Modal data-based simple statistical analysis as an effective petrogenetic indicator: a study from Kadavur gabbro-anorthosite complex, Tamil Nadu, southern India

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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 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: Gabbro-anorthosite, isopleths map, mineralogical parameters, modal data, statistical analysis.

MODAL analysis studies on gabbro-anorthosites have been useful to classify and characterize such rocks. For example, Ashwal worked out the genesis of the Mount Marcy anorthosite massif (Adirondacks, New York, USA) with a particular focus on anorthositic rocks associated with the high-grade terrain. Even for the Apollo-11 samples, modal analyses helped ascertain the heterogeneity in the lunar highland series. However, in recent times, such modal analysis-based approaches for gabbro-anorthosites are lacking. In reality, modal data of igneous rocks represent the actual mineralogical composition and help in accurate nomenclature. Nowadays, however, the emphasis has shifted to other domains, presumably because of the availability of major, trace and isotopic data. Even in this scenario, in the recent past, modal data-based studies have helped resolve the long-standing controversy related to the accretion of gabbroic lower crust at the ridge axis. In this context of the intrusive gabbro-anorthosite complex near Kadavur (10°35’N, 78°11’E), southern India (Figure 1), the present study performs 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 (Figure 1a). However, during 1980s, the region (hosting the Kadavur complex) was known as the Eastern Ghats Belt. Early studies on the Kadavur complex suggest that: (i) the intrusion represents a funnel-shaped concordant body and (ii) the complex bears geological similarities with the Adirondack mountains. However, later studies have argued against the similarities between the Kadavur complex and intrusive rocks in the Adirondack region; on the contrary, it was compared with early Archean, layered gabbro-anorthosite complex. It has been suggested that the Kadavur complex manifests multiple phases of magmatism with corresponding mappable attributes. Recent workers suggest a tholeiitic parentage and an inferred age of ~810 Ma for the anorthositic intrusions. However, it is unclear whether the complex is a product of differentiation from common parent magma or corresponds to discrete and separate magmatic pulses. Hence, this study attempts to resolve this issue with the help of statistical analyses of modal data and relevant correlation characteristics amongst mineralogical parameters.

The present work involves field studies, petrographic analyses and detailed statistical studies on modal variables that help throw light on the petrogenesis of the Kadavur complex.

Figure 1. a, Location of the study area (Kadavur complex) within the regional tectonic frame of the Southern Granulite Terrane. The complex falls within the branch-out portions of the Palaghat–Cauvery shear zone. b, Geological map of the Kadavur complex (by the present authors). Shaded portion represents the area where isopleths maps for different mineralogical parameters were constructed.
complex. The 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 are provided in Supplementary Figure 1. 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 (Figure 1b). Representative field photographs are given in Supplementary Figures 2 and 3.

Structural analyses often play an important role to understand the style of deformation in a terrane showing multiple folding and deformation. In this study, stereo pole diagrams of the foliation planes of country rocks have been constructed (Supplementary Figures 4a–c and e), which indicate that the sheath fold geometry caused by a superposed pattern (Supplementary Figure 4d) is being guided by the shearing mechanism\(^{17}\). 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 Figure 4f). In order to give an idea to the readers about the different types of intrusives within the Kadavur complex, representative hand-specimen photographs and photomicrographs have been furnished in Supplementary Figure 5.

Table 1 presents the arithmetic mean ($X̅$), standard deviation, variance, skewness and kurtosis of different mineralogical parameters (log-normalized). Six types of mineralogical parameters were chosen for correlation studies. These include anorthite percentage (An\(\%\)) of plagioclase, colour index (CI), hydration index (HI), reciprocal of plagioclase crystallization index (RPCI), mafic crystallization index (MCI) and rock crystallization index (RCI) (Table 1). Percentage values of different data were transformed to $Y$ using the transformation equation $Y = \log(X/100 – X)$, where $X$ represents the present data, including several mineralogical parameters\(^{22,23}\). CI was determined following the method given in the IUGS classification\(^{18}\). The other indices, namely HI, RPCI, MCI, RCI and An\(\%\) of plagioclase, were also transformed using the same formula, i.e. $\log(X/100 – X)$. For easy comprehension, Table 1 gives explanations for the different indices.

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**Figure 2 a, b.** Plagioclase–pyroxene-hornblende and plagioclase–orthopyroxene–clinopyroxene mode-based triangular diagram for classification\(^{18}\).
The significance of the calculated correlation coefficients \( r \) was tested at 5\% and 1\% levels of significance\(^{26}\). Table 2 gives the linear correlation coefficient values. To understand the style of several spatial variations of the mineralogical parameters in the layered gabbro-anorthosite bodies, these attributes were plotted in isopleth maps (Figure 3 a–e). The RCI value showed a systematic decrease from the margin of the complex to its central part (Figure 3 a). These decreasing values are consistent with the low proportion of mafic minerals towards the centre, where the anorthositic band is most dominant (Figure 1 b). CI also showed a systematic decreasing pattern from the margin inwards (Figure 3 b). This observation attests to the presence of (plagioclase-dominant) anorthosite occurrence towards the centre. In concordance with the geological map (Figure 1 b), HI showed a gradual fall towards the central part of the complex dominated by an anorthosite layer (which crystallized under a relatively dry condition in the magma chamber) (Figure 3 c)\(^{27}\). MCI (which depends on the reciprocal of hornblende, pyroxene and biotite modal data) showed a systematic decrease towards the peripheral part, which is consistent with the presence of mafic mineral-bearing gabbroic layers (Figure 3 d). Figure 3 e shows that RPCI decreases from the margin inwards. This reflects a higher modal plagioclase percentage towards the (anorthositic) central part. In Figure 3 a–e relevant threshold values have been given to track the style of differentiation readily.

Spatial variations of all the mineralogical parameters corroborate crystallization from initial anhydrous mafic magma. It is possible that for the Kadavur complex, crystallization from initial anhydrous mafic magma. It is possible that for the Kadavur complex, crystallization from initial anhydrous mafic magma. It is possible that for the Kadavur complex, crystallization from initial anhydrous mafic magma. It is possible that for the Kadavur complex, crystallization from initial anhydrous mafic magma.

Table 2. Different mineralogical parameters and their respective correlation coefficients after normalized transformation

<table>
<thead>
<tr>
<th>Pair of mineralogical parameters</th>
<th>Linear correlation coefficient ( r )</th>
<th>Remark</th>
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<tbody>
<tr>
<td>RCI versus HI</td>
<td>0.42</td>
<td>Highly significant</td>
</tr>
<tr>
<td>HI versus CI</td>
<td>0.39</td>
<td>Significant</td>
</tr>
<tr>
<td>RPCI versus CI</td>
<td>0.8</td>
<td>Highly significant</td>
</tr>
<tr>
<td>MCI versus HI</td>
<td>–0.45</td>
<td>Highly significant</td>
</tr>
<tr>
<td>CI versus An% of plagioclase</td>
<td>–0.85</td>
<td>Highly significant</td>
</tr>
<tr>
<td>RPCI versus 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. Correlation coefficients greater than 0.418 are classified as highly significant whereas those ranging between 0.325 and 0.418 are classified as significant\(^{26}\).
Based on our simple statistical analyses of modal data of the Kadavur gabbro-anorthosite complex, we conclude the following important points:

1. The rocks in this complex represent a single magmatic lineage.
2. These rocks lack mineralogical records of mixing of different pulses of magma, at least during crystallization, 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 the appearance (or disappearance) of minerals (including hydrous phases) from the core to the periphery of the Kadavur complex.

Figure 3. Isopleth maps for several mineralogical parameters within the spatial disposition of layered gabbro-anorthosite bodies (taken from Figure 1b of the study area). In all cases arrowheads indicate progressively decreasing values of mineralogical parameters. Numerals represent relevant values of the contours (for details, see text). Explanations of mineralogical parameters are given in Table 1. Threshold values are as follows: a, RCI (rock crystallization 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.

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