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The Integration of Borehole Geophysical logs for Geotechnical Risk Assessment at the Paardekraal 13-Level Ventilation Shaft Project

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ABSTRACT

Downhole wireline logging and borehole radar surveys were undertaken at Paardekraal in two shaft geotechnical boreholes for the planning and design of ventilation shafts for underground platinum mining. Paardekraal is one of production areas of Anglo Platinum's Rustenburg Section, Rustenburg Platinum Mines Limited, on the Western lobe of the Bushveld Complex. The horizons mined for platinum group metals are the Merensky Reef (MR) and the UG2. Old MR support pillars are targeted to provide stable ground conditions for a vertical shaft to access to the UG2 horizon, which lies stratigraphically below the mined out MR.

Studies show that most structures (jointing) in the Bushveld Complex are steep-dipping and could pose a threat to mining operations even over short distances. Mapping of structures intersecting the borehole, their location and their orientation is used to assist in highlighting zones of potential hazard and to characterize rock formations. Key geophysical tools were deployed in the Paardekraal geotechnical boreholes to complement standard drill core geotechnical analyses. The acoustic televiewer records high resolution (2 mm pixel), oriented images of the full circumference of the borehole sidewall and maps in detail the location and orientation of structural features intersecting the borehole. Density and sonic velocity logs provide information on rock strength and competence. Flowmeter, differential temperature, neutron and fluid conductivity logs identify zones of possible ground water ingress (fluid pathways).

A method for integrating the structural and geotechnical information, interpreted from the geophysical logs, into a single, visual log that highlights hazardous geotechnical zones was applied. This so-called Hazard Index (HI) is a weighted combination of the following parameters, namely: intact rock strength (IRS), shear wave slowness (SWAV), fracture frequency (FRAC), joint intersection rating (INTS) (based on fracture tilt combination), water ingress (FLOW) and fracture density projected within the shaft barrel (FDEN).

Borehole radar in reflection mode penetrates the formations around the borehole to distances of up to 50 m (and sometimes further). This gives information about the condition of the rock mass surrounding the borehole and the lateral extension and continuity of major structural features and dykes. Critically, the radar data was analysed for information on the location of old MR workings with respect to the proposed position of the shaft excavations and the integrity of the MR pillar surrounding the shafts.

Key words: Wireline logging, Bushveld Complex, Hazard Index, Risk mitigation, Shaft construction, Raisebore

INTRODUCTION

Paardekraal mine, situated in the Western lobe of the Bushveld Complex in the North West Province of South Africa, is one of the production areas of Anglo Platinum's Rustenburg Section of Rustenburg Platinum Mines Limited (RPM). Figure 1 shows a simplified map of the outcrop of the mafic Rustenburg Layered Suite (RLS), estimated to contain over half the world's platinum group element (PGE) resources (Cawthorn, 1999), and the location of Rustenburg Platinum mine. Platinum is mined commercially from two laterally continuous, shallow dipping (<10°), mainly pyroxenitic reefs, the Merensky Reef (MR) and UG2 (Cawthorn *et al*, 2006). Mining of the MR at Rustenburg Section has advanced down dip from outcrop to depths in excess of 1 km below the surface over the last 50 years. The UG2 reef occurs stratigraphically 120 m below the MR at Rustenburg Section. Mining of the UG2 only commenced more recently (in the last 20 years).

Figure 1. Simplified map showing the outcrop of the RLS of the Bushveld Complex and the location of Rustenburg Platinum mine

With ongoing expansion down dip, vertical shafts are required to provide ventilation for the underground mining operation. In order to avoid intersecting the old MR mine workings above, the UG2 ventilations shafts are sited to intersect old MR pillars. Pillars are sections of reef that were not mined out, either left for stability, or representing reef that was deemed commercially not viable to mine, e.g. potholes. Pillar dimensions vary significantly depending on the original reason for not mining the ground. The true location and extent of old mine pillars are not always well known as old mine plans may be difficult to interpret (being based on outdated positioning techniques and old projection systems) and are often unreliable. Understanding the geotechnical properties of the MR pillar is critical for determining the long-term stability of a shaft excavation through the pillar. Geotechnical boreholes are drilled prior to shaft construction to investigate the integrity of the formations at the planned shaft location.

Conventional shaft sinking is achieved by blind-sink from surface using drill and blast techniques. A geotechnical investigation for conventional shaft sinking is usually concerned with location, support requirements and groundwater inflows. Raiseboring has certain advantages over conventional shaft sinking (McCracken and Stacey, 1989), in particular:

- Damage to the rock mass behind the excavation is minimised, thus maintaining an inherent rock strength and stability;
- A smooth finish on the shaft is maintained precluding the requirement for lining (desirable for ventilation);
- Greater efficiencies in time and cost and manpower are achieved – depending on depth and shaft specifications, a raisebore shaft may be less than 25% of the cost of the equivalent blind sink shaft.

The disadvantage of a raiseboring operation is that it excludes access to the working face and thus precludes immediate ground support on intersection of poor ground conditions. The vertical nature of raisebored shafts (as opposed to bored tunnels for example) means that support is also unavailable behind the advancing face.

For raiseboring the focus of geotechnical investigations is the overall feasibility of the shaft since the ground conditions through which the shaft will pass must be of sufficient quality to allow a free-standing, unsupported excavation for at least the duration of the boring operation (McCracken and Stacey, 1989). Unexpected ground conditions that cannot be dealt with successfully, or intersection of old mine workings, may even force the abandonment of a raise. Current methodology for raisebore risk assessment is based on geotechnical logging of drill core from pilot geotechnical boreholes and takes into account factors such as lithology, major geological features (dykes, faults, folds, contacts, etc.), rock fabric (discontinuity, orientation, spacing, persistence), discontinuity shear strength (joint roughness, infill, alteration, water), rock strength (intact strength, weatherability), groundwater, *in situ* stress and change in stress (McCracken and Stacey, 1989).

A drawback of core-based geotechnical analyses is that they sample just a small fraction of the volume of rock to be excavated, e.g. for a 200 m shaft, less than 0.01% of the volume of the proposed shaft barrel is sampled (Pretorius *et al*, 2007). The assessment of rock mass conditions from drill core necessarily makes assumptions on joint set populations (unless oriented structural information is available, e.g. from oriented core or televiewer logs) and the continuity of joint and structure conditions away from the borehole.

Borehole geophysical methods can deliver many of the critical parameters for a geotechnical risk assessment and range from high-resolution (mm scale), oriented surface scanning techniques (e.g. televiewers), to techniques that obtain a bulk sample of the formation around the borehole (10s of cm penetration into the formation), to off-hole techniques (e.g. radar) that scan away from the borehole (10s of metres penetration, albeit at lower resolution). A combination of measurements samples a much larger volume of the formation that will be affected by the excavation, than the sample taken for laboratory. Since a continuous log is measured *in situ*, the data is also not limited by zones of core loss or breakage.

A perceived drawback of geophysical methods is that the data is not always intuitive and is generally not well understood by mining engineers and geologists without prior knowledge of geophysical methods. A so-called Hazard Index (HI) developed by Anglo Technical

Division's Geosciences Resources Group (Chalk and Chalke, 2007), combines the different geophysical datasets through a weighted formula and serves as an indicator of hazardous rock formations that is visually intuitive and easy to interpret. The concept is similar to standard rock mass classification schemes employed in geotechnical studies, e.g. Barton's Q-system (Barton *et al*, 1974) or Laubscher's Mining Rock Mass Rating (Laubscher, 1990), although at this stage does not provide recommended support requirements based on the outcome of the analysis.

Examples of the application of the geophysical HI in the Paardekraal 13-level UG2 expansion shaft site investigation illustrate the role of the downhole geophysical methods in shaft geotechnical investigations.

METHODOLOGY

For the Paardekraal 13-level UG2 expansion, shaft positions for two vertical ventilation shafts were selected at the location of old MR pillars in the region. Geotechnical boreholes intersecting norites, anorthosites and pyroxenites of the main and critical zones of the Bushveld Complex, were drilled at each location in order to evaluate the integrity of the formations to be excavated, in particular the integrity of the MR pillars. As part of the geotechnical analysis, downhole geophysical wireline logging was conducted with the aim of assessing rock mass properties and mapping structures that may be of potential hazard to the shaft excavation.

The two boreholes were diamond core-drilled vertically to depths of 408.3 m and 384.85 m respectively. The initial outside diameter of the boreholes was 76 mm (NQ) and changes to 60 mm (BQ) around 200 m depth when drilling conditions became too difficult to maintain the larger borehole size.

The following suite of downhole wireline geophysical logging probes was surveyed over the full depth range of the two boreholes:

- 3-arm caliper
- Magnetic susceptibility
- Dual Density / natural gamma / caliper
- Dual Neutron / natural gamma
- Acoustic Televiewer (ATV) / Deviation
- Optical Televiewer (OTV) (above water level)
- Full Waveform Sonic (FWS)
- Fluid temperature / fluid conductivity
- Multi channel P-wave sonic
- Flowmeter (induced flow)
- Borehole Radar

The application of borehole geophysical data for engineering structural and geotechnical studies has been previously reported (see for example: McNally, 1990; Schepers, 1996; Hatherly, 2001; Medhurst and Hatherly, 2005; Trofimczyk, 2006). Oriented structural information is obtained from the ATV and OTV tools. Rock strength (competence) information is obtained primarily from sonic and density logs. Location of water-filled fracture systems is derived from analysis of temperature, fluid conductivity, neutron and fluid flowmeter logs. The borehole radar probe deployed in reflection mode, images steep angle structures that run 'semi-parallel' to the borehole axis up to a radius of ~50 m around the borehole. Although the resolution of the radar (around 1 m) is lower than the conventional wireline logs, this measurement samples the complete rock mass affected by the proposed shaft excavation. The limitation of current slim-line borehole radar probes is that they are omni-directional; hence, it is not possible to determine the absolute orientation of a reflector in relation to the borehole

The geophysical information was compiled into a geophysical Hazard Index (HI) log sampled in 1 m blocks and compiled from a weighted average of the following component ratings:

- Intact Rock Strength (IRS)
- Shear wave slowness (SWAV)
- Joint Intersection Rating (INTS)
- Fracture frequency (FRAC)
- Fracture density at shaft diameter (FDEN)
- Flow Profile / water ingress (FLOW).

Intact Rock Strength (IRS): A derived UCS (Unconfined Compressive Strength) log is calculated using McNally's (Australian coal) formula (McNally, 1990):

$$UCS = 1000e^{((-0.011)\cdot(WAVP))} \qquad (1)$$

The formula is not calibrated to local Bushveld conditions and is thus really a relative bulk rock strength indicator. As a result, it will be affected by IRS and open fractures, but will be less sensitive to minor fractures. So it will indicate IRS between fractures if calibrated. The UCS log is block-processed to 1 m intervals and then converted to a weighting between 0 (high IRS) and 10 (low IRS).

Shear wave slowness (SWAV): The shear wave does not travel through open fractures and water. The shear front collapses completely at open, water-filled fractures. The SWAV log is thus sensitive to rock integrity. A SWAV transit time log is derived from semblance analysis of full waveform sonic wiggle traces. Low transit time (or high velocity) is assigned a low the weighting in the HI. Conversely, a high HI rating is assigned to high values of SWAV. The weighting is based on the assumption that faster rock is more competent. The SWAV weightings as currently applied are not calibrated to any real rock strength parameters due to an insufficient database of core test data for calibration. Although subjective, the same weightings are applied on all shaft geotechnical projects for Anglo Platinum, in the Bushveld, until a modification is justified.

Joint Intersecting Rating (INTS): The ATV and OTV structures are classified into four joint set classes based on dip ranges. The borehole is broken down into geotechnical zones of depth intervals generally ranging from 20 m to 50 m. The selection of geotechnical zones is subjective, but is guided by lithological contacts, zones of consistent fracture patterns and the character and texture of the radargram (i.e. location of key reflectors and limit of penetration of the radar signal). Different weightings are applied to different joint set class combinations. The combination of multiple steep dipping joint sets with shallow dipping joint sets is given the highest weighting. The rating, out of 20, is based on the sum of all possible dip range combinations.

Fracture Frequency (FRAC): The ATV and OTV structures (excluding lithological and drilling induced fractures) for the full borehole depth range are blocked to 1 m intervals and the number fractures counted for each metre block. A rating between 0 (no fractures or joints) and 10 (greater than 15 fractures per metre) is assigned to the HI.

Fracture Density at Shaft Diameter (FDEN): Each structure interpreted from ATV or OTV images is represented by a depth point at the centre of a sine wave described on the 2D display of the image of the full circumference of the borehole sidewall. In case of steep dipping structures, the top of the sine wave / (or fracture) will be higher up the borehole and potentially interacts with other fractures at these locations. These combinations are not captured in the fracture frequency log. The problem is compounded if fracture sets are extended to the shaft diameter (up to 10 m for a main personnel shaft) as illustrated in Figure 2 from one of the Paardekraal geotechnical boreholes. To overcome this problem, a structure log with a shaft diameter, but based only open, major and minor classifications is used to generate the fracture image. This is a fracture intensity log, calibrated for fracture count, blocked at 1 m intervals, weighted and included in the HI calculations. The assumption made is that a set of fractures, acted upon by the same force, would probably extend well beyond the narrow borehole frame of reference, although this may not be the case in individual fractures. High values of FDEN attract higher weighting in a rating from 0 to 10.

Water Ingress (FLOW): In the Bushveld, fluid flow is confined to pathways represented by secondary porosity (faults, shear zones and fracture systems). Identification of zones of water ingress into the borehole is based on the fluid temperature, fluid conductivity and flowmeter logs. Where flow is inferred within a geotechnical zone a weighting is assigned based on the magnitude of flow as well as confidence in the interpretation, e.g. A major event visible on all logs and coupled with the incidence of an open fracture on the ATV image carries the highest weighting on a scale from 0 to 10.

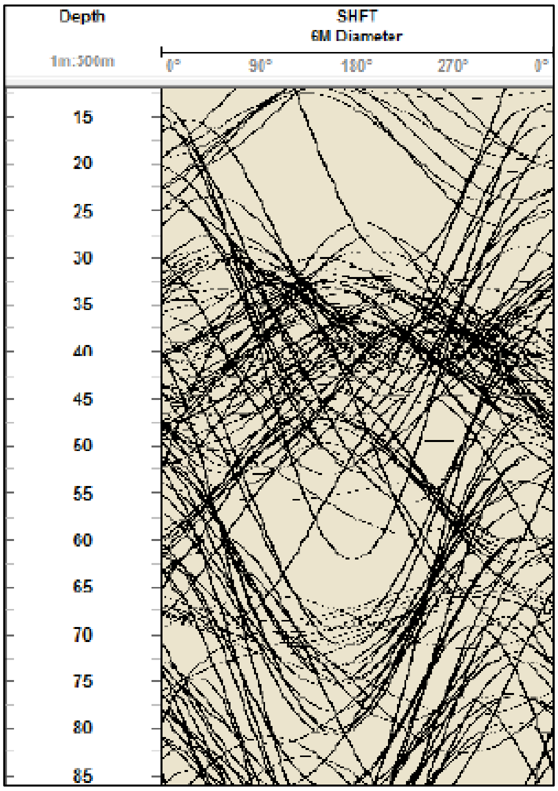

Figure 2. Fractures projected to shaft diameter

The Hazard Index: The HI parameters are combined using the following formula to give a final hazard rating out of 100, for 1 m blocks along the borehole path:

$$\frac{\{UCS\} + \{FRAC\} + (\{INTS\} \times 2) + \{FDEN\} + (\{FLOW\} \times 1.5) + (\{WAVS\} \times 1.5)}{80}$$

(2)

In equation 2, the joint intersection rating, shear wave rating and water flow rating are given extra weight. This increases the influence of major and open structures on the derived HI. Although subjective, the HI scheme has been based on discussions with mining and geotechnical engineers and is weighted in favour of geotechnical factors perceived to have the greatest influence on an underground excavation.

RESULTS

A strip log depth plots of the derived geophysical HI for the two geotechnical boreholes are shown in Figures 3 and 4 (in appendix). The core geology log is displayed in the track to the right of the depth column. Norites are shaded green, anorthosites yellow and pyroxenite in orange. The Merensky Reef is intersected at 185 m depth in BH1 and 221 m below surface in BH2. The various components of the HI are displayed in the tracks following the televiewer image, which is right of the core log. The HI itself is plotted in the final track at right. The location of zones of high rating (>30) and consequently greater geotechnical risk are highlighted by red shading.

In BH1 (Figure 3) the HI highlights two potential hazardous zones. The upper zone from 28-44 m depth, in norite, is heavily fractured with multiple intersecting fractures with a coincident flow anomaly. The drill core over this depth interval is shown in Figure 5 and confirms the geophysical observation. Pre-collar cementation to a depth of 45 m could mitigate the geotechnical risk to shaft sinking in this location.

Figure 5. Core photo of upper hazardous zone in BH1

The second zone highlighted occurs at 190 – 202 m, just below the MR. This zone is characterised by shallow to steep dipping open and major fractures. There is an aquifer (strong induced flowmeter anomaly) at 193 m that corresponds to a 12 cm thick, flat-lying weak layer that is washed out. Significant perturbation of the sonic data including loss of shear wave at the 193 m event is observed. During drilling, the driller was forced to case the borehole through this zone to prevent water loss. The proximity to the MR indicates the possibility of fracture connectivity with the pre-existing, old underground workings. In contrast, a zone of higher fracture density around 165 – 175 m is not flagged as a hazard. A strong shear-wave front, unperturbed by the presence of fractures indicates tight stable fractures with no porosity.

Penetration of the radar signal into the formation to at least 30 m (up to 60 m in places) was obtained throughout the depth range of BH1 and gives an indication of the extent of the MR pillar around the borehole. Of concern, however, was the identification of a strong, sub-vertical that parallels the length of the borehole at a range varying between 5 m and 15 m from the borehole. The event does not intersect the borehole and thus cannot be identified geologically or oriented with respect to the borehole.

In BH2 (Figure 4) the geophysical data shows intersection of generally good, competent formations with HI rating on average <10. Two zones of potential hazard are highlighted on the HI. The lower zone occurs within the UG2 pyroxenite (340 – 355 m) just above the UG2 reef. Although flagged as a hazard, the rating peaks only around 50 and is primarily built around a combination of inferred hazard indicators, e.g. the fractures are generally classified as minor, but a mix of orientations results in a high intersection rating; flow is inferred from the temperature and fluid conductivity logs, but a flowmeter response could not be induced despite high effective pressure being applied.

The upper zone in the depth range 180 m to 225 m encompasses the Bastard reef and MR pyroxenites (Figure 4). This zone comprises three clusters of high density fracture zones displaying mixed sets of different angles and orientations. The uppermost hazard within the hanging wall anorthosite, is not heavily fractured, but includes a definite water flow anomaly that corresponds with an open fracture of moderate dip (33°), which elevates the HI rating. The middle hazard encompasses the Bastard reef and is heavily fractured (fracture frequency is high at 10 per metre over several metres) and broken with multiple open events observed on both the amplitude and travel time images of the ATV. Orientations are mixed contributing to a high intersection rating. Although there is no flow anomaly, an 11 cm thick weak layer at 203.5 m was washed out during the drilling process. The lower hazard zone corresponds to the MR pyroxenite (220 – 223 m) and is intersected mostly by minor fractures, but, again, with a high intersection rating.

The radargram for BH2 is shown in Figure 6 (in appendix). The depth range from 180 m to around 230 m displays significant disruption of the radar signal compared to the rest of the borehole. The high density of fracturing around the Bastard reef has resulted in significant attenuation of the radar signal. The incidence of hyperbolic events (reflections off a point source) around the depth of the MR coupled with reduced penetration of the radar signal may indicate the possible proximity of underground workings within 10 m of the borehole. A classical 45° V-shaped anomaly is generated by radar waves travelling up the borehole and interacting at the interface of the moderately dipping water-filled structure at 184 m. Risk to the long-term stability of a shaft at this pillar location is indicated.

CONCLUSIONS

Two shaft geotechnical boreholes were drilled at Anglo Platinum's Paardekraal mine in the Western Bushveld to investigate the feasibility of raiseboring shafts through old MR pillars, to provide ventilation to the underground UG2 workings. As part of the study, a suite of borehole geophysical probes were surveyed in the boreholes. A method for integrating structural and geotechnical information, interpreted from the geophysical logs, into a single, visual log that highlights hazardous geotechnical zones (a Hazard Index) was applied. In both cases, the predominant geotechnical hazards occur around the location of the MR. Borehole radar data samples the rock mass up to 50 m (and sometimes further) around the borehole and delivers additional information on the existence and continuity of major events away from the borehole that might affect the long-term stability the shaft excavation. In one of the boreholes, a significant off-hole radar reflector, not detected in the drill core or wireline logs, parallels the borehole at close range. In the second borehole, perturbation of the radar signal around the location of the MR pillar may indicate proximity to the old MR underground workings.

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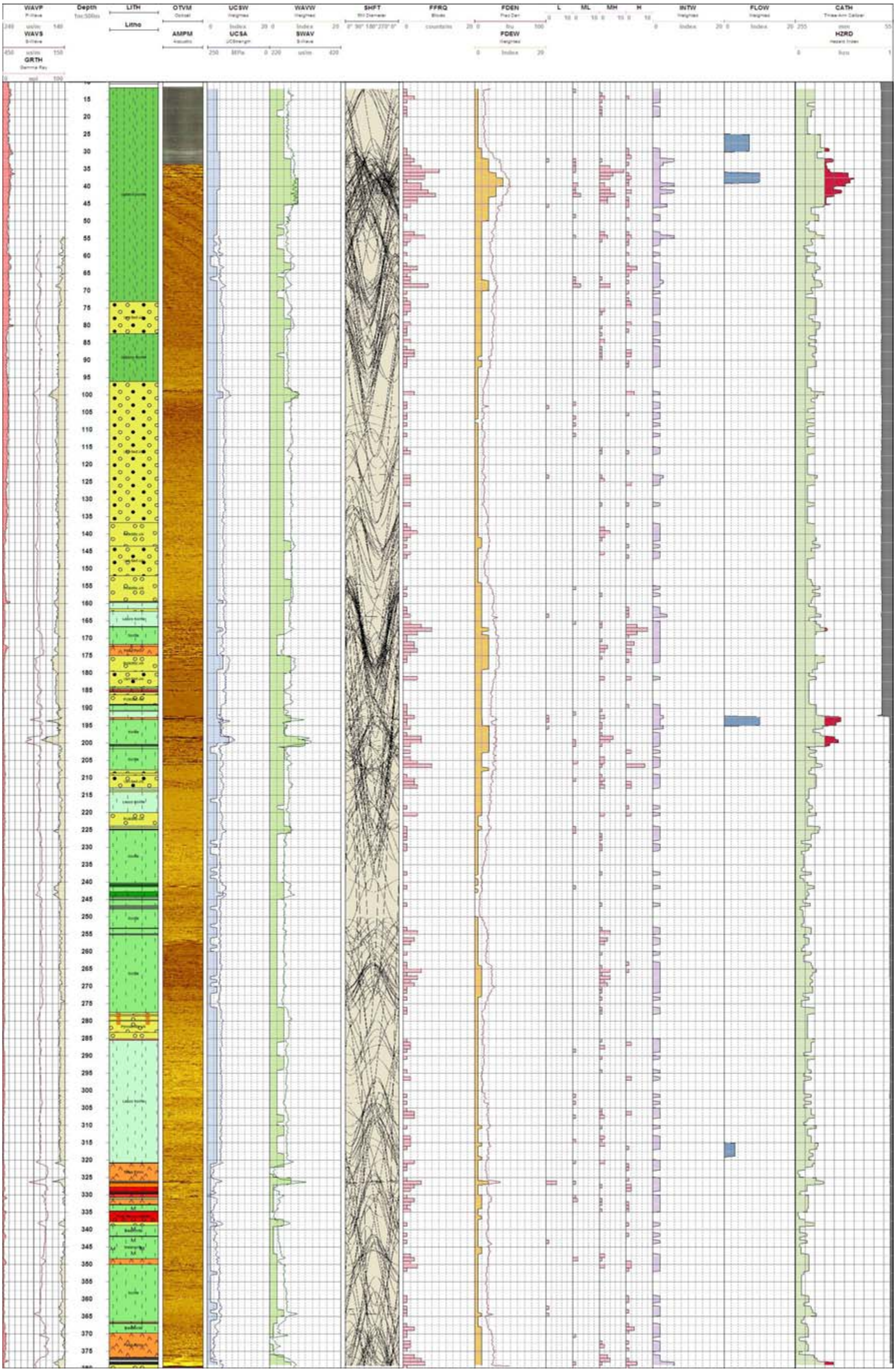

Figure 3: The hazard index (HI) log (far right track) and hazard index components logs for the first surface ventilation shaft borehole (BH1); the HI is shaded red if its value exceeds 0.3 and anything above this threshold is considered as a zone of potential geotechnical hazard.

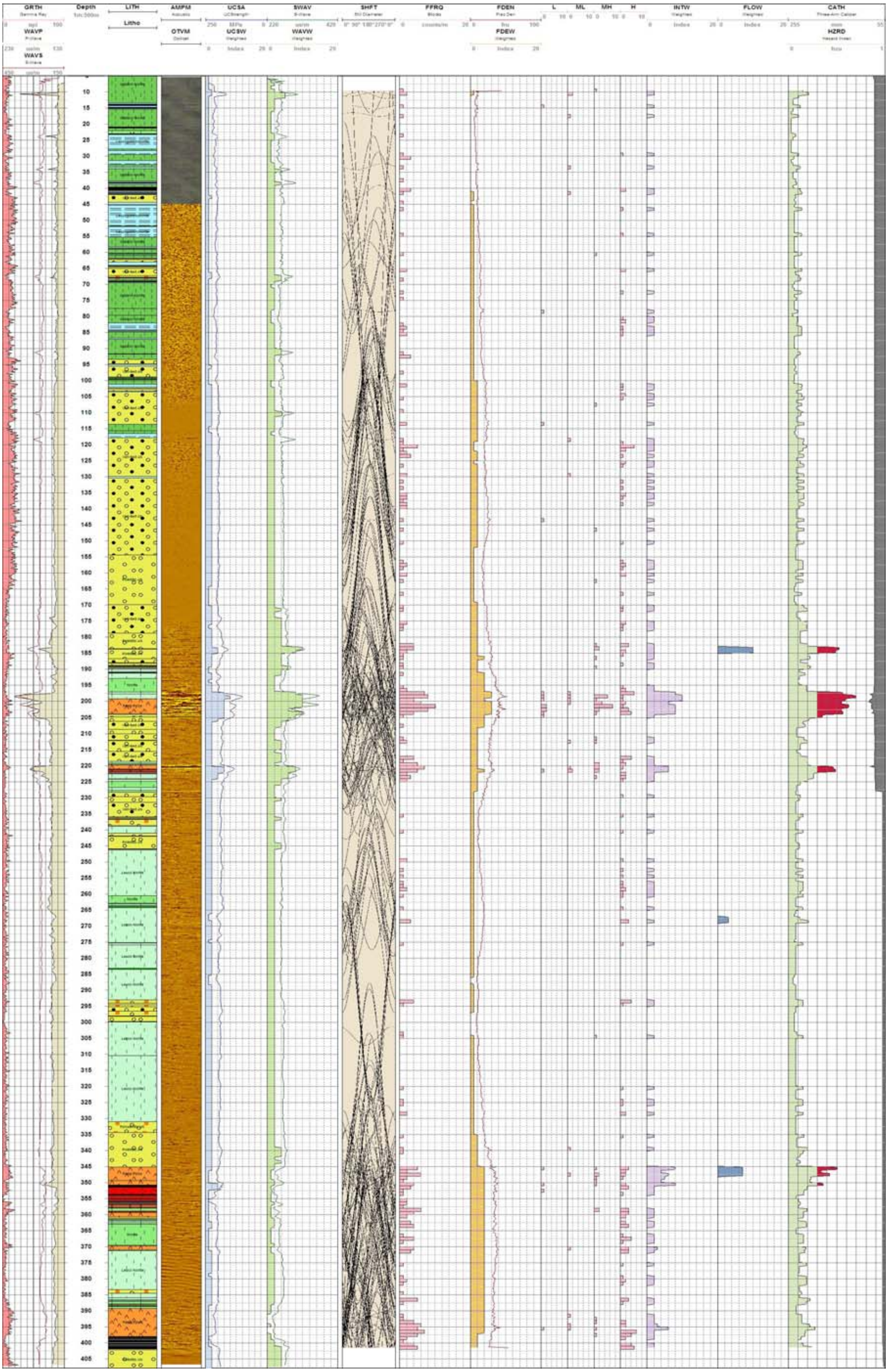

Figure 4: The hazard index log (far right track) and hazard index components logs for the second surface ventilation shaft borehole (BH2).

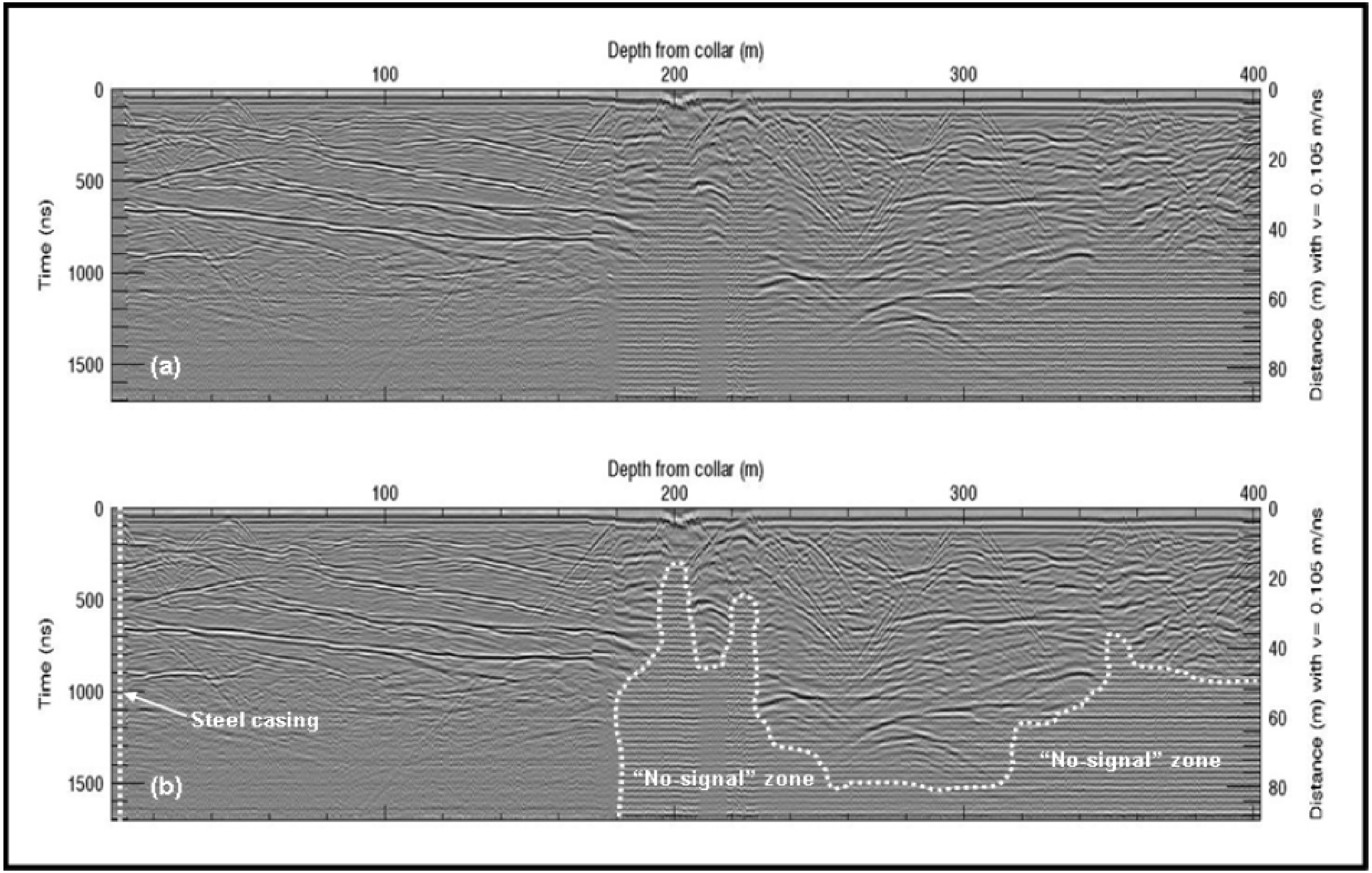

Figure 6. Radargram in BH2 with illustration of zones of loss of signal penetration; the x-axis shows depth down the borehole, y-axis shows time (ns) on the left and calculated distance from borehole on the right