

so far in the rock volume bounded by KRFZ in the west and Patan Fault in the east, the total energy released will account for about one-half of an M 6.8 earthquake. Considering that the region got activated after beginning of the filling of the Koyna dam in 1961, the activity should continue for another period of 3–4 decades.

It may be noted that filling of the Koyna dam had activated the region in the south up to Warna river, much before the impoundment of the Warna dam (Figure 2). Impoundment of Warna dam started in 1985 and a near-full pond level was reached in 1993. Filling of the Warna dam gave an impetus to Koyna–Warna seismicity; however, there was no appreciable extension of the zone of seismic activity further south (Figure 2) and the seismicity was basically confined between Koyna and Warna reservoirs. Because of increased heterogeneity between Koyna and Warna regions, it is inferred that there is no intact fault segment long enough (~ 10 km) to generate another earthquake of $M \sim 6$ like the one on 10 December 1967. However, $M \sim 5$ events will continue and their occurrence will be governed by Kaiser effect, rate of loading of the reservoirs and duration of retention of high levels.

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Discovery of an aborted reversal (geomagnetic excursion) in the Late Pleistocene sediments of Pinjor Dun, NW Himalaya

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We report here the occurrence of an aborted reversal (geomagnetic excursion) in the Late Pleistocene sediments of Pinjor Dun near Chandigarh, NW Himalaya. The event discovered at ~ 697.5 cm level from the base of Kiratpur section corresponds to the OSL date of 40 ± 5 Ka coinciding with the Laschamp excursion¹ and palaeointensity minima² elsewhere. The Pinjor Dun sediments are deposited at a high rate of sedimentation that enables quite enlarged records of remanent geomagnetic field, hence suitable for further high resolution study of the excursion (under progress) to extend its utility as a stratigraphic marker in the Quaternary sediments at the foothills of the Himalaya.

GEOMAGNETIC excursions are the records of departure of the earth's magnetic field from its usual near-axial configuration for brief periods without establishing a reversal³. Such excursions are well established for the Brunhes Normal polarity event (< 0.78 Ma) that continues to the present geomagnetic field (see Jacobs¹ for review). Excursions have been reported in lava flows, marine sediments and lake sediments of various ages in different parts of the world^{1,4}. Previously, Opdyke⁵ discovered the 40 Ka Laschamp excursion in the marine cores from the Indian Ocean. Kotlia *et al.*⁶ reported an

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excursion of 26–28 Ka (Mono Lake event) from Bhimtal lake in Kumaun Himalaya. We report here an excursion from the fine-grained facies (silt–mudstone) of the fluvial sediments of Pinjor Dun in NW Himalaya.

Pinjor Dun sediments are deposited by high-energy fluvial and fluvio-lacustrine conditions in a longitudinal basin (or valley) created by the latest orogenic folding of the frontal Himalaya^{7–9}. Similar basins occur laterally in various parts of the Outer Himalaya, explained as Duns by Wadia¹⁰ (e.g. Dehra Dun, Kothri Dun, Patli Dun, etc.). The Pinjor Dun basin is mainly filled by several southwardly-trending alluvial fans controlled by the piedmont rivers from the higher ranges at the north. The alluvial fan geometry created a proximal to distal grain-size variation and rapid lateral lithogenic changes, making it difficult to correlate different exposed sections in this basin as well as the rest of the Quaternary basins in the foothills. Magnetic polarity being independent of such facies variations, we selected a silt–mud dominant section near Kiratpur (Figure 1) initially to reconstruct the magnetic polarity stratigraphy.

Ongoing incision by the rivers flowing across the long axis of Pinjor Dun basin has exposed several escarpments with their base level around 40–60 Ka and upper part around 20–25 Ka through a thickness of 20–35 m that suggests a very high sedimentation rate of the order 100 to 150 cm/Ka (the average rate of sedimentation in the Siwalik basin is around 45 cm/Ka)¹¹. Such a high rate of sedimentation is quite conducive to preserve the enlarged records of remanent magnetic events.

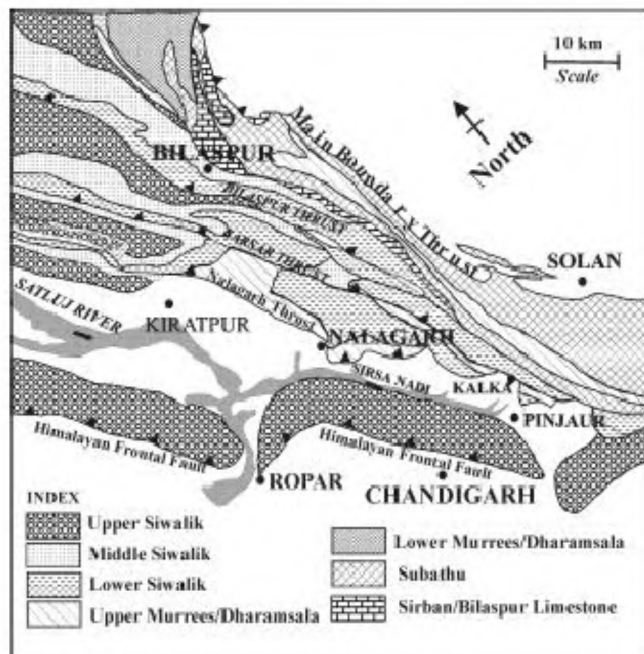


Figure 1. Geological map of the study area after Karunakaran and Ranga Rao²². The studied section is located at Kiratpur and the Pinjor Dun basin extends up to Pinjaur. Several tributaries from NE meet Sirsa Nadi to expose many such sections like Kiratpur.

Moreover the grain-size variants from silt to mudstone are quite suitable for ideal depositional remanent magnetization (DRM) due to abundance of the grains falling in stable single domain (SSD) range¹². We sampled a 35 m thick incised escarpment along the Nangal Hydel Canal near Kiratpur in the Ropar district; Punjab for the magnetic analysis. The details on sediment lithofacies, grain-size analysis and luminescence dating will be published elsewhere.

We collected 7 oriented block samples (measuring approximately 40 cm × 20 cm × 30 cm) judiciously placed near the OSL dates of 40 ± 5 Ka and the top (expected 24 ± 5 Ka) in the Kiratpur section envisaged at the globally reported excursion events of Laschamp (~40 Ka) and Mono Lake (25 Ka). The oriented block samples were cut into vertical and horizontal sections using a hacksaw to get 2.5 cm cubes. The cubes were cleaned using a blower to remove the dust and hacksaw contaminations. Since the sediments are soft and friable, a layer of non-magnetic resin was applied for dust-proof and secure handling during the demagnetization process. A minimum 20 cubes were obtained from each sample block for palaeomagnetic and rock magnetic analyses. Separate un-oriented bulk samples were collected at 38 sites in the studied section using 10 ml non-magnetic (styrene) pots at a mean sampling interval of 75 cm, to study the change in susceptibility with lithofacies and the rock magnetism of representative samples.

The natural remanence was analysed at the laboratory in the Wadia Institute of Himalayan Geology using Digital Spinner Magnetometer (DSM-2) and thermal demagnetizer (TSD-2) of Schonstedt Instruments, USA and alternating field demagnetizer (AFD) of Molspin, UK. Since there is no ideal intensity decay using AFD due to insufficient field available (100 mT) for the complete spectrum of demagnetization, the results were discarded from further interpretation and only the detailed thermal demagnetization (TSD) up to 700°C used successfully. Magnetic susceptibility measurements were made after each step of thermal demagnetization to monitor the change in susceptibility with temperature. Bulk magnetic susceptibility for rock magnetism was calculated by average of six directions of the cubical specimens each at low (0.47 kHz) and high (4.7 kHz) frequencies of applied field. More detailed rock magnetic analysis (remanent hysteresis properties) on the representative samples was conducted at the Environmental Magnetic Laboratory (EML) of University of Liverpool, UK to determine the magnetic mineralogy and granulometry. X_{ARM} , a parameter sensitive to the abundance of SD magnetite was measured at EML using the DTech ARM equipment. An isothermal remanent magnetization was imparted up to a forward field of 4000 mT and back-field of 500 mT to determine the saturation remanence (SIRM) and remanence coercivity

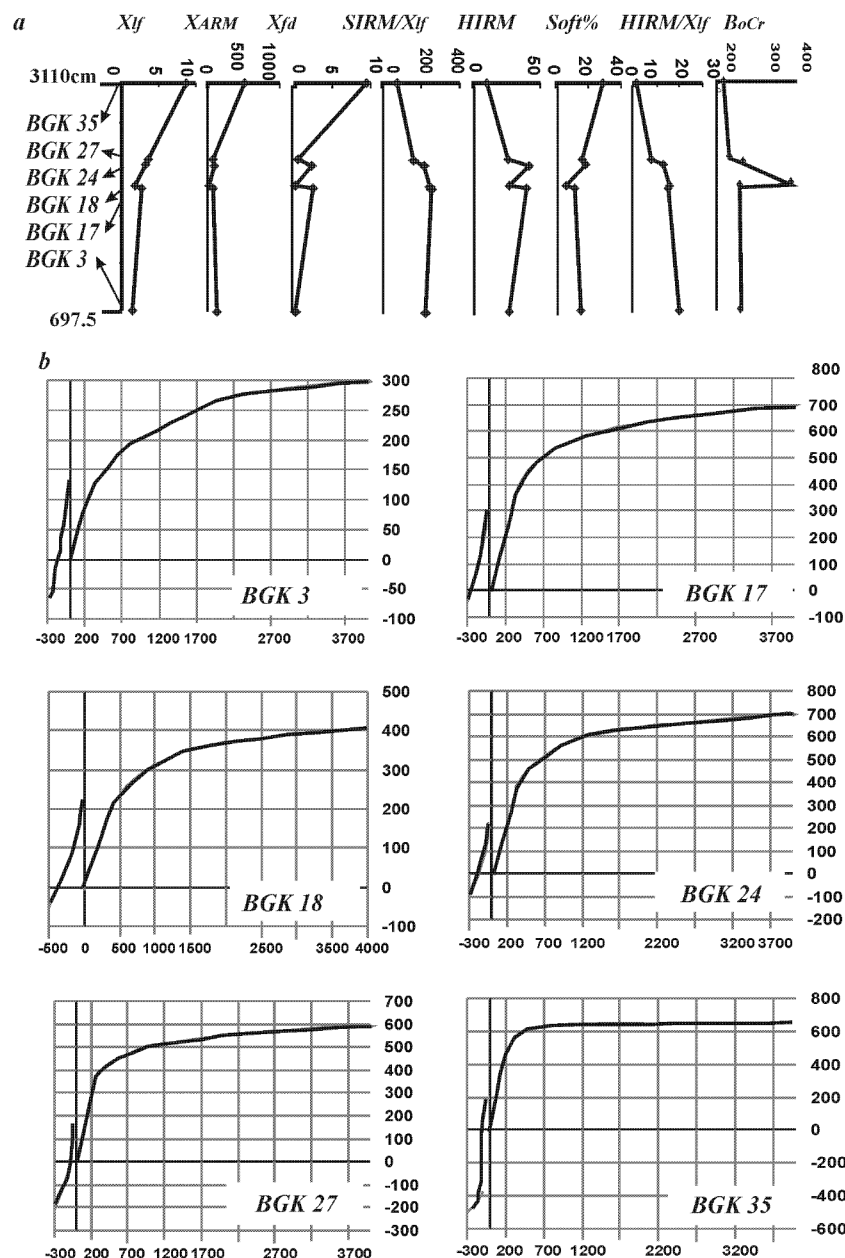


Figure 2. Rock magnetic properties of the representative samples from the studied section. *a*, Commonly used environmental magnetic parameters¹³; and *b*, Result of stepwise acquisition of isothermal remanent magnetization in forward and back-field directions to find the saturation levels of the bulk natural sample.

(B_{0Cr}) and to calculate the ratios $SIRM/X_{lf}$ and $Soft\%$. Hard remanent magnetization (HIRM in mAm^2/kg) was calculated to depict the total concentration of remanence carrying canted antiferromagnetic hematites¹³ and was derived using the vibrating sample magnetometer (Molspin-VSM).

The mean mass specific susceptibility (X_{lf}) for the 38 bulk samples is $10 \times 10^{-8} m^3/kg$ (minimum = 3 and maximum = 35), with the mean coefficient of frequency dependence (X_{fd}) of 4.8%. It is at the lower side than nearby records of (i) loess in China¹⁴, (ii) lake sediments in Ladakh¹⁵ and Kumaun⁶, (iii) marine sediments

of Bengal fan¹⁶, but quite comparable to the overbank deposits of Siwaliks^{11,17} (the bedrock for Dun sediments). The mean X_{ARM} for the representative samples is $150 \times 10^{-8} m^3/kg$ and suggests an abundance of single domain (SD) grains, that results in preservation of stable remanent magnetization. Figure 2*a* depicts the interrelation of studied rock magnetic properties of representative samples. A very good correlation amongst X_{lf} , X_{ARM} , X_{fd} and $Soft\%$ and their inverse relation to the HIRM and $SIRM/X_{lf}$ indicate that the peaks in magnetic susceptibility are expressed by ferromagnetic assemblage, whereas the drop may be inferred as

the haematite reach assemblage. The X_{ARM} and X_{fd} values suggest that the ferrimagnetic component mainly comprises SD magnetite, whereas B_{oCr} and HIRM indicate that the antiferromagnetic component is of haematite origin.

The remanence hysteresis derived from stepwise isothermal remanent magnetizations up to a forward field of 4000 mT and back-field of 300 to 500 mT is plotted in the Figure 2b. The plots for BGK -3, -17, -18, -24 and -27 infer that the complete saturation is not acquired even by the 4000 mT field, although about 70% of the field is acquired below 700 mT suggesting an admixture of the ferri- and antiferromagnetic minerals with predominant magnetization of the ferrimagnetic minerals. However, BGK35 indicates an overall dominance of the ferrimagnetic component. Figure 3 describes the magnetic susceptibility and its relation to different lithogenic factors in the studied section. There is no close correlation amongst the curves, however the magnetic susceptibility appears to be controlled by silt content, suggesting that the SSD grains are quite abundant in siltstones than any other lithotype. A peak in X_{fr} at ~970 cm coincides with that of organic carbon and inversely to the sand content. The X_{fr} is controlled by SD magnetite that favours restricted climate conditions and is supported by the preservation of organic matter with relatively low detrital influx. Another peak in X_{fr} beginning at 2950 cm too supports similar conditions. The magnetic susceptibility variation from 470 cm to 2950 cm is restricted to a window 3 to 15 ($\times 10^{-8} \text{ m}^3/\text{kg}$), suggesting fairly constant sediment

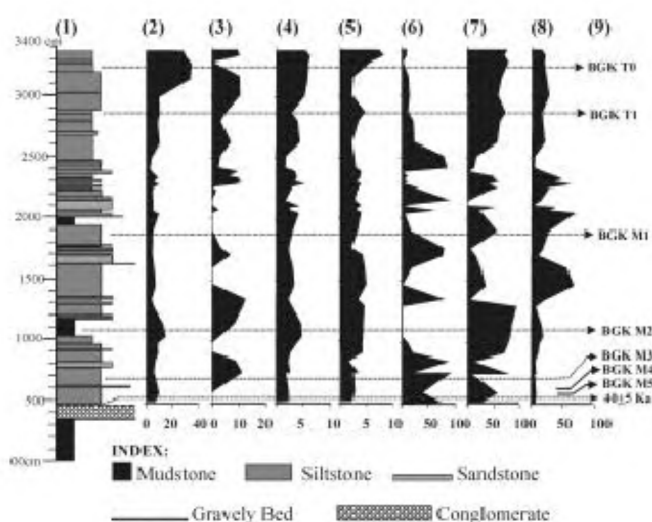


Figure 3. Analytical description of the studied section of Kiratpur (38 bulk samples) analysed to get the parameters: (1), Lithocolumn using the field observations; (2), Low-frequency magnetic susceptibility (X_{lf} , $10^{-8} \text{ m}^3/\text{kg}$); (3), Frequency dependency of susceptibility ($X_{fd}\%$); (4), Total organic carbon (%) using weight loss on combustion at 450°C; (5), Inorganic carbon using the weight loss at 1100°C minus total organic carbon; (6)–(8), Sand, silt and clay percentage using conventional methods; (9) Location of the palaeomagnetic sites and luminescence dating sample.

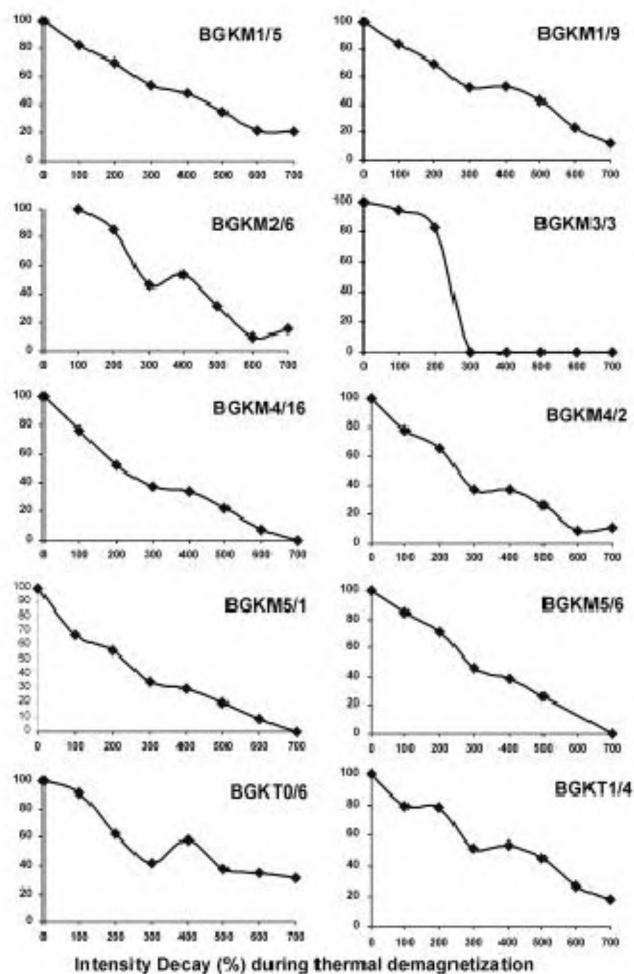


Figure 4. Decay in the intensity of magnetic moments normalized to the intensity at room temperature of the respective samples. X-axis: temperature increments (°C), Y-axis: Normalized intensity of magnetic moments (%).

input conditions; it increases suddenly after 3000 cm till the top of the escarpment. More detailed work is under progress to find whether this peak in magnetic susceptibility could be correlated with the top parts of the other sections in this basin with the reference of the excursion event at the base.

Thermal demagnetization was conducted at intervals of 100°C up to 700°C for all the studied samples. The specimens showing change in susceptibility with temperature are discarded from the analysis. The intensity decay curves (Figure 4) show two major drops, one at 300°C and the other at 600°C, common to all. The vector end-point plots (Zijderveldt diagrams, Figure 5) have shown uni-component system for most of the specimens and 1–3 secondary components for a considerable number of specimens. BGK M1/5 indicates the normal polarity trajectory with a viscous component cleared below 100°C and ferrimagnetic (magnetite/maghemite) component removed at blocking temperature below 600°C. A secondary component with blocking temperature at <300°C was removed for most

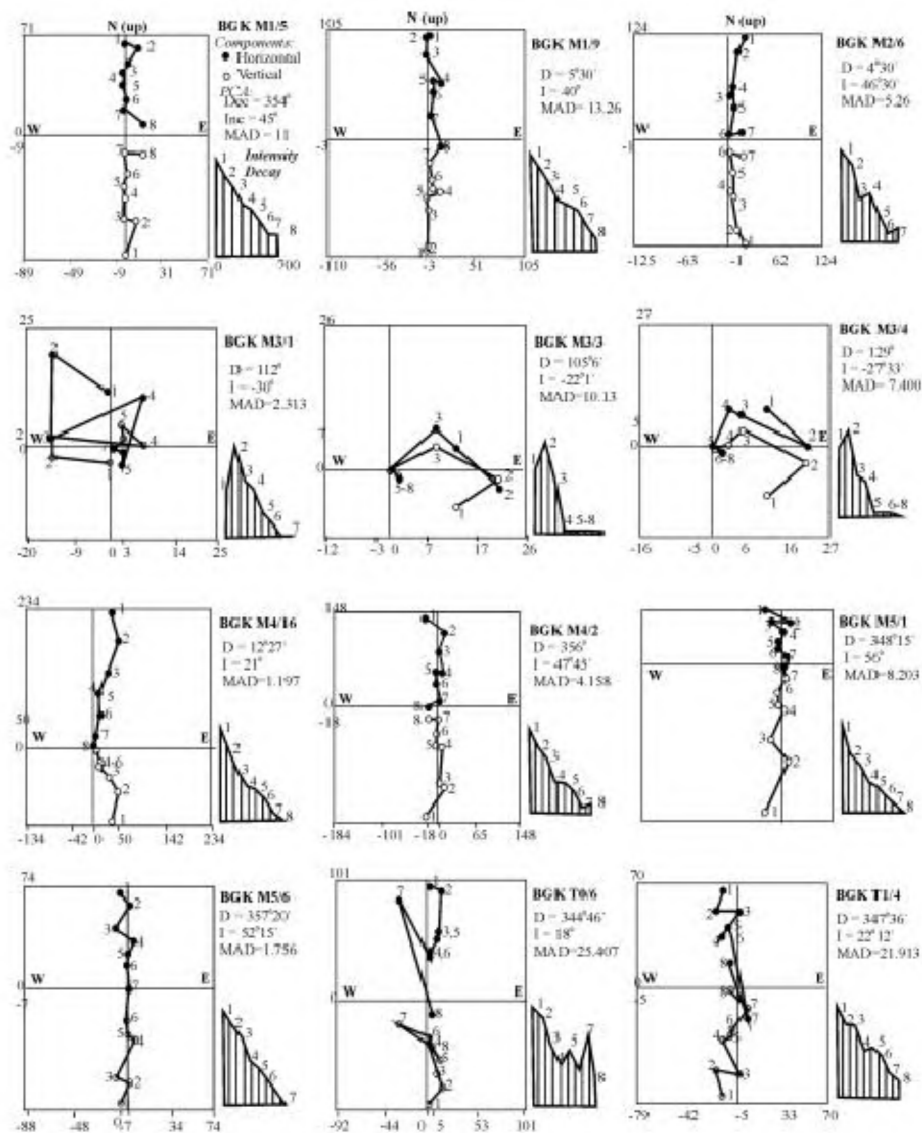


Figure 5. Vector end-point diagrams (Zijderveld plots)¹² of the representative samples from each site after stepwise thermal demagnetization at steps: 1, Room temperature; 2, 100°C; 3, 200°C; 4, 300°C; 5, 400°C; 6, 500°C; 7, 600°C; and 8, 700°C (see text for details).

of the samples. Except the site BGK M3, all the other samples show their secondary component too as normal polarity making low angles with primary component, indicative of overlapping coercivity spectra. The Zijderveldt plots for the specimens of BGK M3 have shown entirely different trajectories characteristic of aborted reversal/excursion. Finally, the excursion at BGK M3 can be assigned using the following criteria.

- (1) After the removal of the viscous component at 100°C the intensity is increased, instead of the usually expected decay as observed in all other samples. This may be due to the antiparallel acquisition of the viscous component (present-day normal polarity) to the reversed component of excursion.
- (2) The virtual geomagnetic pole (VGP) latitudes, fall in the lower hemisphere with the low latitude values and are thus characteristic of excursion¹ rather than a full reversal.
- (3) The demagnetized Natural Remanent Magnetization (NRM) intensity is reduced dramatically in the sample M3 despite X_{lf} being constant (see NRM/ X_{lf} ratio in Figure 6). This is a behaviour suggestive of an excursion event^{2,18}.
- (4) The maximum angular deviation (MAD) values for the principle-component derived directions (D and I) infer that the primary component is highly clustered after 400°C for the M3/3 than the samples below and above it (i.e. M3/4 and M3/1), suggesting transition of the excursion.
- (5) For all the samples, except BGK M3, the Zijderveldt plots (Figure 5) show highly overlapping coercivity spectra for the secondary components, as the primary as well as secondary directions

are acquired in the same polarity (i.e. Brunhes Normal).

- (6) The scattered nature of the secondary component as well as the short record of excursion is probably due to the insufficient 'remanence lock-in time'¹⁹ and/or stronger Post-Depositional Remanent Magnetization (PDRM) overprinting of the primary signatures²⁰.
- (7) The sample BGK M3 occurs just above the OSL date of 40 ± 5 Ka and thus coincides with the Laschamp Excursion^{1,5}.

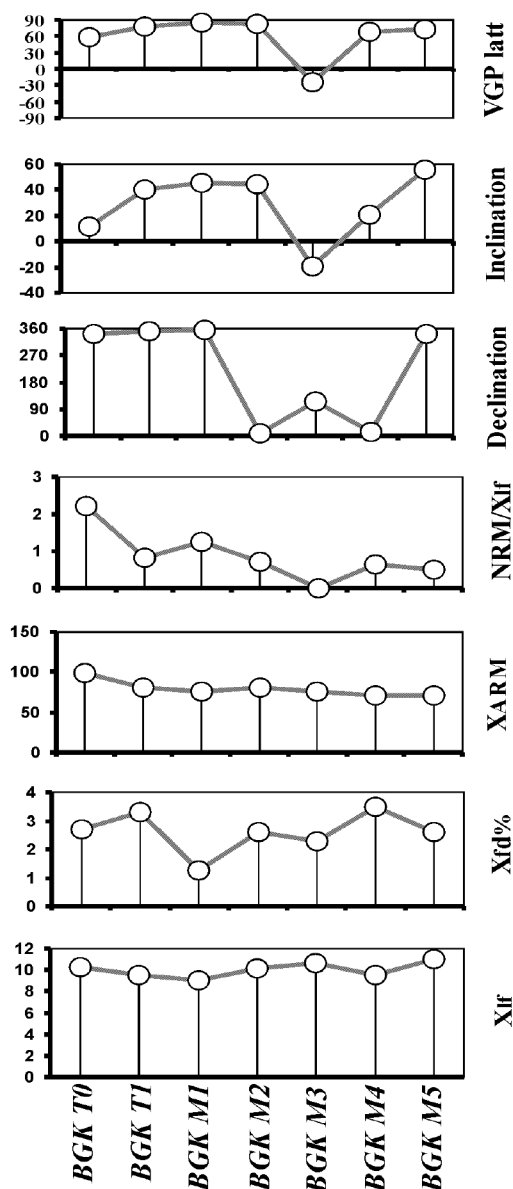


Figure 6. Variation in the lithogenic (X_{ir} , $X_{rd}\%$ and X_{ARM}) and geomagnetic (declination, inclination and virtual geomagnetic pole (VGP) latitude) parameters. Note that the lithogenic factors remain fairly constant, although the geomagnetic parameters are varied, particularly during BGK M3 authenticating the occurrence of excursion.

Thus the selective sampling in the Kiratpur section discovered a geomagnetic excursion coinciding with the ~ 40 Ka Laschamp event¹. The high rate of sedimentation in this basin is quite suitable to get enlarged records from the sediments. A more detailed close sampling for palaeomagnetic and rock magnetic analysis is under progress, to study the behaviour of this excursion for its successful correlation as a bench-mark for the Late Pleistocene sediments in Pinjor Dun and adjacent area. Study of the excursions is of vital importance to understand the non-dipole nature of the geomagnetic field⁴ and the production of cosmogenic radionuclides²¹.

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