

## Drill-Hole Induced Polarisation, Self-Potential and Magnetic Surveys: Case Studies from Mineral Belts of Rajasthan

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**Abstract:** Downhole wide spacing IP (DHIP), Self-potential (SP), magnetic susceptibility and applied potential observations were made along the boreholes drilled for Pb-Zn-Cu sulphide in mineral belts of Rajasthan. The aim was to identify mineralised zones, physical property contrast of the mineral and country rock and presence of mineralisation in the vicinity of the borehole but missed in drilling.

Number of boreholes were surveyed in different parts of the mineral belts of Rajasthan and the relationship between apparent resistivity and chargeability, SP and magnetic susceptibility and lithology of the cores has been studied and analyzed. Chargeability 'high', resistivity 'low', SP 'low/high' and magnetic susceptibility 'high' characterized the sulphide mineralisation. The surveys were successful in detecting the presence of mineralisation in the drill hole, studying the *in situ* physical properties of barren & mineralised rocks and finding the correct depth of the conductor. It helped in conducting mise-a-la-masse surveys and interpretation of surface geophysical data in mineral belts of Rajasthan. Applied potential (Mise-a-la-masse), surveys were able to give information on the lateral extension of the mineralised zones intersected in the borehole.

Five examples of detection of sulphide mineralisation in boreholes of Kayar, Pindwara-Watera and Dariba-Bethumbi mineral belts of Rajasthan are presented. The results indicated average apparent resistivity low value of the order of 1 to 10 ohm-m and magnetic susceptibility of order of  $600-5000 \times 10^{-6}$  cgs units in the sulphide zones, while in the country rocks values recorded were in the range of 3000-24,000 ohm-m and  $50-500 \times 10^{-6}$  cgs units respectively. The diagnostic resistivity response is simply related to the percentage, size and disposition of the sulphide mineralisation. The association of high magnetic susceptibility is indicative of pyrrhotite mineralisation in these zones. The SP 'high' and 'low' could be due to the electrochemical potential developed at the interface of country rock and ore body. Detection IP/resistivity measurements have also improved the prospective search radius of drill-holes and are successful in assessing qualitatively the lateral extent of intersected mineralisation.

**Keywords:** Drill-hole Induced-Polarization (DHIP), Self-potential, Magnetic, Geometric disposition, Rajasthan

### INTRODUCTION

Borehole geophysical studies have been the most important tool in oil exploration and prospecting for coal and ground water but rarely used in mineral exploration. In few cases, these methods have been successfully applied for exploration of metallic sulphide (Bacon, 1965, Labanov et al 1966, Dibbs, 1970, Landstrom et al 1972, Kayal et al 1982, Ogilvy, 1984a, b, Smith, 1985, Pant and Gupta, 1998). Rajasthan offers an excellent opportunity for SP, magnetic susceptibility and IP-Resistivity surveys in drill holes as it has number of mineralised belts rich in Cu-Pb- Zn sulphide ore deposits. The study areas are shown in Fig 1.

As we all know, core drilling is expensive and tests only small volume (statistically) in the rock. In the case of

small targets at depth, near misses can occur. An uncertainty may exist concerning the persistence or attitude of intersected mineralisation away from the hole. A down hole wide spacing IP survey can assist in this situation by increasing the effective search radius of detection and providing information on the geoelectric properties, geometry and persistence of the mineralisation away from the hole intersecting mineralisation, which are useful in interpretation (Ogilvy, 1984a, b).

In electrical logging, SP and resistivity/conductivity are considered the main parameters to confirm conductive zones. Data on many deposits (Gupta et al 1995; Kayal et al 1982) indicate that the existence of low potentials particularly, within sulphide mineralisation in drill-holes is not a general rule. In many cases no SP decrease

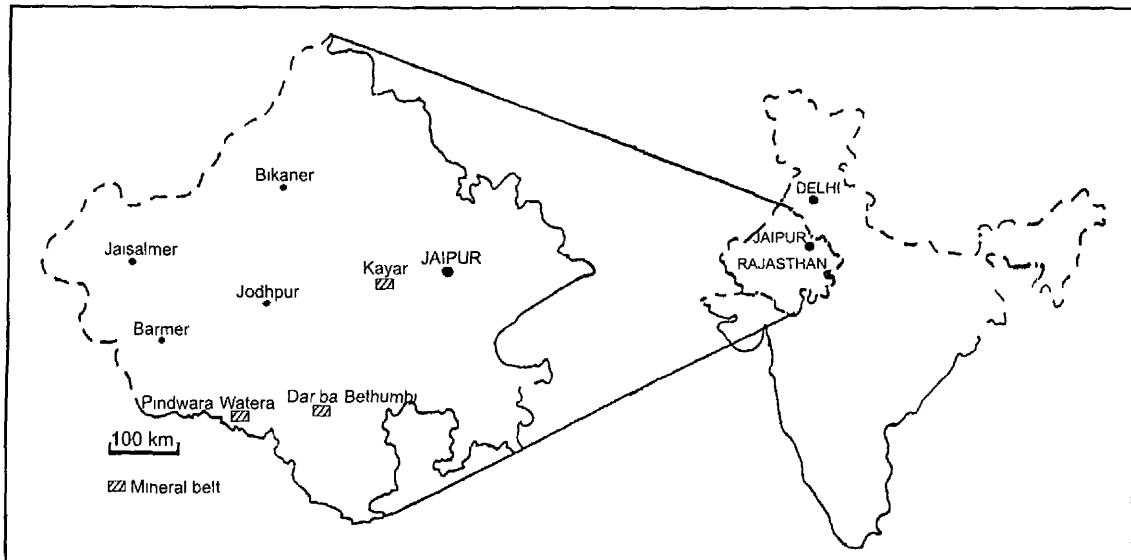


Fig.1. Location map showing areas of drill hole surveys in the mineral belts of Rajasthan

whatsoever is observed at the border between silicate and sulphide. Indeed in some drill-holes, the SP is more positive against sulphides than with the country rock. This inconsistent behaviour of SP in drill-holes complicates the interpretation, and implies that conventional down hole SP measurements are of limited value at country rock/sulphide interface (Hovdan and Bolviken, 1984). DHIP logging is also important because of the occurrence of basemetal deposits in a disseminated form is quite common. EM logging is generally employed for massive sulphide but our experience has shown that some zones of high percentage of sulphide do not respond to EM methods but identified by IP logging as target size generally increased due to the presence of disseminated sulphide halo surrounding massive sulphide. The measurement of magnetic properties provides a rapid qualitative estimate of the magnetic minerals in a rock. These measurements can be interpreted to reflect lithological changes, presence of fractures, the degree of homogeneity, and the alteration state of the rock body (Lapointe et al 1984). The present work describes the investigation- Drill Hole IP, resistivity and SP surveys. The magnetic susceptibility property of cores from basemetal deposits of Rajasthan was also studied, which enabled to characterize the core by the identification of magnetic zones (Ram Gopal et al 1993a, b). The presence of fractures, the degree of rock alteration, lithological variations and sulphide mineralisation associated with magnetic minerals such as pyrrhotite and magnetite have been interpreted.

There are some areas, where conventional methods of geophysical logging failed to detect mineralisation located by drilling due to the presence of unfavourable environment.

Therefore, it was decided to also apply down hole electrical geophysical techniques (detection) along with conventional methods in an attempt to relate mineralisation already intersected and to aid further drilling. Five typical case histories of down-hole IP/resistivity, SP and magnetic susceptibility logs for detecting mineralisation are presented.

#### DRILL-HOLE LOGGING TECHNIQUE

IP drill-hole logging (detection) was carried out using widely spaced multiple electrode IP system (Scintrex make) as shown in Fig 2. It consists of a multi-electrode down-hole cable assembly interfaced to commercial time-domain IP equipment at the surface. The electrodes are made of non-polarizing, lead-clad bronze and are arranged in an equi-spaced pole-dipole configuration with logarithmic spacing of 2.5, 5, 10, 20 and 40 m. The multicore cable is coupled via a winch and slip ring assembly to IP equipment at the surface through optically isolated synchronization link with the transmitter. Multiple wide-spacing data sets are obtained for each in-hole observation point by surface switching off on electrode pairs.

Measurements were made every meter or even more closely depending upon the size and response of mineralised body and the parameters recorded were SP, apparent resistivity and chargeability.

SP logging was conducted using one of the lead electrodes and another non-polarisable electrode fixed near the collar of borehole by switching off the current source. IP/ resistivity measurements were made using

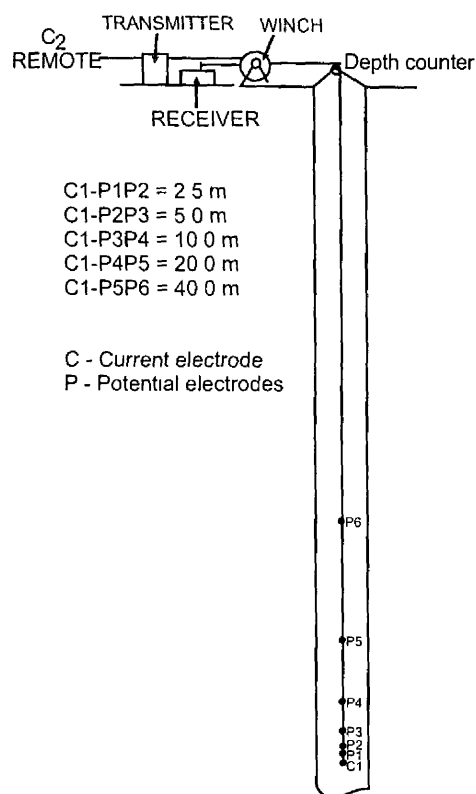


Fig.2. Electrode configuration with Pole - Dipole array of down-hole IP-resistivity

alternating interrupted square wave current pulse of 2-sec duration of ON and OFF

Self-potential was plotted at the depth of the mobile electrode and resistivity and chargeability were plotted at the center of C<sub>1</sub> and P<sub>1</sub> as shown in Fig 2. Magnetic susceptibility of the core samples was measured using GSI make susceptibility meter and plotted against the depth. The core samples were measured at interval of about 1 to 2 m, with three measurements at 0.1 m apart.

The apparent resistivity ( $\rho_a$ ) at a point P due to a point source and its image for the pole-dipole array as given by Ogilvy (1984a) was adopted in calculations.

### DRILLHOLE SURVEY RESULTS

In the mineral belts of Rajasthan, the IP/resistivity logs obtained with the pole-dipole array along with SP and magnetic observations (Ram Gopal et al 1993a), correlate well with the known lithological variations, and provided useful physical property information for the interpretation of surface surveys. Elsewhere, problems were encountered with synchronization failure, inductive coupling and unbalanced capacitive effects caused by the higher than normal contact impedance encountered in-hole.

### Kayar Belt

#### Geophysical Logs

Figure 3 is presented as an example of IP/resistivity, SP and magnetic susceptibility logs with corresponding lithological section in a mineralised drill-hole KYR-19 of Kayar Belt, Ajmer district, Rajasthan (Fig 1). The massive sulphide zone is clearly defined as a pronounced low of apparent resistivity of 0.5  $\Omega$ m (for a = 2.5 m), against background values of nearly 5000  $\Omega$ m. With increasing spacing, there is a reduction in 'peak amplitude' response. The response could only be observed up to a = 20 m, for larger spacing, the responses could not be observed due to synchronization failure.

IP response in detection logging (a = 2.5 m) to the sulphide is 60 ms and against the country rock it is 20 ms. For larger spacing (a > 2.5 m) chargeability response is not detectable.

Low SP (-1150 mV) against the background value (-700 mV), characterizes the sulphide. SP value over sulphides in the borehole need not be always -ve. The cause of SP polarity has been discussed separately after the discussion of results.

Magnetic susceptibility of sulphide is characterized by high order of 600x10<sup>6</sup> cgs units against the background values of 50x10<sup>6</sup> cgs units over pegmatite. It is due to the presence of pyrrhotite associated with or without other sulphide mineralisation.

Figure 4 shows the IP/resistivity, SP and magnetic susceptibility logs in another borehole no KYR-20 intersecting mineralisation and drilled about 75 m northeast of the previous borehole in Kayar Belt, Ajmer district, Rajasthan. The massive sulphide zone is clearly defined as pronounced resistivity low of the order of 1  $\Omega$ m (for a = 2.5 to 10 m) against the background value of 3000  $\Omega$ m over the calc silicate rocks. With increasing electrode spacing, not much reduction of peak amplitude response is observed. This response is not noticed for larger spacing due to synchronisation failure.

IP response in the sulphide is characterized by high chargeability of the order of 160 ms against 40 ms over host rock (calc silicate) for a = 2.5 m. Chargeability value against the sulphide got decreased with increase of electrode spacing up to a=10 m where as it remains same over host rock indicating the limited lateral extension of the rich mineralized zone away from borehole. The same was supported by subsequent mise-a-la-masse survey and proved by drilling (Ram Gopal et al 1993a).

The values of apparent resistivity and chargeability recorded in detection logging are in general of the order

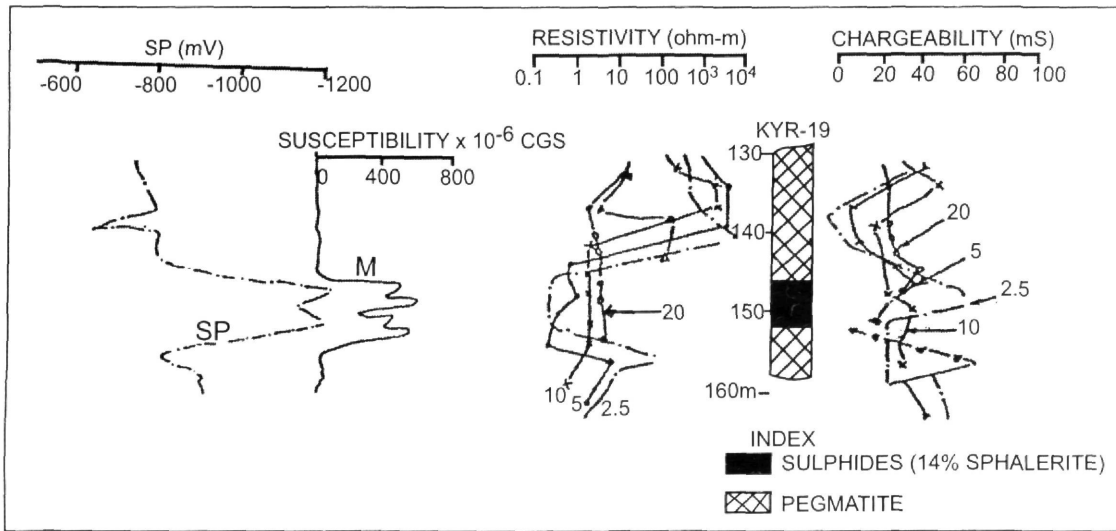


Fig.3. Drill Hole IP-Resistivity, SP and magnetic susceptibility results, Kayar belt, Ajmer district.

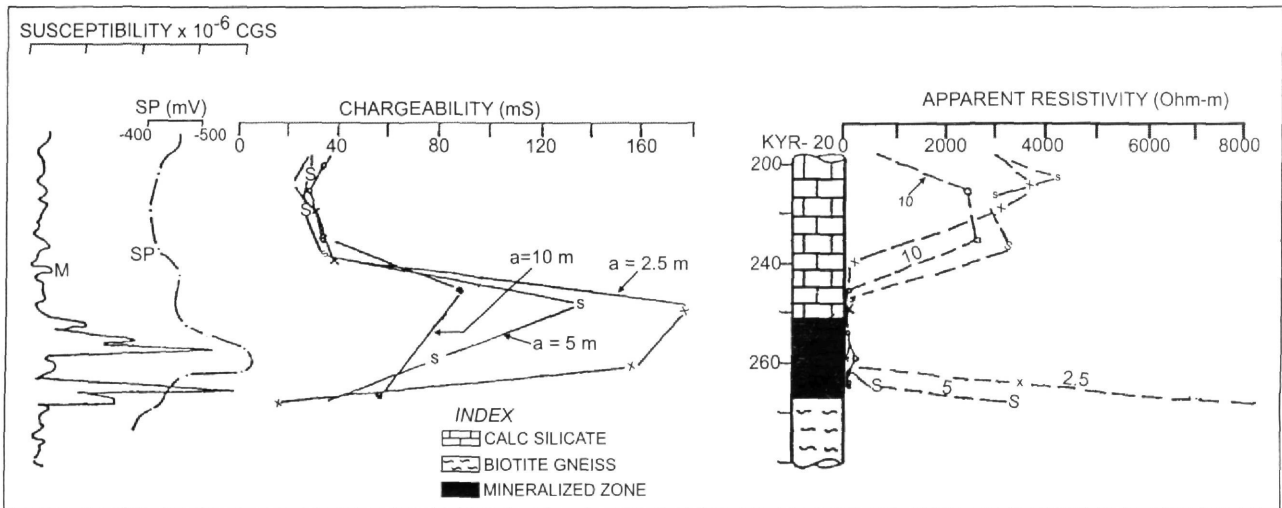


Fig.4. Drill Hole IP-Resistivity, SP and magnetic susceptibility results, Kayar belt, Ajmer district.

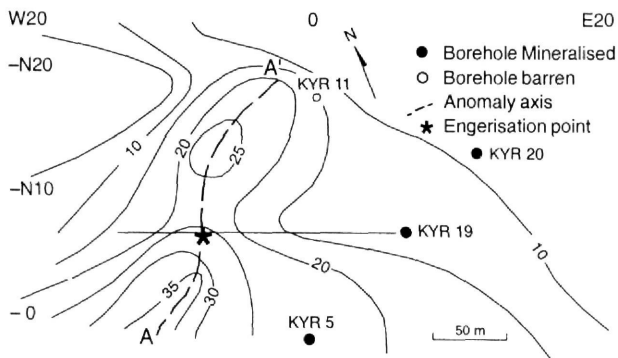
obtained in surface IP cum resistivity profiles (Gupta et al. 1995) and are indicative of the lateral extension of sulphide mineralisation as recorded in surface responses. This further agrees with these findings.

SP for the sulphides is characterized by low order of -600 mV against the background values of the order of -400 mV over calc silicate.

**Applied Potential Data**

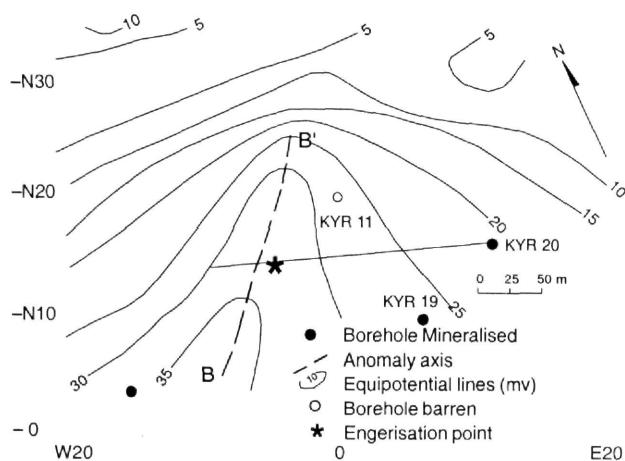
Applied potential equipotential contour map (Fig.5) based on energisation in borehole KYR-19 at 151 m has brought out an elongated contour pattern with an open end towards southwest and closing in northeast (between traverse N 20 and N25).

This elongated pattern has one closure with the peak value of 27 mV located at station no. W 6 of traverse N 15 (Gupta and Radhe Shyam, 2005). The open closure towards southwest indicates a peak value of 38 mV on traverse 'O', signifying a shallower depth to the top of the body in southwest. It was confirmed by borehole KYR-5 on traverse 'O' which has intersected the mineralisation at a shallower depth. Equipotential contours show that the mineralised body has a pitch towards NNE and dipping SE. The dip of the body agrees with the available geological information. The northern extension of the mineralised body was prognosticated up to 220 m, which was subsequently proved by another borehole no. KYR-20 drilled on these recommendations.



**Fig.5.** Applied potential equipotential contour map for borehole KYR-19 (Ore body charged at 151 m).

Applied potential equipotential contour map (Fig.6) based on engersation in borehole KYR-20 at 164 m has brought out an elongated contour pattern with an open end towards southwest and closing in northeast. The anomaly axis is B-B' and the peak potential value is 39 mV at station W 9 of traverse N5. In NE side, the contours are closed between traverse N 25 and N30, indicating that the strike of mineralised zone is limited in NE side. This zone was intersected in borehole KYR-19 also.



**Fig.6.** Applied potential equipotential contour map for borehole KYR-20.

Borehole geophysical surveys employing logging as well as applied potential methods were successful in tracing the later extensions of the mineralised lodes in this block.

#### Pindwara-Watera Belt

Figure 7 shows the IP/resistivity, SP and magnetic susceptibility logs with corresponding lithological section in a drill-hole of Pindwara-Watera Belt, Sirohi district,

Rajasthan (Fig.1). The massive sulphide zone is clearly defined as a pronounced resistivity low of the order of  $1 \Omega\text{m}$  for  $a = 2.5 \text{ m}$ , against background values of the order of  $10000 \Omega\text{m}$  over chlorite- sericite- schist just above the mineralized zone and about  $5000 \Omega\text{m}$  over garnetiferous sericite schist below the mineralized zone. With increasing spacing, there is a reduction in peak amplitude response. This response was noticed up to  $a = 40 \text{ m}$ . This behaviour may partly reflect decrease in resolution with the increased spacing but also suggests that the mineralisation may be well developed away from the hole. It is a qualitative assessment and no limits can be decided on the lateral persistence. Mise-a-la-masse surveys in two boreholes of this prospect have indicated that the mineralised body extends up to  $65 \text{ m}$  in both the directions. Hence, this prognostication was supported by subsequent mise-a-la-masse results and proved by drilling.

The IP logs show high chargeability of order of  $120 \text{ ms}$  for sulphide against background value of the order of  $20 \text{ ms}$  for chlorite sericite schist above the mineralisation and garnetiferous sericite schist below sulphide mineralisation.

Low SP of the order of  $-775 \text{ mV}$  characterizes the sulphide zone against the background values of the order of  $-600 \text{ mV}$  over the host rock. The cause of  $-ve$  SP anomaly has been discussed in the Kayar belt section and it is also valid for Pindwara-Watera sulphide belt.

Magnetic susceptibility of the sulphide is characterized by high magnitude of the order of  $5000 \times 10^{-6} \text{ c.g.s}$  units against the background values of the order of  $250 \times 10^{-6} \text{ c.g.s}$  units over chlorite sericite schist. It is due to the presence of pyrrhotite associated with or without other sulphide mineralisation.

#### Dariba-Bethumbi Belt

Figure 8 shows IP/resistivity; SP and magnetic susceptibility logs with related lithological section in mineralized drill-hole of Dariba-Bethumbi Belt, Rajsamand district, Rajasthan (Fig.1). The massive sulphide zone is clearly defined as a pronounced resistivity low of order of  $0.5 \Omega\text{m}$  for  $a = 2.5 \text{ m}$ , against background values of the order of  $100 \Omega\text{m}$  over host rock (calc. silicate). This response was also noticed for  $a = 5 \text{ m}$  also but, for larger electrode spacing, similar response was not observed. This behavior may suggest that the mineralisation may not be extending away from the hole.

The IP logs show high chargeability of the order of  $150 \text{ ms}$  for sulphides against background value of order of  $100 \text{ ms}$  for calc. silicate rock for  $a=2.5 \text{ m}$ . Similar response is not noticeable for larger electrode spacing.

SP of the order of  $675 \text{ mV}$  characterizes the sulphide

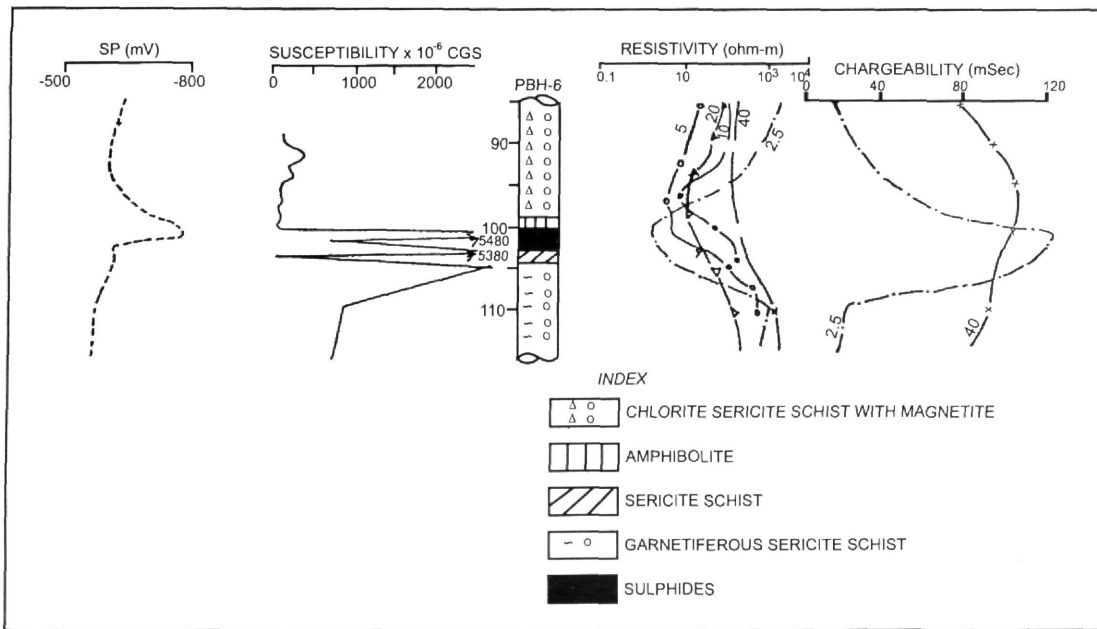


Fig.7. Drill Hole IP-Resistivity, SP and magnetic susceptibility results, Pindwara-Watera belt, Sirohi district.

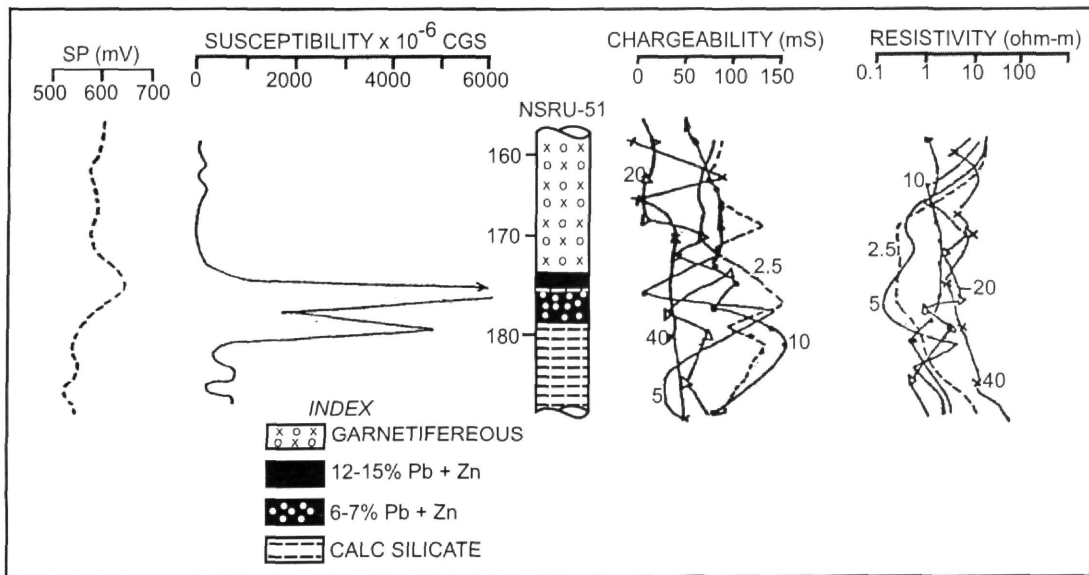


Fig.8. Drill Hole IP-Resistivity, SP and magnetic susceptibility results, Dariba-Bethumbi belt, Rajsamand district.

zone against the background values of the order of 600 mV over the host rock. It shows positive SP anomaly unlike sulphide deposits of Kayar and Pindwara-Watera belts and cause of this polarity has been discussed separately after the discussion of results.

Magnetic susceptibility of the sulphide is characterized by  $6000 \times 10^{-6}$  c.g.s units against the background values of order of  $50 \times 10^{-6}$  c.g.s units over calc/silicate rock. It is due to the presence of associated pyrrhotite in the sulphide mineralisation.

Figure 9 shows the IP/resistivity, SP, magnetic susceptibility logs and the corresponding geological section of another mineralized borehole of Dariba-Bethumbi Belt, Rajsamand district, Rajasthan situated about 4 km south of the one already discussed. The massive sulphide zone is clearly defined by its pronounced resistivity low of the order of  $1 \Omega\text{m}$  (for  $a=2.5$  m) against the background values of the order of  $10,000 \Omega\text{m}$  for mica schist. This response was not noticed for higher electrode spacing indicating the limited lateral extension of the mineralisation in the borehole.

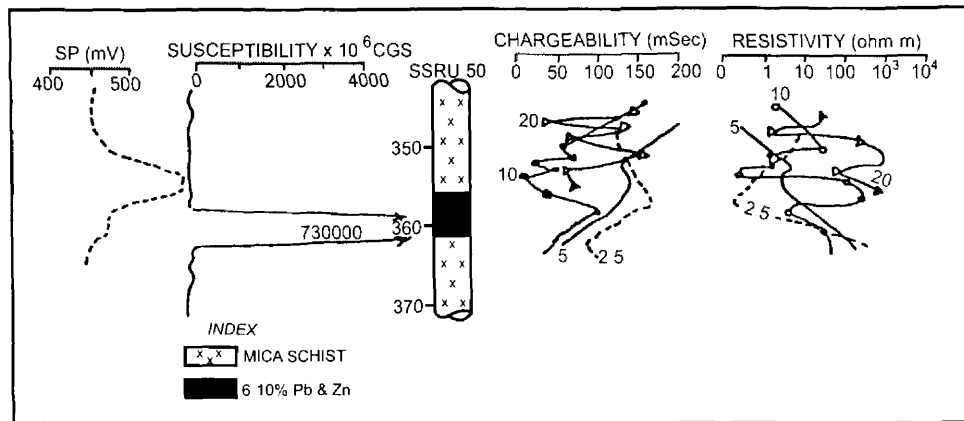


Fig.9. Drill Hole IP Resistivity SP and magnetic susceptibility results Dariba Bethumbi belt Rajsamand district

The IP log shows high chargeability of the order of 160 ms opposite sulphide against the background value of the order of 100 ms against mica schist for  $a=2.5$  with reduced magnitude for  $a = 5$  m. This response is not noticeable for higher spacing.

The sulphide zone is characterized by high SP of the order of 500 mV against the background values of the order of 400 mV over host rock. SP log shows positive SP anomaly.

Magnetic susceptibility of the sulphides is high of the order of  $730\,000 \times 10^6$  cgs units against the background values of the order of  $500 \times 10^6$  cgs units over mica schist. It is due to the presence of pyrrhotite associated with or without other sulphide mineralisation.

**Self-potential Mechanisms in Drill-holes**

Self potential mechanism in drill holes due to local galvanic cells at the interface of electrically good conducting mineralisation and poorly conducting country rocks is illustrated in Fig 10. The direction of the SP gradients in these local cells depends on the redox potential ( $E_h$ ) of the drill hole water with respect to that of the pore water of the surrounding country rock (Hovdan and Bolviken, 1984).

If the  $E_h$  in the drill hole water is more oxidizing than that of the adjacent pore water, then the surface of the sulphide exposed in the drill hole will possess cathodic properties, while the natural surface of the ore body will possess corresponding anodic properties. Direction of positive current flow in the hole will be from the country rock towards the ore body. Self-potentials in the drill hole will be more negative for the sulphide than that of the country rock (Fig 10A). Figs 3, 4 and 7 are the examples of this mechanism.

If the  $E_h$  in the drill hole water is more reducing than that in the adjacent pore water, then the surfaces of the sulphide exposed in the drill hole will possess anodic

properties, while the natural surface of the ore body will possess corresponding cathodic properties. Direction of positive electric current flow in the local cell in the hole will be from the ore body towards the country rock. Self potential in the drill hole will in this case be more positive.

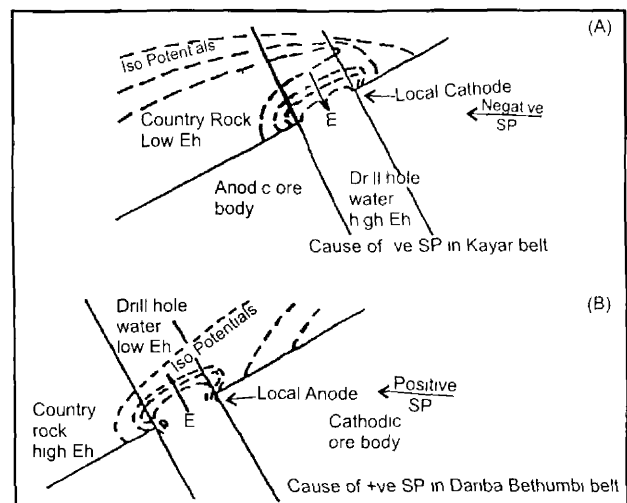


Fig.10. A and B. Schematic illustration of self potential mechanisms in drill hole due to local galvanic cells at the interface of electrically good conducting mineralisation and poor conducting country rocks

(Hovdan and Bolviken, 1984) opposite sulphide than opposite country rock (Fig 10B). Figs 8 and 9 are examples of this type of SP mechanism in the boreholes.

**Geoelectric Properties**

The down hole IP/resistivity log provides the intrinsic geoelectric properties of the mineralisation and its associated rock types (Lynch, 1962) which is useful in the interpretation of geophysical data for mineral exploration.

**Table 1.** Average peak resistivity and magnetic susceptibility values

Rock type	Laboratory Measurements			Borehole Measurements		
	DC Res. ( $\Omega\text{m}$ )	M (mS)	Mag. Suscep. $\times 10^{-6}$ c.g.s units	App. Rest. ( $\Omega\text{m}$ )	M (mS)	Mag. Suscep. $\times 10^{-6}$ c.g.s units
1. Mineralisation	1-8	60-140	40-600	1-5	40-86	Not recorded
2. Pegmatite	5376- 10366	29-53	20-40	2281- 8184	20-55	Not recorded
3. Calc-silicate	5332	9-12	40-50	Not recorded	Not recorded	Not recorded
4. Chert	21835	10-90	10-80	Not recorded	Not recorded	Not recorded
5. Mica schist	3909- 23625	12-20	20-240	5084	10	Not recorded

From the observations, it is established that the geoelectric contrast between the target mineralisation and the surrounding host rocks was in excess of 1:5000 and in few cases it is as high as 1:10,000. For improving interpretation, spot resistivity, Chargeability and magnetic susceptibility values for each lithounits were measured in the laboratory and are given in Table 1. These spot values are nearly of the same order as measured in smaller separation ( $a=2.5$  m) in the drill hole and are in reasonably good agreement. (Ram Gopal et al. 1993b).

In all the cases the apparent resistivity values observed were nearly 1 Ohm.m at mineral intersections, some time as low as 0.5 Ohm-m for massive bodies.

The massive sulphide with pyrrhotite shows high magnetic susceptibility values ( $600 \times 10^{-6}$  to  $5000 \times 10^{-6}$  c.g.s units). The magnetic susceptibility of host rock and surrounding media is in the range  $50 \times 10^{-6}$  -  $500 \times 10^{-6}$  c.g.s units.

### CONCLUSION

The field examples from the study of five boreholes using a down-hole IP/resistivity prospecting system show that the technique has advantage as search radius depends on the range of the largest electrode spacing. In the cases where the mineralisation is intersected by the borehole, multiple-spacing data provide information on the persistence and spatial distribution of the mineralisation away from the hole.

The study carried out from the logs proves the efficacy of the basic logs like SP, resistivity and magnetic susceptibility indicating the presence of sulphide mineralisation and the physical properties of the host rocks and sulphides mineralisation.

The detection logging supported by mise-a-la-masse survey could give qualitative information about the lateral extent of the intersected mineralisation in the borehole.

It has clearly been brought out from the study of logs that relatively the low resistivity, high chargeability, high magnetic susceptibility and low SP indicate sulphide/graphite horizons. However, in the case of boreholes in Dariba-Bethumbi Belt, positive SP peaks are associated with high percentage of Cu, Pb and Zn mineralisation. It may be due to redox potential in drill hole water. Magnetic susceptibility high values observed due to the presence of pyrrhotite or magnetite association yielded diagnostic signatures. This favourable geological setup of association of pyrrhotite with mineralisation is noticed in these mineralized belts of Rajasthan.

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## ANNOUNCEMENT

The XXIV, Indian Association of Sedimentologists Convention and National Seminar on “**Sedimentary Basins of India and their Economic Resources**” scheduled to be held between, 25th and 27th February, 2008 has been postponed to 4th-6th March, 2008. The Revised important dates are: (i) Receipt of registration form - 15.01.2008; (ii) Receipt of Abstract - 31.01.2008; (iii) Receipt of Full paper for Young Sedimentologists Award - 31.01.2008. All correspondence should be addressed to Prof. Mahshar Raza, Convener, Dept. of Geology, Aligarh Muslim University, Aligarh - 202 002. Telephone: 057-2700615 Mobile: 09837186110, FAX: 0571-2700528, email: mahshar@indiatimes.com