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Rock-Magnetic Properties of Kondapalle-Pangidi Layered Complex: Evidences Towards Remanence Feasibility

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*Abstract:***The present study concentrates on the petrography, generation of Fe-Ti oxides and magnetic parameters like magnetic susceptibility and Saturating Isothermal Remanence Magnetization (SIRM) to determine the carriers of magnetic remanence, their textural relations with the silicate minerals and to determine the feasibility of the varied rock types in recording magnetic remanence based on a comparative study of the magnetic susceptibility (serving as a proxy for the induced magnetization) and SIRM (as a representative of remanent magnetization). Studies revealed that although the magnetic susceptibility of the mafic granulites are lesser than the other rocks, they are the most feasible rocks in the terrain for recording remanence. Moreover, the Fe-Ti oxides observed in the reflected light study also bears good correlation with the magnetic parameters which is being explained here.**

*Index Terms:***High grade rocks, Kondapalle-Pangidi Layered Complex, Magnetic Remanence, Magnetic Susceptibility, SIRM**

I. INTRODUCTION

The high-grade metamorphic rocks are the least studied ones in terms of magnetic properties, at least in the Indian context despite the fact that these high-grade rocks are exposed in suitable geological terrains and are storehouses of magnetic minerals (Roposo et al., 2001; Viegas et al., 2013). The petro-structural features of these high-grade rocks have been studied in detail over a decade (Leelanandam 1997; Sengupta et al., 1999; Dharma Rao et al., 2012). These previous studies extensively encompassed the petrological, geochemical, structural and dating aspects, little is known about the rock magnetic signatures. Thus, the present study is aimed to describe the rock magnetic properties in terms of magnetic susceptibility (χ), saturating isothermal remanentmagnetisation (SIRM), magnetic hysteresis and thermos-magnetic studies of the high-grade rocks from Kondapalle to determine the carriers of magnetic remanence.

II. BACKGROUND GEOLOGY

The Eastern Ghat Mobile Belt (EGMB) trends NE-SW broadly and extends from Brahmani River in Orissa to Ongole in Andhra Pradesh for a distance of about 900km with a maximum width of 300km in Orissa in the North. The EGMB is referred to as a polycyclic orogenic belt (Dobmeier and Raith, 2003; Mukhopadhyay and Krishnapriya, 2009) consisting of multiply-deformed and metamorphosed terrain. The Kondapalle area is dominated by several magmatic rocks including the gabbro-norite-pyroxenite-anorthosite layered complex (Nanda and Natarajan, 1980; Dharma Rao et al., 2004) and later enderbite to charno-enderbiteintrusives with a whole rock Sm-Nd age of 1739 ± 220 Ma reported from anorthosite near Pangidi. (Dharma Rao et al., 2004). The rocks of Kondapalle consists of discrete units of deformed anorthosites, gabbros, pyroxenites, granulites and enderbites. The rocks of Kondapalle and the associated rocks of the EGB are structurally represented by a NE –SW trending foliation dipping towards SW (Fig. 1). Three subsequent episodes of deformation are being reported in the area (Dharma Rao et al., 2012). According to these workers, the initial folding event (F_1) is characterised by tight to overturned folds most of which are reclined. Thus, it is evident that the local NE – SW trending foliation are replications of the axial traced of the F_1 folds. This phase of deformation is succeeded by F_2, which is the most dominant deformation phase reported, leading

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to the development of an N–S trending fabric. The gabbros and anorthosites are emplaced along antiforms of F_2. Small scale faults and shear zones are common over here along the hinges of the F_2. Post F_2, the F_3 event is marked by folding of the limbs of F2 forming open wraps with a WNW–ESE to E–W trending axial plane. The gabbro and anorthosite bodies trend variably from NE–SW to NNW–SSE. Colour banding is quite common in the Gabbro-Anorthosite suite of rocks in the Kondapalle. However, the colour banding varies in scale from location to location. Although the anorthosites are highly deformed, they crosscut the lesser deformed pyroxenites (Dharma Rao et al., 2012). Granulite facies rocks were sampled from the areas in and around Kondapalle (Lat. 16°37ʹN,Long.80°13ʹ30ʺ E), 18km north of Vijayawada in Krishna District of Andhra Pradesh, India (Fig. 1). Kondapalle is situated in the Southern segment ofEGMB.

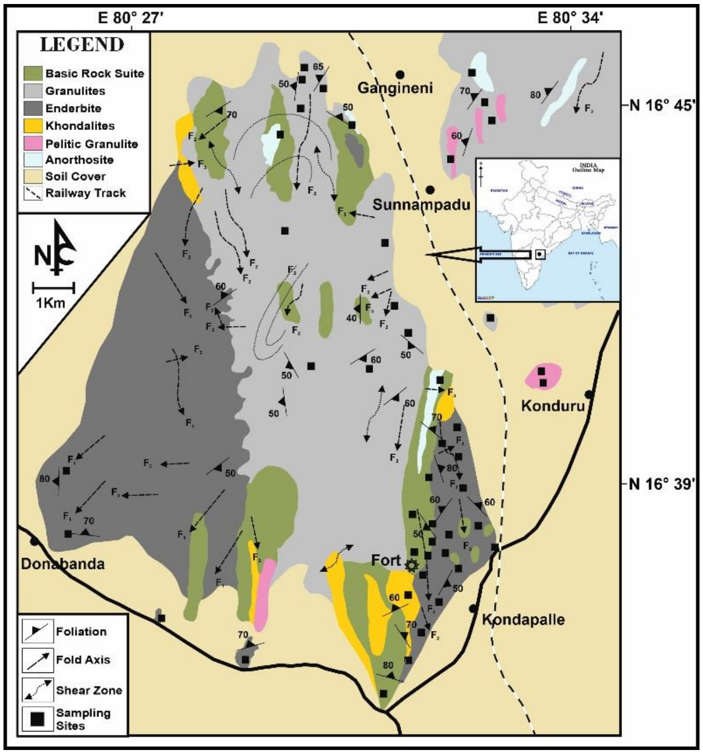

Fig. 1.Geological map of the study area, with trends of regional structures and sampling sites.

III. Petrography And Magnetic Mineralogy

Petrographic study revealed that the chief rock types are orthopyroxene granulite, mafic granulite, anorthosite, leptynite, enderbite and khondalite are the major rock types in Kondapalle area. The orthopyroxene-granulites are coarse grained rocks, show gneissic foliation defined by alternate bands of light (quartzo-feldspathic) and dark (ferromagnesian) coloured minerals. It contains orthopyroxene and plagioclase porphyroblasts with inclusions of biotite, plagioclase and quartz. Myrmekites and perthites are common over here (Fig. 2a). The mafic granulites are mesocratic, medium to fine grained rock. Garnet occurs sporadically in the rocks. It also contains gneissic foliation defined by alternate band of quartzo-feldspathic part and ferromagnesian phases. Orthopyroxene and plagioclase also occur as symplectite with the garnet (Fig. 2b). Antiperthites are also common in the mafic granulite (Fig. 2c). Anorthosite contains coarse grained plagioclase along with clinopyroxene with minor quartz and opaque minerals show granoblastic texture. Plagioclase grains here are devoid of any deformational feature and are euhedral in nature. Khondalites are leucocratic, medium to coarse grained. Garnet and k-feldspar occur as porphyroblasts. Garnet and sillimanite rich bands alternate with quartz-feldspar rich bands produce a strong gneissosity in khondalite (Fig. 2d). Leptynites are leucrocratic, medium to coarse grained, chiefly composed ofquartz and feldspar with accessory garnet and biotite. Gneissic band of alternating Garnet+Biotite rich bands and quartz+feldspar rich bands are found (Fig. 2e). Enderbite contains plagioclase, clinopyroxene and orthopyroxene as the major minerals along with some accessory sphene, biotite and opaque minerals. Grain sizes of plagioclase and pyroxene are bimodal. Deformed/wedge shaped twins within the plagioclase grains are present (Fig. 2f).

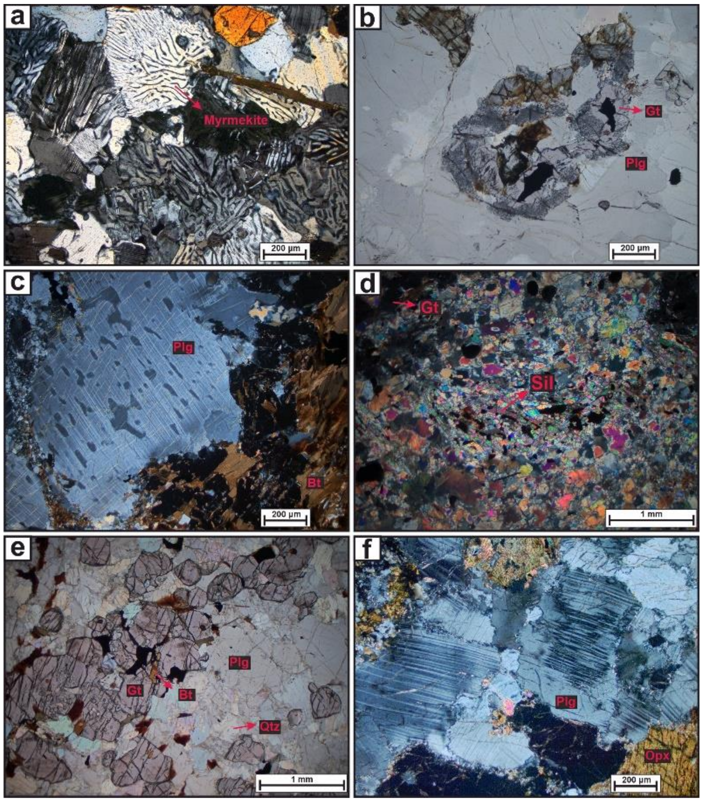

Fig. 2. Textural and micro-structural features observed in the high grade rocks. (a) Presence of myrmekite and perthitic texture, (b) Orthopyroxene and plagioclase displaying symplectite relationship with Garnet in Granulites, (c) Anti-perthitic texture observed in the Granulite, (d) Alternating Garnet rich and sillimanite rich bands in the Khondalites, (e) Gneissic banding of alternating Garnet and Biotite rich units are observed in Lyptinites, (f) Deformed twins of plagioclase are common in the Anorthosites.

The study under reflected light microscope revealed two modes of occurrences of Fe-Ti oxides like magnetite, ti-magnetite and ilmenite within the studied rocks. One is coarse grained and is primary in origin and another one is ultrafine grained secondary origin. During prolonged period of metamorphism, magnetite and ilmenite have a tendency to undergo oxidation and make stable phases. Depending on the temperature conditions, low temperature (<350°C) and high temperature (>600°C) oxidations of primary Fe- Ti oxides are found. Haggerty (1976) proposed a classification of the high temperature oxidation states of the Fe-Ti oxides, following which the high temperature oxidised grains can be classified into "C1" to "C7" stages, depending on the degree of exolution of Ilmenite from $Fe_2O_3 - TiO_2$ solid solution. In the studied rocks C1, C2, C3, and C4 stages are encountered. C1 is characterised by fresh euhedral grains of Ti-magnetite (Fig. 3a). "C2" and C3 stage is characterised by alternate band of ilmenite lamellae within the host titano-magnetite grain (Fig. 3b). In C4 stageilmenite laths merges to form thicker bands with an appearance of a layer of ilmenite sandwiched within Ti-magnetite layers (Fig. 3c). Low temperature oxidation states of the Fe-Ti oxides were classified into five stages (Stage 1 to Stage 5) based on classification proposed byJohnson and Hall (1978) depending on the degree of oxidation which is texturally characterised by the nature of cracks (shrinkage cracks), developed due to cation deficiency resulting from the migration of the Fe-ions out of the titano-magnetite-spinel lattice (Prevot et al., 1968; Akimoto et al., 1984). All these stage-1 to Stage-5 are found within the studied rocks with occurrences of Stage-1 is basically un-oxidised grains devoid of cracks. In stage-2 (Fig. 3d), further, with increasing oxidation the cracks migrate from the periphery towards the centre in a curvilinear pattern 206 with continuous replacement of Ti-magnetites by silicates along the cracks and tend to form a network of veins of silicate minerals with almost replacement (droplet like remains) of Ti-magnetites by silicates at last in stage-5 (Fig. 3e). Besides primary, secondary Ti-magnetites phases are present along the grain boundaries (Fig. 3f), along the cleavage planes of the silicate minerals.

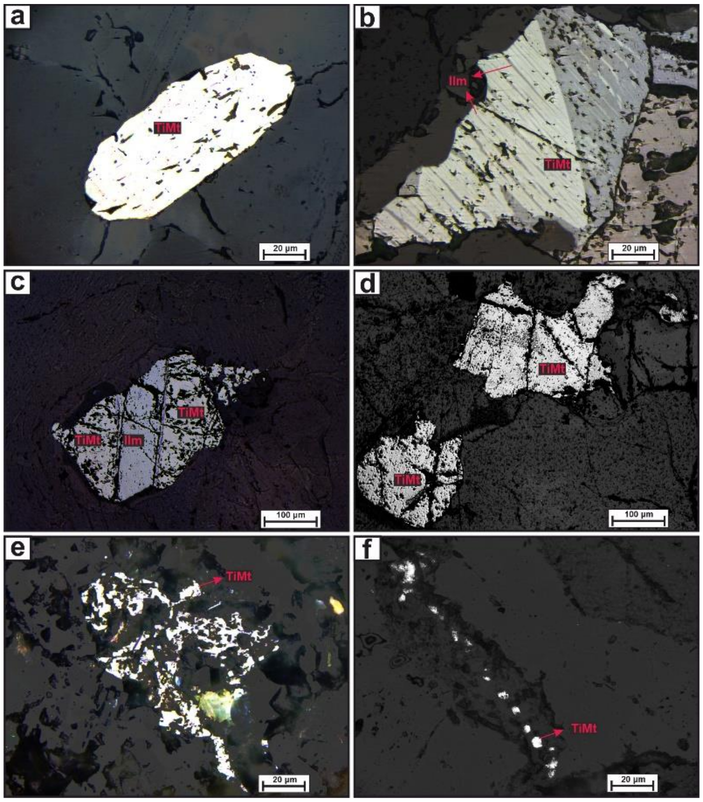

Fig. 3.Generations of Fe-Ti oxides in the rocks of the studies area (a) High temperature C1 phase of fresh homogeneous grain of Ti-magnetite, (b) Ilmenite lamellae exsolved in host Ti-magnetite belonging to high temperature C2, (c) High temperature C3 phase defined by alternating band of ilmenite and Ti-magnetite, (d) Stage-2 of low temperature oxidation stage of Ti-magnetite depicted by cracks developed from periphery towards centre, (e) Higher stage of low temperature oxidation with high degrees of silicate replacement (Stage – 5) with droplet like remains of oxide phase, (f) Presence of secondary Ti-magnetite along grain boundaries of biotite.

IV. MAGNETIC SUSCEPTIBILITY (χ) STUDY

Magnetic susceptibility (χ) indicates the degree of magnetization of magnetic material when gets magnetised by externally applied magnetic field. Mathematically, χ can be represented as the ratio of bulk magnetization (M) within the material and the applied magnetic field (H), i.e. $\chi = M/H$. Here, in the present study, the magnetic material is the natural rocks and the applied magnetic field is the geomagnetic field prevailing during the magnetization of the rock. It should be noted that a rock body may not get magnetised during its formation, but that point when its temperature is below its Curie temperature of magnetic minerals present in Kondapalle rocks. So, it is precise to deal with the magnetic field during the magnetization of that rock rather the same during its formation.

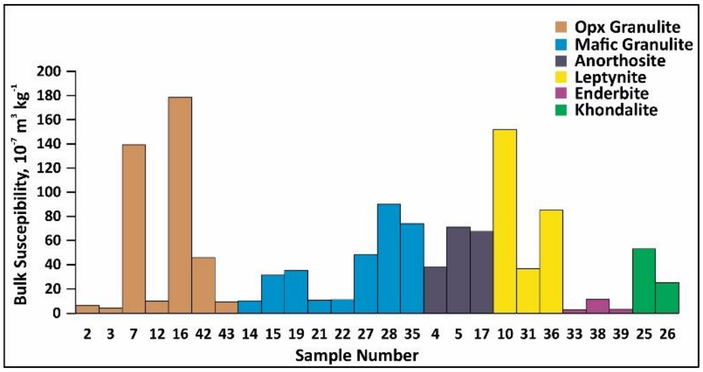

Fig. 4.Distribution of Magnetic Susceptibility in different rock types.

The χ value of the natural rock samples depends on the amount of ferrimagnetic minerals present within the rocks or more precisely the amount of magnetite and Ti-magnetite. Table-I represents the variation of magnetic susceptibility (χ) values in different rock types of the areas. The distribution of the χ values in the studied area is represented by the frequency diagram (histogram) in Fig. 4. From the analysis of data in the studied area it is observed that the highest χ value of 178.49 x 10^{-7} m^3 kg^{-1} are observed in orthopyroxene granulite and the lowest χ value of 2.88 x 10^{-7} m^3 kg^{-1}inenderbitewith an average χ value of 48.06 x 10^{-7} m^3 kg^{-1} (Table I). Comparing the values in Table – I with standard values (see Basavaiah, 2011 for standard values),it suggests that the magnetic minerals residing in the studied rocks are Ti-magnetites. It is observed from the petrographic studies that the ferromagnetic Ti-magnetites are mainly concentrated as primary occurrences. Thus, the higher observed χ values (average 48.06 x $10^{-7}m^3$ kg^{-1}) are due to primary occurrences. Notably enderbite have extremely low χ values compared to the other rock types. χ is weakened by the presence of ilmeno-haematite reflected by the presence of pigments in reflected light study. The χ values also point towards the presence of ilmeno-haematite as comparable with the value in Table I.

V. SATURATION ISOTHERMAL REMANENT MAGNETIZATION (SIRM) STUDY

Isothermal Remanent Magnetization (IRM) is the remanent magnetization acquired without the aid of temperature change. SIRM is the maximum IRM that a sample can obtain and is determined by recording IRM in progressively higher magnetic field. The distribution (based on rock types) and the graphical representation of the SIRM values for the Kondapalle rocks are provided in Table I and Fig. 5 respectively. The ferrimagnetic minerals (e.g. magnetite) have the property of getting saturated with magnetization after the applied field is increased to a certain value (here it is 1T). However, the paramagnetic and diamagnetic minerals are not associated with saturation of magnetization and thus the values of SIRM are proportional to the amount of ferrimagnetic minerals and thus can directly define the potentiality of a sample in recording ancient magnetic field. From the values of SIRM in the studied area, it is revealed that the orthopyroxene granulite (average ~ 1876.2 x 10^{-5} Am^2kg^{-1}), mafic granulite (average ~ 2314.7 x 10^{-5} Am^2 kg^{-1}), anorthosite (average ~ 1790.9 x 10^{-5} Am^2 kg^{-1}), leptynite (average ~ 1876.2 x 10^{-5} Am^2 kg^{-1}) and khondalite (average ~ 1876.2 x 10^{-5} Am^2 kg^{-1}) have high saturating remanences and these rocks are suitable for recording magnetic remanences. The samples which have higher values of SIRM, also have higher values of χ. Again, the high values of χ are higher where the magnetic grains are present as Primary in nature. Thus, combination of the results assures that the dominant ferrimagnetic components which can record ancient magnetic field are mainly primary magnetic minerals in the studied area. The lower trends of SIRM in enderbite (average ~ 418.8 x 10^{-5} Am^2 kg^{-1}) reveal that the concentration of magnetic minerals ismuch lower in them. This may be due to the interferences of thehigh concentration of paramagnetic minerals like the silicates.

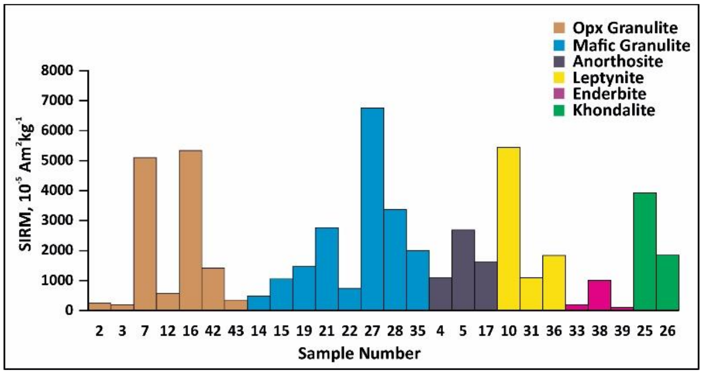

Fig. 5.Distribution of SIRM in different rock types.

Table I.Distribution of magnetic susceptibility, SIRM and SIRM/χ in different rock types.

Rock Type	**Sample Nos.**	**χ (10^{-7} m^3 kg^{-1})**	**SIRM (10^{-5} Am^2kg^{-1})**	**SIRM/χ**
Orthopyroxene Granulite	KP- 02	6.24	230.21	36.88
	KP- 03	4.28	187.05	43.62
	KP- 07	139.28	5090.92	36.57
	KP- 12	10.07	566.32	56.22
	KP- 16	178.49	5328.16	29.84
	KP- 42	45.88	1395.68	30.41
	KP- 43	9.25	334.90	36.17
Mafic Granulite	KP- 14	10.23	165.19	45.43
	KP- 15	31.41	1042.44	33.18
	KP- 19	35.31	1454.60	41.18
	KP- 21	10.74	2749.92	255.98
	KP- 22	11.00	719.12	65.35
	KP- 27	48.18	6746.82	140.00
	KP- 28	90.03	3349.10	37.19
	KP- 35	73.97	1990.58	26.90
Anorthosite	KP- 04	37.99	1080.12	28.42
	KP- 05	71.12	2676.68	37.63
	KP- 17	67.62	1615.97	23.89
Leptynite	KP- 10	151.62	5428.00	35.79
	KP- 31	36.77	1085.52	29.52
	KP- 36	84.96	1872.14	21.50
Enderbite	KP- 33	2.88	172.38	59.84
	KP- 38	11.23	997.29	88.80
	KP- 39	2.96	86.79	29.28
Khondalite	KP- 25	53.13	3918.31	73.75
	KP- 26	25.06	1830.89	73.75

VI. SIRM/χ

SIRM/χ is useful in terms of differentiating between different types of magnetic behaviours. For instance, if both SIRM and χ are low and the ratio is high that indicates a large amount of haematite. Again, if χ is positive with low remanence the magnetic minerals are mostly paramagnetic (Basavaiah, 2011; Basavaiah and Khadkikar, 2004). Thus, a comparative analysis of the values of SIRM, χ and SIRM/ χ helps to identify the magnetic behaviour of the samples as well as the minerals contributing towards such behaviour. The distribution of SIRM/χ is represented in Table I and the variation is also represented in Fig. 6 The highest SIRM/χ value of ~255.98 x 10^2 Am^{-1} with an average ~ 80.65 x 10^2Am^{-1} are observed in mafic granulite and the lowest SIRM/χ value of ~ 21.50 x 10^2Am^{-1} in leptynite with an average ~ 28.94 x 10^2 Am^{-1}. In case of orthopyroxene granulite, mafic granulite and anorthosite both the SIRM and χ are high resulting in high values of the ratio (Table I). Thus, the SIRM/χ ratio is implicative towards the presence of high susceptibility and high remanence bearing minerals like magnetite and Ti-magnetite. In case of the anorthosite, both the SIRM and χ are high resulting in low values of the ratio which also indicate the presence of high susceptibility and high remanence bearing minerals like magnetite or Ti-magnetite. Values of χ are relatively low in enderbite and khondalite which is causing a rise in the SIRM/χ which indicate coarser grain size of the magnetic minerals. The low values for clearly indicate lower concentration of magnetite but the high SIRM indicates the presence of some minerals which have high capability of recording remanences which further indicates the presence of iron sulphides like pyrrhotite or greigite.

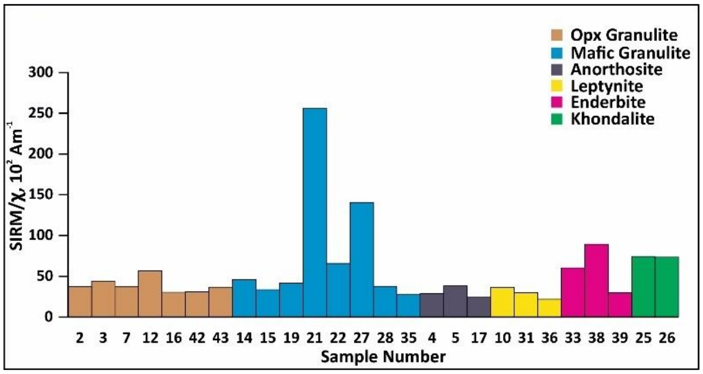

Fig. 6.Variation of the inter-parametric ratio (SIRM/χ) in the rock types of the area.

VII. SIRM VERSUS χ

In the bi-logarithmic Plot of SIRM versus χ (Fig. 7) the distribution defined by high χ and high SIRM is defined by the presence of large amount of Stable Single Domain (SSD) magnetite and Ti-magnetite and both low χ and SIRM characterised by high haematite to magnetite ratio. In bi-logarithmic Plot of SIRM versus χ (Fig. 7) of the rocks fromKondapalle shows positive correlation irrespective of rock types, hence it is evident that the mineral contributing towards high susceptibility also contributing towards high saturating remanence. Such a relation can only obtained by the presence of titanomagnetite or magnetite. This scenario thus explained is also evident from the near constant values of SIRM/ χ.

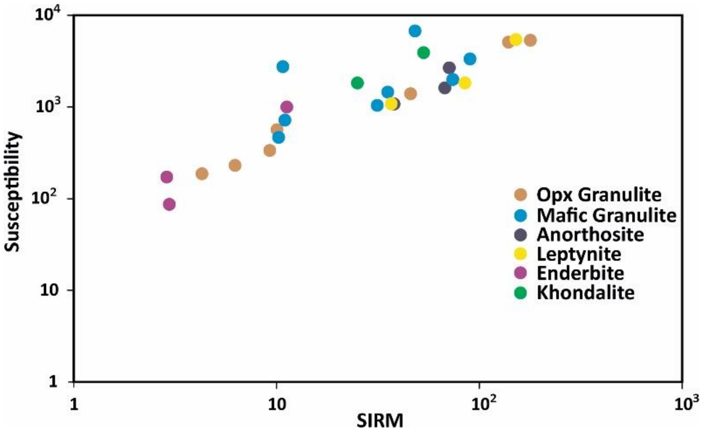

Fig. 7.Bi-Logarithmic plot of susceptibility versus SIRM.

VIII.TEMPERATURE DEPENDENT MAGNETIZATION AND MAGNETIC HYSTERESIS

Thermomagnetic curves for selected samples were obtained as saturation magnetization, Ms, versus temperature (both increasing and decreasing). The Curie temperature (Tc) which is

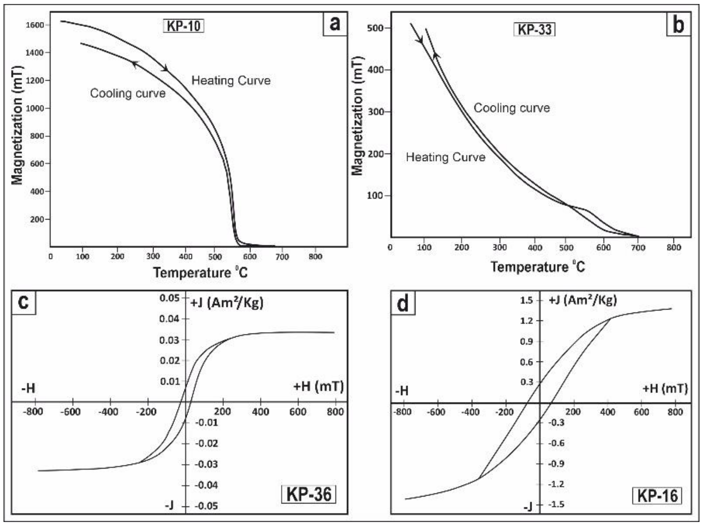

Fig.8.(a) Thermo-magnetic curves representing ferromagnetic nature and presence of magnetite by Curie temperature ~ 580^0C, (b) Thermo-magnetic curves representing paramagnetic nature and presence of haematite by Curie temperature ~ 680^0C, (c) Magnetic hysteresis loop of ferromagnetic rocks, having complete saturation at 300 mT and recording remanence, (d) Magnetic hysteresis loop of paramagnetic rocks, having partial saturation only and recording lower remanence relative to coercivity.

characteristic for a particular mineral and is thus recorded for magneto-mineralogical characterization. Later, the samples were cooled to 100°C to obtain a cooling curve. From the thermos-magnetic curves (Figs. 8a and 8b) it is evident that magnetite and haematite are the chief remanence carriers in the studied rocks (depicted by Curie temperatures at ~580^{0}C for magnetite and ~680^{0}C for haematite). Moreover, signatures of both paramagnetic and ferromagnetic curves are identified depicted by both concave and convex nature of the thermo-magnetic curves. Two types of signatures are observed in the hysteresis loops. First, samples with string ferromagnetism, which saturate completely with considerable remanence (Fig. 8c). Second, the samples with hysteresis loops as in Fig. 8d which represents moderate coercivity and low remanence. This type of hysteresis features are represented by the granulites and the anorthosites.

CONCLUSION

The main objective of this study is to characterize the magnetic properties of the rocks from Kondapalle area, in terms of reflected light microscopic study, magnetic susceptibility and SIRM study. The petrographic study revealed that orthopyroxene granulite, mafic granulite, anorthosite, leptynite, enderbite and khondalite are major rock types in Kondapalle area. These contain chiefly ferromagnetic minerals (magnetite and Ti-magnetite) with a broad range of grain size distribution indicating multiple origins of these Fe-Ti oxide minerals. Evidently, the generations of Fe-Ti oxides and their textural relationship with the silicates were different in all rock types. Rock magnetic measurements of χ and SIRM and their ratio SIRM/χ allowed quantifying magnetic minerals and their properties as parameters and to explain the textural features with the help of rock magnetic properties. The magnetic hysteresis properties depicts that the ferromagnetic in character dominates over the paramagnetic ones and thus are highly suitable as remanence recorders. The magnetic remanence carriers in the studied rock samples are Ti-magnetite with coarse to medium grain size. Magnetite dominates as the ferromagnetic phase, evident from the thermos-magnetic curves. Although paramagnetic haematite is also present, magnetite is the chief remanence carrier. From the relationship of the SIRM and susceptibility, it is also evident that the Mafic granulites are more prone to record the potential magnetic remanence over the other rocks and these high-grade rocks are more feasible / suitable for palaeomagnetic studies.

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