planes. Further, the forward gravity modelling of a synthetic fault structure with both planar and non-planar fault planes reveals the fact that the magnitude of the anomaly differs from each other over the length of the profile.


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Need to intensify base metal exploration activities in Mikir Hills, northeastern India

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Precambrian shield areas are often metal-enriched. Unlike many other contemporary shields, the Mikir Hills, however, does not have any history of metal production in the past. Ultrabasic–basic–intermediate to acid and alkaline magmatism of Precambrian to Cretaceous age depict evidences of mineralization in the shield. Poor understanding of the geological and geo-chronological events is responsible for branding barren signature to the shield. Recently generated geo-chronological data on mineralized Palaeoproterozoic granitoids of the shield provide cognizance to its geological evolution. The merit of metallogenic appraisal brightens as the geochronological data produced recently indicate the existence of granitoids of Palaeoproterozoic age in this craton. Moreover, recent studies have revealed that a majority of felsic to intermediate magmatic with distinct mineralization signatures are mantle-derived I-type granitoids and their metal contents are derived from similar source region. Features of hypogene alteration found prominence in a studied mineralized porphyry granitoid of Kuthori–Bagori locality of Kaziranga magmatic suite having calc-alkaline affinity. Local and regional-scale shear intensive has been observed and the structural elements are oriented in NNE–SSW to NE–SW directions. They are sporadically mineralized through the craton.

Keywords. Base metal, craton, Palaeoproterozoic granitoids, Precambrian shield, Ur mega province.

Although primary base metal sulphide mineralization is predominantly associated with magmatic bodies of mantle or near mantle derivation, their association with exhalative sedimentary bodies must not be ignored. Globally, base metal production comes either from the vast territory of Palaeo-subduction zones or from rift-related centres occupying part of the present Precambrian shield areas. Unlike many productive Precambrian shields of the world, the Mikir Hills (MH) craton bears similarities in geo-tectonic evolution. The magmatic variants include complex polyphase granitoids, alkaline complexes and flood basalts of Precambrian to late Cretaceous age (Figure 1). Sedimentary and meta-sedimentary rocks, however, occupy two-thirds of the total lithounits, whereas magmatic rocks of diverse nature constitute nearly one

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third of the total lithounits of the craton. A limited num-
ber of preliminary reports on the geology of MH are
available where the geo-chronology of different lithounits
and their structural dispositions has not been addressed
properly. The metallogeny of MH is yet to be worked out
detail.

This communication discusses the prospects of base
metal in parts of the MH craton based on case studies car-
ried out on the granitoids of the Kuthori–Bagori locality
of Kaziranga magmatic suite and Kathaljuri granitoids
(KG) of Dizo Valley magmatic suite. The present study
opens up new opportunities for the exploration agencies
to carry out operations in the region.

Copper ores of magmatic affiliation are preliminary
localized in acid to intermediate intrusives, however, car-
bonatite and skarn are not the rare exception. Sulphide
occurrences are reported in various magmatic rock types
such as ultrabasic intrusives in the Lohajuri–Bajajuri
(26°25′30″N; 93°27′48″E) and Tarapung–Borpung
(26°28′10″N; 93°29′30″E) areas in the central portion of
MH; the Borpung Ultramafic Complex with visible sporo-
ad disseminations of sulphides along the shear zones
near Barpung; the metabasics of Dizo Valley
(92°57′24″E, 24°24′17″N), the Kalibany river lineament
and in the Rengengjuri Ghat near Numaligarh
(26°42′49″N; 93°43′48″E).

Indications of mineralization in certain polyphase
granitoids of the craton occurring in the north and north-
western MH have been observed by the present author.
The mineralized granoid (about 2.6 km in diameter),
occuring in Kuthori (Colony–Bagori (Bhalukjuri) (KBG)
locality of Kaziranga magmatic suite (lat. 26°34′N; long.
93°10′E; S.I. toposheet nos 83 F/2 and F/6) was found to
be significant. The grey-coloured, fine-grained stock-like
disconcordant) granitoid body with distinct porphyritic tex-
ture is a member of the Kaziranga Polyphase Granitoids
(KPG). Reports on porphyry mineralization in KPG are
already available. Incidentally, KBG of KPG appears to
be an important prospect for porphyry-type mineraliza-
tion and therefore, has been discussed in detail.

Analytical work was carried out at a number of
national facilities. Fifteen fresh grab and channel samples
from KBG and eight samples of Dizo Valley magmatites
were analysed for major elemental oxides in a SIEMENS
SRS 3000 XRF system. An equal number of samples was
analysed for trace and REE by inductively coupled
plasma–mass spectrometry (ICP–MS) using a Perkin
Elmer Elan DRCII. Whole-rock rubidium–strontium iso-
tope analyses were made in Multicollector Thermal Ioni-
ation Mass Spectrometer, model VG 354 (TIMS).
Sulphur isotopic analyses were made at the same labora-
tory using BG 903 Mass Spectrometer. The results of iso-
topic studies obtained have a standard deviation of 0.05% in
mass spectrometric measurements. NEWPET, 1994
and SYNCLAS, 2003 software were employed for data
processing and interpretation.
Data pertaining to geochronology and tectono-stratigraphic evolution of MH granitoids are inadequate and confined to the field relations of mineralized hosts with the country rocks. However, preliminary geo-chronological data calculated on the basis of whole-rock Rb–Sr isotope for the granitoids of the Kaziranga suites provide the Palaeoproterozoic age (maximum 2152 ± 43 Ma; minimum 1953 ± 39 Ma). Data of both porphyritic and hypidiomorphic granitoids show initial \(^{87}\)Sr/\(^{86}\)Sr ratio around 0.7025%, which indicates that the precursor magma for these granitoids evolved from the upper mantle or lower crust. Magma assimilation and differentiation has been envisaged in the evolutionary process. The medium-grained hypidiomorphic mineralized granitoids of Kathalguri, however, are of younger age (Neoproterozoic?).

The MH vis-à-vis Shillong Plateau has long been described as a detached part of the Indian shield or otherwise an extension of the Central Gneissic Complex or Eastern Ghat Basalt\(^{9,10}\). Some workers are of the view that certain granite plutons are 881–479 Ma old. This conforms the massive volcanic activities in certain parts of the Indian Shield. This Neoproterozoic felsic magmatism of the Shillong Plateau seems to be associated with the disintegration and dispersal of Rodinia activated by mantle plume activities\(^{11}\). In view of the present findings of the existence of felsic magmatic rocks of Palaeoproterozoic age, the Palaeoproterozoic intercontinental re- construction of continents seems to be a valid proposition that has provided added advantage in the metal prospectivity of the MH craton; as it is likely to have formed a part of the metal-enriched proto-continental Ur Mega province\(^{12}\) (Figure 2). It is also suggested that the mineralized Dharwar and Bundelkhand proto-continents were merging along the Central Indian Tectonic Zone (CITZ) during the Proterozoic and extended up to the Singhbhum Craton. It is still a matter of debate whether the influence of CITZ was felt up to MH or MH was part of the metal-enriched western Australian land mass forming together a part of the Ur proto-continent.

The present field study on metallogeny of MH has revealed at least four sulphide mineralization variants, viz. (i) hydrothermal ore solutions filling up shear-dominated regimes affecting basic–ultrabasic and/or intermediate to acid magmatic; (ii) hydrothermal vein fillings, particularly in acid magmatic; (iii) plutonogenic ore associated with porphyry granitoids bearing features of porphyry-type copper sulphide mineralizations and (iv) carbonatite (alkaline) complexes with features of scaly sulphide mineralizations.

In the entire MH cratonic, vein-type mineralization seems to be insignificant as most of the veins are only a few centimetres in width. Veins are prominent in sheared regimes of Kaziranga, Kaliyani and Dizo Valley. The discordant and hypidiomorphic KG occurring in the Dizo Valley show vein-type mineralization. Surface indications of KG, however, do not favour the occurrence of thicker polysulphide veins of economic worth in them.

KGB granitoids contain ample mineralization signatures. Ore minerals are in the form of disseminations; vein/microvein fillings in stockwork patterns perceptibly caused by crackle brecciation and metal enserustations. The granitoids are partly affected by a moderately thick shear zone having NE–SW structural elements (Figure 3).

Petrographic study of KGB has revealed the presence of euhedral plagioclase, microcline, quartz and orthoclase megacrysts (Figure 4a). The groundmass is composed of fine-grained, finely disseminated quartz, plagioclase, biotite, rare hornblende and their hypogene alteration products. Petrographic sections reveal dissemination of opaques (sulphides) and valotile phases as mineral inclusions (Figure 4b–d), besides concentric development of alteration zones around Kuthori (Colony) locality of KGB. Thus, Kuthori (Colony) shows dominance of quartz–biotite–K-feldspar–sericite representing potassic mineralogy; the mineralogy then changes outward to quartz-sericite-pyrite or occasionally to kaolinite/chlorite followed by chlorite–epidote–calcite; intense silicification occurs in certain orientations. These alterations are broadly at par with the alteration–mineralization zoning model of Lowell and Guilbert, normally developed in the porphyry environment\(^{13}\). KG mineralogically represent composition of pure granite and do not show features of hypogene alteration.

Recently published data on the geochemistry of KG approve dominant potassic chemistry, I-type and metaluminous nature; silica-enriched (up to 75%), FeO (total) deficient and variable CaO content. This defines normal calc-alkaline trend and affinity towards crystal fractionation as a major process in the extraction of granite melt from the original magma. Crustal thickening due to

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**Figure 2.** Ur and expanded Ur super-continent with possible position of Assam-Meghalaya Plateau (modified after Rogers and Santoshi\(^{15}\)).
syn-post collision has been reported\(^{14}\). Geochemical and consequent metallogenetic analysis done on the KG provides discouraging results.

Geochemical study of KBG indicates that fine porphyritic granitoids are strongly metaluminous and oxidized or magnetite-bearing (supported by, A/CNK < 1). The overall geochemistry shows that the fine porphyritic granites in question, containing porphyry copper ore, are characterized by moderately high Al and Ca content, high HFS elements (Zr, Nb, Y), Ga and high FeO*/MgO, Ga/Al and Na\(_2\)O + K\(_2\)O/Al\(_2\)O\(_3\) ratios. Such chemical characters of the present rocks are the characteristics of A-type (I-type) granites\(^{15,16}\). In general, I-type magmas are acidic, contain higher fO\(_2\) (prior to second boiling), high ratio of SO\(_2\) : H\(_2\)S and are enriched in incompatible elements, including chalcophile ore metals and total chlorides. The studied granitoids presumably manifest conditions favourable for porphyry-type mineralization. They are partly structurally controlled. The present study reveals that high oxidizing state alone is not responsible for copper occurrence but the FeO*/MgO ratio of the granitoids also has an important role to play in the mineralization.

Further, chondrite normalized REE patterns of these rocks are comparable with the REE pattern of typical A-type granite of Lyngdal area, Norway\(^{17}\). Enrichment in Ba and Rb, and depletion of Sr compared to non-mineralized coarse granitoids has been recorded. The mineralized fine porphyritic granitoids show enrichment in Ta and Hf and depletion in Th and Ce compared to non-mineralized coarse granitoids. However, the tectonic relation between these two varieties is difficult to interpret from the present geochemical study. The overall
REE signature indicates the occurrence of the granitoids within the plate environment in plume-induced rift-related centre\textsuperscript{12}. Proterozoic granitoid rocks of similar composition to the KGB have been reported to contain porphyry copper deposits elsewhere\textsuperscript{18,19}.

The abundance of restite in a melt is another major consideration; the restite-rich granitoids cannot give the concentration of any element than those present in the initial melt poor in restite\textsuperscript{20}. In contrast, convective fractionation provides a better mechanism whereby elements, particularly those of economic importance can be detected. This explains why coarse-grey granitoids (I-type) and coarse-pink granitoids (S-type) are not mineralized, whereas the fine porphyritic KGB granitoids are mineralized.

Another issue related to KGB is the depleted background value of copper in barren parts of host granitoids (±1.0 ppm). Copper is partitioned in the melt phase in calc-alkaline magma because of the existence of a greater number of octahedral coordination sites in them and not partitioned into the co-existing minerals like biotite and hornblende of the hosts. Therefore, copper minerals other than those of ore shell in a porphyry-type mineralization always shadow a poor background value\textsuperscript{21}. Comprehensive chemical analytical data and general features of KGB and KG of the recent study and comparisons are presented in Tables 1 and 2.

Two principal ore mineral assemblages, viz. primary ore and moderately oxidized occasionally intensely oxidized ore dominate KGB. The ore assemblages retain many hypogene textural signatures. Stockwork, finer disseminations, vein–veinlets filling and cumulus are some of the main textural variants exhibited by the constituent polymetal sulphides ores. Moreover, pyrite : chalcopyrite ratio varies zonally. In potassic alteration zone, the ratio

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**Table 1.** Chemical data of Kathori–Bagori (KGB) and Kathalguri host granitoids (KG)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range (in %)</th>
<th>Average n = 15</th>
<th>Range (in %)</th>
<th>Average n = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO\textsubscript{2}</td>
<td>54.4 – 71.5</td>
<td>61.4</td>
<td>69.1 – 70.5</td>
<td>69.9</td>
</tr>
<tr>
<td>TiO\textsubscript{2}</td>
<td>0.3 – 0.7</td>
<td>0.6</td>
<td>0.5 – 0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>12.3 – 15.1</td>
<td>14.3</td>
<td>11.4 – 13.7</td>
<td>12.2</td>
</tr>
<tr>
<td>Fe\textsubscript{2}O\textsubscript{3} (T)</td>
<td>4.4 – 12.2</td>
<td>9.4</td>
<td>3.1 – 5.5</td>
<td>4.3</td>
</tr>
<tr>
<td>MnO</td>
<td>0.1 – 0.3</td>
<td>0.11</td>
<td>Upto 0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>MgO</td>
<td>1.0 – 12.3</td>
<td>2.4</td>
<td>1.5 – 4.8</td>
<td>3.86</td>
</tr>
<tr>
<td>CaO</td>
<td>0.6 – 4.7</td>
<td>3.15</td>
<td>1.3 – 2.6</td>
<td>1.98</td>
</tr>
<tr>
<td>Na\textsubscript{2}O</td>
<td>0.1 – 4.7</td>
<td>3.6</td>
<td>0.3 – 2.2</td>
<td>0.86</td>
</tr>
<tr>
<td>K\textsubscript{2}O</td>
<td>2.9 – 5.7</td>
<td>3.3</td>
<td>5.4 – 6.3</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Concentration (in ppm)

<table>
<thead>
<tr>
<th>Element</th>
<th>Range (in %)</th>
<th>Average n = 15</th>
<th>Range (in %)</th>
<th>Average n = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>0.233 – 38.6</td>
<td>10.55</td>
<td>7.2 – 8.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Ni</td>
<td>2.8 – 10.7</td>
<td>5.7</td>
<td>4.8 – 6.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Cu*</td>
<td>0.6 – 1.9</td>
<td>1.19</td>
<td>0.9 – 2.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Pb</td>
<td>21.7 – 140.3</td>
<td>72.6</td>
<td>20.2 – 123.6</td>
<td>64.1</td>
</tr>
<tr>
<td>Zn</td>
<td>30.8 – 105.4</td>
<td>45.6</td>
<td>41.9 – 55.5</td>
<td>51.7</td>
</tr>
<tr>
<td>Rb</td>
<td>30.8 – 347.8</td>
<td>153.5</td>
<td>272.4 – 318.5</td>
<td>291.6</td>
</tr>
<tr>
<td>Ba</td>
<td>64.3 – 3603.0</td>
<td>1104</td>
<td>426.5 – 4411.0</td>
<td>1851.7</td>
</tr>
<tr>
<td>Sr</td>
<td>25.8 – 519.2</td>
<td>103.6</td>
<td>154.2 – 964.0</td>
<td>428.0</td>
</tr>
<tr>
<td>Ga</td>
<td>14.9 – 79.2</td>
<td>29.53</td>
<td>22.8 – 41.4</td>
<td>31.9</td>
</tr>
<tr>
<td>Nb</td>
<td>16.5 – 137.7</td>
<td>60.9</td>
<td>41.5 – 176.8</td>
<td>109.5</td>
</tr>
<tr>
<td>Zr</td>
<td>145.2 – 2366.1</td>
<td>747</td>
<td>102.4 – 227.1</td>
<td>173.2</td>
</tr>
<tr>
<td>Y</td>
<td>212.2 – 75.7</td>
<td>57.6</td>
<td>55.0 – 119.8</td>
<td>87.2</td>
</tr>
<tr>
<td>La</td>
<td>46.4 – 230.3</td>
<td>73.9</td>
<td>125 – 140.7</td>
<td>131.0</td>
</tr>
<tr>
<td>Ce</td>
<td>55.7 – 447.4</td>
<td>146.2</td>
<td>258.9 – 1848.5</td>
<td>802.0</td>
</tr>
<tr>
<td>Pr</td>
<td>7.0 – 45.4</td>
<td>16.1</td>
<td>26.2 – 32.5</td>
<td>29.4</td>
</tr>
<tr>
<td>Nd</td>
<td>31.5 – 166.0</td>
<td>62.9</td>
<td>95.0 – 128.1</td>
<td>111.7</td>
</tr>
<tr>
<td>Sm</td>
<td>5.8 – 25.4</td>
<td>11.9</td>
<td>14.6 – 22.4</td>
<td>19.0</td>
</tr>
<tr>
<td>Eu</td>
<td>0.6 – 3.5</td>
<td>1.64</td>
<td>1.1 – 1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Gd</td>
<td>5.3 – 20.1</td>
<td>10.72</td>
<td>12.0 – 18.0</td>
<td>15.1</td>
</tr>
<tr>
<td>Tb</td>
<td>0.8 – 2.4</td>
<td>1.54</td>
<td>1.6 – 2.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Dy</td>
<td>4.4 – 13.4</td>
<td>16.22</td>
<td>9.7 – 18.2</td>
<td>14.4</td>
</tr>
<tr>
<td>Ho</td>
<td>0.4 – 1.5</td>
<td>1.11</td>
<td>1.0 – 2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Er</td>
<td>1.4 – 4.6</td>
<td>3.78</td>
<td>5.5 – 7.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Tm</td>
<td>0.2 – 0.6</td>
<td>0.5</td>
<td>0.5 – 1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Yb</td>
<td>1.7 – 6.1</td>
<td>5.05</td>
<td>5.0 – 13.3</td>
<td>8.5</td>
</tr>
<tr>
<td>Lu</td>
<td>0.3 – 1.1</td>
<td>0.89</td>
<td>0.8 – 2.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

* Copper values in barren portion of host granoid; n, Number of samples.
<table>
<thead>
<tr>
<th>Rock-type (QAP) classification</th>
<th>Variable; quartz monzonite, granodiorite and granite</th>
<th>Quasi granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>2152 ± 43 to 1953 ± 39 Ma based on (^{87}\text{Rb}/^{87}\text{Sr}-^{87}\text{Sr}/^{86}\text{Sr} \text{systematic.}</td>
<td>ND. Must be younger</td>
</tr>
<tr>
<td>Host-rock chemistry</td>
<td>Silica composition is variable, but intermediate in central portion of the stock. Occasional high silica percentage is due to silicification reactions. High content of HFS elements like Zr, Nb, LREE; low Sr; high Ga; barren country rocks (granitoids) are abnormally low in Cu (≤ 1.0 ppm); magma composition are calc-alkaline, metaluminous, I(A)-type, strongly oxidized magma, within plate emplacement.</td>
<td>SiO₂ is always &gt; 68 wt%; K₂O and Al₂O₃ vary marginally. The Apatitic Index value (average 0.87) near calc-alkaline group; close affinity to mantle fractionate; low degree of partial melting as seen in the high LREE and flat HREE pattern.</td>
</tr>
</tbody>
</table>

Figure 5. Photomicrographs of ore assemblages with textural disposition (under reflected light). a. Pyrite (Py) cataclasis and infilling of chalcopyrite (Cpy) in the fractures due to shearing. Chalcopyrite remains non-reactive with the pyrite grains (Kuthori ore). b. Partial loss of primary texture-fracturing and veining in sphalerite gets absorbed; chalcopyrite migrates to the boundary of sphalerite (Sph). Textural modification of the type seen along shear planes (Borjuri ore). c. Chalcopyrite and sphalerite present sequential replacement of early pyrite. Sphalerite is the youngest phase in the association (Bagori ore). d. Magnetite (Mag) subseda with dispersed recrystallized pyrite set in silicates. is 1:1, but in the boundary zone gradually pyrite dominates over chalcopyrite and the ratio becomes about 10:1. Ore mineralogy of Kuthori (Colony) area shows fine dissemination of sulphides. The \(^{34}\text{S}/^{32}\text{S} \text{isotope ratio of separated sulphides with } +4.5 \pm 0.05\% \text{ coincides with the lower crust or upper mantle ratio of sulphide ores.}
The dominant ore minerals of Kathalguri are chalcopyrite and bornite with minimum percentage of pyrite. Rare occurrence of pyrrhotite has been noted in KG with occasional occurrence of magnetite and galena (Figure 5).

The foregoing discussion on aspects of mineralization in the MH craton provides the following important conclusions:

(i) MH is projected to be a member of the Ur Megaprovince, wherein mantle-dominated magmatic activities under the influence of plume-induced rift found prominence during the Palaeoproterozoic era or even earlier.

(ii) Palaeoproterozoic calc-alkaline I-type (A-type) magmas derived from the mantle are responsible for the production of enriched A-type porphyry granitoids in the MH craton.

(iii) Overall chemistry of the magmas and strong negative copper anomaly in the unmineralized part of the host granitoid of KGB increase its favourability for hosting porphyry-type mineralization, as is seen in a number of Palaeoproterozoic and later granitoids globally.

(iv) Tracing mineralogical components and hypogene alteration patterns as well as field features observed in KGB are the other positive indications.

(v) Thus, the porphyry model for the genesis of KGB has been suggested, whereas a simple hydrothermal cavity-filling model of insignificant magnitude may be envisaged for the KG.

Finally, a relevant issue is raised for future workers to examine whether KGB like diapiric granitoids under consideration can host porphyry copper ores of economic worth? This is not only important, but also significant in view of branding MH as a barren craton by the national geological exploration agencies so far.


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