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R. Shankar · R. Thompson · T. N. Prakash

Estimation of heavy and opaque mineral contents of beach and offshore placers using rock magnetic techniques

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Abstract Exploration for placer deposits involves heavy and opaque mineral data that are conventionally obtained using toxic and expensive chemicals and time-consuming and tedious microscopic counting of a large number of grains. In this investigation, we have used rock magnetic properties to obtain estimates of heavy and opaque mineral contents of placers from the SW coast of India. Magnetic susceptibility and other magnetic properties show strong correlations with heavy and opaque ($r > 0.87$ and $r > 0.94$; significant at the 1% level) mineral contents. As one or more types of magnetic minerals are invariably present in placers, magnetic properties may be used as a "proxy" for heavy and opaque mineral contents. This simple, rapid, inexpensive, and nondestructive method may be adopted by those involved in placer exploration to rapidly scan a large number of samples and delineate economically important pockets for more detailed investigations. This method saves considerable time and tedium. Using magnetic properties, rather than radioactivity, as a proxy for heavy and opaque mineral contents is more advantageous because one or more magnetic minerals are always present, but a radioactive mineral may not always be present in placers. An important limitation is that the ratio of magnetic to heavy/opaque mineral contents should not vary widely.

Introduction

Placer deposits occur in many of India's beaches and offshore regions. Many agencies, such as the Department of Atomic Energy, Geological Survey of India, and National Institute of Oceanography, are involved in their exploration. A large number of samples must be processed to obtain statistically reliable estimates of heavy mineral percentages. Conventionally, the work includes sieving the samples into size fractions, separation of the heavy mineral fraction, and identifying and counting individual grains under a microscope. The procedure uses bromoform, which is toxic and expensive, and the microscopic work is laborious and time-consuming. We have explored the potential of rock magnetic properties in estimating the heavy/opaque mineral percentages of Kerala beach and offshore placers. Measurement of rock magnetic properties is simple, rapid, easy, and nondestructive. We have determined magnetic susceptibility, anhysteretic remanent magnetization (ARM), and isothermal remanent magnetization (IRM) for the samples used by Prakash et al. (1991). Those authors give details of the processes by which placer minerals have become concentrated on the Chavara coast (Fig. 1). According to Prakash et al. (1991), littoral processes and coastal configuration play a more vital role in the concentration of heavy minerals than proximity to source.

R. Shankar
Department of Marine Geology, Mangalore University, Mangalagangotri 574 199, India

R. Thompson
Geology & Geophysics, Grant Institute, University of Edinburgh, Edinburgh EH9 3JW, Scotland

T. N. Prakash
Marine Sciences Division, Centre for Earth Science Studies, Trivandrum 695 031, India

Samples and methods

Figure 1 shows the study area and sampling locations. After the samples were sieved through ASTM sieves (meshes #60, 170, and 230; sieve pore diameters 250, 88, and 63 μm), the heavy mineral fraction was separated using bromoform, and its weight percentage calculated. About 250 grains in each of the 42 samples were identified and counted under a microscope fitted with a point counter. These data are expressed as number percentages. Further details of sampling and sample processing are given in Prakash (1991).

For rock magnetic measurements, 1- to 5-g subsamples were packed in cubic plastic boxes. Magnetic susceptibility was measured using a Bartington Instruments, air-

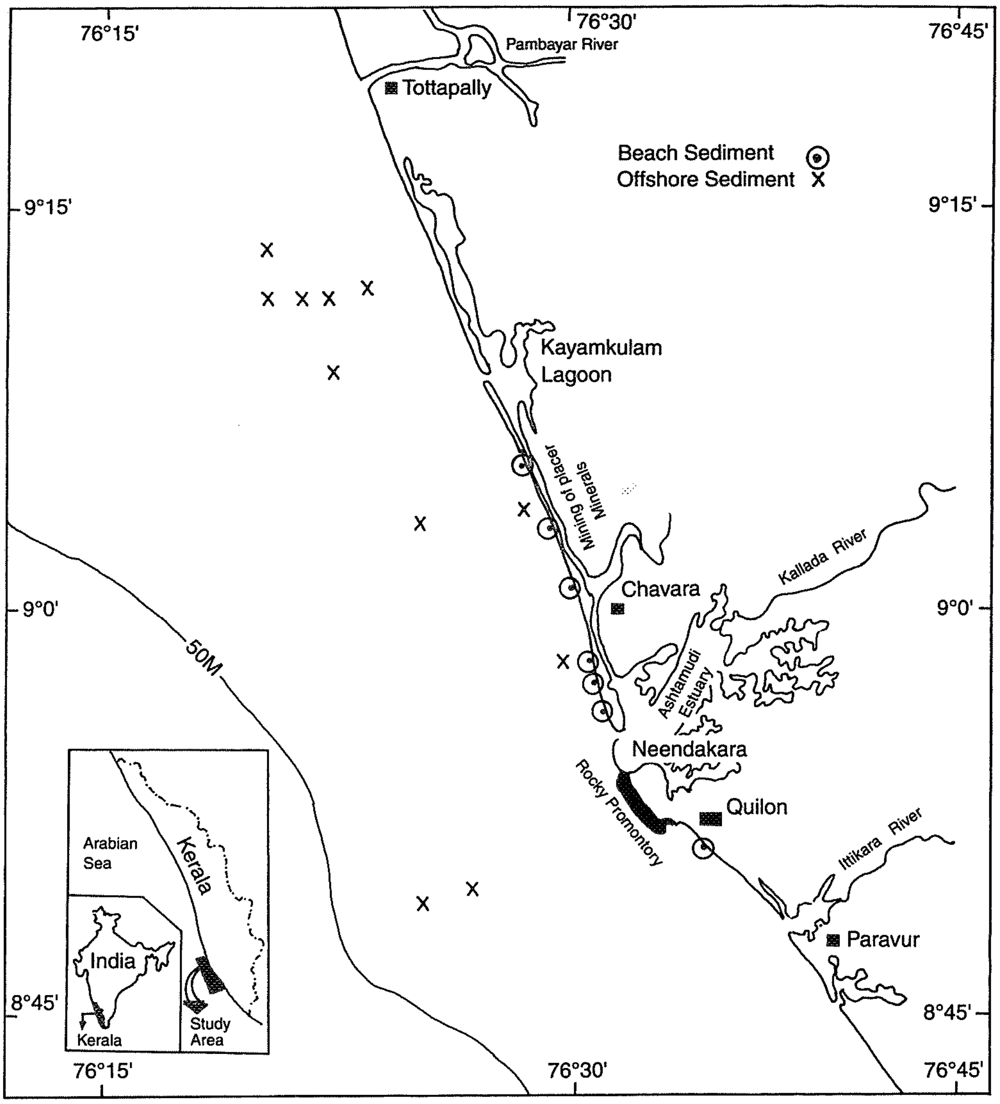


Fig. 1 Sample location map

cored, susceptibility bridge. Susceptibility measurements are particularly fast, taking only a few seconds per sample. ARM was measured by constantly ramping down a mains frequency alternating field from a peak value of 100 mT using a triple variac while the samples were subjected to a steady field of 0.25 mT. Isothermal remanences were grown in 20-, 40-, 60-, 80-, 100-, and 200-mT pulsed fields, using a Molspin discharge magnetizer. High field remanence in a 1-T field was grown using an electromagnet. Remanences were measured on a Molspin fluxgate magnetometer.

Curie temperature was determined for three samples. For this, samples were cold-pressed into 2.5-cm-long cylinders using common salt and a few drops of water with pressures of about 2 kbars, and then dried overnight at 50°C. This simple procedure produced hand samples from the loose beach and offshore sediments that could be given a magnetic remanence and then subjected to thermal demagnetization study. Saturation remanence (SIRM) was grown in the cylinders in a 2-T field. Then, the samples were demagnetized at 80 mT along three mutually perpendicular axes to remove the soft magnetic component and hence allow a study of the Curie temperature of the hard fraction alone. Samples were heated at progressively higher temperatures in a nonmagnetic oven with zero field mu metal shielding. After each heating step, susceptibility and remanence were measured.

Mineralogy was determined using a Philips PW1800 X-ray diffractometer. Samples were scanned from 2° to 60° using CuK_{α} radiation, at a voltage of 40 kV and a current of 50 mA. Mineral identification was made using software that matches the XRD peaks obtained with those of over 3000 minerals in a reference data base.

Results and discussion

Correlation between rock magnetic properties and heavy/opaque mineral percentages

Table 1 presents correlation coefficients of the various magnetic properties studied with the heavy and opaque

Table 1 Correlation coefficients between rock magnetic properties and heavy and opaque mineral contents of Kerala placers ($n = 42$)

	Heavy mineral weight %	Opaque mineral weight %
Magnetic susceptibility	0.87	0.98
ARM[a]	0.88	0.94
IRM[b] 20 mT	0.89	0.98
IRM 40 mT	0.88	0.97
IRM 60 mT	0.88	0.98
IRM 80 mT	0.89	0.98
IRM 100 mT	0.89	0.98
IRM 200 mT	0.89	0.98
IRM 300 mT	0.90	0.98
SIRM[c] 1 T	0.90	0.98

[a] Anhysteretic remanent magnetization.
[b] Isothermal remanent magnetization.
[c] Saturation isothermal remanent magnetization grown in 1-T field.

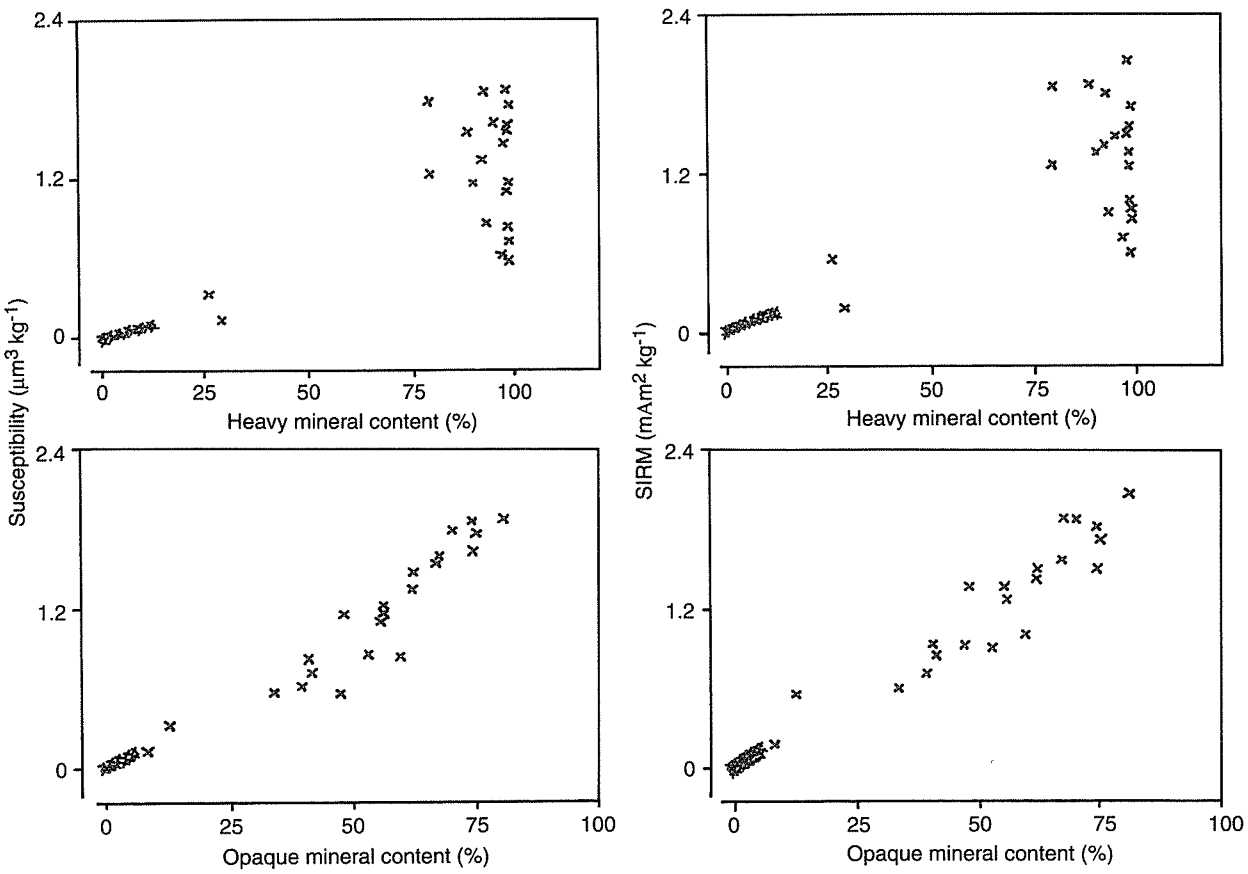
Fig. 2 Magnetic susceptibility (X_m) and saturation remanence versus heavy and opaque mineral percentages. Note the strong positive correlations significant at the 1% level ($n = 42$). The regression equations for estimating heavy (HM %) and opaque (OP %) mineral percentages are:

$$HM\% = 12.4 + 59.1 \text{ magnetic susceptibility}$$

$$= 9.21 + 5.83 \text{ SIRM}$$

$$OP\% = 2.59 + 43.7 \text{ magnetic susceptibility}$$

$$= 0.83 + 4.22 \text{ SIRM}$$



mineral contents in the 42 samples. Two rock magnetic parameters—magnetic susceptibility (X_m) and saturation remanence (SIRM)—are plotted against heavy and opaque mineral contents in Fig. 2. All correlations are strong, positive, and are significant at the 1% level. A striking feature of Table 1 is the nearly one-to-one correlation (around 0.98) of all magnetic parameters with the opaque mineral content, but a lower correlation (around 0.89) with the heavy mineral content. This difference in relationship is expected because the heavy mineral fraction not only contains magnetic minerals but also other heavy minerals. By contrast, the opaque fraction contains principally magnetic minerals.

Magnetic mineralogy

The main minerals contributing to the magnetic susceptibility and the isothermal remanences of the samples are magnetite and ilmenite. Their occurrence in Kerala beach placers was first reported by Tipper (1914). XRD data confirm the presence of both minerals in our samples. The type of ilmenite present is actually titanohematite. A Curie temperature of about 200°C was obtained for the harder magnetic component of the three samples studied (Fig. 3). This temperature indicates that the high coercivity titanohematite has the composition $x = 0.62$ in

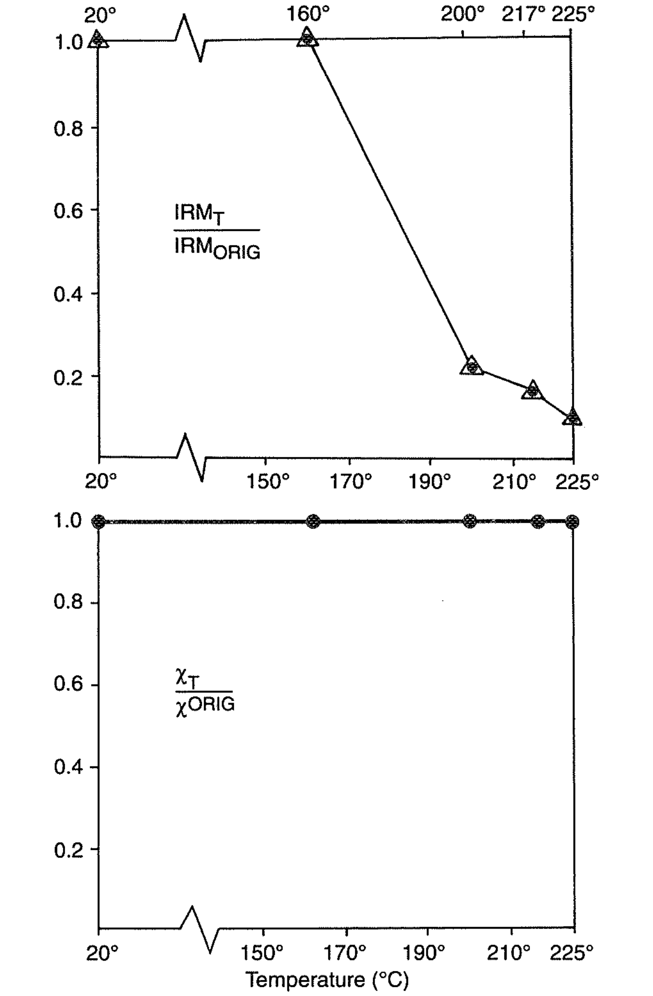


Fig. 3 Plots of IRM_T/IRM_{Orig} and X_T/X_{Orig} versus temperature. IRM_T/IRM_{Orig} decreases rapidly at 200°C, which is the Curie temperature of the samples. Note that X_T/X_{Orig} remains constant with temperature, indicating that there is no change in mineralogy on heating and that the change in IRM is a true Curie temperature

$xFeTiO_3(1 - x)_\alpha Fe_2O_3$ (see Fig. 3 of Westcott-Lewis and Parry 1971).

X-ray diffraction patterns of the three samples also are similar, suggesting similar mineralogy and a similarity in the relative proportions of the various minerals. Other important minerals identified from XRD peaks are zircon, rutile, ilmenite, hematite, and quartz.

The potential of using rock magnetic properties as a proxy for heavy and opaque mineral percentages of a sample depends on the constancy of the ratio of magnetic minerals to heavy/opaque minerals. Generally, this ratio is fairly constant for a given deposit because the minerals have the same provenance; however, for large areas with minerals of different provenances, the ratio can vary significantly. Samples of the Kerala placers that we have studied *do* show a constant ratio of magnetic to heavy/opaque mineral contents, although the IRM acquisition curves, which indicate magnetic mineralogy, show some between-sample variations (Fig. 4). Curves to the left of the diagram show a softer[1] behavior and are probably dominated by magnetite. Curves to the right have a harder[1] behavior typical of titanohematites. Nevertheless, IRMs obtained in different applied fields all give similar correlations with heavy and opaque mineral contents (Table 1).

Comparison with methods and data of other workers

Senthiappan (1989) proposed the use of scintillometer readings to assess the heavy mineral and monazite contents of Kerala offshore sands. However, as mentioned by that author, the presence of one or more naturally radioactive minerals is essential for this type of study. With rock magnetic techniques, there is no such limitation because one or more magnetic minerals are always present in placers. Unfortunately, as correlation coefficients were not given by Senthiappan (1989), we can not compare our data with his in any meaningful way.

Nagamalleswara Rao (1994a) reported correlation coefficients (r) of 0.68, 0.61 and 0.38 ($n = 7$ for each) between radioactivity and heavy mineral percentage for beach placers from three regions of the east coast of India. These coefficients are not statistically significant at the 5% level. Again, "radioactivity merely indicates the monazite abundance in the sands and *does not* [emphasis added] provide a measure of other minerals" (Nagamalleswara Rao 1994a).

For the same three regions, Nagamalleswara Rao (1994b) obtained r values of 0.91, 0.91, and 0.50 ($n = 7$ for each) between magnetic susceptibility and heavy mineral percentage. We obtained similar r values, but on a much larger data set.

The positive correlation of percent magnetite with weight percent of heavy minerals, ilmenite, and pyriboles ($r = 0.78$, 0.66, and 0.48, respectively for $n = 36$) has been suggested as the basis of estimating other heavy minerals by Krishnaiah Setty and Dhana Raju (1988). According to them, magnetite separation using a low-power magnet is simple, rapid, and does not involve instrumentation. Although this method is good, magnetite separation may be rendered difficult if the magnetite is bound with some other mineral. In our own laboratory-based magnetic extraction studies, not all grains pulled out by a hand magnet were magnetite. Many were weathered and composed principally of Fe oxides such as goethite and hematite (Karbassi and Shankar 1994). These difficulties may explain why the correlation coefficients obtained by Krishnaiah Setty and Dhana Raju (1988) are lower than ours.

Advantages and limitations of using rock magnetic properties

Using rock magnetic techniques to estimate the heavy/opaque mineral percentages of a placer sample is simple,

[1] If the remanence of a sample increases rapidly in low magnetic field strengths, such a sample is referred to as magnetically soft. A sample is described as hard if a high magnetic field strength is needed.

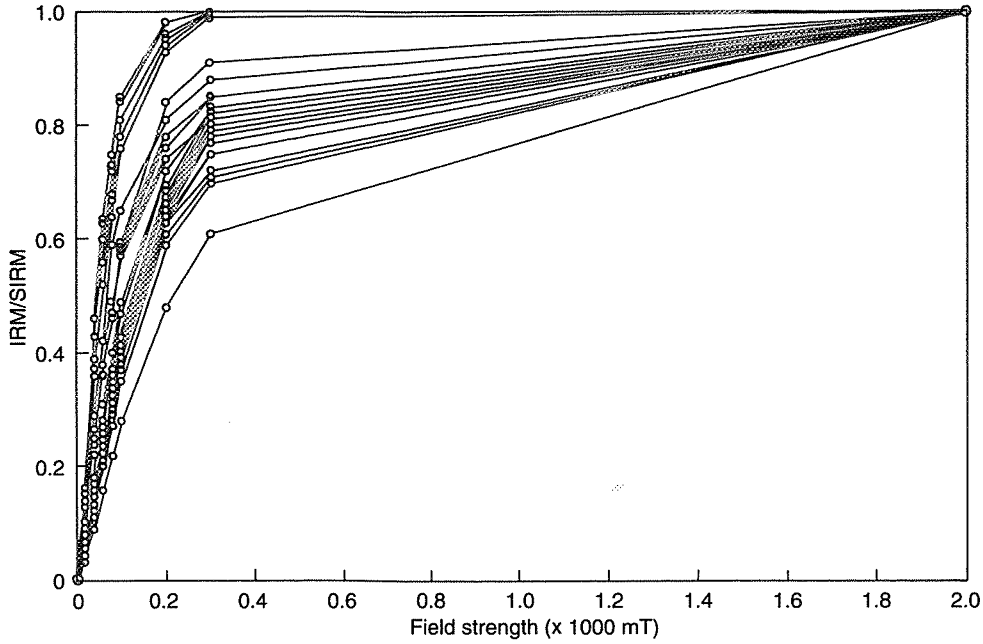


Fig. 4 Isothermal remanence acquisition curves for placer samples. The broad similarity of IRM acquisition shows that any change in sample mineralogy will have little effect on heavy mineral estimates. All the samples are dominated by ferrimagnetic minerals

easy, rapid, and nondestructive. The tedious and cumbersome procedure of counting hundreds of grains under the microscope is circumvented. There is no recurring expenditure for chemicals such as bromoform, which is toxic and also expensive. Using rock magnetic techniques, hundreds of samples can be run in a day. Furthermore, continuous logging of magnetic susceptibility or IRM of cores is possible and susceptibility can be easily measured in situ (e.g., Lancaster 1966). With these advantages, the rock magnetic approach can be gainfully employed to rapidly scan a large number of samples, to demarcate promising areas for further exploration, and to choose critical samples for detailed heavy mineral studies.

The magnetic susceptibility approach is applicable only to individual deposits (in which the relative proportions of heavy and magnetic minerals are fairly constant) as shown by the present study and by Krishnaiah Setty and Dhana Raju (1988) and Nagamalleswara Rao (1994b).

ARM and IRM measurements work equally well when compared to magnetic susceptibility. However, as susceptibility is much more easily measured, it is preferred to ARM or IRM measurement. For samples from large regions, none of the simple proxy methods will work well, because the provenance varies.

Conclusions

Magnetic susceptibility, a property that can be determined easily, rapidly, and nondestructively, may be used as a proxy for the heavy and opaque mineral contents of beach and offshore placers. Agencies entrusted with exploration for placer deposits may consider using this method to save considerable time and tedium for their personnel. Although the method cannot necessarily always be used, it can successfully estimate the heavy/opaque mineral percentages of samples from deposits that have the same provenance. Magnetic susceptibility shows better correlation with the opaque mineral content than with the heavy mineral content because magnetic minerals are present principally as opaque minerals.

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