Anomalous Magnetic Fabric in Apparently Undeformed Lacustrine Deposits: A Case Study from NW Trans-Himalaya, Ladakh, India

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Abstract

In the present study, an integrated approach of field observations and magnetic analysis has been used to study the Khalsar paleolake deposits of the Trans-Himalayan region with the objectives of correlating its magnetic fabric with the mesoscopic features. Any signature of deformation in a lake deposit can be deciphered by visible strain markers like the seismites, micro folds and faults; however, in areas where this visible deformation is absent, it is challenging to carry out strain quantification. Thus a proxy like low-field magnetic susceptibility can be useful for fabric quantification in these sediments. The fluvio-lacustrine deposit at Khalsar is characterized by seismites in its middle part while the upper part is devoid of any such features. The magnetic anisotropy indicates presence of tectonic fabric and E-W trending vertical to sub-vertical foliation in the entire section with magnetite being the major magnetic mineral contributing to laboratory-induced isothermal remanence in these sediments. This vertical to subvertical magnetic fabric is anomalous with respect to the horizontal bedding planes present within this lake deposit. It is envisaged that the vertical magnetic foliation has developed due to migration and deposition of magnetic minerals along the vertical cracks present within the Khalsar lake deposits. This mechanism is similar to formation of ‘pressure solution cleavage’ in mudrocks, in which re-orientation and/or authigenic growth of magnetite can take place leading to the development of an anomalous magnetic fabric.

Keywords: Trans Himalaya, Karakoram Fault Zone, fluvio-lacustrine deposits, Anisotropy of magnetic susceptibility, magnetic mineralogy.

Introduction

Due to their widespread occurrence and relatively simple dating techniques, lake deposits have been an integral part of palaeoclimatic and related environmental studies. However, their potential as an indicator of regional deformation event has remained unexplored due to lack of strain markers at outcrop scale. Fabric quantification of lake sediments is challenging as they generally do not bear any visible mesoscopic markers. Thus, identifying signatures of any deformation event and making kinematic inferences in them is not possible by conventional structural methods and some proxy like low field magnetic susceptibility is warranted. In the past two decades anisotropy of magnetic susceptibility (AMS) has become an important and widely used tool for fabric analysis and strain quantification of sedimentary rocks. During tectonic activities the primary sedimentary fabric is progressively replaced by a tectonic fabric.
different stages of this fabric evolution have been analyzed with the help of AMS by various workers in fold and thrust belts (Averbuch et al., 1992; Bakhtari et al., 1998; Parés et al., 1999; Frizon de Lamotte et al., 2002; Robion et al., 2007, etc.) and especially in mudrocks (Parés and van der Pluijm, 2003, 2004; Parés, 2004). In the last few decades AMS has been increasingly recognized as a useful tool for unraveling the deformation history of sediments, where no evident pervasive tectonic structures develop during deformation, in both compressional and extensional tectonic regimes (Kissel et al., 1986; Mattei et al., 1997; Parés and van der Pluijm, 2003, 2004; Parés, 2004; Cifelli et al., 2004, 2005). The present work is the first attempt to classify the fabric present within the fluvio-lacustrine deposits of the Khalsar palaeolake (Phartiyal et al., 2005; Phartiyal and Sharma, 2009) in the Trans-Himalayan region to infer the share of sedimentary and tectonic signatures in them.

The Shyok River (tributary of the Indus River) valley of the Trans-Himalayan ranges lies in the vicinity of the Karakoram Fault Zone (KFZ) (Fig. 1). The development of the Himalayan and Karakoram reliefs shows that the Indian-Tibetan tectonic orogeny was active during the Quaternary (Gansser, 1980, 1983). Thus, these mountain ranges are still undergoing active orogenesis and the area usually experiences seismic activity and undergoes deformation. The dextral, strike slip Karakoram Fault is one of the major regional structures of the Himalaya with an average long term slip rate of 3-11 mm/year and evidences of movement during the Quaternary times and is said to have accommodated most of the India-Asia convergence in recent geological past (Brown et al., 2002; Rutter et al., 2007 and references therein). In the Ladakh Himalaya KFZ is characterized by presence of thick piles of fluvio-lacustrine deposits, e.g. the Khalsar palaeolake sequence (Fig.1&2). These lake sediments bear signature of deformation events (seismites) in middle part whilst the upper part is completely devoid of any such features (Phartiyal and Sharma, 2009), which makes application of AMS vital to determine the level of strain in portions where the visible deformation (seismites) are absent.

**Geological Setting and Methodology**

Ladakh Himalaya lies in the Trans-Himalayan region, and is bounded by the NE-SW trending Karakoram Fault towards the north and the Indus Suture Zone (ISZ) towards the south (Fig. 1). The three tectonomorphic zones in the area from South to North are- Indus Suture Zone (ISZ); Shyok Suture Zone (SSZ) and Karakoram Plutonic Complex (KPC) (Thakur, 1981; Sinha, 1997). The rocks exposed in the region from south to north belong to Ladakh plutonic complex (consisting of intrusions of tonalite, granodiorite and granite), Khardung Formation (volcanogenic products namely, rhyolite, trachyte, dacite and andesite), Shyok Group (volcanics) and Karakoram plutonic complex (Fig. 1B). Shyok River (a tributary of the Indus) originates from the Rimo glacier, flows in a SE direction and after joining the Pangong range it takes a NW turn and flows parallel to its previous path along the KFZ. wide valley and becomes very wide at the confluence with its tributary, the Nubra river (Fig. 1). Thick Quaternary deposits are exposed along Pharkatokpo Nala, a tributary to Shyok River, around the Khardung village. This tributary joins Shyok River; in the northern part of the highest pass in the world- Khardung La (5,645 m). Similar deposits are visible at the Shyok-Nubra river confluence and along the right banks of Nubra Rivers that extend downstream till Udmuru village (Fig. 1B). This makes the extent of this fluvio-lacustrine deposit > 80 km in length and 2-3 km wide occupying the entire valley width. It
is presumed that movements in the geologically recent times on the Karakoram fault (Chevalier et al., 2005) and the Shyok suture and the related faults were responsible for the formation of the lake (Phartiyal et al., 2005).

Fig. 1: A. Location map and map showing major tectonic units of the Himalaya; B. Geological map of the Khalsar area showing distribution of Quaternary lacustrine deposits in the vicinity of Karakoram Fault Zone.
15 oriented samples were collected at different levels (Fig 3) for AMS studies from the outcrop section located at 34°19’57” N and 74°49’41”E. These samples were collected from the clay and silt sediments avoiding zones of debris flow and coarser material. The soft lake sediment samples were cut by hacksaw blades to obtain cubic specimens, later they were finished on sandpaper and coated with adhesive for measurement. The AMS was measured by KLY-3S Kappabridge (Agico, Czech Republic). For AMS measurements, 116 cubic specimens in total were obtained from 15 samples collected at different levels and the ‘SUSAR’ software was used to calculate the various parameters of AMS.

For magnetic mineralogy the isothermal remanent magnetisation (IRM) acquisition was carried out on selected samples. IRM was imparted at intervals of 20, 50, 70, 100, 200, 300 up to 2000mT on ASC Scientific IM 10-30 Implode Magnetizer and the remanences measured by Minispin Rock Magnetometer of Molspin, UK. Room temperature hysteresis loops were measured on 20–25 mg samples with a maximum field of 500 mT, using a Princeton Measurements alternating gradient force magnetometer (noise level $10^{-6}$ Am$^2$ kg$^{-1}$ for a 20mg sample). High temperature runs of susceptibility ($\chi$-T) were conducted with an Agico KLY 2 Kappabridge in combination with a CS-2 heating unit and ‘SUSTE’ software was used.

To supplement the magneto-mineralogical study, Scanning Electron Microscopy (SEM) was carried out. Two samples one with high susceptibility (>1000 µSI) and other with low (<500 µSI) susceptibility were chosen. Samples were powdered and iron rich components were separated using a bar magnet and then mounted on a glass slide and carbon coated. SEM images were obtained using a Zeiss EVO 40EP Scanning Electron Microscope with an accelerating voltage of 20 Kv and beam current of 3-6nA. Chemical composition was analyzed by EDS attachment using the QUANTAS software. The analyses were carried in the Wadia Institute of Himalayan Geology and partly at the Institut für Geologie und Paläontologie, Universität Tübingen.
Fig. 3: Lower hemisphere equal area projection of the magnetic susceptibility axes (K1-square, K2-triangle, K3-circle) showing dominance of tectonic fabric over primary sedimentary fabric, plotted against the lithosection of the (A) Upper Khalsar section and (B) Middle Khalsar section.
Results

Field observations, extent of palaeolake and lithology:

The section measured in this study is exposed by the Pharkatokpo Nala on the left bank of the Shyok River near Khalsar village (Fig. 1B). The sediments have an extensive lateral as well as vertical extent (Fig 2). The Khalsar section predominantly comprises of clay with occasional silt and sand horizons. However, most parts of the section are covered with boulder beds and debris flow deposits (Fig. 2&3). The clast composition includes chert, volcanics, granite, black slate, quartzite, chlorite schist and phyllite. The section could only be studied in parts (~40 m in parts) therefore a complete and connected stratigraphic sequence could not be derived, the sections has been described as lower, middle and upper after Phartiyal and Sharma (2009).

Lower section: A 6.5 m thick section stands on the southern river bed along the Khalsar-Shakti road. It dominantly comprises silty sand and fine-medium grained sand beds (Fig.3) with boulder bed with sub-rounded to rounded rock pebbles and boulders in the upper part (above 5 m). The stratum is horizontal and the boulder bed shows some clay and sand lenses and layers < 1 m thick at places. The section is traceable to tens of meters in a lateral extent. As the section is dominated by sand fraction, oriented samples could not be taken from it for AMS studies.

Middle section: The 11m thick section shows alternating clay and sand beds. The base of the section is not exposed. Graded bedding is seen and the sediment shows a dominance of sand and silt fraction over the clay fraction. Eight levels of soft sediment deformation structures (seismites) are marked reported from this part by Phartiyal and Sharma (2009). These soft sediment deformation structures are linked to seismic activity and the details of the morphology and complexity of these structures are provided therein. The base of this section at 0.6 m level gives a radiocarbon date of 26,960 ±1000 and 1.9 m level is dated to be 24,300 ±350 yr BP. Eight samples (Kh1-Kh8) were collected from this level for AMS analyses.

Upper section: Out of >40 m upper section the accessible 15 m was sampled that comprises of laminated and uniform 4 m thick clay overlain by mixed sand, silt and clay till 6 m and sand at 6-8 m levels (Fig. 3). Silty clay is encountered at 8-9.2 m levels, overlain by clay at 10-11.2 m and clay imbedded with cobbles and pebbles at 11.2-13 m levels. Clay is encountered at 13-14.2 m followed by sand on the top. The section is devoid of soft sediment deformation structures and is composed of laminated horizontal massive clay beds. A ≥ 80m debris flow caps the section. Seven samples (Kh9-Kh15) were collected from this level for AMS analyses. As the Upper section is devoid of any signature of soft sediment deformation, however the vertical and horizontal slicing/jointing is seen in the section (Fig. 2b), we tried AMS analysis to investigate any deformation pattern in this part of the section and compare it with the part showing visible deformation structures (middle section).
Magnetic mineralogy:

The hysteresis loops are generally wasp-shaped (Fig. 4A), which is indicative of a mixture of magnetic constituents with different coercivity (Tauxe et al., 1996). The Saturation of IRM (SIRM) represents the concentration of remanence carrying minerals (ferromagnetic and antiferromagnetic). Although fields up to 2000mT (SIRM) were applied these samples are nearly saturated by 300mT field indicative of predominantly a ferromagnetic composition (magnetite/titano-magnetite and maghemite/titano-maghemite) (Fig. 4B). The high temperature runs of susceptibility show the presence of magnetite, from the residual remanence intensity at 575°C and above in the $\chi$-T runs (Fig 4C) for majority of the samples.

Fig. 4: A. Hysteresis loops; B. IRM acquisition curves; C. $\chi$-temperature runs of the selected samples.
SEM analysis:

To complement the magneto-mineralogical studies, two samples were put for SEM analysis, Kh 2 sample (KS-10 in SEM analysis), which has a high magnetic susceptibility, shows clear presence of magnetite (Fig. 5A). On the other hand, sample Kh 14 (KS-1/10 in SEM analysis), which has a low magnetic susceptibility, shows dominance of aluminosilicates and absence of magnetite (Fig 5B). The other minerals present are shown in Table-1 and 2. From this analysis it is evident that magnetite controls the magnetic fabric of the high susceptibility samples of the Khalsar lake sediments. On the other hand, aluminosilicates (clay minerals) contributes more to the fabric of the low susceptibility samples.

Fig. 5: SEM analysis of A- Kh2 and B- Kh14 of the middle and the Upper sections.
Table-1: Percentage of major oxides present in the sample Kh 2 of the middle Khalsar section.

<table>
<thead>
<tr>
<th>Element</th>
<th>Series</th>
<th>Net</th>
<th>unnn. C [wt.-%]</th>
<th>Oxide</th>
<th>Oxid. C [wt.-%]</th>
</tr>
</thead>
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<tr>
<td>Sodium</td>
<td>K-series</td>
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<td>Magnesium</td>
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<td>1.01</td>
<td>MgO</td>
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<td>Aluminium</td>
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<td>3.49</td>
<td>Al2O3</td>
<td>5.64</td>
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<tr>
<td>Silicon</td>
<td>K-series</td>
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<td>SiO2</td>
<td>10.13</td>
</tr>
<tr>
<td>Potassium</td>
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<td>0.70</td>
<td>K2O</td>
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</tr>
<tr>
<td>Calcium</td>
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<td>0.52</td>
<td>CaO</td>
<td>0.63</td>
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<td>Titanium</td>
<td>K-series</td>
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<td>0.07</td>
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<td>Iron</td>
<td>K-series</td>
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<td>Fe2O3</td>
<td>80.48</td>
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<tr>
<td>Oxygen</td>
<td>K-series</td>
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<td>22.41</td>
<td>O</td>
<td>-14.19</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td></td>
<td></td>
<td></td>
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Table-2: Percentage of major oxides present in the sample Kh 14 of the upper Khalsar section.

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<tr>
<th>Element</th>
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<th>Oxide</th>
<th>Oxid. C [wt.-%]</th>
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<td>MgO</td>
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<td>8.96</td>
<td>Al2O3</td>
<td>19.24</td>
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<td>Silicon</td>
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<td>Titanium</td>
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<td>Iron</td>
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<td>Fe2O3</td>
<td>9.30</td>
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<td>1011015</td>
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<td>O</td>
<td>11.99</td>
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<tr>
<td>Total:</td>
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<td></td>
<td></td>
<td></td>
<td>98.48</td>
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</table>

Anisotropy of magnetic susceptibility study:

Lower hemisphere equal area projection of the magnetic susceptibility axes (K1-square, K2-triangle, K3-circle) for all samples (Kh1-Kh15) are plotted against the lithosection in Fig. 3a and b. The AMS is usually approximated by a symmetric second rank tensor which can be represented as an ellipsoid with three principal axes (K1≥K2≥K3) and their spatial orientation (Borradaile and Tarling, 1981). The magnetic fabric is reflected by the preferred orientation of mineral grains and/or mineral lattice contributing to the bulk susceptibility of a given specimen. The results provide the orientation and magnitude of the three principal axis of the magnetic susceptibility ellipsoid (K1≥K2≥K3). The magnetic lineation is attributed to K1 and pole to the magnetic foliation (K1-K2 plane) is K3. The magnitudes of these principal axes are used to calculate different parameters like Km (mean susceptibility), P'(degree of magnetic anisotropy), T
(shape parameter that describes the shape of the susceptibility ellipsoid) etc. (Tarling and Hrouda, 1993). In these sediments in primary sedimentary fabric the minimum magnetic susceptibility axis \( K_3 \) lies normal to the bedding plane while the maximum axis \( K_1 \) is scattered within the bedding plane (oblate fabric).

The mean susceptibility \( K_m \) of the lake sediments of Khalsar section shows a wide range from 223 µSI, indicating dominance of paramagnetic minerals to as high as 4720 µSI, indicating dominance of ferromagnetic fractions. Fig.6A is the frequency histogram of mean susceptibility of all the samples and it shows that while some samples have very high \( K_m \) ranging from 3500-5000 µSI, nearly 80% of the samples have mean susceptibility of ~500 µSI. The \( P' \) value is moderate with values for most of the samples lying between 1.12 and 1.24 (Fig.6B). The Jelinek plot (\( P' \) vs. T) (Fig. 6) shows strongly oblate nature of the magnetic susceptibility ellipsoid and high positive value of T.

**Axial orientation and type of fabrics:**

For the Khalsar lake sediments, in the lower hemisphere equal area projections, almost all the specimen of both upper and middle section show either girdle distribution of magnetic lineation i.e. \( K_1 \) along east-west direction or moderate plunge in the E/W quadrant (Fig. 7A & B). \( K_3 \) is clustered in first and 3rd quadrant (N and S direction) (Fig. 7C & D). This kind of distribution of susceptibility axis, regardless the absence of soft sediment deformation structures in the upper level notwithstanding, indicates dominance of tectonic fabric over sedimentary fabric. Following the classification of Robion et al. (2007), almost all the samples are either of type-IV or type-V. The presence of near vertical magnetic foliation and strongly oblate fabric indicates layer parallel shortening. Distribution of \( K_1 \) along the strike of magnetic foliation plane also suggests the same (Fig. 3A & B). In other words the magnetic fabric of these lake sediments shows evidence of deformation under a compressional regime. On the other hand, this can also be caused by growth of authigenic magnetite along the vertical microcracks. As the Khalsar Lake deposit does not show much evidence of deformation, the second option seems more plausible.

**Discussion and Conclusions**

The Shyok River valley running along the KFZ preserves numerous isolated patches of lake deposits. The post-collisional convergence of the Indian plate and the Asian landmass causes intense seismicity (Molnar et al., 1987; Valdiya, 1988, 2001) and this being a continuous phenomenon has resulted in the release of stress along the fault system time and again causing recurrence of earthquakes. Regional tectonic activity has been reported all along the Himalayas at ~35,000-40,000 yrs BP (Cronin, 1982, 1989; Burbank and Fort, 1985; Schroder et al., 1986, 1993; Fort et al., 1989; Sangode and Bagati, 1995 etc.), and around 26,000 yrs BP (Phartiyal et al. 2005; Phartiyal and Sharma, 2009) which led to the formation of several lakes and later revival of neotectonic activities led to their failure thereby exposing their sedimentary records. On the basis of radiocarbon chronology it can be inferred that the lacustrine sequences may have been formed during Late Quaternary times (Phartiyal et al., 2005; Phartiyal and Sharma, 2009). The formation of this lake may also have contributed to the regional tectonic activity at the same time. The possible source of Magnetite in this region is Ladakh and/or Karakoram batholith.
Fig.6: A. Frequency Histogram of the AMS samples showing distribution of mean magnetic susceptibility ($K_m$); B. Frequency Histogram of the AMS samples showing distribution of degree of magnetic anisotropy ($P'$); C. Jelinek plot ($P'$ vs. $T$)
Fig. 7: A. Lower hemisphere equal area projection of magnetic lineation (K1) of the upper level of the lake deposit (n=54; maximum density at 90/66); B. Lower hemisphere equal area projection of magnetic lineation (K1) of the middle level of the lake deposit (n=62; maximum density at 263/42); C. Lower hemisphere equal area projection of pole to the magnetic foliation (K3) of the upper level of the lake deposit (n=54; maximum density at 0/0); D. Lower hemisphere equal area projection of pole to the magnetic foliation (K3) of the middle level of the lake deposit (n=62; maximum density at 0/0).

AMS analysis is widely used in weakly deformed and cleaved mudrocks and soft sediments for evaluating deformation in fold and thrust belts (Rochette and Vialon, 1984; Kissel et al., 1986; Housen and van der Pluijm, 1991; Averbuch et al., 1992; Housen et al., 1993; Mattei et al., 1997; Sagnotti et al., 1999; Gautam and Rösler, 1999; Parés et al., 1999; Gautam et al., 2000; Parés and van der Pluijm, 2002, 2003, 2004; Parés et al., 1999; Frizon de Lamotte, 2002;
Cifelli et al., 2004, 2005; Goddu et al., 2007; Robion et al., 2007; Sinha et al., 2009; Oliva-Urcia et al., 2009). It is seen that in weakly deformed cleaved rocks and sediments, the magnetic foliation can become horizontal to vertical as intensity of deformation and layer parallel shortening increases. Vertical foliation and presence of magnetic lineation within the girdle of magnetic foliation indicate intense deformation. Magnetic fabric in weakly deformed sedimentary rocks may get modified from bedding parallel to cleavage parallel orientation during transition from shale to slate (Housen and van der Pluijm, 1991). Housen et al. (1993) suggested that a composite magnetic fabric may develop where the magnetic fabric represents an intermediate fabric, which is the intersection plane between bedding and cleavage. Parés and van der Pluijm (2002) carried out detailed magnetic analysis of mudstone, slates and schists and concluded that orientation of the magnetic lineation along the tectonic extension is dependent on the original AMS fabric, lithology and the intensity of deformation. Recent study of Oliva-Urcia et al. (2009) has shown that pressure solution cleavage may develop in sedimentary rocks along which authigenic magnetic mineral may grow. Due to this an anomalous magnetic fabric can develop. The Khalsar Lake deposit does not show any major vertical structures or upright foldings that can be correlated with the vertical magnetic foliation. The Karakoram Fault Zone is also dominantly strike-slip, hence a purely compressive layer parallel shortening event is difficult to establish. However, as mentioned earlier, the Khalsar deposit does show vertical dissection/jointing, horizontal partings and micro cracks (Phartiyal and Sharma, 2009; Fig. 2). It is hence argued that the vertical magnetic foliation is caused by migration by solution and possibly authigenic growth of magnetic minerals along these vertical micro-cracks. Soto et al. (2009) suggested that magnetic fabric of sedimentary rocks, which are dominantly paramagnetic, is more reliable indicator of palaeo-stress than ferromagnetic samples. This is because the tendency of magnetite to form or re-orient at later stages due to pressure solution or cleavage formation (Oliva-Urcia et al., 2008). Therefore, it can be argued that the magnetic fabric seen in the Khalsar lake deposit is not controlled by regional tectonics but is controlled by its ferromagnetic fractions which have re-oriented along vertical micro-cracks, possibly by pressure solution.

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References


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