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Development of ductile shear zones during diapiric magmatism of nepheline syenite and exhumation of granulites – examples from central Rajasthan, India

A. B. Roy[1,]*, Krishan Dutt[2] and Sanjeeb Rathore[3]

[1]Department of Geology, Presidency University, Kolkata 700 073, India
[2]H. No. 20/75, Mansarovar, Jaipur 302 020, India
[3]No. 301, A.R. Complex, I-Block, Sector-14, Hiran Magri, Udaipur 313 001, India

The present communication discusses two separate instances where features commonly observed in DSZ are noted, one along the margin of the Kisengarh nepheline syenite and the other in the granulite bodies the Sandmata Complex in Rajasthan, India. The foliations in the nepheline syenite pluton show features similar to the mylonite gneisses that characterize DSZs in orogenic belts. Apart from simulating LS tectonite-type fabric the continuity of similar structures in adjacent cover rocks provides evidence of heterogeneous deformation during upward ascent of nepheline syenite. Based on tectono-metamorphic studies on granulites suggestion is made about the uplift of deep-seated granulites accompanied by ductile shearing on along the margins. The development of DSZ along margins helped in reducing the frictional resistance during upward ascent and emplacement into Archaean gneissic terrane. The process is comparable to buoyancy-induced diapiric uplift of hot plutonic bodies through cooler upper crust.

Keywords: Ductile shear zone, diapiric magmatism, exhumation of granulites, emplacement of plutonic bodies.

THE term 'mylonite' as defined by early workers implied grain size reduction by brittle processes[1–3]. This continued to be the common perception until lately with the result that more importance was given to the microtextural study in understanding the tectonic history and nature of deformation in the shear-zone rocks[4,5]. In the present-day usage, mylonites are considered to be intensely deformed rocks produced predominantly by ductile flow[6]. Evidence of strong crystal-plastic deformation in the mylonites helps to separate these rocks from the cataclastic rocks formed during brittle deformation[7].

The zones of mylonites showing presence of a penetrative foliation, marked by a strong stretching-type lineation are often interpreted as exhumed 'fossil' ductile shear zones (DSZs)[8,9]. Compared to the gneissic foliation that develops in the zones of low strain (Figure 1 *a*), the mylonite foliation in a DSZ appears more regular and

*For correspondence. (e-mail: ashitbaranroy@gmail.com)

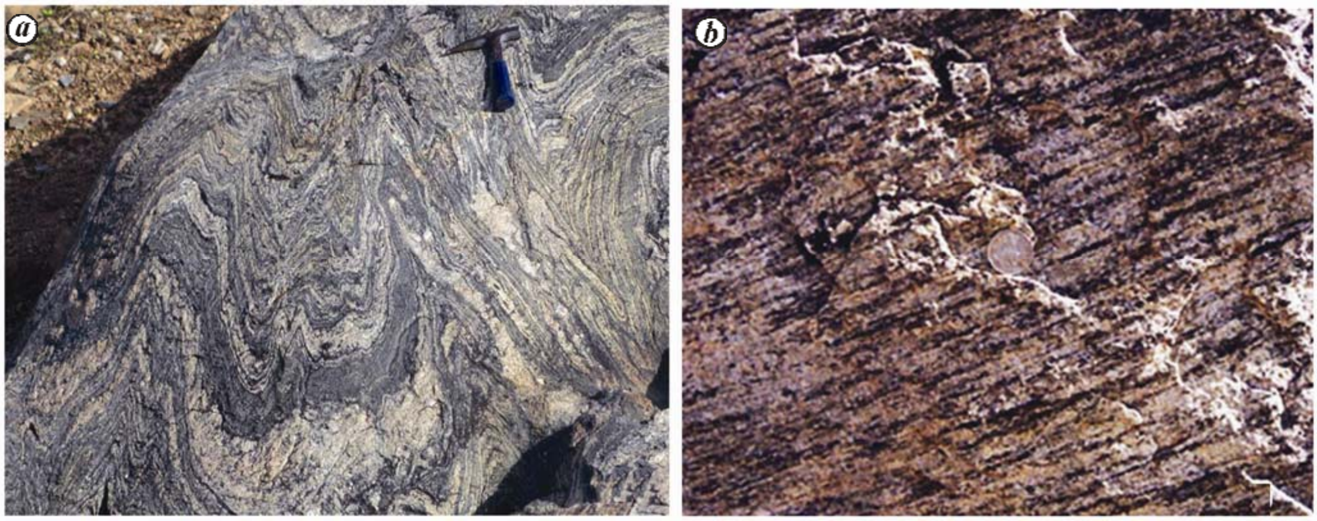

Figure 1. ***a***, Highly contorted, irregular gneissic foliation in banded grey gneiss[21]. ***b***, Mylonitic foliation appearing as regular, penetrative and uniformly planar shaped fabric[16].

penetrative showing uniformly planar shape fabric, usually accompanied by a pronounced stretching lineation (Figure 1 *b*). The concept considerably helps the field geologists who are able to identify mylonite zones (or more precisely DSZs) by recognizing belts marked by the development of uniformly planar foliation along with lineation in otherwise massive rocks without necessitating the need to study microtextures in the laboratory.

With this characterization of mylonites, it is possible to identify DSZs in distinctly different situations other than those we generally describe as tectonic or orogenic deformation triggered by horizontal crustal stresses. The present communication illustrates two different examples where DSZs have developed during diapiric rise of a plutonic body, and during exhumation of granulite bodies, drawing examples from the nepheline syenite at Kishangarh and the granulites of the Sandmata Complex respectively, in Rajasthan, India.

A large isolated body of nepheline syenite along with some detached lenticular outcrops occurs close to the eastern boundary of the Main Delhi Basin (Delhi synclinorium)[10] around Kishengarh, Ajmer district, Rajasthan. Some discontinuous patches of fenitized rocks represented by syenite and alkali diorite occur in close association with these alkaline rocks. The entire alkaline ensemble (described as nepheline syenite for simplicity) forms a single intrusive mass within the meta-sedimentary, meta-volcanic sequence of Kishengarh Group of pre-Delhi age[11] (Figure 2).

A distinctive tectonic feature of the Kishengarh nepheline syenite is the development of penetrative foliation (Figure 3 *a*) accompanied by a strong and prominent lineation (marked by mineral orientation as well as rows of grooves and ridges) in the marginal parts of the body (Figure 3 *b*). The fenitized alkaline rocks, which also show strongly foliated and banded character, have presumably evolved through replication of the earlier formed gneissic structure.

In strong contrast to the foliated and gneissic-type rocks in the marginal parts, the nepheline syenite which occurs in the core region is massive, showing typical granite-like texture[12,13] (Figure 4).

The occurrence of strongly foliated nepheline syenite which locally appears as banded gneiss, assumes significance in view of the fact that these alkaline rocks are considered to be diapirically uplifted plutonic body, remaining virtually unaffected by the later orogeinic deformations[11]. However, the foliation developed in the nepheline syenite of Kishengarh cannot be interpreted as primary flow structure developed through orientation of early crystallized platy minerals by flowing magma. Apart from the development of uniformly planar foliation associated with a set of stretching lineation, the microstructural studies made on more felsic bands in between the schistose layers show the presence of equant and granular grains of nepheline and albite (Figure 5), without any evidence of interpenetrating and/or interlocking grain migration, characters typical of porphyritic igneous rocks. The rock texture clearly proves metamorphic origin of the foliation surfaces.

The uniformly planar shaped geometry of the foliation (Figure 3 *a*) marked by a strong and penetrative lineation (Figure 3 *b*) exhibits a strong resemblance with a tectonite showing 'LS' fabric. Such rocks are commonly described as mylonite gneiss, which develops in DSZs[8].

The banding noted in some of these rocks reveals, on close examination, the presence of extremely drawn-out isoclinal folds bounded by sub-parallel foliation planes (Figure 6 *a*). These intrafolial isoclines often exhibit repeated refolding to produce second-generation isoclinal folds. The banded gneisses showing presence of extremely drawn-out isoclines bounded by sub-parallel

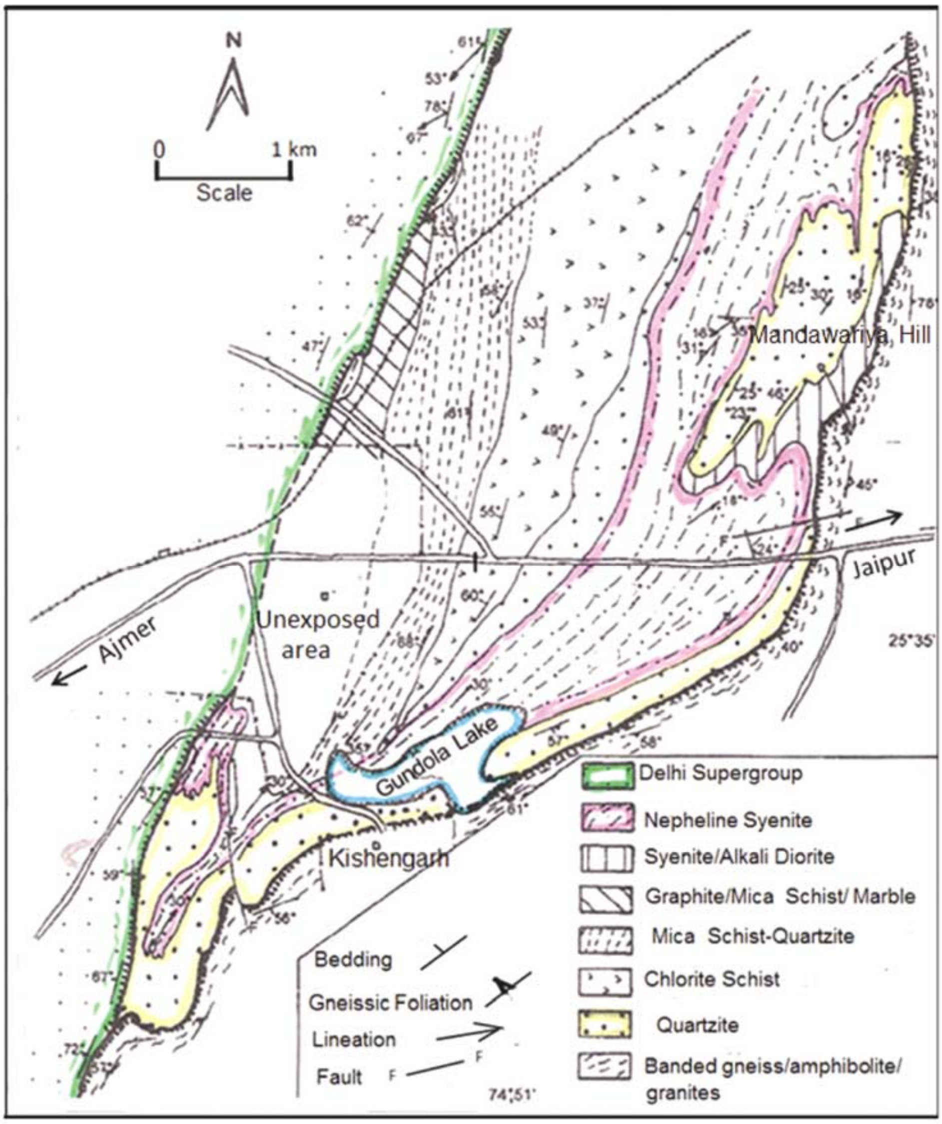

Figure 2. Geological map of the Kishengarh region showing lenticular bodies of nepheline syenite within the Kishengarh Group[11].

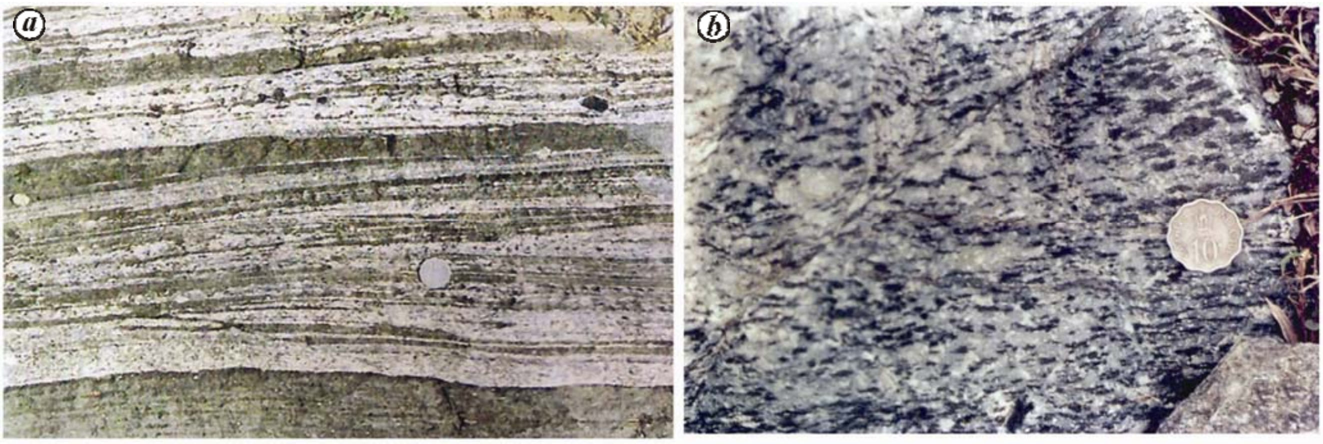

Figure 3. ***a***, Gneissic variety of nepheline syenite showing development of uniformly planar foliation. ***b***, Strongly lineated nepheline syenite exhibiting parallel orientation of hornblende needles.

foliation planes show strong similarity to the 'microlithon' described by DeSitter[14].

The style and geometry of small-scale folds developed in the narrow zone of nepheline syenite along the marginal zones and in the adjacent 'cover' quartzite are unique in the entire region. Field evidence abounds showing development of small-scale isoclinal folds (which are distinctly asymmetric in character), separated from little-deformed thin layers by the shear surfaces (Figure 6 *b*), especially in the adjacent quartzite. Apart from the strict isoclinal geometry, the development of structures in a narrow zone involving the marginal parts of nepheline syenite and the bordering enveloping rocks implies heterogeneous deformation during the emplacement of the nepheline syenite body in the pre-Delhi rocks. Features like penetrative, uniformly planar mylonitic foliation marked by strong stretching-type lineation along the margins of the nepheline syenite body, and similar other structural features indicating the abrupt strain increase towards margins imply that these are the locales of very strong ductile shearing. The continuity of strain in the sheared nepheline syenite through the adjacent cover sequence is an indication of common deformation history.

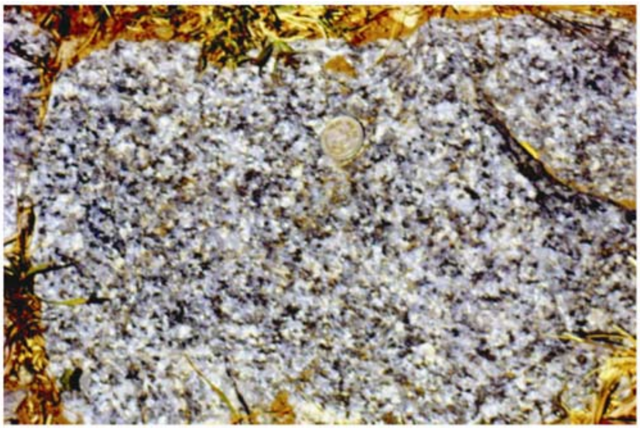

Figure 4. Massive nepheline syenite showing interlocking granitoid-type texture.

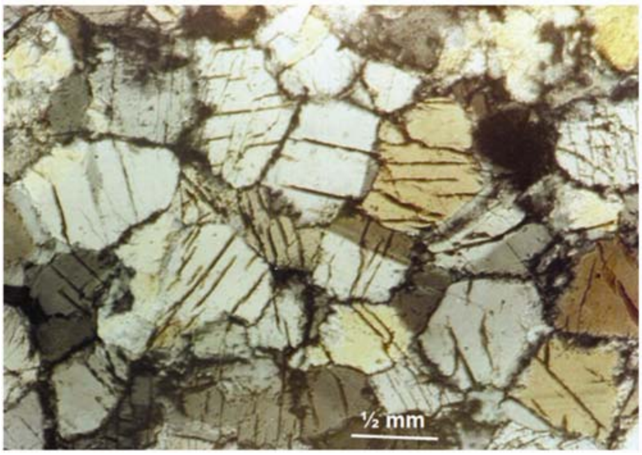

Figure 5. Photomicrograph showing typical granular metamorphic fabric without any sign of interpenetration between grains of nephyeline and albitic plagioclase.

Based on the regional orientation of the gneissic (mylonitic) foliation as developed in the marginal parts, Roy and Dutt[11] interpreted the outcrop pattern of nepheline syenite as an elongate antiformal dome (Figure 7). The broad structural geometry of the nepheline syenite body is also reflected in the disposition of quartzite, which constitutes the overlying cover formation of the Kishengarh Group[11] (Figure 2).

Proof of the compatible structural geometry is provided by the three S-pole diagrams (Figure 8 *a*–*c*) prepared separately for the bedding (better described as bedding foliation) in the cover quartzite, and the bedding (in quartzite) and gneissic foliation (in the marginal parts of the nepheline syenite). The common feature in the three structural diagrams prepared from the area from north to south (Figure 2) suggests broad structural similarity marked by a strong maximum and a weak sub-maximum with weakly defined girdle. The nature of S-pole diagrams provides a clear indication of the asymmetric nature of the regional fold. The β-axis in these two diagrams shows sub-horizontal plunge, with the fold axis lineations forming a cluster around it (Figure 8 *a* and *c*). No distinctive β-axis could be defined for the rocks occurring between the two (Figure 8 *b*). The lineations also appear to have steeper plunges. Though the S-pole orientations are broadly similar, the steeper lineations presumably show effects of later deformation.

The second example on 'anorogenic' development of DSZ is illustrated by the exhumed bodies of granulites in Sandmata Complex[15,16] (Figure 9). The lithological entities of the Sandmata Complex include two distinct tectono-stratigraphic types: (1) the banded gneisses, which also include several bodies of granite–granodiorite, amphibolites, metasediments and their reconstituted equivalents, and (2) granulites comprising granulite facies rocks and their retrograded variants. The former rock type, commonly described as the Banded Gneissic Complex[10], constitutes the Archaean basement showing a complex tectono-metamorphic evolutionary history[17–21]. The granulites, on the other hand, are of late-Palaeoproterozoic age (ranging between 1725 and 1621 Ma)[22], and are massive except in the marginal parts. The contact zones of the two diverse litho-tectonic entities are invariably marked by DSZs.

In the field, the DSZs are recognized by the occurrence of mylonitic and retrograde granulites showing uniformly well-developed penetrative foliation (Figure 10), usually accompanied by a set of prominent lineations. As a characteristic, these narrow DSZs show development of asymmetric fold having thickened hinge zones and long stretched limbs. Apart from these, several small- and intermediate-scale folds of diverse geometry and

Figure 6. ***a***, Interfolial isoclinal fold in mylonitic nepheline syenite bounded between uniformly planar bands of foliation. ***b***, Foliation-bound isoclinal fold between mildly deformed domains in the overlying quartzite of the cover sequence.

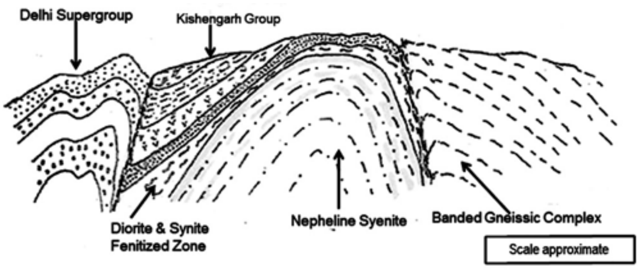

Figure 7. Schematic cross-section across the diapirically uplifted nepheline syenite exhibiting antiformal dome-like structure within the rocks of the Kishengarh Group (reproduced from Roy and Dutt[11]).

orientation, and defined by mylonitic foliation occur close to the margins of the granulite bodies.

Studies in different parts of the Sandmata Complex[15] indicate that the effects of ductile shearing and accompanying mineralogical changes are not merely confined to the margins of the granulite outcrops but also continue into the surrounding banded gneisses. Because of partial melting concomitant with mylonitization, the sheared banded gneisses have been transformed into migmatitic gneisses showing spectacular development of quartz–feldspar-rich bands (leucosomes) alternating with dark schistose layers of the original rocks (mesosomes). Some of these migmatitic rocks which characteristically show growth of eye-shaped phenocrysts of feldspar are described as augen gneiss (Figure 11). Features such as (1) the conformable pattern of deformation in both rock types occurring in the ductile shear zones, and (2) the synkinematic nature of migmatization in the banded gneisses and retrograde metamorphism in foliated granulites, confirm that the formation of foliated and retrograded granulites as well as shearing and partial melting in the banded gneisses were contemporaneous.

The undeformed massive granulites which are separated from foliated varieties have preserved records of high-pressure, upper amphibolite-facies ($P \sim 10$ kbar, $T \sim 675° \pm 60°$C) to granulite-facies ($P \sim 12–14$ kbar, $T \sim 815°$C) peak metamorphism[15]. The foliated character of some granulites is essentially a secondary feature introduced during ductile shearing and fluid-induced retrogression to the amphibolite-facies metamorphic condition corresponding to $P \sim 5$ kbar and $T \sim 575–660°$C.

Granulites, as their $P–T$ data indicate, were generated at great depths. The tectonic emplacement of these deep-seated bodies into higher crustal levels may be rightly termed ‘exhumation’. Some indication about the process of ‘exhumation’ of the Sandmata granulites into the Archaean crust is obtained if we critically examine the metamorphic history of the Sandmata granulites. In spite of diverse views expressed by different workers about the $P–T$ conditions of Sandmata granulite–facies metamorphism, possible $P–T–t$ paths, and exhumation processes[15,19,20,23–25], there are several common traits which help understand the tectono-metamorphic history of these apparently exotic bodies. The most important of these is the general agreement on the timing of peak metamorphism and accompanying dehydration melting ca. 1720 Ma (refs 15, 26, 27, 28).

The uplift (‘decompression’ in metamorphic parlance) of the granulites from a deep crustal level to shallower level of amphibolite-facies condition has been suggested based on the tectono-metamorphic studies on granulites of the Bhinai region[15]. The uplift was accompanied by ductile shearing with concomitant fluid-assisted retrogression along the margins of the granulite bodies and facilitated the development of an S–C fabric[7] under amphibolite-facies metamorphic condition (Figure 12). With the development of a new fabric (penetrative foliation and mineral lineation) along with the growth of lower-grade minerals, the rocks were transformed into a type of mylonitic gneisses which appear to be similar to those described by Passchier and Trouw[8]. The development of DSZs along the margins of massive granulites helped in reducing the frictional resistance (through strain softening) during their ascent and emplacement in the Archaean gneisses.

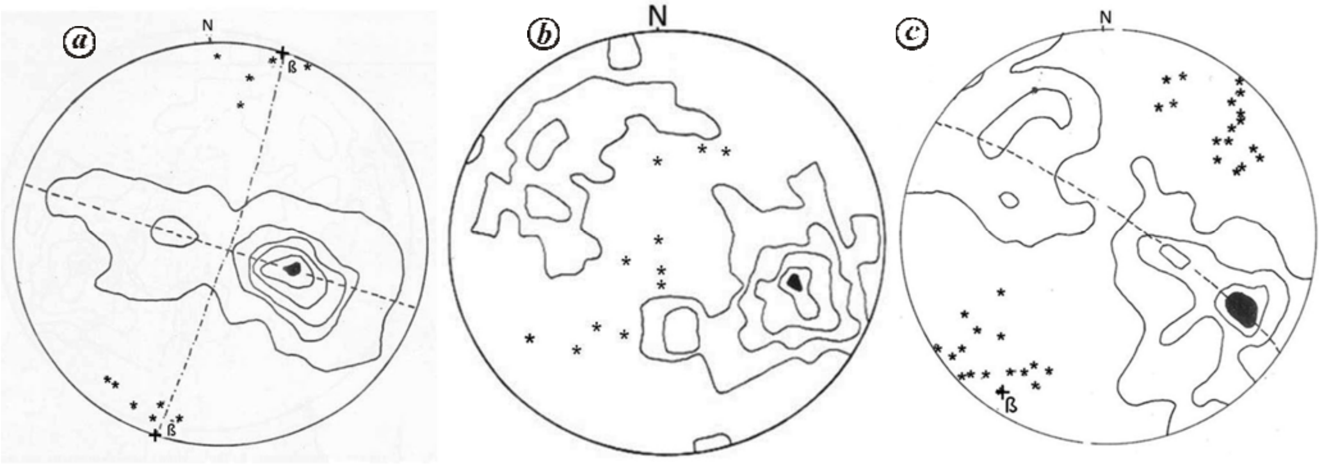

Figure 8. ***a***, Synoptic S-pole diagram for the bedding planes from the quartzite of the Mandwaria Hill region. Total bedding – 250 contours at 0.5–4–8–12–16–20% per unit area. ***b***, Synoptic S-pole diagram for the bedding planes in quartzite and gneissic (mylonitic) foliation planes from south of Mandwariya Hill and north of the Ajmer–Jaipur road. Total surfaces – 97. Contours at 0.5–2.5–6.5–12–14% per unit area. ***c***, Synoptic S-pole diagram for the bedding planes in quartzite and gneissic (mylonitic) foliation planes from the southern part of the area, south of the Ajmer–Jaipur road. Total surfaces – 132. Contours at 0.4–3.5–7–11% per unit area.

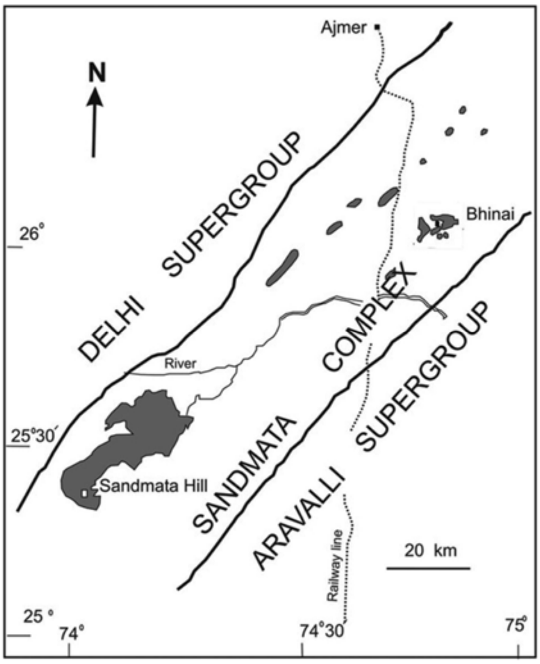

Figure 9. Map of the Sandmata Complex showing isolated bodies of granulite (dark).

Thus the present communication discusses two separate instances where features commonly observed in DSZ have been noted, as in the diapirically uplifted alkaline plutonic body near Kishengarh, and in the exhumed bodies of granulite hosted in pre-existing gneissic terrane at Sandmata Complex.

Structurally, the Kishengarh nepheline syenite is comparable with the other granitoid bodies which also show development of foliations. Paterson *et al.*[29] suggested four different possibilities of formation of foliation in plutonic bodies: (i) by magmatic flow, (ii) submagmatic flow, (iii) high-temperature solid-state deformation, and (iv) moderate- to low-temperature solid-state deformation. Traditional view, however, favours magmatic origin, particularly where the foliation developed in plutons. However, in the case of the Kishengarh nepheline syenite, extensive development of uniformly planar foliation marked usually by a prominent lineation unmistakably suggests that these are mylonitic features that normally characterize DSZ in orogenic belts. Further, the style and geometry of small-scale isoclinal folds developed in the narrow marginal zones of nepheline syenite as also in the adjacent ‘cover’ quartzite, and the evidence of synkinematic growth of minerals parallel to the axial plane foliation of folds (Figure 6 *a* and *b*) are indications of heterogeneous deformation taking place during the emplacement of the nepheline syenite body.

Important and useful information about ascent and emplacement of high-density silicic/felsic magma compatible to that which would solidify as nepheline syenite in brittle–ductile upper crust has been provided by Burov *et al.*[30]. Using a numerical model, the authors explained the deformation pattern and heat transport of ductile, elastic and brittle substances ascending as diapiric bodies. Emplacement depth and final deformation characteristics, according to the authors, depend on diapir size and buoyancy. Small diapirs (less than about 5 km in diameter; a size comparable to that of the Kishengarh nepheline syenite), which cannot reach shallow crustal levels flatten significantly and deform by horizontal spreading, with little upward displacement of roof rocks. Horizontal spreading implies that the direction of extension is also in the same direction.

According Weinberg and Podladchikov[31], the hot solidified diapirs (compared to the relatively much cooler wall rocks), which behave like a typical 'power-law fluid', may rise of up to the distance of a few kilometres in geologically reasonable times. The core of these diapirs deforms more slowly and the margins much faster than in Newtonian diapirs. Such a heterogeneous deformation pattern would lead to development of an isotropic or weakly deformed core surrounded by the strongly sheared marginal parts. Furthermore, the study[32] suggests that the strain rate of the ambient fluid (wall rock) is imposed across the contact into a 'power-law diapir', resulting in similar strains on either side of the contact. In short, the earlier studies[33,34] corroborate the findings based on field evidences on the development of DSZs across the contact of the diapirically risen Kishengarh nepheline syenite.

Figure 10. Finely foliated retrograde granulite showing growth of isolated feldspar simulating a typical mylonite gneiss. Notable feature is the post-tectonic growth of large feldspar porphyloblast pushing aside the foliation.

Figure 11. Evidence of partial melting in the gneissic granite, which has also been transformed into sheared mylonite gneiss with concomitant growth of feldspar to finally change into augen gneiss with phyllonitic matrix.

Figure 12. Photomicrograph of a foliated retrograde granulite. Foliation is guided by amphibole minerals which have grown from retrogressive alteration of pre-existing pyroxenes (mainly hypersthene).

With regard to the Sandmata granulites, a model of uplift based on the tectono-metamorphic studies from a deep crustal level to a much shallower level of amphibolite-facies condition has been proposed[15,16]. The uplift was accompanied by ductile shearing with concomitant fluid-assisted retrogression along the margins of the granulite bodies, which facilitated the development of an S–C fabric[7] during amphibolite-facies metamorphic condition. With the development of a new fabric (penetrative foliation and mineral lineation) along with the growth of lower-grade minerals, the rocks were transformed into a type of mylonitic gneiss, as described by Passchier and Trouw[8]. The development of DSZs along the margins of massive granulites helped reduce the frictional resistance (through strain softening) during further ascent and final tectonic emplacement into the Archaean gneisses[16]. A common feature noted in the nepheline syenite of Kishengarh and the granulites of the Sandmata Complex is the development of sub-horizontal lineation subparallel to the horizontal stretching of the uplifted/exhumed bodies formed at much deeper levels of the crust.

In case of vertical uplift of the granulites in a non-orogenic environment, we suggest the critical role of internal crustal buoyancy forces as a factor for the 'exhumation' of hot granulites into a cooler upper-level gneissic terrain. The main motif force is the thermal state of the rising body. Density of the hotter bodies is always low compared to the cooler upper crust. The thermodynamic condition is the sole cause of uplift/exhumation of not only the granulites, but also mafic and ultramafic magma bodies from a much deeper level to shallower levels of low-density rocks (granitic gneisses and metasediments). The thermal state of the ascending body provides the energy necessary for crustal buoyancy which acts in forcing the deep crustal rocks (granulites) to move upward through the cooler wall rocks. DSZ forms because of the frictional stress between the two solid bodies. The conduction of heat from the 'hot' ascending granulite bodies caused partial melting in the adjacent gneissic rocks (the wall of host rocks) producing migmatitic gneisses (Figure 10). The process is comparable to the buoyancy-induced diapiric uplift of hot plutonic nepheline syenite body through the cooler upper crust.

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