Magneto-mineralogy and Interpretation of Magnetic Fabrics of the High Grade Rocks from Saltora, Bankura, West Bengal

THESIS SUBMITTED FOR THE PARTIAL FULFILMENT OF THE DEGREE OF M.Sc. (APPLIED GEOLOGY) OF JADAVPUR UNIVERSITY

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M. Sc. Final Year
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This is to certify that **Mr. ASTIK PANJA** worked under my guidance on the topic entitled **"MAGNETO-MINERALOGY AND INTERPRETATION OF MAGNETIC FABRICS OF THE HIGH-GRADE ROCKS FROM SALTORA, BANKURA, WEST BENGAL"** in the Department of Geological Sciences. He has completed his work, which is being submitted herewith as a thesis towards partial fulfilment of his **M. Sc. Degree Examination in Applied Geology (2019)** of Jadavpur University.

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ASTIK PANJA

ABSTRACT

The high-grade rocks of Saltora Area, Bengal Anorthosite, Chhotanagpur Gneissic Complex are ideal terrains for the study of uplift related magnetization because the rates of uplift in these regions were much slower than those of phanerozoic orogenic belts. Anisotropy of Magnetic Susceptibility and the rock magnetic studies of the high-grade rocks of the Bengal Anorthosite have two important contributions to make to the geophysical study of the continental crust: 1. First the Proterozoic crustal rocks invariably possesses a strong and stable record the ancient magnetic field acquired at stages of the early tectonic history of this terrain. The magnetism is typically resident in one or more phases of magnetite growth and has recorded the rock magnetism over protracted periods of geologic time. This magnetic record will provide the only evidence for the ancient tectonic history of the Saltora Anorthosite, India and is the essential information required for correlating the crustal rocks of Saltora, India with that of elsewhere. 2. Secondly, the oriental anisotropy of minerals is an important character, which can be measured in form of magnetic anisotropy (MA). Fabric in crustal rocks is mainly controlled by two factors. a. Effect of pressure due to metamorphism, and b. Effect of geomagnetic field over the existing magnetic particles during metamorphism and post-metamorphic episodes.

Considering the principal textural relationship in rocks from different sampling sites, at least three generations of ferromagnetic mineral assemblage are distinguishable

During rapid uplift of the high-grade granulite terrain and at this stage temperatures fell from peak value in the ranges 850°-750°C (Zhang and Piper 1994). This last generation of ferromagnetic mineral growth is also identified as microcrystalline iron oxides. This is due to release of pressure during tectonic uplift of the high-grade terrain.

The overall nature of the magnetic fabric is very interesting from the studied area. From the Km-Pj plot it is seen that the relationship of the bulk susceptibility and the degree of anisotropy is quite complex, and the controlling factor of the magnetic fabrics are not revealed. However, from the stereo-plot it is evident that the maximum and intermediate susceptibility axes plots towards the periphery and the minimum plots at the center, with few exceptions where the plot is reverse. Considering the dominant plot, it can be said that the magnetic foliation in that case is near horizontal and thus explains for the oblate fabric in the Flinn and Jelinek plot. Now as these rocks are high grade rocks they contain a high amount of magnetite developed during metamorphism (Zhang and Piper, 1994) and as these contributes towards high susceptibility of the rocks, it can be considered that the magnetic foliation represents the plain containing the ferromagnetic grains. This explains the magnetic fabric in the high grade metamorphic rocks.

Now in the reverse case, i.e. minimum towards the periphery and maximum and intermediate towards the center have significances from the anorthosite intrusion. As the Anorthosite intrusion event occurred through favorable places, the orientation of the susceptibility axes remained horizontal.

Thus, in the present study the magnetic fabric is mainly mineralogically controlled by ferro-magnetic minerals.

KEYWORDS: AMS, Anorthosite, Fe-Ti oxides, Saltora, Tectonics.

CHAPTER-1

❖ INTRODUCTION:

Massif-type Anorthosites emplaced in granulite facies country rocks are present in many Proterozoic mobile belts of the World (Ashwal, 1993). Saltora anorthosite is a part of Bengal anorthosite which is a narrow 40 km long, "tadpole-shaped" massif that occurs within granulite facies rocks of the Proterozoic Chotanagpur Gneissic Complex at the eastern margin of the Indian shield. The core of the massif consists of grey anorthosite with coarse-grained cumulus plagioclase megacrysts showing magmatic flow-related alignment and the periphery consists of a mixture of the megacrysts and medium-grained, equigranular white anorthosite.

The Proterozoic plutonic regions are ideal terrains for the study of uplift related magnetization because the rates of uplift in these regions were much slower than those of phanerozoic orogenic belts (Watson, 1976). As the rocks are uplifted and cooled through the curie points following tectonism and metamorphism the rocks containing primary magnetic minerals become magnetized in the geomagnetic field directions during their formations, irrespective of the age of the rock. Later they may be subjected to metamorphic and tectonic processes, which produce secondary remnants components in secondary minerals. These secondary magnetization components which can overprint primary thermo-remnant magnetization are partial thermo-remnant magnetizations (pTRM), chemical or thermo chemical remnant magnetization (CRM or TCRM) and viscous or viscous partial thermo-remnant magnetization (VRM or VpTRM) superimposed primary and secondary remanences may be carried by two coexisting magnetic minerals or by coexisting multi domain (MD) and single domain (SD) states of the same mineral (McClelland-Brown, 1982).

Anisotropy of Magnetic Susceptibility and the rock magnetic studies of the anorthosite complexes of the Saltora region have two important contributions to make to the geophysical study of the continental crust:

1. First of all the proterozoic crustal rocks invariably possesses a strong and stable record the ancient magnetic field acquired at stages of the early tectonic history of this terrains. The magnetism is typically resident in one or more phases of magnetite growth and has recorded the rock magnetism over protracted periods of geologic

time. This magnetic record will provide the only evidence for the ancient tectonic history of the terrain.

2. Secondly, the oriental anisotropy of minerals is an important character, which can be measured in form of magnetic anisotropy (MA). Fabric in crustal rocks is mainly controlled by two factors.
   a. Effect of pressure due to metamorphism, and
   b. Effect of geomagnetic field over the existing magnetic particles during metamorphism and post-metamorphic episodes.

These processes lead respectively to the rocks of two MA components: a planar component, easy plane of which coincides with the shear plane of the rock and an orientation component which is of a minor importance in comparison with a relatively strong planar anisotropy since the latter is only due to geomagnetic field.

These dissertations work aims to determine the magnetic anisotropy and rock magnetic properties of the different rocks of crustal layer where it is exposed as deep level and where metamorphic gradients identify extended cross-sections through lower crust. The magnetization will be related to the geological (especially tectonic evolution) history. Anisotropy of magnetic Susceptibility (AMS) was measured to evaluate the relationship between magnetic and tectonic fabrics and any influences on remnants.

The objectives of this work:

1. **To study the magneto-mineralogical characteristics of the rocks and to identify the carriers of magnetic remanence.**
2. **To study the magnetic fabrics of the rocks of Saltora region and its relation with structural fabrics.**

The investigation of magnetic fabric has been undertaken in parallel with magneto-mineralogical measurements. A detailed study has been made on the magnetic mineralogy in order to identify not only the carriers of magnetization but also to get petrographic information for analysis of the relative age of the magnetization components. In most cases it is difficult to determine which particular phase of magnetic mineral is the carrier of an observed remnant component because there are typically several methods of occurrence of the same mineral in the altered and metamorphosed rocks. Polished-thin sections were studied under microscope for the identification of the magnetic minerals and their textures and their textural relationships with the silicate minerals.

CHAPTER: 2

❖ STRATIGRAPHY & REGIONAL GEOLOGY OF THE STUDIED AREA:

2.1. Description of the studied area:

The Bengal Anorthosite massif is an E–W trending 40 km long elongated body covering an area of about 250 km2, a central width of 8 km and with a long narrow tail at the western end (Fig. 2). In addition to the main massif, there is another regionally parallel small isolated Anorthosite outcrop, 2.5 km south of the south-central margin of the main massif (Roy, 1977). Apophyses and interlayering of anorthosite with the host gneisses, and inclusions/rafts of the country rocks (gneisses, metabasics and metasediments) within the massif are ubiquitous. The eastward extension of the pluton abuts against Gondwana trough sediments of the Damodar basin (Damodar graben), and westward the outcrop thins out gradually. The gneissic country rock has been intruded by widespread mafic (basic granulite and amphibolite) and ultramafic (hornblendite) rocks and granites (Mukherjee and Ghose, 1999; Ghose and Mukherjee, 2000). A large number of E–W trending sub-parallel discontinuous bands of metabasic rocks consisting of amphibolites and basic granulites and ranging in thickness from less than a millimetre to tens of meters, occur both within the anorthosite massif as enclaves, as well as in the surrounding country rocks (Roy, 1977). These rocks exhibit similar mineral assemblages both inside and outside the anorthosite massif (Manna and Sen, 1974). On the basis of field relationships, major oxide chemistry and partial trace element data, a non-comagmatic relationship between anorthosite and associated metabasic rocks has been suggested (Roy and Saha, 1975; Bhattacharyya, 1984; Mukherjee, 1993b). The presence of high-grade metamorphic rocks (charnockite, granulite, leptynite, khondalite, migmatite, metabasic rocks and quartzofeldspathic gneisses) together with massif anorthosite and peralkaline rocks in the CGGC (Ghose, 1983, 1992), suggests similarity of geological environment with that of the Eastern Ghats mobile belt in the south (Fig. 1).

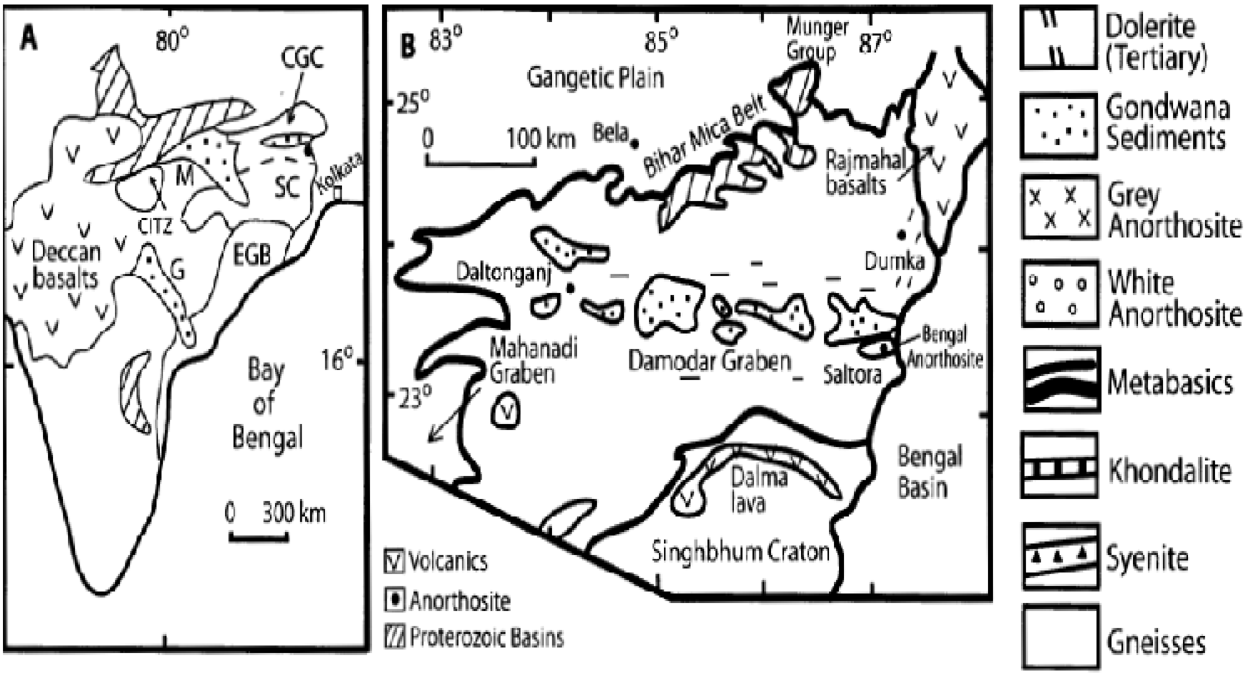

Figure 1: (A) Location map of the Bengal anorthosite at Saltora (solid circle), Eastern India. EGB - Eastern Ghats Belt, SC – Singhbhum craton, CGC - Chotanagpur Gneissic Complex, CITZ - Central Indian Tectonic Zone, dashed line Singhbhum shear zone, stippled area - Gondwana Basins: M-Mahanadi Basin, G-Godavari Basin. (B) A simplified map of the CGC showing location of the Bengal anorthosite at Saltora and other anorthosite occurrences (solid circle), Gondwana Basins along the Damodar Graben (stippled area) and Proterozoic Basins (inclined bars).

The Bengal anorthosite massif is composed of a core of coarse grey anorthosite surrounded by medium-grained equigranular white anorthosite. In addition to the detached outcrops of the grey anorthosite core, there are other isolated pods of grey anorthosite within the massif (Fig. 1). A transitional zone of mottled anorthosite is developed at the interface of the grey and white anorthosites with a gradational contact. The white anorthosite exhibits a conspicuous banded fabric near the metabasic enclaves due to the presence of streaks of mafic minerals. A coarse gabbroic anorthosite is encountered as a very small isolated pocket within the white anorthosites. Development of a hydrated phase at the contact zone with the country rocks as well as within the metabasic enclaves of the anorthosite massif is noted by the development of abundant biotite.

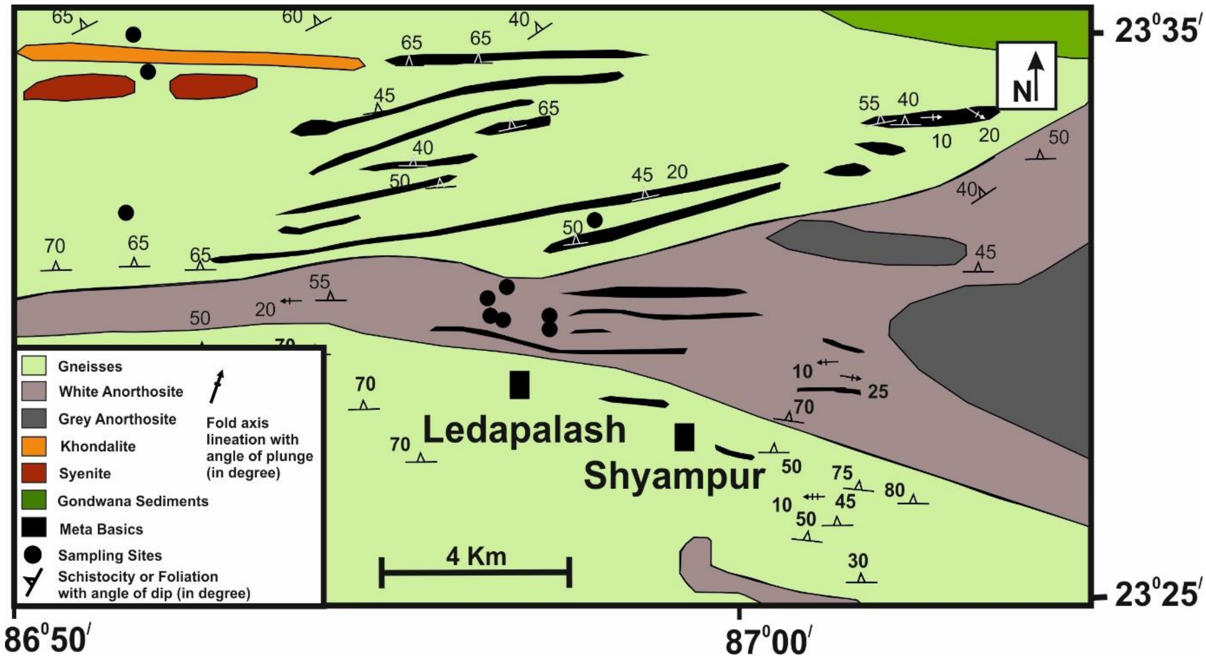

Figure 2: A detailed map of the Bengal anorthosite and its surrounding areas (Modified after Roy, 1977; Bhattacharyya and Mukherjee, 1987) and an orientation plot for primary flow structures in anorthosite (after Mukherjee, 1995).

2.2. Geochronology:

The major granitic activity in the CGGC has been dated between 1741 ± 102 Ma at Rajhara and Daltonganj in the western part (Ray Barman and Bishui, 1994; Ray Barman et al., 1990) and 1590 ± 30 Ma in the mica belt suggest that the emplacement of anorthosite preceded the granitic activity. The metabasic rocks, however, preceded the massif anorthosite emplacement as well as the major granitic activity as evident from the occurrence of metabasic enclaves within the anorthosite massif and the granites. Indeed, the foliation within the E–W trending metabasic bands inside the massif shows a marked parallelism with the S1-regional foliation of the enveloping country rocks, an observation consistent with the older age of the metabasic bands compared to the anorthosite massif. A younger tholeiitic dolerite dike known as Salma dike, dated at 65 ± 1 Ma by the 40Ar/39Ar method (Kent et al., 2002), cuts across the entire lithological sequence and extends beyond to the Gondwana sediments of Raniganj coal field in the north. The stratigraphic relationship between the Bengal anorthosite and associated country rocks and their approximate ages are given in Table 1.

Table 1
Stratigraphic relationship of the Bengal anorthosites and associated rocks of the eastern part of Chotanagpur gneiss-granulite Complex (CGGC) (cf. Ghose and Mukherjee, 2000)

Age	Lithology
Recent	Alluvium
Lower Tertiary (65 ± 1 Ma)	Dolerite
Permo-Carboniferous (Lower Gondwana)	Sandstone with shale partings and coal seams
----------Unconformity----------	
Mesoproterozoic	Pegmatite, aplite and quartz vein Alkali granite Syenite
Palaeo-Mesoproterozoic (1700 – 1400 Ma)	Porphyritic biotite granite Bengal anorthosite massif Metabasic rocks: basic granulite and amphibolite, and Meta-ultramafic rocks: hornblendite
Palaeoproterozoic (> 1700 Ma)	Enclaves of supracrustals viz. metapelites (mica schist, sillimanite schists and khondalite), meta-arenite (quartzite and quartz-magnetite rock) and calc-silicate gneiss, in remobilised basement gneisses consisting of Quartzofeldspathic gneiss, Migmatite, Augen gneiss, Biotite/hornblende gneiss, and Leptynite (unclassified)

2.3. Structure and tectonics:

Previous workers assigned a tectono-magmatic status to the Bengal Anorthosite on the basis of the relationship between the regional structure and flow patterns within the massif, which they interpreted as primary (Roy, 1977; Kumar et al., 1984; Bhattacharyya and Mukherjee, 1987; Mukherjee, 1995; Dastidar et al., 1997). Structural imprints on the anorthosite and associated rocks suggest three phases of deformational episodes. The first episode (D1) is marked by tightly appressed or isoclinal folds (F1) with concomitant development of E–W trending strong regional axial plane Schistosity (S1) in conformity with the Satpura orogenic trend of central India. The second deformational episode of regional scale is also manifested by isoclinal folds (F2) on S0 and S1 planes with variable plunge either toward the west or East with E–W axial traces. Broad warps along N–S axial traces represent the third deformational episode (D3). Statistical analysis of structural data near Nandanpur Indicates that large plagioclase plates and gneissic xenoliths within the anorthosite massif are strongly oriented in an ESE–WNW direction (strength parameter, C ¼ 1:34) - a feature interpreted as the direction of laminar flow in the intruding pluton near Nandanpur (Mukherjee, 1995). The parallelism of the plagioclase plates/xenoliths and the regional axial trace of F2-fold in different parts of the massif suggests that the stress field active along regional F2-axial trace controlled the flow kinematics, and the massif was intruded syn- to post-tectonically with respect to the F2-folding (Mukherjee, 1993a). Further, because of the juxtaposition of the massif with the E–W trending Damodar graben in the north, and the close proximity of its eastern fringe to the NNE–SSW trending marginal fault of the Bengal basin, a regional tectonic control in the emplacement of the Bengal anorthosite massif was suggested (Mukherjee, 1993a). The domal structure defined by the oval-shaped anorthosite with its axis of elongation parallel to regional E–W foliation possibly indicates simultaneous deformation of both the intruded pluton and the host country rock. The anorthosite massif shows interfingering pattern with the country rocks at its eastern and western edges.

2.4. Sampling Method:

Extensive geological field work has been carried out to collect the systematic oriented block samples of massif anorthosites during field work in and around Saltora, Bankura. Samples were collected in the form of Blocks as well as chips using Hammer and Chisel and Magnetic Compass. Samples were distributed over surface outcrops as rock exposures of different varieties. The chip samples were sliced in specific thickness for the preparation of thin sections as well as polished sections separately. The thin sections were studied under petrological microscope and the polished sections were studied under the Reflected Light Microscope. The oriented samples were cored as 2.5cm in diameter by rock driller in the laboratory. The rock cores were sliced as 2.2 cm long cylinders for different types of rock magnetic measurements in laboratories and susceptibility and AMS measurements by Bartington Susceptibility Meter (MS2).

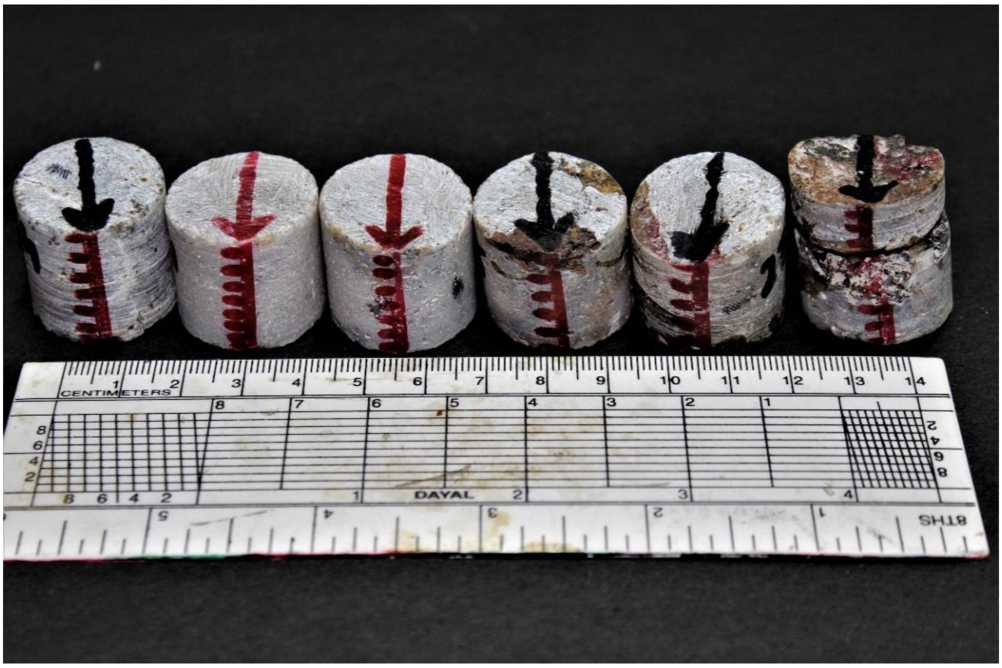

Figure 3: Rock samples after drilling by rock driller in the laboratory.

CHAPTER:3

3.1 MINERALOGY AND PETROGRAPHY:

Petrographic studies of the rocks of Saltora region reveals that the major rock type of the studied area in Anorthosite. This belongs to the Bengal Anorthosite. The Bengal anorthosite is characterized by a bimodal granularity through the occurrence of cumulates of subhedral to euhedral plagioclase megacrysts in grey anorthosite, and an equidimensional mosaic of medium to fine granular plagioclase in white anorthosite. Major occurrence of gabbroic anorthosite represents a distinctive mineralogical variant.

Anorthosite:

The very coarse to coarse-grained grey anorthosite is dominantly composed of large megacrysts of dark grey to bluish plagioclase, commonly ranging from 1 to 5 cm in length, with subordinate amounts of clinopyroxene and hornblende. Minor amounts of biotite, Fe–Ti oxides and occasionally hypersthene and garnet have also been recorded in some samples. Large plates of poikilitic plagioclase sometimes contain early-formed subhedral crystals of twinned plagioclase, Fe–Ti oxides, amphibole, epidote, and fine inclusions of iron oxide and mica in the form of rods or laths. The megacrysts are weakly zoned, sometimes showing reverse zoning. The plagioclase plates are randomly oriented except in places, where they are aligned. Occasional presence of small anhedral granular plagioclase shows two distinct modes of occurrence: one bordering the large plagioclase plates and the other intergranular between euhedral plagioclase laths.

Gabbroic Anorthosite:

The gabbroic anorthosite is a coarse grained, massive, dark brownish-grey rock, and consists dominantly of clinopyroxene and plagioclase with minor amount of orthopyroxene, hornblende, garnet and Fe–Ti oxides have been observed as accessory phases. Amphibole occurs in two distinct modes: (a) euhedral to subhedral prismatic crystals of hornblende, and (b) irregular-shaped marginally developed secondary grains around clinopyroxene. Both biotite and chlorite are found as alteration products of clinopyroxene and hornblende.

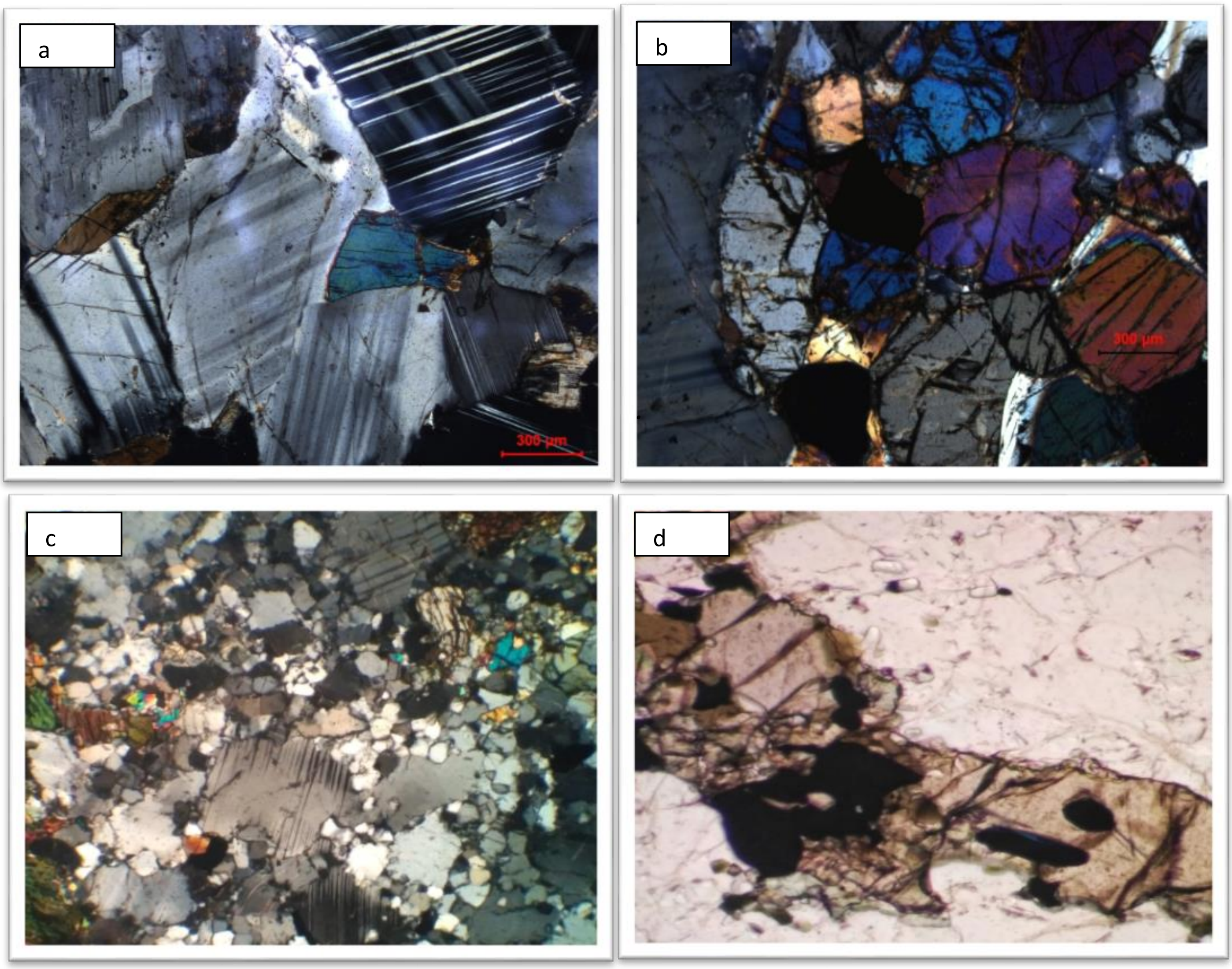

Figure 3.1: Photo micrograph of Anorthosite in Cross Polarized Light under transmitted light microscope (a) Granoblastic texture in Anorthosite defined by euhedral grains of coarse plagioclase and finer pyroxene. Plagioclase grains are showing wedge twinning. (XPL, Mag. 20x) (b) Association of opaque with silicate minerals in Gabbroic Anorthosite rocks. (XPL, Mag. 20x). (c) Porphyritic texture in Anorthosite. (XPL, Mag. 20x). (d) Occurrence of Opaque as inclusion within the pyroxene grain. (XPL, Mag. 40x)

CHAPTER-4

4.1. MAGNETIC MINERALOGY:

A rock may be regarded as a heterogeneous assemblage of minerals, ferromagnetic, paramagnetic and diamagnetic, each grains of which makes its own contribution to the total (bulk) susceptibility. The most important factors influencing rock magnetism are the type of magnetic minerals, its grain size, and the manner in which it acquires a remanent magnetization. The most important magnetic minerals are Iron-Titanium oxides. Iron-Titanium oxide minerals constitute the major opaque oxides in different rocks from Saltora region (Bengal anorthosite massif), Bankura. The magnetic properties of anorthosites and the other high grade rocks are found mainly as a function of their primary Fe-Ti oxide minerals and the subsequent changes during metamorphism. So, the primary Fe-Ti oxide mineralogy plays an important role in the field of rock magnetism.

The mineral structure consists of a close packed lattice of oxygen ions, in which some of the interstitial spaces are occupied by regular arrays of ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron ions and titanium (Ti^{4+}).The relative proportions of these three ions determine the ferromagnetic properties of the mineral. The composition of an iron-titanium oxide mineral can be illustrated graphically on the ternary oxide diagram (Fig.4.1), the corners of which represent the minerals rutile (TiO_2), wustite (FeO), and hematite (Fe_2O_3).The proportions of these three oxides in a mineral define a point on the ternary diagram. The vertical distance of the point above the FeO-Fe_2O_3 baseline reflects the amount of titanium in the lattice and the horizontal position along the FeO-Fe_2O_3 axis expresses the degree of oxidation.

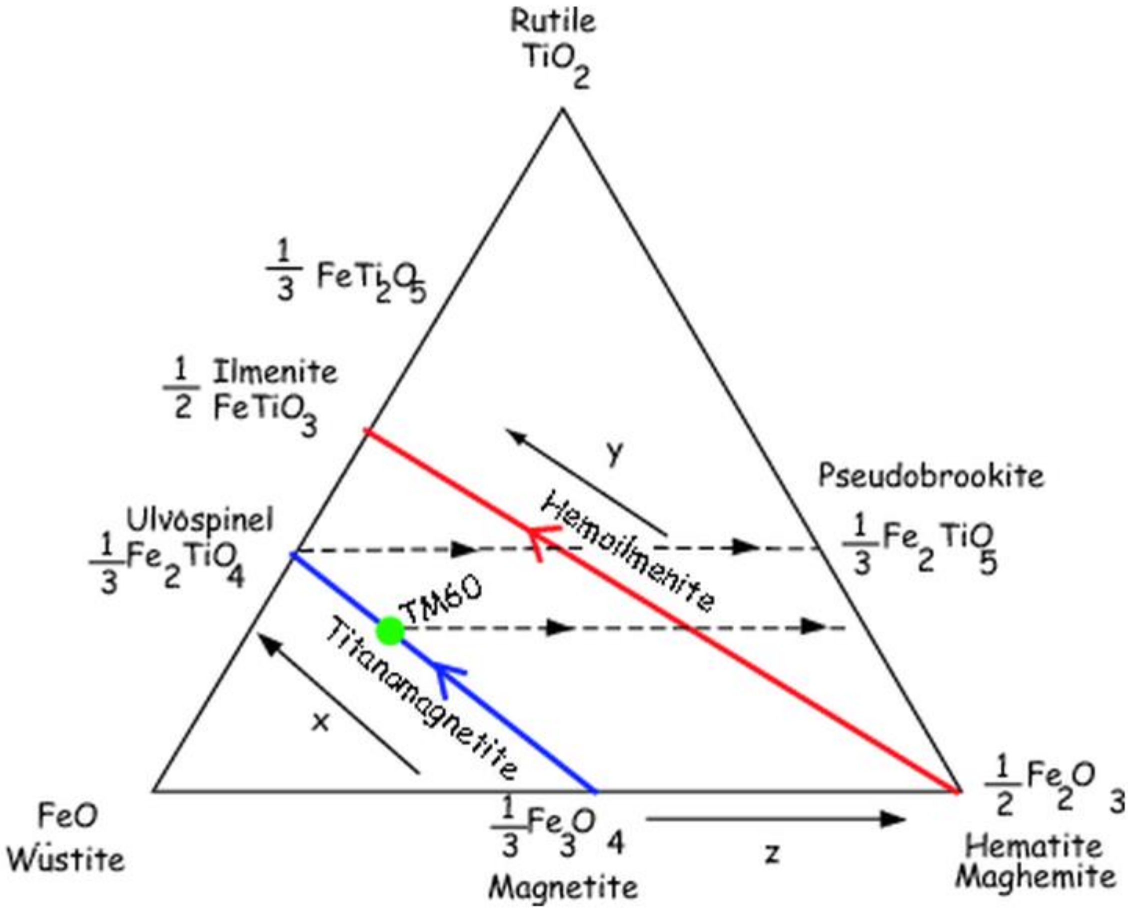

Figure: 4.1 Ternary diagram for iron-oxides. The solid lines are solid solution series with increasing titanium concentration (x). The dashed lines with arrows indicate the direction of increasing oxidation (z). [Figure redrawn from Butler, 1992.]

The primary Fe-Ti oxide minerals in granulitic rocks constitute the members of the Titanomagnetite series, which have played a significant role in the magnetization of the rocks. The mineral that originally forms as a stoichiometric member of the solid solution series between Magnetite and Ulvospinel is "Titaniferous Magnetite" (Buddington and Lindsley, 1964) or simply Titanomagnetite. Their actual composition can be expressed by the ($Fe_{3-X}Ti_XO_4$), where the value of X is given by $0 < X < 1$. In case of Magnetite (Fe_3O_4) the value of X is equal to 0 and 1 for Ulvospinel (Fe_2TiO_4). The value of X is dependent upon the relative order of recrystallization of silicates and oxides and, therefore, will depend on temperature, oxygen fugacity and composition of the source rock of the metamorphosed rocks. The extent of solid solution is limited between many of lamellar exsolution intergrowths of spinel minerals.

During a prolonged period of metamorphism, the titanomagnetite and ilmenite minerals, which crystallize initially in igneous rocks, have a general tendency for oxidation to make stable phases of all Fe-Ti oxide minerals of metamorphic rock. Two different types of oxidation of titanomagnetite can be distinguished depending upon temperature and corresponding pressure.

(i) First, High Temperature Oxidation that occurs above 600°C and,

(ii) Second, Low Temperature Oxidation that occurs about 350°C or below that temperature.

(i) High Temperature Oxidation of Fe-Ti Oxides:

Two different textural assemblage of Fe-Ti oxide minerals develop from the oxidation of titanomagnetite:

(a) “Oxidation-exsolution” (Buddington and Lindsley, 1964) or “exsolution” lamellae of ilmenite along (111) parting planes in titanomagnetite, which is, called trellis ilmenite (Buddington and Lindsley, 1964).

(b) Post “exsolution” pseudomorphic-oxidation products rutile, titanomagnetite and pseudobrookite.

Both the assemblages develop above 600°C but at the different oxygen fugacities. Ilmenite, which is produced by oxidation-exsolution, is structurally controlled within the titanomagnetite host. With more intense oxidation the titanomagnetite host is gradually depleted in the Ulvospinel component as larger concentrations of ilmenite development. The exsolved ilmenite continues to follow the path of oxidation without any dramatic effects on the titanomagnetite host. A saturation point is finally reached, which results in the exsolution of Pleonaste solid solutions and with the oxidation of the residual titanomagnetite to titanohaematite.

Haggerty (1976) has classified the stages of high temperature oxidation. The letter “C” prefixes each stages of oxidation resulting from Cubic phase:

C1 Stage: Optically homogeneous titanomagnetite solid solutions enriched With Ulvospinel.

C2 Stage: Titanomagnetite having the small number of "exsolved" ilmenite lamellae along (111) crystallographic plane.

C3 Stage: Titanomagnetite with densely crowded "exsolved" ilmenite lamellae along (111) crystallographic plane.

C4 Stage: Mottling of lamellar ilmenite – intra-lamellar titanomagnetite inter-growth and development of ferri-rutile in metailmenite lamellae.

C5 Stage: Rutile and titanohaematite extensively develop within the metailmenite lamellae and rutile-titanohaematite assemblages develop incipiently within the titanomagnetite.

C6 Stage: The incipient pseudobrookite forms during this stage and three phase assemblages, rutile, pseudobrookite and exsolved spinel develop with or without unoxidized titanomagnetite.

C7 Stage: pseudobrookite$_{(S\ S)}$ and hematite$_{(S\ S)}$ coexist with this stage of oxidation.

(ii) Low Temperature Oxidation of Fe-Ti Oxides:

The effects of low temperature oxidation are quite different from those of the high temperature oxidation. At the time of low temperature oxidation the titanomagnetites have cation deficiency and due to the increase of cation deficiency in the titanomagnetite-spinel lattice with increasing degree of low temperature oxidation ultimately results in the formation of monophasic non-stoichiometric cation deficient spinel, called titanomaghemite (γ-Fe_2O_3). This process of oxidation is known as "Maghemitization". It has been demonstrated that low temperature oxidation promotes migration of Fe-ions out of the titanomagnetite-spinel lattice resulting in cation deficiency in titanomagnetite (Prevot et al., 1968; Johnson and Melson, 1978; Johnson and Hall, 1978; Akimoto et al., 1984).

The remarkable morphological changes that occur during low temperature oxidation are the formation of irregular and curvilinear cracks in the titanomagnetite grains. These cracks were interpreted as the result of change in volume due to the original spinel lattice during oxidation (Larson and Strangway, 1969; Johnson and Hall, 1978; Akimoto et al., 1984). Johnson and Hall have termed them as “shrinkage cracks”. Johnson and Hall (1978) have proposed five different stages on the basis of microscopic features associated with progressive low temperature oxidation.

The following stages are the proposed low temperature oxidations:

Stage-1: Unoxidised titanomagnetite: Homogeneous titanomagnetite rich in high titanium, free of cracks (Unoxidised).

Stage-2: Partial oxidation: The growth of very fine to submicroscopic cracks along the grain boundaries of titanomagnetite is indicated by the change into bright color.

Stage-3: Formation of cracks: Cracks are curvilinear and prominent with the presence of some non-opaque minerals replacing original titanomagnetite towards their grain margins.

Stage-4: Formation of veins: Early formed cracks were filled with silicates and numerous new cracks developed from the earlier cracks as branches. Red pigmentary strain appears growing surrounding the silicates.

Stage-5: Relic grains: Isolated, bright, greyish white relic grains are left after almost complete replacement of titanomagnetite by non-opaque silicate minerals.

4.2. GENERATION OF Fe-Ti OXIDES - THEIR TECTONIC IMPLICATION:

The magneto-mineralogical study under reflected light microscope reveals that the different rock samples that were collected from different places of Saltora region, Chotanagpur Gneissic Complex, show both high temperature oxidations as well as low temperature oxidation signatures of primary Fe-Ti oxides. Most of the primary Fe-Ti oxide grains are medium to fine grained. Some sample contains very few grains of fine grained ilmenite.

Some samples exhibit the different stages of high temperature oxidation stages of primary homogeneous Fe-Ti oxides among which “C1” and “C4”, stages are extremely common.

Most of the collected samples show signatures of low temperature oxidation of primary Fe-Ti oxides. Mainly **stage 2**, **stage 3** and **stage-4** low temperature oxidation stages are observed within homogeneous primary titanomagnetite.

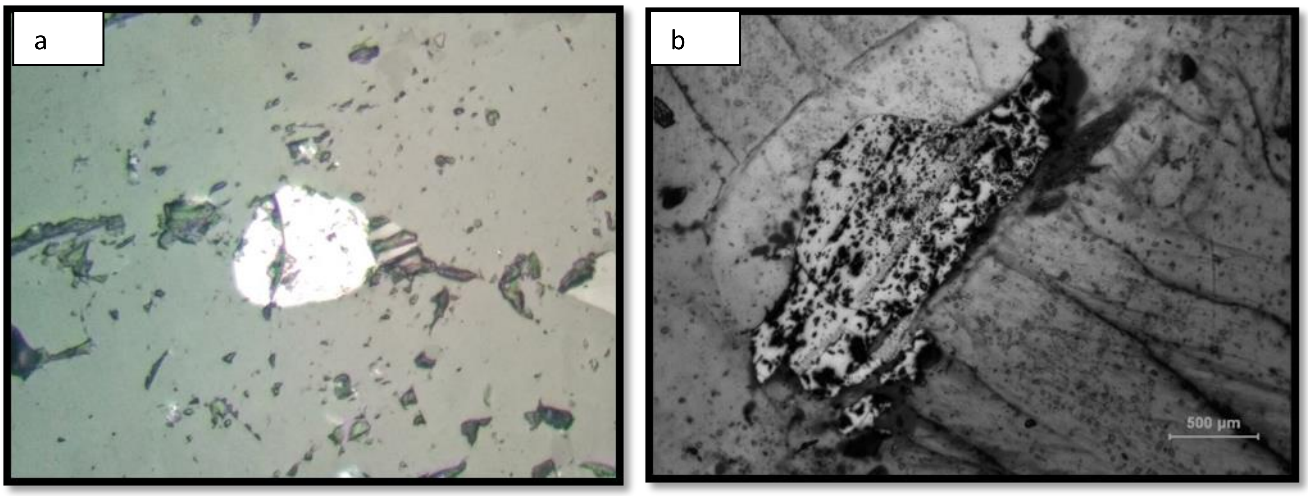

Figure 4.2: Photomicrograph of high temperature stages of oxidation. (PPL, 40x)

(a) C-1 stage, (b) C-4 stage.

At least three generations of Fe-oxides are present within the rocks: Primary (high and low temperature) and secondary (along grain boundary). Hence these rocks have the potential of recording remanent magnetic vectors and thus suitable for palaeomagnetic studies. The presence of ex-solution lamellae of inhomogeneous titanomagnetite and ilmenite grains and the signature of the stages of high temperature oxidation developed during peak temperature of metamorphism. The low temperature component of Fe-Ti oxide and the secondary ultra-fine grains minerals of the Saltora area represent uplifment of Earth crust and slow cooling post metamorphism.

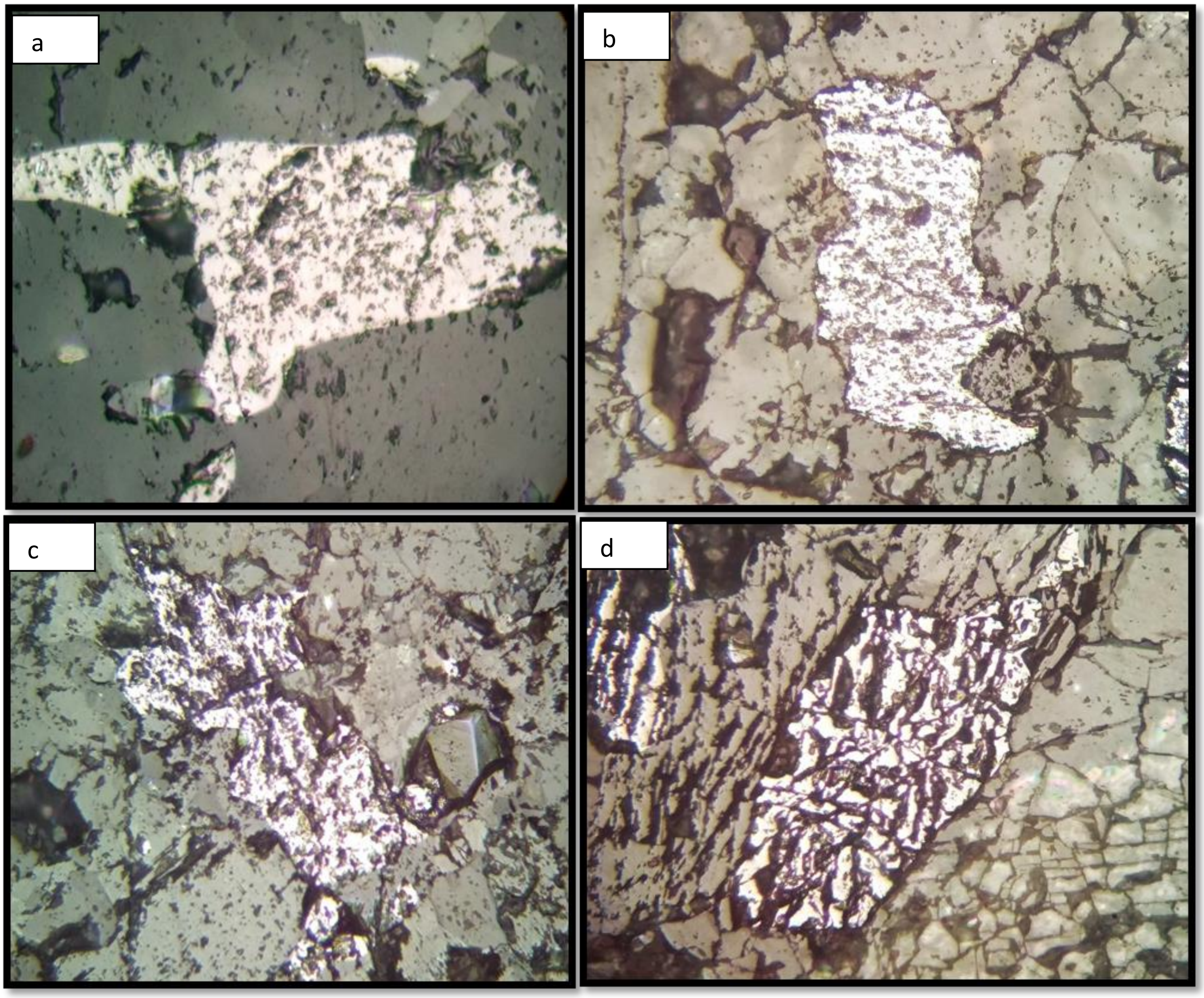

Figure 4.3: Photomicrograph of cracked titanomagnetite showing low temperature oxidation (PPL, Mag. 40X).

(a) Stage-2, (b) Stage-3, (c) stage-3, (d) stage-4

CHAPTER-5

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY (AMS) STUDY

5.1. THEORETICAL BACKGROUND

Anisotropy of susceptibility in minerals i.e. dependence of susceptibility on the direction along which it is measured in a sample, arises from either fundamental anisotropy in the **crystal structure** (**magnetocrystalline anisotropy**) or from non-sphericity of **shape** of mineral particles. The former is a property of all common magnetic minerals, but shape anisotropy due to aligned, elongated particles or to a planar or linear distribution of particles is the most common cause of anisotropy of initial susceptibility observed in rocks. Elongated or platy grains can be aligned for instance by flow in a partially solidified igneous rock or by preferential horizontal settling of platy or elongated grains in sediments. In metamorphic rocks stress is often the aligning agent and a special form of anisotropy may occur termed **textural anisotropy** caused by the occurrence of planes or strings of interacting **magnetic particles**.

Thus, magnetic anisotropy has come to be used as a profitable tool for the detection of srock fabrics, which may not otherwise be apparent.

Shape anisotropy arises from the dependence of demagnetizing factor **N** on particle shape. In an applied field **H**, the effective field, $\mathbf{H_i}$, inside a particle is

$$\mathbf{H_i = H - NM}.$$

Where **M** is the volume intensity of induced magnetization, **N** is the demagnetizing factor of the particle along the direction of applied field.

$$\mathbf{H_i = H - N\,K_i\,H_i}$$

$$\mathbf{K_o = \frac{K}{(1 + K_i\,N)}}$$

Where $\mathbf{K_i}$ and $\mathbf{K_o}$ are the intrinsic and observed susceptibility respectively. The dependence of $\mathbf{K_o}$ on **N** implies variation in $\mathbf{K_o}$ according to the direction in which it is measured in a non-spherical particle. For shape anisotropy to be significant in an elongated particle, $\mathbf{N\,K_i > \sim 0.01}$. This condition is easily met in iron and titanomagnetite minerals, and elongated grains of the latter are the most common cause of the observed anisotropy of initial susceptibility in igneous rocks. In low fields magnetocrystalline anisotropy is not observed in cubic minerals and therefore does not contribute to initial susceptibility anisotropy of rocks, although it does contribute in high field measurements.

In haematite and pyrrhotite, $\mathbf{N\,K_i < \sim 10^{-3}}$ and anisotropy due to the magnetic effect of shape is negligible. However, haematite often occurs in the form of platelets whose crystallographic and easy magnetic axes are in the plane of the particles. Thus there can be susceptibility anisotropy of magnetocrystalline origin in haematite bearing sediments brought about by preferential settling of particles with their planes horizontal or by stress or flow induced alignment in other rocks. In some metamorphic rocks, pyrrhotite particles, also of platy form, are aligned by stress. Quantitatively, anisotropy is conveniently described by the ratio of maximum to minimum susceptibility (the **anisotropy factor**) observed in a rock sample. Typical values are 1.01 – 1.20 in igneous rocks and sediments and up to 2.0 in some markedly structured metamorphic rocks such as scales.

Another aspect of magnetic anisotropy in minerals is its possible influence in deviating from the ambient field direction, the direction of thermo-or chemical remanent magnetization acquired by minerals, thus undermining one of the basic assumptions of palaeomagnetic interpretation. Such a deviation is possible because in an anisotropic mineral the induced magnetization is not in general parallel to the applied field, and TRM or CRM will tend to be acquired along the easy axis (maximum susceptibility) in a particle. This aspect of magnetic anisotropy has been studied by Stacey (1960), Uyeda, Fuller, Belshe and Girdler (1963), Fuller (1963), Irving and Park (1973). The deviation of a TRM direction from the ambient field is expected to be rather small (< ~ 5º) in most non-metamorphosed igneous rocks with anisotropy factors not exceeding ~ 1.2, but can be substantial if more marked anisotropy is present.

5.2. MAGNETIC FABRICS:

The susceptibility ellipsoid is triaxial, dimensions defined by the magnitudes of the principal susceptibilities. These lie along three orthogonal axes of symmetry of the ellipsoid and are designated the maximum, intermediate, and minimum susceptibilities $\mathbf{K_{max}}$, $\mathbf{K_{int}}$, and

$\mathbf{K_{min}}$. These qualities are combined in various ways to describe different features of the ellipsoid and of the magnetic fabric it represents.

Parameters $\mathbf{P_1}$**,** $\mathbf{P_2}$**,** and $\mathbf{P_3}$ are defined by:

$\mathbf{P_1 = K_{max} / K_{int}}$ **= Lineation (L),**

$\mathbf{P_2 = K_{max} / K_{min}}$ **= Anisotropy Factor,**

$\mathbf{P_3 = K_{int} / K_{min}}$ **= Foliation (F).**

L is a measure of the extent of lineation parallel orientation of particles contributing the susceptibility, and **F** of their planar distribution. The ratio $\mathbf{P_3 / P_1}$ is termed the <u>**Eccentricity**</u> **(E)** of the ellipsoid.

$\mathbf{E = (K_{int})^2 / (K_{max} . K_{min})}$**.**

E > 1, the ellipsoid is **Oblate**, and if $\mathbf{K_{int} \approx K_{max}}$, the ellipsoid is **Disc-shaped**. If **E < 1**, the ellipsoid is **Prolate**, and as $\mathbf{K_{int}}$ approaches $\mathbf{K_{min}}$ the ellipsoid becomes increasingly **Cigar-shaped**. These two ranges of **E** correspond to the dominance of foliation and lineation respectively.

The basic measurements available for analyses of an anisotropy ellipsoid are the susceptibility, **X**, and along its major, intermediate and minimum axes and their orientations.

If crystalline anisotropy can be ignored, as for magnetite, then if the three axes are equal, $\mathbf{X_{max} = X_{int} = X_{min}}$, i.e., if the sample is isotropic, these correspond to an average spherical shape for all the grains in the sample. Departure from the average spherical shape can therefore be quantified as the magnitude of anisotropy and the ratios between the three axes can be used to determine whether the shape is predominantly **prolate** (cigar / cylinder shaped) or **oblate** (pancake / disc shaped). **An oblate ellipsoid would be characterized by** $\mathbf{X_{max} \approx X_{int} > X_{min}}$**, while a prolate ellipsoid would have** $\mathbf{X_{max} > X_{int} \sim X_{min}}$**.**

The **mean susceptibility**, $\mathbf{K_{mean}}$ is given by $\mathbf{(K_{max} + K_{int} + K_{min}) / 3}$.

5.3. METHODOLOGY FOR DETERMINING THE ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

5.3.1. INTRODUCTION:

The main laboratory equipment is the MS 2 Magnetic Susceptibility Meter. The MS2 Magnetic susceptibility comprises a portable measuring instrument, the MS2 meter and a variety of sensors. Each sensor is designed for a specific application and sample type and is connected to the MS2 meter via a sample coaxial cable. The meter displays the magnetic susceptibility value of materials when these are brought within the influence of the sensor. An RS 232 serial interface allows the instrument to operate in conjunction with custom software running on a portable data logger or PC. The MS2 meter is powered by internal chargable batteries. The circuits within the MS2 powers the sensors and processes the measurements information produced by them.

Figure 5.1. Bartington Susceptibility Meter (Model: MS2) in AMS laboratory, JU

The measurements are obtained digitally using a time dependent method. This results in precise and repeatable measurements. The sensors are independently calibrated and are therefore fully interchangeable between MS2 instruments. The range of sensors measurements of individual laboratory soil and rock samples, sediment cores, soil surface, rock exposures or down auger holes.

5.3.2. PRINCIPLES OF OPERATION:

The magnetic state of a specimen is generally described by the following equation.

$$B=\mu_0 (H+M)$$

Where B=Flux density of the specimen in TESLA (T)
μ_0 is the permeability of free space N/A^2. This is a constant ($4\pi \times 10^{-7}$), His the applied field strength in A/m. Dividing the above equation by H we get $\mu=\mu_0+\mu_0 k$

Where k= volume magnetic susceptibility of the specimen(Dimensionless)

Rearranging we get,

$\mu_0 k= \mu-\mu_0$

The MS2 instrument measures the Magnetic Susceptibility in the following way.

The sensor consists of a very high thermal stability oscillator for which a wound indicator is the principle frequency determining component. When the indicator contains only air the value of μ_0 determines the frequency of oscillation.

When the indicator is placed within the influence of the specimen to be measured the value of μ determines the frequency of oscillation. The meter to which the sensor is connected digitize the μ_0 and μ dependent frequency values with a resolution of better than 1part in a million computes the value of magnetic susceptibility.

The value of μ_0 is constant but the variable of interest is relatively small. Therefore an thermally induced sensor drift needs to be eliminated by occasionally obtaining a new 'air' value (to re-establish the μ_0 reference by depressing the zero button on the MS2 meter.) The μ value is obtained by pressing the measure button. The magnetic susceptibility value is displayed digitally and output via a serial interface.

5.3.3. GENERAL DESCRIPTION OF THE METER MODEL MS2

The MS2 circuitry is housed in a sealed enclosure weighing 1.2 kg (2.6lb) with approximate dimensions of 260 mm x 158mm x 50 mm (10 inch 6inch x 2inch). The operating switches a TNC sensor cable connector and a four digit LCD are situated on the front panel (FIGURE TO BE INSERTED). The RS232 serial interface connector and a battery charger input socket are located on the rear panel of the instrument,. Internal Ni-Cd batteries provide 8 hours continuous use and can be recharged from either the mains or a vehicle dashboard. An instrument stand is provided for laboratory use and a carrying bag is supplied for field portability.

5.3.4. DATA PROCESSING

The following software is available in the laboratory for data processing:

- **MULTISUS**: This window software runs on user's PC and provides data capture from the MS 2 Meter, via the RS 232 serial port, when used with the MS2B, MS2C, MS2E, MS2G, MS2H sensors when used with MS2 B sensors the program allows volume or mass specific susceptibility measurements with correction for sample volume or mass where appropriate, and calculation of the coefficient of frequency dependent susceptibility when used in conjunction with the MS2 C, correction for the ratio of core to sensor diameter can be automatically applied. The software offers baseline drift correction for all the above sensors.
- **AMSWIN-BAR**: This windows programme permits the measurement of the anisotropy of magnetic susceptibility. Sample adapters are provided with the software.
- **AMS2**: The latest version of AMS BAR is an interactive environment for measuring Magnetic Susceptibility Anisotropy, Calculating the principle components of the Fabric ellipsoids for a single specimen, and providing a summary of the principle components and their associated errors for a group of samples. The AMS2 software has been specifically designed for Bartington instrument MS2 Susceptibility meter with a 36mm sensing coil using an IBM PC (or true compatible) micro computer running under MS-DOS 2x or greater, for standard 25mm diameter paleo-magnetic specimens.

5.4. EXPERIMENTAL RESULTS:

5.4.1. USEFULNESS OF AMS STUDY:

If mineral grains have a shape of crystalline anisotropy their magnetic properties will vary with direction if these grains are aligned by:

a. Current flow during deposition (In sediments)
b. Current flow within a silicate melt during consolidation of a large intrusion (igneous rocks) or
c. Preferential growth in an applied stress during field Metamorphism (metamorphic rocks).

Then the resultant rocks will have anisotropic magnetic properties. Thus AMS is a rapid indicator for fabric where other methods of determinations are usually laborious.

The results from the Anisotropy Susceptibility measurements and ellipsoid calculations by AMS-BAR software of the studied rock cores of my field area reveal that the eccentricity is greater than 1, i.e getting oblate ellipsoid which implies that the minerals responsible for magnetic susceptibility are aligned along the foliation present in the rock which is defined mainly by plagioclase grains.

The results from the anisotropy of the magnetic susceptibility measurements and ellipsoid calculation by AMS-BAR software of the studies rocks are shown in the following table.

TABLE 5.1. Few results of ellipsoid calculation by AMS-BAR software

Sample No.	**No. of cores**	**K_m**	**F**	**L**	**D**	**$K_1(D^0/I^0)$**	**$K_2(D^0/I^0)$**	**$K_3(D^0/I^0)$**	**P_j**	**T_j**
APS-2	6	41.5	1.1	1.1	1.2	187/10.1	95.1/10.7	319.5/75.2	1.32	0.14
APS-3	6	49.6	1.1	1.1	1.1	108.1/30.2	202.5/7.5	305.0/58.7	1.14	0.57
APS-5	7	79.1	1.1	1.0	1.1	196.0/10.8	293.2/33	90.3/54.8	1.26	0.45
APS-7	6	135.1	1	1.1	1.2	139.1/62.3	292.1/24.9	27.4/11.3	1.19	0.14
APS-9	5	608.8	1.5	1.1	1.6	183.1/9.8	273.7/3.8	24.7/79.5	1.81	0.85
APS-10	8	7.7	1.2	1.1	1.3	220.9/10	127.2/20	336.0/67.5	1.52	0.65
APS-11	5	2.5	1.3	2.1	2.8	66.9/60.9	321.4/8.4	227/27.6	2.54	0.30
APS-12	6	2.2	1.8	1.5	2.6	172.6/14.9	345.1/75	82.1/1.9	2.11	0.09
APS-14	6	56.6	1.2	1.0	1.2	143.6/21.3	239.1/13.9	359.8/64.2	1.16	6.4

5.4.2 FLINN TYPE PLOT:

To have an idea whether the rock had gone through a major tensile strain state or a compressive strain state, Flinn Type plot study (Flinn 1962) is carried out. In this type of study, two parameters, namely lineation and foliation are compared in the X and Y axes respectively. A line subtending an angle of 45 degrees with the positive direction of the x axis is drawn, which demarcates two domains prolate on top of it and oblate below. The parameters Lineation and Foliation are found out from maximum, intermediate and minimum susceptibility Eigen values. So if Maximum, intermediate and minimum susceptibilities are shown as K_1, K_2, K_3 respectively then they show as below. To understand the degree of anisotropy, E value is also calculated. Lineation=K_1/K_2, Foliation=K_2/K_3, E value =$(K_2)^2/K_1K_2$. Flinn type plot of all the samples is shown in the following figure.

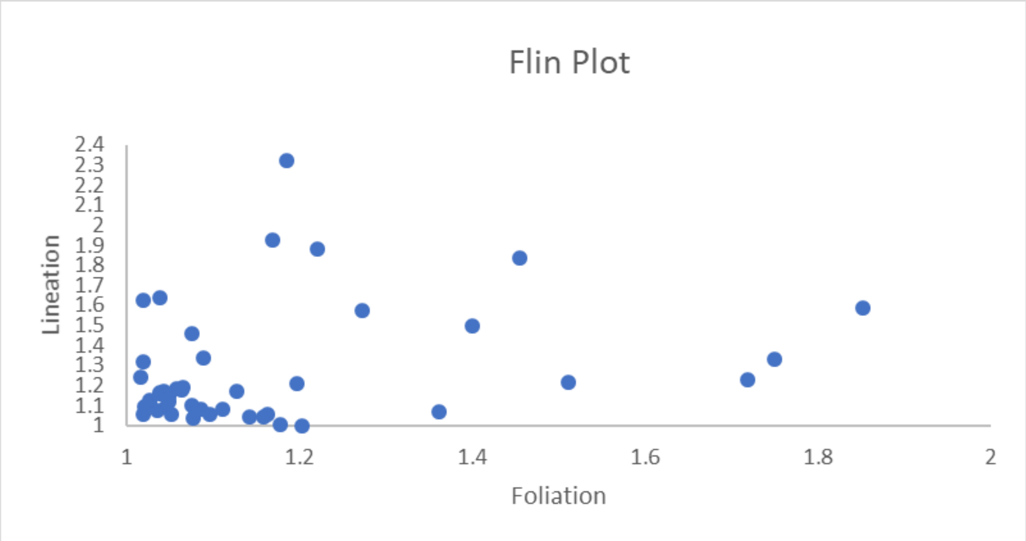

Figure 5.2: Flinn type plot for all samples.

5.4.3 JELINEK PLOT:

A plot of shape parameter "T" and the degree of anisotropy "Pj"(Jelinek,1981;Hrouda,1982). Oblate shapes have positive T values whereas prolate shapes have negative T values. Triaxial shapes (neutral ellipsoid) plot close to T=0.0.

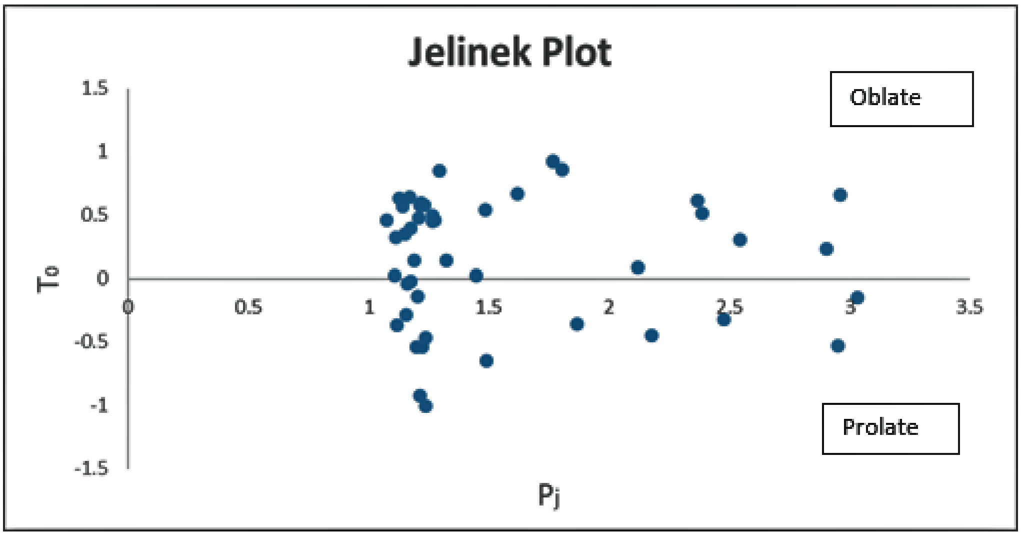

Figure 5.3: Jelinek plot of all the samples.

5.4.4 Km-Pj Plot:

In this type of study, two parameters, namely mean susceptibility and corrected anisotropy degree are compared in the X and Y axes respectively.

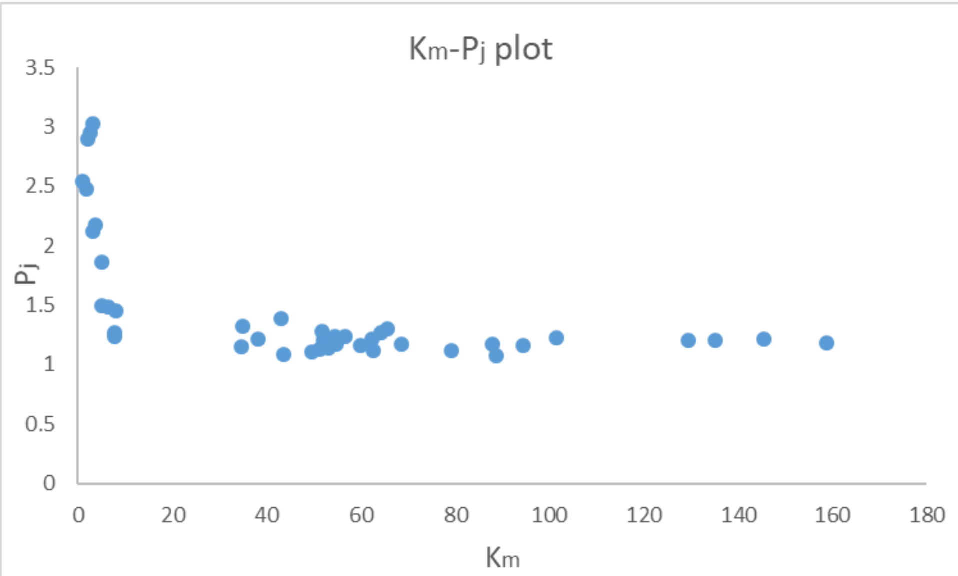

Figure 5.4: Km vs Pj plot of the rocks of Saltora region.

(a) Two trends are observed from the Km Pj plots which have two different explanations.

(b) They are: Low-susceptibility and High Pj and High susceptibility low Pj.

(c) High susceptibility and low Pj points towards the rock units which have the magnetic fabrics controlled by the mineralogy, i.e. ferromagnetic susceptibility and can no way be related to deformation or tectonism. These are basically found to obtain the oblate shape of susceptibility ellipsoid.

(d) The low susceptibility and high pj are more prone to deformation signatures and correspond to shape anisotropy. These are represented by the prolate ellipsoid.

5.4.5 Plots of AMS data (STEREO PLOTS)

The Eigen values that are obtained during the AMS study were plotted in the Circular Diagram with the help of STEREO software. Based on the intensity of the maximum, minimum and the intermediate values of the Eigen values on the circular diagram they are classified into two categories which may be termed as STRONG CLUSTER and WEAK CLUSTER.

The magnetic foliation planes are constructed through the plots of the maximum and the intermediate Eigen value plots the same software. Based on the variation attitude of this magnetic foliation planes the stereo diagrams can be classified into two types which are called Strong Girdle and Weak Girdle.

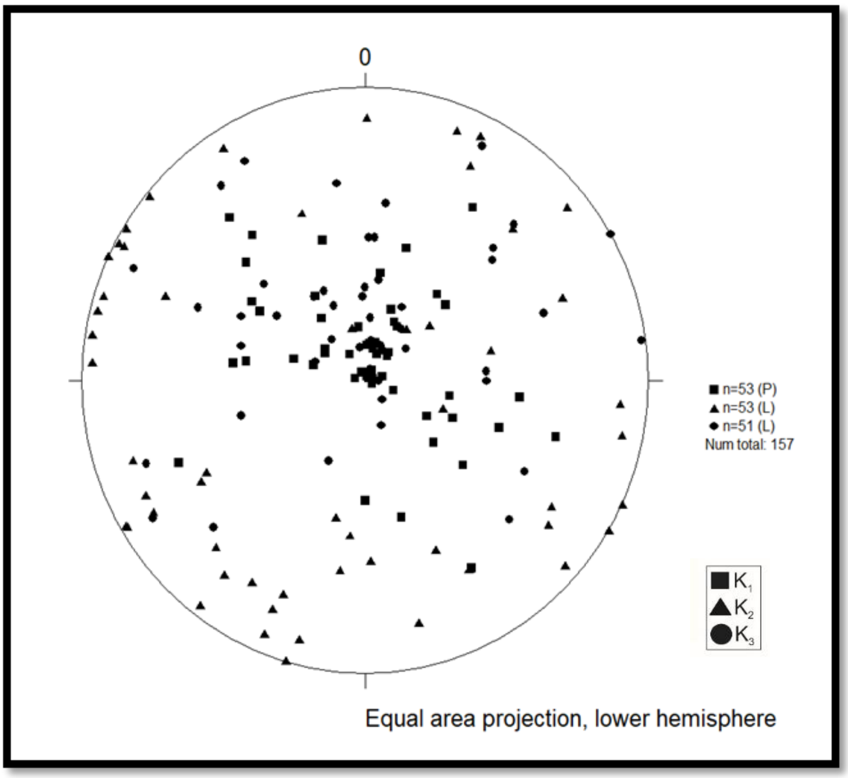

Figure 5.5: Plotting of Anisotropy directional data on a stereographic projection.

5.4.6 OBSERVATIONS FROM HE EXPERIMENTAL RESULTS:

Most of the flinn plots are present in the oblate field._This means that the ferromagnetic minerals are present along a certain plane. This plane may be the foliation developed during the regional deformation of the terrain, however, not replicated in the mesoscopic studies. Thus, orientation anisotropy is absent in the present studies. The magnetic fabric is chiefly metamorphic and do not implicate any primary signatures. Metamorphic magnetic fabric dominated by the ferromagnetic minerals generally deformational and impinged during any secondary processes. The Maximum and intermediate susceptibility axes plot mostly about the periphery. The minimum susceptibility axes tend to cluster in the centre. The oblate fabric as known from the flinn and Jelinek plots are represented by the dispersion of the maximum and intermediate axes about the periphery. However, there are exceptions where the minimum migrates towards the periphery which infers the small number of samples in the prolate field. The oblate fabrics are mainly from the high-grade rocks.The prolate fabric is mainly observed in the anorthosites and massif type rocks.

CHAPTER-6

❖ RESULTS, DISCUSSIONS AND CONCLUSION:

RESULTS FROM PETROGRAPHY AND MINERALOGY:

Petrographic studies of the high grade rocks from Saltora region reveal that the major rock type of the studied area Anorthosite with patches of Gabbro. The Anorthosites may be correlated with the various events of Anorthosite intrusion in the Proterozoic mobile belts of the world (Ashwal, 1993).

The Fe-Ti oxide minerals in studied rocks from the Saltora area are medium to coarse-grained indicating a slow cooling during prolonged period of metamorphism. The presence of ex-solution lamellae of inhomogeneous, titanomagnetite and ilmenite grains and the signature of the middle stages of high temperature oxidation like igneous parent rocks; these features indicate that these rocks have suffered a prolonged period of high temperature metamorphism. The presence of ultra-fine grained or droplets of secondary magnetites, which occur along the grain boundaries and at places along the cleavage planes of silicates are indicative of upliftment of Earth's crust with slow cooling.

Considering the principal textural relationship in rocks from different sampling sites, at least three generations of ferromagnetic mineral assemblage are distinguishable. The earliest one is the homogeneous titanomagnetite solid solution of FeO + TiO_2. These are coarse to medium sized irregular grains occurring separately or associated with pyroxene grains. The second generation consists of the titanomagnetite grains hosting exsolved lamellae of ilmenite appear to indicate a later tectono-thermal event. Considering this textural association, this ferromagnetic variety appears to have formed due to variable amount of titanium concentration in titanomagnetite during cooling from peak metamorphic condition. The last generation of ferromagnetic mineral is developed as specks or platelets within the silicate grains and these minerals occur along the late generation cracks of silicate minerals. This secondary magnetite crystallizes from iron-bearing solution under low-temperature condition.

During rapid uplift of the high-grade granulite terrain and at this stage temperatures fell from peak value in the ranges 850°-750°C (Zhang and Piper 1994). This last generation of ferromagnetic mineral growth is also identified as microcrystalline iron oxides. This is due to release of pressure during tectonic uplift of the high-grade terrain.

RESULTS FROM AMS STUDIES:

The overall nature of the magnetic fabrics is very interesting in the studied area. From the Km-Pj plot it is evident that the relationship of the bulk susceptibility and the degree of anisotropy is quite complex, and the controlling factor of the magnetic fabrics are not revealed. However, from the stereo-plot it is revealed that the maximum and intermediate susceptibility axes plots towards the periphery and the minimum plots at the center, with few exceptions where the plot is reverse. Considering the dominant plot, it can be said that the magnetic foliation in that case is near horizontal and thus explains for the oblate fabric in the Flinn and Jelinek plots. Now as these rocks are high grade rocks in nature, they contain a significant amount of titano-magnetite developed during metamorphism (Zhang and Piper, 1994) and as these contribute towards high susceptibility of the rocks, it can be considered that the magnetic foliation represents the plain containing the ferromagnetic grains. This explains the magnetic fabrics in the high-grade metamorphic rocks.

Now in the reverse case, i.e., minimum towards the periphery and maximum and intermediate towards the center have significances from the Anorthosite intrusion. As the Anorthosite intrusion event occurred through favorable places, the orientation of the susceptibility axes remained horizontal.

Thus, in the present study the magnetic fabrics are mainly mineralogically controlled by ferro-magnetic minerals.

❖ CONCLUSIONS AND SCOPE OF FURTHUR STUDIES:

Thus, the present study is implicative towards the development of magnetic fabrics and its relation to ferromagnetic mineralogy in high grade terrains. The following major conclusions can be drawn from the present study:

In high grade metamorphic terrain, the magnetic fabrics are rarely controlled by petro-fabric or tectonic events; rather they are controlled by ferromagnetic mineralogy.

The high-grade metamorphic rocks are type sections for study of magnetic mineralogy and are store houses of a range of Fe-Ti oxide generations. Considering the principal textural relationship in rocks from different sampling sites, at least three generations of ferromagnetic mineral assemblage are distinguishable. This is because of several tectono-thermal events experienced by such high-grade terrains.

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