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Increasing Resource Efficiency Through Sonic Drilling

Beate Orberger,† (SEG M), GEOPS Université Paris Sud, Bât. 504, 91405 Orsay Cedex, France, and CATURA Geoprojects, 2 rue Marie Davy, 75014 Paris, France, **Huug Eijkelkamp** and **Harm Nolte,** Eijkelkamp SonicSampDrill, Uitmaat 8, 6987 ER Giesbeek, The Netherlands, **Mike Buckland,** Unit 351, 86 Queen Street, Sheffield S1 2FW, United Kingdom, and **Monique Le Guen,** ERAMET Group, 1 rue Albert Einstein, 78190 Trappes, France

Introduction

"On-line-on-mine-real-time" automated logging is more and more used by mining companies for statistical mineralogical, chemical, and geotechnical studies. Therefore, cost-intensive drilling must have high recovery rates and yield coherent, undisturbed, and complete cores to obtain reliable data that is needed for precise geomodeling, resource and reserve calculations, and metallurgical test work (Fig. 1).

Major Drilling Challenges in Unconsolidated Terranes

Unconsolidated ore deposits such as Ni (Co-Sc) laterites, bauxites, alluvial gold, diamond, titanium oxides, and zirconium are impossible to drill by conventional diamond drilling methods (e.g., Uludag, 2010; Sarala, 2015). These deposit types typically are heterogeneous in grain size, poorly consolidated, and highly variable at vertical and horizontal scale. Fine-grain-size sediments such as clays are often lost but can host significant value such as economic gold (Nesterenko et al., 2013). This leads to erroneous models and decision-making.

The challenges during drilling, exploration, geometallurgical parameter evaluation, and ore beneficiation in these heterogeneous layers impact the economics and choice of the mining method. These factors are clay-rich layers and lenses, heavy mineral concentrations (Au, diamond, Ti, Zr), and the presence of trapped groundwater. It is difficult to estimate the hardness of different sampling intervals and the degree of induration during drilling. Operators rely on the observation of drilling pressures and penetration rates as well as chip/sand logging. Furthermore, pulverization by the drill bits and disaggregation during sample return make it difficult to identify indurated layers (Jones, 2006). These conditions are unfavorable for rotary air blast (RAB)

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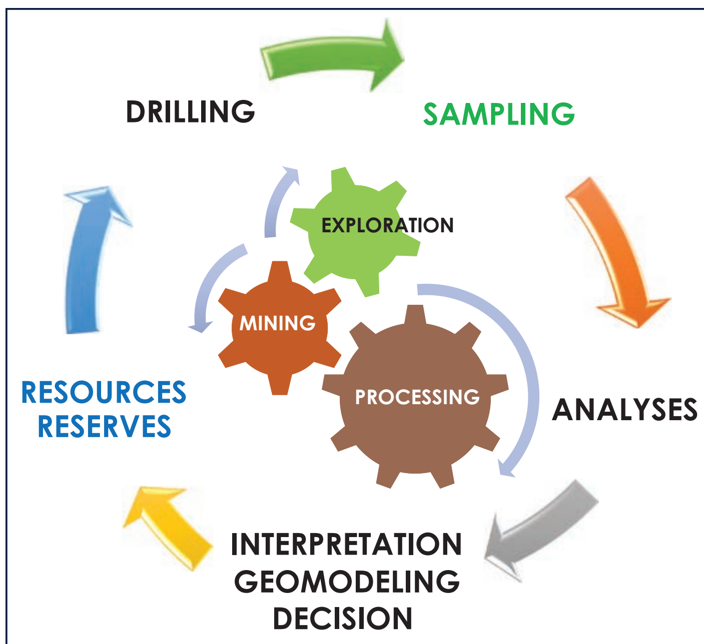

FIGURE 1. Drilling in the cycle of exploration, mining, and processing.

†Corresponding author: e-mail, beate.orberger@u-psud.fr

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drilling, as indurated or lateritized materials impede the bit and therefore the penetration. Alternating wet-dry ground conditions, such as in permafrost or tropical climates, create sample hang-up in drilling and sampling equipment. High water inflow may be coupled with fluidized sand, causing rod jamming. Finally, plastic and swelling clays may block inner tubes and also impede the bit. At extreme heavy mineral concentrations, downhole contamination may occur, or layers of economic interest may be diluted by layers of noneconomic interest.

Sonic drilling meets the highest technological standards and is more and more used for complex unconsolidated ore deposits, as this technology provides undisturbed cores in a short time span (≈50 m/day) with low failure rate and low waste.

Sonic Drilling History

High-frequency vibrational material cutting was discovered in the late 1940s. In the 1960s the first sonic drilling prototype was developed in the USA. In the 1970s and 1980s, drilling heads for field application were patented. It took about 40 years for sonic drilling techniques to reach the market, thanks to advances in the resonant drilling system and the reduction of drilling costs. Sonic drilling had its first application in the oil and gas industry, then spread to the geotechnical and environmental sectors, reaching the mining industries in approximately the last 20 years.

Sonic Drilling Principles

The major difference between conventional rotary and sonic drilling is that the sonic drilling head includes an oscillator motion additional to the rotary motion, causing high vibratory forces (50–150 Hz) up and down while being pushed down and rotated. The combined vibratory, rotary, and axial forces allow high-speed drilling, producing continuous large sample cores without or with little addition of air, water, or mud, while reducing 70 to 80% of waste. It overcomes hydraulic fracturing, borehole erosion, and vulnerable structures.

Recently, sonic drilling is increasingly used for unconsolidated soil environments without rotation and little addition of fluid, resulting in minimal disturbance to cores. In particular, developments of rigs and tools significantly reduces friction on the drill string and drill bit due to liquefaction, inertia effects, and a temporary reduction of porosity of the soil. Depending on the climate and geological environment, LargeRotoSonic (LRS) or CompactRotoSonic (CRS) drills are operated.

Alluvial Gold in Permafrost Regions

The Far East of Siberia, 700 km north of Magadan, represents a permafrost region, rich in placer gold, which is mined at surface and underground. The sediments are composed of sand, gravel, and clay. Coarse-grained gold occurs in sands, fine-grained (0.25–1 mm) and gold dust (< 0.1 mm) in the clay layers. The gravel beds are in part formed by glaciers.

Permafrost soils are subject to thawing in summer from the surface to a variable depth, from 30 cm to several hundreds of meters. The surface layer down to several meters, which experiences repeated freezing and thawing, is called the "active layer." The active layer slowly expels its water during the thawing periods of several months, causing a morass, or a rough surface consisting mainly of rock fragments. Hydrolaccoliths (pingos), consisting of frozen sediments or bedrocks forming round-shaped hills of several tens of meters high and up to 450 m in diameter, are frequent.

Sonic drilling was performed on an ancient mining area as reconnaissance drilling using the LRS drill head with the AquaLock piston sampler, with vibrations able to be used at temperatures as low as –40°C. Boreholes (4-m depths) were performed down to the interface with the basement gneiss at a 10- to 12-m spacing. Twenty-five boreholes were drilled in only 2.5 days at a consistent speed of 15 m/10 h shift. Sonic drill tools were tested, and best recoveries were obtained with Sonic Duo (dry) and an 8-in core and 10-in casing. For the first time the clay layer with fine gold and gold dust could be recovered. Traditional drilling technologies imply a sampling forecasting error of up to 30%. Sampling by sonic technology leads to more precise gold location forecasting and to reliable mining planning, as gold-poor and gold-rich areas could be precisely localized due to improved recovery and lack of mixing of layers during drilling. A significant operating expense reduction could be achieved, as only gold-rich areas will be mined, and gold recovery could be increased by about 50%. At present, 80 m/24 h have been drilled since the beginning of 2017, with increased production during May to July (94 m/24 h) (Figs. 2, 3).

Alluvial Diamonds

Northeastern Angola is famous for gem-quality alluvial diamonds originally derived from kimberlite. Mining activities take place in many areas of

FIGURE 2. The LargeRotoSonic drill rig in the permafrost region of Far East Siberia hosting alluvial Au deposits.

FIGURE 3. Sonic drilled cores in the permafrost region hosting alluvial Au deposits (Far East Siberia; Eijkelkamp SonicSampDrill).

Calonda formation gravels consisting of channelized ancient river systems hosting variable thicknesses and grades of diamond deposits, as well as variable diamond quality. The channels are located beneath meters to tens of meters of overburden, often composed of clay and sand layers. The present landscape is hilly with variable thicknesses of overburden on slopes and valleys. The diamonds typically occur in 0- to 5-m-thick gravel layers overlying the bedrock located from 3- to 50-m depth. The objectives of drilling are twofold: first, prospecting to locate diamond-bearing gravels and determine their thickness and depth below surface and, second, to direct production activities to maximize profitably and extend mining block life. Drilling results allow accurate measurement of overburden, the thickness of diamond bearing gravel to the bedrock, and their composition. The CRS-V type drill rig is used to drill a grid with a spacing usually commenced at 200 m, or 100 m in areas of potential interest, reducing further to 50 m or less once gravels of interest are found. Typically, 1,500 to 2,000 m are drilled each month working 12-hour days, five days a week, with depths varying between 5 and 25 m. These methods have successfully led to the preferential targeting of high-grade channels (Figs. 4, 5).

Sonic drilling contributed to high-grade and high-value diamond production during the last four years. Such terranes were impossible to drill by conventional methods. A second CRS-V crawler and support truck is currently being purchased, and neighboring diamond mining companies have also purchased similar units.

FIGURE 4. Full core recovery: sonic drilled in alluvial diamond prospects (northeast Angola).

FIGURE 5. Full core recovery showing the gravel bed and country rocks (sonic drilled in alluvial diamond prospects, northeast Angola).

Nickel Laterites-Bauxites

Nickel laterites (0.5–3% Ni) and bauxites (Al-rich, 35–65% Al) are tropical (paleo or modern) soils. Ni laterites form on serpentinized peridotites, while bauxites present paleosoils developed or transported on (to) granitic or carbonate-clay–bearing rocks (karst). These soils are the product of alternating rainy and dry seasons, leading to leaching and accumulation of metals as concretions, veins, or metal sequestration in rock matrix minerals. These ore types present heterogeneous materials, both in grain size (micrometer to centimeter) and in mechanical behavior (hard and soft). Moreover, laterites can host up to 40 to 50 wt % of water.

Ni laterites representing about 60% of the world's Ni production (Butt and Cluzel, 2013) were essentially mined for garnierite ore occurring in saprolite and/or tectonic breccia at the bottom of the laterite profile at the interface with the protolite (serpentinized peridotite). At present, many Ni laterite ores of lower grades (1–2 wt %, cutoff grade about 0.8 wt %) and higher mineralogical complexity are mined. Laterites may host also cobalt and scandium (southeastern Australia) of up to about 500 ppm (Emsley, 2014; Chassé et al., 2016). In these ores, nickel, cobalt, and scandium are locked in phyllosilicates and/or oxyhydroxides dispersed in the rock matrix. Intensive geometallurgical studies are required to define comminution parameters and to design the processing flow sheet.

Sonic drilling tests were performed on the Weda Bay Ni laterite deposit (Halmahera, Moluques Islands, Indonesia, ERAMET Group). Nickel occurs heterogeneously in saprolites of variable compositions including a high amount of swelling clay minerals (smectite) mixed and partly intergrown with serpentine minerals. A CRS drill head with AquaLock piston sampler (70-mm core diam) was used on a 12.5- × 12.5-m grid with depths varying from 14 to 16 m. The core production was 40 to 60 m/day. Optimization of the drilling method is currently undertaken in the European Union-supported SOLSA project (see "Forthcoming solutions for optimizing mining and processing") (Fig. 6).

A project on bauxite was performed in South American Surinam, hosting part of the richest bauxites in the world. These bauxites represent about 72% of the country's export. A Sonic drilling campaign was performed close to the capital, Paramaribo, at Lelydorp. Bauxite (karst deposits) occurs below an overburden layer, which was dredged away before drilling. Drilling started with a clay layer composed of kaolinite (10-m borehole spacing) with drilling depths of 15 to 18 m. Again, a CRS drill head with AquaLock piston sampler was used (dual wall) without any use of water (only air). About 100% core recovery was achieved. Resource estimates of bauxite (sensu stricto) but also metal-rich red clays were significantly improved (Fig. 7).

Drilling and Tooling Costs vs. Production

An estimation of the drilling and tooling costs (avg over 5 years) for companies who purchased the drilling machines is to page 12 . . .

FIGURE 6. Sonic drilled core from Ni laterites (Weda Bay, Indonesia, ERAMET Group).

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FIGURE 7. Full core recovery: sonic drilled in bauxite (Surinam).

presented in Figure 8. In this figure two sampling methods are compared: Single-Wall 3-in CoreBarrel and AquaLock 70. Machine operating costs present about two-thirds of the total costs. About 50% of the machine operating costs are related to labor, while 25% belong to the depreciation of the drilling machine (Fig. 8).

AquaLock 70 tooling and machine operating costs are lower compared to the SingleWall 3-in CoreBarrel due to lower drill bit replacement and water consumption costs.

The commercial sonic drill service price for a sonic drilled meter in an urban environment with geological conditions of medium difficulty using the CoreBarrel sampling method is calculated at about US$110/m. It includes maintenance, fuel and labor costs, water tooling, an 8.5-hr shift, a crew composed of one operator and two assistant operators, an average production of 44 m/shift, a risk factor related to efficiency, and a profit factor. Compared to conventional diamond drilling, sonic drilling lowers the project costs in difficult to very difficult environments (Fig. 9).

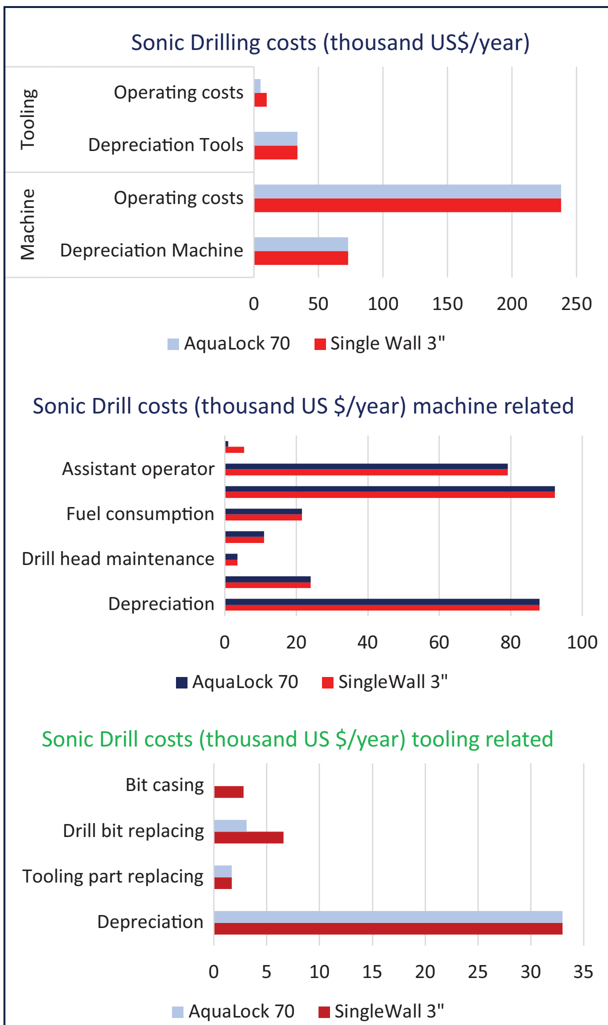

FIGURE 8. Sonic drill costs (thousand US$) per year.

Forthcoming Solutions for Optimizing Mining and Processing

At present, important developments in sonic drilling are performed in two European Union H2020 research and innovation projects (www.rtm-mining.eu and www.solsa-mining.eu). The Real-Time Mining (RTM) project aims to optimize extraction, processing, and logistics in complex mine settings to decrease environmental impact and increase resource efficiency. The SOLSA project develops an expert system, composed of a sonic drilling rig and a core scanner, integrated for the first time. The expert system combines chemical and mineralogical analyses on undestroyed drill cores and monitored data while drilling at the drill site. The SOLSA cloud will host actionable data produced by smart deep learning software to rapidly define regions of interest on drill cores, which will then be analyzed by the SOLSA combined analyses benchtop system at the mine site. The SOLSA expert system will be validated for Ni laterite ore in New Caledonia.

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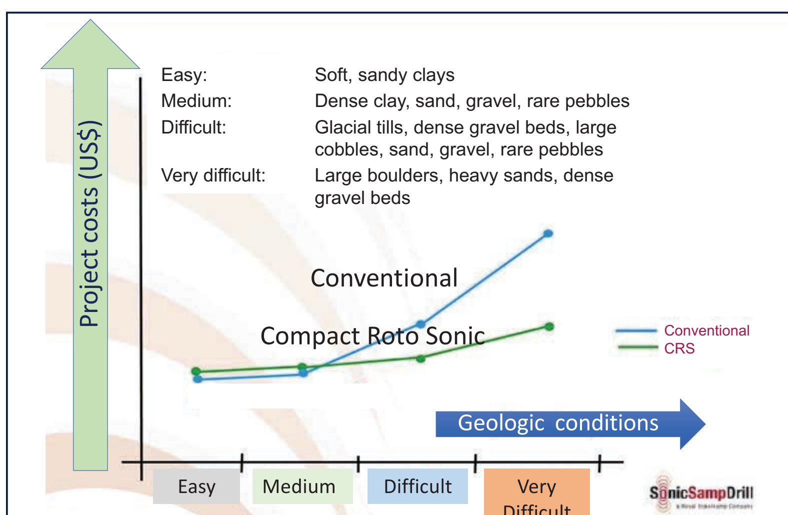

FIGURE 9. Sonic drilling compared to conventional rotary drilling demonstrated in projects costs vs. geologic conditions.