

Deep Sublevel Cave Mining and Surface Influence

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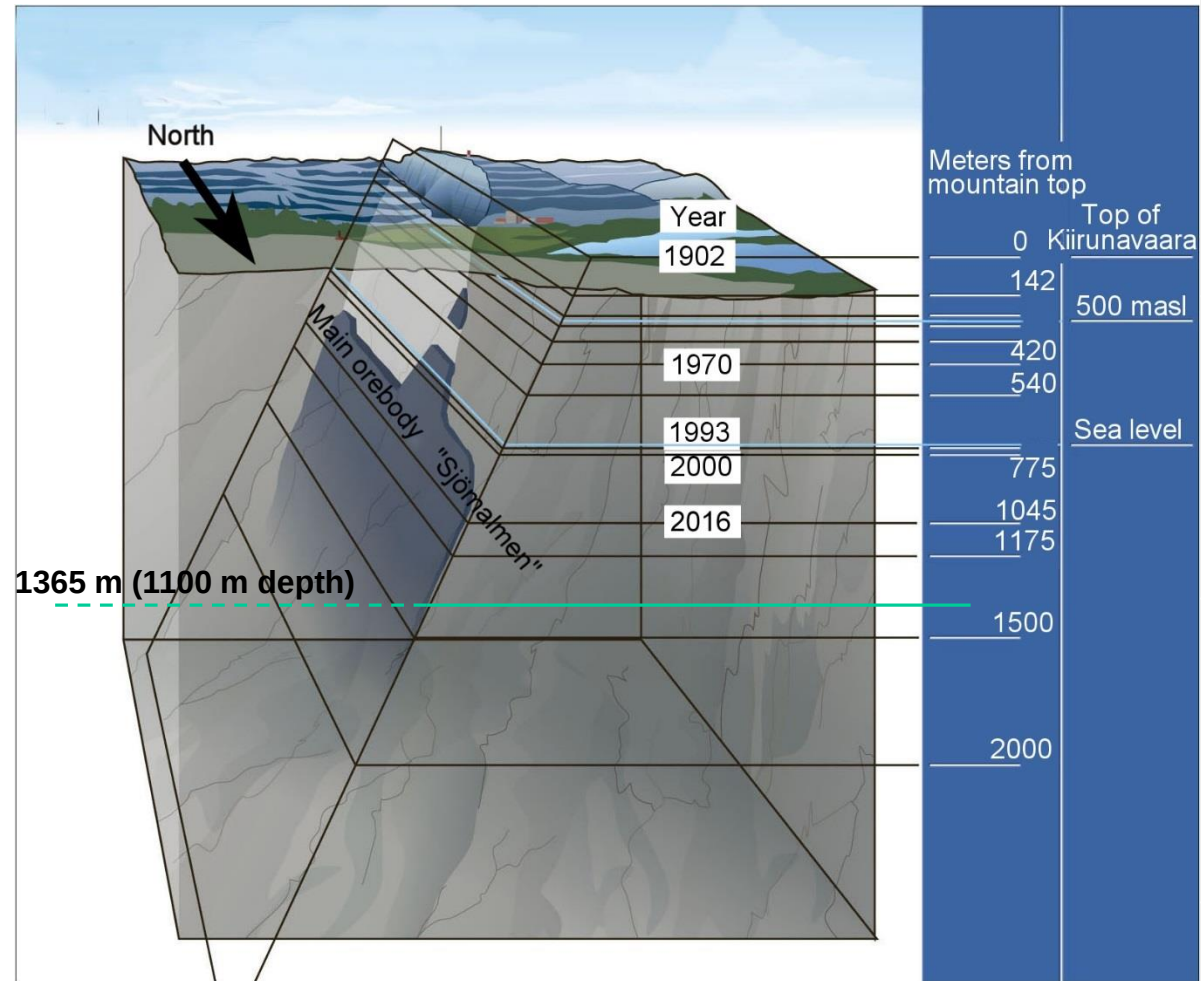
Cave Mining & The Surface...

- Cave mining
= cost-efficiency, mechanisation, automation
- Increasing depth
= higher stress, more difficult mining
- Increasing depth
= more ground surface effects? Or less?
- What do we know? Same mechanisms?
Change in mechanisms or behavior?
More or less surface influence?

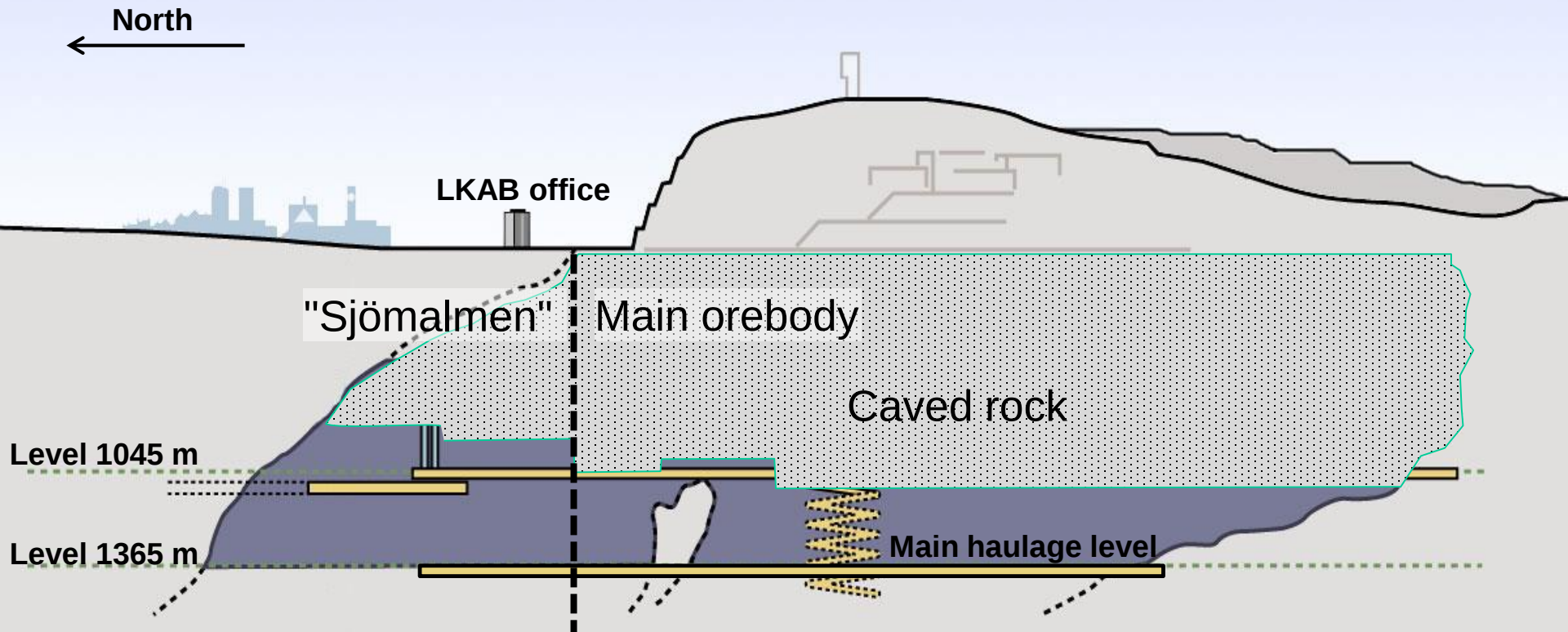
The LKAB Kiirunavaara Mine



- 28 Mton annual iron ore production
- SLC mining
- Mining at > 800 m depth
- Haulage level at Level 1365 m (1100 m depth)
- "Urban transformation" process...



The Kiirunavaara Orebody (Looking East)



Summer of 2007



Summer of 2008



Summer of 2009



Fall of 2016



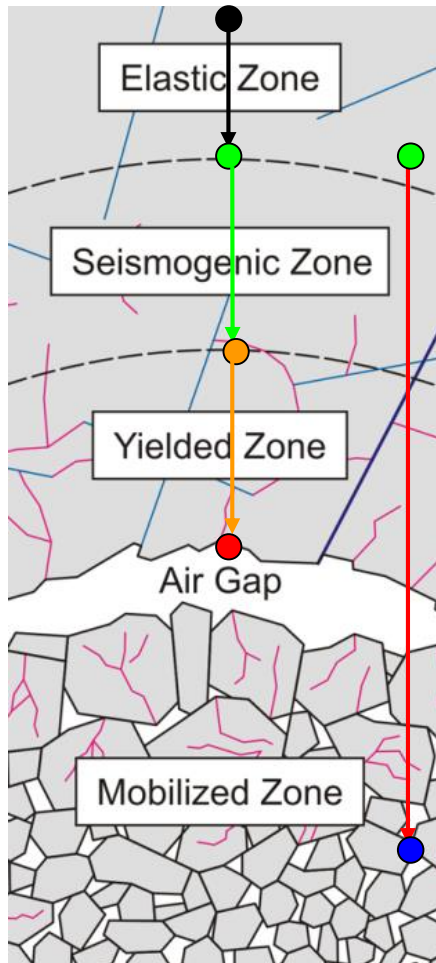
Problem Statement & Approach

- Predictions of surface effects:
 - Important for planning of urban transformation
 - Validity of current empirical methodology ("limit angles") outside data range?
 - Change of mechanisms and/or behaviour for deep SLC mining?
- Numerical modeling approach:
 - 3D "caving algorithm"; mining to Level 1365 m
 - 2D "Ltu caving simulation"; mining to Level 1800 m
 - Calibration against cratering and deformation data

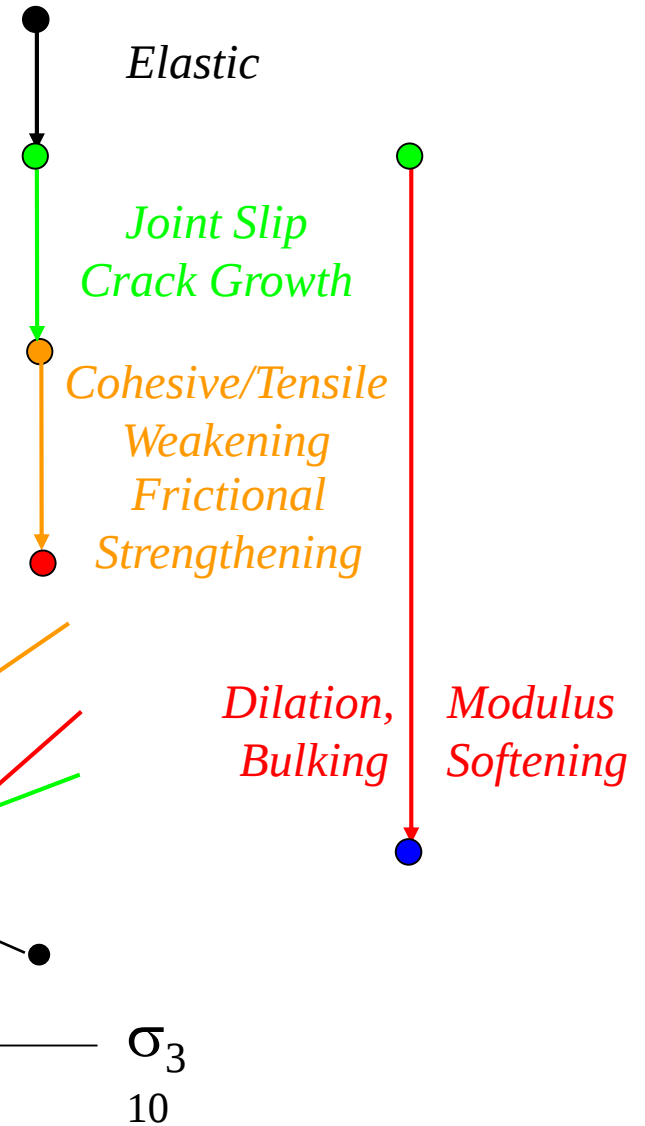
3D Cave Modeling of Sjömalmen

- The Itasca Caving Algorithm
 - Discontinuum approach not (yet...) feasible for mine-scale analysis
 - Caving algorithm developed using a continuum-based approach (funded via ICS & MMT projects)
 - Strain-softening material model
 - Controls for tension weakening, modulus softening and bulking limits
 - Rigorous mass-balance routine
 - Zone density adjustments to represent bulking

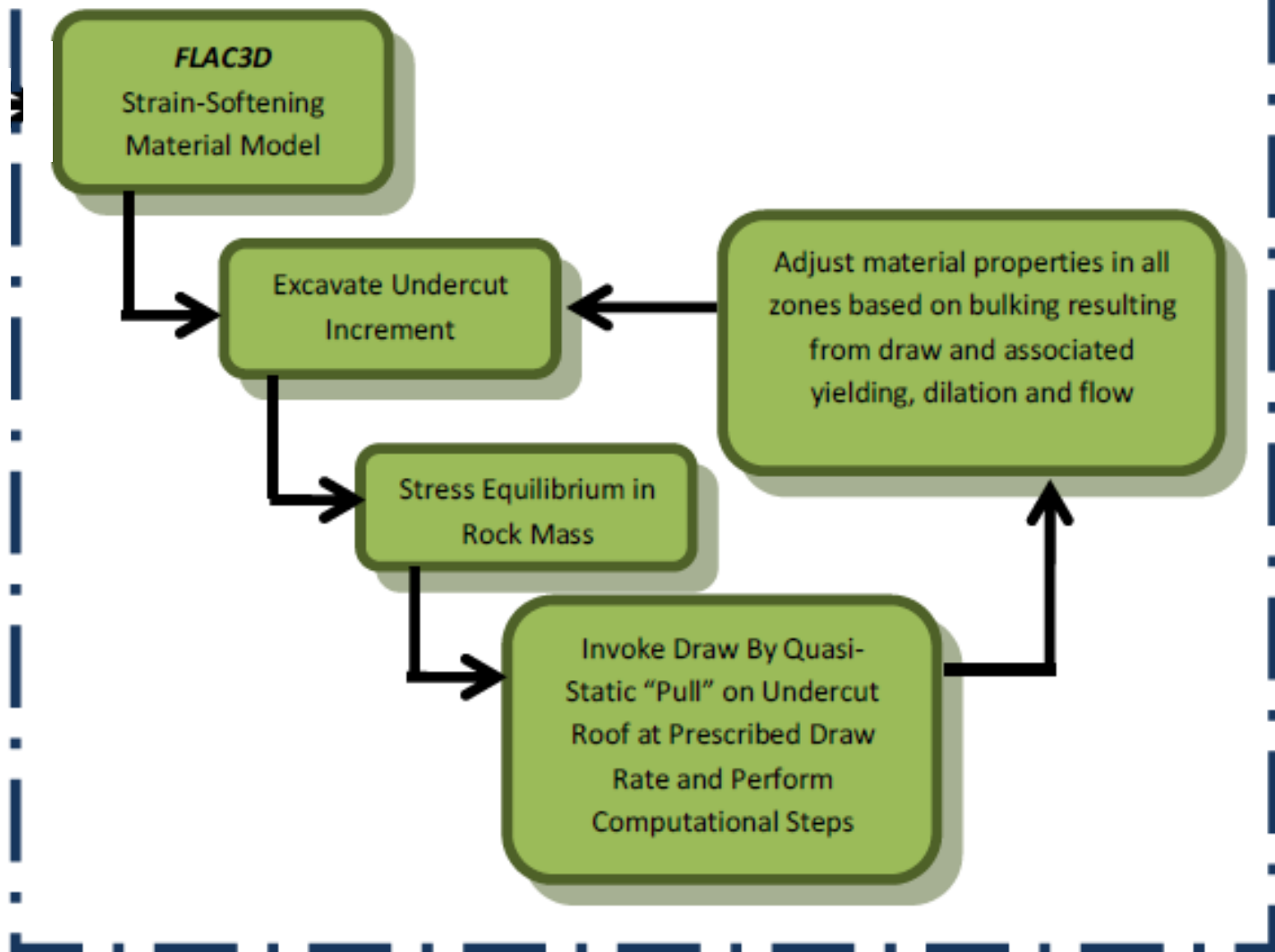
Caving Mechanics



- In Situ Stress
- Elastic
- Damage Threshold
- Seismogenic
- Yield
- Peak Strength
- Failure
- Residual Strength
- Air Gap
- Caved
- Mobilized Zone
- Fully Bulked



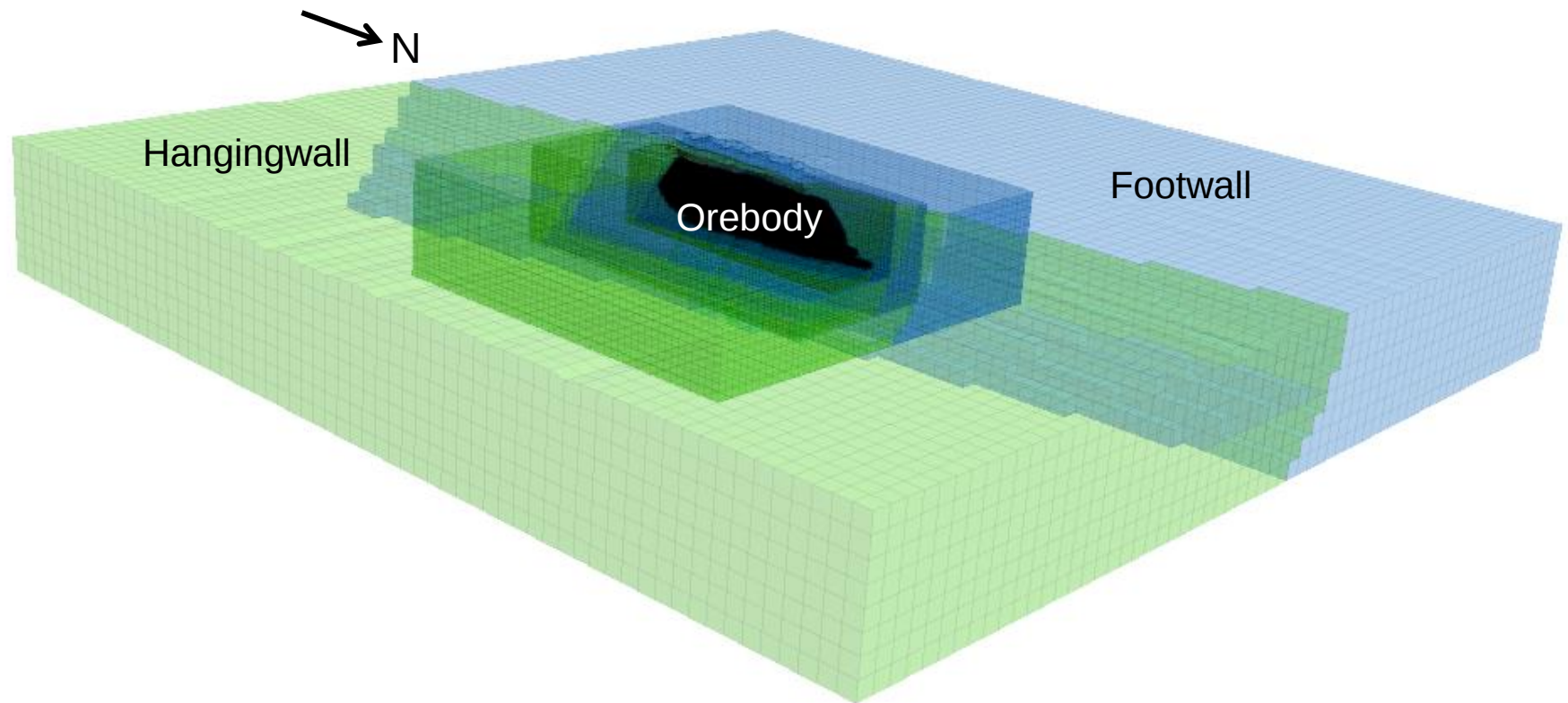
Caving Algorithm



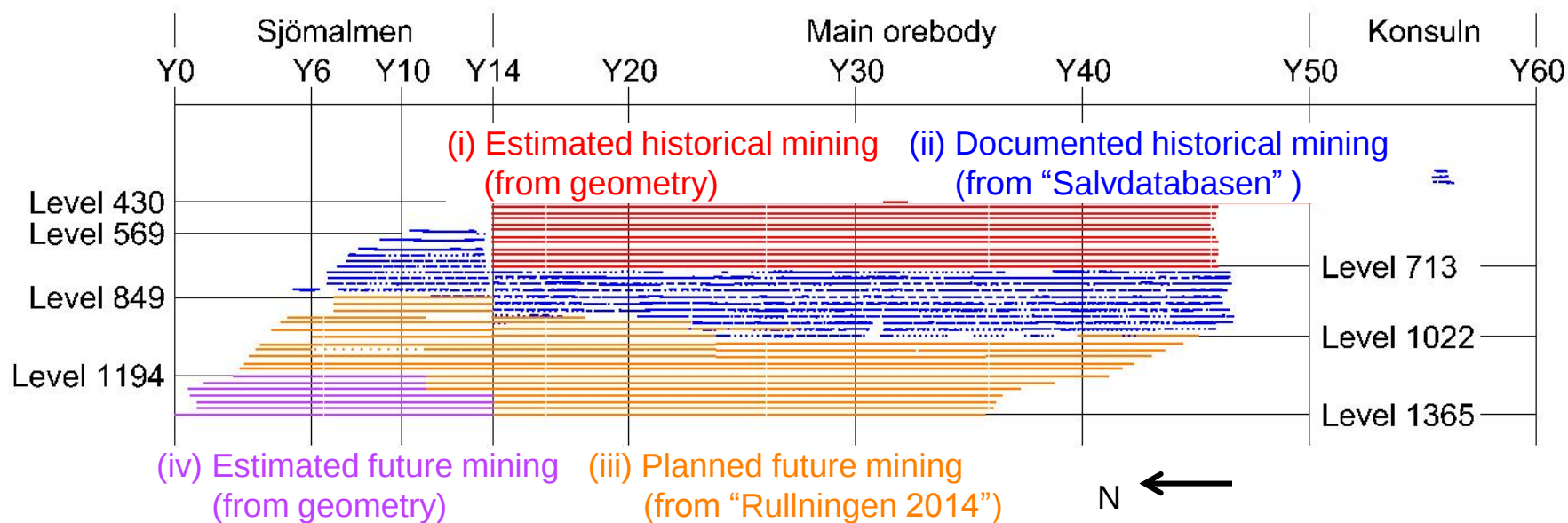
CaveHoek Constitutive Model

- Hoek-Brown failure criterion – input data:
 - GSI , ρ , m_i , σ_{ci} , E_i , ν_i
- Strain-softening after peak:
 - Cohesion weakening
 - Friction strengthening
 - Tension weakening
- Bulking & dilation shutoff
(zero when maximum bulking reached)
- Modulus softening based on straining and fragment aspect ratios

3D Model Setup



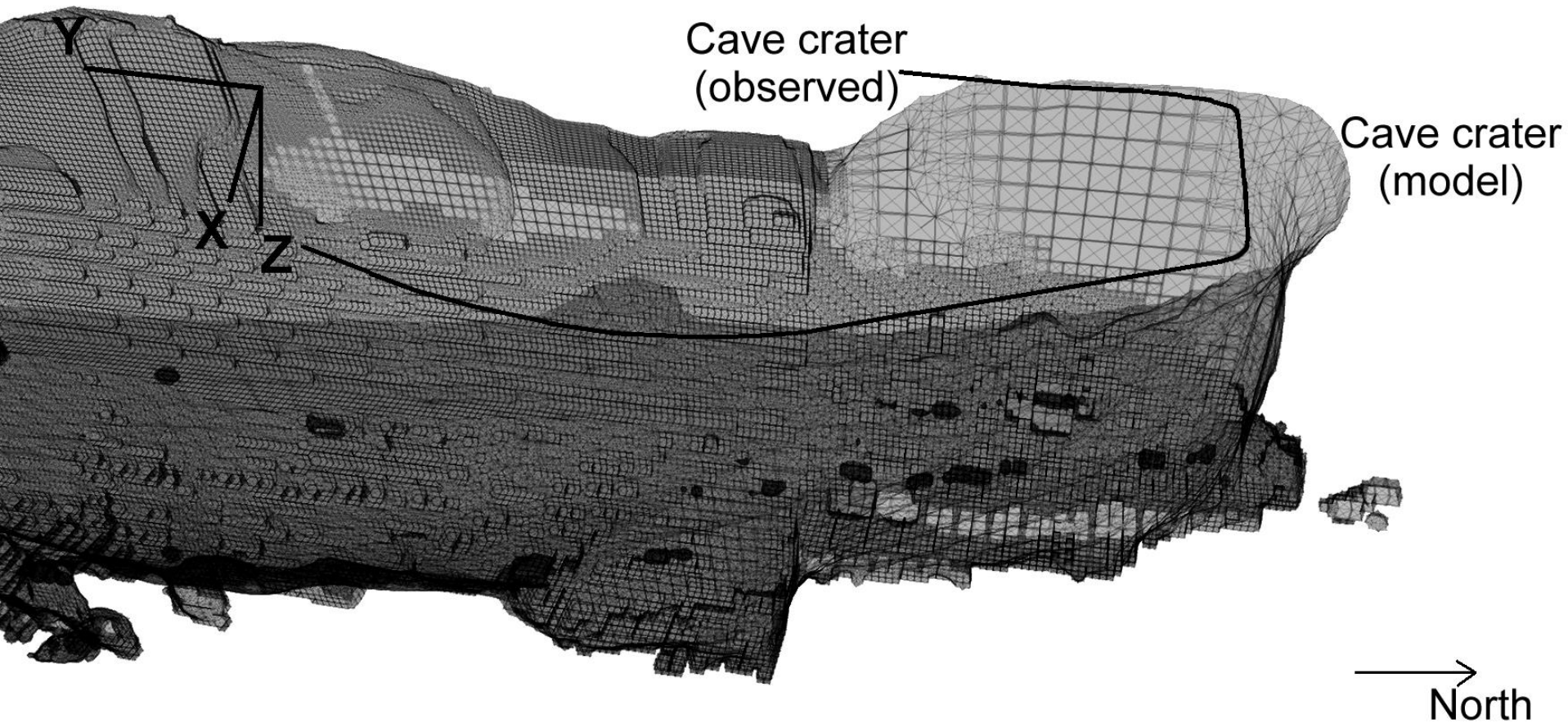
Orebody and Draw Schedule



3D Model Calibration

- Rock mass properties from:
 - Characterization data
 - Previous analyses & experience
- Calibration with observed surface cratering:
 - Twelve cases analyzed; mining up until year 2014
 - Best agreement:
 $\sigma_{ci} = 104 \text{ MPa}$, $E_{rm} = 8.1 \text{ GPa}$, $GS/ = 58$
- Validation against deformation data:
 - Independent data set
 - Model slightly conservative

3D Model Calibration – Year 2014

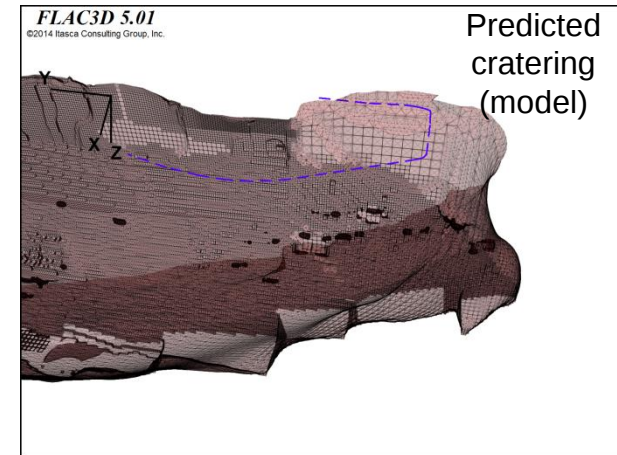
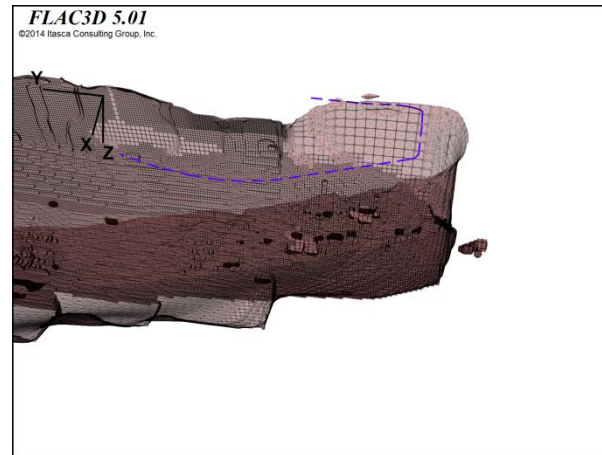
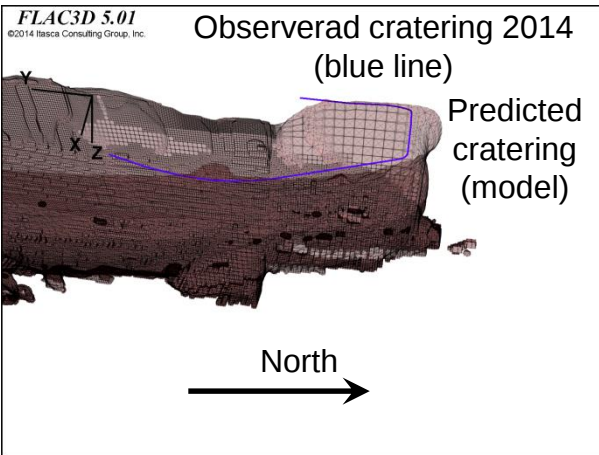


Calculations for Future Mining: Surface Cratering

Year 2014

Year 2018

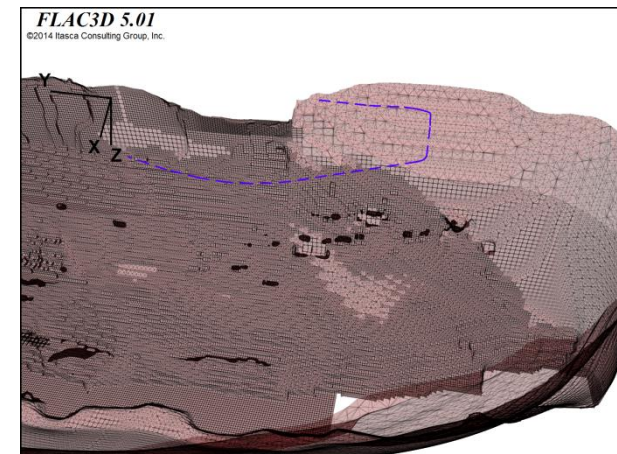
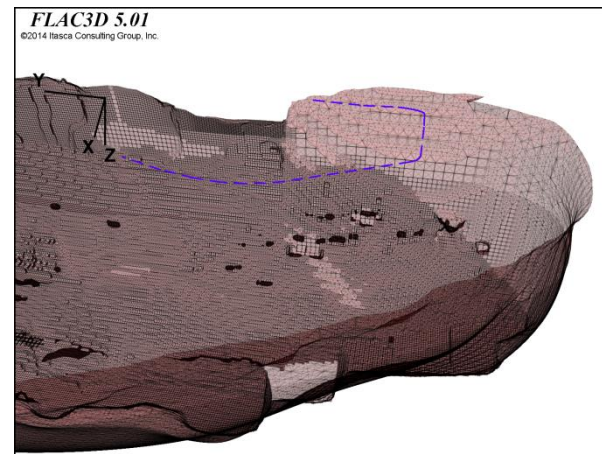
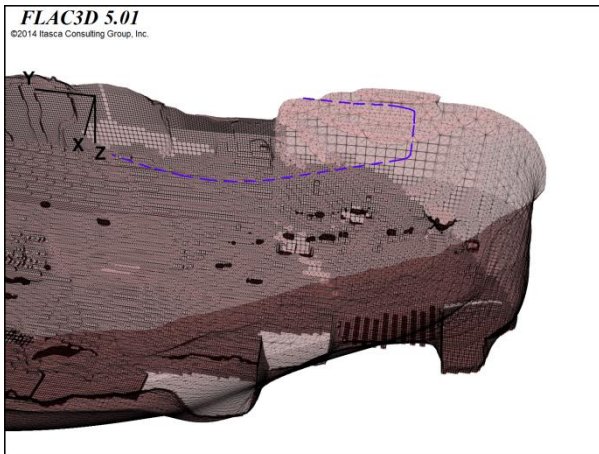
Year 2023



Year 2028

Year 2033

Level 1365 m

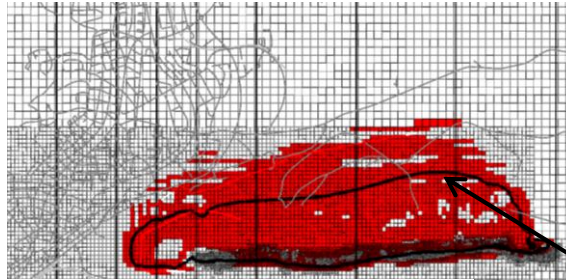


Calculations for Future Mining: Environmental Strain Criterion

Year 2014

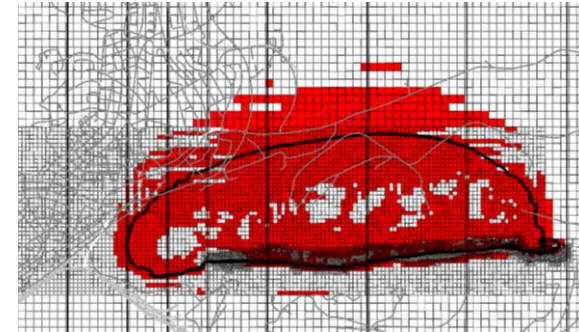
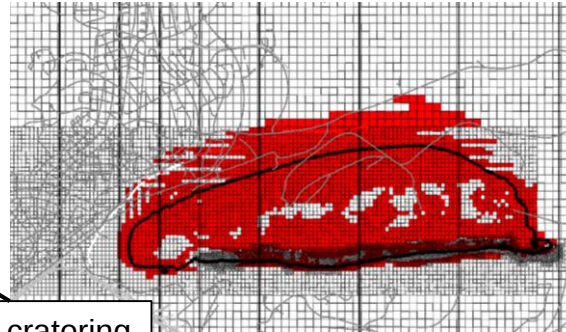
Year 2018

Year 2023



Area with exceeded
environmental strain limit (red)

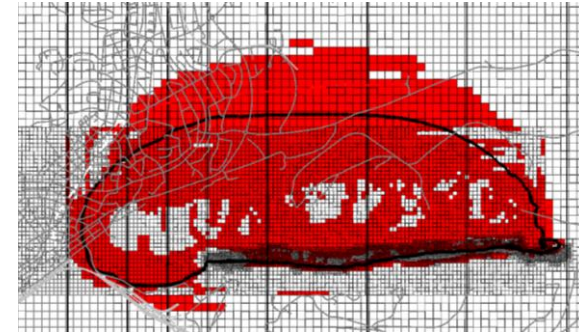
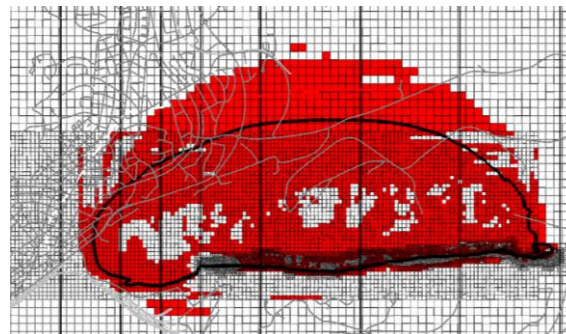
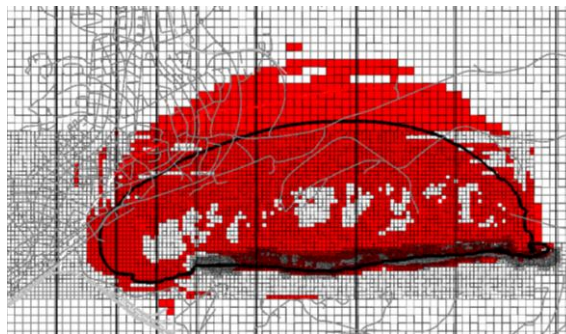
Surface cratering
(black line)



Year 2028

Year 2033

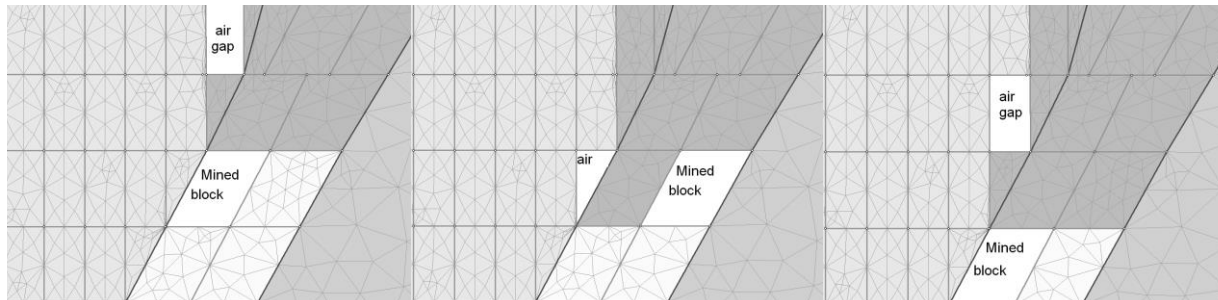
Level 1365 m



North
←

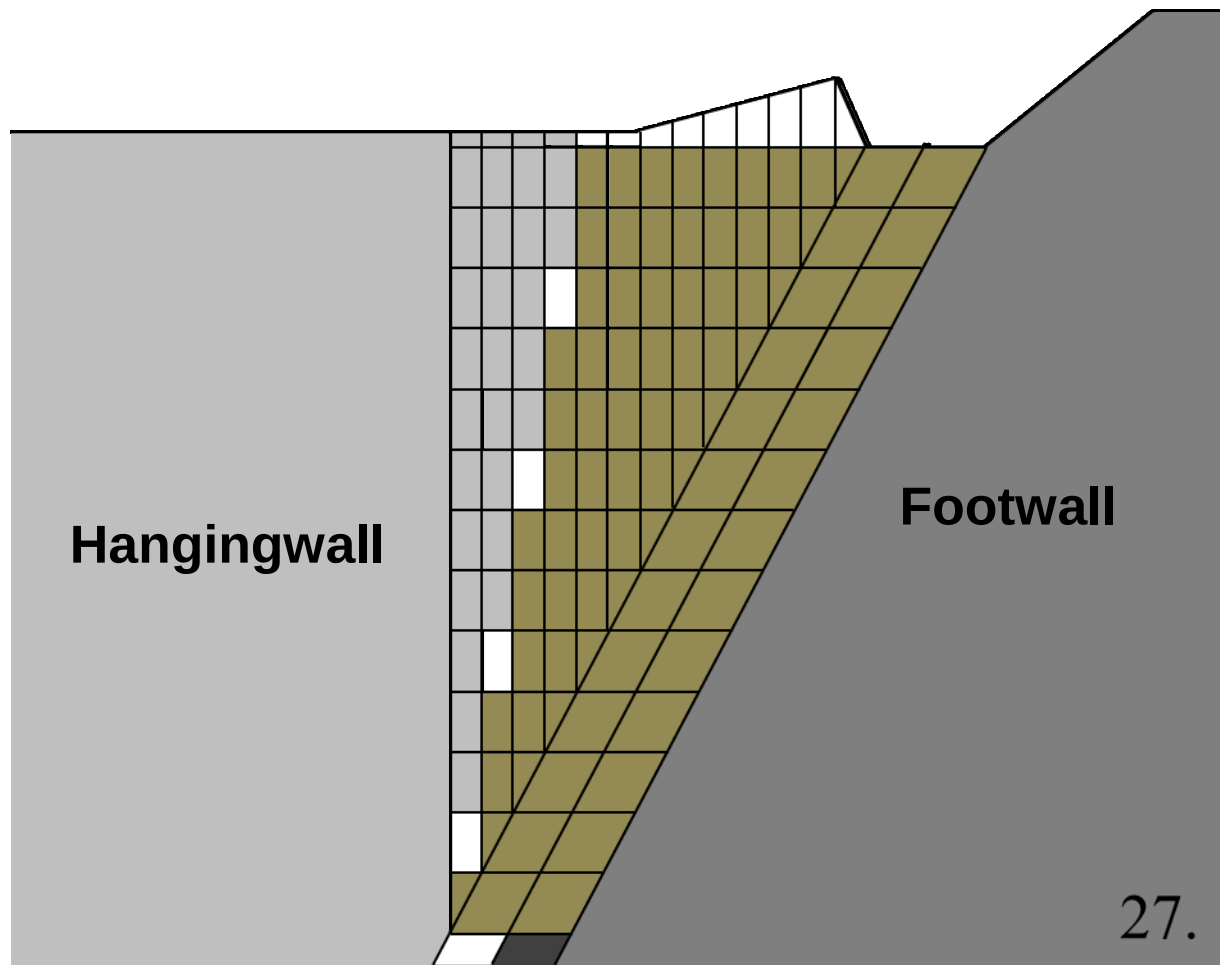
2D Cave Modeling of Deep Mining

- Ltu (Luleå University of Technology) simple 2D approach [Villegas & Nordlund]
- Upward progression of "air gap"



- 2D representative section (Y2600) simulated using *FLAC*

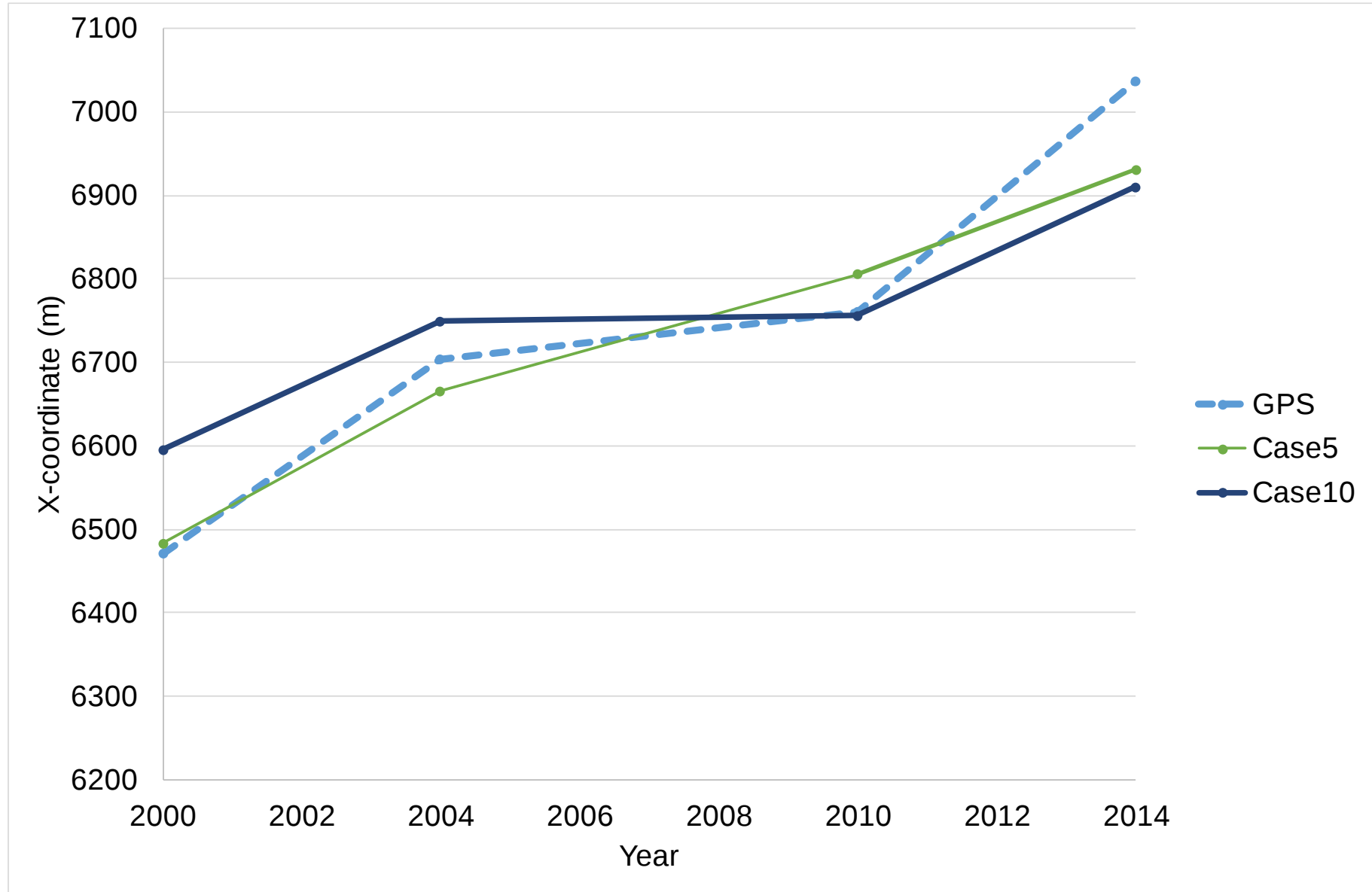
2D "Ltu" Caving Simulation



2D Model Calibration

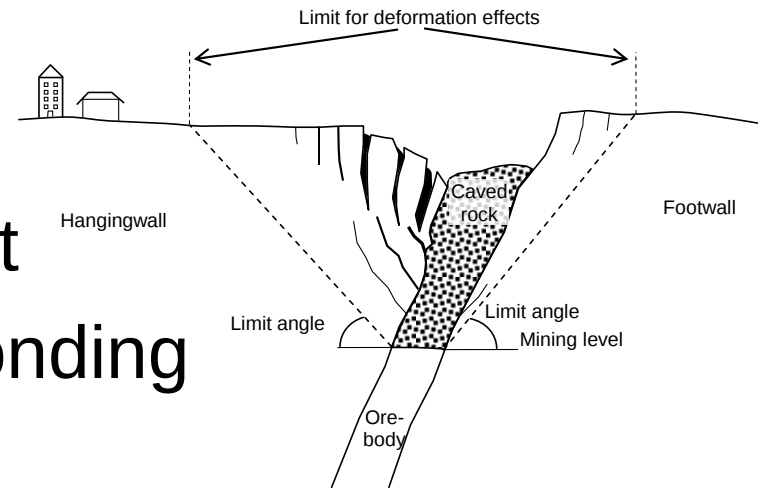
- Similar to 3D model, rock mass data from characterization, previous work, etc.
- Variation of:
 - Material models (Mohr-Coulomb, Hoek-Brown)
 - Post-peak behavior (perfectly plastic, softening)
- Calibration with deformation data (strains; environmental limit criterion):
 - Fair agreement but no unique set of data
 - Mining and caving sequences less influential

2D Model Calibration



2D Calculations for Future Mining

- Mining to Level 1800 m
- Evaluation of location of environmental criterion limit
- Results shown as corresponding "limit angles"



Model case	Level 1200 m	Level 1400 m	Level 1600 m	Level 1800 m
Case 5	55°	47°	31°	36°
Case 10	43°	46°	40°	37°

Conclusion (I)

- Deeper sublevel cave mining will likely lead to continued caving and ground deformations, at least to the same extent experienced so far
- None of the modeling approaches indicated any decrease in mining-induced deformations (e.g., due to increased confinement with depth)
- Calibration against observations proved invaluable for increasing the reliability in the models later used for prediction purposes.

Conclusion (II)

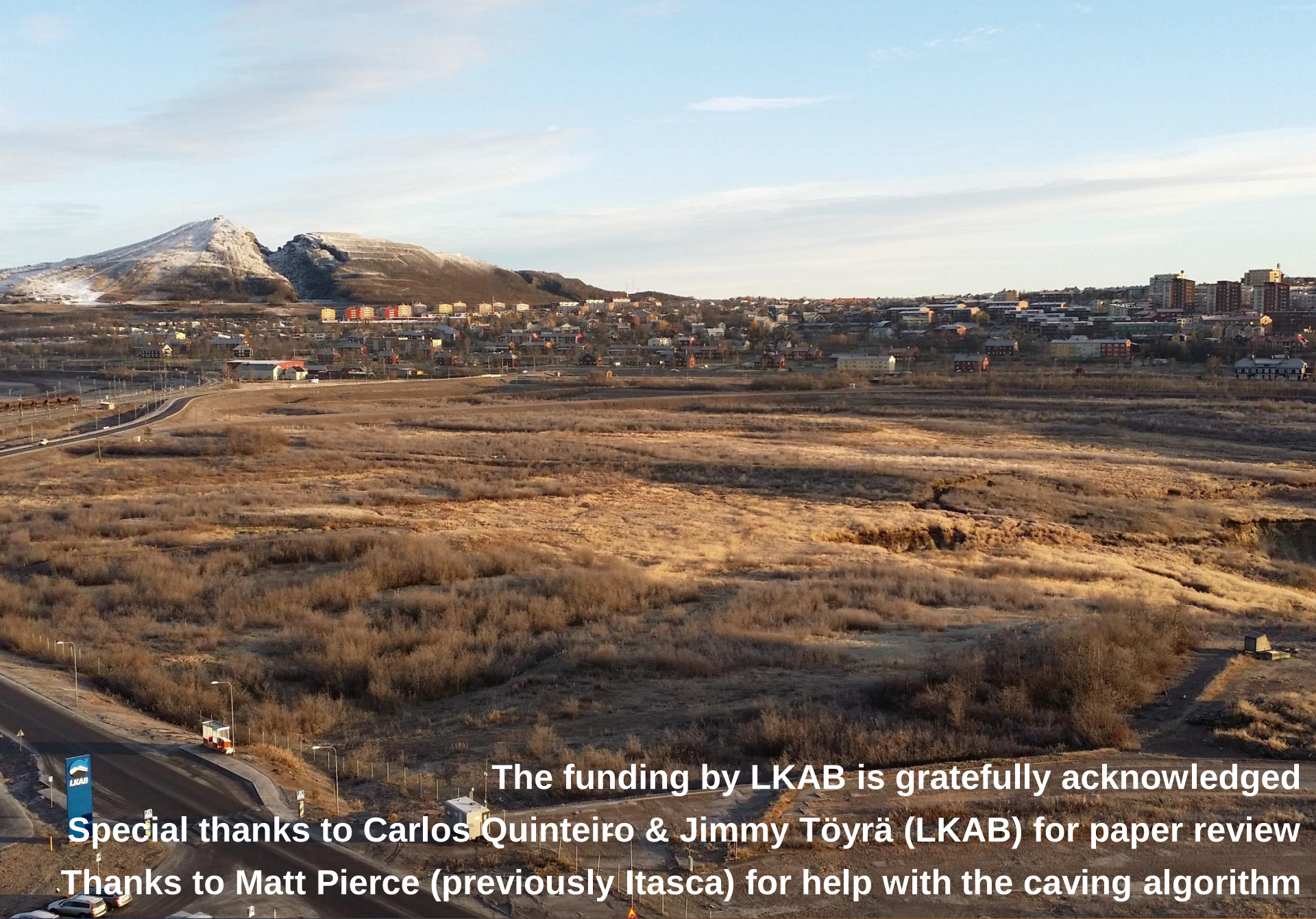
- Both modelling approaches have distinct pros and cons:
 - 2D is 2D...
 - 2D approach may be too simplistic with regards to caving simulation and material models used...
 - 3D approach is more time-consuming...

Prognosis Work & Future Modeling (I)

- Current "limit angles" reasonable for continued mining to Level 1365 m
- Steeper angles applicable for the northern tip of the orebody
- Limit angles may be ***non-conservative*** for deeper mining; further verification required

Prognosis Work & Future Modeling (II)

- Improved characterisation of the rock mass in the cap rock and hangingwall important for increased reliability in predictive analyses
- Models may be used as a tool for directing investigations by conducting sensitivity analysis of selected scenarios
- Possible influence of large-scale structures to be investigated through modeling, to increase understanding and target investigations



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