# *Borehole GPR investigations from underground for mapping the extension of old working at a Pb-Zn Mine in Rajasthan, India*

S Nelliat, B. Butchi Babu, PC Jha, YV Sivaram and SN Verma
National Institute of Rock Mechanics,
Bengaluru, India
sandeepnelliat@gmail.com

S Dutta and A Jha
Rajpura Dariba Mines, Hindustan Zinc Limited,
Rajsamand Dist., Rajasthan, India

***Abstract*—Conventional GPR reflection surveys in base metal sulphide mines are sometimes marred by scattering due to heterogeneity or presence of disseminated sulphide minerals. Surface scanning in such areas have its own limitations as the depth of investigation is adversely influenced by the highly lossy medium. Alternatively, borehole GPR investigation from underground can be an efficient tool for sensing the proximity of old workings including cavities left over by past ore extraction.**

**In the present study two borehole GPR techniques were used from underground to establish the boundary of old workings in a Pb-Zn mine. Cross-hole transmission mode data from a stepped-frequency GPR was analysed to delineating the zone of influence created by ancient mining activity. Two parameters namely velocity and attenuation of radar waves were used to examine the intervening geological medium. Single-hole reflection survey was also carried out to scan the medium around the borehole. The result of cross-hole GPR survey is a plot of radar wave attenuation along the horizontal plane of survey. The attenuation plot clearly delineated the zone affected by past mining activity; however cavity type features were not mapped. Even though exploratory drill holes showed evidences of old workings up to 250-260 m depth from the ground surface, the present borehole GPR investigation from an underground gallery at 298 m depth confirmed that old workings did not cross the horizontal plane of investigation.**

***Keywords—cross-hole GPR; borehole GPR profiling; water-logged working; radar wave attenuation; radargram; conductive fluid; seepage; Pb-Zn mines***

## I. INTRODUCTION

Mining for metals in India is going on for the past several centuries and relics of ore extraction over the Pb-Zn deposits of Dariba, Rajasthan typically depict mining activities from the ancient times [1]. Several older workings in the form of irregular pits, trenches and small diameter shafts are seen around the area. Some of the abandoned workings are in the form of unlined/lined shafts and show signatures of the then dewatering practices. In Dariba area ancient prospectors had carried out mining up to an estimated depth of 260 m from the ground surface (500 mRL), which makes it the deepest ancient mine in Rajasthan. Delineating the exact course of the excavation and water-logging pertaining to past mining are extremely crucial for carrying out fresh mining below the old workings. Conventionally, exploratory drilling from surface as well as underground is carried out to ascertain the strata condition around a developing drive. Most of the time boreholes are spaced far apart and do not encounter old workings as they are small in size and localised. However, in the event of puncturing a water filled cavity, the fear of inundation and loss of men and machinery is high.

At present, mining in the East load area of Rajpura-Dariba Mines is being carried out below the level of 100 mRL. At 200 mRL, an underground drive was excavated on the footwall at a distance of 12-20 m from the ore body. Several exploratory boreholes (inclined and horizontal) were drilled from the drive along the strike length of the ore body. One of the boreholes drilled at +15$^{o}$, encountered a water filled cavity at a distance of 23 m and lead to water ingress into the drive. Drilling proved that old workings extended up to 220 mRL, however it was not possible to rule out their extension to deeper levels. In this backdrop, borehole investigation was carried out using a stepped-frequency GPR [2, 3, 4] from the 200 mRL drive to assess the rock mass condition. Nine horizontal boreholes (45-55 m deep) all crossing the ore body and extending in to the hangwall rocks were used for investigation. The distance between the adjacent boreholes varied from 25-30m.

Two borehole techniques, vis-à-vis, cross-hole GPR survey and borehole GPR profiling was used for investigation. In cross-hole survey, the transmitter and receiver antennas [5] were singly placed in two adjacent boreholes and the transmission mode data was acquired. In borehole profiling both the antennas were placed in the same borehole and reflection data in common offset mode was recorded along the length of borehole. Radar wave attenuation differentiates the target better [6] and therefore was used in cross-hole interpretation. The reflection patterns from borehole profiling was used to infer the rock mass in terms of areas resembling mined out cavities/ water logged old workings.

## II. Geology of the Area

The Pb-Zn mines of Dariba falls within the Dariba-Bethumni metallogenic belt which comprises of medium to high grade metamorphic equivalents of orthoquartzites, carbonates and carbonaceous rocks belonging to Bhilwara Super Group. The structure of the belt is as an isoclinal fold having synformal closure at Dariba in South and antiformal closure at Bethumni in the North [7]. Lead-Zinc deposits of various sizes and grades occur throughout the belt in both calc-silicate bearing dolomite and graphite mica schist horizons. The latter in general contains low grade disseminated sulphides of large volumes. Sphalerite and galena mineralisation exhibits lithological, stratigraphic and structural control. The nature of mineralisation is sedimentary which subsequent remobilized and recrystallised during polyphase deformation and metamorphism.

Dariba Mine is located at the southern extremity of the belt and the ore body here consists of Main Lode and East Lode. Main lode with a N-S strike is further divided into two, vis-à-vis the North lode and the South lode. The East lode is located about 150-200 m away from the hangwall side of the South lode and has a length of 600m. It strikes N-S and dips easterly at 60° to 70°. The average width of the East Lodes is 18 m and it tends to decrease with depth. Four sets of joints are developed due to deformation and the shears are represented by narrow zones of crushing, brecciation and gouging, mostly 0.1-2.0 m wide. Reverse type faults with low south-easterly dipping planes and striking N40°-60°E are seen at the site.

Borehole GPR investigations at the site was carried out from the 200 mRL drive on the footwall rock. Nine horizontal boreholes between 310N and 530N were utilized for the survey. BH-42 is the southernmost hole and as we move to the North the borehole number increases to BH-49. Borehole BH-39 is the northernmost hole which is adjacent to BH-49. A plan showing the boreholes with their nomenclature is shown in figure 1.

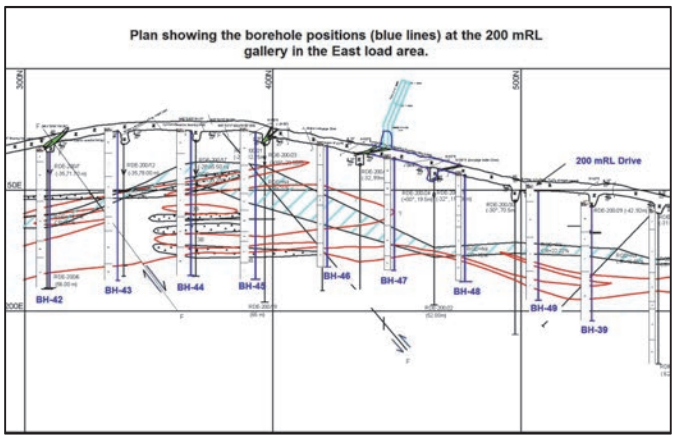


Fig.1: Site plan showing boreholes used for GPR survey located in the 200 mRL drive.

## III. Methodology

Ground Penetrating Radar (GPR) is a high resolution geophysical tool that uses EM waves in the frequency range of 1-3000 MHz for probing the ground. In this frequency range, the wave propagation through the medium is frequency-independent and is mainly governed by the electrical properties such as electrical conductivity $(\sigma)$, dielectric permittivity $(\varepsilon)$ and magnetic permeability $(\mu)$. Important wave field properties like velocity (v), attenuation (α) and the EM impedance $(z)$ are related to the electrical properties by the following relations.

$$v = \frac{1}{\sqrt{\varepsilon.\mu}} \quad \text{....(1)}$$

$$\alpha = \sqrt{\frac{\mu}{\varepsilon}}.\frac{\sigma}{2} \quad \text{....(2)}$$

$$z = \sqrt{\frac{\mu}{\varepsilon}} \quad \text{....(3)}$$

To account for relative permeability of the ground, dielectric constant $(\kappa)$ is defined as

$$\kappa = \frac{\varepsilon}{\varepsilon_o} \quad \text{....(4)}$$

where $\varepsilon_o$ is the permittivity of vacuum (8.85 x $10^{-12}$ F/m). At higher frequencies the variations in $\mu$ is practically insignificant and hence velocity of radar wave is dependent on $1/\sqrt{\kappa}$.

In general, the earth medium attenuates the EM energy by not being a true dielectric (e.g., crystalline solids) as there are free charges. This leads to attenuation of the EM field and limited depth of penetration [8]. The earth materials show wave propagation parameters like radar wave velocities between 0.07-0.15 m/ns, attenuation in the range 0.1 dB/m to 10-100 dB/m) and EM impedance from 100-150 Ω [9]. A comprehensive review of GPR method with respect to EM fields, material properties, system design, signal measurements and data processing is given by [10], [11] and [12].

In the present study a stepped-frequency GPR (SFR) is used for data acquisition. The concept of SFR involves transmitting a fixed bandwidth from a pre-defined start frequency to a stop frequency in frequency steps that increases linearly (figure 2).

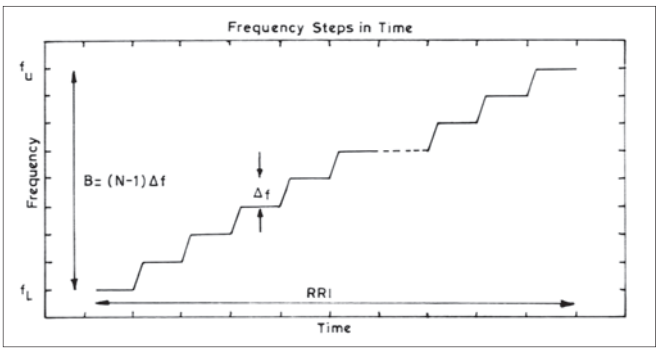


Fig. 2: Representation of a stepped frequency series

In an SFR, if there are $N$ steps (normal values like 51, 101, 201, etc.) with each step having a fractional bandwidth

of $\Delta F$, then the signal bandwidth is given by $B = (N - 1)\Delta F$. Each frequency step in a given bandwidth is transmitted as a pulse enabling the receiver to measure the reflected energy as a function of frequency. The measured signal indicates the amplitude of energy scattered from the subsurface and hence the target response is a sequential measurement over the entire bandwidth [4].

The SFR uses two separate antennas for sending and receiving the signals. These antennas are identical passive elements which are band pass filters [5]. Different antennas are normally used for low and high frequency operations. The input signal of an SFR can be expressed as

$$f(t) = A \exp[\, j2\pi\, (f_1 + n\Delta F)\, t] \qquad (5)$$

$$\text{for} \quad \frac{n-1}{N} T \le t \le \frac{n}{N} T \quad ; \quad 0 \le n \le N-1,$$

where $A$ is the signal amplitude, $j$ is a complex number, $T$ is the signal period, $N$ is the total number of frequency steps and $\Delta F$ is the frequency step interval.

Depending on the central resonance frequency of the antenna, the signal bandwidth of the transmitter has to be adjusted for optimum performance. In SFR, the user selects a frequency band that optimizes the antenna performance for a specific ground condition. This enables the user to extract maximum information with the available hardware. The dynamic range in decibels (dB) for a specified bandwidth in hertz (Hz) is given by

$$dynamic\ range = 20\ log\left(\frac{V_{max}}{V_{min}}\right)\ dB \qquad ....(6)$$

where $V_{max}$ is the largest receivable signal and $V_{min}$ is the minimum detectable signal. The present version of SFR had a dynamic range of 140 dB.

In cross-hole GPR survey, two boreholes were utilized at a time. The antenna and cable system were push in to the respective boreholes by using suitable HDPE pipes. To start with, both transmitter (Tx) and receiver (Rx) antennas were placed deep inside the boreholes at the same depth. During data acquisition both antennas were pulled out of the borehole in equal steps of 0.5 m (figure 3). SRF data was recorded for each Tx-Rx positions from the deepest point to the borehole collar.

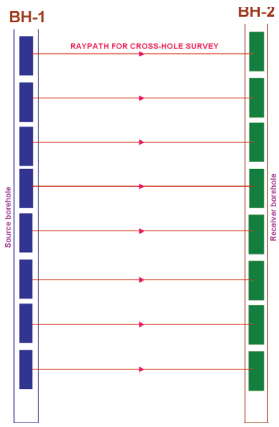


Fig. 3. Schematic layout for cross-hole GPR survey.

Based on the frequency response of the intervening medium, a wide bandwidth was selected for survey. For the present site data acquisition was done over a bandwidth of 10-550MHz. GPR wave velocity and attenuation between the transmitter hole and receiver hole was measured in a sequential manner as shown in. The borehole geometry (i.e. the borehole depth, inclination, the separation between the two holes), antenna movement steps, strength of the signal, etc., were carefully recorded as they form key elements for data processing and interpretation.

Processing of cross-hole transmission data was done to determine the velocity and radar wave attenuation in the intervening medium. Velocity analysis from one-way travel time showed that there was no noticeable changes in the radar wave velocity in the rock material that could be used to get a meaningful interpretation of targets. Analysis for radar wave attenuation was done by extracting the maximum amplitude value for each recorded trace (for each Tx-Rx position). After getting the amplitude values for each trace in the data set, these amplitudes were normalized in respect to maximum amplitude. The normalized amplitudes for each cross-hole GPR test was then converted into dB values and plotted to obtain the 2D image of the radar wave attenuation.

Borehole profiling is an adaptation of the conventional GPR wherein the antenna is moved along the length of borehole to map the ground condition around the borehole [13]. In profiling mode, GPR generally records the common-offset reflections from the subsurface (figure 4). Normally the field amplitudes are measured with respect to time of excitation of the EM pulse accounting for the two way travel. The signal attenuation characteristics of the medium define the depth of penetration. While in operation the transmitter and receiver were inserted into the same borehole with a separation between two antennas equal to one antenna length. A fixture with HDPE pipe was made for movement of Tx-Rx unit. Borehole profiling was done in an inside-out manner wherein Tx-Rx unit is pulled out from the deepest point in the borehole.

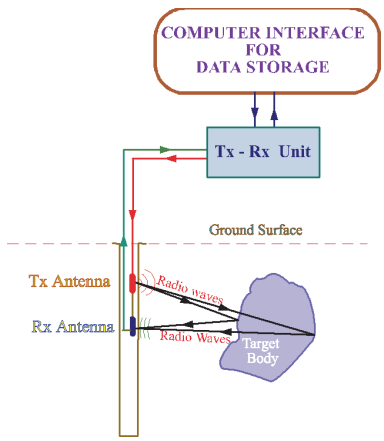


Fig. 4. Schematic layout for borehole GPR profiling.

Processing of the two-way travel time data followed several steps including use of scaling operation (window function), frequency filtering (Hanning operation), averaging (background subtraction), moving average operation,

smoothing, etc. After carrying out signal processing (in time domain) on individual data series the output is integrated by a software. The image of the subsurface is conventionally called a radargram. Both magnitude and phase plotting was done to delineate targets in the reflected signal. Interpretation of the subsurface in terms of ranging and resolving the targets are done based on the pattern of reflections.

There are distinct advantages of using an SFR for which they are referred to as the second generation of GPRs. It is possible to determine the working bandwidth of an antenna by frequency domain measurements. As a result system can be calibrated for the ground condition. The signal strength at the receiver antenna can be monitored and therefore the characteristics of the earth material can be estimated. It is also possible to do spectrum-related signal processing such as frequency filtering, deconvolution, Hilbert transform, etc. easily as data is in frequency domain. Due to use of multiple narrow bands the target resolution and depth of investigation is enhanced [4].

## IV. Results and Discussions

The outputs of cross-hole GPR survey are the plots of radar wave velocity and radar wave attenuation for the study area. Since there were no noticeable changes in the radar wave velocity in the rock material they are not discussed here. However, the plot of the radar wave attenuation is very interesting. In case of borehole GPR profiling, the strength and patterns of reflected signals from different horizons are used to infer various targets in the radargram. Since the reflections from targets of interest (old workings) have to be viewed in the backdrop of reflections from geological interfaces, the interpretation is carefully done after correlating with bore logs. For sake of brevity, radargrams for survey in two boreholes, boreholes BH-43 and BH-45 are only discussed in this paper. Interpretations of results are as follows:

### *Cross-hole GPR Survey*

The normalized plot of the radar wave attenuation between borehole BH-39 and borehole BH-42 (refer Fig. 1) is shown in figure 5. Depending on the depths of boreholes, the 2D image from the horizontal plane of survey (covering foot wall, ore body and hanging wall) is constrained. Various geological features such as the ore body, shear zones and projection of probable old workings are superimposed over the attenuation plot. The attenuation plot of the study area shows values ranging from 0-28 dB/m. This signifies the fact that there is a large contrast in electrical conductivity in the medium. The distribution of contours in the 2D plot shows variations in orientation and spacing between contours. Closely spaced contours signify sharp change in medium property representing geological boundary. Wide spacing between contours means defused interfaces. Closed contours indicate zones that are circular on the plane of survey.

The attenuation plot from cross hole survey shows three distinct zones. Zone-1 is identified as an area with GPR wave attenuation in the range of 0-10 dB/m, Zone-2 has attenuation values ranging from 11-20 dB/m, and Zone-3 has the highest attenuation of 21-28 dB/m. Zone-1 is primarily a closed envelope (appear in blue colour) between the boreholes BH-43 and BH-44 with its centre around 18 m deep from the open face of 200 mRL gallery. A relatively lower value of radar wave attenuation around this area is inferred as resistive rock mass. Though it is known that the sulphides are conductive, disseminated sulphides are resistive [14]. The low conductivity can also be because of larger joint spacing which means that the rock mass is particularly good as compared to the other areas. Borehole logs from these boreholes confirmed that the shear zone is not fully developed and rocks are characterised by tight joints. Apparently no signatures of old workings or weak zones are seen here

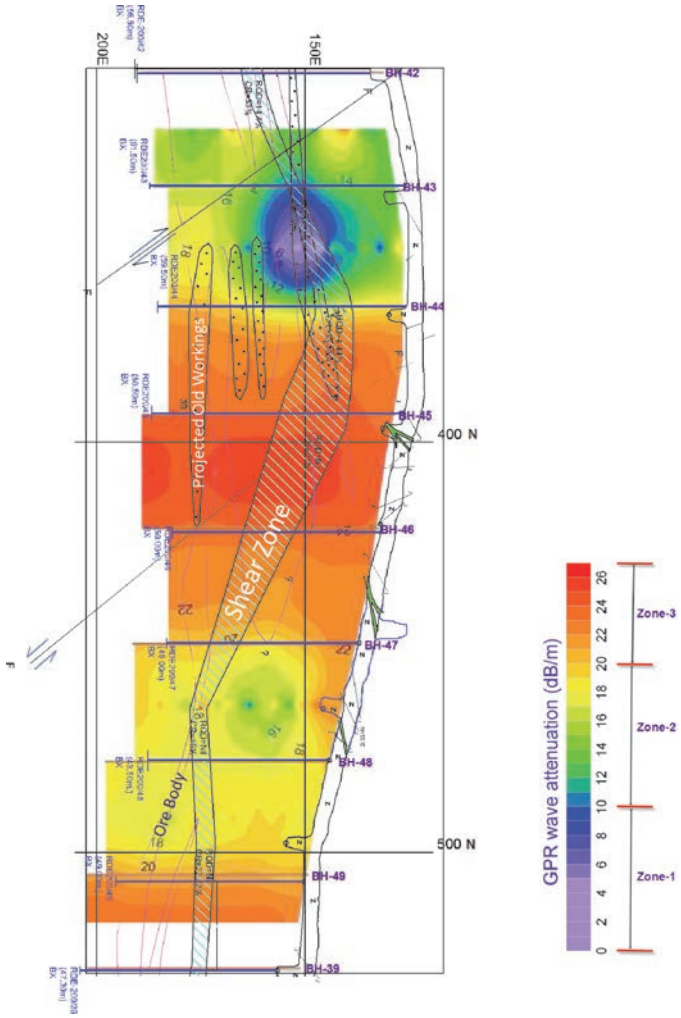


Fig. 5. Plot of radar wave attenuation for the study area.

Zone-2 is marked by the green-yellow coloured contours in the attenuation plot which pertains to attenuation values of 11-20 dB/m. There are two separate regions which fall under Zone-2, viz-à-viz the northern region between boreholes BH-47 and BH-39 and the southern region between BH-44 and BH-42. These regions with intermediate values of attenuation might be representing the rock mass from the general background. Closer look at the contours and their pattern show a correlation with the orientation of the shear zone. In the southern region (between BH-44 and BH-42) the

contours of attenuation align with the direction of the shear zone. The comparatively lower attenuation values (12-16 dB/m) here might be due to presence of mineralized zones and fresh water. In contrast, the northern region (between BH47 and BH39) has higher radar wave attenuation (16-20 dB/m). This difference might be indicating the extent of saline water mixing in these two regions. The geological section in this area shows that the shear zone is more developed towards the northern side as compared to the southern side. The near vertical disposition of the shear zones and presence of saline water in the old workings above the study area may have allowed mixing of conductive fluids in the northern region. No signature of old working is seen crossing the plane of investigation.

Zone-3 is identified as a crucial zone as the radar wave attenuation values (21-28 dB/m) are the highest. This zone is spread between the boreholes BH-46 and BH-44. Here the contours of attenuation are aligned in the direction of survey boreholes and there are no contour closures matching the size of old working. This shows that strata condition remains consistent as we proceed from the foot wall side to the hanging wall side. The higher values of attenuation in the central part of this zone might be due to the presence of high grade Pb-Zn deposits or due to the presence of saline water that percolated from the old workings above. Geological section around this area shows that shear zone is developed to its maximum in Zone-3 and hence the presence of highest attenuation values around this area is justified. Even though direct evidences of old workings is not seen, the study area definitely falls in the zone of influence.

*Borehole GPR Profiling*

Radargrams for two boreholes, vis-à-vis BH-43 and BH-45 are presented here. The radargram for BH-43 (56 m deep borehole) is shown in figure 6. The GPR reflection in the first half of the radargram (0-26 m depth) shows strong reflections from some shallow level targets as well as poor reflections from deeper levels. The discontinuous reflection from 12-22 m distance from the borehole collar is a fault followed by shear zone which was confirmed from available core log. The attenuation plot (Fig.5) around BH-43 shows resistive ground in the middle portion, however, the radargram shows a complex reflection pattern which might be due to mineralized pockets. As such no cavity type feature is mapped in the radargram.

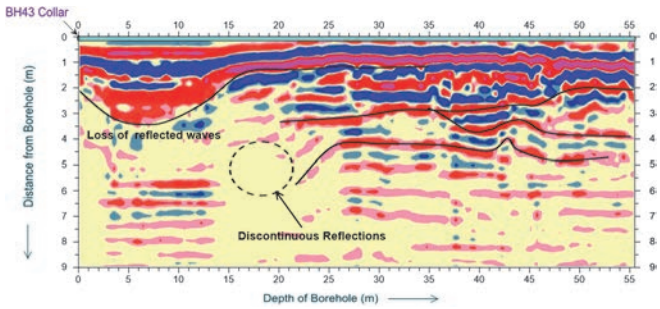


Fig. 6: Radargram from GPR profiling in borehole BH-43

The radargram for BH-45 (figure 7) shows very feeble reflections from beyond 4-5 m depth indicating towards a conductive ground. The attenuation plot (fig.5) also confirms this as the area comes under Zone-3 which is affected by saline water from the old workings. The reflections from subsurface are more or less consistent and show that reflectors are mainly the geological interfaces. Two circular patterns are seen at 3-5 m distance from the borehole axis at a depth of 5-10 m and 38-42 m in to the boreholes.

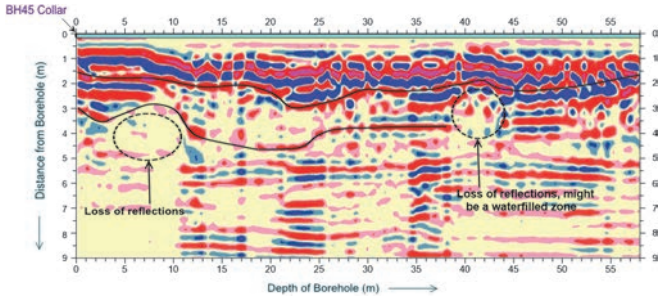


Fig. 7. Radargram from GPR profiling in borehole BH-45

The target at 5-10 m distance from the borehole collar appears to be a geological feature as it extends laterally over a large area on the radargram; however the circular target corresponding to 38-42 m position in the borehole looks a lot like reflections from old working. The complex nature of the reflections and presence of circular targets indicate that borehole might be in the near vicinity of some old workings.

## V. Conclusion

The present study involving borehole GPR investigations in horizontal drillholes for an underground mining gallery is one of the first in Indian mines. Two techniques, vis-à-vis cross-hole GPR and borehole GPR profiling was carried out from a set of boreholes. Two important results were derived from the GPR survey. The radar wave attenuation plot from cross-hole GPR survey showed normalized attenuation values in the range of 0-28 dB/m for the intervening medium. GPR profiling in boreholes showed patterns of reflected signal from different horizons which was used to infer targets of interest in the radargram.

The study area is divided into three zones based on the radar wave attenuation. Lower attenuation values (0-10 dB/m) of Zone-1 is interpreted as relatively resistive ground indicating better rock mass condition, disseminated sulphides or area with fresh water (no mixing of conductive water from old workings). Zone-2 (11-20 dB/m) is characterized by jointed rock mass showing moderate level of saline water mixing through shear zone. Zone-3 (21-28 dB/m) is bothersome as the shear zone is widest and the rock mass condition is relatively poor. Here the saline water from old working appears to have percolated down to the survey area. The closing of contours of 26-28 dB/m in Zone-3 shows the central position having closest proximity to the old workings (zone of influence). The radargram from GPR profiling in BH-45 also showed some loss of signal and circular targets indicating that borehole might be in the near vicinity of some old workings.

Delineating the course of excavation and water-logging due to past mining are crucial for carrying out fresh mining

below the old workings. When conventional methods like drilling fail to locate the exact boundary of the old working; geophysical methods can be used from surface or underground to pin-point the target around the borehole. The present investigation using borehole GPR from an underground gallery in a Pb-Zn mine has shown that the method could be successfully applied for sensing the proximity to old workings and other geological interfaces.


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