Forensic analysis of a rock burst event at the Kiirunavaara Mine — results and implications for the future

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• The Kiirunavaara Mine
  – Owned and operated by LKAB
  – Sublevel caving
  – 4 km long, 80–160 m wide
  – Ore known to 1365 m level
  – Mineralization to 1500/1800 m
  – Current mining at 907–964 m
  – Annual production: 28 million tons
  – New haulage level at 1365 m; investment of 12 billion SEK ≈ 1.6 billion USD
Kiirunavaara – production blocks

Ore pass groups
Mining blocks
Haulage level 1045 m

North
The February 2 rock burst

Course of events

- Magnitude 3.0 event at 7:58:02 pm, Feb 2, 2008
- Extensive damages to 878, 907, 935 m levels
- Mucking on 878 m level – mucking operator managed to leave area unharmed
- Transportation on 907 m level – rock fallout hit truck cabin causing a fatality
- No operation on 935 m level
The February 2 rock burst
The February 2 rock burst

Cross-cuts

Fallouts on 907 m level (> 700 m³)

North

Ore pass no. 191

Structures: 168/60
The February 2 rock burst

Mining sequence

- Adjacent production blocks mined to larger depths
- Caving not initiated evenly in block 19 (cross-cuts not fully released from the hangingwall)
The February 2 rock burst

Post-event analysis

• Damage mapping
• Structural mapping
  – Two large-scale structures (one previously unknown): 168/60, 40 m spacing
  – Two joint sets: 300/70, 045/85; 1-2 m spacing
• Analysis of seismic data
  – Wave-form correlation analysis
  – 3 events of similar characteristics
    • Oct 27, 2007, magnitude 1.6
    • Nov 30, 2007, magnitude 1.6
    • Jan 11, 2008, magnitude 1.3
Plausible causes of the February 2 event

1. *Failure of rock pillar between ore passes*
   Damage in ore passes $\Rightarrow$ reduced pillar width
   $\Rightarrow$ pillar failure? $\Rightarrow$ seismic event?

2. *Failure of rock pillar between hangingwall and orebody*
   Mining sequence $\Rightarrow$ rock pillar
   $\Rightarrow$ pillar failure? $\Rightarrow$ seismic event?

3. *Shear slip along geological structure*
   Large-scale structures + increased load (mining)
   $\Rightarrow$ slip? $\Rightarrow$ seismic event?
Approach and methodology

- 3D, discontinuum, mine-scale model ⇒ 3DEC
- Modeling used as a tool to increase understanding
- Static analysis
- Mining up until February 2, 2008
- Input data from previous studies and investigations following the February 2 event
- Continuum & discontinuum modeling
  Linear-elastic & perfectly plastic material models
  Variation of mechanical properties
3DEC model: Drifts and ore passes

Ore pass no.
191 192 193 194

Levels:
- 878 m
- 907 m
- 935 m level
- 907 m level
Joint sets: 300/70 & 045/85
Mining stage 6: February 2, 2008

- Block 16
- Block 19
- Block 25

Levels:
- 907 m level
- 878 m level
Hypothesis 1: Failure of rock pillar between ore passes

- Evaluation of stresses and yielding in rock pillar for all mining stages
- Moderately stressed pillars ($\sigma_1 = 20$–$40$ MPa) and only local yielding
- Similar for all mining stages (April 2005 – February 2008)
- Not likely that pillar failure should have occurred at the time of the seismic events in block 19
Hypothesis 2: Failure of rock pillar between hangingwall and orebody

- Evaluation of stresses and yielding in rock pillar for all mining stages
- Significant stress increase in stage 3 (Oct 27, 2007); may have caused seismic event
- Only small changes in subsequent stages
- Maximum inferred seismic magnitude $\approx 0.2$
- Not likely that additional failure of the rock pillar should have occurred
Hypothesis 3: Shear slip along geological structure

- Evaluation of shear deformations (along joints) in the discontinuum model
- Slip along large-scale structures (168/60) & other joint sets
- Plausible reason for several seismic events
- Maximum inferred seismic magnitude \( \approx 0.8 \text{–} 1.0 \)
- Less shear displacement in final mining stage => not fully explained!
Conclusions

• Shear along a pre-existing geological structure is the most likely cause of the observed rock bursts
• Numerical modeling could not fully explain the largest seismic event (February 2, 2008)
  – discretization?
  – strength parameters?
• Useful methodology for further modeling as support to strategic mine planning
Implications

• The Kiirunavaara mine is now regarded as a seismically active mine

• Remedial measures and additional work:
  – Installation of a mine-wide seismic monitoring network
  – Installation of dynamically resistant rock reinforcement
  – Development of stringent reentry protocols
  – Revised opening sequence in production blocks
  – Development of a structural-geological model
Future numerical modeling

• **Discontinuum modeling required**
  – Model shear displacements explicitly including any interaction between different seismically active structures.

• **Future mining of block 19**
  – Comparison of different mining/sequencing alternatives
  – Further calibration against period of increased seismic activity recorded using the new seismic network

• **Mine-scale modeling of other production blocks**
  – Same methodology as for block 19
  – Possibility to include the entire mine in one model?

• **Quantify mechanical behavior**
  – Quantify possible differences in mechanical behavior of geological structures in different portions of the mine
4 seismically active structures

Future mining: leave "ore pillar"?
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