. The interval at ~250 cm for Bhatodi, Sarola and Mastani Tanks and interval at 
~130 cm for Supa, Pushkar and Vaghad Tanks suggest a noteworthy shift in the 
tank sedimentation system. This, in turn, implies some change in the monsoon 
rainfall characteristics within the catchment of the tanks.