Geochemical analysis and scientific conservation of the exterior surface of the ancient Kedarnath temple, Uttarakhand, India

Vimal Kumar1,*, S. S. Panda1, B. P. Nauni1, Ram Ji Nigam1 and Barun K. Mukherjee2

1Archaeological Survey of India (Science Branch), 29, New Cantt Road, Dehradun 284 001, India
2Wadia Institute of Himalayan Geology, G. M. S. Road, Dehradun 284 001, India

Kedarnath temple is situated on the Garhwal Himalayan range near River Mandakini in Rudraprayag, Uttarakhand, India. The temple (more than 1200 years old) was badly affected by devastating floods and landslides during 13–16 June 2013. To protect the aesthetic value of this ancient temple, a systematic scientific conservation has been carried out. The present study describes the geochemical character of the rocks mounted on the temple. It also evaluates weathering trend of the rocks by studying petrography and the analysis of major oxides, using optical microscopy, X-ray fluorescence and X-ray diffraction. Petrography and discrimination clusters analysis show that the rock is granitic gneisses in composition and is peraluminous in nature, while the new rock KDN2 sample shows paralkaline character.

Keywords: Ancient temple, conservation, exterior surface, geochemistry, petrography.

Materials and methods

Stone specifications

Four representative rock samples were collected from different parts of Kedarnath temple (Figure 1). The samples were labelled as old KDN1 (OK1, collected from the temple site), old KDN2 (OK2, near the temple site), new KDN1 (NK1, quarry stone), new KDN2 (NK2, quarry stone near the helipad behind the temple).

Analytical procedures

Microscopic studies: The photomicrographs of rock samples and thin sections were studied using optical
microscope (Nikon, SMZ-800) with EDF software to determine the rock texture and composition\textsuperscript{8–10}.

XRF: The 200 mesh size powdered rock samples were analysed using a high-power X-ray tube of 4 kW capacity which provides more power wavelength dispersive – XRF (Bruker S-8, USA)\textsuperscript{6,7,11,12}.

XRD: The labelled rock samples were powdered and analysed using an XRD system (Panalytical X’pert Pro) through paid instrument facility of Wadia Institute of Himalayan Geology, Dehardun\textsuperscript{6,7,11,12}. XRD pattern was decoded using JCPDS software.

Discriminant function: The discriminant function (DF) values were evaluated using the formula described by Elatikpo et al.\textsuperscript{13}. Positive DF values suggest an igneous origin, whereas negative DF values point to sedimentary origin\textsuperscript{14}. The formula used is given below

\[
DF = 10.44 - 0.21 \text{SiO}_2 - 0.32 \text{Fe}_2\text{O}_3 (\text{total Fe}) - 0.98 \text{MgO} + 0.55 \text{CaO} + 1.46 \text{Na}_2\text{O} + 0.54 \text{K}_2\text{O}.
\]

Conservation methods

The conservation methods to protect and preserve the exterior stone surface of Kedarnath temple were adapted from the literature\textsuperscript{15–17}.

Results

Microscopic studies

Figure 2 shows microscopic images (10×) with surface roughness intensity of all the four types of stone samples collected from the temple site. The megascopic features show that the stones are dull white in colour with alternate dark and light bands; mineralogically the stones are composed of quartz, feldspar and mica. The rock samples show uneven surface-topography. Figure 3 shows 3D image of surface roughness intensity manifests intense roughness on the surface of tested samples. Figures 4 and 5 show thin-section photomicrographs of the tested rock samples; the photo plates have been recovered both in plane polarized light and crossed nicole. The rocks were essentially composed of quartz, K-feldspar, plagioclase-albite and micas (biotite) along with unidentified accessory minerals. The feeble twinning in plagioclase was also noticed during thin-section studies. The mechanical strength and mineralogical texture have also been observed in these images (Figures 4 and 5)\textsuperscript{8–10}.

![Figure 1. Megascopic features of rock samples collected from Kedarnath temple and nearby areas.](image1)

![Figure 2. Two-dimensional microscopic images (10×) of the studied samples with surface roughness intensity.](image2)

![Figure 3. Three-dimensional microscopic images (10×) of the studied samples with surface roughness intensity.](image3)
Table 1. Analysis of major oxides of four representative rock samples collected from the temple site

<table>
<thead>
<tr>
<th>Entry</th>
<th>Major oxides (%)</th>
<th>Old KDN 1</th>
<th>Old KDN 2</th>
<th>New KDN 1</th>
<th>New KDN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Na₂O</td>
<td>3.25</td>
<td>2.69</td>
<td>3.84</td>
<td>2.80</td>
</tr>
<tr>
<td>2</td>
<td>MgO</td>
<td>0.40</td>
<td>0.44</td>
<td>0.39</td>
<td>1.32</td>
</tr>
<tr>
<td>3</td>
<td>Al₂O₃</td>
<td>14.23</td>
<td>14.20</td>
<td>11.95</td>
<td>9.27</td>
</tr>
<tr>
<td>4</td>
<td>SiO₂</td>
<td>72.19</td>
<td>70.88</td>
<td>75.44</td>
<td>74.67</td>
</tr>
<tr>
<td>5</td>
<td>P₂O₅</td>
<td>0.18</td>
<td>0.30</td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>K₂O</td>
<td>5.23</td>
<td>0.92</td>
<td>3.20</td>
<td>1.02</td>
</tr>
<tr>
<td>7</td>
<td>CaO</td>
<td>0.90</td>
<td>0.33</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>8</td>
<td>TiO₂</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>9</td>
<td>MnO</td>
<td>2.32</td>
<td>2.98</td>
<td>2.73</td>
<td>2.64</td>
</tr>
<tr>
<td>10</td>
<td>Fe₂O₃</td>
<td>99.04</td>
<td>98.48</td>
<td>99.04</td>
<td>98.47</td>
</tr>
</tbody>
</table>

Figure 4. Microscopic image of thin section of OK1 and OK2 samples with crossed nicole and plane polarized light. Scale: View length ~1 mm.

Figure 5. Microscopic image of thin section of NK1 and NK2 samples in crossed nicole and plane polarized light. Scale: View length ~1 mm.

Figure 6. Al₂O₃/(CaO + Na₂O + K₂O) versus Al₂O₃/(Na₂O + K₂O) plot showing the dominantly peraluminous nature of the analysed rock samples 19,20,22.

XRF: The chemical composition of four different powdered samples was analysed using XRF. Table 1 shows results of analysis of major oxides. The rock sample contains SiO₂, which falls in the higher side in the range of 70.88–75.44 wt% and low content of Fe₂O₃ and MgO (2.32–2.98 wt%) and (0.39–1.32 wt%) respectively. Figure 6 shows a plot of Al₂O₃/(CaO + Na₂O + K₂O) versus Al₂O₃/(Na₂O + K₂O) for the data obtained from XRF results.

XRD: Figures 7 and 8 show the XRD patterns of new and old rock samples respectively. The new KDN1 is mainly composed of quartz (score 52), albite (score 32), orthoclase (score 24), anthrolite (score 20) and K-feldspar (score 21) whereas the new KDN2 has quartz (score 51), albite (score 31), orthoclase (score 15), anorthite (score 21) and Na-feldspar (score 18). Quartz (score 57), albite (score 22), orthoclase (score 21) and K-feldspar (score 19) were present in the old KDN1, whereas quartz (score 53), albite (score 18), orthoclase (score 18) and anorthite (score 17) were reported in the old KDN2.
DF: All four samples showed positive DF values, indicating that the rocks were igneous in origin (Table 2). The analysed rock samples were poor in ferromagnesium content (Fe$_2$O$_3$ + MgO + TiO$_2$). For protolith identification, the rock samples were determined using a DF in case the MgO < 6% and SiO$_2$ < 90% for all quartzofeldspathic rock\textsuperscript{13,14}.

Discussion

XRF results show that Na is consistently less than K in the new KDN1 and KDN2 samples. Alumina (Al$_2$O$_3$) content is generally within the same range (9.27–14.23 wt%) for all the analysed samples. However, few samples show increasing Al$_2$O$_3$, and decreasing SiO$_2$

![Figure 7](image1.png)

**Figure 7.** X-ray diffraction (XRD) pattern of the new (a) KDN1 and (b) KDN2 rock powder samples of the temple with theta spacing.

![Figure 8](image2.png)

**Figure 8.** XRD pattern of old (a) KDN1 and (b) KDN2 rock powder samples of the temple with theta spacing.
Table 2. Calculated discriminant function (DF) of four representative rock samples collected from the temple site

<table>
<thead>
<tr>
<th>Entry</th>
<th>Analyte (%)</th>
<th>Old KDN 1</th>
<th>Old KDN 2</th>
<th>New KDN 1</th>
<th>New KDN 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SiO₂</td>
<td>72.19</td>
<td>70.38</td>
<td>75.44</td>
<td>74.67</td>
</tr>
<tr>
<td>2</td>
<td>Fe₂O₃</td>
<td>2.32</td>
<td>2.98</td>
<td>2.64</td>
<td>2.64</td>
</tr>
<tr>
<td>3</td>
<td>MgO</td>
<td>0.40</td>
<td>0.44</td>
<td>0.39</td>
<td>1.32</td>
</tr>
<tr>
<td>4</td>
<td>CaO</td>
<td>0.90</td>
<td>0.92</td>
<td>1.02</td>
<td>4.44</td>
</tr>
<tr>
<td>5</td>
<td>Na₂O</td>
<td>3.25</td>
<td>2.69</td>
<td>3.84</td>
<td>2.80</td>
</tr>
<tr>
<td>6</td>
<td>K₂O</td>
<td>5.23</td>
<td>5.69</td>
<td>3.20</td>
<td>2.82</td>
</tr>
<tr>
<td>7</td>
<td>DF</td>
<td>2.20</td>
<td>1.78</td>
<td>1.17</td>
<td>1.24</td>
</tr>
</tbody>
</table>

content with systematic increase in CaO and Na₂O. These data suggest that the rocks were derived from a quartzo-feldspathic (granitic) source and the geochemical trends match with the characteristics of Archaeon granitic rocks18,19. The non-variability of the alumina (Al₂O₃) in the entire samples were analysed and fall in the range of 9.27–14.23 wt%, which suggests a calc-alkaline affinity. This could also be due to their low Fe–Mg-bearing silicate mineral. Representative major oxides of all four samples were almost similar to gneiss-1 and gneiss-2 which were reported by Hussain et al.20 and Adegbuyi et al.21. All tested samples exhibit peraluminous character, except the new KDN 2 which shows peralkaline character. This was confirmed by the methods reported in the literature19,21,22 (Figure 6).

Hard minerals like quartz and albite show huge proportions and data of major oxides of all tested samples indicate granitic gneiss23 in nature with peraluminous characters and show similar results as reported by Rutland24. Quartz, the major constituent in all the four samples, showed higher resistance with respect to pressure, temperature and deformation. The variations in temperature exert significant influence on the disintegration of rocks. In the Kedarnath area during daytime the rocks get heated up by the high-intensity sunrays, causing expansion, while at the night, the temperature falls to sub-zero levels, causing cooling, which results in contraction of the rocks. The rapid physical changes due to expansion and contraction exerted by the stones of the ancient Kedarnath temple decays very easily and crumbles since the rock is a bad conductor of heat25. It was also observed that minerals within the rocks vary in their rate of expansion and contraction according to their composition and chemical characteristics. The cubical expansion of quartz is twice that of feldspar26. Dark-coloured rocks are subjected to fast changes with temperature compared to light-coloured rocks27. The differential expansion of minerals on a rock surface generates stress between the heated surface and cooled unexpanded parts, resulting in fragmentation of rocks26. However, the presence of less amount of moisture content and water shows the small flexibility of minerals which prevents brittleness and surface stress of the rocks. Under extreme weather conditions, rainfall influences chemical weathering. It controls the moisture supply for chemical reactions; this eliminates soluble constituents of the minerals27. Studies have shown that K-feldspar breaks down and forms secondary clay minerals such as illite and kaolinite under extreme weathering conditions28–35. The weathering of feldspar is represented as follows

\[
\text{Feldspar} \rightarrow \text{illite} \rightarrow \text{kaolinite}^{28}. \\
2\text{KI AlSi}_3\text{O}_8 + 2\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{Feldspar} \\
\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + \text{K}_2\text{CO}_3 + 4\text{SiO}_2, \\
\text{Kaolinite} \\
6\text{K(AlSi}_3\text{O}_8) + 4\text{H}_2\text{O} + 4\text{CO}_3 \rightarrow \text{Orthoclase} \\
\text{K}_2\text{Al}_4(\text{Si}_6\text{Al}_2\text{O}_{20})(\text{OH})_4 + 12\text{SiO}_2 + 4\text{K}^+ + 4\text{HCO}_3, \\
\text{Illite} \\
2\text{KA}_4\text{Si}_6\text{O}_{20}(\text{OH})_4 + 2\text{H}_2\text{O} + 2\text{CO}_3 + 13\text{H}_2\text{O} \rightarrow \text{Illite} \\
5\text{Al}_2\text{Si}_2\text{O}_4(\text{OH})_4 + 4\text{H}_2\text{SiO}_4 + 2\text{K} + 2\text{HCO}_3, \\
\text{Kaolinite}
\]

These types of weathering trends were not found in the tested samples of Kedarnath temple. XRD studies reveal that quartz, albite, orthoclase, anthroite and K-feldspar are the main primary minerals in all sample profiles. These minerals are observed mainly in less-weathered samples.

Conservation issues and treatment

The exterior stone surface of Kedarnath temple had become blackish due to deposition of sandy dust, dirt and dried vegetation and micro-vegetation growth under extreme cold weather conditions. Sand and thick dust layers were redeposited on the exterior surface of the temple during and after the natural disaster of June 2013 (Figure 9). These depositions provided favourable
conditions for the growth of small insects on the stone surface. They also tarnished the aesthetic value of the temple. Such biogenic and micro-vegetation growth secretes plant acids which digest major oxides of the stones, and cause weathering of the stone surface17.

The layers of dust, dirt and micro-vegetation growth were manually removed by applying 2–3% solution of suitable mild base with non-ionic detergent with the help of soft nylon brushes. A 2% aqueous antimicrobial solution was sprayed on the clean and dried surface of the temple to prevent further growth of micro-vegetation15–17.

Conclusion

The present study shows that the analysed rock samples are granitic gneiss in nature with peraluminous character, whereas the new KDN2 sample shows paralkaline character. The old KDN1 sample acts as a reference and the remaining two samples show similar geochemical properties. The conservation efforts are essential to protect and preserve the aesthetic value of Kedarnath temple and preserve its 1200-year-old ancient heritage. The conservation has drastically enhanced the aesthetic beauty of the temple. Thus, this study has importance for the preservation and protection of ancient monuments.

Disclosure statement: The authors report no potential conflict of interest.


ACKNOWLEDGEMENTS. We thank the Superintending Archaeologist, Dehradun circle, Dehradun for support during the conservation work, and all the active teams of the science branch, Archaeological Survey of India, who were actively worked for Conservation work of Kedarnath temple. We also thank the Joint Director General (Conservation), Archaeological Survey of India, Dehradun (ASI) for the constructive suggestions and support during the project, and the Director General, New Delhi and Ministry of Culture, Government of India, for financial and administrative support for the project.