CHAPTER I

INTRODUCTION
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1.1 GENERAL BACKGROUND

The genesis and emplacement of highly viscous magma of acidic composition and enormous areal extent of the granitoid batholiths, occasionally exceeding several thousand km., baffled the geologists during the fifties in attempting to arrive at a consensus on these issues. But with the advent of geophysical techniques (and especially the studies of gravity anomalies), the geochemical researches in Precambrian shield areas and finally the classic theory of diapirism whose chief exponent was Prof. Hans Ramberg of the University of Uppsala, Sweden, enabled the geologists to satisfactorily answer nearly all questions relating to the emplacement of acid plutonic complexes in the orogenic settings of the various types and in the extensional anorogenic settings as well. But it may not be an overestimation to state that granite diapirism, unlike salt diapirism (Talbot and Jackson, 1987) goes almost hand in hand with the onset and continuance of most orogenic movements.

1.2 ACID VIS-A-VIS BASIC MAGMATIC EMBRAZEMENT

It is a paradox that gigantic acid plutons are common while acid volcanics are by no means so, and in reality, are too limited both in areal extent and the volume of material extruded. In contrast, basic volcanics and continental and oceanic flood eruptions cover vast areas of the earth while
their plutonic, subsurface or shallow crustal equivalents occur only as swarms of dykes and sills of diabase to dolerite (gabbroic) composition. Besides, the former are generally genetically related to the crustal shortening and attendant crustal thickening while the latter to crustal extension and attendant crustal thinning. These features enabled the Ramberg school to believe that the granitoid bodies probably rise almost in solid or pseudoplastic state (or as Bingham bodies) and pierce through the lower and middle relatively denser crust but stop short as soon as the gravitational instability is overcome.

1.3 CLASSIFICATION OF GRANITOID DIAPIRS

The diapiric bodies have been classified in various ways and the different categorizations have generally accrued from examination of different naturally emplaced granitoid bodies under different tectonic settings (e.g. Alpine, Andean, Hercynian and Caledonian-Scandinavian) by different workers. Diapiric rise of granitic masses might be pre-tectonic, syntectonic and post-tectonic with reference to the deformation observed in the supracrustal rocks. These in Precambrian terrains generally have an affinity to the lithostratigraphy of greenstone belt sequences. They have been categorized as katatectonic, mesotectonic and epitectonic by Buddington (1959) more or less synonymous with the terms syn-orogenic, ser-synorogenic and post-orogenic respectively, used by Stephansson (1975, see also
Stephansson and Johnson 1976).

1.4 SHAPES OF DIAPIRS AND RELATED STRAINS IN SUPRACRUSTAL ROCKS

Most of the diapiric granitoid bodies generally seem to have oval outlines in plan, this being perhaps the least work configuration; but if prepectonic, or syntectonic, they could have lenticular outlines parallel to the principal trend of the orogenic belt and may show strong deformation and formation of the gneisses and migmatites by anatexis at their margins. A fine example of such a diapir is the Sendra complex in the Middle to Late Proterozoic Delhi fold belt of Western India, forming the western flank of the Aravalli Mountain Range (Heron, 1953). On the other hand, Untala and Gingala granites (the oldest in the orogenic belt, Chaudhari et al. 1983) on the eastern flank are typical pre- to syntectonic ones with their outlines showing the effects of strong sinistral shear component.

The three dimensional shape of a diapir or a pluton may resemble a mushroom, a sheet, an arcuate sheet or a an arcuate ridge or a balloon (with nearly semispherical 3-D shape) or oblique, elliptical or circular cones. Most of the shapes produced in the model analogue experiments in centrifuges using materials such as silicone putty, or painter's putty and plasticenes of different stiffness, seem to have shapes close to mushrooms, oblique mushrooms or balloons or conical balloons (Jackson and Talbot 1989;
Ramberg 1970; Ramberg and Sjostrom, 1973; Schwerdtner and Tröeng, 1978; Schwerdtner et al. 1978, 1983; Schmeling et al. 1988). These experimental studies also evince that diapirism strongly influences the strain states in the rocks they emplace and what is more, progressive diapirism or diapirism within diapirism (a term called polydiapirism, see Stephansson 1975, Ramberg 1970, Schmeling et al. 1988) also changes the previously formed strains, both in shape of the deformation ellipsoid and the magnitude of the principal strains. The diapirs themselves generally exhibit subvertical two sets of subperpendicular fabrics and a vertical or subvertical lineation within the centre, whilst at the boundaries, the foliations vary from subhorizontal to subvertical dependent upon the erosion level. This is supported by strain studies within and around natural diapirs such as the diapirs belonging to the Scandinavian Caledonides (Stephansson, 1975), Rum Jungle and Pine Creek geosynclines of Northern Australia (where a twin diapirism is encountered -Stephansson and Johnson 1976) and in case of the Donegal granite in the English Lake district (Holder 1978, 1982) and Chindamora batholith in a part of the Barberton belt extending eastnortheastward into Zimbabwe( Ramsay 1975, 1981, 1989).

Mathematical modelling of diapirs by Fletcher (1972), Dixon (1975), Cruden (1988) and Schmeling et al. (1988) corroborate most of the observations and in recent years the progressive diapirism and the interference of balloon
expansion strains and tectonic natural strains has been studied by computer simulation in two dimensions (Brun and Pons, 1981) and in three dimensions as well (Guglielmo 1992, 1993a, 1993b). The computer experiments are mostly in conformity with the mathematical models but have an added advantage in actually seeing a diapir change its shape and alter the strains in surrounding rocks.

1.5 STRAINS WITHIN DIAPIRS

From the classic work of Ramsay (1989) on the Chindamora plutonic body in Zimbabwe, it has become clear that the strain states at the outer rims are almost uniaxially oblate because of the force of the incoming more acidic crystal-mush magma in the centre exerting radially outwards. But as the outer rings consolidate, the force might act inwards and constrain the central part of the diapir during the last of the stages of diapiric rise which then might show prolate strains. It is possible to analyse the strain from ductile shear zones, boudinaged and folded veins within and around the diapirs. This also helps in reconstructing the initial diameter of the ring of a certain composition within a diapir as shown by Ramsay (1989). As the balloon inflates, it gives rise to chocolate tablet or irregular boudinage of initially the outermost layer which first gets congealed followed by the next. Perhaps the best way of computing the strain according to this author is to treat the individual xenoliths as part of a once continuous
chain or curviplanar surface, now ripped by highly oblate deformation. Though Ramsay (1989) described that complementary shear zones or varying orientations would occur at or close to the margins of the batholiths, with near circular outlines, this author feels that only three complementary shear zone orientations are possible in such a case, this being the least work configuration in case of diapirs with circular outlines. However, in case of elliptical diapiric structures, this may not be particularly true. If the batholith has not been considerably unroofed by denudation, gently dipping shear zones will abound in the upper part of the batholith. Thus it is possible to construct the history of emplacement of granitoids of different composition from the three dimensional strain computations and also the initial diameter of each of the rings of a magma pulse of a given composition from a simple mathematical relationship.

1.6 THE GRANITOIDS OF BUNDELKHAND REGION

It is out of scope of the present thesis to touch upon and discuss the controversies that centre around the genesis of acidic magmas as the deductions to this effect are generally based on strong support from geochemical data. But, from petrographic studies and extensive field work in the massif in Bundelkhand, it is very obvious that the granitoids chiefly belong to the I type (Chappel and White 1974) with all granites being exclusively one mica (biotite) granites,
muscovite appearing only in pegmatitic bodies which too are very sparse in the massif). Besides, the molybdenum mineralization is found in contiguity of the 'reefs' in medium grained porphyritic adamellite granite at different places but is better developed at Kaesarra Kalan and Nathikhera. Tin deposits are entirely absent. However, compositional expansion to the extent postulated by Chappel and White (1974) is not noticeable owing to the low erosion level. Thus it seems plausible to accept that the granites were derived from a deep-seated basic layer or even from the upper mantle which developed a periodic gravitational instability of three dimensional nature with greater rate of propagation in EW direction which stands supported by the EW axial direction of major folds within the supracrustal septa. The S type granites seem to be absent and it is also difficult to assume that they belong to an admixture of both S and I types as shown by Pitcher (1978, 1979) in case of some of the Andean batholiths, on account of want of petrographic evidence and more precisely the lack of sufficient geochemical data on the HREE and LREE patterns and geochemical anomalies. But it is possible that a majority of the granites that are exposed at the present erosional level belong to the A type granites.

1.7 THE DIAPIRS OF THE BUNDELKHAND REGION

The complex of Bundelkhand granitoids as mentioned in the foregoing, though does appear to have a compositional
restriction but this could be attributed to various reasons such as low erosion level and the engulfment by late post-tectonic more acidic granites almost everywhere in the massif, with the result that most of the syntectonic diapirs are, in essence, "blind" diapirs whose existence is revealed only by careful examination of the post-tectonic granitoid diapirs, all of which appear to have considerably coalesced together, so much so that it is indeed very difficult to demarcate their boundaries in any way but with a great deal of dexterity. Most of the deformation observed within the post-tectonic diapirs can be closely linked with the deformation pattern observed in the Bijawar Group rocks which unconformably overlie the massif at its southern margin. There are marked changes in the orientation and magnitude of the maximum principal compressive stress from the initial to the final phase of deformation.

1.8 THE QUARTZ REEFS

One of the most spectacular tectonic features of the Bundelkhand granitoids Complex is the presence of a large number of quartz reefs, having pronounced relief and compartmentalizing the massif into vertical slivers of very remarkably identical thickness. These have a slight or sometimes pronounced sigmoidality suggestive of a brittle-ductile inhomogeneous simple shear and nearly consistent NE-SW trend except for some small reefs which are the dextral and sinistral counterparts of the main NE-SW
trending reef. The individual quartz veins within the reefs have however an orientation ranging between N340° and N011° suggesting that the α orientation had considerably altered during the initial opening of reefs and at the time of secretion of quartz (Basu 1986, see also Chakrawarty and Basu, 1981). A complete account of the emplacement kinematics of the quartz reefs could be found in Roday et al. (1995; see also Diwan, 1994). The views of Basu (1986) and Roday et al. (1995) are not in agreement with those of Mishra (1960) and Jhingran (1958).

1.9 THE BASIC DYKES

A second imposing feature of the granitoids of Bundelkhand is the presence of swarms of basic dykes, again with a consistent orientation. While the reefs are restricted to the central more acidic core occupied by high K adamellite granites, the basic dykes are limited to the outer less acidic margin of low K fine grained adamellite granites. The swarms of the basic dykes are restricted only to the southern half of the massif, were generated possibly by melting at shallow level and this disposition and other field characters clearly suggests the existence of an EW trending subvertical fault passing approximately in the Central part of the massif with northern block having moved up relative to the southern and thus exposing the older supracrustals, the migmatites and gneisses; the latter more or less absent in the southern half of the massif except in
the Girar-Baraitha region.

1.10 SHEAR ZONES

In the massif of granitoids of Bundelkhand occur four major EW trending subvertical sinistral ductile shear zones and these are spaced approximately at regular intervals. Their dextral counterparts on major scale are usually absent except at Karitoran (Roday et al. 1993; Diwan 1994). The ductile shear zones of both senses on minor, microscopic and mesoscopic scales are ubiquitous throughout the massif, but more particularly in contact regions with supracrustals and with the suprabatholithic Bijawar Group rocks (where they have been converted into phyllonites). Some of the positive dilational shear zones of brittle-ductile type are also developed close to, and parallel or subparallel to the quartz reefs on account of change in the azimuth direction of $\alpha$. Strain studies in case of some of the shear zones by constructing $\gamma/d$ profiles (Ramsay and Graham 1970) and from angular departures between C (cissallement) and S (schistositie) surfaces (Berthe et al. 1979) carried out by Diwan(1994, see also Roday et al. 1993) have attempted to highlight the displacement patterns but in this thesis complete geometry of the shear zones and exact orientations of the maximum displacement vectors of shear zones of different generations are described together with $\gamma/d$ curves for nearly a score of outcrop scale shear zones. The perpendicularity of the fabrics of two generations, one
ESE-WNW in trend and related to early sinistral EW striking shear zones and the later striking N050° related to the later WNW-ESE trending maximum principal compressive stress, $\sigma_1$, is explained and is in agreement with the mathematical models of Fletcher (1972), Dixon (1975), Cruden (1988) and Schmelling et al. (1988).

1.11 PALAEOSTRESS ANALYSIS

It has been shown that the orientation of $\sigma_1$ has changed through time within the massif from initial NE-SW, to final WNW-ESE through nearly NS middle phase, with plunge remaining subhorizontal or gentle in each case. While during initial stage, sigmoidal quartz reefs were emplaced, the final phase was responsible for the emplacement of swarms of basic dykes, in the outer less acidic peripheral region, nearly perpendicular to the orientation of the quartz reefs in the central region. Because of the relative homogeneity of the outer ring of low K granitoids, it was possible for the long tensile continuous fissures to form and allow the propagation of these fissures with attendant intrusion of more mobile basic magmatic material within them. The reefs are restricted invariably to the inner core since more silica is available for secretion within the central relatively more acidic granitoids. Hence these taper out as soon as they reach the less acidic outer margin. The disposition of dykes and reefs does not point to a deformational break between the two compositionally contrasting rings but rather a varied
rheologic response to the same set of forces of the two basically different granitoid types.

Because of the changes in orientation of the maximum principal compressive stress, \( \sigma_1 \), the faults of the same orientation show different senses of movement in different parts of the massif. Thus any faults group forms a heterogeneous assemblage of faults of different generations later reactivated. The palaeostress analysis was carried out for a large number of faults from the data on slickensided striae, fault plane attitude and sense of movement as adduced by stepping of the slickensided fibres. The program ROMSA (of Lisle 1988) was used for this purpose but it was rewritten in GWBASIC with considerable modifications. While Lisle's program involves manual contouring of \( \sigma_1 \) based on PTOTAL, the program given directly prepares a plot on any basis such as P1, PTOTAL, \( \sigma_3 \) based and also prepares a rose diagram or histogram based on the values of differential stress ratio \( R \) (given by \( \sigma_2 - \sigma_3 / \sigma_1 - \sigma_2 \)). The plot can be made for direct plotting on the printer by simply pressing the PRINT SCREEN key or for taking a photograph of the monitor since colour plotters are generally not available for use in many organizations.

For each faults group, the values of total, normal and shear stresses could be computed together with total angular shear from the initial and final position of the fault plane pole with reference to the three principal stresses as cartesian coordinates. This could be performed by using an
orientation net (de Paor 1990) or by using the computer program TOTS. It has been demonstrated that the heterogeneous fault sets could be separated into homogeneous subsets by the relationship between absolute values of normal and shear stresses, under differently oriented principal vector combinations.

1.12 STRAIN DETERMINATIONS FROM DEFORMED XENOLITHS

The xenoliths (Balk, 1959; Marre, 1986) of magmatic material, essentially cogenetic but emplaced earlier are found in the later more acidic varieties. The xenoliths of supracrustals are also encountered within the granitoids but were excluded from analysis. The three dimensional analysis of deformation from the shapes of xenoliths in three nonparallel sections was carried out at as many as 16 localities within the massif with about 20 to 30 xenoliths in each group at each locality. The data was plotted in the Flinn diagram (Flinn 1962, 1965, 1978), Ramsay's plot (1967), Ramsay and Wood's plot (1973), the Nadai diagram (Nadai, 1965, Hsu, 1966, Hossack 1968) and Burns and spry diagram (1969). For these plots the parts of the software CLOOS (Roday, 1994; see also Diwan 1994) were used and the listings of appropriate programs are given in the text in appendixes at the ends of the chapters. It was found that the superposition of the later shearing deformation had changed the original presumably uniaxially oblate shapes to one of less oblateness because of change in the principal stretch.
orientations. Based on the model given by Ramsay (1989), the initial diameter ratio in case of one diapir was found to be about 1.5 same as the present one for the outer quartz-dioritic ring of the pluton, but the actual initial diameter and final diameter vary suggesting that the ballooning along long axis was of the same rate and therefore presumably pre-tectonic.

1.13 COMPUTER SIMULATION OF DIAPIRISM

As it is too well documented in case of several granitoid bodies that diapirism considerably alters the strain states in the rocks in which it takes place, a computer program DIAPIR was used to simulate the diapiric shapes on map prepared (see e.g. Brun and Pons 1981; Guglielmo 1992, 1993a, 1993b). The diapirism was simulated for spherical as well as ellipsoidal shapes and for conditions of combinations of pure shear and ballooning, simple shear and ballooning in a transcurrent faulting type environment, by a combination of simple and pure shear with either preceding the other. The program automatically contours the values of equal \( v \) and equal \( \varepsilon_2 \) to obtain the deformation ellipsoidal shapes and the values of strain magnitudes. The program was especially written to simulate the deformation in case of diapirs in the region studied where the diapirs are post-tectonic with reference to the deformation within the supracrustal rocks and have therefore changed the strain states already developed within them but are pre-tectonic
with reference to the shearing deformation under a rotational stress field and are therefore a combination of the two types of interplay of strains developing within the granitoids and the supracrustals and the suprabatholithic Bijawar group rocks.

1.14 COMPUTER PROGRAMS

Extensive data processing and simulation studies were carried out during the course of the present doctoral work, all written by the author in collaboration with his project colleagues and research supervisor; some of the programs were modified from the pre-existing programs, which have been duly acknowledged.

1.14.1 Program FOURBIN -(from Hudleston, 1969; for general theoretical details see Hudleston, 1973) for Fourier analysis of fold profiles. Actual plotting routine on \( b_a/b_x \) graph written by the author.

1.14.2 Program FOLDGC for geometrical analysis of folds based on thickness dip variation based on Ramsay's classification (1967) and Hudleston's(1973) parameter and his \( \phi_\alpha/\alpha \) plot.

1.14.3 Program to prepare the \( \gamma/d \) profile across zones of inhomogeneous ductile simple shear.

1.14.4 Program to prepare a plot of Flinn diagram (modified from a part of package CLOOS)

1.14.5 Program to prepare the Nadai plot

1.14.6 Program to prepare a plot of \( 1/a \) against \( 1/b \) after Ramsay (1967).
1.14.7 Program to prepare a plot of \((\varepsilon_1 - \varepsilon_2)/(\varepsilon_2 - \varepsilon_3)\) after Ramsay and Wood (1973).

1.14.8 Program to prepare a plot of the triangular diagram after Burns and Spry (1969).

1.14.9 Program QUADRANT to prepare contoured plot of \(\alpha_1\) or \(\alpha_3\) for a heterogeneous fault population, together with the preparation of the histogram for the values of \(R\), the differential stress ratio according to Lisle (1987, see also Lisle 1979a; Jeager, 1962).

1.14.10 Program TOTS (modified from de Paor, 1990) to compute the values of \(\alpha_1, \alpha_3, \tau, \psi\) which also allows separation into homogeneous subsets.

1.14.11 Program DIAPIR to simulate the interference of expansion related and tectonic strains under variable conditions of coaxial and noncoaxial deformations and under circular and elliptical ballooning with maximum ellipticity normal or parallel to the shear direction.

1.14.12 The software package DIPS prepared by the Department of Civil Engineering, School of Rock Mechanics, University of Toronto was used for preparing the equal area projections or Schmidt projections of the data on planar and linear elements.

1.15 RELATIONSHIP WITH SUPRAGRANITOIDS

Finally it may be added that the deformation of the post-tectonic granitoids can be very closely linked with the deformation in the Bijawar Group rocks with sinistral shear zones present in these rocks. The F1 fold axes trend ESE and
F2 fold axial traces trend NNE, subperpendicularly to each other the first when α1 was directed NE and reefs were formed and the second when α1 was directed NW to WNW and basic dykes were emplaced in great number forming huge swarms. The relationship between these two is highlighted by Roday et al. (1989).

1.16 REGIONAL TECTONIC RELATIONSHIPS

In passing, it may be mentioned that if the map outline of the massif could be clearly observed, it approximates the geometry of a parallelogram (original square deformed by nearly homogeneous simple shear). Two sides of this are prominent but the northern and eastern are concealed under the Gangetic alluvium. One side of the parallelogram trends EW or ENE-WSW, parallel to the line of the Narmada and Son valleys (a prominent Central Indian lineament that extends eastward right up to the southern margin of the Shillong plateau, see West, 1962) and the other is parallel to the axis of the Godawary graben. All major and minor shear zones developed within the massif are parallel to these two lineaments the EW trending sinistral ones being more common in occurrence owing to the proximity to the Narmada graben. It may be pointed out that the axial traces of early folds in the Bijawar Group sequence trend parallel to the acute bisectrix (trend ESE) of these two faults when α1 was directed in NE-SW direction. The later fold axes trend NNE-SSW when the stress field had changed with α1 orientation
close to NW or WNW-ESE. This has caused reversal along original sinistral strike-slip faults as well, a feature very common in case of superimposition of differently oriented stress fields. The orientation of the sigmoidal quartz reefs is also in accord with this tectonic pattern and some of the high peaks in the Himalaya such as Nandadevi and Annapurna ranges lie exactly on the northeastward extension of the quartz reefs. Thus the parallelism of shear zones, faults, reefs, basic dykes have a global tectonic implication and seemingly intimately related to the deformation of the basement of the Tethyan sediments. The geophysical studies suggest the extension of the continental crust underneath the Gangetic alluvium (Sastri et al. 1971), generally known in Indian stratigraphy as Faizabad ridge extending northeastward (Valdiya, 1973).

1.17 SUBSEQUENT DEFORMATION IN RELATION TO PRINCIPAL STRAINS

The discussion in section 1.16 above obviously implies that the later deformation, though of collisional nature has not produced intense deformation in the cover sediments owing to lying within the horizontal plane and not vertical or subvertical as in majority of the orogenic settings. In other words, transcurrent movements (whether ductile, brittle-ductile or brittle) are more common giving rise to low amplitude stubby fold structures in cover sediments with their hinges torn apart by extension unlike the collisional belt in which folds grow in amplitude in the direction of the
earth's gravitational field or vertical or subvertical $\lambda_1$. In the massif of the Central Indian Bundelkhand granitoids and their cover sediments, $\lambda_2$ has remained vertical during the later phase of granite emplacement and accompanying deformation of the cover sediments.

1.18 THE GRAVITY ANOMALIES

In recent years, there has been much attention in correlating these gravity anomalies and particularly the Bouguer anomalies to demarcate the granitoid diapirs (e.g. see Stephansson, 1975). Diwan (1994) attempted to correlate the two from the available data from the NGRI map of Bouguer anomalies but could only broadly demarcate the two zones. Unless we have highly sophisticated and accurate data on the scale of nanogals it may not be possible to demarcate very accurately even those syntectonic "blind" diapirs that have been mentioned in the earlier account and which the author strongly believes are present but not exposed due to low erosion level.

1.19 MECHANISM OF EMBLACEMENT

A great deal has been said about the mechanism of emplacement of granitic magmas, the rates of emplacement, the viscosity of granitoid magmas, the derivation from an entirely hyaline fluid to begin with and so on. The studies on these aspects are still under considerable scrutiny and a subject of in depth research. Possibly, in view of this, the
author has no alternative to arrive at the exact mechanistic explanation for the granitoids of this region except that he has only tried to compare the other granitoid bodies in the world which have emplaced under more or less similar tectonic settings. It might be futile to extend these studies any further than what the author has attempted to do owing to the rather limited knowledge at this stage of research still in progress in different terrains of granitoids in the Precambrian shield areas.