3.0. Introduction

This study mainly comprises of an integration of three independent approaches; i) Field sedimentology, ii) Mineral magnetism and iii) Petrography. Well established methods are adopted for all these approaches independently whereas an integration of rock magnetic and petrographic study makes a novel attempt. A detailed documentation of the lithofacies assigning well defined units is followed by the sampling for petrography and rock magnetic analysis. Since the previously published magnetostratigraphic data has also been used, the methods on magnetostratigraphy too are described.

3.1 Field Sedimentologic Approach

After an extensive reconnaissance survey in the Mizoram area, total 13 well exposed sections of 38m to 1618m thicknesses are selected (see fig 4.1). This includes the magnetostratigraphically dated sections of Bongkown-Durtlang and Tuirial near Aizawl. The sedimentologic observations in each section include documentation of grain size and colour variation, upper/lower contact relationships, geometry of the sand bodies, lateral changes and primary sedimentary structures that are useful to describe the depositional environments. The detailed lithologs are prepared for all these sections (described in succeeding paragraphs). The description is made by assigning numbers to each sedimentologic unit at meters scale. These units describe various fining/coarsening up cycles, colour and inter association of the sand-shale packages. The salient lithologic characters and their relation to depositional environments are inferred following the classical texts (e.g., Reading, 1981; Leeder, 1982; Einsele, 1992). Two distinct types of sandstones (grey and buff) are further studied in detail by comparing their geometries, petrography, grain size, grain contact relationships and frequency of occurrence within the section.
Fig. 3.1. Graphical representation of methodology used in this thesis.
Fig. 3.2 Sedimentological methodology approach steps- 1&2: Measurement of lithological units from centimetres to meters scale. 3&4. Detailed documentation of lithology. Further steps are as preparation of Lithologs, Lithological characters and Depositional Environment.
Ph. Plate 3.1. Lab techniques used for Petrographic and Heavy mineral analysis.

1&2 Microscope used for Petrographic and Heavy mineral counting methods.

3,4&5 Laboratory treatment for removal of clay and organic material.

6. Gravity separation method used for heavy mineral collection.
3.2.1 Petrography:

An authentic elaboration of a rock cannot be made without their study in thin sections under microscope. The petrographic studies can elaborate the geologic history of the rock by understanding the provenance, depositional environments, rock fabrics, porosity, permeability, diagenetic history, alteration and cementation. Standard methods of preparation of thin section are used for this purpose.

The detailed petrographic analysis was carried out using Gazzi-Dickinson point counting method (Gazzi, 1966; Dickinson 1970) due to the less grain size variability within true mineralogical difference (as suggested in Ingersoll 1979, Dickinson 1984, 1986). The thin section analysis was carried out for a total of 75 representative samples of fine- to medium-grained sandstones. The thin section study was done in two stages by measuring more than 500 grains in each section the first stage followed by more than 300 grains in the second lot of sections prepared for each sedimentologic column. Sections are examined by measuring grain sizes, angularity, sphericity, grain to grain contact, inclusions and alterations. The rock fragments are identified based on their characteristic texture and mineralogical association. The sandstones constituents are denoted as quartz (Q), feldspar (F), rock fragments (Rf), mica (Mi), dense minerals (D- both opaque and non-opaque), cement (Ct) and the matrix (Mx). Quartz is the most common detrital constituent; therefore the optical characters of mono- and polycrystalline quartz, together with inclusion, shape and grain boundaries are noted separately. The quartz undulation extinction is an optical property which express strained crystal subjected to deformation. The feldspar identification and content was made to give an idea about provenance and nature of weathering. The mica, chlorite and clay minerals provide information about the source as well as the energy conditions due to low settling velocity. The rock fragments are direct clues for source rock and therefore identified based on their mineralogical association. The matrix percentage gives information about the maturity of sandstone. The cement is important diagnostic component in the sandstone that directly gives an idea about depositional environment of sandstone. The measured grain size is further used for grain size analysis using statistical analysis of mean, median, mode, sorting, skewness, kurtosis, modality index. These parameters are useful for understanding fluid flow energy. The sphericity, roundness and angularity observation gives information about weathering history of sandstones.
3.2.2 Heavy Mineral Analysis

The heavy minerals are found in small quantities in sandstone but they are most useful for source rock interpretation due to their resistance to mechanical and chemical weathering, transportation and diagenesis. They are also useful for understanding gradual unroofing of the orogenic slabs of provenance. The heavy mineral analysis was carried out for representative samples. These samples were first treated with 10% HCl for several times till the complete removal of clayey material from the sample. Then 60gm of each sample was used for heavy mineral separation. The Bromoform (sp. gr. 2.89) is used as heavy liquid for separation. The sample is stirred more than 4 hours in heavy liquid for total extraction of heavy minerals from sample. The collected heavy minerals are washed several times by ethanol. Then these heavy minerals are mounted over Canada-balsum for thin section study. The point counting method was adopted for these thin sections and more than 300 points were counted from each slide.

3.3. Rock Magnetism

The study of natural magnetism can be classified into three main branches as, i) Geomagnetism, which deal with the study of the behavior of magnetic field of the earth and its atmosphere, ii) Palaeomagnetism is the study of past magnetic fields recorded in the rocks, iii) Rock magnetism (also called mineral magnetism) is the study of rocks, minerals and soils with reference to composition, concentration, and granulometry of the magnetic minerals present in them (Collinson, 1987; O’Reilly, 1984; Dunlop and Ozdemir, 1997). The present thesis mainly used the third approach i.e., of rock magnetism and is elaborated below. Whereas, the magnetostratigraphy is elaborated in brief; as the two published magnetostratigraphically sections are used here to constrain the ages.
3.3.1. Principles of Rock magnetism

Types of magnetic materials

In nature, every material is ‘magnetic’ sensu-stricto with their inherent response to the external magnetic field classifying it into dia-, para-, ferro-, ferri and antiferromagnetism (Tarling and Hrouda 1993; Collinson, 1987; Thompson and Oldfield, 1986). Rock is a heterogeneous assemblage of minerals, composed of more than 90% of silicates and/or carbonates (in general) that are diamagnetic or paramagnetic in nature with less than 5% of iron oxides/magnetic minerals (ferrimagnetic minerals). The ferrimagnetic minerals can carry the most characteristic signatures of inherent magnetization and remanent magnetism controlling overall magnetic properties (Thompson and Oldfield, 1986).

Amongst the rock magnetic parameters, magnetic susceptibility is the most common fundamental property that measures the degree to which a substance may be magnetized and is denoted as $\chi$. It is defined as the ratio of intensity of magnetization (M or I) to the magnetizing force field (H). The magnetic behaviour of a solid depends on the magnetic moments of the atoms or ions in it. The net magnetic moment of an atom or ion arises from incompletely filled shells that contain unpaired spins (O’Reilly, 1984; Dunlop and Ozdemir, 1997). The atoms or ions in a solid are not randomly distributed but occupy fixed positions in a regular lattice, which reflects the symmetry of the crystalline structure and which controls interactions between the ions. Hence, the different types of magnetic behaviour observed in solids depend not only on the presence of ions with unpaired spins, but also on the lattice symmetry and cell size. Detailed descriptions of the kinds of magnetic materials are as follows,

- Diamagnetism
- Paramagnetism
- Ferromagnetism
- Ferrimagnetism
- Antiferromagnetism
- Canted Antiferromagnetism
Fig. 3.3. Types of alignment of the magnetic moments in atoms after various magnetic materials. The solid arrow represents the external field while the hollow arrow represents the net magnetic moment in the material.

**Diamagnetism:**

Diamagnetism is characteristically observable in materials in which all the electron spins are paired. Diamagnetism arises from the interaction of an applied magnetic field with orbital motion of electrons and results in a very weak negative magnetization. The magnetization is lost as soon as the magnetic field is removed (Fig 3.1 a). Diamagnetic susceptibility is weak and negative and is independent of temperature. Many important rock forming minerals belong to this class.

**Example:** Quartz (SiO$_2$), Calcite (CaCO$_3$), Dolomite (CaCO$_3$,MgCO$_3$), Water (H$_2$O).

**Paramagnetism:**

Paramagnetic materials are weakly magnetic with small positive susceptibility. The magnetic moment of unpaired electron orbital within individual atoms are uncoupled so that each atom behaves independently. The resultant magnetic moment can align with a magnetic field (Fig. 3.1 b). The alignment is opposed by thermal energy which favors
chaotic orientations of the spin magnetic moments. The magnetic energy is small compared to the thermal energy, and in the absence of a magnetic field the magnetic moments are oriented randomly. When a magnetic field is applied, the chaotic alignment of magnetic moments is biased towards the field direction. A magnetization is induced proportional to the strength of the applied field and parallel to its direction. Susceptibility varies inversely with temperature as given by the Curie-Weiss law.

\[ k = \frac{C}{T}, \text{ Where, } C = \text{constant; } T = \text{Temperature} \]

**Example**: Clay minerals (e.g. Kaolinite, Montmorillonite), Mica (e.g. Biotite, Chlorite), Silicates (e.g. Amphibole, Pyroxene, and Olivine).

**Ferromagnetism**:

Ferromagnetic material is much stronger than diamagnetic and paramagnetic materials. It is particularly associated with Iron, Nickel, and Cobalt having positive and relatively large susceptibility and remanence. In some metals (Fe, Ni and Co) the atoms occupy lattice positions that are close enough to allow the exchange of electron between neighboring atoms. The exchange is a quantum mechanical effect that involves a large amount of energy called the exchange energy of the metal. The exchange interaction produces a very strong molecular field within the metal. This aligns the atomic magnetic moments exactly parallel to each other and produces a spontaneous magnetization (Fig. 3.1 c). Rock samples may contain thousands of tiny ferromagnetic grains. The magnetization loop of a rock sample shows the effect of magnetic hysteresis. At or above particular critical temperature called ‘Curie temperature’ magnetic moments are randomized and thus the ferromagnetic material behaves as paramagnetic.

**Example**: The elements Fe, Ni, and Co and many of their alloys.

**Ferrimagnetism**:

The metallic ions in antiferromagnetic material occupy the voids between the oxygen ions. In certain crystal structures the sites of the metal ions differ from each other in coordination of the surrounding oxygen ions. In the sub-lattices, tetrahedral sites have four oxygen ions as nearest neighbors and octahedral sites have six. The most common iron oxide minerals have an inverse spinel structure. Each sub-lattice has an equal number of
ions. The same numbers of divalent ions occupy the octahedral sites, while the corresponding number of tetrahedral sites is empty. When the indirect exchange process involves antiparallel and unequal magnetizations of the sub-lattice resulting in a net spontaneous magnetization, the phenomenon is called ferrimagnetism (Fig 3.1 e). Magnetite \( \text{Fe}^{3+}\{\text{Fe}^{2+}\text{Fe}^{3+}\}\text{O}_4 \) is prime example of ferrimagnetic material and other examples include Titano-magnetite \( \text{Fe}_{3-x}\text{Ti}_x\text{O}_4 \), Maghemites \( \gamma\text{Fe}_2\text{O}_3 \), Pyrrhotite \( \text{Fe}_x\text{S}_{x+1} \) and Greigite \( \text{Fe}_3\text{S}_4 \).

**Antiferromagnetism:**

In oxide crystals the oxygen ions usually keep the metal ions far apart, so that direct exchange of the electrons between the metal ions is not possible. In certain minerals interaction between magnetic spins become possible by the exchange of the electrons from one metal ion to other through the electron ‘cloud’ of the oxygen ion. This indirect exchange process results in anti-parallel directions of adjacent atomic magnetic moments (Fig 3.1 d) giving two sub-lattices with equal and opposite intrinsic magnetic moments. As a result the susceptibility of an antiferromagnetic crystal is weak and positive, and the remnant magnetization is not possible.

**Example:** Ulvospinel \( \text{Fe}_2\text{TiO}_4 \), Ilmenite \( \text{FeTiO}_3 \), Troilite \( \text{FeS} \).

**Canted Antiferromagnetism:**

Imperfect antiferromagnetic forms exhibit parasitic ferromagnetism which may result due to impurities or lattice defects, and by spin canting (Fig 3.1 e). The spins are not exactly anti parallel and are inclined at a small angle, do not cancel out completely and thus results spontaneous as well as remanent magnetizations. An important geological example is hematite \( \alpha\text{-Fe}_2\text{O}_3 \), in which both the spin-canted and defect moments contribute to the ferromagnetic properties and another example is iron hydroxide (Goethite \( \alpha\text{-FeOOH} \)).

### 3.3.2 Domain Theory

The concept of magnetic domains was proposed in order to explain the existence of spontaneous magnetization in a demagnetized state of the material. Ferromagnetic particles comprises of infinitesimal region of uniform magnetization called magnetic domains. Domains are small (1-100’s microns), but much larger than atomic distances. Magnetic
domains are separated by zones of finite thickness called domain wall. Magnetic domains are otherwise called as magnetic grains. Size and concentration of the domains are explained by some magnetic properties such as frequency dependent susceptibility, coercivity and remanence. Four major magnetic domains/grain sizes are recognized (Fig 3.3)

![Diagram of Single Domain and Multidomain](image)

*Fig. 3.4 Magnetic domains*

**Single Domain (SD)**

The grain contains only one domain referred as single domain, the entire grain is uniformly magnetized (Fig 3.3). The theoretical range of SD size in magnetite is narrow (0.03 to 0.1 µm) whereas it is larger for hematite (0.03 to 15 µm). The magnetization of a SD particle is very stable and has relaxation time of more than 1000 Ma (Fig. 4.4). The SD grains can be very efficient carriers of remanent magnetization and thus play an important role in paleomagnetism.

**Pseudo-single Domain (PSD)**

When the grain size is larger (0.1 to 20 µm) than SD with more than one domain (<2 or 3 domains) it is referred as Pseudo-single Domain. Grains in this size range contain a small number of domains and can have substantial magnetic moment. PSD grains can be important carriers of Paleomagnetism.
**Multidomain (MD)**

Magnetic grains larger than a few µm (> 20 µm) in diameter with more than two domains are called as multi-domain particle (Fig 3.3). The domains are separated from one another by thin region, about 0.1 µm thick called domain wall. MD grains are magnetically soft and it is easy to impart a remanent magnetization. MD grains exhibit anisotropy in magnetism and thus useful to determine anisotropy magnetic susceptibility (AMS) studies.

**Superparamagnetic (SP)**

The term Superparamagnetic is referred to the ultrafine (< 0.03 µm) ferro- or ferrimagnetic grains by Neel (1955). Superparamagnetic behavior strongly depends on temperature and is paramagnetic at room temperature. They exhibit ferro- or ferrimagnetic properties of stable single domain grains at lower temperatures. Susceptibility of these SP grains is much greater (at low frequency) than SD and PSD grains. (Fig 3.4)

![Graph between magnetic grain size vs. temperature](from, Butler, 1992)

**Fig 3.5** Graph between magnetic grain size vs. temperature (from, Butler, 1992)

However, SP grains play a leading role in environmental magnetic and soil magnetic studies as their concentration in the soils/paleosols is mainly controlled by the climate and pedogenesis.
3.3.3. Magnetic Minerals:

The most important magnetic minerals and their properties relevant to magnetic studies are described below.

Iron Oxides:

Although there are number of iron oxide minerals, the three most commonly occurring minerals – magnetite, hematite and maghemite – are considered here.

Magnetite: \((\text{Fe}_3\text{O}_4)\)

It is the single most important magnetic mineral on earth. It occurs in igneous, sedimentary and metamorphic rocks. It is an important source of iron ore. Crystallographically, it is cubic with spinel structure, with oxygen anions forming a face centered cubic framework with Fe cations in the interstitial space between the anions. In solid solutions magnetite is an end member of the series Titanomagnetites.

Hematite: \((\text{Fe}_2\text{O}_3)\)

This mineral occurs widely in nature, being particularly common in soils and sediments of environmental significance. Hematite possesses hexagonal crystal structure in which alternate planes contain trivalent ions magnetized in (almost) opposite directions. The slight departure from antiparallelism called spin canting is crucial. It turns hematite from an antiferromagnetic mineral into weakly ferromagnetic mineral. Hematite being 200 times weaker than magnetite is thermally more stable.

Iron can be replaced by titanium giving rise to titanohematites. At one end is hematite \((\alpha-\text{Fe}_2\text{O}_3)\) and at the other end is ilemnite \((\text{FeTiO}_3)\). The general formula is \(\text{Fe}_2-y\text{TiyO}_3\).

Maghemite: \((\gamma-\text{Fe}_2\text{O}_3)\)

It occurs widely in soil. Its chemical formula is identical to that of hematite. Maghemite is the fully oxidized form of magnetite. It has a cubic crystal structure with a unit cell somewhat smaller than that of magnetite.
Iron Oxyhydroxides:

Weathering of bedrock produces numerous hydrous iron oxides such as goethite, limonite, lepidocrocite.

Goethite: \((\alpha-\text{FeOOH})\)

Goethite is hexagonal and antiferromagnetic but not perfectly so. It also possesses a weak ferromagnetism. Of all the hydrous iron oxides goethite is magnetically significant in its own right.

Others such as ferrihydrite \((5\text{Fe}_2\text{O}_3.9\text{H}_2\text{O}\) also known as limonite) and lepidochrocite \((\gamma-\text{FeOOH})\) may undergo chemical changes to produce hematite and magnetite, which may be magnetically important in the soil.

### 3.3.4. Laboratory Methods, Instruments and Parameters used

The concepts of mineral magnetism are based upon the mineral response to laboratory induced magnetic fields of known directions and magnitudes at controlled temperatures (-196 to 800 °C) but more routinely at ambient temperatures. This response totally depends upon compositions, crystal structures and associations of the magnetic materials. Magnetic susceptibility is the most fundamental mineral magnetic parameter that defines the degree to which a material can be magnetized in an external magnetic field. If the ratio between the induced magnetization and the inducing field is expressed per unit volume, the volume susceptibility \((k)\) is defined as \(k = M/H\), where \(M\) is the volume magnetization induced in a material of susceptibility \(k\) by the applied external field \(H\). Volume susceptibility is a dimensionless quantity. Its value depends on the measurement system used: \(k\) \(\text{SI} = 4 \pi k(\text{cgs}) = 4 \pi \text{ G Oe}^{-1}\), where G and Oe are abbreviations for Gauss and Orstedt, respectively. The SI system is used in the present work.

In order to normalize the mass of the sample analysed, the mass specific susceptibility is estimated defined as \(\chi = k/rho\), Where \(rho\) is the density of the material. The dimensions of mass susceptibility are therefore usually cubic meters per kilogram. The magnetic susceptibility is measured at very low fields, usually not exceeding 0.5 mT, which have no influence on the NRM. It is therefore referred to as low-field susceptibility. For
comparison, fields of ~50 mT are required to change orientation in magnetite domains. High-field susceptibilities are measured in fields of a few hundred militeslas (mT) and require specific equipment. Magnetic susceptibility is also defined as the reversible part of the magnetic hysteresis and is elaborated in the following section.

A magnetic susceptibility meter manufactured by Bartington (UK) has been used to measure the susceptibility. The laboratory sensor MS2 of Bartington enables the measurement of discrete samples (10 cc volume) at field frequencies of 0.465 KHz and 4.65 KHz and an AF intensity of 80 A/m (= 0.1 mT). Any magnetic material brought within the influence of this field effect a change in frequency of oscillation. This change is transmitted to the MS2 meter via a coaxial interconnection cable. The MS2 meter converts the pulse information from the sensor into an initial susceptibility value. Power for the instrument may be supplied from either a 12-V DC adaptor or from internal rechargeable Ni-Cd batteries.

The frequency dependence can be determined from measurements in dual-frequency mode. The different frequencies used are low (0.465 KHz) and high (4.65 KHz). This enables to detect the contribution from viscous grains at room temperatures to account for the presence of SP fraction.

3.3.4.1. Magnetic Hysteresis

When the external field is removed, the magnetization disappears in diamagnetic and paramagnetic materials. On the other hand, the ferromagnetic materials preserve remanent magnetization even in the absence of external magnetic field. When applying the strong field, the sample acquires its saturation magnetization ($M_s$) and removal of this field leaves the sample with saturation remanence ($M_{rs}$). Subsequent application of the magnetic field in opposite direction brings the magnetization to zero, but the magnetization does not fall at origin. This behaviour is called ‘hysteresis’ and a plot of the variation of the magnetization ($M$) with magnetic field ($H$) is called ‘hysteresis loop’ (Fig 3.2). The field required to decrease the magnetization to zero is called the coercive force ($H_c$) and where the remanance become zero is called $H_{CR}$. The sample can be saturated in the opposite direction when sufficient reverse field is applied (Fig 3.2). These magnetic parameters ($M_s$, $M_{rs}$ and $H_c$) are mainly dependent on the composition and granulometry of the magnetic minerals.
Fig. 3.6. Magnetic Hysteresis loop for ferromagnetic material (Thompson and Oldfield, 1986)

A hysteresis loop displays the response of a material to an applied magnetic field which is measured in that applied field. The loops are indicative of magnetic mineralogy but are also sensitive to subtle changes in grain size which complicates the interpretation of results from natural samples. Classically, the ratios of $M_r/M_s$ and $B_{CR}/B_c$ are plotted on a so-called ‘Day’ plot (Day et al. 1977).

Data usually fall in a narrow band which has been calibrated experimentally with material of known grain size so that grainsize indicative information can be extracted. Roberts et al. (1995) empirically documented that a measured loop is composed of the weighted contribution of each component in the absence of magnetic interactions, i.e. at low concentration (<0.1%). In many studies, the only parameters used are $M_r$, $M_s$, $B_{CR}$ and $B_c$. It is clear that a wide range of loop shapes is possible and that considerably more information is present in a hysteresis loop than is given by these parameters. Recently, additional methods to retrieve more information from hysteresis loops have been proposed, including unfolding the loop into pseudo-waveform which can be subjected to Fourier analysis (Jackson et al. 1990), fitting analytical functions to the loops (Von Dobeneck 1996) and decomposing the loops assuming that given fractions of SD and SP material are present in a sample (Tauxe et al. 1996). So called ‘wasp-waisted’ loops have generated...
much interest (Roberts et al. 1995, Tauxe et al. 1996) as significant magnetic contribution of two (or more) distinct coercivity fractions in a sample generating such loops.

Tauxe et al. (1996) modelled loops as consisting of SP and SD contributions and applied the results to submarine basaltic glasses. It is possible to generate all types of hysteresis loops from these two ‘end member distributions’, depending on their relative contributions. Von Dobeneck’s (1996) procedure cannot be applied to wasp-waisted loops, but ‘regularly’-shaped loops can be analysed in detail and subtle differences between sets of loops can be visualised and interpreted. Since the advent of readily available instruments capable of measuring hysteresis behaviour of rock samples (e.g., Flanders, 1998), rock magnetist have measured many different geological materials. Hysteresis is extremely sensitive to grain size, domain state, mineralogy and state of stress. Virtually all geological material of rock magnetic interest has remanence and reversal properties dominated by non-uniform magnetization states. Magnetic modelling of hysteresis loops is therefore essential for understanding the origin of magnetic remanence and coercivity (see summary by Dunlop and Ozdemir 1997).

### 3.3.4.2 Isothermal Remanant Magnetization (IRM):

Remanent magnetism resulting from short-term exposure to strong magnetizing fields at constant temperature is referred as isothermal remanent magnetism (IRM). In the laboratory, IRM is imparted by exposure (usually at room temperature) to a magnetizing field generated by an electromagnet. IRM is the form of remanence produced in hysteresis experiments and is acquired by ferromagnetic grains with coercive force less than the applied field. The maximum remanence that can be produced is called the saturation isothermal remanent magnetization (SIRM). The field at which saturation is reached depend on the composition and microstructure of the specimen.

The IRM measurements were conducted by a set of instruments comprising of an impulse magnetizer and the magnetometer. A pulse magnetizer (see Photo 3.2) is designed to produce a short-duration high field pulse for the purpose of magnetizing geological samples. The field is produced by the discharge of energy from a capacitor bank through a coil surrounding the sample cavity. The capacitor bank is first changed to the desired voltage (corresponding to the desired field). It is then discharged through the coil very
quickly to magnetize the sample. The impulse magnetizer is ideally suited for the study of acquisition of IRM and the Coercivity of remanance of discrete samples. Both are characteristic rock magnetic properties that are used for preliminary magnetic carrier identification. Coercivity of remanence is a very useful hysteresis parameter that can be used in determining magnetic mineralogy and grain size and in helping to characterize magnetic mixtures. It is the field that reduces the saturation isothermal remanence to zero.

**Fluxgate Spinner Magnetometer:**

The magnetic field of the specimen within the fluxgate results in a DC output signal proportional to the component of the magnetic moment parallel to the principal axis of the fluxgate. To improve the signal to noise ratio, the specimen is rotated at 6 Hz to get a sinusoidal output signal at that frequency. The amplitude and phase of this signal provides a measure of the magnitude and direction of the horizontal component of magnetization of the specimen. The system is controlled by a Rockwell 6502 microprocessor. A timing disc with 128 slots sensed by a photocell is used to sample the output signal 128 times every revolution. Each "sample" is digitized via a 12-bit analog to digital converter (ADC) and then stored in one of 128 "slots" in the processor memory. Each "slot" requires 24 bits, i.e. 3 bytes of memory (each bit may have a value of 0 or 1; 1 byte = 8 bits). For each subsequent revolution the 128 new samples are added to their previous counterparts and stored again. A single long slot and second photocell is used to detect each complete revolution of the timing disc. By stacking signals from N revolutions the signal to noise ratio is improved theoretically by a factor of N. The result is independent of variations in rotation rate. When the pre-selected number of revolutions is completed (24 for SHORT, 120 for LONG), the 128 summed values are Fourier analyzed to determine the amplitude and phase of the first harmonic at the rotation frequency. The result is expressed as NORTH and EAST components relative to the principal axis of the fluxgate in the horizontal plane. The readout module incorporates a pulse counter. Results are converted by the 6502 into a stream of pulses (at a rate of 10 per second) of the correct length. For the SHORT time constant there is one figure after the decimal point, and for the LONG time constant there are two. Thus the number 35.30 is sent as a string of 3530 pulses (3.53 ms duration).
3.3.4.2.2 Anhysteretical Remanant Magnetism (ARM)

An ARM is acquired by the action of an asymmetric alternating field applied to a sample. The aim of ARM is to drive the magnetisation of the sample backward and forward around the origin of its hysteresis loop, while magnetizing it with a small steady field. ARM is generally imparted at a high alternating field measured and then demagnetised using smaller alternating fields, without the application of the steady field. The alternating field is decreased from a desired peak level to a lower value, usually zero. While the alternating field is decreasing, the required asymmetry is obtained by simultaneously creating a direct current (DC) bias field, either by switching off compensation coils or by a dedicated coil generating a small magnetic field comparable to the intensity of the geomagnetic field (~ 30 to ~ 60 μT). For low field values up to ~80 μT, the ARM intensity is linear with the inducing DC bias field. For the low concentrations of magnetic minerals that usually prevail in sediments, ARM is a first-order approximation linear with concentration. Compared to MD particles, SD particles have high ARM intensities per unit mass, which makes ARM an attractive proxy for SD grains. Banerjee et al. (1981) and King et al. (1982) have given models for ARM versus χf as a grain-size indicator for granulometric purposes, a procedure which has been used widely since then. Below is shown model based upon relationship of SIRM/ARM to χfd% developed by Oldfield et al (1985). The instrument used is called a D-2000 AF Demagnetizer (see Photo plate 3.2).

3.3.5 Mineral Magnetic Parameters:

Coercivity of Remanance (B_{CR}):

The reverse remagnetization of a sample where the IRM retained be reduced to zero is defined as the Coercivity of Isothermal Remanance (often expressed in mT).

S-Ratio:

The S-Ratio (abbreviated after Karen Stober, Stober and Thompson, 1979) is an empirically derived parameter based on observation that the coercivity of IRM profiles of natural samples containing mixtures of magnetic minerals in a range of grain sizes very often exhibits their greatest degree of separation from each other at a coercive field of -100mT. This makes the IRM/SIRM ratios of the samples at this field particularly sensitive to
differences in their overall composition. The S-ratios of samples tend to be most sensitive
to differences in their mineralogy (i.e., ferrimagnetic versus canted antiferromagnetic
constituents). These are less sensitive to the difference in the grainsize of magnetic
minerals.

**Concentration Dependent Parameters:**

Such parameters mainly reflect the amount of magnetizable material in the sample, though with varying degrees of sensitivity to different fractions (mineralogical or
granulometric) of the magnetic assemblage depending upon the parameters used. These
include K, X, Xfd, ARM, SIRM, HIRM, IRMsoft, VRM, NRM, Ms, and RRM. These are
often expressed per unit volume or mass.

**Concentration Independent Parameters:**

These parameters reflect relative proportions of magnetic minerals of different types
and/or grain sizes, and are thus mainly unaffected by bulk concentration of magnetic
material in a sample. These are inter-parametric quotients (or ratios) primarily influenced
either by the mineralogical or granulometric composition of the sample’s magnetic
assemblage, rather than its bulk concentration. The most important concentration
independent parameters include S-ratio, SIRM/X, XARM/X, XARM/SIRM, Xfd%,
HIRM%, and IRMs, SIRM/Ms, B_{CR}/BoC, and Mrs/Ms.

The various mineral magnetic parameters (and their combinations) discussed here are
employed for the purpose of answering three broad questions.

They are:

- Composition (i.e., which magnetic minerals are present?)
- Concentration (i.e. how much of each one is present?)
- Granulometry (i.e. what are the dominant grain sizes present?)
<table>
<thead>
<tr>
<th><strong>Table 3.1:</strong> Standard Hysteresis parameters and the equipments used for the present study.</th>
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<tr>
<td><strong>K and χ</strong></td>
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<tr>
<td><strong>χ$^{fd}$</strong></td>
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<td><strong>IRM</strong></td>
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<td><strong>IRM$^{20mT}$</strong></td>
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<td><strong>IRM$^{100mT}$</strong></td>
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antiferromagnetic hematite of geothite in a sample.

**Instrumentation:** Pulse magnetizer, Fluxgate magnetometer.

**Units:** mA m²kg⁻¹

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Instrumentation</th>
<th>Units</th>
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<tr>
<td>IRM&lt;sub&gt;300mT&lt;/sub&gt;</td>
<td>'Hard' Isothermal Remanent magnetization: SIRM - IRM 100mT, can be used for approximating the concentration of remanence carrying canted antiferromagnetic hematite of geothite in a sample also, but is more sensitive than IRM-100 mT.<strong>Instrumentation:</strong> Pulse magnetizer, Fluxgate magnetometer.</td>
<td><strong>Units:</strong> mA m²kg⁻¹</td>
<td></td>
</tr>
<tr>
<td>SIRM/(\chi)</td>
<td>The ratio of these parameters can be diagnostic of either mineralogy type (e.g., a low - theoretically zero ratio indicates the presence of paramagnetic minerals) or where samples have similar mineral types and concentration, dominant magnetic grain size. Reduced by increased ferrimagnetic versus canted antiferromagnetic contribution, by increased grain size from SD upwards, by an increase in SP contribution to (\chi). Comparison to other ratios and quotients makes it possible to identify mass contributory causes of variation in SIRM/(\chi).</td>
<td><strong>Units:</strong> kA m⁻¹</td>
<td></td>
</tr>
<tr>
<td>((B_0)_c)r</td>
<td>Demagnetization Parameter: The reverse field strength (mT) required to return a magnetized sample from its SIRM to zero is termed the coercivity of remanence ((B_0)_c)r. <strong>Instrumentation:</strong> Pulse magnetizer, Fluxgate magnetometer</td>
<td><strong>Units:</strong> mT</td>
<td></td>
</tr>
<tr>
<td>'S' ratio</td>
<td>Demagnetization parameter: The ratio is obtained using IRM 100mT (a backfield discriminates between ferrimagnetic mineral types) and SIRM.</td>
<td></td>
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<tr>
<td>HIRM</td>
<td>High field Ramenent Magnetization is loss of magnetization after saturation expressed on specific basis (SIRM-IRM&lt;sub&gt;-100&lt;/sub&gt;). The total concentration of remanence carrying canted antiferromagnetic hematites can be approximated. <strong>Instrumentation:</strong> Pulse magnetizer, Fluxgate magnetometer.</td>
<td><strong>Units:</strong> mAm⁻²kg⁻¹</td>
<td></td>
</tr>
<tr>
<td>HIRM/(\chi)lf</td>
<td>This ratio indicates the proportion of antiferromagnets to ferrimagnets of the SD/SP range.</td>
<td><strong>Units:</strong> kAm⁻¹</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Summery:

The basic and applied methods are used to attempt the studies on marine to continental transition. The field sedimentology produce direct evidence for understanding the nature of marine to continental transitions, while the petrography gives the hinterland contribution. The mineral magnetic characterization detects the changes in depositional environments as oxidative or reducing. The integration of these three methods gives information about the marine to continental transition in both the basins.