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Technologies for Optimizing Drilling and Blasting in Open-Pit Mines

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ABSTRACT: A necessary requirement for optimization over the complete mine/mill/leach operation is continuous and accurate data at all steps of the process allowing fragmentation, crushabilily/ grindability/ leachability, slope stability, and safety to be evaluated simultaneously. In an ideal sy.stem, these data would be analyzed centrally and used in a feedback loop to modify mining operations and process-control variables as necessary to improve performance. The objective of the project described in this paper is to demonstrate technologies that can increase the amount of information obtained during drilling, and understand how this information can best be used to improve blasting results, route blasted rock, and increase the efficiency of downstream mineral processing. The technological goals of the project presented in this paper include development of various sensors, data-acquisition systems, and online analysis tools that will allow real-time characterization of the rock mass and bore-hole measurements of mineral content during drilling.

1 INTRODUCTION

Mining and mineral processing have traditionally been approached as if they were separate entities. However, the mining industry is beginning to look at mining and milling as two interrelated components that must be optimized as a whole. There is increasing realization that greater expenditures on blasting can lead to tremendous crushing and grinding energy savings or to an increase in leach recovery (e.g. Bulow et al., 1998). One of the requirements for being able to optimize the complete mine/mil 1/leach feedback loop is accurate, online, and continuous data on key inlonnation on the state of different parts of the "system." This information includes the characteristics of the rock about to be blasted, the characteristics of the blasted rock about to be sent to the primary crusher, the characteristics of the rock about to enter the flotation circuit, and so on. In recent years, online systems have been developed to provide some of this information on a continuous basis.

This paper focuses on optimization of blasting, an often overlooked part of the mine/mill/leach system. The information vital to optimizing blast design includes characterization of the rock mass prior to blasting; it is widely accepted that characterizing fractures and other discontinuities in the rock mass is one of the most important inputs to blast design to achieve optimal rock fragmentation. The work described here includes development of sensors, data acquisition systems, and online analysis tools that will allow real-time geophysical characterization of the rock mass and down-hole measurements of mineral content. In addition to optimizing the rock fragmentation that results from blasting, knowing the exact location of waste rock, rock to be milled, and rock to be leached, can minimize the amount of dilution that occurs in blasting and subsequent mucking and hauling.

Image-processing techniques are being used to perform pre-blast rock-mass characterization and post-blast fragmentation analysis. These analyses are then used to evaluate the effectiveness of geophysical and x-ray-fluorescence (XRF) data in improving blast design and routing of blasted rock. The ultimate goal of the project is to integrate geophysical and XRF data with drilling data to create an adaptive, online analysis tool to optimize subsequent drilling and blasting. This technology would also yield environmental benefits by minimizing the amount of mineable ore on waste piles and maximizing the amount of processable ore sent through the mill and put on leach piles (Hopkins et al. 2000).

2 DATA COLLECTION ACTIVITIES

Two state-of-the-art techniques form the basis for the pre- and post-blast data collection activities. The first is ground penetrating radar (GPR) information that was collected and used to characterize, in three dimensions, the rock mass prior to blasting. This information was supplemented with other drill information such as penetration rate, power, torque, drilling time, hole depth, weight on bit, vibration, specific energy, and the blastability index, which were all collected by the Acquila system installed on the drill rig. In addition, laboratory data collected from drill cores, and geological and structural maps were available. The information is being used to characterize the rock mass in terms of the parameters that are known to have the greatest influence on blastability, namely intact rock strength, fracture density, fracture orientation, fracture aperture, and the location and orientation of major structural features. These data are being evaluated in conjunction with data obtained using the new technologies being developed as a part of this project (vibration of the drill stem and XRF analysis of the drill cuttings).

The second state-of-the-art technique involves the analysis of post-blast fragmentation using image-processing techniques. The Split image-processing system, developed at the University of Arizona, was used for this purpose. In this system, digital images are taken during the process of mucking or hauling the blasted rock. As an example, for a 30-by-30-foot hole pattern with 50-foot-deep holes, it takes about 30 bucket loads (assuming a 60-yard bucket) to remove the rock associated with each drill hole. A digital video camera is used to take video images on a bucket-by-bucket basis of an entire shot. Following the work of BoBo (1997), images were taken from the cab of the shovel. Images were scaled using a laser rangefinder device, and a laptop computer is used to process the images in the field using the Split software. Details of the Split software are given in Girdner et al (1996), Kemeny (1994), and Kemeny et al. (1993). The Split software estimates the complete size distribution of the blasted rock with an error less than 10% (Girdner el al. 1996).

The last task for the data collection activities is to create 3D maps throughout the shot area that show the pre-blast rock-mass parameters, the post-blast fragmentation, and the input explosive energy. GPS devices on the buckets allow the post-blast fragmentation information to be assigned to a location, which can be corrected for throw and other factors. The GPR and/or fragmentation information may be averaged to index all the information for a particular block size of interest.

3 DEVELOPMENT OF NEW SURFACE BLAST DESIGN MODELS

The data collection activities described above were the initial source for empirical data sets needed to develop the proposed new surface-blast design models. As described below, substantial data are available for each blast site. For the pre-blast stage: GPR 3D rock mass data, mine model geological information, blast-hole drill data from the drill monitoring system, and geotechnical properties of the intact rock together with ore content. Blast data: physical characteristics of each drill hole (diameter, location, depth, etc.), amount and type of explosive in each hole, timing patterns, and video tape of the blast itself. For the post-blast stage: rock-mass characteristics (size distribution, particle shapes, etc.) across the blast area, shape of blast pile, and other properties deemed useful. The first step was to use multivariate statistical techniques to help identify important relationships between pre-blast, post-blast and actual blast design parameters. Then, using these initially identified relationships, and knowledge of existing blasting theory, empirical blast-design models are being developed. We propose to investigate several modeling approaches including neural networks (ability to develop mappings between input conditions and output parameters in complex environments) and fuzzy logic. Fuzzy-logic-based systems are well suited for making design decisions with imprecise, incomplete and uncertain information.

3.1 Development of an On-line Adaptive Surface Blast-Design System

Working closely with the mine operators and equipment developers, we propose to develop the functional components of an On-line Adaptive Surface Blast-Design System.

Adaptive blast design means that the blast design can be modified in real time, by changing hole patterns or the type and amount of explosive, based on newly acquired information about the rock mass. In order to implement an adaptive blast-design strategy for open-pit mines, two problems must first be solved.

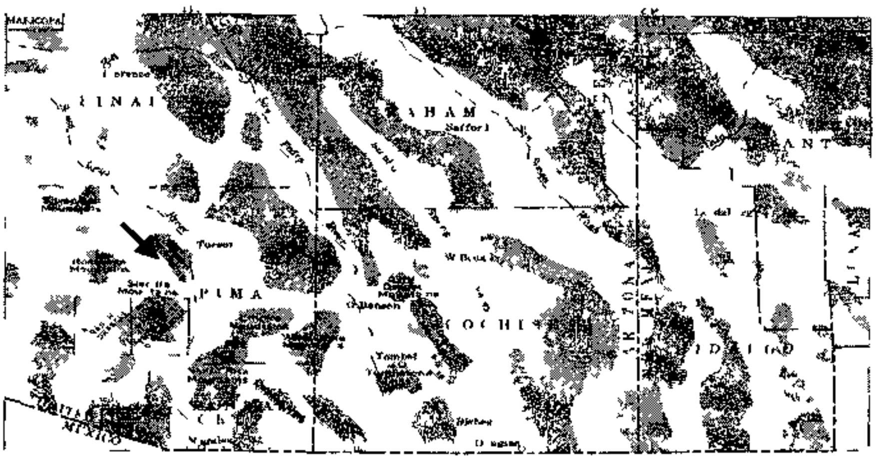
First of all, technologies must be developed to accurately predict in-situ rock-mass properties. These properties must be available for a given shot before or during the drilling of holes for the shot. Secondly, accurate blast models must be available to provide guidance on how modifications to the blast design should be made in light of new information. For greatest accuracy, these models must be mine-specific, and constantly evolving based on new data. This requires feedback mechanisms in the operation that provide updated information on in-situ rock conditions, blasting parameters, and post-blast fragmentation.

The approach is simple, and is based on only three variables per hole: drilling specific energy, blast energy (kcal/ton), and post-blast F80. We recommend this as a first step in implementing an adaptive blast-design strategy. However, a limitation ot this ıelatıvely simple appıoach ıs that it does not take into account several othei important parameters, most notably fractures and the specific mineralogy ot each unit volume ot the lock mass In addition it uses only single vanables to account tor the blast palameters (kcal/ton) and to chaiactenze post-blast fragmentation (F80) Although the model pıedıcts tıagmentatıon it does not predict other quantities that aie critical for downstream processing such as the cıushabılıty and grindability ot the fragments (tor mill processing) 01 the leachabihty ot the tiagments (tor SX-EW pıocessıng) Technologies undei development as part ot the anient project that are providing data dunng drilling can be used lo address some ot these shoıtcomıngs (Hopkins et al 2002) These newly available dala are being used lo impiove the adaptive blast-design model

The path to commeıcıalızatıon is to integrate the blast design tool with existing commercial systems that collect and display data while drilling The time tıame tor commeıcıalızatıon ıs on the order ot 2-3 yeais The blast-design tool can also be commeicialued as a stand-alone syslem in which case all relevant data would be integrated and analyzed ott-line to produce a blast design In this case the time-frame tor commercialization is 1-2 years

4 FIELD TESTS IN OPEN-PIT COPPER MINES

The test sites for the work described here are located in south eastern and south-western Arizona (indicated by the arrows in Figure 1) The Molenei mining district hosts the largest producing porphyry-coppei deposits in North America The mining complex consists ot several open-pit mining areas, a concentrator with a capacity ot 75,000 tons ot ore pei day, and the woild's largest solvent extraction /electiowinning facility Over 780,000 tons ot rock per day are ıouted to either ın-pıt crushing systems or leaching stockpiles In 1999, the Morenci mining distnct produced over one-billion pounds ot copper Mineralization is associated with a co-magmatic calc-alkaline series ot porphyrıtıc intrusions ıanging in composition from dionte and granodionte to quartz monzonite and granite (Türler et al 2002)



Fiaine Location ot the field tests in southeım Aıızona

The Siernta Mountains are about 25 miles southwest ot Tucson Anzona The mine tor the field woik is located in the eastern foothills ol the Siernta Mountains The mine contains a low-grade copper deposit and became operational in 1969 Ransome (1922) noted thai the Siernta range consisted primai ily ot an intrusive granitic core flanked by sedımentaıy and volcanic ıocks that have been metamorphosed to various degiees He also observed that the intruded locks on the eastern side included volcanic and clastic sedımentaıy ıocks ot Mesozoıc age as well as Paleozoic limestone and Precambııan gıanıte Where the test mine is located, the geology shows tertıaıy intrusive rocks including andésite, dıorıte, gıanodıorite, quartz monzonite porphyiy and Jurassic quaitz monzonite (Coopei 1971) The mine has an annual ore production ot 40 million tons (ot which 22 million tons goes to a solvent extraction/electrowinmng facility) The average giade ot copper is 0 3% and ot Molybdenum is 0 03% The mill cutoff value foi copper is 0 33% Cu proved by including site-specific information in the analysis.

5 TECHNOLOGIES USED

5.1 X-ray-flitorescence(XRF) mineral-content sensor

X-ray-fluorescence (XRF) spectroscopy is routinely used to analyze atomic composition in a wide range of applications including mining, oil-well logging, environmental monitoring, and materials evaluation. The research challenges of adapting the technology for use as a downhole tool include ensuring reliable and accurate measurements in a harsh environment, ensuring worker safety, and minimizing interference with the drilling operation.

For the prototype system, dust and cuttings are collected through a nozzle placed near the borehole. A ventun-suction system using compressed air supplied rrom the drill rig provides a continuous sampling of material during drilling. Exhaust from the ventun system is routed to the cyclone where the solid material is separated from the air. Detailed information about the system is given by Türler et al. (2002).

Figure 2 While corresponds to high copper concentrations compared to darker colors, which indicate relatively low copper concentrations.

The borehole profiles shown in Figure 2 indicate that the distribution of copper ore varies considerably over the length of the borehole, and between boreholes on the same bench. These results must be confirmed by analyzing the effect of sampling bias introduced by the collection method.

There is also interest in determining if the XRF data can be used to help identify rock types or rock pioperties such as hardness that would be valuable lnlormation for blasting engineers. Classification methods were used to analyze 71 samples, for which 11 groups were identified (Figure 3). The rock classification task is complicated by several factors including sampling errors, mixing of dust particles in the borehole, and the difficulty of trying to discern rock properties based on elemental composition. The accuracy of classification techniques can be improved by including site-specific information in the analysis.

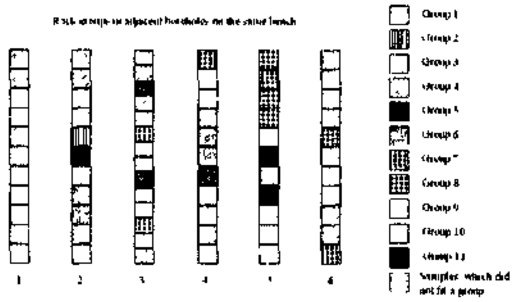


Figure 3 Rock groups in ad|acent boreholes on the same bench

Work to date has demonstrated the feasibility of collecting samples during drilling and using x-ray-fluorescence (XRF) spectroscopy to analyze mineral content. There are several paths to commercialization. An integrated sample collection and real-time mineral-content analysis system could be built either as a stand-alone system, or integrated with existing software packages that collect and display other drill data. The technology for sampling dust/cuttings during drilling can be commercialized separately; in this scenario the samples would be analyzed off line, e.g., in the mine's assay lab.

Commercialization would be pursued with companies manufacturing drill rigs or equipment for rigs; companies have expressed an interest in the technology. The XRF analysis and display system can also be commercialized separately; in this scenario the portable system would be used by mining personnel to obtain real-time measurements of mineral content in the field using existing sample-collection techniques. Integrating analysis and display software developed for the project with commercially available portable XRF systems is the fastest path to commercialization for this technology, and could be achieved within 1-2 years.

5.2 Fracture detection using GPR measurements anil drill monitoring systems

Cross-hole radar surveys are conducted using a zero-offset profile method to obtain arrival time versus depth in adjacent boreholes. For the field tests in Arizona, the borehole radar system transmitting at either 50 MHz (for hole spacings between 20 and 30 feet) or 100 MHz (for holes spaced less than 20 feet apart) was used between adjacent boreholes (Hopkins el al. 2002). The bench where experiments were conducted at one of the mines included a fault.

providing the opportunity to test the sensitivity of radar to highly fractured zones. The radar data was used to help interpret data collected during drilling, and to determine the ability of the radar to delineate the fault zone. The first results show that GPR measurements distinguish the competent rock from the rock mass in the fault zone (Figures 4 a,b).

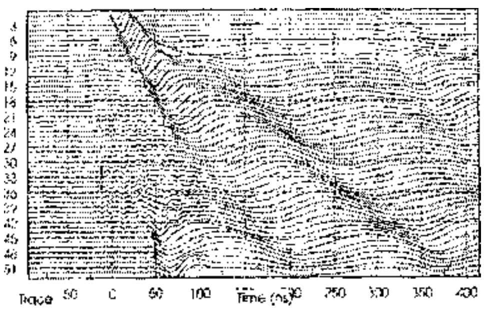


Figure 4a GPR signal from a heavily disturbed rock mass. Vertical axis is the depth of the borehole versus travel time of the waves.

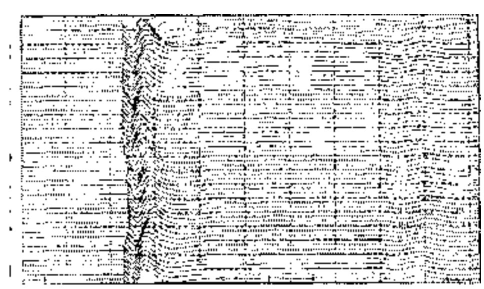


Figure 4b GPR signal between the boreholes in competent rock.

The commercialization potential of field geophysical systems such as cross-hole radar depends on the value of the data. Costs are higher than for systems that can be deployed on the drill rig because of increased labor costs. Incorporating the geophysical data with other drilling data is less straightforward because it would not be collected at the same time. However, the data collected is likely to be more easily interpreted than data collected on the rig, and equipment to measure data is well developed and commercially available. Time to commercialization of a stand-alone system including software to analyze and visualize data is on the order of 1-2 years. The commercialization timeframe for a system integrated with other drill and rock-mass data is on the order of 2-3 years.

5.3 Fracture détection using accelerometers mounted on the drill rig

To determine the feasibility of using accelerometers to measure drill-rig vibration data during drilling and using the data to infer information about rock and fracture properties, field tests have been conducted using sensors attached to the rig.

The accelerometers used have a bandwidth of 400 Hz and a range of +/- 40g. A specially designed collar to house the accelerometers was placed around the drill stem just below a vibration dampner that is original equipment on the drill rig. This placement allowed the accelerometers to be as close to the drill bit as possible, Data was transmitted via FM radio at 418 and 433 MHz to a PC-based data-acquisition system (Figure 5). A sampling rate of 2000 samples/sec/channel was used to collect the data (Hopkins et al. 2002). The use of a wireless transmission system allowed installation of the collar on the drill stem and data collection during drilling with minimal impact on the rig and drilling operation.

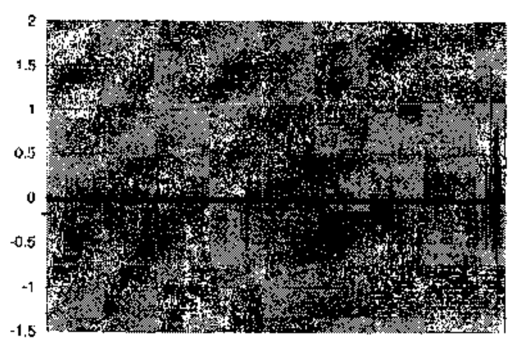


Figure 5 Vibrations recorded on the drill stem by accelerometers. The horizontal axis is time (seconds) and the vertical axis is acceleration (g).

Data are being analyzed to determine if vibration of the drill stem can be used to identify fractures. Commercialization potential depends on value added by additional information gained from geophysical measurements under investigation. A system based on vibration measurements made on the drill rig has the shortest path to commercialization because it can be incorporated into existing commercial systems that collect and display other drill data. The project's drilling partner is interested in commercializing the technology if it proves viable, so that commercialization within a timeframe of 1-2 years is possible.

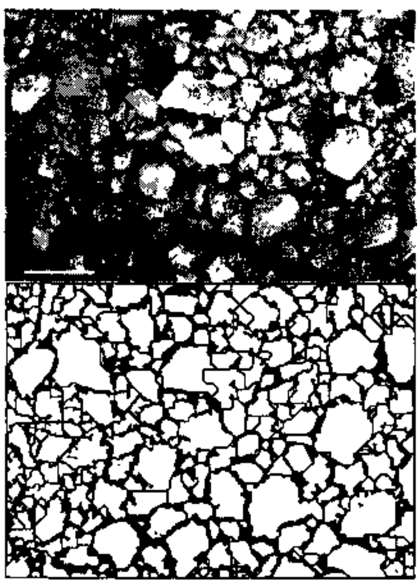
5.4 Split image processing software

A proven method to assess fragmentation is to acquire digital images of rock fragments and to process these images using digital image-processing techniques. For post-blast size characterization, this' is the only practical method to estimate fragmentation because screening is impractical on a large scale. The image-processing techniques being used for the assessment of fragmentation were developed at the University of Arizona between 1990 and 1997. Since 1997, development work has continued at Split Engineering, LLC.

At one of the test mines in Arizona, the Split online system is installed at the in-pit primary crusher, where digital images of both feed and product are continually processed and recorded (Figure's 6a and 6b). These systems are set to process three contiguous images of either feed or product approximately every 90 seconds. The feed cameras are located at the truck dump bays; the product cameras are located above the discharge belts. The resulting size data from the Split system is imported into a minewide database where truck-by-truck averages of the feed and product sizes are determined.

a-

b-



Figuie 6 a- Image of pnmary-crusher pioduct (scale marker in the bottom left-hand cornei is 6-inches long), b- Delineated image produced by the Split image-analysis software

Several new technologies are being utilized to trace the crusher feed and product size information back to the original position of the rock on the bench. This is accomplished on a truck-by-truck basis utilizing technologies that include an accurate time/date stamp incorporated into the Split data associated with each truckload of ore. Modular Mining's dispatch system to trace the trucks back to the bench, and GPS-equipped shovels to determine the location of the material dumped into each truck (Kemeny et al., 2001, 2002). The values of the post-blast 80-percent passing size (F80) around each hole are averaged, and this hole-by-hole data is used in the development of fragmentation models.

5.5 Measuremeiu-wlnle-drilling (MWD) Data

In one of the field tests, data was recorded over a four-day period in March 2002. Drill data was collected through a SR-2 cable connected directly to the drill monitoring system. As the available memory in the system was small (less than 6 Mb), all blasthole data had to be downloaded immediately after drilling to prevent the data from being overwritten. Data from nineteen blastholes were recorded during the trial. In some cases, the MWD data was lost because the computer system crashed during drilling. In other cases data was lost when the satellite signal was lost. In one instance, it took a very long time to drill the hole, and the size of the MWD file generated by the acquisition system exceeded the available memory size and was lost. During drilling of each blast hole the drilling time, hole depth, rotation of the drill bit, weight on bit, torque, air pressure, vibration, blastabilility index and specific energy were recorded.

5.5.1 Data A cquisition

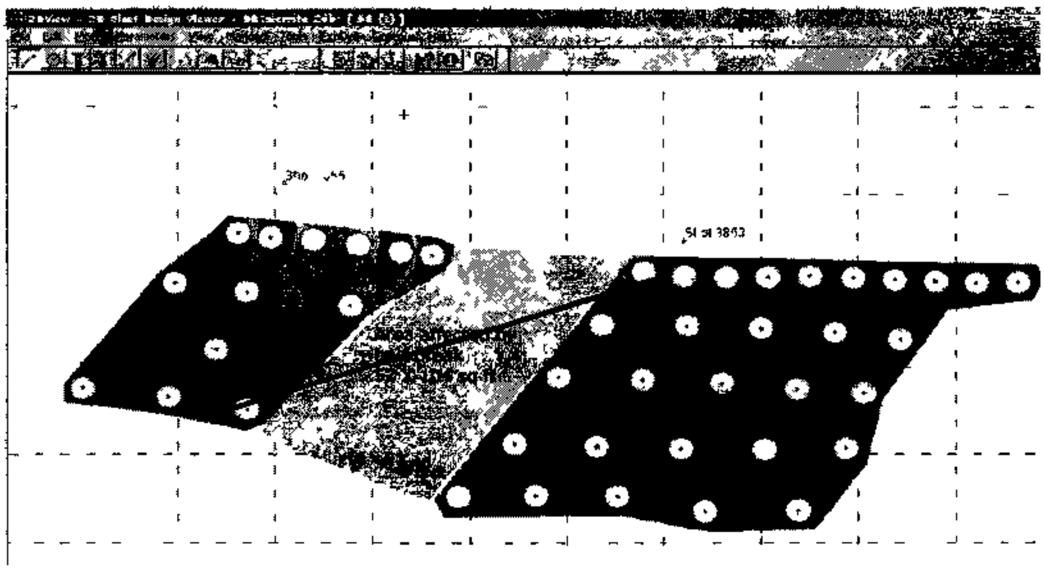
The normal sampling rate of the MWD acquisition system used was increased from approximately 5 Hz to 15 Hz during the trial. As there is more than one channel for data acquisition, the actual acquisition rate per channel is about 2 Hz per channel. Data was recorded directly into a laptop computer on the drilling rig because the higher sampling rate generated larger files than normal and the radio system at the mine site was already close to its maximum capacity.

5.5.2 Data Analysis and Interpretation

Based on the similarity of the mechanical processes in crushing and drilling, the concept of specific energy is potentially a link between MWD data and comminution properties (Segui 2001). Specific energy is defined as the work done per unit volume excavated. The concept is based on the assumption that a ceıtaın amount ot eneıgy ıs necessaıy to excavate a given volume ot rock The amount ot energy depends entirely on the nature ot the rock In tıyıng to îelale this theoretical value to what would be required to crush the ıock in a mill, it would be necessaıy to account tor eneıgy losses in the process, toi example, machine wear and mechanical losses

Contoui maps ot specific energy were created for all the shots monitored duiing the field tests SE contoui maps tor two shots separated by a backbieak zone ot about 15 m aie shown in Figure 7 A highly tiactured fault zone between the two shots created the backbreak effect There were no blastholes in that area and, thus, no information available in terms ot M WD data

The geological maps of the mine show a northeast-southwest fault that crosses exactly over the two shots pictured in Figure 7 What can be interred from available specific-energy data is that the rock strength is different on the two sides ot the fault The lock mass on the eastern side ot the fault is softer than the lock on the western side



Fıguıe 7 Specific eneıgy contours of the Iwo shot locations Lighlei coloıs coıespond to higher specific energy values compared to darkeı coloıs which indicate lelatively low specific energy values Low specific eneıgy ıs associ ated with softei rock The stiaight line indicates the trace ot the fault line on the bench

6 CONCLUSIONS

Woik to date has demonstrated the feasibility ot ıntegıatıng dulling, rock-mass, blasting and post-blast liagmentation data to improve blast design Data horn field tests has been used successfully to ınpiove blast-fragmentation models Thus, an adaptive blast-design tool that would allow blasting engineers to bettei optimize blast paiameters including the location ot boıeholes, the charge per hole, and the timing ot detonation, has strong commercialization potential With this system, blasting could be optimized tor specific downstieam piocesses on a hole-by-hole basis, and would be applicable to most any piocess including crushing and grinding, leaching, and disposal on a waste pile

Modeling work to date is based on thiee parameteis that aie available tor each blast hole drilling specific eneıgy explosive energy per volume ot ıock and post-blast 80% passing size determined using the Split imaging system

New technologies undei development as part ot the ciment project aie providing data during dulling on ıock properties, hactures, and mineral content These data will be used to improve the blast-design models A dull collar housing accelerometers and a wueless Iransmission system has been demonstrated in the field Field tests conducted with a prototype dust-collection system demonstrate that it is possible to continuously sample dust and cuttings during drilling Ground-penetrating radar measurements seem promising to determine the major discontinuities on the bench Ongoing woik is focused on understanding how to use the ıadaı and vibration data to detect tractuies and on developing a fully poitablc on-line dust collection system tor mineral content measurements

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