Chapter III

Determination of finite strains from deformed xenoliths
3.1 INTRODUCTION

The theory of diapirism and the observations on natural batholiths or plutons (Stephansson 1974, Stephansson and Johnson 1976, Pitcher 1978, 1979; Holder 1978, 1982; Ramsay 1989) together with model analogue experimental studies (Ramberg 1970, Schwerdtner and Troeng 1978, Schwerdtner et al. 1978, 1983) and simulation experiments by mathematical theory or finite element techniques (Brun and Pons 1981, Dixon 1975, Cruden and Charlesworth 1988, Schmelling et al. 1988, Guglielmo 1992, 1993a, 1993b) have proved beyond doubt that granite diapirism or polydiapirism i.e. diapirism within diapirism proceed due to density inversion. The material of lower density pierces the crustal rocks as it cannot lie below crustal material of higher density. Gradual fractionation of a highly basic magma gives rise to instrusions of first a
some what basic magma and followed by more and more acid magmas as the process progresses. Thus an initial quartz-dioritic diapiric body may in turn be pierced within its core by a granodioritic one, followed again within its core by the adamellite one and finally by highly viscous and very acid granitic one. Thus, concentric ring like structure is produced in which the first emplaced member of the calc-alkaline series lies farthest from the core of the body, the second emplaced next to the first one and so on.

Because the first emplaced layer is like a balloon and gets chilled on reaching the country rocks, the second emplaced balloon exerts a pressure on the first emplaced one and pushes it apart. This ruptures the first chilled layer at many places and nearly equal producing chocolate tablet boudinage. The fragments of this first layer then get enclosed within the second magmatic pulse and this process continues. Thus, it is natural to find the xenoliths of supracrustal rocks within the outermost tonalitic ring, the xenoliths of tonalite into the next inner ring of granodiorite, again those of granodiorite into the next ring of adamellite and finally that of adamellite into the central acidic granitic core. Because of the expansion or ballooning force, these xenoliths get deformed in ellipsoidal shapes and allow the finite strain to be determined.

3.2 THE XENOLITHS AND METHOD

Because the pluton is essentially pre-tectonic, the gneissic products from it are generated during the Aravallian orogeny, the xenoliths sometimes get very
highly deformed into long ribbons which in turn are folded together with the
expansion related fabric, the gneissic fabric and the compositional banding. The
oxenolith shapes were therefore only analysed where they were deformed enough
to be recognized as xenoliths and where two subperpendicular sections are
available for measurement of finite strains. On tops of diapirs, $\lambda_1$ is horizontal
but at its sides it is generally subvertical as seen by the stretching lineations
although these were observed at very few localities. At twenty seven localities in
the area, the Rfs of about 30 to 40 deformed xenoliths were measured in $\lambda_2\lambda_3$
horizontal plane and a subvertical $\lambda_1\lambda_3$ plane normal to the mean direction of
long axes of xenoliths. Thus for each set the values of mean Rxz and mean Ryz
were obtained, the means obtained were the geometric means (since the initial
shape of the xenolith is irregular because of rupture in all possible directions) by
(Lisle 1979a, 1979b):

$$R_g = (R_{f_1} \cdot R_{f_2} \cdot R_{f_3} \cdots R_{f_n})^{1/n}$$

The results of this study are discussed in section 3.4

3.3 THE EXAMPLE OF NATURALLY DEFORMED XENOLITHS

This account is primarily meant to give the details of type and shapes of
xenoliths encountered and is actually the description of photographs that appear
in the chapter Fig 3.1 is the example of highly mafic rock xenolith of in tonalite
near Mundol village. The shape suggests that it has been dislodged from a layer
or with an aspect ratio of 2:1. Fig 3.2 is the photograph of a xenolith of supracrustal rock enclosed with low potassic granite at Puriakheri. The xenolith is triangular in shape in horizontal plane and even more irregular in vertical sections. From the layering present within the xenolith, the long axis is taken as the mean of length parallel to bands within the xenolith and the longest one. The short axis length is taken as a mean of several lengths subperpendicular to banding seen within the xenolith. For this xenolith, the Rf obtained in this manner is 1.85:1. Fig 3.3 at Puriakheri shows a similar xenolith as in Fig 3.2 except this the xenolith itself is in the process of being split apart into two. This shape is tabular and more uniform and therefore it is fairly straightforward to obtain its ratio. Fig 3.4 near Mundol is a large xenolith of similar material in similar rock as in 3.3. In Figs. 3.3 and 3.2, it has a semielliptical shape and the other half appear after some distance.

Fig 3.5 shows the xenolith of marble in rock of granitic affinity NNE of Intali. This is an ellipsoidal xenolith and it is elliptical in plan with an approximate aspect ratio of 2.4:1.

Fig 3.6 at Vijaypura shows early pegmatite xenoliths within quartz-diorite. This pegmatite intrusion had presumably occurred after the initial ring of tonalite was emplaced and congealed. The pegmatite veins that intrude the rocks are cogenetic but were episodic and occurred time and again after the emplacement of each ring, presumably from a crustal source only. Figs 3.7 to
3.13 show a series of photographs of mafic rocks xenoliths of different shapes, but most of them fairly regular, enclosed in plgigranite to quartz-diorite rocks. Fig 3.14 shows the xenolith of mafic rock enclosed in quartz-dioritic to granodioritic host. Figs 3.15 and 3.16 show mafic rock xenoliths considerably deformed with their long axes parallel to fabric in host granodiorite. Fig 3.17 shows the tear drop shape basic rock xenolith in granodiorite. Figs 3.18 and 3.19 show the xenoliths of tonalite in K-felspar rich granite.

3.4 THE FINITE STRAINS

From the geometric means in $\lambda_1 \lambda_3$ and $\lambda_2 \lambda_3$ planes the values of $\sqrt[3]{\lambda_1}$, $\sqrt[3]{\lambda_2}$ and $\sqrt[3]{\lambda_3}$ were obtained for each locality by

$$a = R \lambda_1 \lambda_3 / R \lambda_2 \lambda_3$$

$$b = R \lambda_2 \lambda_3$$

$$\sqrt[3]{\lambda_1} = a^{2/3} \cdot b^{1/3}$$

$$\sqrt[3]{\lambda_2} = a^{-1/3} \cdot b^{1/3}$$

$$\sqrt[3]{\lambda_3} = a^{-1/3} \cdot b^{-2/3}$$

Fig 3.21 shows the $\lambda_2 \lambda_3$ ellipses on horizontal surface. Because the only reasonably deformed shapes are considered, this might only throw light as to the ballooning or expansion related strains. It must not be forgotten that the ballooning mechanism was followed by two major tectonic deformations and a
last minor one as well and these must have modified the original shapes. But the shapes where the effect of later orogenic deformation must have been minimum have been considered.

From the values of quadratic extensions, the natural strains were calculated and the value of Lode's parameter $\nu$ was obtained from the equation.

\[
\nu = \frac{2\varepsilon_2 - \varepsilon_1 - \varepsilon_3}{\varepsilon_1 - \varepsilon_3}
\]

where, $\varepsilon_1 = \ln\sqrt[3]{\lambda_1}$, $\varepsilon_2 = \ln\sqrt[3]{\lambda_2}$, and $\varepsilon_3 = \ln\sqrt[3]{\lambda_3}$.

Fig. 3.2 shows the contours of equal Lode's parameter drawn on the basis of these studies. The strains are highly oblate on the flatter sides of pluton and are generally oblate everywhere except near the tips where it belong slightly prolate with value between 0 and -0.2 generally speaking but sometimes much less than -0.2. That the constrictional strains do occur at the tips of plutons as shown by the computer based study by Brun and Pons (1981, see also Singh 1996) is supported by the Fig 3.20 which is from south of Kheroda near the southern tip of the pluton. The two quartzofelspatic veins are folded but appear to have been initially at large angle or nearly subperpendicular to eachother. Note that both the veins are gently folded. The gneissic banding is axial planar to the folds in one vein. The gneissic banding trends ESE. The NNE trending vein shows better development of folds while the one with WNW to W trend
and at acute angle to gneissic banding is only gently folded. But there is folding of both veins subperpendicular to each other which suggest that at this point the deformation must be constrictional which is also supported by the strain determination work. The angles $\Psi_{ZX}$, $\Psi_{YZ}$ and $\Psi_{XY}$ (in case of prolate deformation) were computed from the equations given by Flinn (1962). While drawing the $\lambda_2\lambda_3$ ellipses in Fig 3.21, it was necessary to measure the $\Psi_{YZ}$ angle or the angle between $\lambda_2$ direction and projection of the cone of lines no finite longitudinal strain in $YZ$ or $\lambda_2\lambda_3$ plane. This is given by equation,

$$\cos^2\Psi_{YZ} = \frac{a^{23} b^{13} - 1}{a^2 - b^2}$$

The $v$ value contours shown in fig.3.21 are related to $k$ or Flinn's parameter by the equation:

$$k = \frac{1-v}{1+v}$$

Hence the counters of equal $v$ of 0.8, 0.6, 0.4, 0.2, & -0.2 are the same respectively as those of $k = 0.1111, 0.25, 0.4287, 0.6666$ and finally 1.5. Thus the strain ellipsoid shape relates to the initial ballooning is everywhere oblate except at the triple points near the tips of diapir, where it passes through presumably a condition of plane strain to slightly prolate shape.
3.5 GENERAL CONCLUSIONS

The strain study carried out from moderately deformed xenoliths suggests that the overall deformation within and around plutons is generally oblate with oblateness being of high order, on the flatter side of plutons and becoming less oblate where there is angular departure of $<90^\circ$ between shortening direction and foliation trajectories. It is believed that in case of elliptical ballooning as in case of Untala granite the strains must be oblate on the sides of the elliptical outline. Since the pressure exerted will be more on account of smaller radius. In the direction of tips of plutons, the oblateness will be of lower order, since the force required to cause deformation has to be transmitted through a larger radius.

There are also the triple points for foliation trajectories as shown by Brun and Pons (1981) where slightly constrictional deformation can be expected. The author believes that since only moderately deformed xenoliths in generally fabric free regions (or with only incipient fabric) are considered in the analysis these finite strains might be a reasonably good estimate of only the ballooning strains. The regions of high tectonic deformation, (also superposed perhaps on high ballooning deformation) away from the acid periphery are omitted and therefore the results may be close to naturally realistic at least for the granite-adamellite interface.