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Densities and Magnetic Susceptibilities of Precambrian Rocks of Different Metamorphic Grade (Southern Indian Shield)

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Abstract. Densities of 1294 Precambrian rocks from the Southern Indian Shield, confined to low-grade granite-greenstone (Karnataka) and high-grade granulite (Eastern Ghats Belt) terrains are presented and categorized into 16 metamorphic and igneous varieties. In Karnataka, densities of granites (2.65 g/cm^3), gneisses (2.68 g/cm^3) and granodiorites (2.73 g/cm^3) are considerably less than those of greenstone belts (2.84 g/cm^3) and dolerites (3.03 g/cm^3). An average density of 2.75 g/cm^3 is obtained for surface rocks from this terrain. Over the Eastern Ghats belt, densities of charnockites range from 2.71 g/cm^3 to 3.12 g/cm^3 as they vary from acidic to ultrabasic composition. An average density of 2.85 g/cm^3 is obtained for surface rocks from this belt. The contrast in the average densities of surface rocks from the low- and high-grade terrains may play a significant role in a proper assessment of the regional gravity fields over these terrains. The results compare well with the data from similar terrains in other shield regions. Magnetic susceptibilities for 482 of these samples are also presented. All the rock types include a wide range of susceptibilities, as is to be anticipated in metamorphic terrains. A plot of density versus magnetic susceptibility for thirteen of these rock types suggests a linear relationship.

Key words: Densities – Magnetic susceptibilities – Precambrian metamorphic terrains

Introduction

The two-fold classification of shield areas into low-grade greenstone-granite terrains and high-grade granulite terrains is by now widely known (Windley and Bridgwater 1971). Regional gravity investigations indicate that these diverse metamorphic terrains are usually characterized by gravity fields which are mutually distinguishable (Gibb and Thomas 1976; Subrahmanyam 1978). While the long-wavelength components of these gravity fields are often attributed to deep-seated crustal and upper mantle inhomogeneities, the local anomalies are generally accounted for by near surface lithologies and their surface distribution. Thus, the interpretation of local gravity anomalies in crystalline areas requires adequate knowledge of the densities of the various exposed metamorphic and igneous rocks over the terrains. This point has been stressed by Marshall and Narain (1954), Woollard (1962), Gibb (1968), and Smithson (1971), among others. Density data for various rock types from the crystalline terrain are important, not only for interpreting the gravity anomalies, but also for estimating the mean density and composition of the crust in different parts of the continents.

Precambrian rocks in the Southern Indian Shield occur in both the low- and high-grade metamorphic environments, confined to the provinces of Karnataka, Bastar and the surrounding Eastern Ghats Belt (Fig. 1). While Karnataka and Bastar constitute the low-grade terrains of the shield, the Eastern Ghats Belt belongs to granulite facies metamorphism. The present study is a compilation and presentation of the density and susceptibility data for various rocks from these terrains. The significance and implication of the density data for a proper assessment of gravity fields associated with the metamorphic terrains in shield areas will also be discussed.

The metamorphic rocks involved in the present study range from greenschist to granulite facies. Similarly, the igneous intrusive rocks range from acidic to ultrabasic. Major rock types include metasedimentary-metavolcanic sequences (Archaean schists), biotite and hornblende gneisses, granites, granodiorites, amphibolites, dolerites, migmatites of uncertain origin, anorthosites, granulite facies gneisses, acid to ultrabasic charnockites, khondalites and other minor varieties. While a reasonable amount of data is available for schists, gneisses, and granites from Karnataka (Qureshy et al. 1967), data for rocks from the high-grade Eastern Ghats Belt are very meagre.

During the course of gravity and magnetic surveys by one of the authors over these metamorphic terrains (Subrahmanyam 1978), about 655 fresh rock samples were collected. Their densities (and susceptibilities for 482 samples) were measured in the laboratory. These data are supplemented with density data already published for another 639 samples (Balakrishna and Ramana 1968; Balakrishna et al. 1968, 1971, Qureshy et al. 1967) and the results are presented here.

Sampling and Distribution

In general, rock samples were collected from outcrops situated near gravity and magnetic stations. Samples for which data were published earlier (639 samples) also cover all the important lithologic formations in the Southern Indian Shield. Special attention has been paid to charnockites and other granulite facies rocks from the high-grade Eastern Ghats Belt as little data have been available from this province uptill now.

Density Measurements

Laboratory density measurements were based on the formula

$$\rho=\frac{W_1}{W_1-W_2},$$

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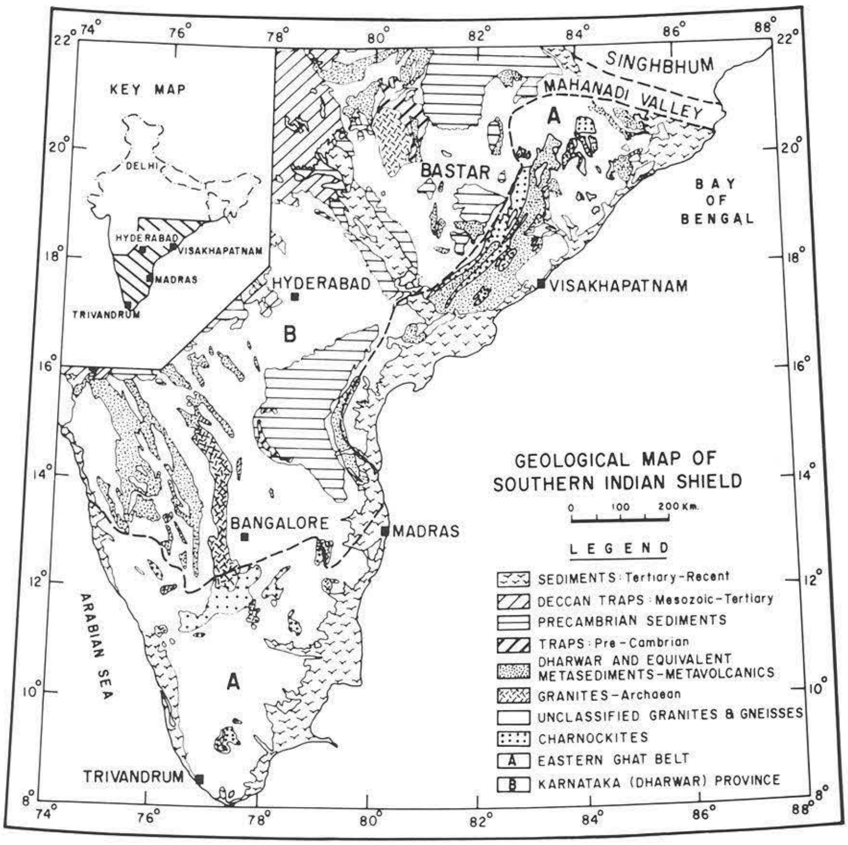

Fig. 1. Geological map of the Southern Indian Shield

where ρ is the density, W_1 is the weight of the sample in air, W_2 is weight of the sample in water. All the samples measured were either igneous or metamorphic rocks having little or no pore space so the density values obtained are very close to the actual grain density of the rock. The accuracy of the results is expected to be within ± 0.02 g/cm^3 or about 1%.

Results

The 1294 rock samples have been categorized into sixteen major metamorphic and igneous varieties; these varieties and the density values are summarised in Table 1. For rock types with sample numbers exceeding twenty, histograms were also prepared and are shown in Figs. 2–4. Descriptions of the rock types and the densities obtained are discussed below, for the low- and high-grade metamorphic terrains separately.

Rocks from Low-Grade Terrains

Granites. The data for granites are mostly from the published work of Qureshy et al. (1967) and Balakrishna et al. (1971). In Karnataka, these granites intrude both the gneisses and schists. A concentration at 2.60–2.70 g/cm^3 is clearly seen in the histogram (Fig. 2) with the average value being 2.65 g/cm^3. Like the biotite gneisses, these granites do not show a wide distribution on the histogram which probably indicates a uniform composition.

Table 1. Densities of igneous and metamorphic rocks from South India

Sl. No. Rock Type	No. Samples	Mean (g/cm^3)	S.D. (g/cm^3)	Range (g/cm^3)
1. Gneisses and granites (undivided)	544	2.67		2.54–3.24
Low-grade terrain				
1. Granites	371	2.65	0.02	2.54–2.83
2. Biotite gneisses	135	2.68	0.05	2.55–2.80
3. Granodiorites	11	2.73	0.03	2.70–2.78
4. Archean schists	82	2.84	0.20	2.48–3.35
5. Amphibolites	54	3.01	0.10	2.81–3.35
6. Dolerites	82	3.03	0.07	2.74–3.19
High-grade terrain				
7. Syenites	4	2.66	0.04	2.59–2.70
8. Anorthosites	64	2.85	0.13	2.58–3.28
9. Gneisses	38	2.89	0.11	2.70–3.24
10. Migmatites	21	2.89	0.10	2.70–3.14
11. Khondalites	25	2.89	0.18	2.59–3.33
12. Hornblendites	5	3.21	0.15	3.05–3.47
13. Acid charnockites	140	2.71	0.07	2.57–2.89
14. Intermediate charnockites	114	2.78	0.08	2.66–3.15
15. Basic charnockites	124	2.99	0.15	2.67–3.41
16. Ultrabasic charnockites	24	3.12	0.13	2.84–3.36
Total	1294			

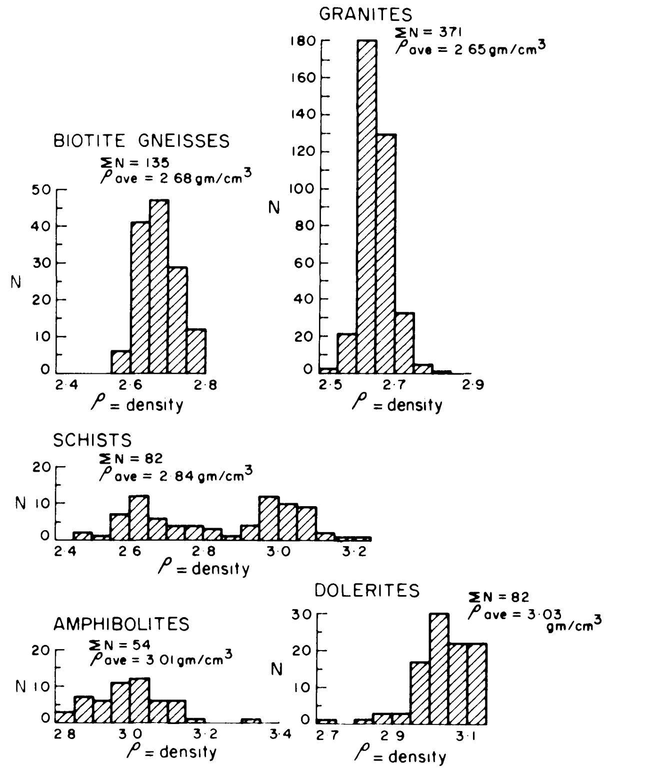

Fig. 2. Density histogram for rocks from Karnataka low-grade terrain

Biotite Gneisses. These are associated with schists, migmatites, granitic gneisses and amphibolites and are characterised by their monotonous occurrence and uniform appearance. This is reflected in the narrow density range of 2.55–2.80 g/cm^3. An average value of 2.68 g/cm^3 has been obtained for these rocks. The histogram (Fig. 2) shows a peak in the range 2.65–2.70 g/cm^3.

Granodiorites. Data for only 11 samples could be obtained for this variety despite their widespread occurrence. The density range is 2.70–2.78 g/cm^3, the mean value 2.73 g/cm^3.

Archaean Schists. These rocks are abundantly distributed over the low-grade greenstone-granite terrains and are intruded by younger K-rich granites. Both were engulfed by a vast gneissic complex known as the Peninsular Gneiss. The present data are for rocks from Karnataka province. A mean density of 2.84 g/cm^3 is obtained but with a wide range. In Fig. 2, the histogram shows two modes, one between 2.45 g/cm^3 and 2.70 g/cm^3 and the other between 2.90 and 3.10 g/cm^3. The two modes correspond approximately to the chlorite and hornblende varieties of schist. Some biotite schists may have been included in the latter variety. Usually crystalline rocks do not show densities less than 2.6 g/cm^3 and the lower densities of 2.48–2.60 g/cm^3 in the present data may be due to weathering of some of the measured samples.

Amphibolites. These occur as enclaves within the gneisses with width varying from a few centimetres to more than a metre. An average density of 3.10 g/cm^3 is obtained but with a range 2.81–3.35 g/cm^3, which is well illustrated by the histogram (Fig. 2). This may be due to contamination of the original basic rocks by later granitization processes.

Dolerites. Karnataka province is noted for widespread occurrence of dolerite dyke swarms of Precambrian age. An average value of 3.03 g/cm^3 is obtained with a range 2.74–3.19 g/cm^3 for these rocks. But the histogram (Fig. 2) shows a concentration towards the basic end (2.95–3.15 g/cm^3) with a tail towards the acidic end.

Rocks from High-Grade Terrains

These are mostly confined to the Eastern Ghats Belt with its regional granulite-facies metamorphic grade. It is believed that this belt may represent a deeper crustal domain (Subramaniam 1967) as it is characterized by the widespread distribution of the charnockite-khondalite suite of rocks, anorthosites, garnetiferous gneisses, migmatites and other minor varieties. In the present sampling, special attention has been paid to the charnockitic rocks. The categorisation of charnockites into four varieties, acidic to ultrabasic (Holland 1900) is retained here. In almost all the rocks, garnet occurs in variable amounts which to some extent makes the densities obtained dependent on this factor (Tanner 1969; Smithson and Brown 1977).

Anorthosites. The anorthosite occurrences are a common characteristic of all the high-grade shield terrains in the world. In the Eastern Ghats Belt these are reported to occur in nineteen localities (De 1969; Kanungo and Chetty 1978) but the present data are from only three of these outcrops. Densities ranging from 2.58–3.28 g/cm^3 with an average of 2.85 g/cm^3 have been obtained. The densities generally increase as the anorthosites tend to gabbroic composition. The histogram (Fig. 3) shows a tail towards the high density end but a peak near 2.80–2.85 g/cm^3 is also seen. In comparison with data for anorthosites from other continents, in particular Canada where they generally range from 2.70–2.78 g/cm^3 (Gibb 1968; Tanner 1969; Smithson 1971) the average of 2.85 g/cm^3 obtained in the present case appears to be slightly on the high side. Whether this is due to the inclusion of anorthosites which tend to be more gabbroic in composition and are thus necessarily of higher density, is at present not clear. Based on density data alone, these rocks could be classified as gabbroic anorthosites.

Granulite Facies Gneisses. These are associated in the field with the charnockite-khondalite suite of rocks, migmatites and other rock types. An average density of 2.89 g/cm^3 has been obtained with a range of 2.70–3.24 g/cm^3. However, the histogram in Fig. 3 shows a concentration between 2.80–3.00 g/cm^3.

Migmatites. As described by Smithson (1971), these are 'mixed rocks containing a granitic portion and a darker, more dense portion'. Variations in density are probably a result of the increase or decrease of either of these portions. About 21 samples (density range 2.70–3.14 g/cm^3), yield a mean value of 2.89 g/cm^3, which is well illustrated by the histogram (Fig. 3) with a tail towards the acidic end.

Khondalites. These are garnet-sillimanite gneisses and schists which, together with the pyroxene granulites, constitute the basement into which the magma responsible for generation of acid charnockites has intruded. Compositionally these are similar to the stronalites of Strona valley in Italy. Khondalites are highly susceptible to weathering and it is often difficult to obtain a fresh sample in the field. This factor and the garnet content in these rocks tend to alter their density values considerably which is reflected in their wide density range (2.59–3.33 g/cm^3) shown in

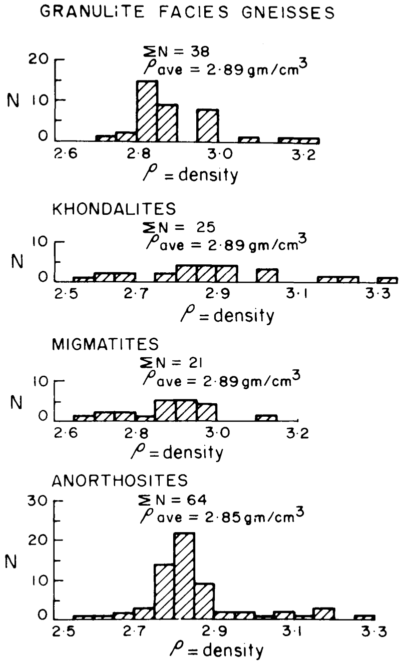

Fig. 3. Density histogram for rocks from Eastern Ghats high-grade belt

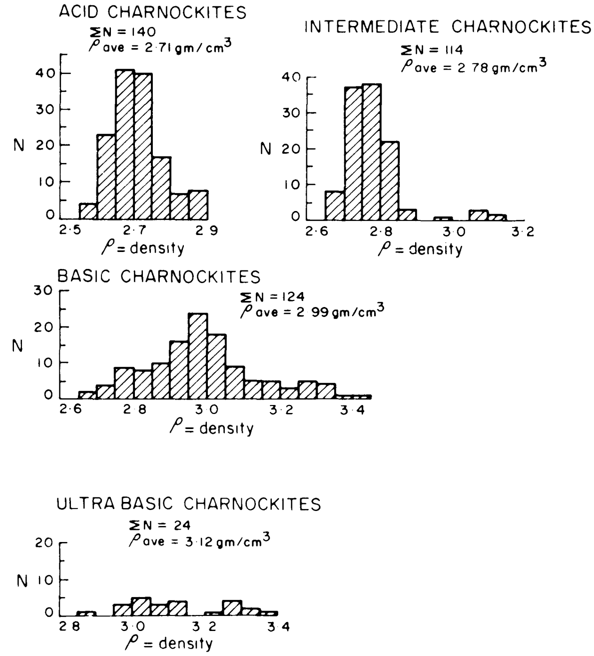

Fig. 4. Density histogram for charnockites from Eastern Ghats high-grade belt

the histogram (Fig. 3). For 25 samples, the average density is 2.89 g/cm ^{3}.

Acid Charnockites. According to Holland (1900) these are hypersthene granites having a specific gravity of 2.67 g/cm ^{3}, and 75% silica. Subramaniam (1959) redefined charnockite as a hypersthene quartz feldspar rock and included in this variety, enderbites, hypersthene syenites, alaskites and leptynites and suggested their magmatic origin. In the present analysis, an average density value of 2.71 g/cm ^{3} has been obtained, which is very near to that reported by Holland (1900) and well reflected in the histogram (Fig. 4) by the peaks in the range 2.65–2.75 g/cm ^{3}.

From the histogram, it can be seen that for about 20 samples the densities are on the high side, between 2.80–2.99 g/cm ^{3}. This may be due either to the presence of large amounts of garnet, known to occur in these rocks, or their intercalations with the higher density basement rocks (basic charnockites).

Intermediate Charnockites. These are hybrid rock types formed by interaction of the magma, which gave rise to the acid charnockites described above, with the basement rocks (Subramaniam 1959). Several hill ranges in South India are composed of these rocks. An average density of 2.78 g/cm ^{3} with a range of 2.65–3.15 g/cm ^{3} has been obtained. The histogram (Fig. 4) indicates a tail towards the basic end, while the majority of the samples lie in the range 2.70–2.85 g/cm ^{3}, probably indicating a uniform composition.

Basic Charnockites. Pyroxene granulites and their variants constituting the basement are classified as basic charnockites (Subramaniam 1959). Data for 124 samples yield an average value of 2.99 g/cm ^{3} but the histogram (Fig. 4) indicates a wide range, 2.67–3.41 g/cm ^{3}. Peaks are observed near 3.00 g/cm ^{3} and the average of 2.99 g/cm ^{3} may be a good representative value. For about 15 to 20 samples, the histogram (Fig. 4) shows lower values of 2.65–2.75 g/cm ^{3}. This may be due to contamination of these basement rocks by acid charnockite magma intrusion.

Ultrabasic Charnockites. According to Subramaniam (1960) these are syntectonic lenses of norite with pyroxenite schleiren occurring in large masses of charnockite outcrops. A mean density of 3.12 g/cm ^{3} has been obtained for this variety. Fig. 4 shows the histogram.

In addition to the above rocks, 4 samples of syenites have yielded an average density of 2.66 g/cm ^{3}, while 5 samples of hornblendites gave an average of 3.21 g/cm ^{3} (Table 1). A comparison of the present data from both the low- and high-grade metamorphic terrains in the Southern Indian Shield with those from similar terrains in other shield areas of the world is much in order as geologically and geochemically these are comparable. This comparison is presented in Table 2. It is quite obvious that the data obtained from the present study for various rock types are in fair agreement with those obtained from other shield areas of the world.

Density of the Upper Continental Crust

For a proper assessment of the gravity anomalies due to local geological variations in a given region, at least an approximate idea of the probable density of the exposed crystalline continental crust is necessary. Woollard (1962, 1969), arrived at a figure of 2.74 g/cm ^{3} for density of the upper crust instead of the 2.67 g/cm ^{3} which is normally used. On the other hand, Gibb (1968) suggested that the exposed metamorphic rocks in shield areas tend to possess an average granodioritic composition as against the tonalitic composition proposed by Woollard (1962). According to Gibb the value of 2.67 g/cm ^{3} is more representative of the average density of surface rocks in shield areas and hence more suitable for Bouguer reduction in continental areas. Smithson (1971) analysed density data from widely separated continental masses like the U.S.A., Antarctica and Europe. His data fall within the range 2.70–2.79 g/cm ^{3} and more or less confirm Woollard's (1962, 1969) average value of 2.74 g/cm ^{3}. Smithson (1971) con-

Table 2. Mean densities of some metamorphic and igneous rocks

Rock type	Present study			Woollard (1962)			Gibb (1968)			Smithson (1971)		
	N	*R*	*M*	*N*	*R*	*M*	*N*	*R*	*M*	*N*	*R*	*M*
Gneisses and granites (Undifferentiated)	544	2.54–3.24	2.69	117	2.59–3.14	2.74	944	2.50–2.78	2.64	58	2.58–2.77	2.70
Schists (Undifferentiated)	82	2.60–3.35	2.84	51	2.62–3.14	2.84	25	2.55–2.96	2.73	128	2.59–3.11	2.75
Amphibolites	54	2.81–3.35	3.01	–	–	–	132	2.66–3.47	3.01	68	2.85–3.20	3.03
Granulite facies gneisses	38	2.70–3.24	2.89	–	–	–	–	–	–	13	2.63–3.20	2.86
Granodiorites[a]	11	2.70–2.78	2.73	–	–	–	–	–	–	–	–	–
Anorthosites	64	2.58–3.28	2.85	–	–	–	27	2.63–2.97	2.78	–	–	–

N: Number of samples; *R*: Range; *M*: Mean
[a] *M* given by Daly et al. (1966) is 2.72 ($N = 11$)

tends that even the so-called granitic terrains do not have mean density as low as 2.67 g/cm^3 which disagrees with Gibb's (1968) conclusions. A high-grade granulite terrain (Jotunheim) in central Norway similar to the Eastern Ghats Belt of the present study, however, gives an average upper crustal density of 2.86 g/cm^3 which is considerably higher than that of the normal upper continental crust which is either 2.74 g/cm^3 or 2.67 g/cm^3.

The foregoing data from different continental regions of the world indicate that substantial variations in mean upper crustal densities resulting in gravity anomalies of considerable magnitude do occur. In view of this, a proper assessment of the density data for rocks from the Southern Indian Shield presented in this study, is very necessary. This may enable us to arrive at a suitable value for the mean upper crustal densities for both the low- and high-grade metamorphic terrains which would be very useful for better quantitative interpretation of gravity data.

Over the low-grade Karnataka province, the major rock types are, gneisses, granites, granodiorites, Archean schists, amphibolites and dolerites. A simple way of obtaining the average density of the upper crust in Karnataka is to average the densities of all these rocks. The average density of 735 samples, including all the varieties, is 2.75 g/cm^3. For rocks in Northern Manitoba in the Canadian Shield, Gibb (1968) however, has obtained the mean (2.67 g/cm^3) by weighing the densities of each rock type according to their surface distribution. Over Karnataka province, the more abundant rock types are the gneisses, schists and granites. The average for 588 samples of these rocks is 2.69 g/cm^3 which is close to that obtained by Gibb (1968). However, it should be noted from Table 1 that in this averaging, low-density granites predominate in number (371) over the high-density gneisses and schists (217) which suggests that the average value of 2.69 g/cm^3 is a low estimate. Until the areal distribution of surface rocks is accurately known, the only way to obtain the mean value is to average out the densities of all rock types which, as mentioned earlier, yields a value of 2.75 g/cm^3. This value is intermediate between the high-density schists (2.84 g/cm^3) and the low to medium density granites (2.65 g/cm^3) and the gneisses (2.69 g/cm^3), and could be used as the density for the crystalline basement in interpretion of gravity anomalies due to local geological variations over Karnataka province.

A similar analysis could be attempted to obtain the average upper crustal density of the Eastern Ghats Belt. Results from the other shield areas have already indicated that granulite terrains are made up of high-density rocks and so also possess higher upper crustal densities (Tanner 1969; Fairhead and Scovell 1976; Anfiloff and Shaw 1973; Smithson 1971; Subrahmanyam 1978). Tanner (1969) indicated that the increase in grade of metamorphism tends to increase the density by an amount somewhere in the range 0.05–0.20 g/cm^3. Acid to ultrabasic charnockites, khondalites, granulite facies gneisses, and anorthosites are the major rock types which constitute the upper crust in the high grade Eastern Ghats Belt and these may control its upper crustal density and composition to a large extent. About 550 samples of the rock types mentioned above give an average density of 2.85 g/cm^3. It is interesting to note that Smithson (1971) obtained nearly the same value (2.86 g/cm^3) for a granulite terrain in Central Norway. Within this high grade belt, acid charnockites, which are essentially hypersthene granites, and syenites, have the lowest values of 2.71 g/cm^3 and 2.66 g/cm^3 respectively and, as shown elsewhere (Subrahmanyam 1978), are probably the cause of some strong local negative anomalies over the southern parts of the Eastern Ghats Belt.

Thus, the densities of surface rocks from the Southern Indian Shield suggest a possible density and compositional contrast between the low- and high-grade metamorphic terrains. The available data suggest that the upper crustal density contrast may amount to 0.1 g/cm^3 to 0.16 g/cm^3, a result which will have a direct bearing on the quantitative interpretation of gravity anomalies over these metamorphic terrains.

Susceptibility Measurements

Magnetic susceptibilities (*K*-values) of various rock types were determined for 482 of the above samples, using Mooney's susceptibility bridge apparatus. The rock types included acidic to ultrabasic charnockites, schists, dolerites, amphibolites, low- and high-grade gneisses, granodiorites, granites, migmatites and khondalites. Table 3 presents these data, where the rock type, number of samples, mean and range are indicated. A notable feature is the decrease in susceptibility values of charnockites as they grade from ultrabasic to acidic varieties. The highest value obtained is 157079×10^{-6} SI for ultrabasic charnockites, but in general, all the rock types show a wide range of susceptibilities (see Table 3), as might be anticipated for metamorphic rocks. Geological processes like deformation,tectonism and metamorphism have strong effects on the magnetization of rocks (Heiland 1946) so that in metamorphic rocks, which have been subjected to the above pro-

Table 3. Magnetic susceptibilities for some metamorphic and igneous rocks from South India

Sl. No.	Rock Type	No. Samples	Mean $K \times 10^{-6}$SI	Range $K \times 10^{-6}$ SI
1.	Khondalites	12	1,898	226– 7,401
2.	Biotite gneisses	24	3,720	138– 10,317
3.	Migmatites	20	7,904	138– 35,186
4.	Granites	47	11,020	226– 38,956
5.	Acid Charnockites	76	11,385	226– 53,407
6.	Granodiorites	10	11,523	226– 28,274
7.	Granulite facies gneisses	30	15,883	440– 13,823
8.	Amphibolites	44	18,610	666–103,672
9.	Intermediate charnockites	76	19,289	226– 85,451
10.	Basic charnockites	83	21,614	226–113,097
11.	Dolerites	28	27,696	892– 99,274
12.	Archean schists	25	31,239	226– 87,964
13.	Ultrabasic charnockites	6	33,640	452–157,079
Total		482		

cesses, the magnetic character or the orientation of the magnetizing minerals will be highly disturbed and non-uniform. This normally results in a large scatter of the observed susceptibilities.

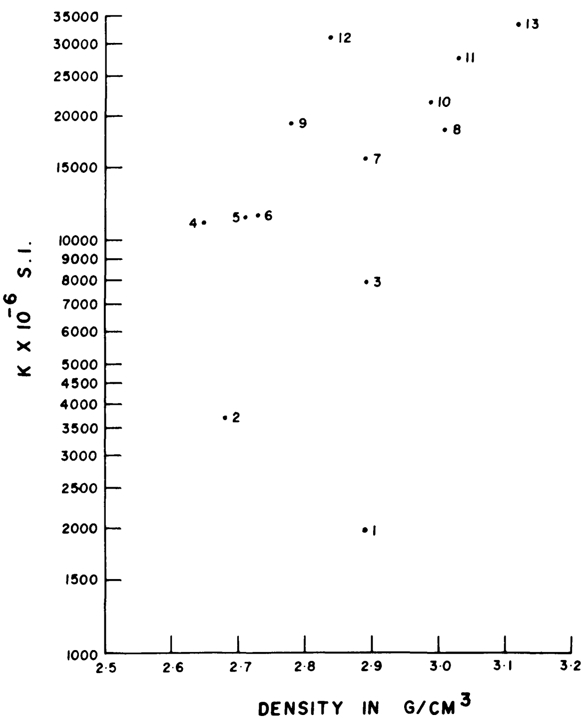

Fig. 5. Diagram showing density-magnetic susceptibility relationship for Precambrian rocks from the present study area. *Numbers* indicate the rock types listed in Table 3

Density-Susceptibility Relationship

The density of a rock is primarily dependent on its mineral and chemical compositions. Henkel (1976) suggested that in acid plutonic rocks the amount of mafic minerals present controls the density while in basic rocks it is controlled by the amount of plagioclase. Similarly, SiO_2 content also has a significant effect on the density: acidic rocks, high in SiO_2, have low densities while basic rocks are low in SiO_2 and have high densities.

The magnetic susceptibility of a rock is significantly controlled by the magnetite content of that rock (Aravamadhu 1974; Henkel 1976). Aravamadhu (1974) obtained a linear relationship for variation of susceptibility with percentage by weight of magnetite for samples of charnockites and khondalites in the present study area. Lidiak (1974) observed that the magnetic properties of a rock depend to a certain extent on their grade of metamorphism and the degree of oxidation and in general observed an increase in *K*- values as the rocks grade from greenschist to granulite facies.

Henkel (1976) studied the correlation between density and magnetic susceptibility for Precambrian rocks from northern Sweden and observed that these, together with the magnetite content in rocks provide a useful tool for classifying rocks and for investigating the geological processes behind their formation. For the present rocks from South India, the magnetite contents have not been determined but the covariation of susceptibility with density could at least be examined.

A plot of density versus susceptibility for thirteen rock types is shown in Fig. 5.

Excluding Archean schists, migmatites and khondalites, the remaining rock types exhibit a linear relationship as K-values increase with increase in densities. One interesting feature for charnockites is that the increase in density from acidic to ultrabasic varieties is also marked by an increase in their K-values. As mentioned earlier the SiO_2 content decreases from acidic to ultrabasic and as can be seen, this is marked by an increase in densities. Data on the magnetite content of these rocks are not however available so the effect of this on these relationships cannot be assessed.

Conclusions

The present density data have demonstrated a significant density contrast between the upper crusts underlying the low- and high-grade metamorphic terrains. An average density of 2.75 g/cm^3 is obtained for the upper crust in Karnataka geological province which appears to be nearer to the values suggested by Woollard (1962), Smithson (1971), and Ramberg (1976). In contrast to this, the average upper crustal density in the Eastern Ghats Belt is relatively high (2.85 g/cm^3), which is in agreement with data from some granulite terrains in other shield areas and, in particular, the granulite terrain in Central Norway (Smithson 1971).

A linear relationship between density and susceptibility has been observed for most of the rock types presented in this study. In general, the susceptibility increases with density. This dependence is more pronounced in charnockites and may be directly related to the magnetite content of these rocks.

The possibility of determining the average composition of the upper crust from the average surface densities can be examined. Gibb's (1968) estimate of 2.67 g/cm^3 closely corresponds with that of the granodiorite reported by him and he suggested that in northern Manitoba and Finland the average composition of surface rocks may be granodioritic rather than tonalitic. However, even for the small number of samples of granodiorites presented in this study and also those of Daly et al. (1966) the densities are relatively high at 2.73 g/cm^3 which is nearer to the value of 2.75 g/cm^3 suggested for surface rocks in Karnataka. Incidentally, this value is also nearer to the value of 2.74 g/cm^3 suggested for surface rocks having tonalitic compositions (Woollard 1962). Thus, from estimates of average densities in the present study, it was not possible to determine whether the surface rocks have granodioritic or tonalitic composition. The problem may perhaps be resolved when more data on granodiorite samples become available.

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