Submagmatic fabric in the 2.6 Ga Bundelkhand granitoid, India: evidence from microstructure

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Primary foliations in igneous rocks are the key to understanding processes within the magma chamber, cooling history, paleostress regime and strain during emplacement of granitoid plutons. In the 2.6 Ga Bundelkhand granitoid rocks, weak to moderately strong regional fabric is the result of submagmatic grain-supported flow during syn-kinematic emplacement of the magma. Microstructural and outcrop-scale evidences provide an excellent record for interpreting the significance of this fabric development vis-à-vis rheological state during fabric formation. Preferentially oriented tabular feldspar phenocrysts in the granitoid show deformation such as reformed shape, marginal fragmentation and recrystallization, whereas the finer interstitial grains of quartz remain undeformed or mildly deformed. On the basis of the characteristic foliated structure of the Bundelkhand granitoid and the specific contrasting deformation characteristics of feldspar and quartz grains, we propose that the fabric is submagmatic in origin and perhaps formed during syn-emplacement deformation environment of the granitoid.

Keywords: Igneous rocks, microstructure, submagmatic fabric, syntectonic emplacement.

MAGMATIC fabrics provide critical petrologic information regarding magmatic to subsolidus kinetic history and processes operating within the magma chamber of igneous rocks. Since the pioneering work on magmatic foliations in the early part of the last century[1,2], widespread interest was generated on the genesis of the fabric and its implications[3–12]. Foliation in granitoid rocks can be formed by magmatic flow, submagmatic flow and high-to low-temperature solid-state deformation[13]. Deformation of magma is common in syntectonic plutons and has been presented in several works[4,14,15], where the influence of regional tectonics on the ascent and emplacement of magma, and structures generated at the magmatic or submagmatic stage have been illustrated. Magmatic foliation may result from magmatic flow, defined as deformation by displacement of magmatic melt, with consequent rigid-body rotation of suspended crystals, without sufficient interference between crystals to cause plastic deformation in them[9–12]. Microstructural evidence of magmatic flow includes (a) preferred orientation (parallel or sub-parallel alignment of elongate euhedral crystals) of primary igneous minerals with no evidence of plastic deformation, (b) aligned crystals surrounded by anhedral, non-deformed quartz, and (c) small or insignificant solid-state strain in the interstices between aligned euhedral crystals[9,12]. The transition state from magmatic (submagmatic flow)[9] to solid-state flow (subsolidus flow)[9] may form during the cooling of magma, though reliable microstructural criteria for such a process are not unambiguous and difficult to obtain[12]. In the literature, critical assessment of the characteristics of submagmatic flow is sparse and therefore remains an important problem. The term ‘submagmatic flow’ is not universal and some ambiguity exists on its usage. The terms ‘pre-RCMP’ and ‘post-RCMP’ for ‘magmatic’ and ‘submagmatic’, have been suggested respectively[16], where RCMP is the ‘rheologically critical melt percentage’[17,18]. However, as the RCMP concept is not well-defined, the older terms ‘magmatic’ and ‘submagmatic’ are preferable[19]. Submagmatic flow implies grain-supported flow, which occurs, as indicated by experimental studies, when the melt content comes down to ~20% (ref. 12). When melt percentage is very low, it is suggested that the strain may be accommodated by (a) melt-enhanced embrittlement, (b) melt-assisted grain-boundary sliding, (c) contact-melting-assisted grain-boundary migration, (d) strain partitioning into melt-rich zones, (e) intracrystalline plastic deformation, and (f) transfer of melt to sites of low mean stress[13]. In submagmatic stage, the microstructural features should indicate deformation in ‘hot condition’ as some percentage (perhaps silica-rich liquid) is still in liquid condition. Overall, the criteria as suggested by Vernon[12], which are useful indicators of submagmatic flow are: (a) recrystallized feldspar with exsolution lamellae, myrmekite structure, evidence of change from homogeneous to heterogeneous deformation, presence of later magmatic minerals such as quartz and/or feldspar filling fractures in plagioclase crystals, etc. There are differences of opinion regarding the character of fabric and microstructures, and

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evidence of plastic deformation/recrystallization and fracture developing during submagmatic flow of magma[20–22]. Since there is a fair degree of uncertainty in pin-pointing the unmistakable criteria in favour of submagmatic flow, it was rightly pointed out that the reliable criteria for 'submagmatic flow' are essential, to show that melt was still present during regional deformation[9]. But, these criteria are more difficult to obtain. It was pointed out that microstructural evidences may be used to evaluate hypotheses for the mechanisms of pluton emplacement and therefore are important in understanding the mechanics of pluton emplacement history[12]. In the present work we examine microstructures and microfabrics to find evidence of deformation of crystal-melt systems in Bundelkhand granitoid pluton in north central India and thereby interpret the foliation development in magmatic condition.

The Bundelkhand granitoid has a weak to well-developed and penetrative foliation defined by preferential alignment of potassium and plagioclase feldspar phenocrysts (grain shape foliation, GSF). This GSF is seen throughout the granitoid with variable degrees of development. We call this as regional foliation in the granitoid. At places, the foliation is absent and the rock is characterized by 'unfoliated' and 'irregular' magmatic texture. Since in this study we concentrate on the regional foliation in Bundelkhand granitoid, particularly on its genesis, rather than discretely developed mylonitic foliation present only along the ductile shear zones, our study area is so chosen that it is least affected or unaffected by the later ductile shear zone-related tectonic overprinting. We will present our shear zone-related fabric development in a separate contribution.

Our primary objective is to evaluate whether the regional fabric is a deformation-induced foliation formed by solid-state flow, or is the result of magmatic/submagmatic flow formed during syn-kinematic ascent and emplacement of the granitoid magma. We describe the development of microstructure in the granitoid by careful documentation of microstructural evidences in the rock. Given that the magmatic/submagmatic foliation bears the signature of emplacement of the large granitoid, including the kinematics of emplacement of the melt on the one hand and deformation signature of the solid state deformation on the other, it is important to analyse the signatures of foliation development and the genesis of formation of regional foliation in large igneous bodies like Bundelkhand granitoid. We have critically analysed the textural characteristics and their probable implications on the genesis of foliation development in order to understand their application in granitoid in general. To the best of our knowledge, there have been no attempts of study on the genesis of the foliation development in the Bundelkhand granitoid. We hope our results will provide an insight into the genesis of the regional foliation at least in part of the granitoid.

Our reconnaissance study covers a larger part of the Bundelkhand granitoid supplemented by an extensive study in a small area, about ~22 km northwest of Jhansi (25°26′38.49″N, 78°34′03.76″E), in the northern part of the craton (Figure 1).

Geological setting

The Bundelkhand craton of the north central part of peninsular India occupies ~26,000 sq. km area (Figure 1, inset) and consists of Meso-Neoarchaean Bundelkhand gneissic complex (3500–3300 Ma)[23,24], metasedimentary and metavolcanics, Madawara igneous complex and Neoarchaean–Palaeoproterozoic (2500 Ma)[24] Bundelkhand granitoid[25–27]. Apart from these, kilometre-scale long and tens of metre-scale wide quartz veins are present throughout the craton as NE–SW trending topographically high linear bodies, and NW–SE trending extensive mafic dyke swarms[27].

Satellite imagery and accompanying field checks clearly depict that the entire craton is affected by ~E–W, NE–SW, NW–SE and N–S trending shear zones/fractures.

Character of granitoid rocks

The Bundelkhand granitoid is coarse-grained, mainly monzogranite to granite variety and consists of abundant feldspar (with albitic plagioclase dominant over K-feldspar) and quartz; amphibole, biotite, epidote, sphene and zircon constitute common accessory minerals. The modal percentage of feldspar megacrysts varies from 40 to 65 vol%. Both grey and red-coloured granitoid rocks occur side by side, with the red ones grading into the grey ones (Figure 1). The red granitoid is dominant over the grey variety throughout the craton. The lack of any cross-cutting relationship between grey and red granitoid, and absence of enclaves or tongues of one rock type into another near the boundary zones suggest that these granitoid rocks are synchronous. The modal data plot, on the IUGS quartz–alkali feldspar-plagioclase diagram for plutonic rocks, of all the samples of the study area falls in the granite field (Figure 2).

Occasional E–W trending tens of centimetre to metre-scale enclaves of older amphibolite, oriented parallel to the E–W foliation in granitoid, are present within the granitoid rocks.

The granitoid rocks have a GSF penetrative foliation, defined by preferential alignment of flat faces of feldspar phenocrysts (Figure 3), that sometimes grades into irregular, unfoliated magmatic texture. The foliation in most of the exposures dips at steep angle and trends ~E–W throughout the extent of the Bundelkhand granitoid. Majority of the feldspar phenocrysts long axes are parallel to the foliation. Occasionally, a few feldspar phenocrysts are oriented at low angle (<30°) with the main foliation.

Although there is variation in orientation of the foliation, defined by preferential alignment of the feldspar phenocrysts, but on the whole it is steep-dipping to vertical and ~E–W trending. The mean orientation of foliation in the area of study is 092°/80°S (Figure 4 *a*). Trend of foliation in granitoid was plotted in a rose diagram (Figure 4 *b*). The major trend of the foliation measured on flat surfaces is 075°–255° and a minor concentration of trends along 125°–305° (Figure 4 *b*).

Apart from the regional foliation defined by preferential alignment of feldspar crystals, as stated above, the foliated granitoid is overprinted by narrow, linear, near-vertical, later ductile and brittle shear planes/joints in a discrete manner. Mylonitic foliation with near-horizontal stretching lineation developed in outcrop- to tens of metre-scale wide discrete ~E–W trending ductile shear zones. The mylonitic fabric, overprinted on the early formed foliation, reformed/destroyed the regional foliation along and adjacent to the ductile shear zone but away from the ductile shear zones the feldspar phenocrysts-defined regional foliation remained intact/undisturbed texturally and orientationally. Since we have focused on the regional GSF, detailed characterization and discussion on the ductile shear zone and brittle shear fracture is not attempted here.

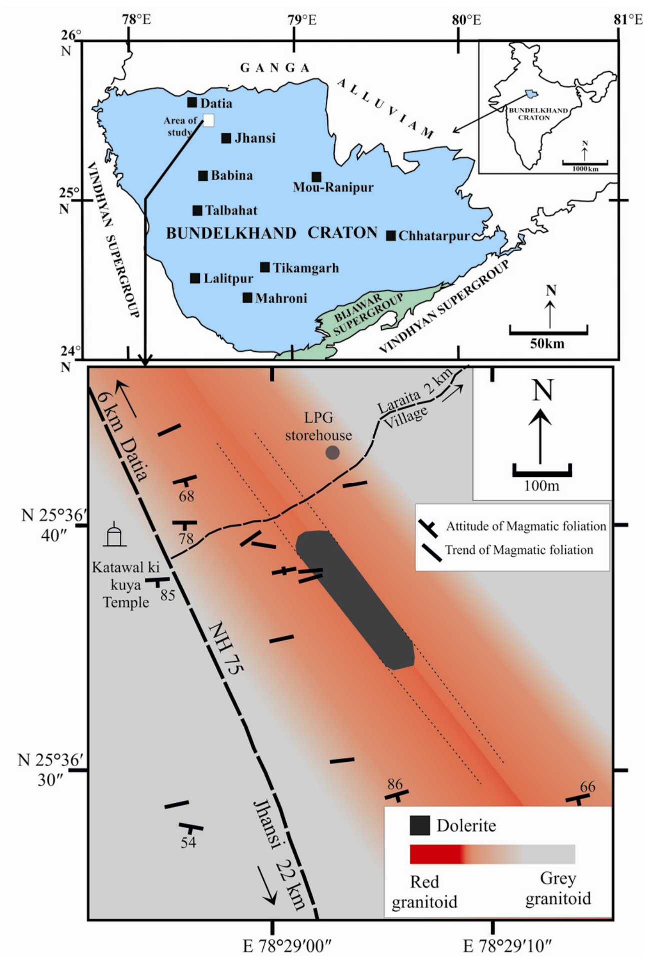

Figure 1. Geological map of the study area. (Inset) Bundelkhand Craton and its surrounding geological terrains.

Character of grain shape foliation

In outcrop-scale to micro-scale, the inequidimensional, elongate, tabular feldspar megacrysts and phenocrysts, and occasional amphibole and biotite grains are

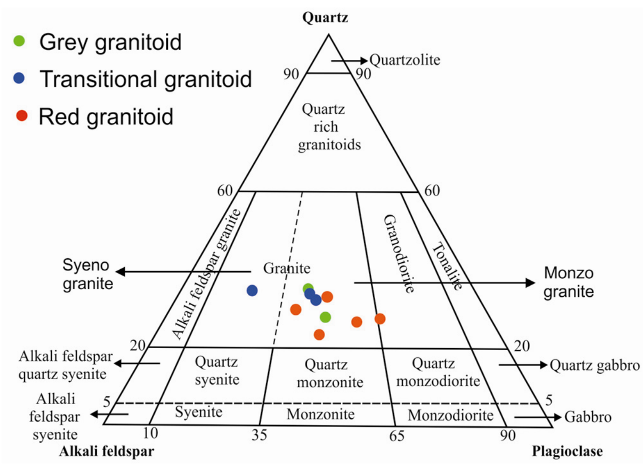

Figure 2. Modal data plot on the IUGS quartz–alkali feldspar–plagioclase diagram of granitoid rocks of the study area. Majority of the samples plots fall in the monzogranite field.

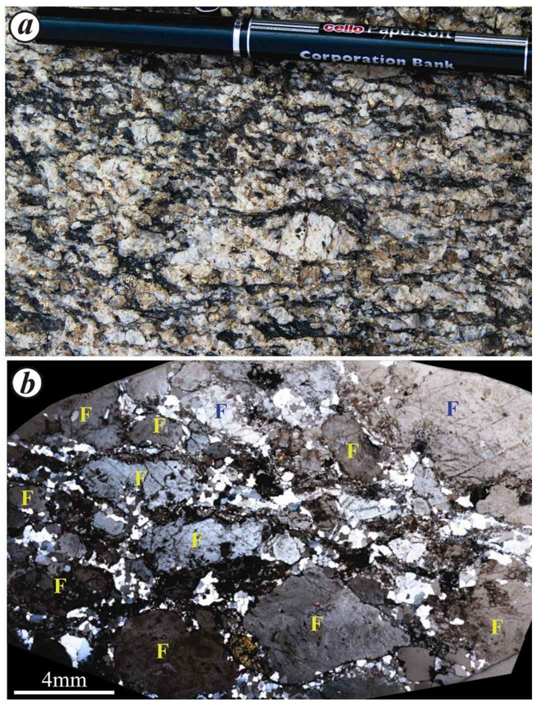

Figure 3. ***a***, The granitoid rock showing crude foliation (parallel to pen) defined by preferential alignment of feldspar phenocrysts (white). Some feldspar grains reformed their shapes. Length of pen = 14 cm. ***b***, Photomicrograph of foliated granitoid showing preferential alignment of feldspar crystals which are deformed to varying shapes.

preferentially arranged imparting a foliation/banding, which in turn gives a crude but conspicuous apparent gneissic appearance to the rocks (Figures 3, 5 and 6). Foliation defined by phenocrysts of feldspar is swerved around centimetre-scale megacrysts of feldspar (Figure 5). The megacrysts are sometimes deformed to rhombic shape, with incipient development of tails from original square or tabular shape (Figure 5). The rhombic shape with tails of feldspar megacrysts indicates lattice bending, suggesting deformation due to shearing. The phenocrysts and matrix minerals appear magmatic. The phenocrysts of feldspar grains vary in size and shape. Some phenocrysts are tabular with straight boundaries, while others are lensoid with narrow, long or short tails (Figure 3 *a*). The polished surface of the granitoid rocks shows preferential alignment of the long dimension of feldspar phenocrysts of different shapes and sizes, with interstitial quartz grains occurring in thin linear to irregular 'seams' (Figure 6). The boundary of feldspar grains is commonly irregular to rounded, coarsely serrated and at places fractured (Figure 6). The near-rounding nature and fracturing along the boundary of feldspar phenocrysts possibly indicate 'wear and tear' of the feldspar grains, perhaps formed by their movement against the surrounding grains. The feldspar phenocrysts are generally euhedral to subhedral, tabular to equidimensional square crystals, conspicuously larger in size than the quartz grains present in interstitial space between the feldspar phenocrysts (Figures 6 and 7). The long axes of the tabular feldspar laths lie parallel to layering and typically have a preferred alignment (Figures 3 *b* and 6). The length of long and short dimension of feldspar phenocrysts varies from 2.5 to ~5 mm and 1.5 to 3.8 mm respectively. Along the boundaries of some of the large feldspar crystals, 'tongue-like' intrusions of small quartz aggregate into the feldspar crystals are seen (Figure 8). Similar features have been described as 'submagmatic microfactures'[28], suggesting the presence of melt during fracturing[12]. It appears that the silica-rich melt had migrated into the open space formed due to fracturing in the feldspar crystals. Deformation microstructures in feldspar grains are conspicuous. Feldspar crystals commonly show intracrystalline deformation manifested by strong undulose extinction, deformation twins, subgrain formation, bending of twin lamellae, cracks near the boundaries, recrystallization and fragmentation mainly along the grain

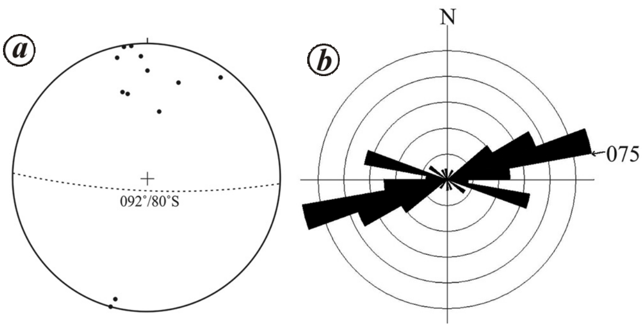

Figure 4. ***a***, Stereographic plot of the poles of foliation planes in granitoid. Mean orientation of foliation plane is 092°/80°S. ***b***, Rose diagram shows trend of foliation in granitoid. Dominant trend is 075°–255°; minor trend is 125°–305°.

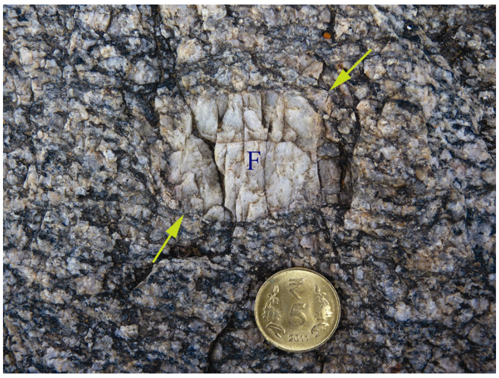

Figure 5. Granitoid rock showing crude foliation defined by preferential alignment of feldspar phenocrysts. The foliation is swerved around a large megacryst of feldspar (F), which is deformed to rhombic shape with short narrow tails. Arrow point to the change of original grain boundary in the megacryst. Coin diameter = 2.2 cm.

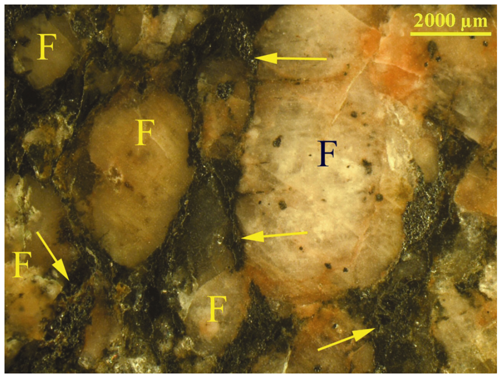

Figure 6. Photograph of polished surface of granitoid showing strong preferential alignment of long dimension of feldspar phenocrysts (F) bordered by thin 'seams' of quartz (shown with arrow) in the interstitial space between feldspar phenocrysts. The boundary of feldspar phenocrysts are reformed and rounded, and at places fractured and serrated.

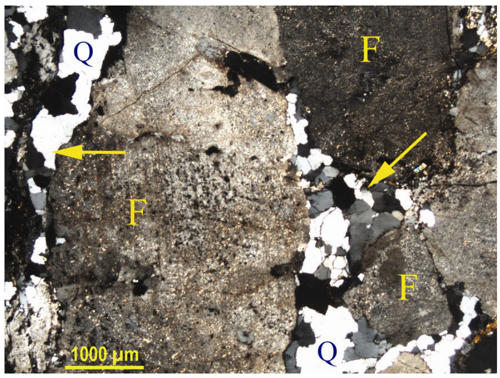

Figure 7. Photomicrograph showing small pockets/seams of aggregate of polygonal quartz grains (arrows) in the interstitial space between large feldspar phenocrysts (F).

boundaries (Figures 9 and 10). The adjacent quartz grains occur in the interstitial space between deformed feldspar grains remain undeformed (Figures 9 and 11). The contrasting deformation characteristics of feldspar and quartz grains in the same samples are conspicuous. Presence of undeformed or mildly deformed quartz surrounding the partly recrystallized plagioclase phenocrysts suggests that the quartz grains were not present when the feldspar grains were ductilely deformed. The deformation in feldspar grains suggests *P–T* conditions near or just above the minimum temperature of feldspar recrystallization (~450°–500°C)[29,30]. The fracturing and recrystallization along grain boundaries of feldspar phenocrysts suggest deformation at high stain rate followed by recrystallization slightly above the recrystallization temperature of feldspar. There are obvious indications for the presence of residual silica-rich melt during plastic deformation of plagioclase phenocrysts.

Quartz present in the interstitial space between feldspar crystals (Figures 6–8), occurs in linear to curvilinear 'seams' as aggregate of near-equidimensional polygonal grains (Figures 7 and 8). They are more or less equidimensional in shape and equigranular in size, and the grain boundaries are straight or slightly curved; they usually have ~120° angular relation at tri-junction of boundaries (Figures 7 and 11). Throughout the area, the size of the quartz grains is diminutive in comparison to majority of the feldspar grains (Figures 7–9). The length of the long and short dimension of quartz grains varies from less than 1 to 2 mm, and 0.08 to 1.15 mm respectively. A few subhedral to anhedral equant feldspar grains of smaller size are, however, also occasionally present along with quartz in the interstitial space. Quartz grains are usually deformation-free and only a few show sweeping undulose extinction (Figure 11).

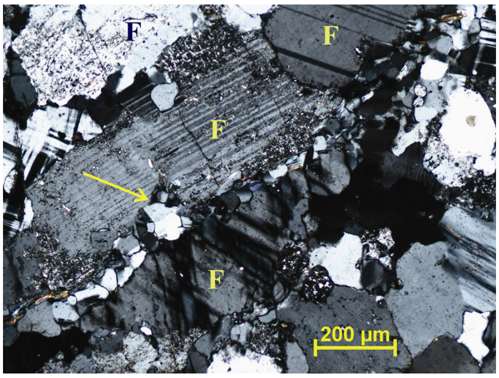

Figure 8. Photomicrograph of granitoid rock showing tabular phenocrysts of feldspar crystals (F) with thin 'film' of aggregate of small polygonal quartz grains present along the boundary of feldspar phenocrysts. Tongue-like protrusion of small quartz crystals within feldspar are also seen (arrow).

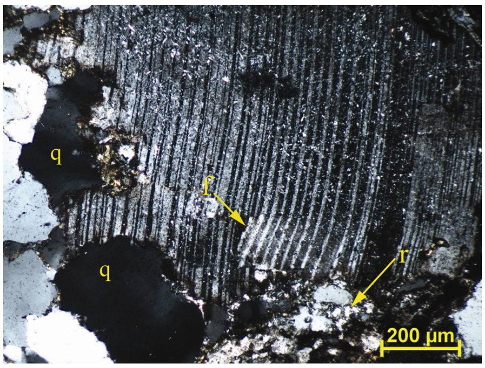

Figure 9. Photomicrograph of plagioclase phenocryst showing bending of twin lamellae, incipient fragmentation (f) and recrystallization (r) along the boundary, while the quartz grains (q) remain undeformed.

Discussion

The magmatic/submagmatic processes are related to cooling (including subsolidus cooling) of the magma[12]. These processes include nucleation and subsequent growth of different minerals, emplacement of the magma and transformation of minerals during subsolidus cooling. The signatures of these processes are distinctly visible in the microstructures of the rocks under study.

The granitoid rocks show bimodal distribution of grain size, in which large feldspar is present as megacrysts and phenocrysts, constituting bulk of the rock (≥70% by volume, see Figure 2), while the interstitial space, either continuous or discontinuous, straight or irregular, is occupied by medium- to fine-grained crystals made up

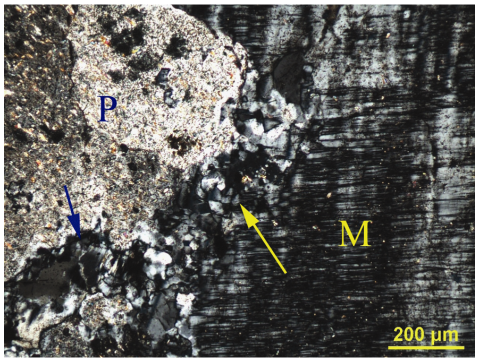

Figure 10. Photomicrograph of feldspar phenocrysts (plagioclase (P) and microcline, (M)) showing undulose extinction and recrystallization (arrow) along the boundary.

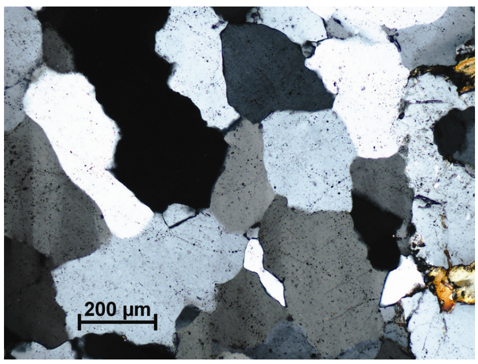

Figure 11. Photomicrograph showing aggregate of quartz grains with straight or slightly curved grain boundaries meeting at ~120°.

mainly of quartz (~22%–33%; see Figure 2), occasional feldspar and a few ferromagnesian minerals. This bimodal grain size distribution with a conspicuous foliation defined solely by the alignment of the tabular feldspar crystals is evident. The occasionally present amphibole and biotite grains also show alignment with feldspar. The foundation of the fabric in the granitoid is fully controlled by the phenocrysts of feldspar, while the finer quartz grains 'fill' the interstitial space without any 'contribution' to the foliation development.

In the Bundelkhand craton granitoid rocks show three important structural/textural aspects: (a) conspicuous foliation defined by parallel to sub parallel alignment of the tabular euhedral to subhedral feldspar crystals; (b) feldspar phenocrysts form a rigid framework in the mushwork of crystals in which the feldspar crystals form ≥70% of the whole rock, while the near-equidimensional, polycrystalline quartz grains 'fill' the interstitial space in the crystal mush, and (c) feldspar grains show intracrystalline to brittle deformation, particularly along the boundaries, but the associated quartz grains in the interstitial space are deformation free.

Here we explain this unique combination of microstructures in terms of cooling history of the granitoid magma in the craton on the basis of our observations in all scales as follows.

(1) After generation of the magma, an initial phase of slow cooling rate yields few nuclei just below the liquidus temperature in a plutonic environment. The feldspar phenocrysts begin to crystallize at a greater depth in a high confining pressure condition, and crystallization continues for a prolonged period resulting in the growth of large euhedral to subhedral tabular to equidimensional crystals, with little hindrance of free growth. As the crystals grow larger, a mush of phenocrysts of feldspar perhaps in contact with each other submagmatic flow of the mush of crystallizing mass (given that the proportion of melt in the magma was between 20% and 40%, sufficient to allow for submagmatic flow) occur in the 'deforming' magma[13]. During the period of flow of the partially crystallized magma, the feldspar crystals align themselves in the existing stress field of the emplacing magma body. The magma laden with feldspar crystals along with accessory amphibole and biotite crystals, which were also crystallized along with feldspar crystals by that time, are oriented with parallel to sub-parallel alignment of their long dimension, in order to maintain the dynamic equilibrium during the emplacement of the magma in a regional stress field[9]. The foliation in granitoid thus results from the submagmatic flow, where rigid body rotation of phenocrysts in a flowing magma body produced crude to moderately strong foliation. During this alignment and realignment of the mush of hot feldspar crystals, which are in contact with each other (since ~70% or more magma is crystallized by that time), interfere with each other in grain-supported flow, resulting in stress particularly along the contacts of the hot feldspar crystals. This stress causes plastic deformation mainly along the grain boundaries of feldspar crystals which have been deformed in a ductile to brittle manner depending upon strain rate at the point of deformation. The remaining silica-rich residual melt in the interstitial space of the feldspar mush migrate into sites of lower pressure between feldspar crystals when they were realigning themselves. The tabular feldspar crystals align perpendicular to the regional N–S-directed contraction perhaps in a syn-tectonic deformation environment, during emplacement of the magma body. Since the interstitial space was occupied by melt phase, no solid-state deformation could take place at the intestinal space. The feldspar crystals undergo rotation and sliding, with progressive interaction between the crystals in contact with each other during their alignment and realignment, perpendicular to shortening direction[31]. The amount of melt present inside the feldspar mush, during submagmatic flow of the magma, is not high enough to prevent predominant grain–grain contact, of feldspar crystals accounted for the unmistakable evidence of fracturing and dislocation creep along their boundaries[32].

(2) After emplacement of the crystal-laden magma at a shallower depth the interstitial melt was crystallized forming quartz ± feldspar aggregate. Since crystallization of quartz in the interstitial space takes place at shallower depth, i.e. in a low confining pressure condition in comparison to the depth and duration of crystallization of the feldspar phenocrysts, the evolving polycrystalline mass of quartz in the interstitial space is of fine- to medium-grained. The presence of mildly deformed/undeformed magmatic quartz adjacent to strongly deformed and recrystallized feldspar phenocrysts suggests the existence of residual silica-rich melt during the deformation of feldspar.

Therefore, we suggest that a protracted cooling history of the melt, an initial episode of slow cooling rate at a greater depth, yields few nuclei just below liquidus temperature in a thermally insulated plutonic environment which help produce large phenocrysts of feldspar. After this stage, the magma emplaced to a shallower level perhaps in a shearing environment, which included plastic deformation of already crystallized feldspar crystals to produce a foliation in submagmatic condition. At shallower level, the magma stabilizes at a lower temperature when the interstitial melt rapidly cools to form numerous nuclei resulting in the formation of small crystals of more or less equal size. The aforesaid mechanism explains the contrasting intracrystalline deformation character of feldspar and quartz, relative timing of crystallization of feldspar phenocrysts and interstitial quartz.

Given that the feldspar crystals show ductile deformation signature while the quartz crystals remain undeformed, it clearly negates solid-state flow required for the generation of subsolidus foliation in granitoid rocks in the present area.

It appears that the shearing process continued, even after emplacement and complete solidification of the magma, with sinistral sense of shear causing transition from magmatic to solid-state flow and development of E–W trending near-vertical discrete ductile shear zone and shear fractures, perhaps in last stage brittle environment in the Bundelkhand granitoid. Therefore, the whole evolution of the granitoid pluton was probably controlled by the magma flow in the first stage followed by tectonic stress and solid-state deformation[33].

Here a working model has been provided to explain the genesis of the regional fabric in the Bundelkhand granitoid, which is a pioneering effort from this terrain. However, we also emphasize that our interpretations on the development of regional foliation and the possible cooling history of the magma need to be tested in other localities. Our perception on the cooling history of the Bundelkhand granitoid rocks and formation of foliation in the submagmatic stage may not only help understand the emplacement process of the granitoid, but also to determine the criteria which would be useful for distinguishing foliations formed by the submagmatic process operating during emplacement elsewhere.

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