Improved blasting results through precise initiation – results from field trials at the Aitik open pit mine

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Summary

Blast-induced fragmentation plays a leading role on mining efficiency, hence many studies have been conducted in order to understand the mechanisms behind rock breakage and to improve the fragmentation. This report presents the results from field tests conducted at the Aitik mine belonging to Boliden Mineral AB in Sweden, which is part of a project called Vinnova. The project aims to evaluate the effects of short delay time blasting on fragmentation and other post-blast parameters which influence the comminution process, e.g. swelling and crushing.

A total number of 6 benches were assigned for trials with different inter-hole delay times. Two of the benches were blasted with pyrotechnic Nonel caps and were used as references for further comparisons. Two benches were blasted with 1 ms of inter-hole delay time by use of electronic detonators. Two other benches were also blasted by electronic detonators, but with 3 ms and 6 ms of inter-hole delay time respectively.

MWD (Measure While Drilling) system was used to log and analyze the drilling process in order to investigate the penetration rate and specific energy of drilling, which represent the hardness of the rock. GPS (Global Positioning System) and RTK (Real time Kinematic System) were used for measurements of benches’ swelling. The blasts were also filmed using a high-speed camera.

Image analysis with Split-Desktop software was used to analyze the fragmentation of the rock after blasts. A series of images was shot from trucks carrying the ore and was later analyzed to obtain the fragmentation for each bench.

Minestar integrated operation and mobile equipment management system was used to log the data from the fleet in the mine. The data were later used together with the crusher energy consumption logs to evaluate the energy efficiency of the crushing process for the ore from each bench.

The tests showed that the inter-hole delay time of 3 ms resulted in the finest fragmentation among all benches; all examined values i.e. $x_{50}$, $x_{80}$ and $x_{max}$ showed improvements upon other benches. However, the crushing energy of the ore from this trial was the highest among all.

Two trials with 1 ms inter-hole delay time did not result in any significant variation compared to reference benches. The difference in $x_{50}$ values were ignorable, the same is true for crushing energy of the mentioned trials.

The bench with inter-hole delay time of 6 ms resulted in the lowest crushing energy among other trials. However, the bench gave more boulders and coarser fragmentation compared to reference benches.

Altogether, the results did not lead to any solid conclusion regarding the effect of the short delay times on fragmentation. Such ambiguity might be resulted by various sources of errors in data acquisition and analysis, as well as uncertainties regarding geology of the test area. In order to investigate the effect of delay times on blast results, more trials with more detailed data acquisition method is necessary.
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1 Introduction

Blasting, as one of the most utilized methods of rock extraction, plays a leading role on mining efficiency. The primary purpose of all blasting is to fragment the rock into pieces of suitable dimensions for further handling. Through the fragmentation, blasting directly influences post-blast operations’ costs, e.g. haulage, crushing and grinding. An improved fragmentation can result in reduced costs for transportation of the blasted rock, as well as reductions in energy consumption during crushing and grinding of the blasted rock. In addition to that, improvements in metal recovery and environmental aspects can be achieved through improved fragmentation.

Production blasting in mining industry mainly consists of drilling blastholes in particular patterns, charging them with certain amounts of explosive and finally detonating them in a specifically designed sequence. The initiation sequence has been of significant importance since the mechanism of rock breakage by blasting in large scales, e.g. bench blasting, compels the blastholes to be initiated in a specific way. The sequence should be designed in a way that compressive shockwaves, produced by detonation, find enough time to reach the free face and their tensile reflections reach the rock and break it in tension. Such constraint is due to the fact that available detonation caps had not been developed to handle very short time intervals of wave propagation speed. In addition to that, large scatter of delay time in conventional pyrotechnic caps did not permit blast designers to consider theories of dynamic fracture mechanics and wave propagation in practice.

Yet new horizons opened up on practical usage of wave propagation and dynamic fracturing theories when reliable electronic detonators became available in the late 1990s. These detonation caps are now capable of delay times down to 1 millisecond and are of higher precision compared to conventional caps. The availability of electronic caps permitted the theories of overlapping, interaction and superposition of shockwaves to be put in practice. Precise initiation with short delay times has been practiced in many countries (Australia, Chile, United States, New Zealand, etc.) and has resulted in noticeably better fragmentation, throw, swelling and digability, hence considerable savings. However, quantitative computational models that describe this phenomenon are lacking. To address this issue, a research project, funded by Vinnova, has been commenced. The project aims to further investigate the theories and to develop better computational tools for simulation of blasting with electronic programmable delay (EPD) caps.

1.1 The Vinnova Project

The hypothesis proposed by Rossmanith (2002) states that by using short delay times, fragmentation might be improved in areas between blastholes where the shockwaves meet, overlap and interact. The Vinnova project mainly aims to investigate this hypothesis through full-scale field tests and computer simulation of blast performance. The project is a joint effort between the industrial partners, LKAB and
Boliden Mineral AB, and Luleå University of Technology (through Swebrec-The Swedish Blasting Research Centre). The project is primarily funded by Vinnova (the Swedish Governmental Agency for Innovation Systems), with supplementary funding by LKAB, Boliden Mineral AB and Swebrec.

The main objectives of this project are to: (i) achieve a better fragmentation, throw and other blast-induced results in quarries and mines; and (ii) study the extension of Rossmanith’s concept to a three-dimensional geometry by identifying the rock volumes within a blast, where the wave interaction from neighboring blastholes may lead to additional damage and consequently enhanced fragmentation.

The project comprises nine different tasks involving computer simulation of blast performance, coupled with full-scale field tests and model scale tests. This report presents the results from field tests conducted at the Aitik mine.

1.2 Precise initiation

1.2.1 Electronic vs. conventional caps

Blasting caps are commercially available on the market in various forms. Fuse caps, electric detonators, non-electric detonators and electronic detonators are the different types.

The oldest of all is fuse caps, which roots back to black powder. Unreliable burning speed and hazardous nature of black powder makes this method of detonation dangerous to be used in modern mining, of which the safety is extremely critical. However, fuse caps are widely used in the mining industry, especially in developing countries.

Electric blasting caps are very similar to fuse caps, but insulated electric wires were used instead of the fuse. Introduction of a pyrotechnical delay element in these caps allowed an offset between two following charges, which led to creation of initiation sequences. Electric detonators are sensitive to heat, shock, static electricity, radio frequency energy and electromagnetic radiation; resulting in safety issues in their usage.

In 1960s total non-electric initiation systems were introduced by Dyno Nobel. These caps had all advantages of electric detonators in addition to safety benefits. Insensitivity of non-electric detonators to electricity, radio frequency energy and electromagnetic radiation, in addition to their wide operational flexibility made them the world’s most widely used type of detonators. Despite all benefits of this type of caps, they are impracticable in precise initiation blasting due to the long delay times and large scatters of their pyrotechnical delay element.

In 1990’s, an idea was introduced that suggested using an embarked electronic clock to replace the pyrotechnical delay element that creates inaccuracy for the conventional detonators. Extensive research from 1990 to 2000 led to the introduction of pre-
programmed or programmable electronic detonators. These caps offer an amazing flexibility in the choice of initiation timing between 1 and 15000 milliseconds. Such flexibility together with very high accuracy of detonation times opens doors for short delay complex initiation sequences.

1.2.2 Previous studies and potential improvements

Although many researchers have studied the subject of optimum delay time to improve blast-induced fragmentation, controversy swirls about a coherent conclusion. According to reduced-scale tests conducted by Stagg and Nutting (1987), the optimal delay time regarding fragmentation is 3.3 to 55 ms/m of burden; their tests showed coarse fragmentation from short delays (<3 ms), where breakage approached presplit conditions with a major fracture between blastholes and large blocks in the burden region. Otterness et al. (1991), based on 29 small-scale shots, also state that delay times of 3.3-13 ms/m of burden resulted in 12-20% improvement in fragmentation.

On the other hand, Rossmanith (2003) suggests that interaction of the waves is of importance in blasting fragmentation. Since the speed of wave propagation is rather fast in typical rock, Rossmanith’s theory leads to usage of short delay times. He claims that by use of electronic detonators with short delay times, the fragmentation can be notably improved.

Through field tests at Barrick Goldstrike mines, McKinstry et al. (2004) have also suggested a delay time of 3 ms between holes of the same row to take advantage of interference of stress waves to improve the fragmentation. However, the only available information on their tests is about the spacing, which was mentioned as 7 meters.

Likewise, Rosenstock (2005) has confirmed the positive effect of very small delay times. He states that short delay blasting has resulted in 10-20% increase in productivity and a reduction of 50% in the costs of drilling and blasting in Australian mines.

Vanbrabant and Espinosa (2006) conducted a series of field tests to examine the effects of overlapping of the negative tails of stress waves via the use of short delay times of electronic detonators. They observed an average improvement of 45% in the mean particle size of the fragmentation.

Small-scale tests in grandiorite blocks, conducted by Katsabanis et al. (2006), showed that the worst fragmentation is achieved by instantaneous initiation and it improves with increasing delay times up to 1 ms. By up-scaling the results, Katsabanis concluded that delay times of few milliseconds per meter of burden result in improved fragmentation in full-scale grandiorite blasting.

Rorke (2007) argues that a substantial reduction of fragmentation have been documented at 2-7 ms inter-hole delay time compared to the conventional pyrotechnic delays in blasting of hard rock. In soft rocks the differences were less clear.
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However, full-scale experiments of Ouchterlony et al. (2010) showed contradictory results. Their experiments included a drill pattern with 3.4 m spacing and 2.6 m burden, i.e. spacing/burden ratio of 1.3. Designed inter-hole delay times of their tests were 1.92 ms/m of burden and 3.84 ms/m of burden; the inter-row delay time was 67 ms. They reported coarser fragmentation for the electronic detonators compared to pyrotechnic caps.

Johansson and Ouchterlony (2012) also conducted a series of small-scale tests to investigate the influence of delay time on the fragmentation. No distinct difference was observed in the fragmentation for the case of shock wave interaction compared to no shock wave interaction. Yi et al. (2012) performed a series of numerical simulations of the aforementioned tests which led to the conclusion that improved fragmentation can be achieved through a properly chosen delay time. Their simulations were using the same methodology as Schill (2012), who carried out the simulations with LSDYNA (Hallquist, 2007) and the RHT (Riedel et al., 1999) material model for inter-hole delay times of 0, 1.5 and 5 ms. Schill (2012) had also concluded that there was an effect of the interacting stress waves on the fragmentation.

Altogether, previous studies show a potential for electronic detonators and short delay times to improve fragmentation. However, more studies need to be conducted in order to draw a confident conclusion whether the short delay times are beneficial to fragmentation or not.

### 1.2.3 Theoretical background

The entire fragmentation process in blasting is based upon the rapid detonation of explosives. Once initiated, the explosive releases an enormous amount of energy through chemical reactions, which results in high-pressure gases in the blasthole. The reaction advances throughout the explosive column at a speed of approximately 2000 m/s to 6000 m/s, depending on the Velocity of Detonation (VoD) of the explosive. The rapidity of such reaction causes an almost instantaneous pressure rise in the hole, which produces a shockwave in the rock (Hustrulid, 1999).

Of the various types of waves that can propagate, the body and surface waves are of the most importance in rock breakage. Primary or longitudinal waves (P-waves) and secondary or shear waves (S-waves) play the leading role in blasting. These waves propagate in the rock at very high speeds (3000-5000 m/s) and cause strains and stresses which form cracks or open existing cracks in the rock, resulting in breakage (Esen et al., 2003).

According to wave propagation concept (Hustrulid, 1999), the positive pressure of shockwave falls rapidly to negative values, which implies a sudden change from compression to tension. In a more detailed description of this concept, Rossmanith (2002) states that a stress wave of pulse type with finite length and duration consists of a leading part and a tailing part (Figure 1). The leading parts are characterized by...
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the index “+” and the tailing parts by index “−”. The +/- sign does not necessarily indicate compression or tension, but the leading and tailing parts.

Figure 1: Representation of stress wave/pulse in the a) space domain and b) time domain; after Rossmanith (2002).

Pulse length or pulse duration is important in short delay blasting; the pulse length in Figure 1 is $\Lambda_w$ and its duration is $\tau_w$. They both consist of a positive leading part and a negative tailing.

The focus of traditional blasting technique is mostly on the compression pulse of the shockwave, i.e., the leading part. But since the tensile strength of rock is much lower than its compressive strength, the availability of a free face in the surrounding of the blasthole is critical to allow the compressive pulses to reflect and return as tensile pulses to open up cracks and/or break the rock in tension. The free faces are generally generated through the sequenced initiation of blastholes in a way that the delay time provides enough time for the previous blastholes to break the rock and move it forward (Vanbrabant and Espinosa, 2006).

By use of electronic detonators, it is now possible to make the waves interact in such a way that tensile and shearing pulses are overlapped to increase the effect of the stress waves. The tensional states achieved in this way can be larger than those obtained by the reflection of compression pulses. In addition to that, the blastholes in other rows detonate in a confined environment (Vanbrabant and Espinosa, 2006).

For a clearer presentation of the aforementioned concept, Rossmanith (2002) suggested the usage of Lagrange diagrams. For the sake of simplicity the stress waves are assumed planar, i.e., one-dimensional; the three dimensional effects of blastholes and charges are also ignored. Figure 2 illustrates the fronts and ends of a P-wave and an S-wave of a short pulse on a Lagrange diagram, which consists of a time axis versus a position axis. The tangents of the associated lines are the inverse of the
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speeds of the waves. Since the propagation speed of P-waves is larger than that of S-waves, its associated line is of smaller slope. \( \tau_s \) and \( \tau_p \) represent the duration of compressive and shear waves, of which a part is the positive leading followed by a negative tailing.

![Diagram showing the definition of fronts and ends of P-wave (PF, PE) and S-wave (SF, SE) for a short pulse; after Rossmanith (2002).](image)

Short delay blasting aims to take advantage of the interaction and superposition of tensile tailings of the stress waves from several blastholes. A schematic representation of the interaction of two stress waves from two instantaneously initiated blastholes is presented in Figure 3. As seen, different types of interactions take place for the fronts and ends of the S and P-waves. It should also be reminded that each of the waves includes a positive leading part and a negative tailing part in the duration of its front and end (Rossmanith, 2002). The diagram in Figure 3 shows the basis for the design of short delays to increase the amplitude and effective length of the most favorable wave interactions, as well as to avoid formation of destructive interactions (Vanbrabant and Espinosa, 2006).
7

Figure 3: Lagrange diagram of the interaction patterns of the waves from two simultaneously initiated blastholes; after Rossmanith (2002).

By introducing a delay time to the diagram in Figure 3, the initiation point of the delayed blasthole will be shifted upwards on the time axis, reshaping the interaction patterns. In order to reach a favorable pattern of interactions, one should carefully consider the rock mass characteristics from wave propagation point of view, i.e., wave propagation speed as well as geological aspects. More details on the calculation procedure of short delay time interaction can be found in Rossmanith (2002) and Vanbrabant (2010).

Inspired by Rossmanith and co-workers (1997; 1998; 2002), the delay times in this project were chosen to create an overlap of the negative tails of the radial particle velocity (P-waves) generated by the blastholes, since it is practically easier to measure particle velocities than stresses. Vanbrabant (2010) presented this approach through a Lagrange diagram (Figure 4), where the ideal case of overlapping can be seen. The ideal timing between two blastholes is determined by measuring the primary wave velocity and velocity of the tensile tail at certain distances from the blasthole. In addition to that, the duration of the compressive pulse at the blasthole has to be taken into account. The results of several small-scale tests on mortar blocks (Johansson, 2011; Johansson and Ouchterlony, 2013; Petropoulos, 2012) were utilized to evaluate the shockwave interaction scheme and its influence on fragmentation.
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Figure 4: Ideal case for tensile tail overlap (Vanbrabant, 2010).

For an ideal case as in Figure 4, the timing should be as follows:

\[ T_{ideal} = T_d + T_1 - T_0 \]

where,

\( T_d \) = traveling time of the shockwave between the shot hole and the subsequent neighboring hole.

\( T_1 \) = duration of the first (compressive) half-wave at the neighboring hole (at one hole spacing).

\( T_0 \) = duration of the first half-wave at the shot hole when the charge detonates (at distance \( D = 0 \)).

In our first attempt, the blastholes are initiated and superimposed based on wave travel time between two blastholes and the positive phase \( \delta t \). The initiation time \( \Delta t \) between blastholes is calculated as \( \Delta t = t_1 + t_2 \) with \( t_1 = 8.6 \) m/5000 m/s and \( t_2 = 3/4 \cdot 2 \cdot \delta t \). The term \( t_1 \) is the ratio of hole spacing and p-wave velocity and \( t_2 \) a factor for phase and positive part of the period. The Fast Fourier transform (FFT) is not used for estimation of hole initiation delay time due to data scatter.

For second and third trial the calculations led to \( \Delta t_2 = 7.4 \) ms and \( \Delta t_3 = 5.5 \) ms of delay time. Note that the travel time of shockwave between the holes is a rough
approximation due to conical shape of waves and limited amount of data especially for second trial. Based on the above estimations, the upper practical linear inter-hole delay time was set to 6 ms.

Two other delay times of 1 ms and 3 ms were chosen based on successful full-scale experiments of Chiappetta (2011) in several mines in South America (Chile, Peru, Mexico and Colombia). According to Chiappetta (2011), the best fragmentation is produced by an inter-hole delay time of 1-3 ms.
2 Field test description

2.1 Test area description

Aitik, situated outside the town of Gällivare in the north of Sweden, is the largest copper mine in Sweden. The deposit consists of chalcopyrite and pyrite yielding copper, gold and silver. Approximately 31.5 Mtonnes of ore is mined and concentrated here every year. The annual ore production is expected to reach 36 Mtonnes in 2014. The open pit is currently 3 km long, 1.1 km wide and 450 meters deep (Figure 5).

The ore is a low-grade copper mineralization with about 0.27% of copper, 0.16 ppm gold and 2.07 ppm silver. The ore zone is 2500 x 300 m in size; it strikes approximately N20°W and dips about 45° to the west.

Figure 5: Aerial image of Aitik mine (Boliden’s photo archive)

The Aitik deposit is situated within an area of metamorphosed plutonic and volcano-sedimentary rocks of Precambrian age (1.9-1.8 Ga). Rock types within the deposit are strongly deformed and altered, and the mining area is divided into footwall, ore zone and hanging wall, based on structural boundaries and copper grades.

The footwall mainly consists of quartz monzodiorite and feldspar-biotite-amphibole gneiss with <0.26 % Cu. The ore zone comprises garnet-bearing biotite schist towards
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the footwall, and quartz-muscovite-sericite schist towards the hanging wall. The hanging wall mainly comprises fine-grained, banded feldspar-biotite-amphibole gneiss, which is separated from the ore zone by a major fault. Pegmatite dykes are most frequent in the hanging wall and ore zone, where they occur both along strike (north-south) and cross-cutting the foliation. They range in thickness from 0.5 to 20 meters. Within the ore zone both types often carry chalcopyrite and pyrite, and occasional molybdenite. Up to 50 cm wide baryte veins containing varying amounts of magnetite, actinolite, quartz, epidote, chalcopyrite and pyrite are spatially associated with the ore zone. Strong alteration in Aitik occurs as extensive biotitization and sericitization in the ore zone, accompanied by garnet porphyroblasts, quartz and pyrite. The main copper-bearing mineral in Aitik is chalcopyrite (>98 %). Bornite and chalcocite are present in trace amounts. Other ore minerals include pyrite, magnetite, pyrrhotite, ilmenite and molybdenite, where pyrite is by far the dominant sulphide. The highest copper grades occur in the potassic altered biotite schist in the ore zone (Figure 6, Wanhainen 2005).

Figure 6: Geology of the Aitik Cu-Au-Ag deposit and its close surroundings. Horizontal section at 100-200 m depth (Wanhainen, 2005).

The ore flow in Aitik, Figure 7, starts with drilling and blasting, then the ore is loaded with excavators and hauled with trucks to the in pit crusher. The ore is crushed and transported on a conveyor belt, to two ore piles that feeds the grinding mills. After grinding the ore goes through flotation, thickening, dewatering and finally drying. The concentrate is transported to the Rönnskär smelter. Actual mine production areas and ore profile are illustrated in Figure 8 and Figure 9.
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Figure 7: Schematic ore flow from mine to smelter.

Figure 8: Mine production areas (6 – waste rock; 5, 7, S1, S2 – ore with satellite open pit Salmijärvi). There are three crushing stations, one at surface level and two inside the pit.
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The selected test area for blasts is shown in Figure 10 and Figure 11. The area is located in southern part of the mine at levels 210 and 225 m, representing fairly similar geological characteristics and thus, reducing the possible influence of geology on blast results from different benches.

Figure 9: Ore profile.

Figure 10: Test area S1, bench 210, blasts 11 (ref) and 12 (6 ms).
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2.2 Blast trial design and test matrix

2.2.1 Description of zero tests

The purpose of the so-called zero trials, is to evaluate the characteristics of typical vibration signals at about 10-15 m behind the blast in order to find blasthole time delay for optimum fragmentation suggested by earlier research (Rossmannith, 2002; Vanbrabant and Espinosa, 2006; etc.). The signals are generated by production holes (Ø311 mm) in the Aitik mine. The holes are approximately 18 m long, of which approximately 15 m was loaded with emulsion explosive. In particular, wave frequency, the propagation velocity and the wave amplitude are of interest and the results will be used for estimation of the optimum inter-hole blast delay.

The overall objective is to find a relation between the blasthole timing and blast fragmentation. Between the rows, standard delays are used (176 ms). For the entire blast the hole initiation took place with help of electronic caps which have an accuracy of ± 0.13 ms for interval 0 - 1300 ms and ± 0.01 % for interval 1301 - 15000 ms. The selected electronic caps were of type i-kon™ RX Electronic Detonators due to programmability and durability of them.

2.2.2 Test Matrix

This section describes all the trials in addition to the two reference benches in terms of blast design, e.g., delay time, drilling pattern, blast direction, etc. The blasting reports are placed in Appendix 1.

Table 1 shows the names, date of blasts and assigned inter-hole delay times of the trials and reference blasts. Two benches were blasted with 1 ms inter-hole delay time.
and two benches were blasted with respectively 6 ms and 3 ms of inter-hole delay time. Benches S1_210_11 and S1_225_13 were blasted with Nonel initiation system. Since Nonel is the normal initiation system used in the Aitik mine, benches S1_210_11 and S1_225_13 were monitored and used as the references for the comparison of the results of the trials.

Table 1: The test matrix.

<table>
<thead>
<tr>
<th>Campaign</th>
<th>Date</th>
<th>Delay time, ms</th>
<th>Bench no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Ref.</td>
<td>March 7, 2012</td>
<td>42</td>
<td>S1_210_11</td>
</tr>
<tr>
<td>1</td>
<td>March 28, 2012</td>
<td>6</td>
<td>S1_210_12</td>
</tr>
<tr>
<td>2</td>
<td>July 26, 2012</td>
<td>1</td>
<td>S1_225_11</td>
</tr>
<tr>
<td>3</td>
<td>August 28, 2012</td>
<td>3</td>
<td>S1_225_12</td>
</tr>
<tr>
<td>2nd Ref.</td>
<td>August 28, 2012</td>
<td>42</td>
<td>S1_225_13</td>
</tr>
<tr>
<td>4</td>
<td>September 12, 2012</td>
<td>1</td>
<td>S1_225_14</td>
</tr>
</tbody>
</table>

S1_210_11

Figure 12 shows the first reference bench initiated with a Nonel system. This bench was used to compare the short inter-hole delay time trials with the conventional initiation system. The detailed data are shown in Appendix 2.

![Figure 12: Bench S1_210_11.](image)
**S1_210_12**

The first trial was planned to be blasted with 6 ms inter-hole delay time. There were 81 contour blastholes and 302 production blastholes. The volume of the blasted material was 301 379 m$^3$ and the amount of explosives was 303 401.5 kg. Hence, the specific charge of the bench was 1.00 kg/m$^3$. Figure 13 shows the map of the bench and Figure 14 illustrates the delay time and the blast direction of the bench. The charge report of the bench is shown in Appendix 3.

Figure 13: Bench S1_210_12.
Figure 14: Delay time and blast direction.
S1_225_11

The second trial was planned with 1 ms inter-hole delay time. This bench had 82 contour holes and 245 production blastholes. However, together with bench S1_225_11, half of bench S1_225_10 was blasted at the same time with the same inter-hole delay time (Figure 15 and Figure 16). The volume of the blasted material only for bench S1_225_11 was 243,980 m³ and the amount of the explosives was 256,752.2 kg. The specific charge was 1.05 kg/m³. The detailed charge report is shown in Appendix 4.

Figure 15: Benches S1_225_10 and S1_225_11.

Figure 16: Blast direction.
S1_225_12

The third trial was planned with 3 ms inter-hole delay time. The bench had 67 contour blastholes and 308 production blastholes. The volume of the blasted material was 302 888 m³ and the amount of the explosives was 325 340 kg. The specific charge was 1.07 kg/m³. Figure 17 shows the drilling pattern of the bench. Figure 18 illustrates the delay time of the bench and the connection design of the blastholes. The charge report is shown in Appendix 5.

Figure 17: Bench S1_225_12.
This is the second reference blast. This bench was blasted with the regular blast design as used in the mine. The blast design of the bench was 46 ms inter-hole delay time and 176 ms inter-row delay time. Figure 19 shows the bench and Figure 20 shows the bench with a part of the next bench which was blasted at the same time. The bench had 56 contour holes and 325 production blastholes. The volume of the blasted material was 316,073 m$^3$ and the amount of the explosives was 350,779.4 kg. The specific charge was 1.11 kg/m$^3$. The detailed data are shown in Appendix 6.
Improved blasting results through precise initiation

Figure 19: Bench S1_225_13.
Figure 20: S1_225_13 Nonel system.

S1_225_14

This is the last trial with 1 ms inter-hole delay time. The bench had 47 contour holes and 301 production blastholes (Figure 21). The volume of the blasted material was 300 631 m$^3$ and the amount of the explosives was 329 629.7 kg. The specific charge was 1.10 kg/m$^3$. The charge report is shown in Appendix 7
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Figure 21: Bench S1_225_14.
2.2.3 Design of field campaign

Three different zero-trials were conducted before the main trials. Each trial was evaluated with focus on finding wave characteristics to be used for the decision of optimum inter-hole delay time. The wave characteristics were determined based on the wave arrivals from time-separated blastholes with help of Aitik standard pyrotechnic initiation (Nonel).

The first trial did not produce any useful results and therefore will not be discussed further in this report. But the other two trials on September 20, 2011 and November 10, 2011 were used for further analysis. For both zero trials, acceleration and Velocity of Detonation (VoD) were measured for selected production holes. Figure 22 shows a triaxial accelerometer mounted on a removable steel anchor.

Blast trials in general show the amplitude and dominating frequency for short distances between blastholes; gauges often reach frequencies and accelerations as high as 5 kHz and 5000 g respectively. Therefore, accelerometers were chosen based on experiences from earlier full-scale trials and small-scale trials with similar types of shock accelerometers. See for example Ouchterlony et al. (2003), Nyberg et al. (2005), Wimmer et al. (2012), Shirzadegan (2012) and Johansson (2012).

![Figure 22: A Triaxial accelerometer (PCB 350B50) mounted on a steel anchor. The orientations of the positive components are x-vertical upward, y-horizontal to the left and z-horizontal out of the figure with center blasthole in positive z-direction.](image)

The anchors were grouted with help of about 13 liters of concrete (coarse concrete Weber Saint-Gobain) in the bottom of 3.5 m deep and ø152 mm vertical boreholes, which were drilled directly in the hard rock behind the blast. A similar grouting method was used earlier to measure wave arrivals behind blast, see Ouchterlony et al.
Improved blasting results through precise initiation (2003). A casing (Ø70 mm PVC pipe) was used in order to mount the gauges, determine the orientation and prevent water and concrete to get in contact with the instrument cables. The concrete curing time varied from approximately 2 days for the first two castings to about 1 week for the third casting (Figure 23).

![Diagram of downhole installation of accelerometers](image)

**Figure 23**: Schematic illustration of the downhole installation of the accelerometers in a gauge hole.

For all the gauge holes (GH), one vertical and two horizontal components were used and one of the horizontal ones was pointing at the closest blasthole which was supposed to generate a useful signal.

In order to get as clear signals as possible, i.e. to avoid interference from many wave arrivals at the gauge points, three and four production holes for the two zero trials, respectively, were time separated from the main blasts with approximately 176 ms interval time.

Figure 24 shows the two gauge holes with local mine coordinates (X, Y, Z) at approximately 15 m and 25 m, respectively, from the center production hole no 113. The distances were chosen based on practical issues, not too close to the blast due to
the risk for back break which would damage the gauge holes and not too far from blastholes due to wave attenuation, i.e., no realistic wave frequency for blasthole timing design.

The measurement line connects the gauge holes with the center hole. The center hole, together with holes 112 and 114, was blasted slightly after the full blast in order to reduce the noise level from blastholes at long distance. Each of the gauges has 3 components (x, y, z) according to Figure 22.

Figure 24: The layout for zero trial no. 2 (60_1) September 20, 2011. 8.6 m Spacing and 7.0 m Burden.

Figure 25 shows two gauge holes approximately 10 m apart with the closest one approximately 15 m from the center production hole (256). Four production holes (255-258) were time delayed with 176 ms compared to the other production holes and the holes were drilled to about 19 m depth.

Figure 25: Layout for zero trial no 3 (N6-75-13) November 10, 2011. The line connects the center blasthole with the two gauge holes.

Some of the key technical specifications for the data recording instruments are given below.
Improved blasting results through precise initiation

Accelerometers

- Type: Triaxial ICP shock sensor (PCB 350B50)
- Filter: Built in 2\textsuperscript{nd} order low pass filter (-3 dB at 20 000 Hz)
- Dynamic range: \( \pm 98 \text{ km/s}^2 \)
- Sensitivity: 0.5 mv/g
- Frequency Response: \( \pm 1 \text{ dB for 3 to 10 kHz} \)

Cables

- Type: Coaxial cables
- Impedance: 50 \( \Omega \)
- Max frequency: 500 MHz
- Shielding and inner conductor: Copper
- Mantel: PVC

Recorder

- Typ: LAAN-XI 3050
- Standard frequency range: 51.2 kHz
- High frequency range: 102.4 kHz
- Actual sampling rate for the trials: 65536 sample/sec/channel
- Individual modules

VoD

In order to keep control of the explosive performance, VoDs were measured for a limited number of production holes.

Recording unit

- Micro Trap
- Cable: robcable – LR 3.48 ohm/m.

2.3 Data acquisition

2.3.1 Swelling data

The GPS data before the blasts had been provided by the mine. The swelling data have been obtained the next day of the blast by using a Real Time Kinematic GPS system (RTK). RTK surveying is a carrier phase-based relative positioning technique, employing two or more receivers simultaneously tracking the same satellites. This method is very useful because one can determine the coordinates in real time. The base receiver remains stationary over the known point and is attached to a radio transmitter. The rover receiver is normally carried in a backpack and is attached to a radio receiver. The base receiver measurements and coordinates are transmitted to the rover receiver through the communication radio link. The initial ambiguity parameters
are determined almost instantaneously using a technique called on-the-fly ambiguity resolution. Once the ambiguity parameters are fixed to integer values, the receiver will display the rover coordinates right in the field. In other words no post-processing is required. The expected positioning accuracy is of the order of 2 to 5 cm; however, the accuracy can be improved by staying over the point for a slightly longer period of time, i.e., 30 seconds, to allow averaging the position (El-Rabbany, 2002).

2.3.2 High speed video filming

Every blast has been filmed using a high speed camera. The camera that was used was a Casio Exilim Pro EX-F1 at 300 fps (frames per second). The camera was installed perpendicular to the north direction of the benches within the concrete bankers (power station B6) locating close to the eastern wall of the mine. In all cases, the camera was activated 15 minutes prior to blast. During the last trial (S1_225_14), a technical problem occurred causing a delay in the blast of more than 30 minutes. The recording range of the camera is about 29 minutes. Hence the blast was out of the recording range and no video record was obtained.

2.3.3 Images of the trucks for fragmentation analysis

A series of images per truck have been taken in order to choose the most appropriate one giving the best visibility of the material, i.e., without dust or water spray behind the truck. The resolution of the images is 10 Megapixels (3872x2592) 24 bit depth. The focus length of the images is 300 mm. The camera settings were without flash because it created white spots on the images. The selected file type was JPG image. The camera used was a Nikon D3000 equipped with a Tamron AF 70-300 mm lens. All the images per blast have been taken from the same shooting point in order to minimize errors related to changing shooting positions which may cause compatibility problems between the images per set of them. The error can reach up to 40%. The most favorable shooting position is when the back side of the truck body is parallel to the shooting axis and clearly visible.

All the images have been taken by using a tripod with a height of 1.90 m and the system was located at a higher point than the truck axis in order to maximize the projected material in the image.

2.3.4 Measuring of the truck body sizes

The truck body size was directly measured using a measuring tape because the Aitik mine does not use the commercial Caterpillar truck bodies, but custom made ones. The Aitik mine uses three different models of Caterpillar mine trucks (795 F AC MSD II BODY (347 tons), 793 D X BODY (237 tons) and 793 C (223 tons) (Figure 26 and Table 2). The number of the trucks was not used because the mine’s workshop mounts the same truck body on different truck chassis, which means that if the number of the truck was taken into consideration the truck body dimensions would
Improved blasting results through precise initiation have been wrong. Hence, the outer shape of the truck body was taken into consideration to distinguish between the three different truck bodies.

Figure 26: The different truck bodies at the Aitik mine.
Table 2: The truck body dimensions.

<table>
<thead>
<tr>
<th>Truck type</th>
<th>Outer [m]</th>
<th>Inner [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>795 F AC MSD II BODY</td>
<td>8.73</td>
<td>8.21</td>
</tr>
<tr>
<td>793 D X BODY</td>
<td>7.64</td>
<td>7.12</td>
</tr>
<tr>
<td>793 C</td>
<td>6.95</td>
<td>6.32</td>
</tr>
</tbody>
</table>

2.4 Drill cuttings

This section briefly describes the use of drill cuttings for analyzing the geology and mineralogy in Aitik. For each production hole, a representative sample of about 2 kg was collected. The samples were put in plastic bags and mixed. Each plastic bag was analyzed 6 times with help of an XRS roentgen analyzer to obtain average values of minerals. For amounts of copper above 0.5 % the bags were sent to laboratory for further analyses.

The content of pegmatite was estimated by visual inspection and no exact analysis was done. If pegmatite was found, the specific production hole was marked on a map.

2.5 Post-test analysis

There are many software packages for fragmentation image analysis such as SplitDesktop, FragScan, GoldSize, CIAS, IPACS, Fragmetrics, etc. Fragmetrics is an installed system for evaluation of fragmentation at the Aitik mine. This system is installed on a shovel and evaluates the fragmentation per bucket of the shovel. However, based on the produced results (poor quality images) this system was not considered reliable enough to carry out the fragmentation analysis. The image resolution of the taken images by this system was ranged from 240x90 to 441x242 pixels. There were restrictions related to manual delineation, i.e., someone can only delineate a particle but not erase a line splitting a particle into two or more parts.

The fragmentation has been evaluated by means of image analysis software. The selected software was SplitDesktop (version 3.1.0.76 64 bit) developed by Split Engineering LLC, which at this date is the latest version (Split Engineering, 2013).

The image analysis procedure includes importing the image, placement of scales and setting the degree of delineation. The software requires at least two scales to estimate fragmentation; hence one scale was located at the bottom of each truck body and one at the top of it. These scales are usually equal when one uses the internal dimensions of the truck body, however in some cases the upper part of the truck body is not visible; the used dimension in this case is the canopy length.

The settings of the software had been defined in the beginning of the image analysis. The fines factor had been set to 50% in all analyzed images in order to keep this.
sensitive factor constant, e.g., if someone increase the fine factor, the distribution curve will move to finer area and vice versa. Several users have been involved in the image analysis, which means that if the fine settings were altered, the evaluation method would have become subjective. No auto-fines option was used as well as boulder detection because the given results were not correct. This option masks the background of the image and not the broken material or masks boulders with pour lighting and/or different color. The only parameter that was changed was the delineation factor in order to reduce the editing time (Figure 27). This parameter does not influence the results; the only influence is on the required editing time for manual delineation.

The auto-delineated images require more analysis because the auto-delineation option of the software is not accurate enough to produce reliable results, i.e., a detailed manual delineation was needed for each image.
Figure 27: Process flow of the image analysis.

Figure 28 shows an image without (a) and with (b) the delineation. The particle size distribution is retrieved from the cropped, scaled, auto-delineated and manually corrected image (Figure 28b).
Figure 28: A sample image without (a) and with (b) delineation. The image without delineation (a) has been cropped and scaled at two positions (thin lines), the delineated image (b) is the result of auto-delineation of the software followed by detailed manual delineation corrections.

Figure 29 shows a magnified cut-out of the image in Figure 28. The image with auto-delineation does not provide any useful information about the particle size distribution, since the borders of the particles (blue area) does not isolate particles properly. Figure 29b shows the same cut-out after manual correction of the delineation. The cyan area is masked out to be excluded from the sieving analysis and the particles are properly isolated by the blue area; the red area represents the fines, which cannot be delineated due to poor visibility of the small particles.
The sieving series have been defined with respect to minimum fragment size, which has been set to 4.00 mm. The upper limit has been free to reach the size of the biggest estimated particle. The same sieving series has been used for the entire image analysis.

2.6 Software evaluation

At the beginning of the image/fragmentation analysis some errors occurred among the analyses by different users. Hence, these errors should be identified in order to minimize them and to produce reliable results. Consequently, different kind of evaluations of the software have been carried out, such as (i) consistency of the software, i.e., if the software produces the same results for the same analyzing conditions, (ii) issues related to lighting conditions, i.e., the influence of the shadows or the different color areas on a truck body, (iii) internal image resolution and (iv) relative error among different users, i.e., delineation quality.

2.6.1 Internal resolution

The term internal means that the original image has a particular resolution, in this case 10 Megapixels (3872x2592 pixels), and it was imported into the software by automatically scaling down the resolution of the image. The software has this function in order to decrease the processing time of an image. Some of the images have been analyzed by using 2 Megapixels internal resolution and others with 10 Megapixels resolution (original size). The software has been evaluated for different internal resolutions. This factor varies from 2 Megapixels up to 10 Megapixels. As the resolution increases, the computational time increases as well. Sometimes the software by default sets the internal resolution to 2 Megapixels without any notification.
For this evaluation one image has been used and analyzed at ten different resolutions by the same user, i.e., the user dependency was removed. Figure 31 shows the variation of the dimensions of the scales with respect to the internal resolution. The different internal resolutions have been fitted by using power regression, which fits quite well.

Figure 30 shows the position of the scales in the truck body the scale at the upper part of the image is called top scale and the lower one is called bottom scale.

![Image: The scale positions.](image)

### Resolution analysis

![Graph: Resolution analysis](image)

The results of the internal resolution analysis are shown in Figure 32. The analysis for each image is presented in Appendix 8.
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Based upon Figure 32, the internal resolution does not have any influence on the results, even if the resolution of the scale changes (pix/m) according to Figure 31.

2.6.2 Relative error among the users

The error analysis has been carried out on 6 randomly selected images which have been analyzed by all the users. The relative error, i.e., the error between different users, was found to be large (up to 30%) (Figure 33). The relative error among the users was minimized down to 1 %, i.e., a few millimeters, by detailed manual delineation of the images by only one user. This size is smaller than the cut-off value of the distribution curve. Table 3 shows the absolute error in percentage between the users, which can be considered rather high. The results showed that the error is larger in the mid-section of the distribution curve than the coarse region of it.

Figure 32: Fragmentation curves with different resolutions.
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Table 3: The relative error among different users.

<table>
<thead>
<tr>
<th></th>
<th>X_{50}</th>
<th>X_{60}</th>
<th>X_{70}</th>
<th>X_{80}</th>
<th>X_{90}</th>
</tr>
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<tbody>
<tr>
<td>User 1 vs. User 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.73</td>
<td>12.92</td>
<td>7.07</td>
<td>2.09</td>
<td>3.82</td>
<td></td>
</tr>
<tr>
<td>33.46</td>
<td>15.18</td>
<td>8.63</td>
<td>6.59</td>
<td>6.79</td>
<td></td>
</tr>
<tr>
<td>25.10</td>
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<td>4.15</td>
<td>12.02</td>
<td></td>
</tr>
<tr>
<td>8.13</td>
<td>1.06</td>
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<td>0.41</td>
<td>0.37</td>
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</tr>
<tr>
<td>User 2 vs. User 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.03</td>
<td>0.59</td>
<td>1.91</td>
<td>3.22</td>
<td>5.51</td>
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</tr>
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<td>11.00</td>
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<td>23.94</td>
<td>13.43</td>
<td>8.81</td>
<td>5.15</td>
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</tr>
<tr>
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</tr>
<tr>
<td>User 1 vs. User 2</td>
<td></td>
<td></td>
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<tr>
<td>10.99</td>
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<td>0.05</td>
<td>10.56</td>
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<td>22.97</td>
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<td>10.47</td>
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<td>6.51</td>
<td>6.09</td>
<td>6.23</td>
<td></td>
</tr>
</tbody>
</table>

Figure 33 illustrates the fragment distribution curves of the users visualizing the error along the entire curve.
Improved blasting results through precise initiation

2.6.3 Delineation error

The images have been analyzed by the same user and they show the same type of truck (equal dimensions of the truck body). Two images are presented in Table 4 to show the difference in the delineation quality. This is the most crucial factor for obtaining reliable results. The image on the right is not a corrected image, which means that several particles are covered by the delineation (blue area) or a single particle is split into smaller particles. This is a result of different color of the particle due to different material or lighting conditions (shadow); generally the darker areas of a particle were covered 100% by the delineation. The cyan area is used in order to mask the background of the image and the visible truck body. Neither of the areas is considered in the analysis by the software.

The introduced error by these blue areas was too large to be acceptable. Further processing of the images was required to reach an acceptable delineation level. All the analyzed images have been delineated by one user. The level of delineation almost reached the delineation of each visible individual particle.
Table 4: Delineation error.

<table>
<thead>
<tr>
<th>Corrected</th>
<th>By User</th>
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<td><img src="image2" alt="By User Image" /></td>
</tr>
<tr>
<td><img src="image3" alt="Corrected Image" /></td>
<td><img src="image4" alt="By User Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DSC_0351</th>
<th>DSC_0351</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>F10</td>
<td>39</td>
</tr>
<tr>
<td>F20</td>
<td>105</td>
</tr>
<tr>
<td>F30</td>
<td>186</td>
</tr>
<tr>
<td>F40</td>
<td>305</td>
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<tr>
<td>F50</td>
<td>392</td>
</tr>
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<td>F60</td>
<td>472</td>
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<td>663</td>
</tr>
<tr>
<td>F90</td>
<td>830</td>
</tr>
<tr>
<td>Topsize</td>
<td>1319</td>
</tr>
<tr>
<td>(99.95%)</td>
<td></td>
</tr>
</tbody>
</table>

2.6.4 Variation of the images

The images of each truck show a large range of sizes and their fragmentation analysis varies a lot. This is due to the fact that some of the trucks had mainly big boulders and other trucks had mostly fine material. This difference is shown in Table 5, where the left truck contains mostly boulders and coarse material and the right truck having more fine material.
The selection of the images has been arbitrarily done to minimize the influence of the user selecting the images, i.e., to avoid choosing only images with fine material or boulders. No criteria have been used regarding the image selection. Each folder with images contained two subfolders such as morning and afternoon images. There were at least two days of photo shooting per bench. The images were randomly distributed among the users.

Table 5: Difference between different trucks.

<table>
<thead>
<tr>
<th>DSC_0147</th>
<th>DSC_0162</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>F10</td>
<td>40</td>
</tr>
<tr>
<td>F20</td>
<td>119</td>
</tr>
<tr>
<td>F30</td>
<td>264</td>
</tr>
<tr>
<td>F40</td>
<td>414</td>
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<td>F60</td>
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<td>934</td>
</tr>
<tr>
<td>F90</td>
<td>1212</td>
</tr>
<tr>
<td>Topsize</td>
<td>(99.95%)</td>
</tr>
<tr>
<td></td>
<td>1569</td>
</tr>
</tbody>
</table>
2.6.5 Compatibility of the images

The images from the first two benches (S1_210_11 and S1_210_12) have had compatibility problems with respect to the rest of the benches. The images of these benches have been taken at a different angle than the truck axis. Hence, there is a deviation on the results because the projection of the scales on a 2D-plane does not correspond to the actual size of the real dimensions of the truck body. One attempt has been made to correct this deviation of the image analysis by delineating the side and the back side of some trucks. A total of 3 pairs of images have been analyzed to estimate the deviation of the two sides of the truck (Appendix 9). Table 6 shows an example of the two different perspectives of the same truck; the difference between the two images is obvious.

However, this is very arbitrary because there are other sources of error in this case, such as the projected area on the image, i.e., as the optical axis of the camera starts deviating from the truck axis, the camera can take images of different perspectives of the truck body. This means that the material is not the same at the side of a truck as the back side of a truck e.g. for a flaky particle, one can see the largest surface of it at the side of the truck but at the back side of it one can see the smallest projected area.

Table 6: The difference in fragmentation between two perspectives.

<table>
<thead>
<tr>
<th>DSC_0331</th>
<th>DSC_0339</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
</tr>
</tbody>
</table>

Size Distribution

<table>
<thead>
<tr>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size [mm]</td>
</tr>
</tbody>
</table>

DSC_0331  
DSC_0339  

Improved blasting results through precise initiation
The images taken by the side of the trucks give an overestimation of the fragmentation, i.e., coarser material. This has been observed in all the comparisons between the images. The difference of the curves is not constant but it changes by changing the mass passing.

The fragmentation analysis has been carried out based on three values, the median size ($x_{50}$) and the oversize material ($x_{80}$) and the top size ($x_{99.95}$). The other fractions of the distribution have not been considered such as the fine part of the distribution which is given by fitting a model.

In order to make the fragmentation curves of these images comparable to the results of the other benches, the curves have been normalized. Since the analysis of the images from the side of the trucks always resulted in coarser fragmentation, the curves could be corrected by applying a correction factor, which shifted the curves towards the right side of the graph (finer fragmentation). Three pairs of images of trucks have been used to normalize the curves, each pair consisted of one image from the side of a truck and an image from the backside of the same truck. Hence the fragmentation curves of benches S1_210_11 and S1_210_12 are compared to the rest of the benches by their normalized curves.
3 Results

3.1 Geological and structural data

This section provides a qualitative assessment of photos taken on the wall above the trials of March 28: S1_210_12, July 26: S1_225_11, August 28: S1_225_12 and September 12: S1_225_14 and geological data of the content of pegmatite in drill cuttings.

Figure 34 shows the geology of trial S1_210_12 consisting essentially of muscovite schist and Figure 35 shows the geology of S1_225_11 to S1_225_14 with a mixture of muscovite schist, biotite schist and biotite gneiss, which is considered to affect the blast results quite similarly. Pegmatite occurs sparingly in there blasts.

![Figure 34: Trial blast S1_210_12 with mostly muscovite schist (yellow).](image)

In Figure 35, blast S1_225_13 has been used as second reference because it was in the same geological area. The bench was blasted with the regular blast design in the mine (42 ms inter-hole delay time and 176 ms inter-row delay time).
Improved blasting results through precise initiation

Figure 35: Geology for bench 225. Note that S1_225_13 is not in the trial series. Muscovite schist (yellow), Biotite schist (green) and biotite gneiss (blue).

Figure 36 shows a photo of the slope face S1_210_12 with some pegmatite and fractures present that may affect blasting performance; but these are not measured due to incomplete data. On the slope face of blast S1_225_11 to S1_225_14 there are also some small amounts of pegmatite.

Figure 36: Photo of slope face trial S1_210_12 with some pegmatite and sets of fractures.

Drill cut-mapping has been done with a focus on finding the pegmatite. The results show small amounts spread out with no coherent veins. In the case of photos of the slope faces, no data are available for digital photogrammetry to identify the joint sets predominating in each trial which means that the assessment of the joints is
qualitative. The results show presence of some pegmatite, but the dip and partly unknown orientation makes it difficult to assess the amount of pegmatite from photos.

The main results from interpretation of geological drill cuttings from the trials of March 28: S1_210_12, July 26: S1_225_11, August 28: S1_225_12 (Höglund, 2012) and images indicate that there are only a few holes with cuttings containing pegmatite and some pegmatite veins running out of the faces.

Figure 37 shows the result for blast S1_225_14 with visual inspection of drill cuttings and the red dots indicating that pegmatite was found for the specific production holes. The results from the other trials have less findings of pegmatite.

![Figure 37](image)

From a geological assessment, all the pegmatite veins have ore concentrations, suggesting that they are quite narrow; metals are mobilized along the contact between the veins and the surrounding rock and if the veins are wider they usually have no ore concentration in the vein center.
3.2 Zero trials

This section presents results from triaxial acceleration recordings for two zero trials with gauges at approximately 15-25 m distance from selected and time-separated blastholes. Additionally, the section shows some results from monitoring of the VoD for a limited number of production blastholes that were loaded with the same explosives and approximately the same amount as the selected ones. Zero trial number 1 did not produce any useful results but for trials no. 2 and 3 useful data were acquired from three and five blastholes respectively.

Figure 38 shows examples of acceleration recordings (m/s²) vs. time (s) from trial no. 2 (the upper diagram) and trial no. 3 (the lower diagram). The recordings covered 10 s and 3 s of tri-axial data for trials no. 2 and no. 3 respectively. The vertical (x) component is strongly distorted for trial no. 2, i.e., both zero line offset and probably cable connection problems. The problem of zero line offset occurs when the signal from an accelerometer does not level out at zero line but shows a residual acceleration. At about 4 seconds, the time-separated blastholes seem to detonate which is shown as 3 strong arrivals. The time interval is nominal 176 ms between the holes but in reality slightly different due to pyrotechnic cap scatter.

For trial no. 3, all signals are recorded with normal noise level and no distortion. The time-separated holes are shown to the right but there is a gap between the two latest clear arrivals (about 250 ms time difference) and a weak arrival at about 176 ms before the last one.

The amplitudes for the two recordings are strongly different probably due to scaling error and the amplitudes in general are low (see Figure 23, Ouchterlony et.al., 1997) in comparison with earlier recordings in the Aitik mine.
Improved blasting results through precise initiation

Figure 38: Recording of triaxial signals from gauge hole at about 15 m from the center blasthole. Upper one is from trial no. 2 (September 20, 2011) and the lower one from trial no. 3 (November 10, 2011).

In order to get the most representative wave for estimating the wave characteristics, only blastholes close to gauges are used, i.e., holes at approximately 15 m and 25 m away from the closest center blasthole. In practice, the three latest arrivals in the upper figure and the 5 latest arrivals in the lower figure are used. The figures also show the normal amplitude dependence with distance, i.e., the amplitudes increase with decreasing distance from the blasthole.

Figure 39 (right figure) shows the vertical x-component for gauge no. 1 for the last blasthole in Figure 39 (left figure), (18.5 m distance to wave generating blasthole) and the signal power density spectrum, i.e., how the power of a signal or time series is distributed with the frequency. The time period T is approximately 8.9 ms, i.e., 1/T=112 Hz which is the principal frequency for the signal. The Fast Fourier Transform (FFT) of the same signal has a dominating frequency of about 104 Hz and a frequency resolution of 8 Hz. Note that often the FFT does not have a clear peak and therefore not coinciding with the frequency based on time period T from zero-crossing time interval in time domain. The sampling rate for the time signal is 65 536 samples/second which is strongly over-sampled due to expected high signal frequencies up to 4 kHz for gauges close to blastholes.
Improved blasting results through precise initiation

Table 7 shows the results from evaluation of n=4 values for trial no. 2 and n=21 values for trial no. 3 for gauge holes GH 1 and GH 2, see example in Figure 39. The positive phase is often shorter than the negative phase, and therefore the period T is often greater than two times the positive phase $2\delta t$. Similar result has been found by Yang (2012), i.e., the principal frequency and the frequency calculated by FFT is often not the same.

As a special case the horizontal z-component for trial no. 3 (GH 1) has a first strong negative phase and a relative long positive phase. The negative sign is probably due to orientation of the gauge, i.e., rotated a half turn but the reason for the long positive phase is not clear.

Table 7: Time periods and frequency for the signals at approximately 15 and 25 m from the center blasthole for trial no. 2 (September 20, 2011) and trial no. 3 (November 10, 2011).

<table>
<thead>
<tr>
<th></th>
<th>Positive Phase $\delta t$ ms</th>
<th>Period T ms</th>
<th>$2 \cdot \delta t$ ms</th>
<th>$1/T$ Hz</th>
<th>Power Spectral Density Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average trial 2</strong></td>
<td>3.8</td>
<td>7.0</td>
<td>7.6</td>
<td>154</td>
<td>110</td>
</tr>
<tr>
<td><strong>Standard deviation trial 2</strong></td>
<td>0.5</td>
<td>1.4</td>
<td></td>
<td>35</td>
<td>75</td>
</tr>
<tr>
<td><strong>Average trial 3</strong></td>
<td>2.6</td>
<td>6.6</td>
<td>5.2</td>
<td>285</td>
<td>210</td>
</tr>
<tr>
<td><strong>Standard deviation trial 3</strong></td>
<td>1.3</td>
<td>6.1</td>
<td></td>
<td>209</td>
<td>99</td>
</tr>
</tbody>
</table>
3.3 Fragmentation

3.3.1 Bench S1_210_11

Bench S1_210_11 is the first reference bench of the trials with a total number of 25 images analyzed. The images of the reference bench have been taken from the side of the trucks. This means that the truck axis and the optical axis are not the same, and have a difference of a particular angle. This angle is different from truck to truck or from image to image. This bench has been used as a reference bench only for the first short delay bench (S1_210_12, 6 ms). All the analyzed images are shown in Appendix 10. Table 8 shows the results of the image analysis.

<table>
<thead>
<tr>
<th>Size[mm]</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>100.0</td>
</tr>
<tr>
<td>2000</td>
<td>99.0</td>
</tr>
<tr>
<td>1000</td>
<td>88.2</td>
</tr>
<tr>
<td>750</td>
<td>79.0</td>
</tr>
<tr>
<td>500</td>
<td>61.2</td>
</tr>
<tr>
<td>250</td>
<td>38.9</td>
</tr>
<tr>
<td>125</td>
<td>26.7</td>
</tr>
<tr>
<td>88</td>
<td>21.8</td>
</tr>
<tr>
<td>63</td>
<td>18.0</td>
</tr>
<tr>
<td>44</td>
<td>14.7</td>
</tr>
<tr>
<td>31</td>
<td>12.0</td>
</tr>
<tr>
<td>22</td>
<td>9.9</td>
</tr>
<tr>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>11</td>
<td>6.7</td>
</tr>
<tr>
<td>7.8</td>
<td>5.5</td>
</tr>
<tr>
<td>5.5</td>
<td>4.6</td>
</tr>
<tr>
<td>4.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 8: Fragmentation results of bench S1_210_11 and the results every 10 % of the passing mass.

<table>
<thead>
<tr>
<th>S1_210_11</th>
<th>% Passing</th>
<th>Size[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F10</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>F20</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>F30</td>
<td>152</td>
<td></td>
</tr>
<tr>
<td>F40</td>
<td>263</td>
<td></td>
</tr>
<tr>
<td>F50</td>
<td>378</td>
<td></td>
</tr>
<tr>
<td>F60</td>
<td>485</td>
<td></td>
</tr>
<tr>
<td>F70</td>
<td>604</td>
<td></td>
</tr>
<tr>
<td>F80</td>
<td>768</td>
<td></td>
</tr>
<tr>
<td>F90</td>
<td>1093</td>
<td></td>
</tr>
<tr>
<td>Topsize</td>
<td>2377</td>
<td></td>
</tr>
</tbody>
</table>

Figure 40 shows the fragment size distributions of the entire series of the images of bench S1_210_11. The scatter of the distribution is rather large. Two potential explanations can be given, firstly that the scatter is due to photographing the sides and secondly, due to the blasted material. The histograms (Figure 41) show the frequency of the appearance of the different material sizes. Moreover, it shows that there is a high amount of material with fragment sizes greater than 1000 mm.

The histograms with the same sieving series were very coarse and large amounts of particles with different sizes were hidden due to the low resolution. One solution to that was to increase the resolution of the sieving series, i.e., to create shorter regions of the particle sizes.
Improved blasting results through precise initiation

The 3-term Swbrec function has been used to fit the data (Ouchterlony, 2005):

\[ P(x) = \frac{1}{\left(1 + \left(\ln\left(\frac{x_{\text{max}}}{x}\right) / \ln\left(\frac{x_{\text{max}}}{x_{50}}\right)\right)^b\right)} \]  

(1)

Where, \( x_{\text{max}} \) is the maximum fragment size, \( x_{50} \) is the median fragment size and \( b \) is an undulation parameter. The fitting parameters are presented in Table 9.

Table 9: The Swbrec function fitting parameters

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Start</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>1.1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>( x_{\text{max}}/x_{50} )</td>
<td>1.1</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>( x_{\text{max}} )</td>
<td>5.0</td>
<td>4000</td>
<td>5000</td>
</tr>
</tbody>
</table>

The quality of the fit of the Swbrec function is based on the determination coefficient \( r^2 \) which is equal to 0.99 in all the cases (Figure 42).

Based on the analysis, the fragmentation of the first reference bench (S1_210_11) contains fragments larger than 2491 mm \( (x_{80}) \), see Figure 43.

![Figure 40: Fragmentation curves of S1_210_11.](image)
Improved blasting results through precise initiation

Figure 41: The size distribution histogram of the material.

Figure 42: The final cumulative curve of the fragmentation of S1_210_11 by the Swebrec function.
Improved blasting results through precise initiation

3.3.2 Bench S1_210_12

This was the first bench with short delay time and was blasted on March 28, 2012 using electronic detonators with 6 ms delay time between the holes (176 ms inter-row delay). It was blasted under semi-confined conditions, which means that there was material in front of the burden of the bench (Figure 44).

3.3.2.1 VoD measurements

In this bench some VoD measurements have been conducted (Figure 45) from the first three holes. The average VoD is 5562 ± 95 ms/s.

Figure 43: Scatter of $x_{50}$ and $x_{80}$ of the passing mass.

Figure 44: Bench S1_210_12
Improved blasting results through precise initiation

Figure 45: VoD from blast S1 210_12 March 28, 2012.
Figure 46 shows the actual inter-hole delay time and the deviation from the designed inter-hole delay time. The results are from the same blastholes as in Figure 45. One can see that the actual delay time is very close the designed time.

Figure 46: Measured of the inter-hole delay time.
3.3.2.2 Fragmentation

The fragmentation of the bench is shown in Table 10. The analysis was carried out based on 49 images. The analyzed images are shown in Appendix 11.

Table 10: Fragmentation results of S1_210_12 and the results every 10 % of the passing mass.

<table>
<thead>
<tr>
<th>Size[mm]</th>
<th>% Passing</th>
<th>Size[mm]</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>99.9</td>
<td>F10</td>
<td>36</td>
</tr>
<tr>
<td>2000</td>
<td>99.0</td>
<td>F20</td>
<td>102</td>
</tr>
<tr>
<td>1000</td>
<td>83.9</td>
<td>F30</td>
<td>185</td>
</tr>
<tr>
<td>750</td>
<td>73.3</td>
<td>F40</td>
<td>288</td>
</tr>
<tr>
<td>500</td>
<td>58.2</td>
<td>F50</td>
<td>396</td>
</tr>
<tr>
<td>250</td>
<td>36.3</td>
<td>F60</td>
<td>524</td>
</tr>
<tr>
<td>125</td>
<td>22.9</td>
<td>F70</td>
<td>684</td>
</tr>
<tr>
<td>88</td>
<td>18.0</td>
<td>F80</td>
<td>892</td>
</tr>
<tr>
<td>63</td>
<td>14.4</td>
<td>F90</td>
<td>1212</td>
</tr>
<tr>
<td>44</td>
<td>11.3</td>
<td>Topsize (99.95%)</td>
<td>2483</td>
</tr>
<tr>
<td>31</td>
<td>8.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>7.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>5.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The variation of the fragment distribution curves and the histograms (Figure 47 and Figure 48) is larger than that of bench S1_210_11. The oversize material is of the same magnitude as the first reference bench. However, bench S1_210_12 produced coarser material in terms of boulders.
The Swebrec function has been used to fit the data of the image analysis (Figure 49) and the fit is quite good ($r^2 = 0.999$).

The results showed a few outliers up to 1820 mm for the median fragment size ($x_{50}$) and up to 2976 mm for $x_{80}$ (Figure 50), which is significantly larger than that of bench S1_210_11. Additionally, bench S1_210_12 gave several outliers for both $x_{50}$ and $x_{80}$. This trial indicates marginal effects on the fragmentation compared to the reference test. Though, the results of this bench have been normalized (section 2.6.5) with the results from the rest of the benches due to different shooting angle.
Improved blasting results through precise initiation

Figure 49: The final cumulative curve of the fragmentation of S1_210_12 by the Swebrec function.

Figure 50: Scatter of $x_{50}$ and $x_{80}$ of the passing mass.
3.3.3 Bench S1_225_11

Bench S1_225_11 was blasted on July 26, 2012. It was blasted under free face conditions since all the material from bench S1_225_10 had been removed (Figure 51). This was the second bench of the trials and was designed to have 1 ms inter-hole delay time by using electronic detonators. This was the only free-face blasted bench.

![Figure 51: Bench S1_225_11.](image)

The fragmentation analysis has been carried out based on 40 images. The images were taken from the backside of the trucks and the fragmentation is as follows (Table 11). The analyzed images are shown in Appendix 12.

**Table 11: Fragmentation results of S1_225_11 and the results every 10 % of the passing mass.**

<table>
<thead>
<tr>
<th>Size[mm]</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>100.0</td>
</tr>
<tr>
<td>1000</td>
<td>97.2</td>
</tr>
<tr>
<td>750</td>
<td>87.5</td>
</tr>
<tr>
<td>500</td>
<td>66.8</td>
</tr>
<tr>
<td>250</td>
<td>39.8</td>
</tr>
<tr>
<td>125</td>
<td>26.0</td>
</tr>
<tr>
<td>88</td>
<td>20.6</td>
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<td>63</td>
<td>16.5</td>
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<td>44</td>
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<td>31</td>
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<td>22</td>
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<td>16</td>
<td>6.7</td>
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<td>11</td>
<td>5.3</td>
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<td>5.5</td>
<td>3.4</td>
</tr>
<tr>
<td>4.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% Passing</th>
<th>Size[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F10</td>
<td>29</td>
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<tr>
<td>F20</td>
<td>83</td>
</tr>
<tr>
<td>F30</td>
<td>155</td>
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<td>F50</td>
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<td>644</td>
</tr>
<tr>
<td>F90</td>
<td>792</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>1456</td>
</tr>
</tbody>
</table>
The variation of the fragment distribution curves is narrower than the previous two benches. This can be explained by the shooting angle of the photos, which was constant in this case. Moreover, there are less boulders than the previous bench as shown in Figure 53. The percentage of the material exceeding 1000 mm is also smaller compared to Figure 48.

Figure 52: Fragmentation curves of S1_225_11.

Figure 53 shows a concentration of the particle sizes in the middle region of the graph between 100 and 1000 mm with a tendency for the coarser region.

The Swebrec function also gives very good fit ($r^2=0.998$) in this case (Figure 54).

The scatter of the data is limited with one outlier in the median particle size ($x_{50}$) (Figure 55), 80 % of the material does not exceed the value of 934 mm.
Improved blasting results through precise initiation

Figure 53: The size distribution histogram of the material.

Figure 54: The final cumulative curve of the fragmentation of S1_225_11 by the Swebrec function.
Improved blasting results through precise initiation

3.3.4 Bench S1_225_12

Bench S1_225_12 was blasted on August 28, 2012. It was blasted under confined conditions as a small part of bench S1_225_11 had been left (Figure 56). The third bench was designed with 3 ms inter-hole delay time using electronic detonators.

Totally 40 images have been analyzed to estimate the fragmentation. The shooting direction of the images was from the backside of the trucks. The fragmentation
analysis is presented in Table 12. The complete image analysis is shown in Appendix 13.

Table 12: Fragmentation results of S1_225_12 and the results every 10 % of the passing mass.

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>% Passing</th>
</tr>
</thead>
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<td>2000</td>
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<td>1000</td>
<td>98.2</td>
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<tr>
<td>750</td>
<td>93.9</td>
</tr>
<tr>
<td>500</td>
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<table>
<thead>
<tr>
<th>% Passing</th>
<th>Size [mm]</th>
</tr>
</thead>
<tbody>
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<td>F10</td>
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<td>152</td>
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<tr>
<td>F50</td>
<td>220</td>
</tr>
<tr>
<td>F60</td>
<td>291</td>
</tr>
<tr>
<td>F70</td>
<td>371</td>
</tr>
<tr>
<td>F80</td>
<td>474</td>
</tr>
<tr>
<td>F90</td>
<td>634</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>1319</td>
</tr>
</tbody>
</table>

The variation of the material is even narrower for this bench than bench S1_225_11 (Figure 57). The amount of boulders is smaller compared to the previous benches. Figure 58 shows the histograms of all the analyzed trucks.

The Swebrec function gives a quite good fit ($r^2=0.999$) as well in this case (Figure 59).

The scatter is shown to be smaller for this bench compared to bench S1_225_11 (Figure 60).
Improved blasting results through precise initiation

Figure 57: The fragment size distribution of S1_225_12.

Figure 58: The size distribution histogram of the material.
Improved blasting results through precise initiation

**Figure 59**: The final cumulative curve of the fragmentation of S1_225_12 by the Swebrec function.

**Figure 60**: Scatter of $x_{50}$ and $x_{80}$ of the passing mass.
3.3.5 Bench S1_225_13

This is the second reference bench since the blast design was the same as the regular one used in the mine. This bench was blasted at the same time on August 28, 2012 as bench S1_225_12 and under confined conditions (Figure 61).

![Figure 61: Bench S1_225_13.](image)

Totally 40 images have been analyzed to carry out the fragmentation analysis. The results of the analysis are presented in Table 13. The analyzed images are shown in Appendix 14.

<table>
<thead>
<tr>
<th>S1_225_13</th>
<th>Size[mm]</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>95.5</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>89.9</td>
<td></td>
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<tr>
<td>500</td>
<td>77.7</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>50.8</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>33.0</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>21.6</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>17.4</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>7.8</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>4.3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S1_225_13</th>
<th>% Passing</th>
<th>Size[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F10</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>F20</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>F30</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>F40</td>
<td>171</td>
<td></td>
</tr>
<tr>
<td>F50</td>
<td>244</td>
<td></td>
</tr>
<tr>
<td>F60</td>
<td>319</td>
<td></td>
</tr>
<tr>
<td>F70</td>
<td>407</td>
<td></td>
</tr>
<tr>
<td>F80</td>
<td>532</td>
<td></td>
</tr>
<tr>
<td>F90</td>
<td>751</td>
<td></td>
</tr>
</tbody>
</table>
| Topsize   |           | 1776     

(99.95%)

Table 13: Fragmentation results of S1_225_13 and the results every 10 % of the passing mass.
Figure 62 shows the distributions of all the analyzed images and Figure 63 portrays the histograms of all the images. Only two images show a significant amount of boulders, the same is pointed in Figure 65 as well by the outliers at $x_{80}$ values. The combined distribution curve is shown in Figure 64 and it is fitted by the Swebrec function.

Figure 62: The fragment size distribution of S1_225_13.
Improved blasting results through precise initiation

Figure 63: The size distribution histogram of the material.

Figure 64: The final cumulative curve of the fragmentation of S1_225_13 by the Swebrec function.
Improved blasting results through precise initiation

3.3.6 Bench S1_225_14

Bench S1_225_14 was comparatively small and blasted together with bench S1_225_15. It was blasted under confined conditions since material from bench S1_225_13 was lying in front of the burden (Figure 66). The tested inter-hole delay time was set to be 1 ms again by using electronic detonators. This bench was blasted on September 12, 2012. In this report only the fragmentation of bench S1_225_14 has been analyzed.

The fragmentation analysis is based upon 40 images. The results are shown in Table 14. The analysis of the images is presented in Appendix 15.
Improved blasting results through precise initiation

Table 14: Fragmentation results of S1_225_14 and the results every 10 % of the passing mass.

<table>
<thead>
<tr>
<th>Size[mm]</th>
<th>% Passing</th>
<th>% Passing</th>
<th>Size[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>100.0</td>
<td>F10</td>
<td>15</td>
</tr>
<tr>
<td>1000</td>
<td>96.6</td>
<td>F20</td>
<td>55</td>
</tr>
<tr>
<td>750</td>
<td>89.3</td>
<td>F30</td>
<td>110</td>
</tr>
<tr>
<td>500</td>
<td>74.2</td>
<td>F40</td>
<td>183</td>
</tr>
<tr>
<td>250</td>
<td>47.9</td>
<td>F50</td>
<td>266</td>
</tr>
<tr>
<td>125</td>
<td>32.3</td>
<td>F60</td>
<td>352</td>
</tr>
<tr>
<td>88</td>
<td>26.2</td>
<td>F70</td>
<td>451</td>
</tr>
<tr>
<td>63</td>
<td>21.6</td>
<td>F80</td>
<td>577</td>
</tr>
<tr>
<td>44</td>
<td>17.5</td>
<td>F90</td>
<td>765</td>
</tr>
<tr>
<td>31</td>
<td>14.4</td>
<td>Topsize</td>
<td>1438</td>
</tr>
<tr>
<td>22</td>
<td>11.9</td>
<td>(99.95%)</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>8.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.8</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 67 illustrates the fragment distribution curves of all the images analyzed for bench S1_225_14. The histogram (Figure 68) shows that the material size concentration is closer to 100 mm. The Swebrec function fits the data quite well ($r^2=0.999$), see Figure 69. The scatter in this case is larger than bench S1_225_13 (Figure 70).
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Figure 67: The fragment size distribution of S1_225_14.

Figure 68: The size distribution histogram of the material.
Improved blasting results through precise initiation

Figure 69: The final cumulative curve of the fragmentation of S1_225_14 by the Swebrec function.

Figure 70: Scatter of $x_{50}$ and $x_{80}$ of the passing mass.
3.4 Comparative fragmentation results

The following figures illustrate the fragmentation of the four trials with different delay times and the two reference benches. The first two benches (S1_210_11 and S1_210_12) have been shifted in order to make them comparable with the other trials (Figure 71) according to the procedure described in section 2.6.5.

![Aitik Fragmentation](image)

Figure 71: Fragmentation results.

Bench S1_210_12 with 6 ms inter-hole delay time shows the coarsest fragmentation among all benches. The first reference (S1_210_11) is shown to have very similar fragmentation to Bench S1_210_12.

The benches with 1 ms inter-hole delay time (S1_225_11 and S1_225_14) gave coarser fragmentation than the second reference bench (S1_225_13) with the Nonel system. The best (finest) fragmentation was observed in the bench with 3 ms inter-
hole delay time (S1_225_12). Bench S1_225_14 gave a fragmentation which is very close to that of the second reference bench (S1_225_13).

Figure 72 shows the median, oversize and maximum (99.95 % mass passing) fragment sizes for the trials as well as the reference benches. One can see that the smallest values for the evaluated fragment sizes correspond to bench S1_225_12 with 3 ms inter-hole delay time. The burden has been assumed to be 7 m to create the first horizontal axis (ms/m burden) based on the drilling pattern maps.

![Figure 72: Median and oversize vs. Delay time.](image)

The following figures (Figure 73 and Figure 74) illustrate the scatter of the median ($x_{50}$) and the oversize material ($x_{80}$).
As mentioned above, the scatter is quite large for the first two benches probably due to the shooting angle. Especially for the bench with 6 ms inter-hole delay time which gave four outliers, i.e., the value of the upper quartile plus the difference between the first and the third quartiles increased by a factor of 1.5, with very large particles for the median size reaching up to 1820 mm (Figure 73). The scatter becomes significantly smaller for the rest of the trials. Only one bench did not give outliers, i.e., bench S1_225_12 with 3 ms inter-hole delay time, which in addition gave the finest fragmentation. The benches with the shortest inter-hole delay time (1 ms) gave outliers with larger particle sizes than the second reference bench (S1_225_13).
Figure 74 illustrates the scatter of the oversize material ($X_{80}$). In practice this figure shows the amount of boulders produced per blast. The second bench (S1_210_12) with 6 ms inter-hole delay time gave more boulders than the first reference bench. The other trials gave smaller amount of boulders. The benches with 1 ms delay time showed similar amount of boulder. The second reference bench gave two outliers; however, the maximum size of the material was smaller than the benches with 1 ms delay time and very close to the bench with 3 ms delay time. The last bench did not give any outlier.

Based on the above figures the bench giving the best fragmentation is the bench with 3 ms inter-hole delay time or 0.42 ms/m burden. However, limited data about the geology introduce uncertainties.

Improved blasting results through precise initiation
3.5 Swelling

The swelling is presented as the profile of the bench in two different directions, i.e., north and east. The GPS data before the blast have been provided by the mine and the data after blast have been acquired by use of a GPS RTK system.

The analysis of the data is based on the average values before and after the blast. In the following graphs the lower red line shows the average value of the elevation of the bench before blast as well as the scatter of it (blue points). The upper blue line shows the average value of the swelling. This value has been calculated by taking the average of the bench level before the blast and subtracting the measured points after the blast. Finally, the swelling value is the average of the differences by the aforementioned procedure. The swelling data have been analyzed in two directions, i.e., north and east, with respect to elevation measurements.

3.5.1 Bench S1_210_11

Swelling data were not available for this bench.

3.5.2 Bench S1_210_12

Figure 75 shows the elevation data before and after the blast in the north direction for the first trial. The large scatter of the elevation is due to “peaks-and-valleys” formed by crating effect or the differential movement of the blasted material. The poor stemming of some of the blastholes could be a possible explanation for the crating effect. However, the elevation before blast is remarkably constant and it is not known if the same system (RTK) has been used to obtain the measurements as after the blast.
Figure 75: Measured swelling for bench S1_210_12 in the north direction.

Figure 76 illustrates the elevation in the east direction of the bench. It is obvious that the elevation measurements before the blast exceed the boundaries of bench S1_210_12. Only the values in the same range have been considered in the analysis.

The difference of the elevation gives the average swelling of the bench, which for this bench is 4.76 m.
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Figure 76: Measured swelling for bench S1_210_12 in the east direction.

3.5.3 Bench S1_225_11

The scatter is rather large for the elevation before and after the blast. The average values of the elevations have been analyzed. The north and the east direction of the bench have been plotted against the elevation as well as the average of each elevation (Figure 77 and Figure 78).
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Figure 77: Measured swelling for bench S1_225_11 in the north direction.
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The average swell of bench S1_225_11 is 4.48 m.

3.5.4 Bench S1_225_12

The scatter is large also for this bench. Figure 79 and Figure 80 show the elevation in two directions, i.e., north and east. As the measuring points go to the boundary of the bench (between S1_225_12 and S1_225_13), the elevation of the blasted material becomes smaller and smaller up to the end of the bench. This is due to the transition zone of the initiation system from electronic to Nonel. The delay time between the electronic system and the Nonel was 42 ms, this difference gave enough time to the blasted mass to change its movement behavior and to form a groove between the two
parts. This effect is more pronounced in Figure 80 because it shows a side section of the bench.

Figure 79: Measured swelling for bench S1_225_12 in the north direction.
Figure 80: Measured swelling for bench S1_225_12 in the east direction.

It is very difficult to extract the points, where the mass movement shows a different behavior because there is a tendency for the swelling to be smaller at the end of the bench. The average calculated swelling for this bench is 5.37 m.
3.5.5 Bench S1_225_13

As mentioned for the previous bench, this bench shows a similar behavior, i.e., at the beginning the bench shows shorter swelling than the rest of the mass movement. It is more obvious in the east direction (Figure 82) than the north one (Figure 81). This bench was blasted with regular Nonel initiation system.

![North - Elevation](image)

Figure 81: Measured swelling for bench S1_225_13 in the north direction.
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The swelling for this bench averaged to 4.85 m.

### 3.5.6 Bench S1_225_14

This is the last trial of the field tests with 1 ms delay time. Figure 83 shows the north direction of the bench against the elevation before and after the blast. Additionally, it shows the swelling of bench S1_225_15, but there are no data regarding the initial elevation of bench S1_225_15.

Figure 82: Measured swelling for bench S1_225_13 in the east direction.

The swelling for this bench averaged to 4.85 m.
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Figure 83: Measured swelling for bench S1_225_14 in the north direction.
Figure 84: Measured swelling for bench S1_225_14 in the east direction.

The swelling for this bench was 5.68 m.
3.5.7 Comparative results of the swelling of all the benches

Figure 85 and Figure 86 illustrate the entire swelling of all the benches (trials and references) in two directions, i.e., north and east, before and after the blasting. Some points after the blast in Figure 85 overlap the points before the blast because these points have been taken on the ramp next to the bench. However, these points have not been considered in the analysis. Table 15 shows the average swelling of all the trials.

Table 15: The measured average of all the trials.

<table>
<thead>
<tr>
<th></th>
<th>Swelling [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1_210_12</td>
<td>4.76</td>
</tr>
<tr>
<td>S1_225_11</td>
<td>4.48</td>
</tr>
<tr>
<td>S1_225_12</td>
<td>5.37</td>
</tr>
<tr>
<td>S1_225_13</td>
<td>4.85</td>
</tr>
<tr>
<td>S1_225_14</td>
<td>5.68</td>
</tr>
</tbody>
</table>

Figure 85: Swelling in north direction for all the trials.

In Figure 86, there are some gaps between the benches because that area was not accessible. There were deep ditches between the blasted bench and the new round. Those areas were too unstable to be measured in a safe manner.
Figure 86: Swelling in east direction for all the trials.

All the figures above have been plotted in a Box-and-Whisker plot (Figure 87) to observe the behavior of the mass movement when the delay time changes.
Improved blasting results through precise initiation

It is difficult to define any significant difference in swelling between the trials. Figure 88 portrays the delay time of the trials without the reference bench. It seems that the delay time does not significantly influence the swelling factor. There is, however, a tendency of swelling to decrease with increasing delay time.
3.6 Crusher data

The ore from the test areas was transported and crushed at the crusher station in the pit at the 165 m level. The crusher station consists of two parallel gyratory crushers (local names KR4 and KR5), model Allis Superior 60-109. The new crusher on the surface was used during periods of maintenance and breakdowns of the crusher station in the pit. The opening of the main crushers is 1520 mm and the diameter at the lower part of the mantle is 2770 mm. The closed side setting, 190-270 mm, determines the crusher product. The coarsest rocks after crushing vary from 350 mm to 400 mm with variations depending on the characteristics of the ore.
To evaluate the effect of the fragmentation from trial and reference blasts, the energy consumption for crushing of ore material was measured (in kWh/tonne). The energy consumption is registered by ABB control system and the ore tonnage is extracted from corresponding truck cycles, using the Minestar system. Minestar is an integrated operations and mobile equipment management system by Caterpillar.

Drill rigs are equipped with Aquila Drill Management system including the MWD (Measure While Drilling) application that measures drilling characteristics, i.e. torque, rate of penetration, weight on bit etc. MWD logs were used to evaluate drilling characteristics of the benches in terms of penetration rate (PR) and specific energy (SE).

Specific energy is a concept that represents the work done per unit excavated. The concept was introduced by Teale (1964) and has been evaluated by Schunesson (2007). Teale (1964) introduced the following equation for specific energy:

\[
SE = \left( \frac{F}{A} \right) + \left( \frac{2\pi}{A} \right) + \left( \frac{NT}{P} \right)
\]  \hspace{1cm} (2)

where,

- \(SE\) = Specific Energy [N.cm/cm\(^3\)]
- \(F\) = Feed Force [N]
- \(A\) = the cross-section area of the drill hole [cm\(^2\)]
- \(N\) = Rotation Speed [RPM]
- \(T\) = Torque [Nm]
- \(P\) = Penetration Rate [m/minute]

Penetration rate and Specific energy of six benches are presented in Figure 89. The MWD data for bench S1_210_12 was not recorded due to mine network issues.

It should also be mentioned that the following method was implemented for the analysis of MWD data:

- Fractured rock at the surface and secondary drilling values were found and eliminated for every single blasthole.
- Large errors and false values of PR and SE caused by large fractures or drill bit problems were eliminated.
- The MWD database was sorted by use of coordinates of the blastholes within each bench.
- Mean values were calculated only for validly logged blastholes.
Improved blasting results through precise initiation

Figure 89: MWD data analysis – penetration rate and specific energy

Figure 89 shows higher penetration rates and lower specific energy for blasts on level 225. It can be explained by a variation in presence of pegmatite dykes that have a negative effect on drilling performance due to their higher strength. Blast S1_225_12, consisting of a mixture of muscovite schist, biotite schist and biotite gneiss without visible mapped pegmatite, gave the highest penetration rate and the lowest specific energy.

Data from crusher energy consumption together with corresponding specific energy of benches (except bench S1_210_12, which had no available data) is presented in Figure 90. It should be mentioned that the crushing energy values were logged in an unsorted way, i.e., the ore from various benches was mixed in the crusher. In order to overcome this issue, the Minestar database has been used to filter out favorable recordings for the trial benches. The method to extract crushing energy consumption values is as follows:

- Minestar data were sorted out based on the coordinates of benches and the loading time.
- Payload values for trucks were filtered; untrue or false recordings were eliminated, as well as trucks from unrelated benches.
- Mean crusher efficiencies were calculated for KR4 and KR5 separately for the duration of each truck's payload crushing.
- Idle status and downtimes of crusher lines were eliminated from database.
- Average crushing energy values were calculated using only in-function crusher lines.
- Crusher efficiency values were correlated to payloads of trucks by timestamps of crusher lines and trucks.
Improved blasting results through precise initiation

Short inter-hole delays are supposed to give finer fragmentation and, consequently, lower crushing energy consumption. According to Figure 90, trial from bench S1_210_12 with 6 ms delay time gave the lowest energy consumption. However, there are no clear trends, meaning that a large-scale test with more blasts during a long-term period may be required to get statistically proven correlations.

3.7 Feed-back from operators

Conversations with shovel and crusher operators regarding their subjective opinion about mucking and crushing of the ore from the mentioned benches were used as supplemental measurement of blast performance. For blast S1_225_15 (1 ms), it was indicated a very high crusher throughput, no boulder breakage needed, visually finer material and less boulders experienced during mucking. It was also noticed a relatively high swelling of this blast, resulting in easier mucking.

Generally, the feedbacks describe the material from all other blasts as normal without noticeable difference to a fine and “easy-to-muck”.

Figure 90: Crushing energy consumption and specific drilling energy.
4 Discussion

In order to draw conclusions from the aforementioned test blasts, it is necessary to acquire an abridged overview of the results in a comparative form. Table 16 summarizes the most important results for each bench.

Table 16: Summary of the most important results of all trials.

<table>
<thead>
<tr>
<th>Bench</th>
<th>Type</th>
<th>Penetration rate (m/min)</th>
<th>Specific Energy (N.cm/cm³)</th>
<th>Swell (m)</th>
<th>x₅₀ (mm)</th>
<th>x₈₀ (mm)</th>
<th>Crusher consumption per payload (KWh/Ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁₂₁₀₁₁</td>
<td>Ref.</td>
<td>0.507</td>
<td>4038</td>
<td>-NA-</td>
<td>498</td>
<td>906</td>
<td>1.97</td>
</tr>
<tr>
<td>S₁₂₁₀₁₂</td>
<td>6 ms</td>
<td>-NA-</td>
<td>-NA-</td>
<td>4.8</td>
<td>401</td>
<td>899</td>
<td>1.29</td>
</tr>
<tr>
<td>S₁₂₂₅₁₁</td>
<td>1 ms</td>
<td>0.616</td>
<td>3598</td>
<td>4.5</td>
<td>284</td>
<td>582</td>
<td>1.46</td>
</tr>
<tr>
<td>S₁₂₂₅₁₂</td>
<td>3 ms</td>
<td>0.662</td>
<td>3362</td>
<td>5.5</td>
<td>211</td>
<td>471</td>
<td>1.72</td>
</tr>
<tr>
<td>S₁₂₂₅₁₃</td>
<td>Ref.</td>
<td>0.606</td>
<td>3426</td>
<td>4.8</td>
<td>242</td>
<td>489</td>
<td>1.54</td>
</tr>
<tr>
<td>S₁₂₂₅₁₄</td>
<td>1 ms</td>
<td>0.599</td>
<td>3527</td>
<td>5.9</td>
<td>241</td>
<td>527</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Swelling data for bench S₁₂₁₀₁₁ were not available, as well as MWD data for bench S₁₂₁₀₁₂. The values mentioned in Table 16 are the mean values for comparative purposes only.

Penetration rate and specific energy both indicate the hardness of the rock. For the sake of simplicity only specific energy will be taken into consideration as the governing MWD parameter since it provides more normalized values compared to Penetration rate (See section 3.6). For further simplicity in comparisons, only x₅₀ is considered as the main fragmentation representative parameter.

Figure 91 illustrates a graphical presentation of the main parameters in Table 16. Fragmentation of the rock from each bench is indicated by the comparative size of the bubbles as values of x₅₀. The positions of bubbles on the chart show the mean crushing energy and mean rock hardness (Specific drilling energy) for each of the test blasts. Due to unavailability of MWD data for bench S₁₂₁₀₁₂, the position of the bubble on the horizontal axis is assumed equal to that of bench S₁₂₁₀₁₁ for visual comparison of crushing energy and x₅₀. Additionally, the swelling of the benches is not shown in the graph due to the small differences in swelling.
Figure 91: Graphical illustration of main results of trials.

As seen in Figure 91, there is a significant difference between $x_{50}$ values for benches S1_210_11 and S1_210_12 compared to the rest of the benches. Such variation might be due to different shooting angles of images from which the fragmentation is derived. Considerably larger specific energy of bench S1_210_11 in comparison with other benches (which indicates harder rock) might be another explanation for that. Since the specific energy of bench S1_210_12 is fictitious one cannot comment on the effect of rock hardness on the fragmentation of this bench. However, the crushing energy of bench S1_210_12 (6 ms) is the lowest among all, which shows the rock was easier to crush despite of its comparatively large $x_{50}$.

In a partial comparison between benches S1_210_11 and S1_210_12, considerably lower crushing energy of the latter can be explained by better fracturing of particles as a result of short delay time (6 ms), but such conclusion cannot be considered as consistent since the MWD data were not available for bench S1_210_12.

The differences among four benches on level 225, i.e., S1_225_11, S1_225_12, S1_225_13 and S1_225_14, are not as large in comparison to the aforementioned benches on level 210. Drilling energy for the bench S1_225_12 (3 ms) is the lowest among all as well as its $x_{50}$; other fragmentation values, e.g., $x_{80}$ and $x_{\text{max}}$, also show an improvement compared to the reference and other benches.

Bench S1_225_14 (1 ms) showed slightly larger specific energy and almost the same value of $x_{50}$ as the reference bench (S1_225_13). The crushing energy was slightly lower than the reference but all variations were so small and no significant distinction can be seen between this bench and the reference bench.
The other bench with 1 ms delay time (S1_225_11) has also more or less the same crushing energy as the reference bench (S1_225_13) as well as bench S1_225_14 (1 ms). However, the specific energy of drilling is larger and that might be the reason for its slightly larger $x_{50}$ value.

Altogether, the differences in fragmentation and crushing energies of benches were not as discernible as experienced by for example Vanbrabant and Espinosa (2006). On the other hand, data limitations and variations in geology and confinement conditions of benches introduce uncertainties regarding the results of the field tests. In addition to that, errors emerged by instrumentation, e.g., the MWD and crusher logging systems, as well as those originated in the analysis of the data, e.g., fragmentation analysis (See section 3.3), reduce the confidence level of the results. Undetermined errors in different stages of blast preparation, such as drilling and charging, also add to the ambiguity of the correlations.
5 Conclusions

According to the results and discussions, following statements summarize the conclusions of four trials and two reference blasts:

- The bench with inter-hole delay time of 6 ms resulted in the lowest crushing energies among all trials. The bench resulted in more boulders and coarser fragmentation than the second reference bench and other benches. However, different shooting angles of images for different trials introduced uncertainties about the fragmentation analysis.

- The bench with inter-hole delay time of 3 ms gave the finest fragmentation among all trials. All examined values, i.e., $x_{50}$, $x_{80}$ and $x_{\text{max}}$ showed improvements compared to the other benches. Although the $x_{80}$ and $x_{\text{max}}$ values are significantly smaller, the improvement of the mean fragment size is negligible. On the other hand, the crushing energy of the rock was the highest among all trials.

- The two trials with 1 ms delay time resulted in almost identical results as the second reference bench. The variations in $x_{50}$ values were ignorable. The same was true for crushing energies for both benches.

- Altogether, the variations in the fragmentation of the trials are insignificant and are nearly within the same statistical error.

- Swelling values of the benches were similar. Different delay times appear to have only minor effects on the swelling of the broken rock.

- VoD measurements on bench S1_210_12 showed good accuracy of electronic detonators regarding the precision of short delay times and no misfire was observed.
6 Recommendation and future research

The results from these trials showed the need for further investigation of the short delay times, with more detailed data acquisition. Some short inter-hole delay times must be reexamined; these are 6 ms and 3 ms in order to clarify the results from the trials described in this report. However, from the mine operators’ point of view, based on their visual observations, the trials with 1 ms delay time had the finest fragmentation. Additionally, detailed investigations are required by “Mine-to-Mill” concept to acquire reliable data from the crusher and from the further process of the broken material. The future trials are recommended including extensive data acquisition and analysis method, such as swelling data, stereographic analysis of the slopes above the trials to identify the rock mass structure, Complete logging of MWD data as well as core drilling, high speed filming of the blasts to observe the mass movement, extensive fragmentation analysis based upon high-quality images shot from a constant axis, detailed follow-up of the ore during crushing and grinding in order to investigate the crushing energies and to observe the presence of microfractures in the particles after crushing. A better camera with a better zoom lens must be used in order to take clearer and sharper images from the truck bodies as well.

The blasting conditions, i.e. confined or free face, for the further investigations must be kept as consistent as possible due to the potential effect on the fragmentation of trial. It has been proven by Johansson & Ouchterlony (2011) and Petropoulos et al. (2012) that the fragmentation under confined conditions is coarser than the free face blast. Moreover, there is a transition zone in every trial bench when the blast is largely elongated, which from free face blast changes to blast under confined conditions. At this point a question arises regarding the part of the bench which has to be considered as representative for the entire bench for fragmentation analysis. However, the crusher data acquisition takes into consideration the entire bench.

The crusher data acquisition must be done very carefully and only the data from the particular benches must be collected and not mixed data with other benches. This process requires a person in the crusher control room to follow the trucks from the trial benches because afterwards it is very difficult up to impossible to distinguish the correct values of the crusher’s energy consumption.
Improved blasting results through precise initiation
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Fragmentation in production rounds and mill throughput in the Aitik mine, a summary of development projects 2002-2009

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