Modal-data based simple statistical analysis as effective petrogenetic indicator: a case study from Kadavur Gabbro-Anorthosite Complex, Tamil Nadu, Southern India

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Abstract

Field and petrographic studies on the Neoproterozoic Kadavur intrusive complex (10°35´N:78°11´E) (located in the southern granulite terrane of the Indian shield) reveal the following three distinct types: (i) earliest phase of deformed schistose gabbro-anorthosite (ii) most dominant layered gabbro-anorthosite and (iii) locally developed pegmatoidal gabbro-anorthosite. A simple modal-data based statistical analysis of layered gabbro-anorthosite type yields highly significant or significant correlation coefficients for different mineralogical parameters and strongly supports differentiation from a common magma. Typical dispositions of the mineralogical parameters (as depicted by isopleths patterns) suggest maintenance of a magmatic lineage in varying hydration ambience that developed several petrographic variants within the layered type.

Keywords: Modal-data based study; gabbro-anorthosite; mineralogical parameters; isopleths map; single magmatic lineage
Modal analysis studies on gabbro-anorthosites have been useful to classify and characterize such rocks. For instance, Ashwal\textsuperscript{1} worked out the genesis of the Mount Marcy anorthosite massif, (Adirondacks, Newyork)\textsuperscript{1} with a particular focus on the anorthositic rocks associated with the high-grade terrain\textsuperscript{2,3}. Even for the Apollo 11 samples, modal-analyses ascertain the heterogeneity in the lunar highland series\textsuperscript{4}. However, during recent times, such modal-analysis based approach for gabbro-anorthosites has become obscured. In reality, modal-data of igneous rocks represent actual mineralogical composition and help in accurate nomenclature. The usefulness of the modal analyses now-a-days is being neglected and emphasis has been shifted to other domain presumably because of the availability of major, trace and isotopic data\textsuperscript{5,6}. Even in this scenario, in the recent past, modal-data based study was rewarding to resolve the long-standing controversy related to accretion of gabbroic lower crust at the ridge-axis\textsuperscript{7}. In context of the intrusive gabbro-anorthosite complex near Kadavur (10°35´N: 78°11´E), Southern India (Fig.1a and b), this study highlights statistical analyses of several mineralogical parameters to present a cogent petrogenetic history. The Kadavur complex was initially reported from the Southern Granulite Terrane (SGT) of the Indian shield (Fig.1a)\textsuperscript{8,9}. However, during that time, the region (hosting the Kadavur complex) was known as Eastern Ghats Belt\textsuperscript{10}. Early studies\textsuperscript{11} on Kadavur complex suggest that i) the intrusion represents a funnel-shaped concordant body, and ii) the complex bears geological similarities with Adirondack mountains. However, later studies\textsuperscript{12} argue against similarities between Kadavur complex and intrusive rocks in Adirondack region; contrarily it was compared with early Archean layered gabbro anorthosite complex. Lately\textsuperscript{13,14} it has been suggested that the Kadavur complex manifests multiple phases of magmatism with corresponding mappable attributes\textsuperscript{13,14}. Recent workers\textsuperscript{15,16} suggest a tholeiitic parentage and an inferred age of ~810Ma for the anorthositic intrusions. However, as on date, it is unclear whether the complex is a product of differentiation from common parent magma or this corresponds to discrete and separate magmatic pulses. In this view, this article attempts to resolve this issue with the help of statistical analyses of modal-data and relevant correlation characteristics amongst mineralogical parameters.

Present work involves field studies, petrographic analyses and detailed statistical studies on modal variables that help us to throw light on the petrogenesis of the complex. The Kadavur intrusive complex is accommodated within-country rocks which include hornblende schist, amphibolite, granite gneiss, quartzite and migmatite. The country rocks are often
foliated with down dip lineations. Some representative field photographs of the country rocks have been furnished in the Supplementary Fig. S1 (a-f). Field mapping indicates the presence of three distinct types of gabbro-anorthosite in the complex (i) schistose gabbro-anorthosite (ii) layered gabbro-anorthosite, and (iii) locally present pegmatoidal gabbro-anorthosite (Fig.1b); representative field photographs are given in supplementary Fig.S2 (a-d) and Fig.S3 (a-d). Structural analyses often play an important role to understand the style of deformation in a terrane showing multiple folding and deformation. In this view, stereo pole diagrams of the foliation planes of the country rocks have been constructed [supplementary Fig. S4 (a-c and e)] which indicate a sheath fold geometry caused by a superposed pattern [Fig. S4 (d)] is being guided by the relevant mechanism. The stereo pole diagram for the igneous foliation (developed on the layered gabbro-anorthosite type) suggests evidence of intrusion with a nearly sub-vertical girdle axis (supplementary Fig. S4f). In order to give a lucid idea to the readers about the different types of intrusives noted within the Kadavur Complex, representative hand-specimen photographs and photomicrographs have been furnished in supplementary Fig. S5. Modal mineralogy (vol %) of the layered gabbro-anorthosite has been presented in supplementary Table S1 and projected on Plag-Px-Hbl (Fig.2a) and Plag-Opx-Cpx (Fig.2b) ternary diagrams following the IUGS recommendation. It is apparent from Fig. 2(a and b) that there are several petrographic variants (so far the nomenclature is concerned) and the corresponding IUGS recommended names for each of the specimen has been tabulated in Supplementary Table S1. The statistical studies based on modal-data variables of granitic rocks (and other coarse-grained igneous rocks) to understand petrogenesis was successfully attempted by earlier workers. In addition, appropriate log-transformations on the modal data need to be made to eradicate the closure effect while calculating the correlation coefficients. In the present study, a total of thirty-four representative samples of layered gabbro-anorthosite (Fig.1b) were chosen to evaluate the – (i) average variation in mineralogical composition, and (ii) nature of correlation among the significant mineralogical parameters. For this purpose, we collected point-count data using an automated point-counting stage mounted on a routine polarizing microscope method. During modal-data analysis, the following cautions were observed (i) each slide was thoroughly examined immediately before the modal analysis so that the minerals can be identified easily (ii) the number of point counts was kept at a sufficiently large number (2000-2200) with horizontal spacing of 0.3mm and vertical spacing of 1mm. For the modal analysis, sample was chosen from the different part of the layered gabbro-anorthosite bodies on a half km grid. The
arithmetic mean ($\bar{X}$), standard deviation, variance, skewness and kurtosis of different mineralogical parameters (log-normalized) were presented in Table 1.

Six types of mineralogical parameters were taken for correlation studies. These mineralogical parameters include anorthite percentage of plagioclase, colour index, hydration index, reciprocal of plagioclase crystallization index, mafic crystallization index and rock crystallization index (see Table 1). Percentage values of different data were transformed to Y using the transformation equation $Y = \log(X/100-X)$ where X is the present data including several mineralogical parameters. The Colour index (CI) was determined following the method given in the IUGS classification. The other indices namely Hydration Index (HI), Reciprocal of Plagioclase crystallization Index (RPCI), Mafic Crystallization Index(MCI), Rock Crystallization Index(RCI) and An% of Plagioclase were also transformed using the same formula $\log(X/100-X)$. For easy comprehension, the explanations for the different indices have been given in Table 1. The significance of the calculated correlation coefficients ($r$) was tested at 5% and 1% levels of significance. The linear correlation coefficient values are given in Table 2. To understand the style of several spatial variations of the mineralogical parameters in the layered gabbro-anorthosite bodies, those attributes were plotted in isopleth maps (Fig. 3a-e). The rock crystallization index value shows a systematic decrease (Fig. 3a) from the margin of the complex to its central part. These decreasing rock crystallization indices are consistent with less proportion of mafic minerals towards the centre where the anorthositic band is most dominant (Fig 1b). The colour index also shows a systematic decreasing pattern from margin inward (Fig. 3b). This observation attests the presence of (plagioclase – dominant) anorthosite occurrence towards the centre. In concordance with the geological map (Fig. 1b), the hydration index shows a gradual fall (Fig. 3c) towards the central part of the complex dominated by anorthosite layer (which crystallized at a relatively dry condition in the magma chamber). The mafic crystallization index (which depends upon the reciprocal of hornblende, pyroxene and biotite modal-data) shows a systematic fall towards the peripheral part which is consistent with the presence of mafic mineral-bearing gabbroic layers (Fig. 3d). Fig. 3(e) shows the reciprocal of plagioclase crystallization index and it decreases from the margin inward. This is the reflection of a greater amount of modal plagioclase percentage towards the (~anorthositic) central part. In each figure (Fig.3 a-e), relevant threshold values have been given which would readily track the style of differentiation.
Spatial variations of all the mineralogical parameters corroborate crystallization from initial anhydrous mafic magma. It is possible that for Kadavur complex, crystallization of constituent minerals had been continuing in a magma chamber for a prolonged period following a similar process as documented for gabbro-anorthosite bodies from Kuliana region, Singhbhum, eastern India. The origin of Precambrian gabbro-anorthosite bodies has been variously interpreted either invoking a differentiation from a single magmatic lineage or as a outcome of several magmatic pulses. The proponents of a single magmatic differentiation history include studies by several workers. According to Weaver et al., the presence of hydrous phase (caused during melting of depleted mantle) and crystal fractionation involving plagioclase cumulates play important role in generating the gabbro-anorthosite (layered) complex. Contrarily, multiple-stage model of development of gabbro-anorthosite mass has been invoked by a number of workers. Therefore, in the backdrop of the available petrogenetic views, it will be worthwhile to resolve this issue (single magmatic lineage or several magmatic pulses) for the present case.

Based on our simple statistical analyses on modal-data of Kadavur gabbro-anorthosite complex, we conclude following important points:

1. The rocks in this complex represent a single magmatic lineage.
2. The rocks in the complex lack mineralogical records of mixing of different pulses of magma, at least during the crystallization of rocks, if not during the pre-crystallization stage. On this basis, the rocks are interpreted to record the differentiation of a single magma of tholeiitic nature. The trend (and nature) of the differentiation process is well outlined by appearance (or disappearance) of minerals (including hydrous phases) from the core to the periphery of the Kadavur complex.

REFERENCES


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FIGURE CAPTIONS:

Fig. 1a: Location of the investigated area (Kadavur Complex) within the regional tectonic-frame of the Southern Granulite Terrane(SGT)\textsuperscript{9}. The location of Kadavur Complex falls within branch-out portions of Palaghat-Cauvery Shear zones\textsuperscript{9}.

Fig. 1b: Geological map of the Kadavur complex (mapped by the present authors). Shaded portion represents the area where isopleths maps for different mineralogical parameters were constructed.

Fig. 2(a) and Fig. 2(b): Plagioclase- Pyroxene- Hornblende and Plagioclase- Orthopyroxene- Clinopyroxene mode based triangular diagram for classification\textsuperscript{18}.

Fig. 3 (a-e): Isopleth maps for several mineralogical parameters within the spatial disposition of layered gabbro anorthosite bodies (taken from Fig.1b of the study area). In all cases arrow heads indicates progressively decreasing values of mineralogical parameters. Numerals represent relevant values of the contours (For details, see text). Explanations of mineralogical parameters are given in Table1. Threshold values are as follows: (a) RCI (Rock Cystallization Index ): -3 for anorthosite > (-3) for gabbroic rocks ; (b) CI (Colour Index ): <5 for anorthosite and >5 for gabbroic rocks; (c) HI (Hydration Index): <3 for anorthosite and >3 for gabbroic rocks; (d) MCI (Mafic Crystallization Index): -1 for anorthosite and >(-1) for gabbroic rocks; (e) RCPI (Reciprocal of Plagioclase Crystallization): -5 for anorthosite and > (-5) for gabbroic rocks.
**TABLE CAPTIONS:**

**Table 1:** Statistical data for different mineralogical parameters.

**Table 2:** Different mineralogical parameters and their respective correlation coefficients after normalized transformations (for details see text).
Fig. 1
Fig. 2
FIG. 3
Table 1: Statistical data for different mineralogical parameters

<table>
<thead>
<tr>
<th>Mineralogical Parameters (with abbreviations)</th>
<th>Explanation*</th>
<th>Arithmetic mean (X̄)</th>
<th>Standard deviation</th>
<th>Variance</th>
<th>Kurtosis</th>
<th>Skewness</th>
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<tbody>
<tr>
<td>An% of Plagioclase</td>
<td>-</td>
<td>0.21</td>
<td>0.12</td>
<td>0.014</td>
<td>0.0003</td>
<td>0.0005</td>
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<tr>
<td>Colour Index (CI)</td>
<td>After IUGS18</td>
<td>-0.85</td>
<td>0.54</td>
<td>0.29</td>
<td>0.17</td>
<td>-0.0074</td>
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<tr>
<td>Hydration Index (HI)</td>
<td>Hbl + Biot / Plag</td>
<td>-3.29</td>
<td>0.68</td>
<td>0.46</td>
<td>0.45</td>
<td>-0.09</td>
</tr>
<tr>
<td>Reciprocal of Plagioclase Crystallization index (RPCI)</td>
<td>Opq / Plag</td>
<td>-3.44</td>
<td>0.8</td>
<td>0.64</td>
<td>0.65</td>
<td>-0.06</td>
</tr>
<tr>
<td>Mafic Crystallization Index (MCI)</td>
<td>opq / Hbl + Pyx + Biot</td>
<td>-2.76</td>
<td>0.70</td>
<td>0.49</td>
<td>1.03</td>
<td>0.31</td>
</tr>
<tr>
<td>Rock Crystallization Index (RCI)</td>
<td>Hbl + Pyx + Biot + Epi + Apat / Opq</td>
<td>-1.06</td>
<td>0.97</td>
<td>0.95</td>
<td>3.29</td>
<td>0.33</td>
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</table>

*For mineralogical parameters namely CI, HI, RPCI, MCI and RCI values were calculated on the basis of modal data (Supplementary Table S1). Plag: Plagioclase, Hbl: Hornblende, Pyx: Pyroxene, Biot: Biotite, Apat: Apatite, Opq: Opaque, Epi: Epidote.

# Mineralogical parameters were log-normalized.
Table 2: Different mineralogical parameters and their respective correlation coefficients after normalized transformation

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Pair of mineralogical parameters</th>
<th>Linear correlation coefficient (r)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Rock Crystallization Index vs Hydration Index</td>
<td>0.42</td>
<td>Highly Significant</td>
</tr>
<tr>
<td>2.</td>
<td>Hydration Index vs Colour Index</td>
<td>0.39</td>
<td>Significant</td>
</tr>
<tr>
<td>3.</td>
<td>Reciprocal of Plagioclase Crystallization Index vs Colour Index</td>
<td>0.8</td>
<td>Highly Significant</td>
</tr>
<tr>
<td>4.</td>
<td>Mafic Crystallization Index vs Hydration Index</td>
<td>-0.45</td>
<td>Highly Significant</td>
</tr>
<tr>
<td>5.</td>
<td>Colour Index vs An% of plagioclase</td>
<td>-0.85</td>
<td>Highly Significant</td>
</tr>
<tr>
<td>6.</td>
<td>Reciprocal of Plagioclase Crystallization Index vs An% of plagioclase</td>
<td>-0.77</td>
<td>Highly Significant</td>
</tr>
</tbody>
</table>

Degrees of freedom (F) = 32; Correlation coefficient values (at F=32) were tested at 5% level of significance: 0.325 and at 1% level of significance: 0.418; significance: 0.325 and 1>. Level of significance = 0.418. Correlation coefficients having value greater than 0.418 are classified as HS (Highly Significant) whereas values ranging between 0.325-0.418 are classified as S (Significant).