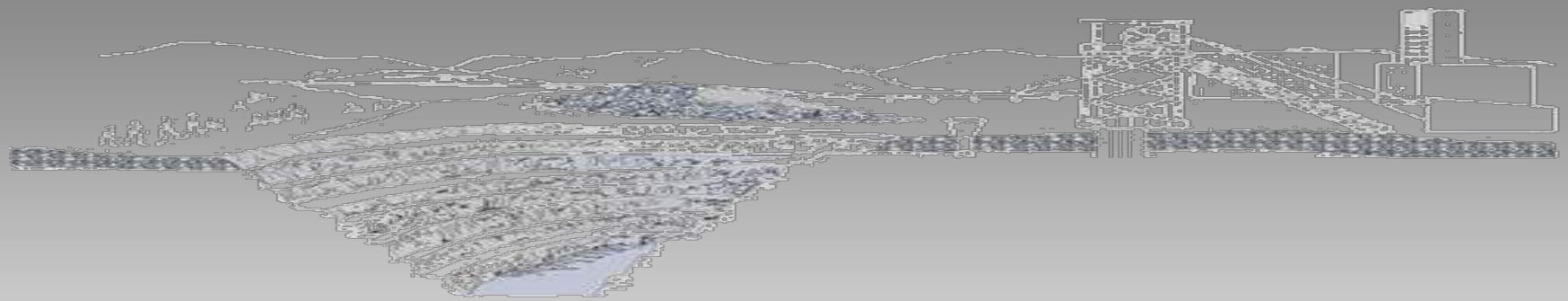


Design & Operating Principles in Caving Methods

V.N. Kazakidis, PhD, PEng

School of Engineering

Laurentian University, Sudbury, Ontario

vkazakidis@laurentian.ca

May 2015

Laurentian University
School of Engineering

Contents

A. Principles

B. Variations & Examples

SLC

BC

C. Design Issues (safety + environmental + regional stewardship)

D. Operating Issues

E. Optimization

- o Design
- o Operating
- o Economics
- o Bottom line

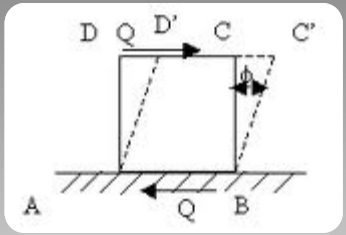
F. Delay-impact Example

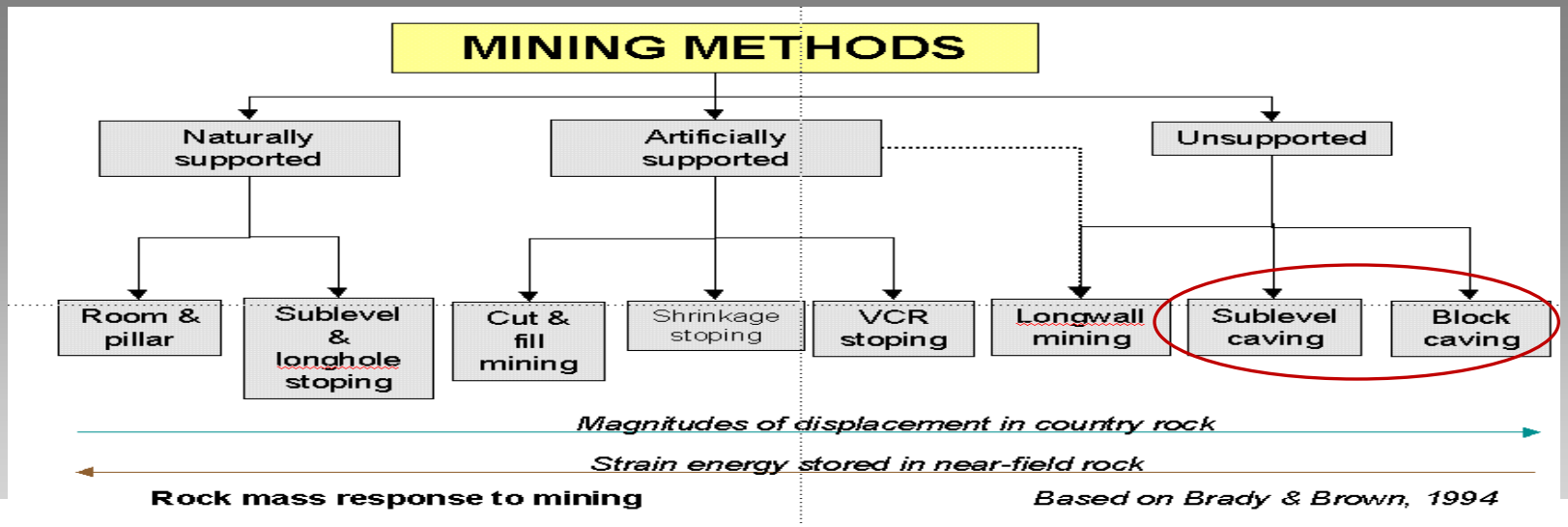
i. Recovery
ii. Dilution
iii. Grade
iv. Tonnage
v. Cost
vi. Time
vii. Resources utilization
viii. Delay impact
ix. Return on investment, $, %
x. Flexibility/robustness/risk
xi. Contingency

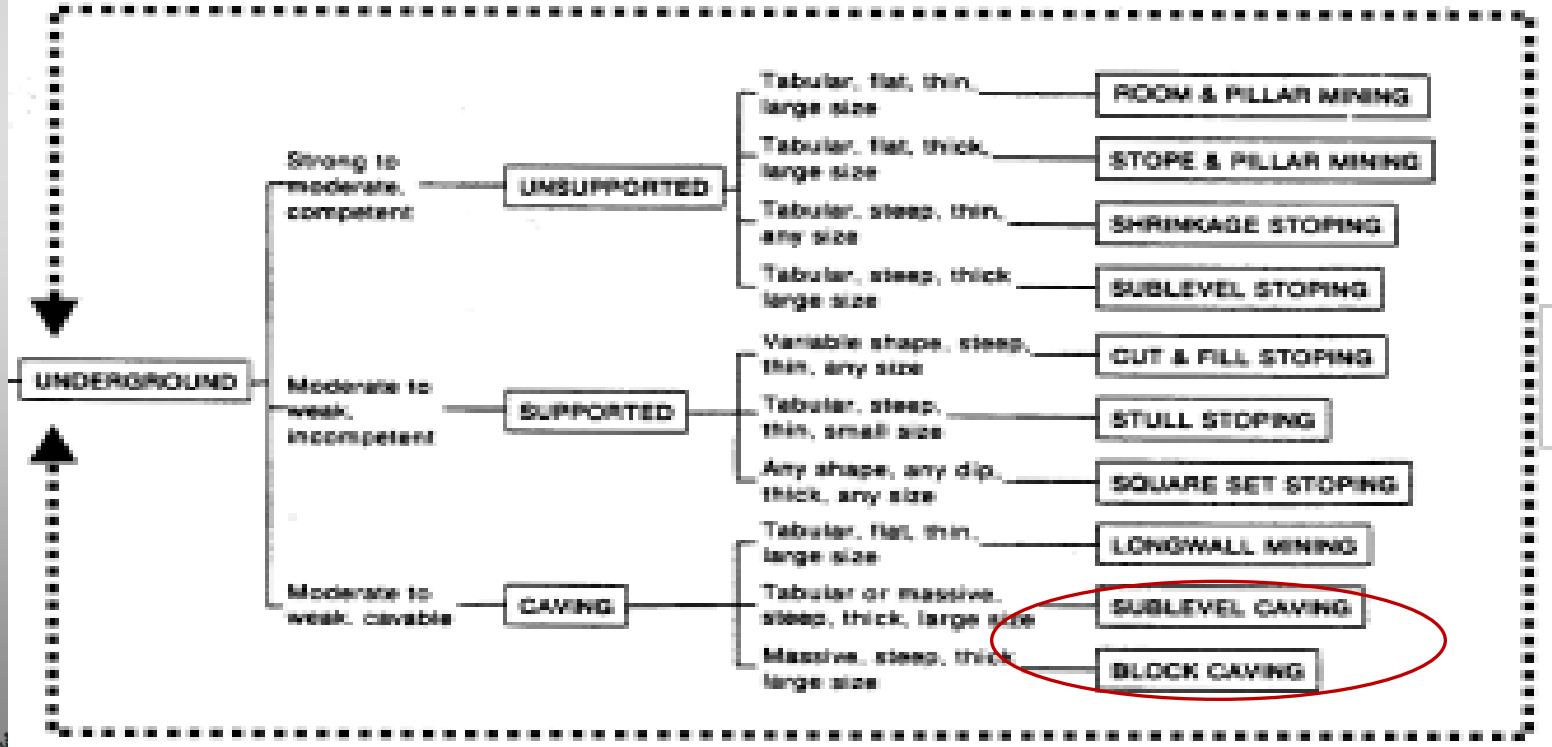
G. Video

Caving method requirements

- Large orebodies
- Fragmentable rock mass
- Ground subsidence allowance

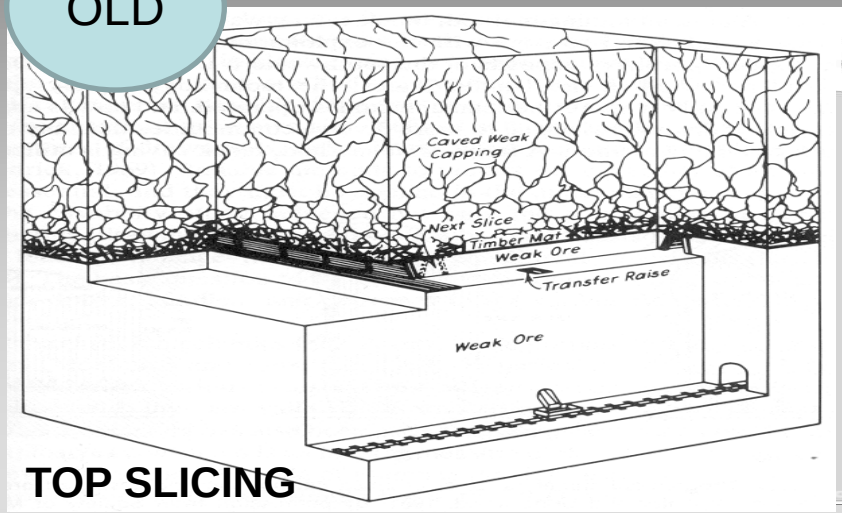



MINING METHODS
Naturally supported
Artificially supported
Unsupported
Room & pillar
Sublevel & longhole stoping
Cut & fill mining
Shrinkage stoping
VCR stoping
Longwall mining
Sublevel caving
Block caving
Magnitudes of displacement in country rock
Strain energy stored in near-field rock
Rock mass response to mining
Based on Brady & Brown, 1994


UNDERGROUND
Strong to moderate, competent
Moderate to weak, incompetent
Moderate to weak, cavable
UNSUPPORTED
SUPPORTED
CAVING
Tabular, flat, thin, large size
Tabular, flat, thick, large size
Tabular, steep, thin, any size
Tabular, steep, thick large size
Variable shape, steep, thin, any size
Tabular, steep, thin, small size
Any shape, any dip, thick, any size
Tabular, flat, thin, large size
Tabular or massive, steep, thick, large size
Massive, steep, thick large size
ROOM & PILLAR MINING
STOPE & PILLAR MINING
SHRINKAGE STOPING
SUBLEVEL STOPING
CUT & FILL STOPING
STULL STOPING
SQUARE SET STOPING
LONGWALL MINING
SUBLEVEL CAVING
BLOCK CAVING
Low
Displacement of country rock
High

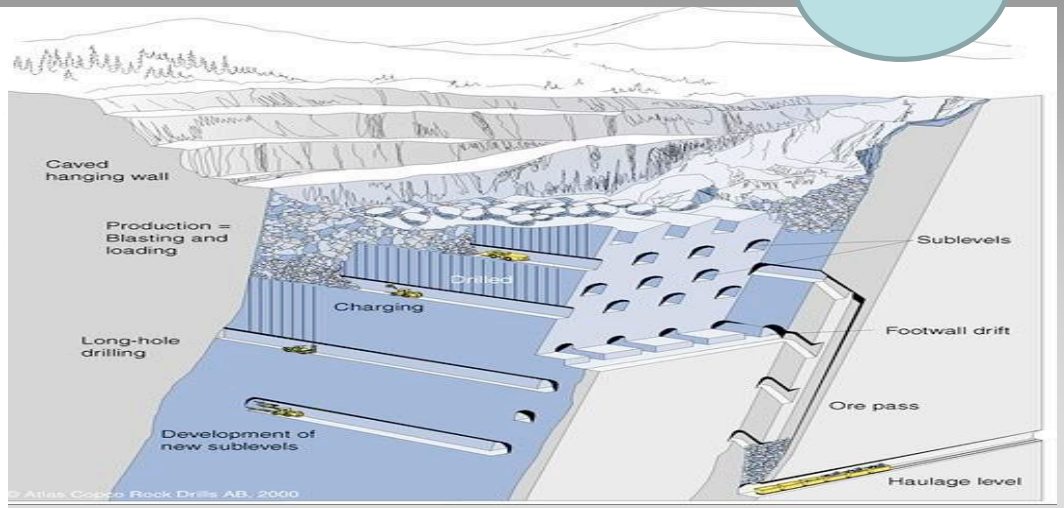
Caving Mining Methods

OLD

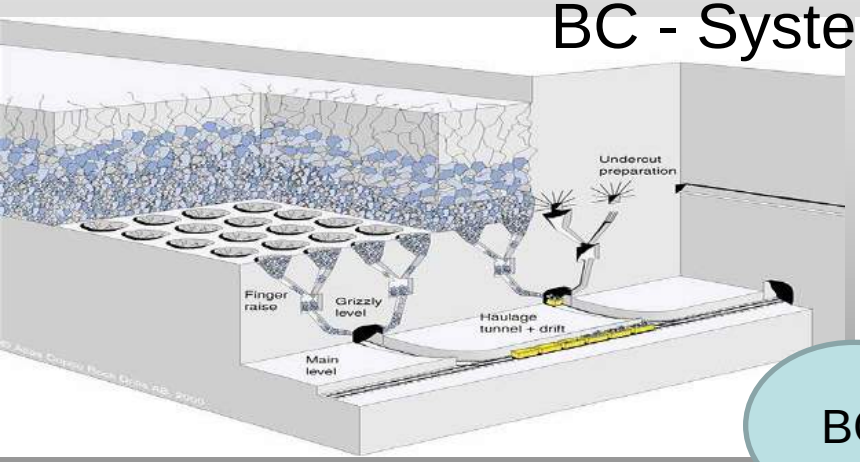


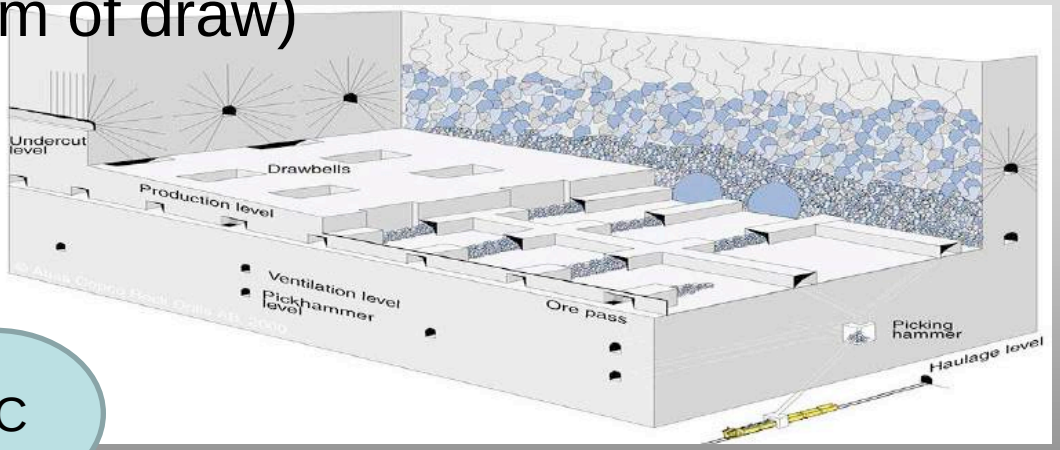
TOP SLICING

SLC



BC - System of draw)





BC

With gravity draw and grizzly drifts

With LHD loading in draw drifts

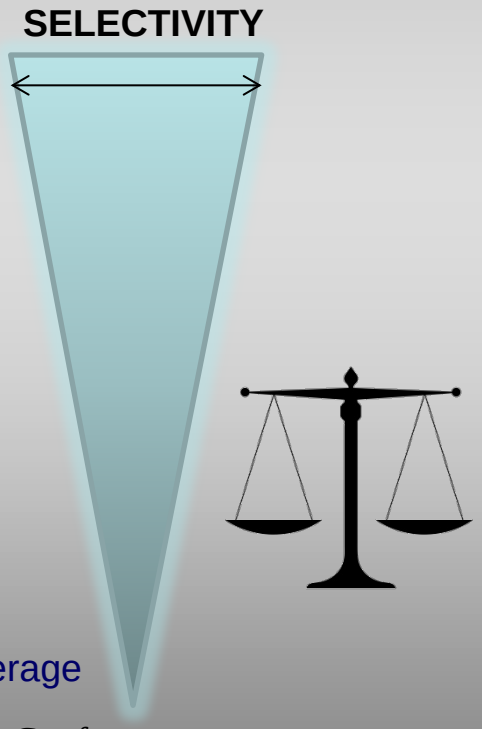
Caving Mines

Mining method production & cost

Average productivity, daily production and relative mining cost associated with various mining methods from mines using such methods as their major source of stope muck.

SUMMARY - UNDERGROUND MINING METHODS

Method	Tonnes / Manshift	Avg. Tonnes / Day Milled	Relative Mining Cost/Tonne
Resuing	0.20 - 0.50	50 - 100 +	70+
Shrinkage	20 - 28	200 - 800	20 - 50
Cut and fill	12 - 48	500 - 1500	20 - 70
Room and Pillar	15 - 150	1500 – 10 000	7 - 20
Open stoping	20 - 115	1500 – 25 000	7- 25
Sub-Level Caving	65 - 180	1500 – 50 000	7 - 17
Block Caving	300 - 2000	10 000 – 100 000	1 – 2.5 ~ 9$/t average



Source: BMO Capital markets 2011 Global Metals and Mining Conference

Contents

A. Principles

B. Variations & Examples *SLC BC*

C. Design Issues (safety + environmental + regional stewardship)

D. Operating Issues

E. Optimization

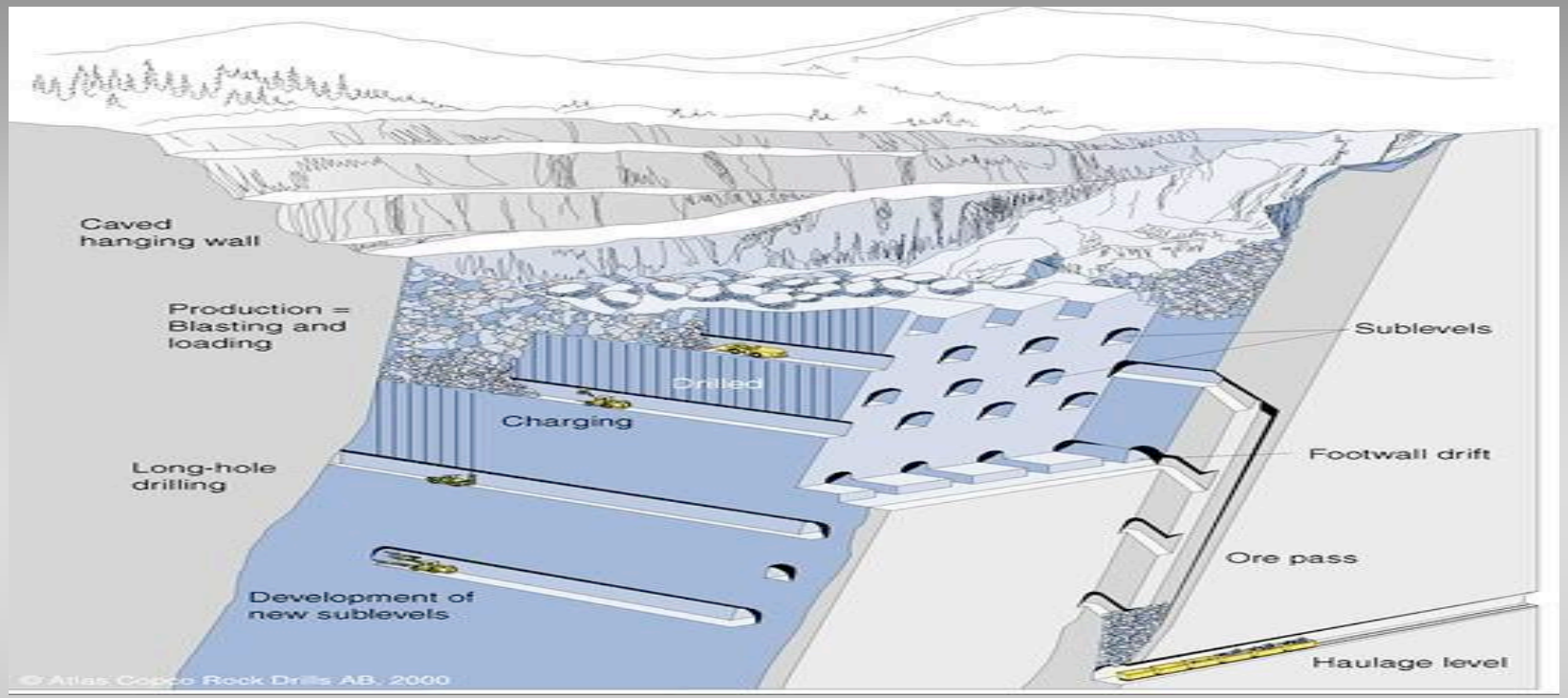
- o Design
- o Operating
- o Economics
- o Bottom line

F. Delay-impact Example

G. Video

i. Recovery
ii. Dilution
iii. Grade
iv. Tonnage
v. Cost
vi. Time
vii. Resources utilization
viii. Delay impact
ix. Return on investment, $, %
x. Flexibility/robustness/risk
xi. Contingency

Sublevel Caving - SLC

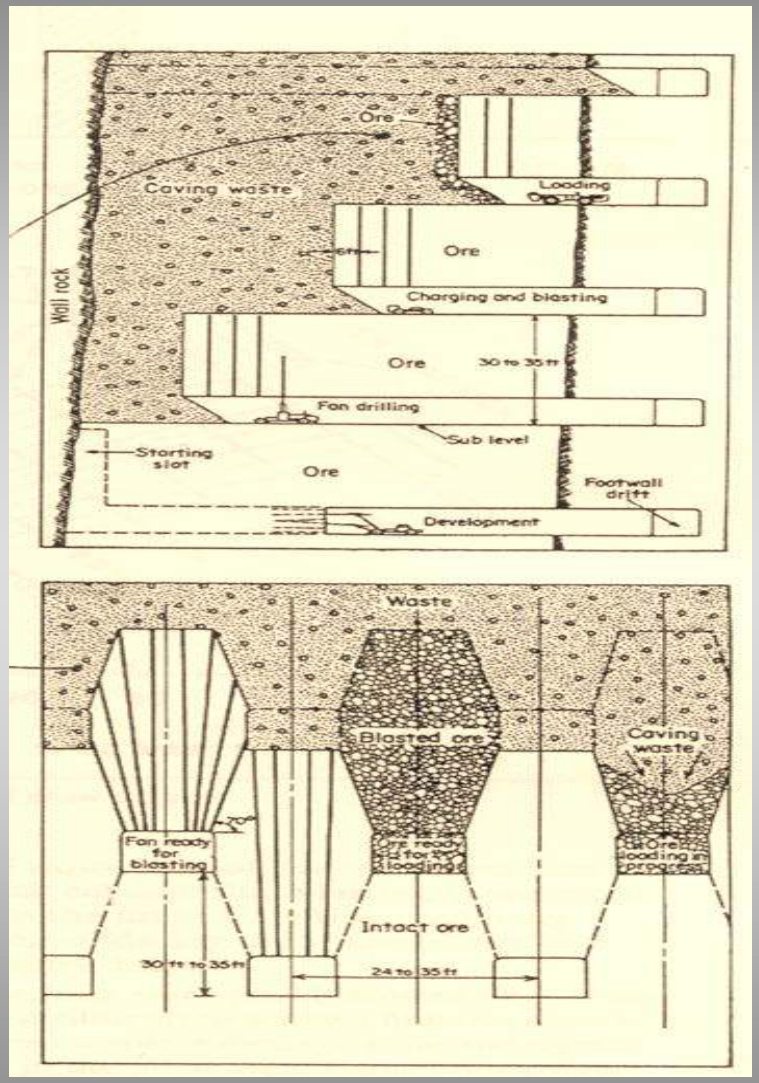


Schematic layout for sublevel caving (after Hamrin, 1982)

DEFINITION: A mining method which is applicable to low grade near-vertical metallic or nonmetallic deposits. Mining progresses downwards while the ore between sublevels is broken overhand with long hole uppers (fan-holes). The overlying waste rock (hangingwall or capping) caves into the void created as the ore is drawn off. Mining is conducted on sublevels from development drifts and crosscuts, connected to the main haulage level below by ramps, orepasses, and raises. Every tonne of ore is drilled and blasted which results in improved cavability and fragmentation compared to Block Caving. With care, recoveries in the order of 80% with dilution below 25% can be achieved.

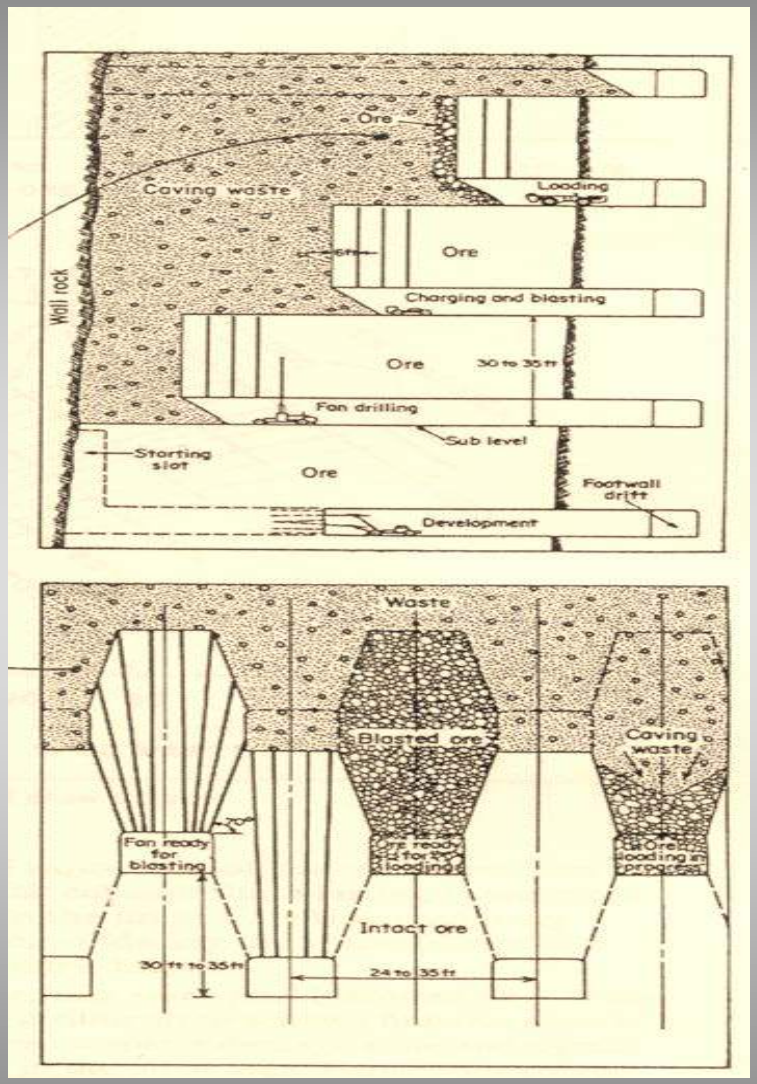
The basic principles of SLC are:

- As ore is pulled from the blasted ring, it will be replaced with broken waste
- This waste will be mixed with some of the ore as the chocked material is moving
- Top down, flexible, low capital, selective for fragmentation.
- Continous repetitive process, highly amenable to mechanization and automation for ‘rock factory’
- Declining in popularity due to relatively high development cost & low recovery, replaced with BC or sublevel open stoping.

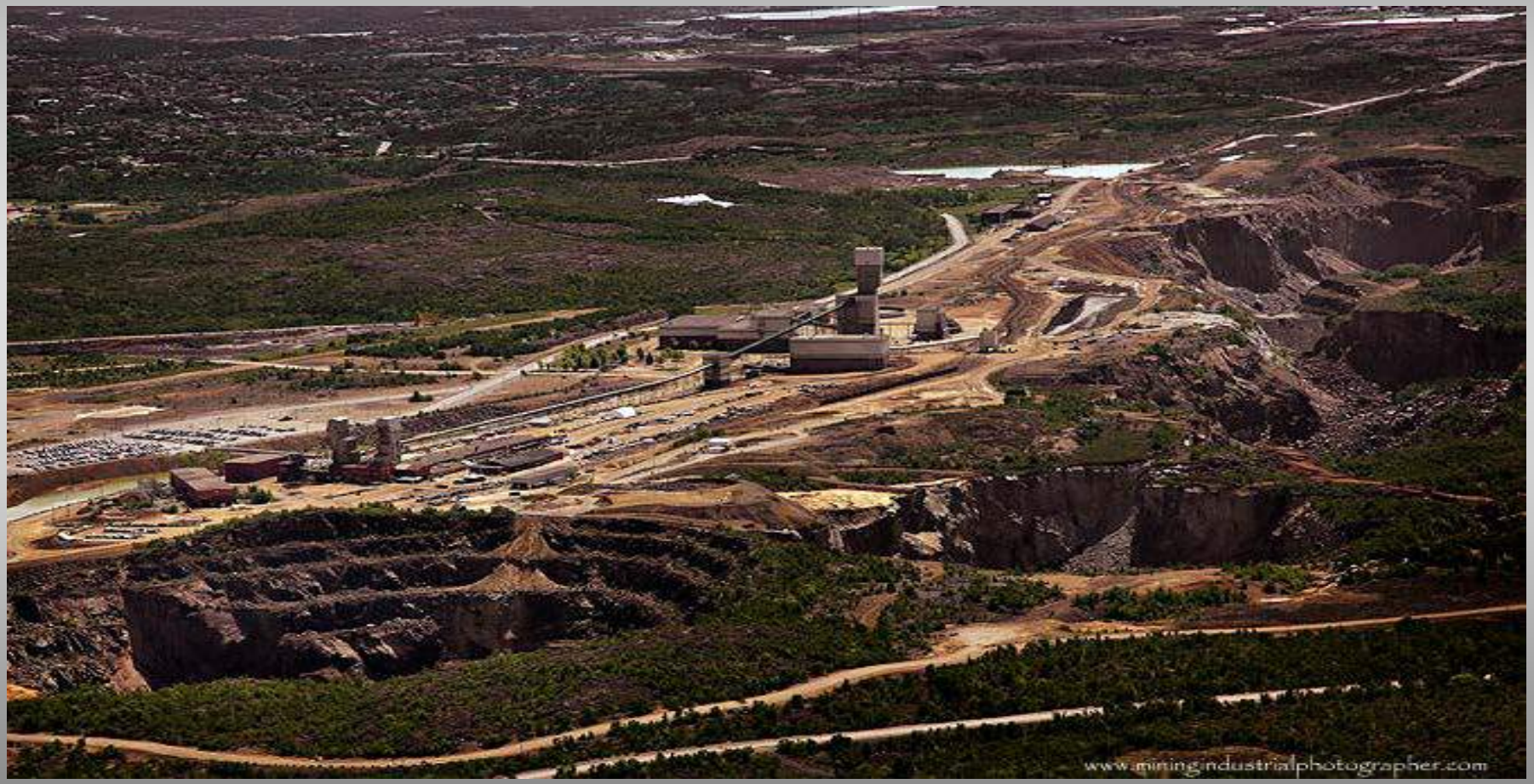


Page & Bull, 2001

SLC requirements:

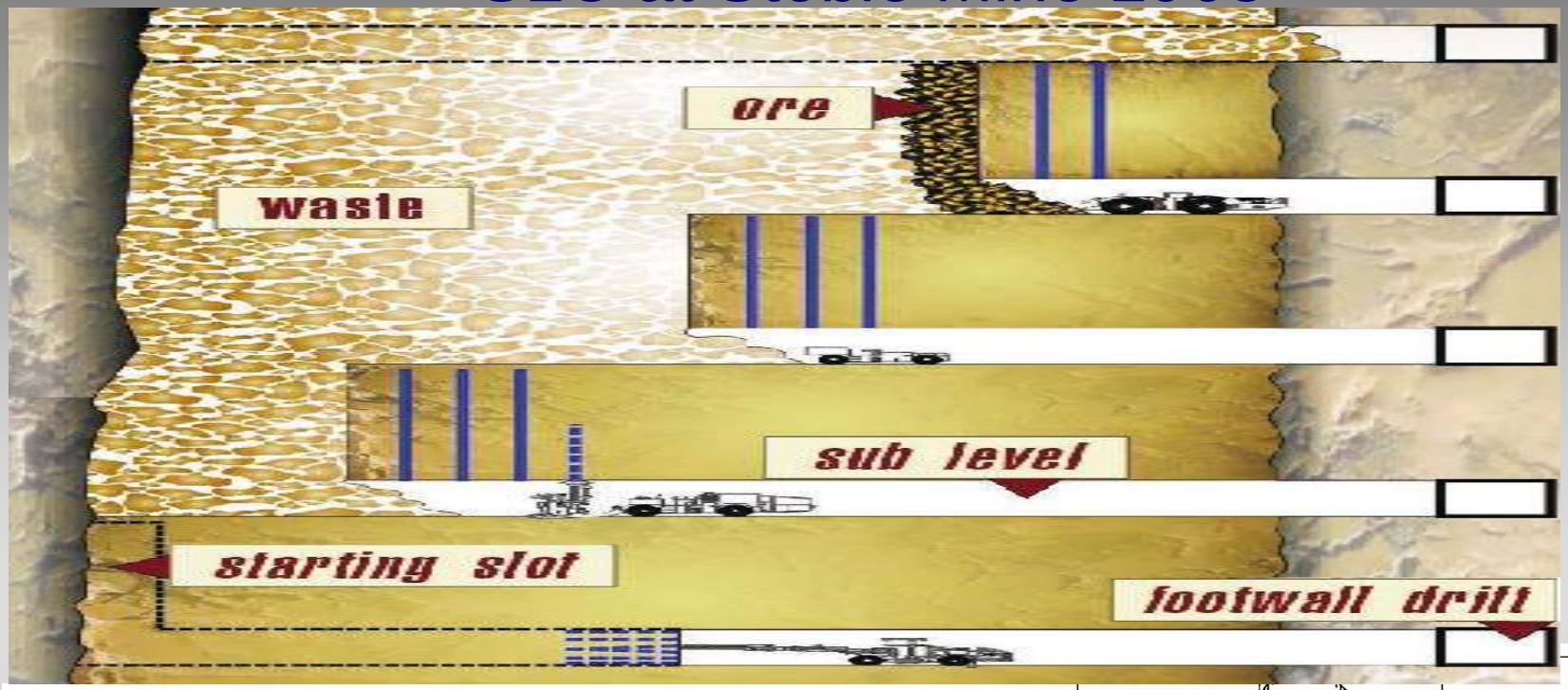


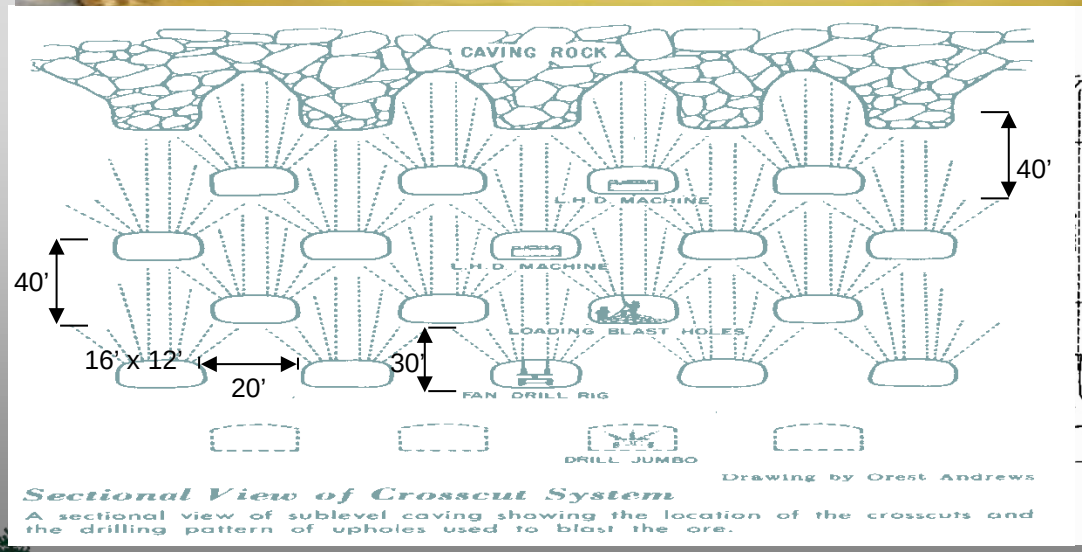
- Massive, steeply dipping orebody
- Good cavability of ore/HW
- Solid enough ore to limit brow wear
- Competent FW for development
- All design and operational efforts are directed towards extracting as much ore as clean as possible, delaying the appearance of dilution, and continuing the draw of the economic mixture of ore and waste for as long as possible.

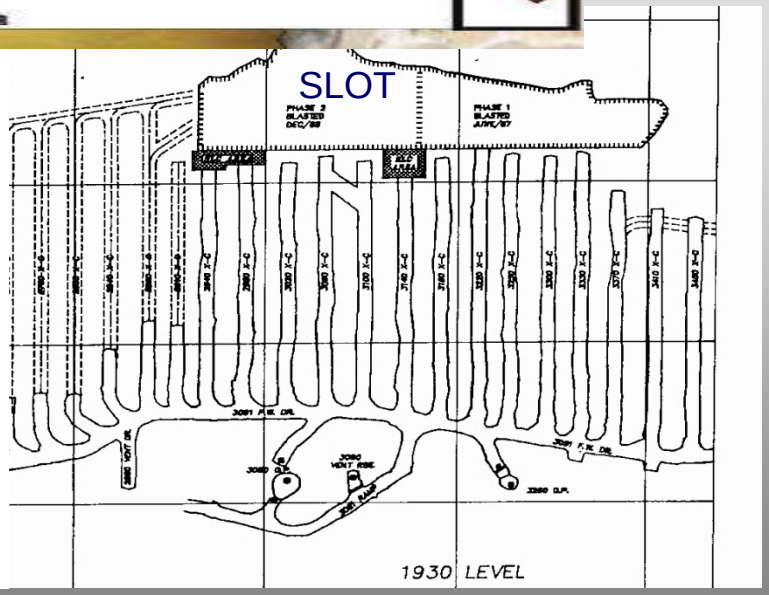


Stobie Mine (SLC) - SUDBURY - CLOSED IN 2012

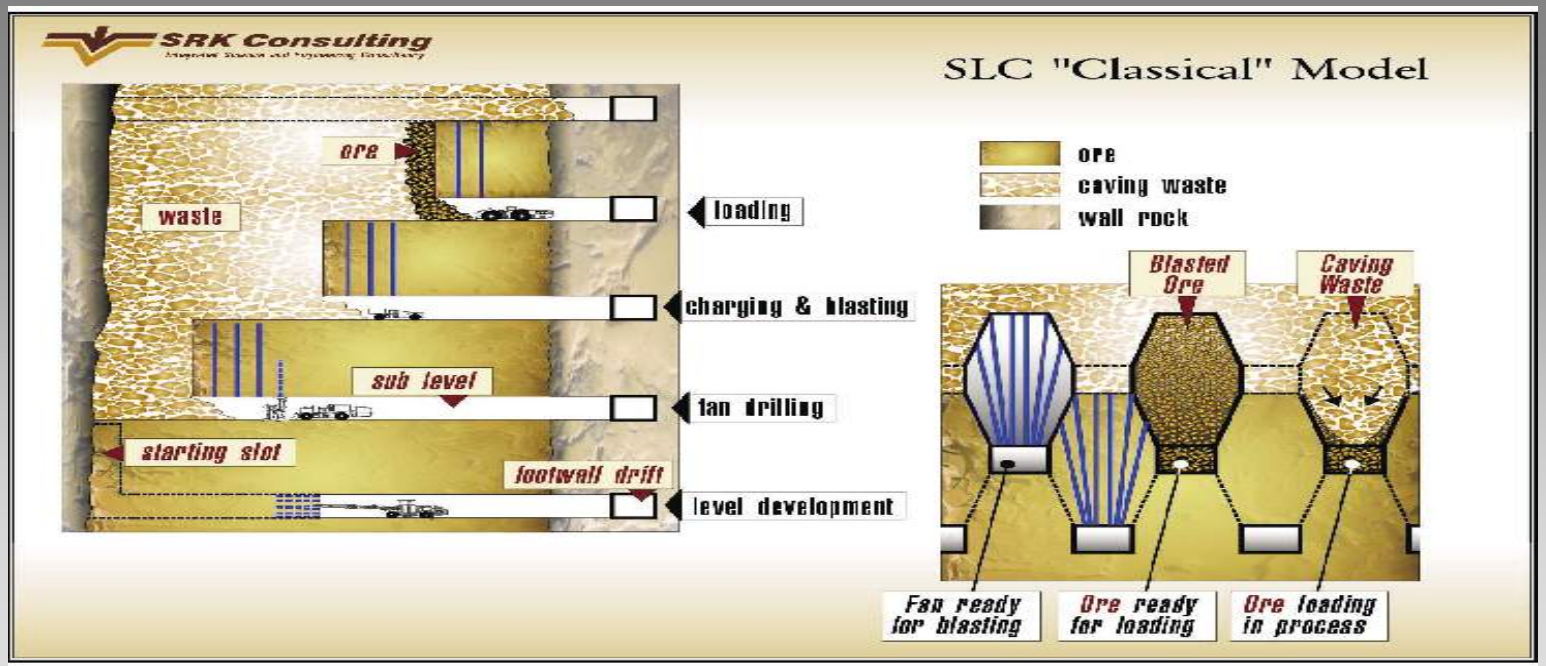
SLC at Stobie Mine 1968

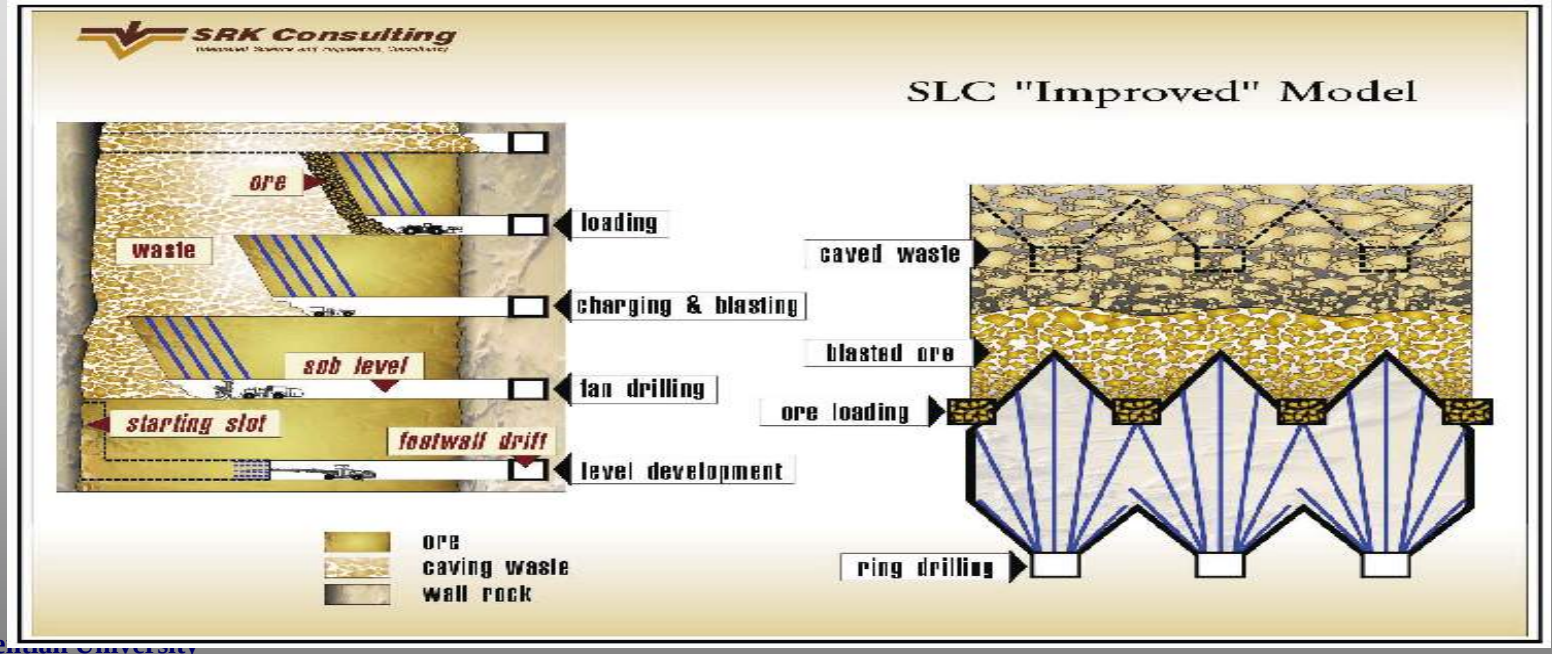






SLC MODELS


SRK Consulting
SLC "Classical" Model
ore
waste
loading
charging & blasting
sub level
fan drilling
starting slot
footwall drift
level development
ore
caving waste
wall rock
Blasted Ore
Caving Waste
Fan ready for blasting
Ore ready for loading
Ore loading in process

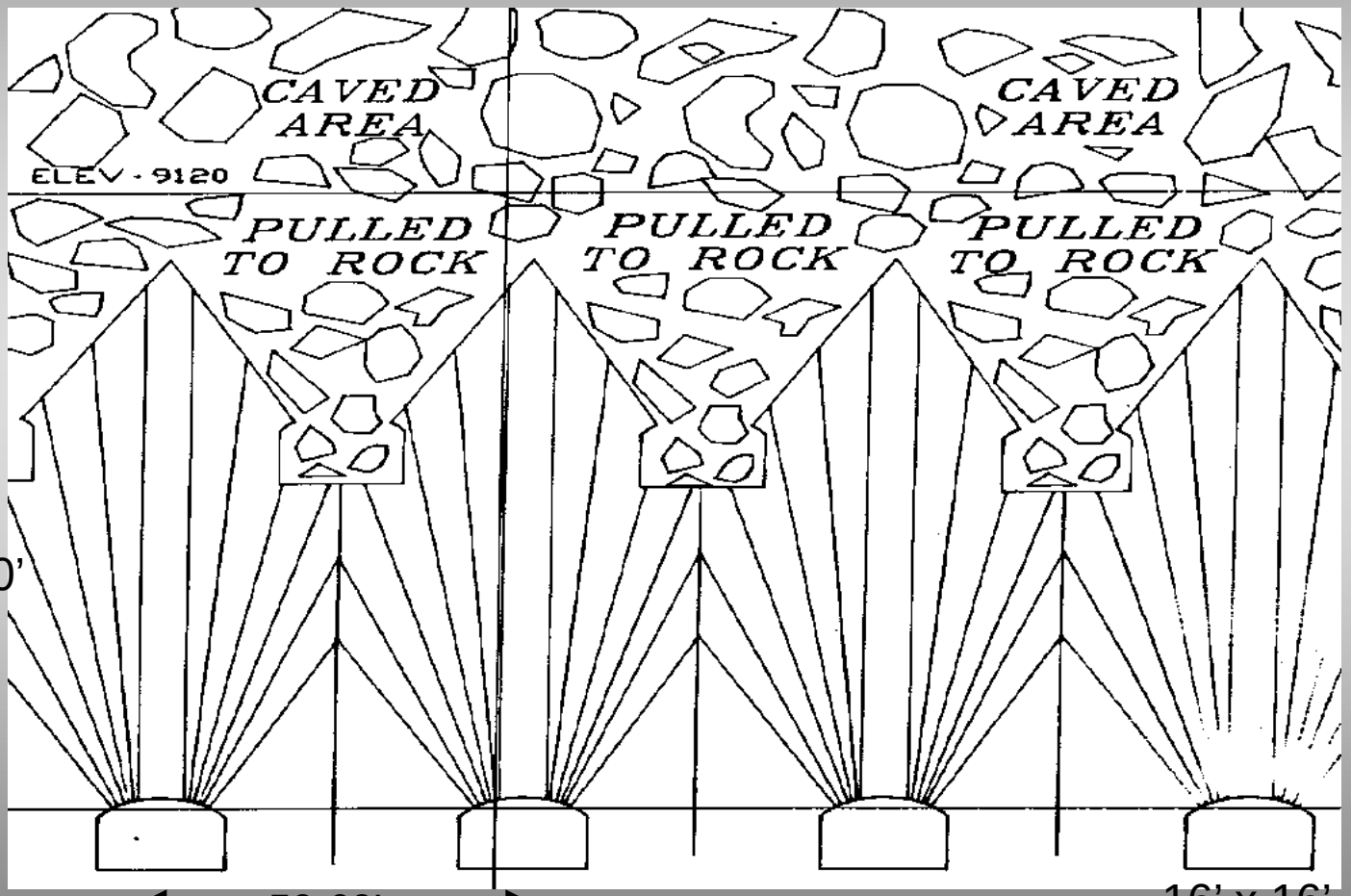

SRK Consulting
SLC "Improved" Model
ore
waste
loading
charging & blasting
sub level
fan drilling
starting slot
footwall drift
level development
caved waste
blasted ore
ore loading
ring drilling
ore
caving waste
wall rock

SLC at Stobie Mine

Lower Development - More tonnage/ring blast

Recovery = 80-90% Dilution = 10-20%

Productivity>30t/manshift Production = 12,000 t/day



130’

100’

50-60’

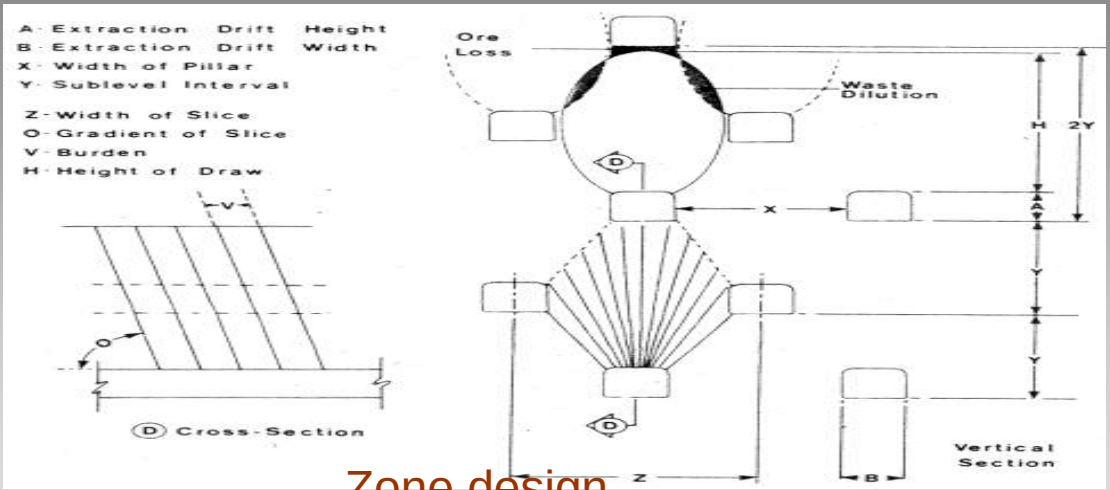
16’ x 16’

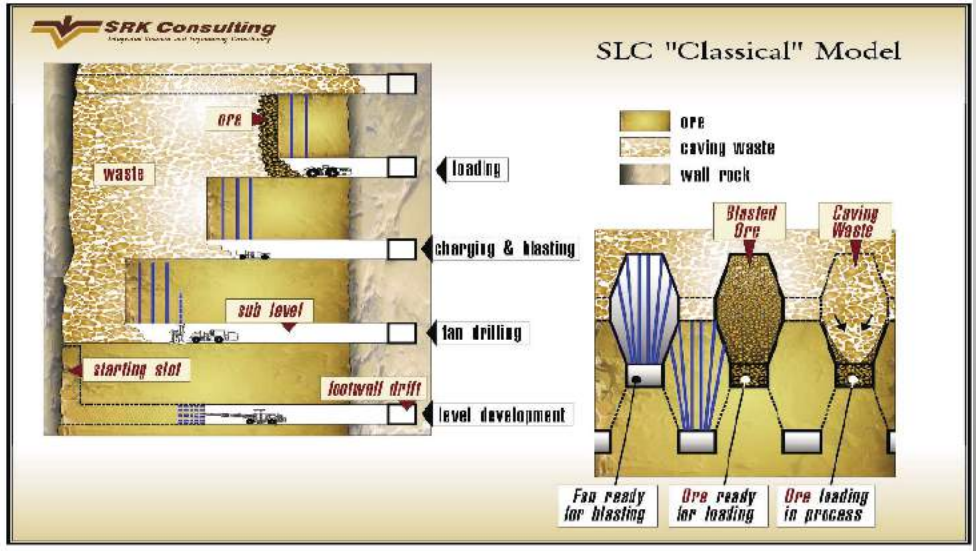
Ring burden = 8’ Tow spacing - 11’

Design parameters for SLC layouts

Stope design

- Drift dimensions
- Pillar width
- Sublevel interval
- Slot design
- **Ring pattern** (burden, spacing, inclination)
- **Brow condition**
- Support
- **Grade control**

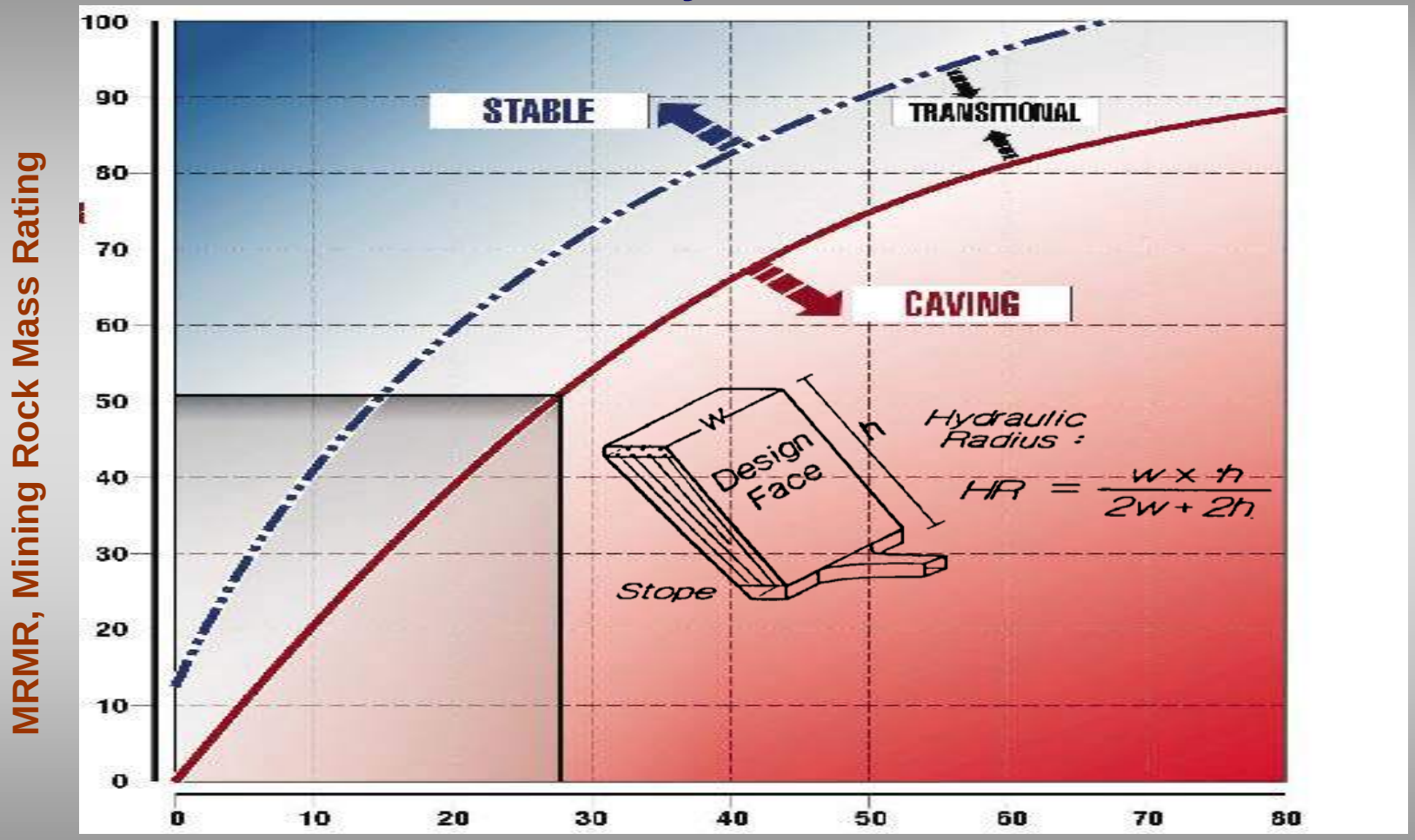




Zone design

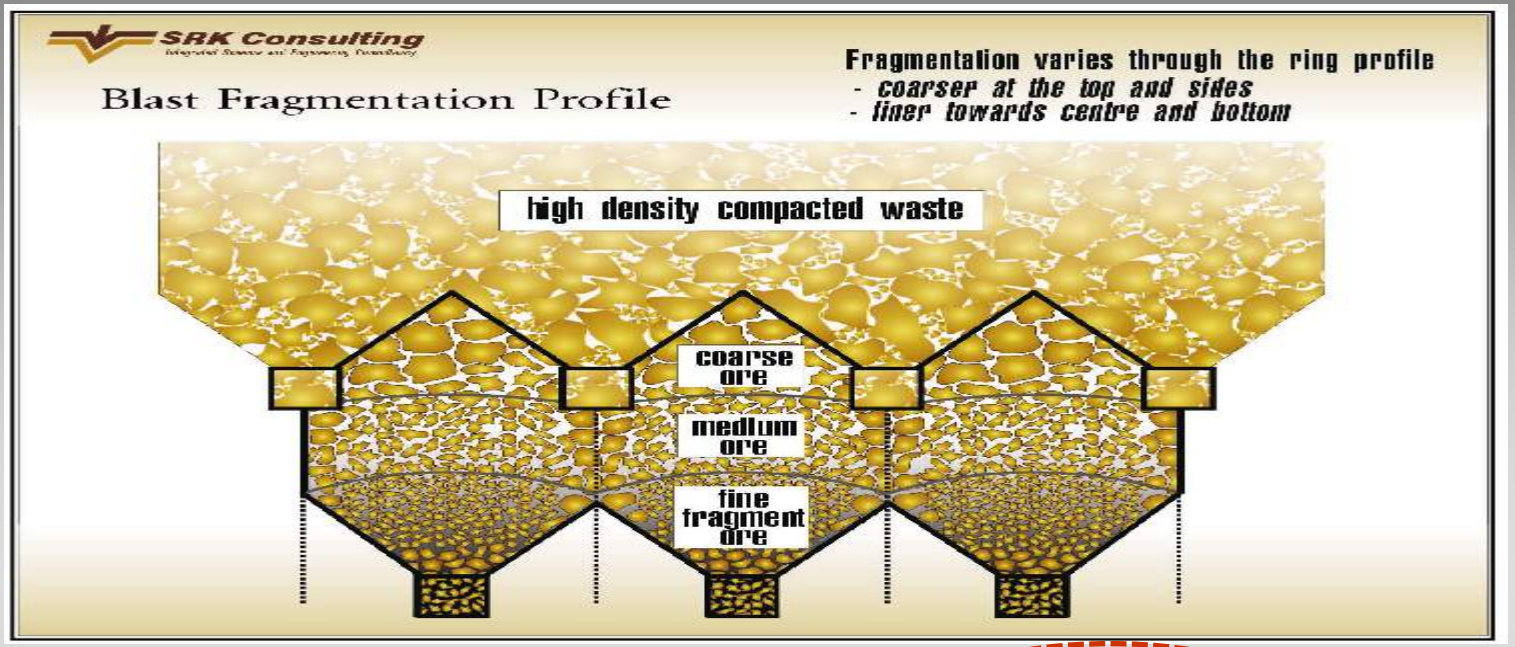
- Permanent openings (access-crusher-passes)
- **Crown**
- Development sequence
- **Mining sequence** (long-transverse)
- Haulage distance
- Production drilling sequence
- Draw - **mucking sequence**
- Dilution/recovery control Dilution blanket
- Fragmentation management (**oversize – fines**)
- Subsidence- displacements

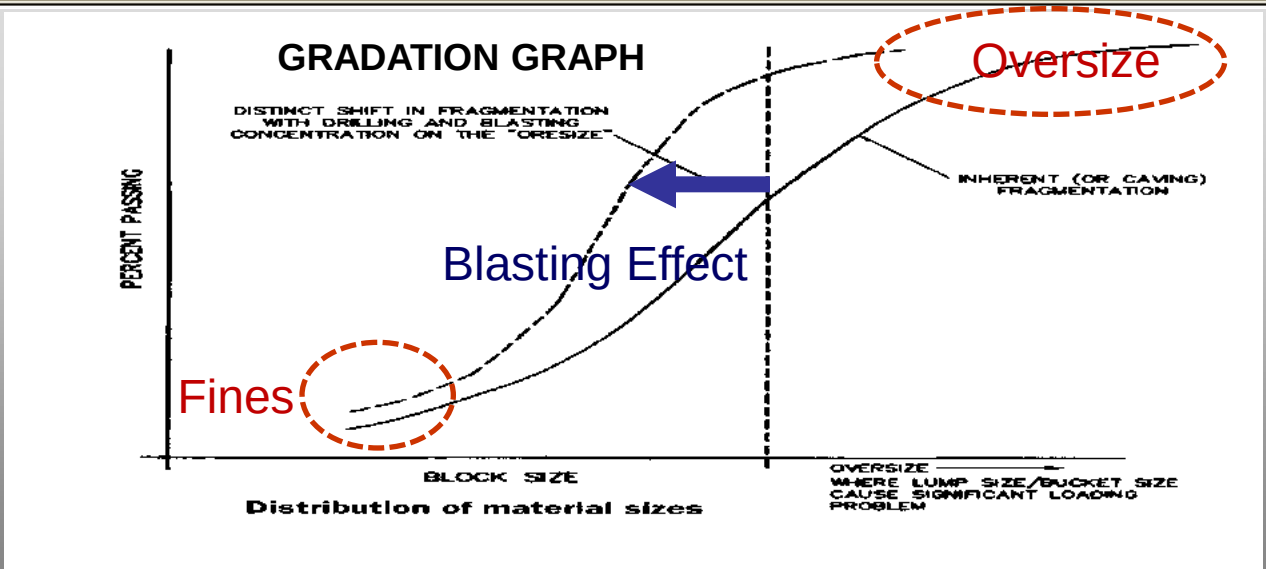
Cavability as a function of rock mass conditions & hydraulic radius



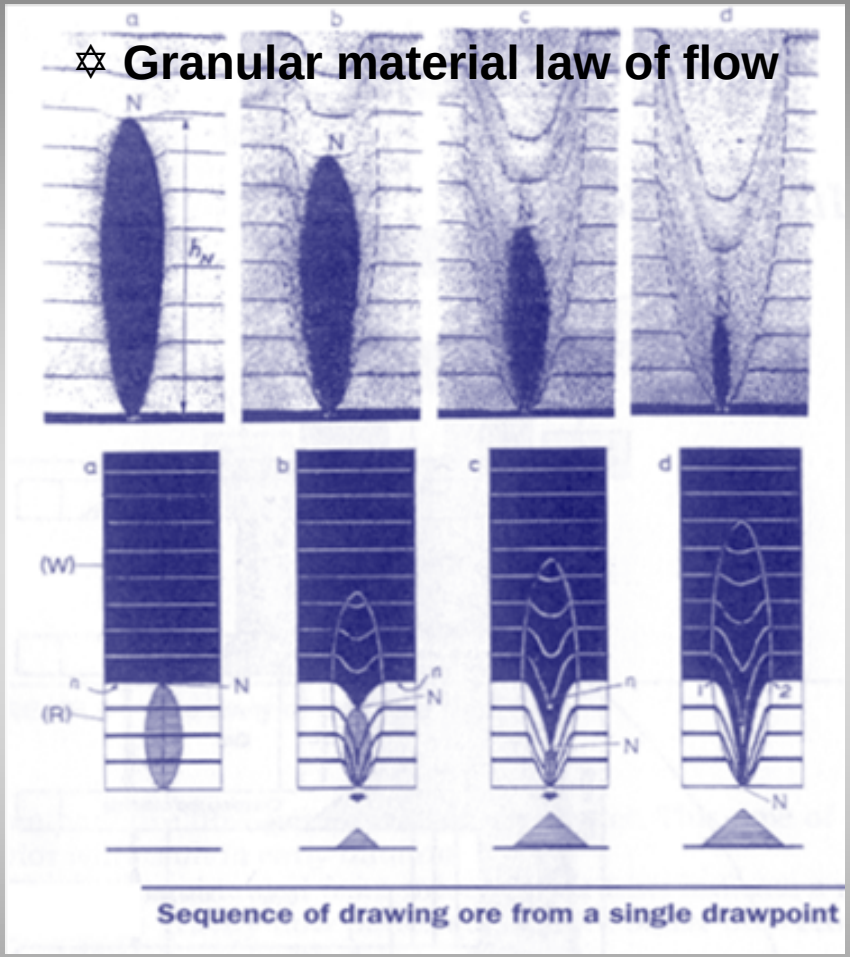
Stability Diagram (Laubscher, 1994) : STABILITY vs CAVABILITY

Fragmentation Control

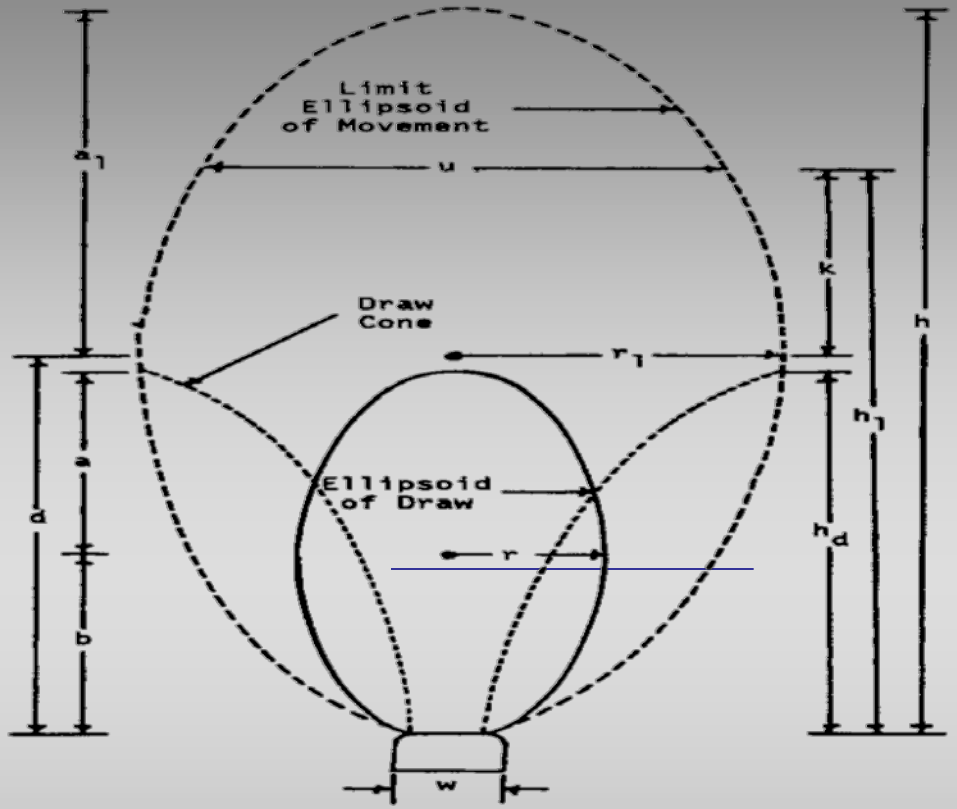




Gravity Flow Mechanics – Draw & Grade Control



Sequence of drawing ore from a single drawpoint

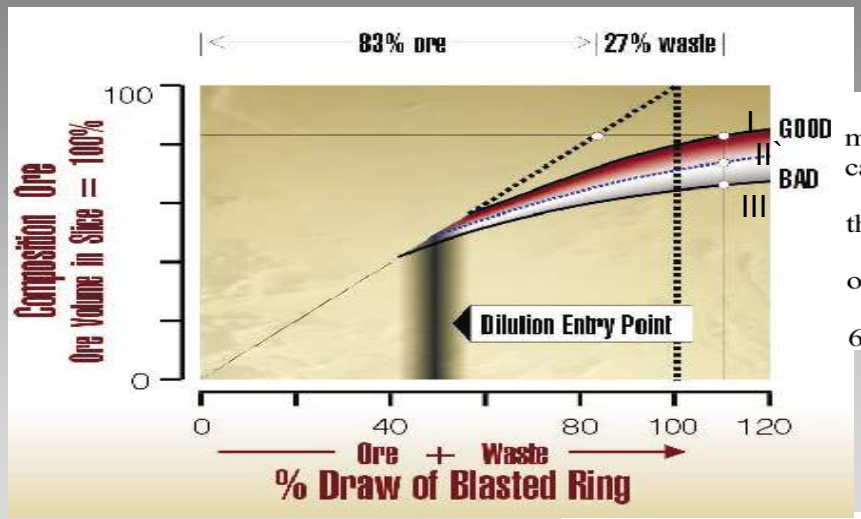


Design of Drawpoints based on ellipsoid theory (Kvapil, 1965)

✡ **A good system of draw and grade control** is key to the success of an operation and a number of changes will likely be needed before the ideal system is found during the mine life cycle.

PFC

Dilution



Conventional draw curves

As a guide for evaluating the extraction (assuming 110% of material [ore and waste] extraction), the following classification can be used:

1. Class I: Extraction is good as the ore is at least 80% and the waste is less than 30%.
2. Class II: Extraction is acceptable in certain cases as the ore is at least 75% and the waste is no more than about 35%.
3. Class III: Extraction is poor as the ore constitutes about 65% and the waste 45% or more.

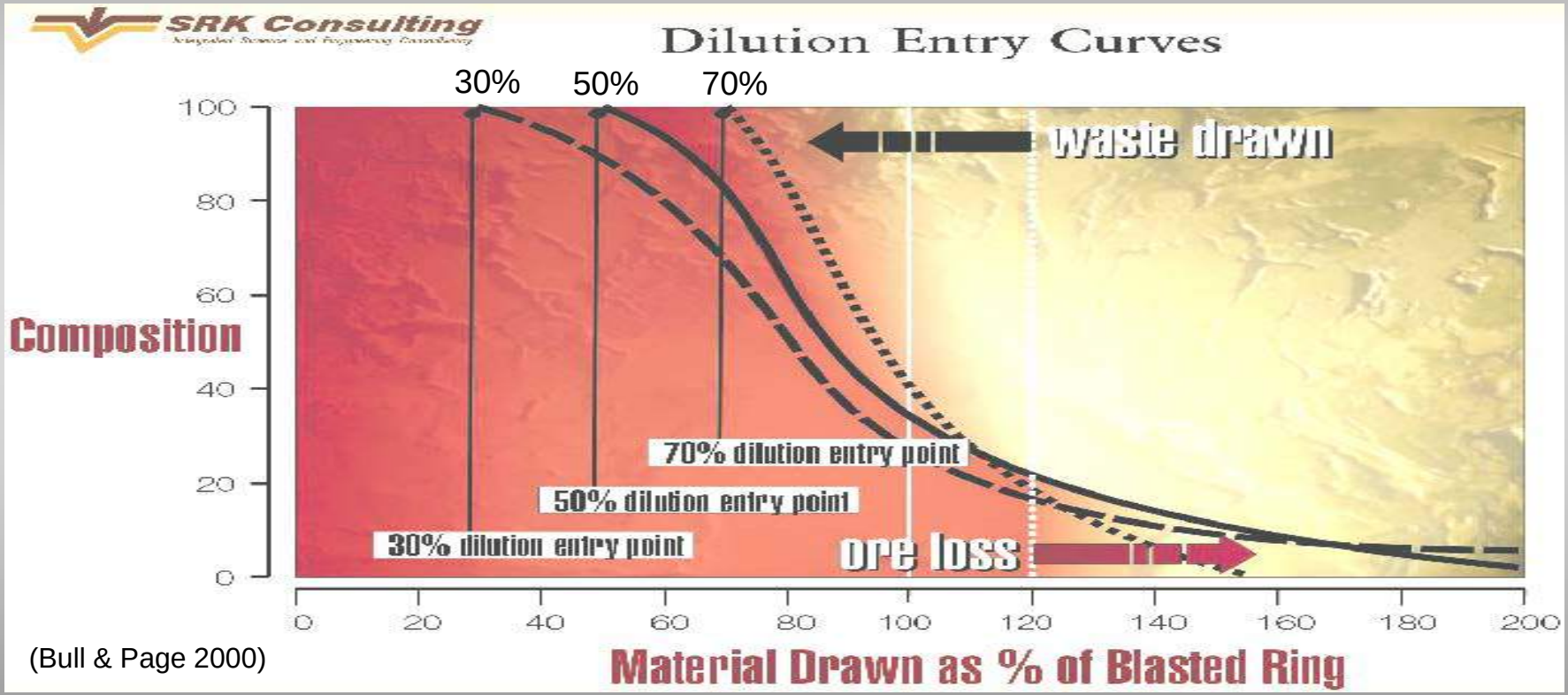
(Kvapil, 1992)

Simplified chart of dilution development

If after a material extraction of 71%, the ratio is 60% ore and waste 11% (point A), one can expect that with 120% material extraction the ration will be about 77% ore and at least 43% waste (point B)

Dilution - Recovery in SLC: Grade & Tonnage Prediction

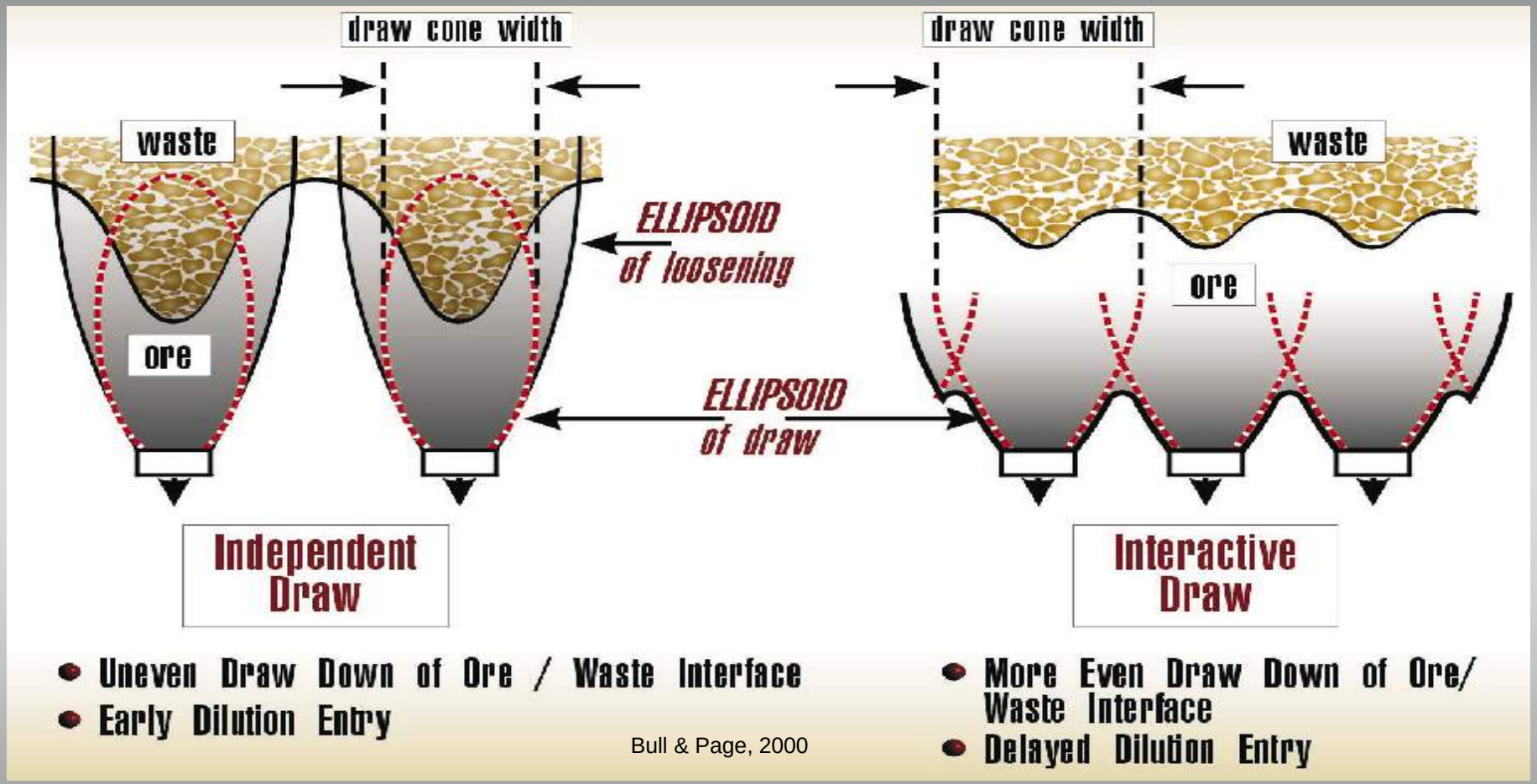
Draw model for calculation of extraction tonnage & grade



(Bull & Page 2000)

The model shows the proportion of ore (below the line) and dilution (above the line) as extraction increases along the x-axis.

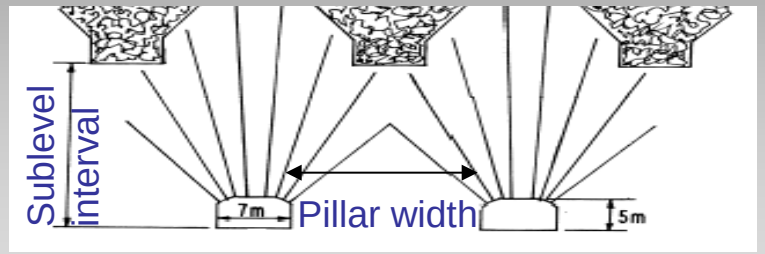
Design considerations

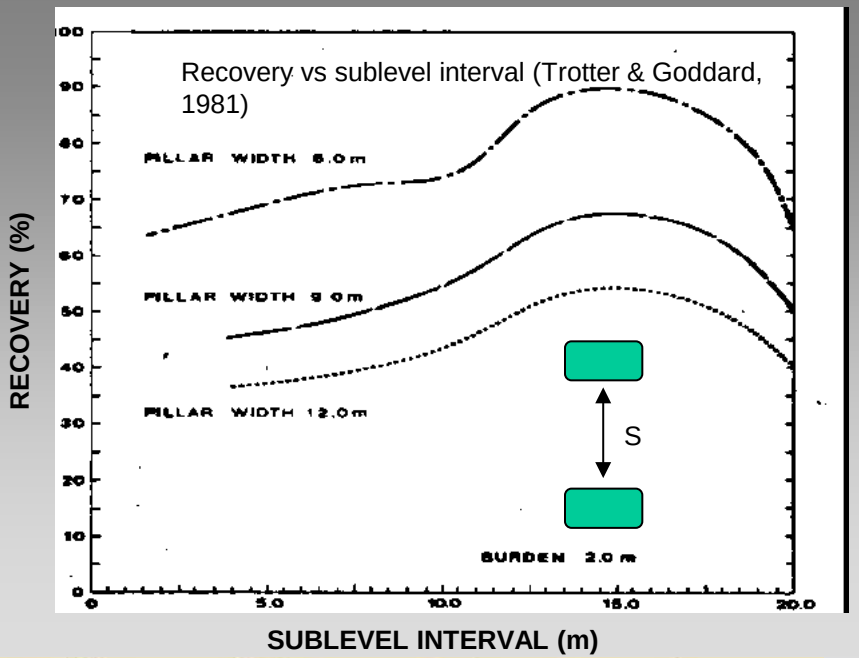


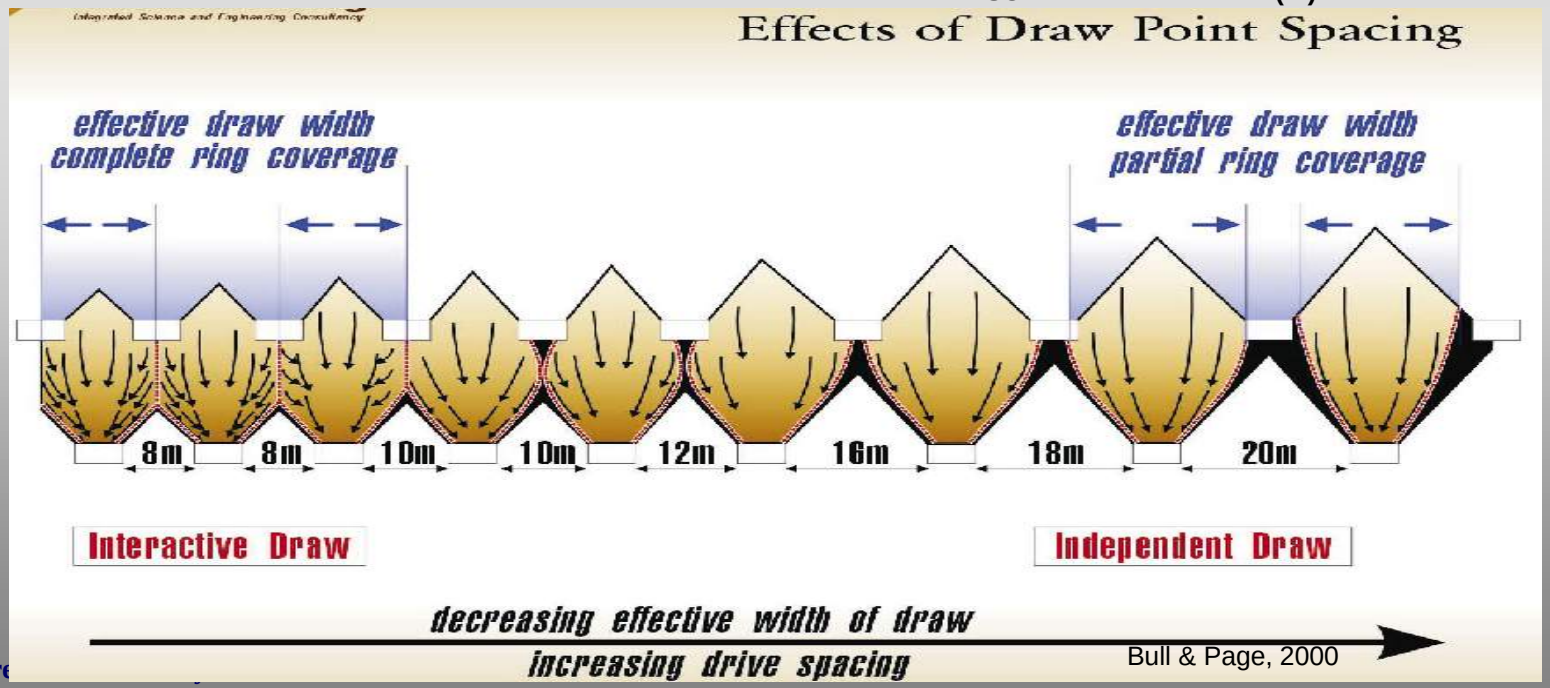
Bull & Page, 2000

Independent vs interactive draw

Design considerations

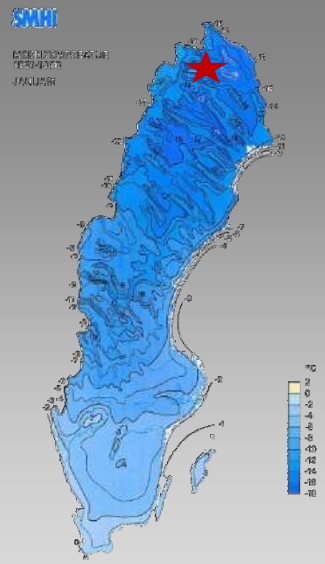


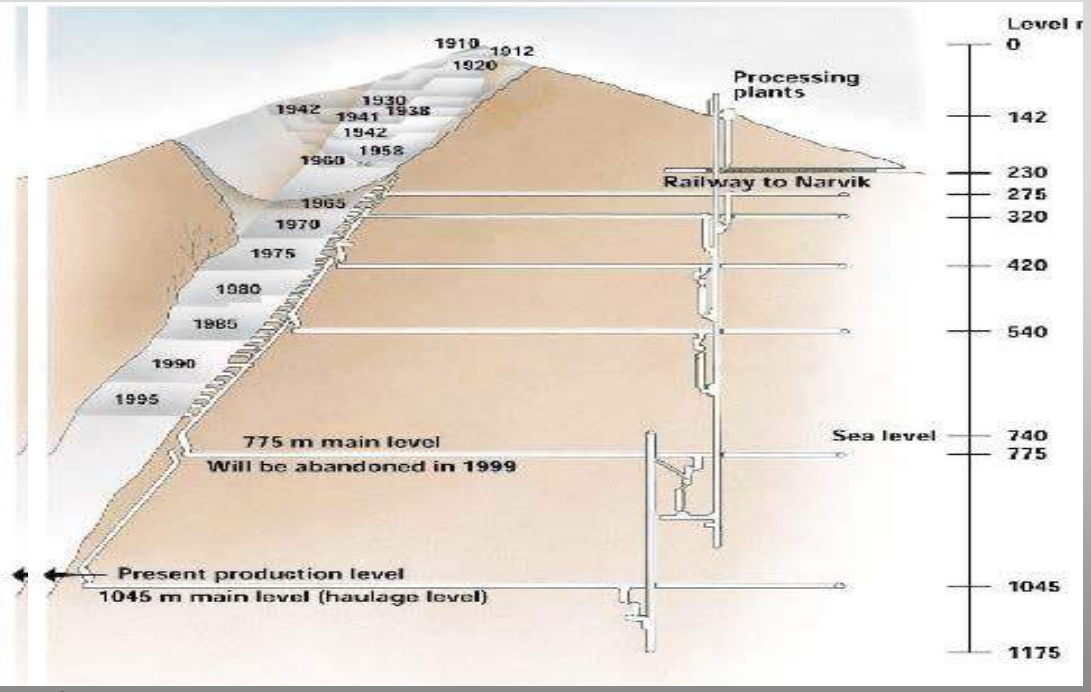


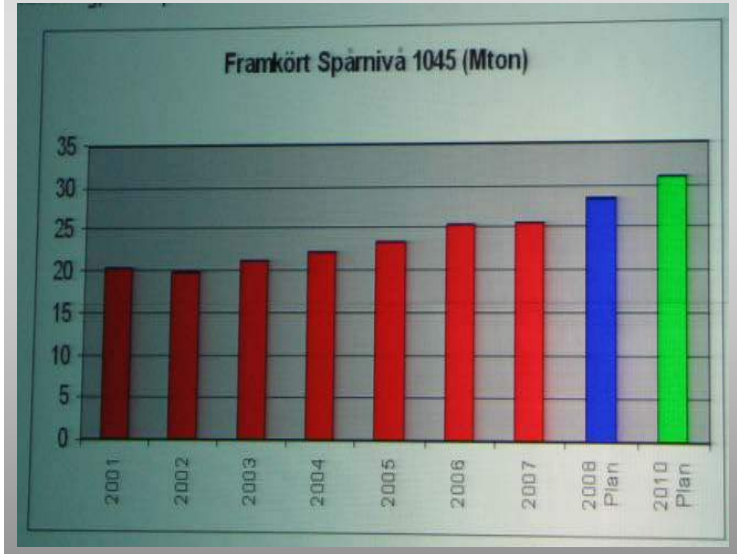


Bull & Page, 2000

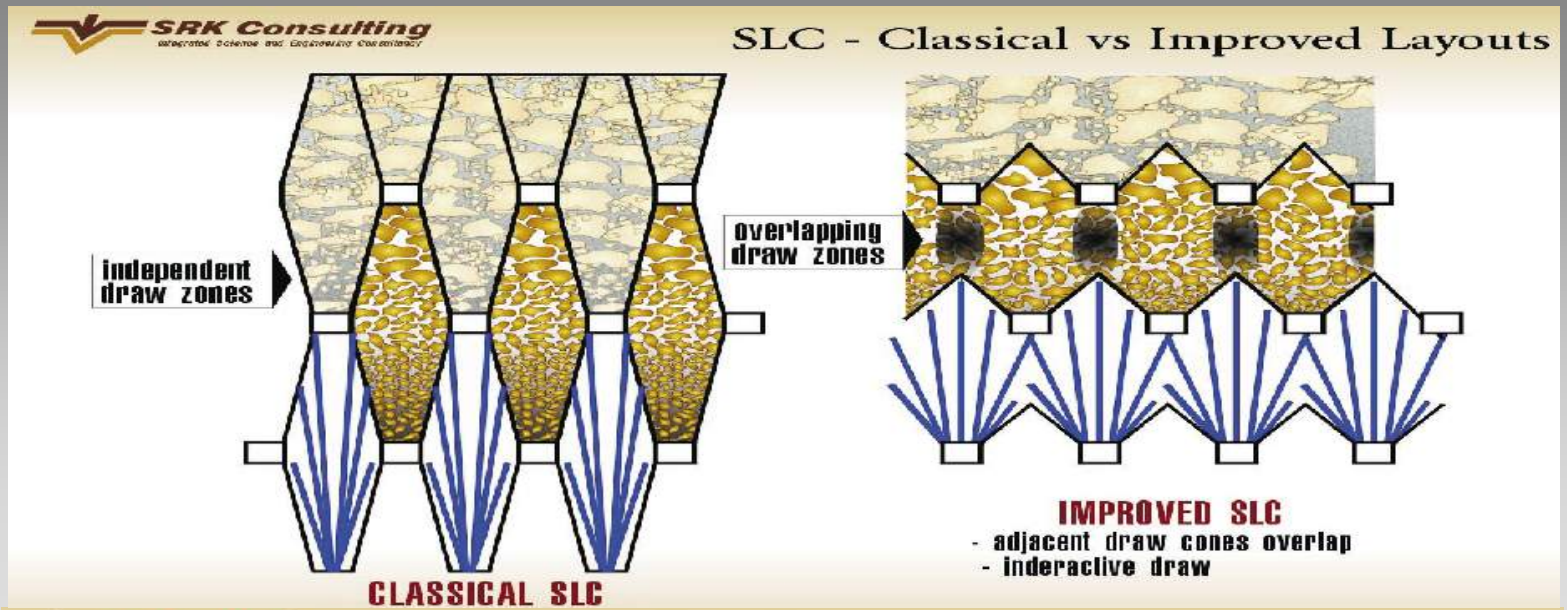
SLC at the Kiruna Mine, Sweden

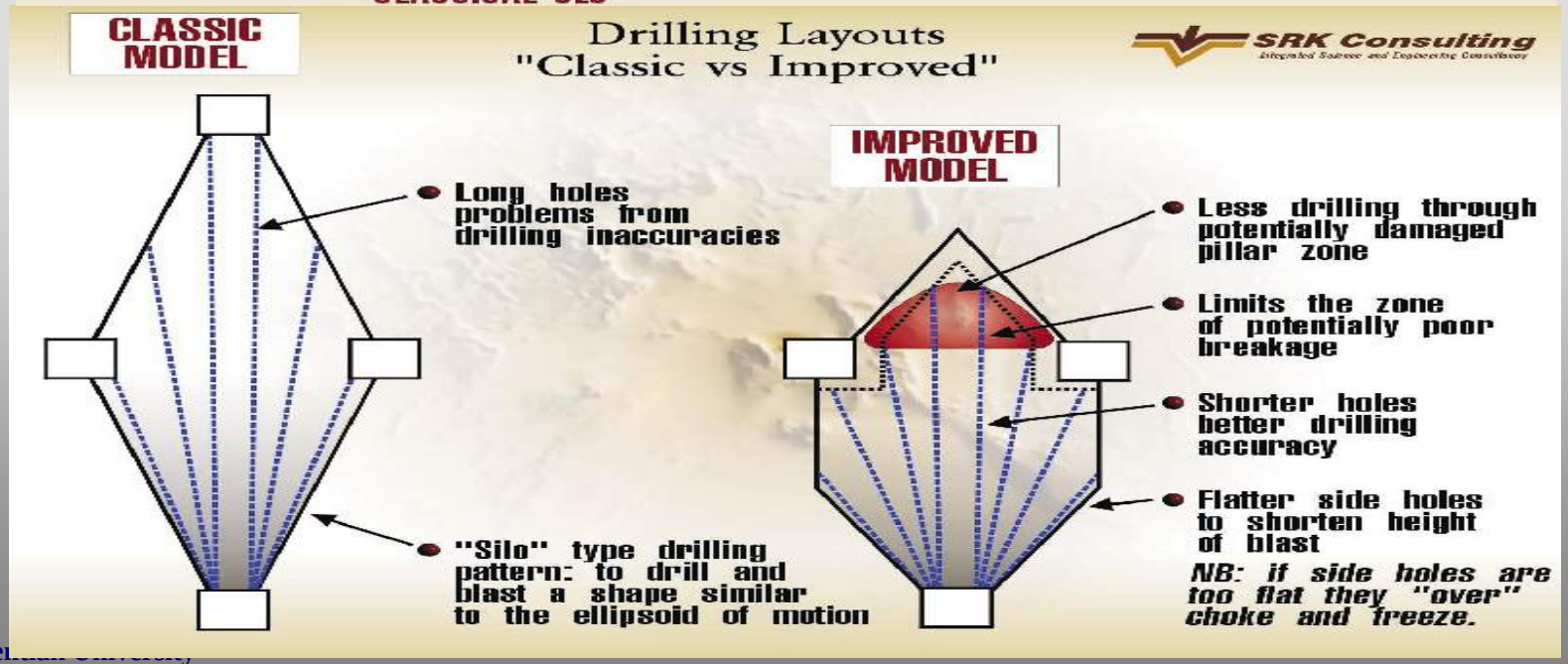




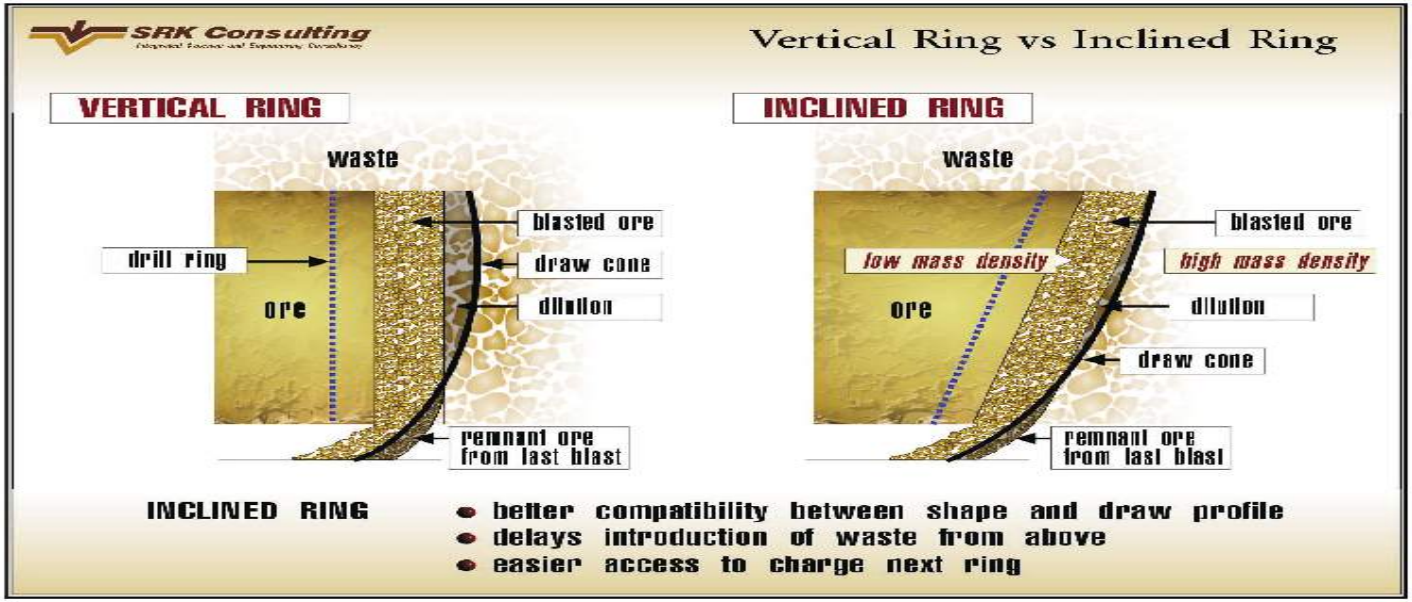


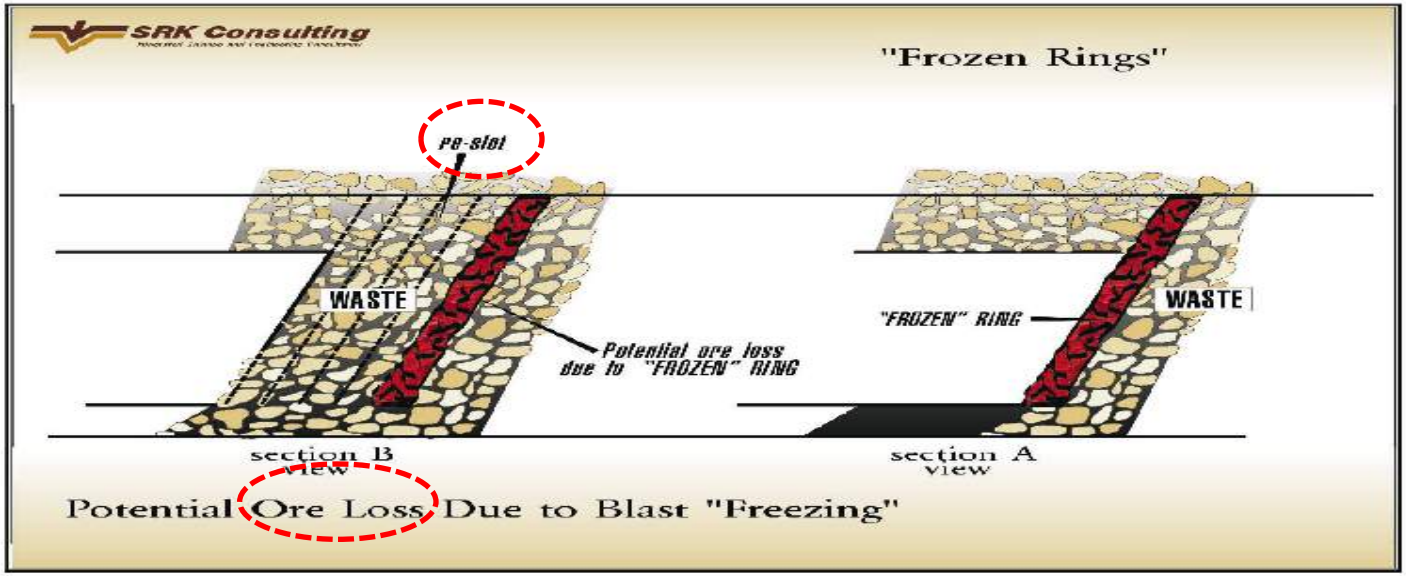
Operating issues in SLC





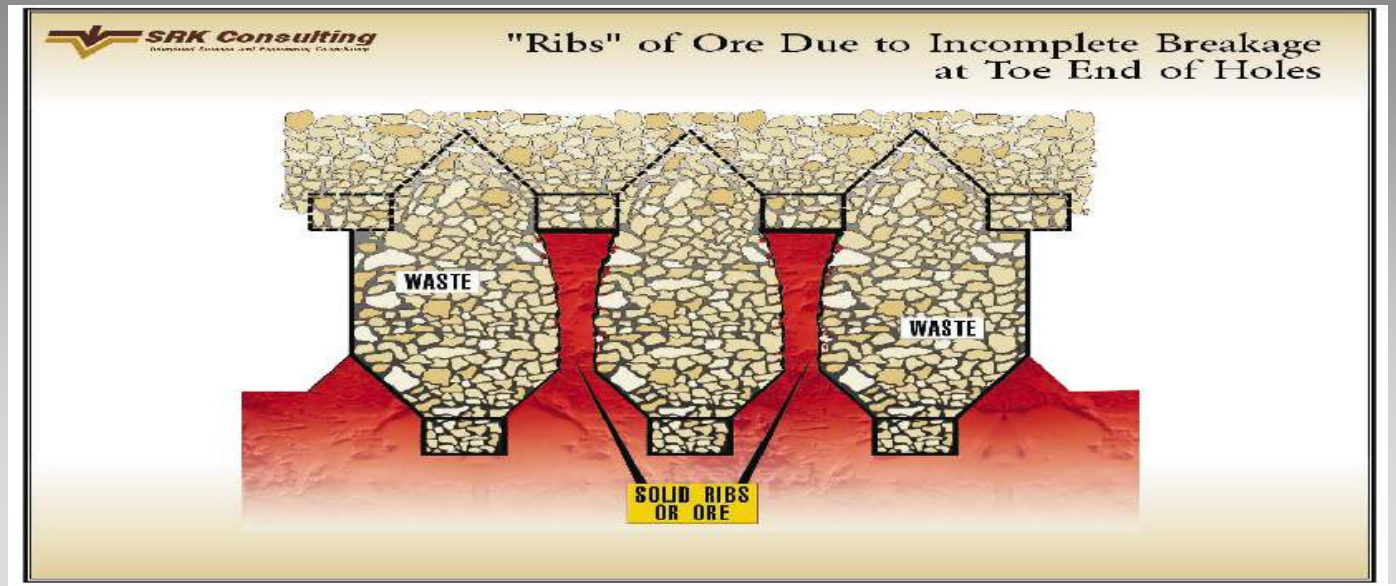
Examples of operating problems in SLC





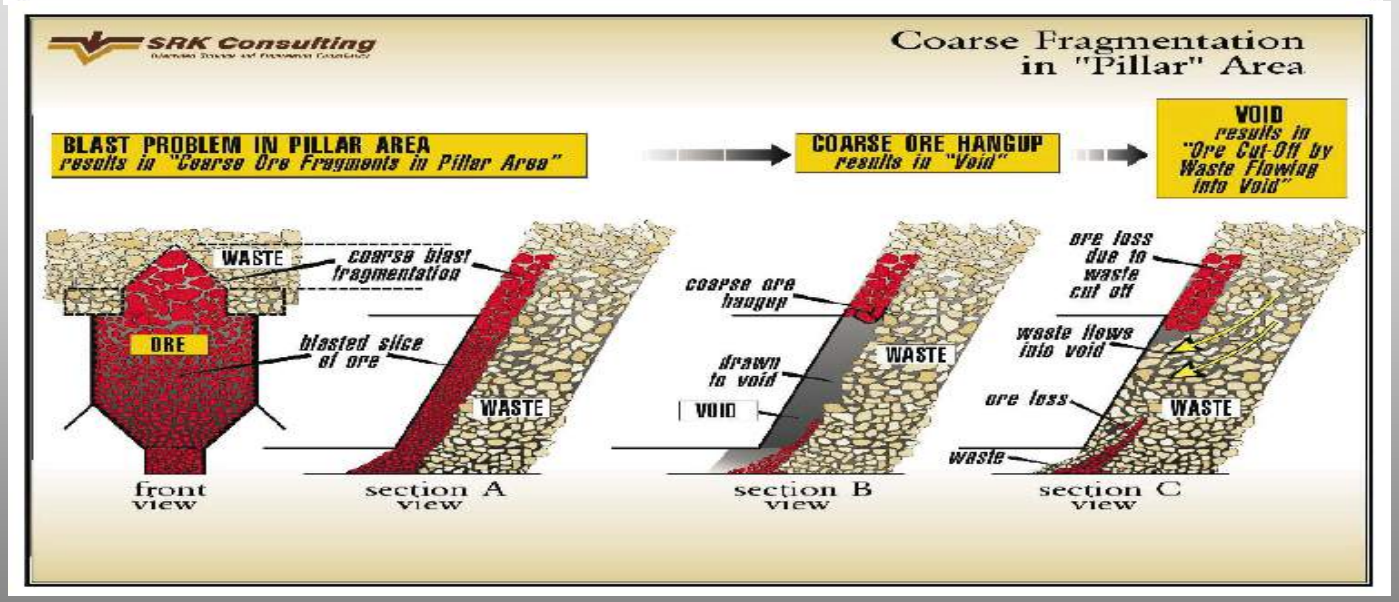
Examples of operating problems in SLC

RIBS



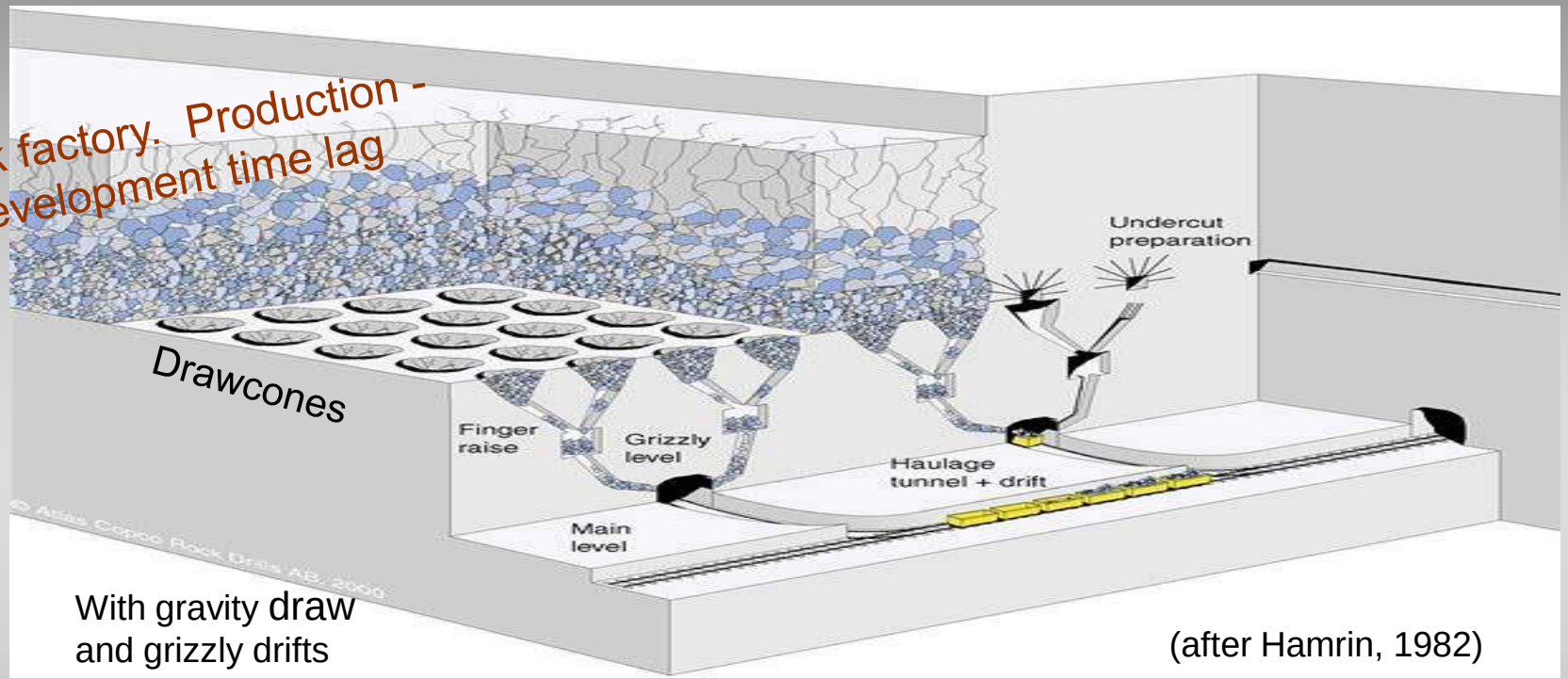
ORE LOSS

PILLAR



Block Caving - BC

- Block/Panel/Mass Caving -



Has the potential to rival surface mining in production capacity and costs.

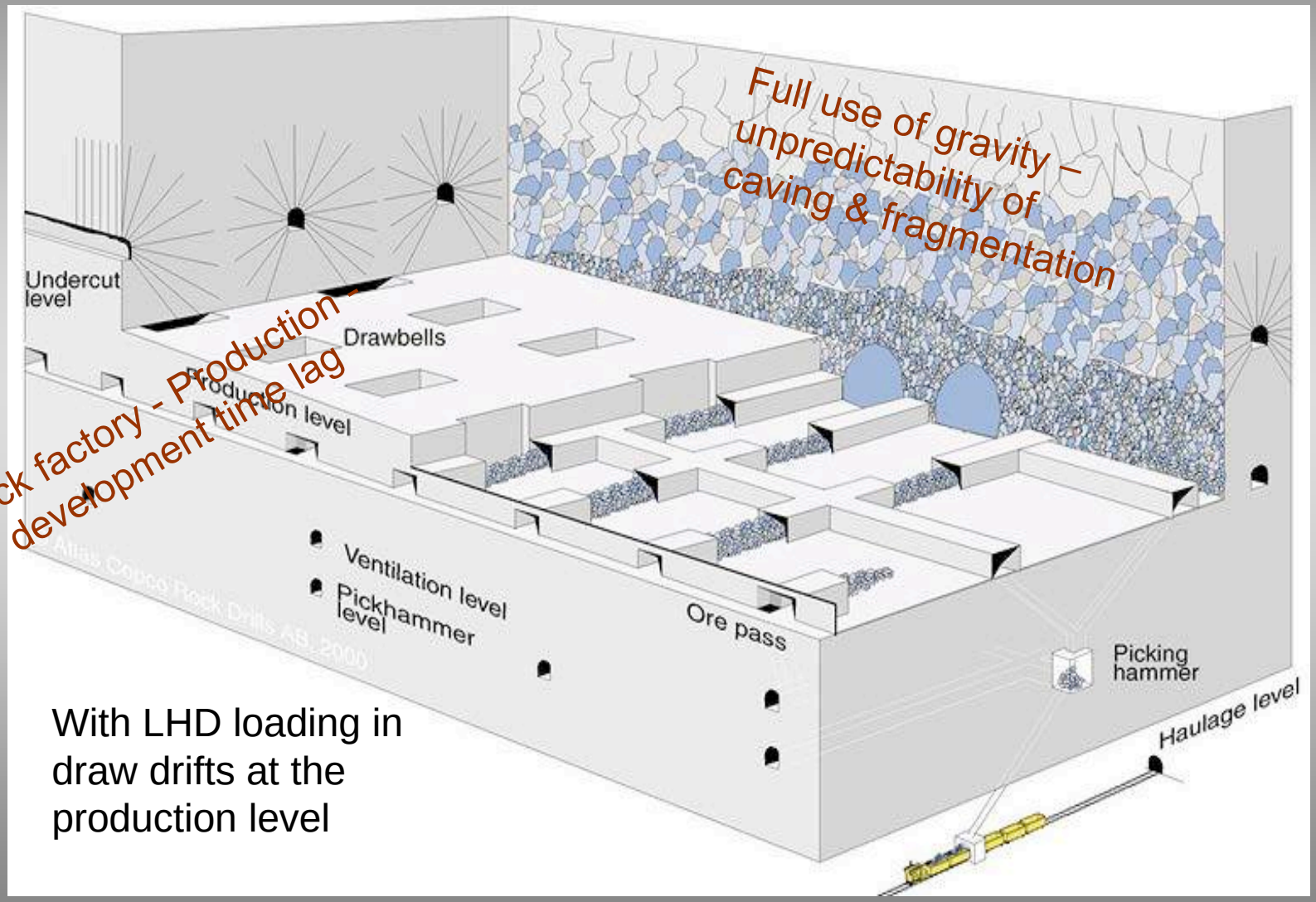
Principle: "If a single enough area is undermined, any rock mass will eventually cave".

With care, recoveries in the order of 120% with dilution held below 20% can be achieved.

Key question: "can it be caved, drawn, handled safely and delivered to the surface for processing-economically "? ← OPTIMIZATION

Block Caving - BC

- Block/Panel/Mass Caving -



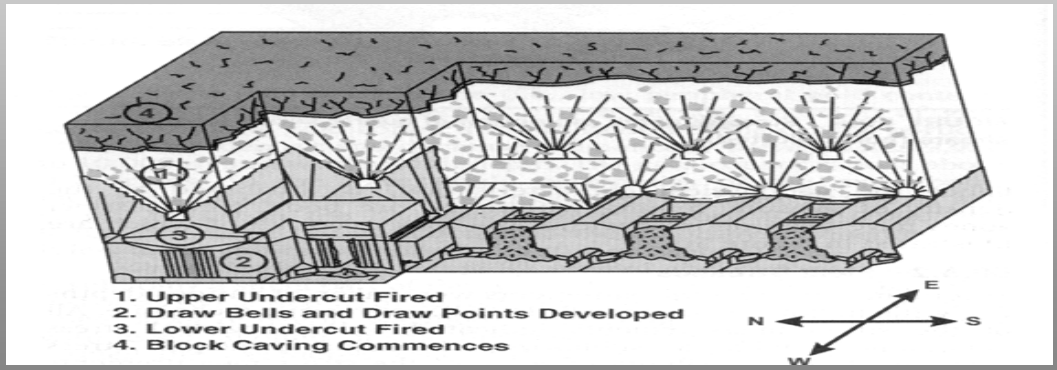
With LHD loading in draw drifts at the production level

The basic principles of BC are:

- Applicable to low grade subvertical massive ore deposits

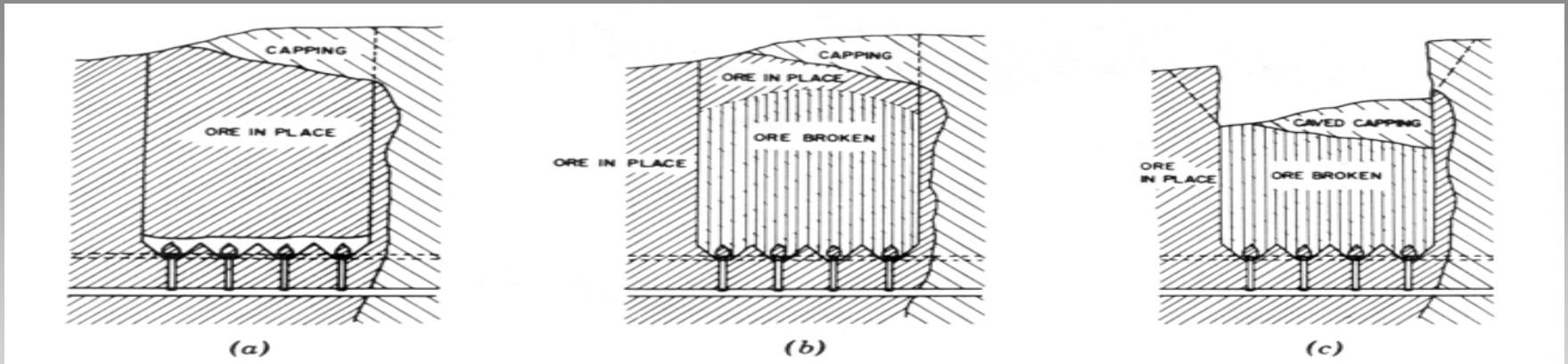
Cu, Fe, Mo, Zn, diamonds

- Ground subsidence allowance
- Both ore and waste are caved and drawn from below. Mining progresses downwards, while the ore is undercut. The waste will be mixed with some of the ore as the chocked material is moving
- The efficiency of the method is a function of the cavability and the fragmentation control of the material
- Continuous repetitive process, highly amenable to mechanization and automation for 'rock factory'
- High initial capital cost. Time lag from development to production
- Risk for premature collapse, hang-ups, air blasts, oversize, mud-rushes.

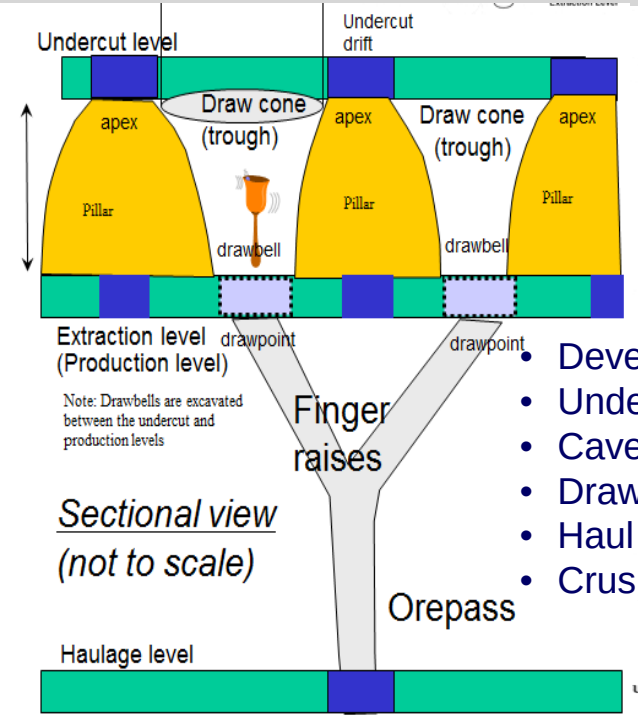


ORE RESOURCE
BFS
ORE RESERVE

Block Caving Principles

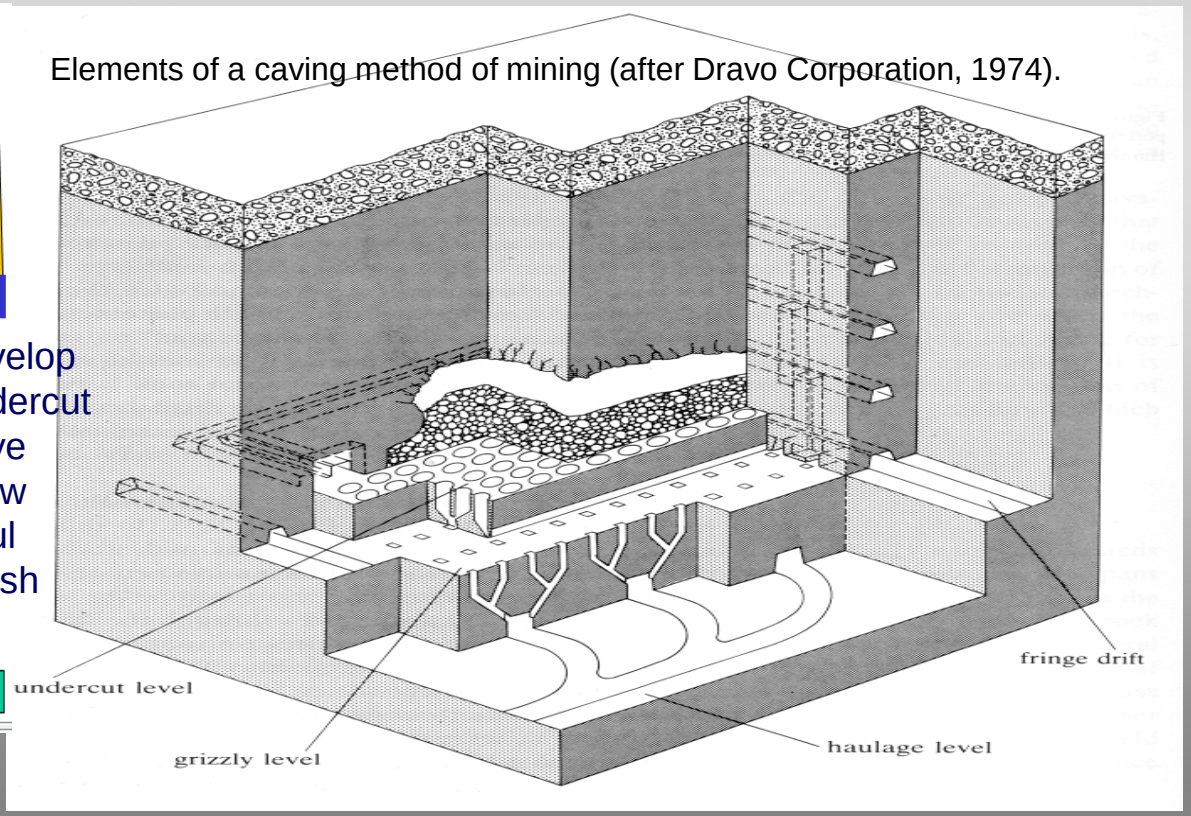


Progressive stages (a, b, c) of block caving, showing caving of ore and waste.



- Develop
- Undercut
- Cave
- Draw
- Haul
- Crush

Elements of a caving method of mining (after Dravo Corporation, 1974).

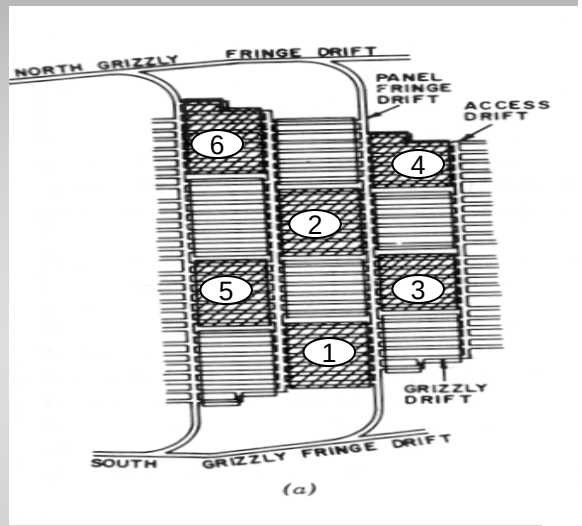


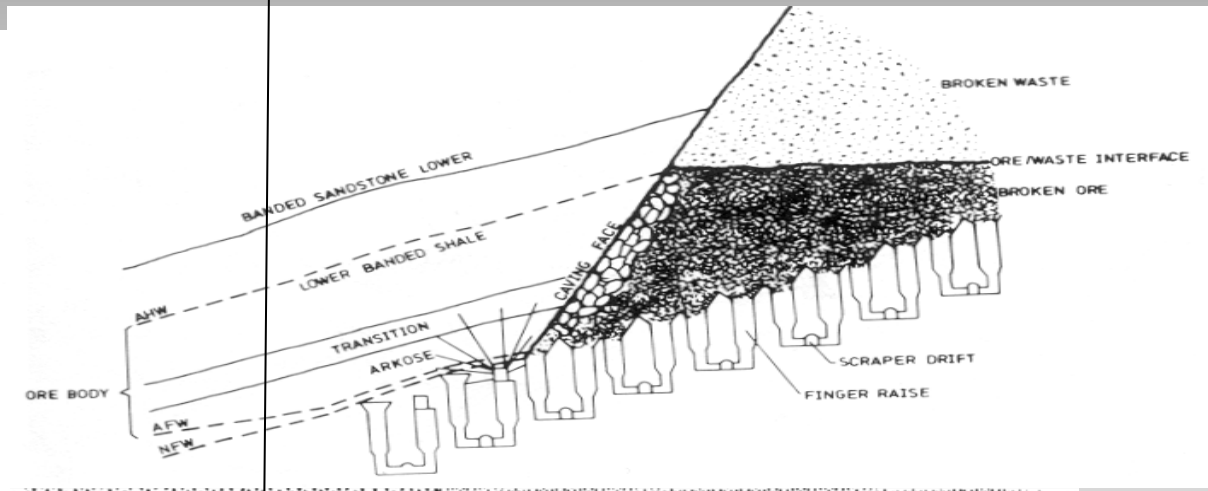
Variations of Caving Methods

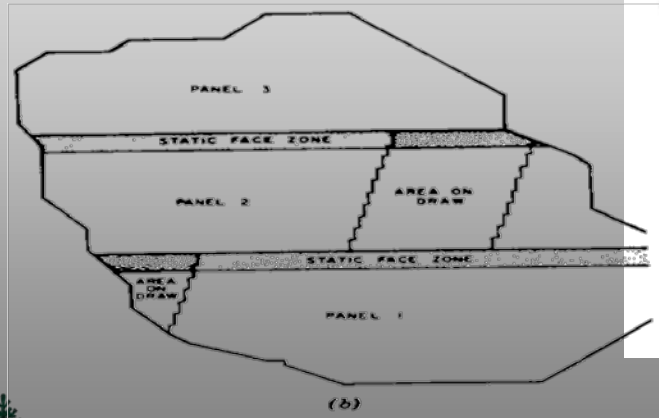
Shape of caving area

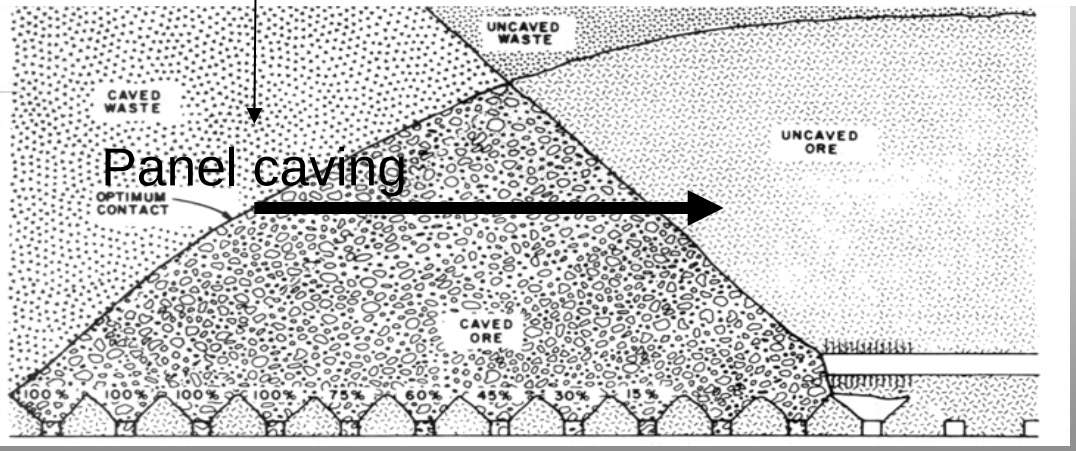
Block caving

Mass caving









Panel caving

Variations of Caving Methods - A

Shape of caving area

- Block caving`
- Panel caving
- Mass caving

Orebody/mining regularity

Regular ← → Irregular

Extend of active caving zone

Fracture intensity

Highly fractured ← → Moderately fractured

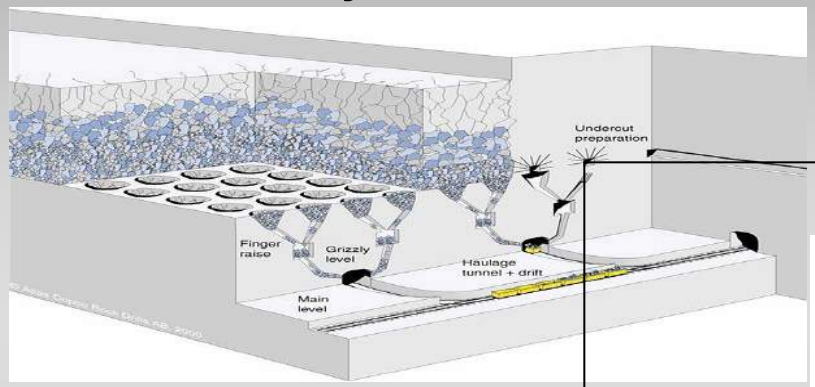
Strength

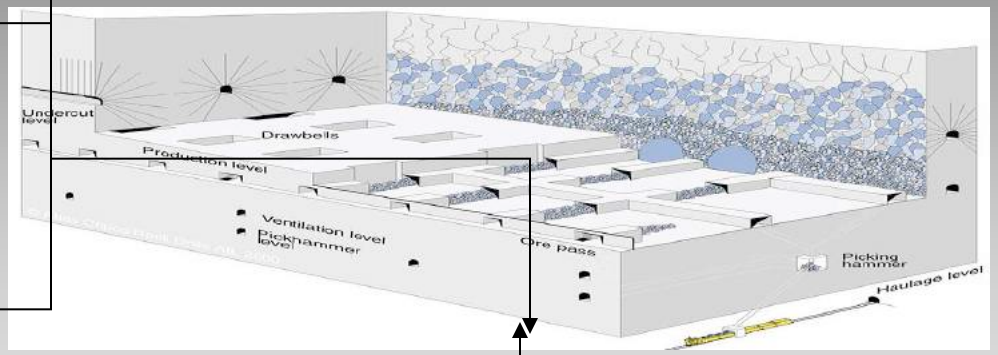
Weak → Strong

Variations of Caving Methods - B

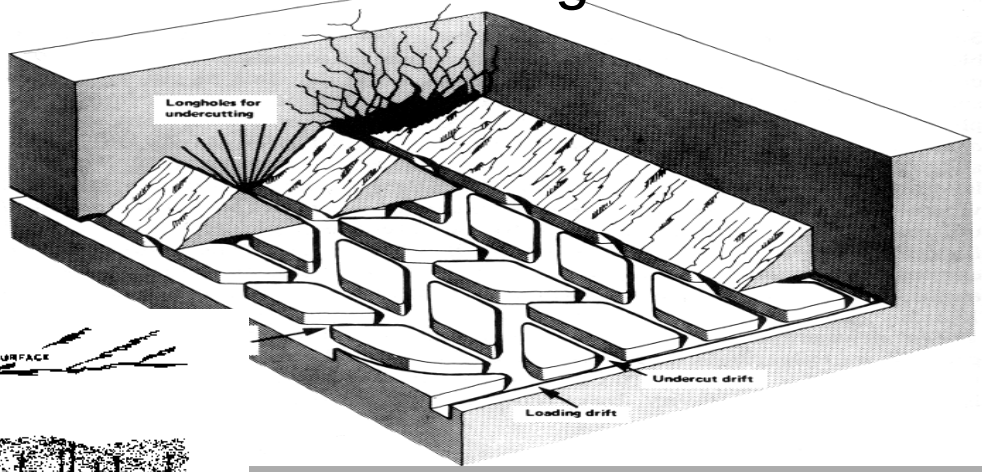
System of Draw

Gravity draw



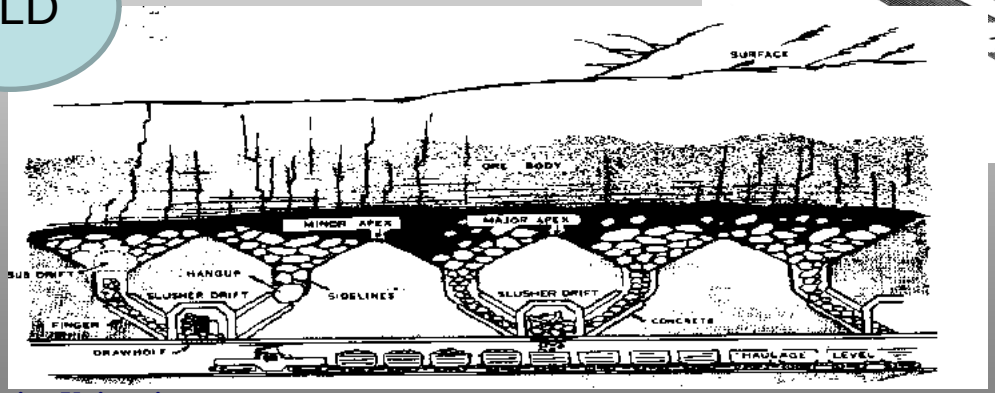


Draw Drift Loading – LHD fleet

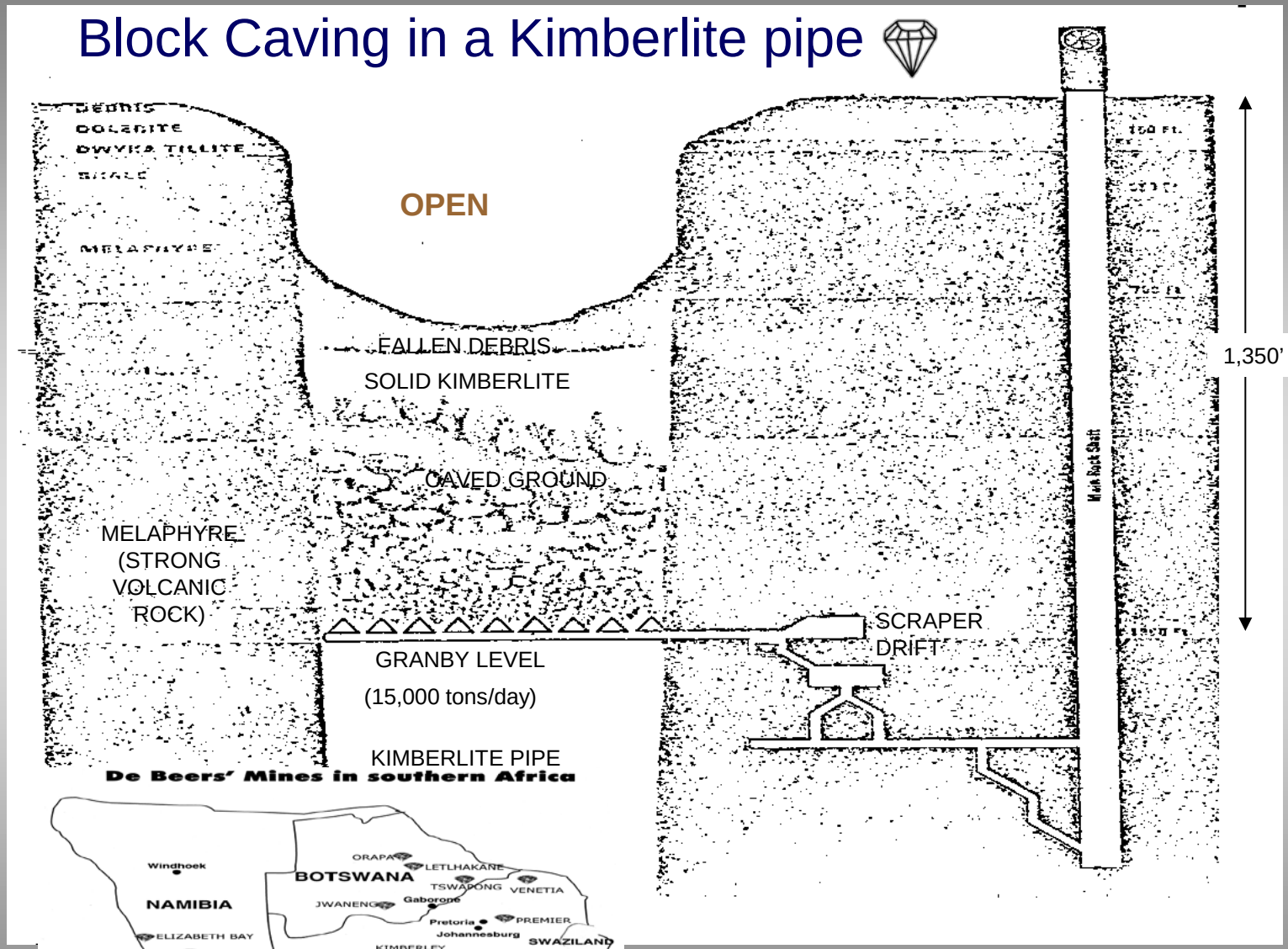


Slusher

OLD



Block Caving in a Kimberlite pipe

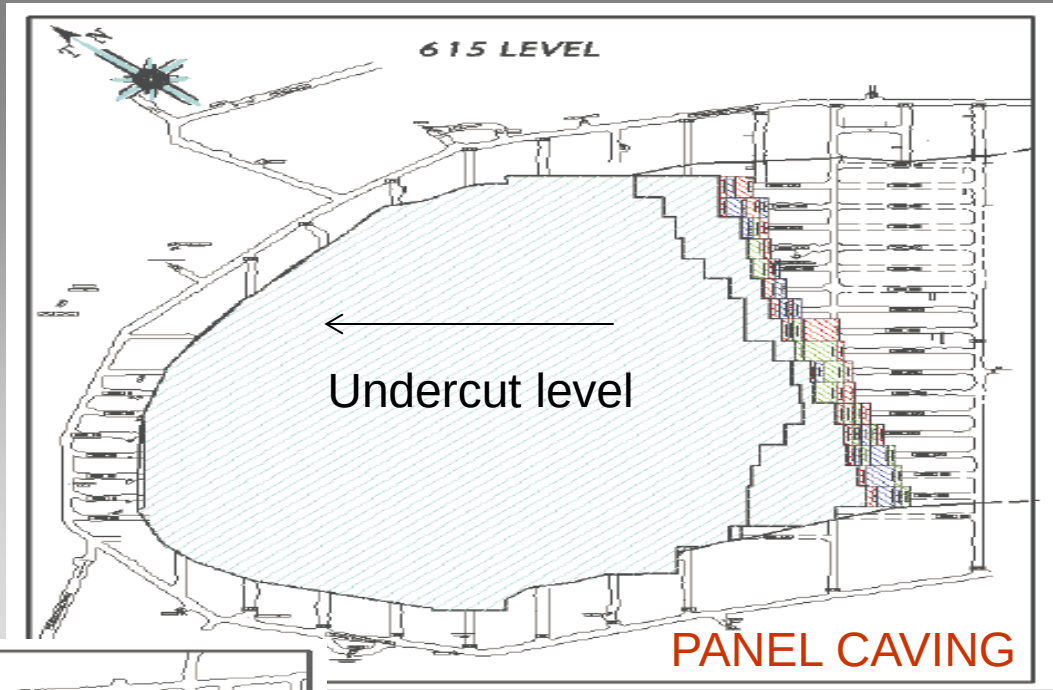


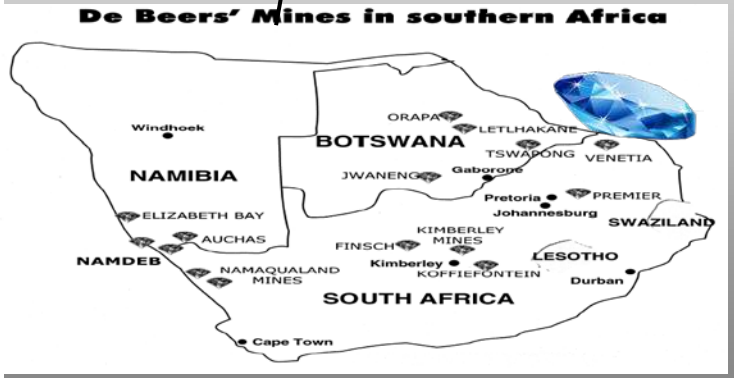
Premier diamond mine, SA

(Bartlett & Croll, 2001)

Levels
- Undercut (top)
- Extraction - production
- Haulage (bottom)

Production (extraction) level

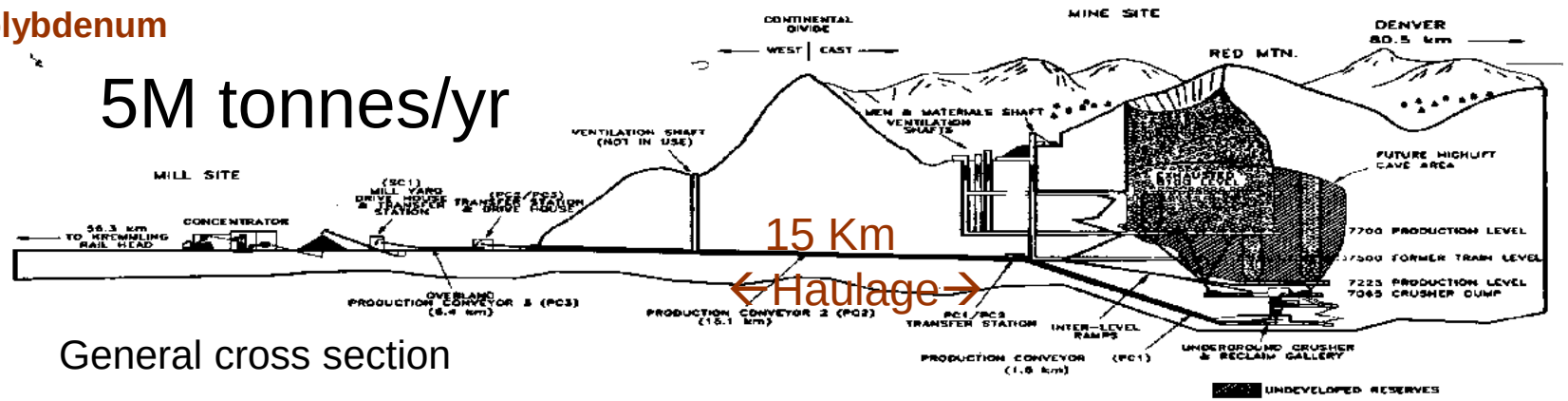




Henderson Mine & Mill Nevada, USA

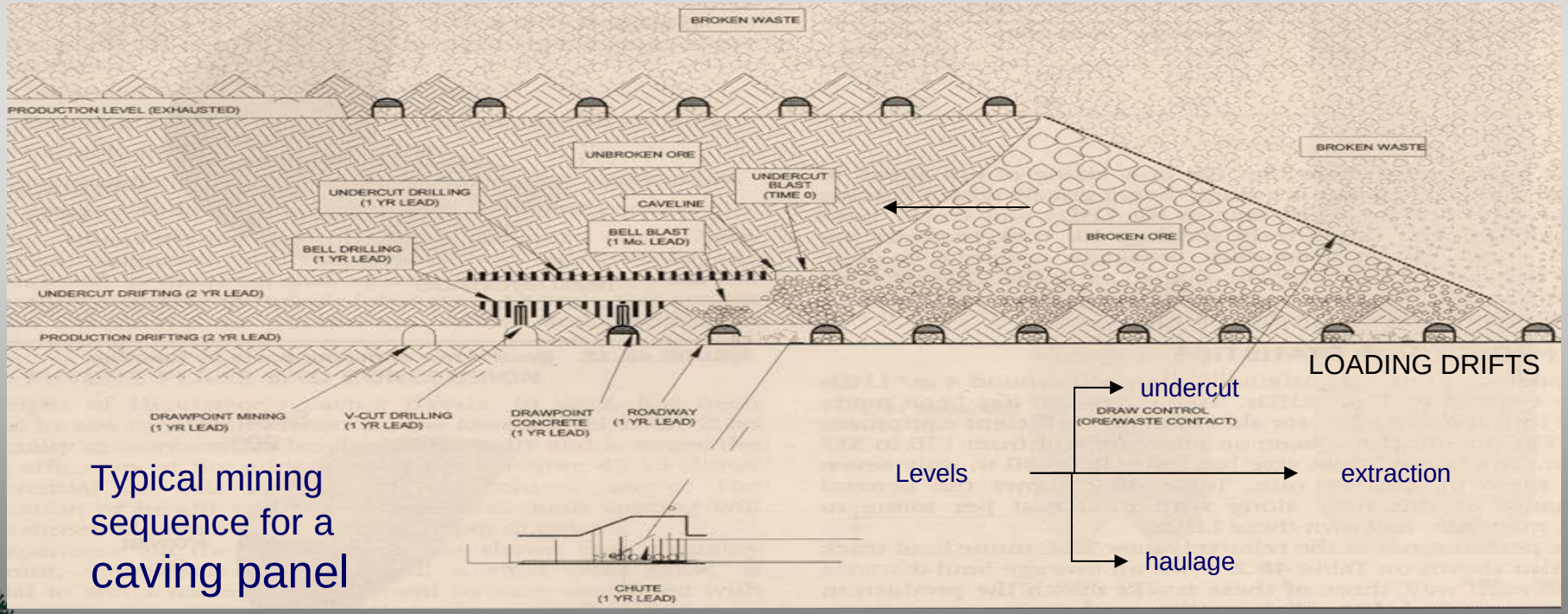
Molybdenum

5M tonnes/yr



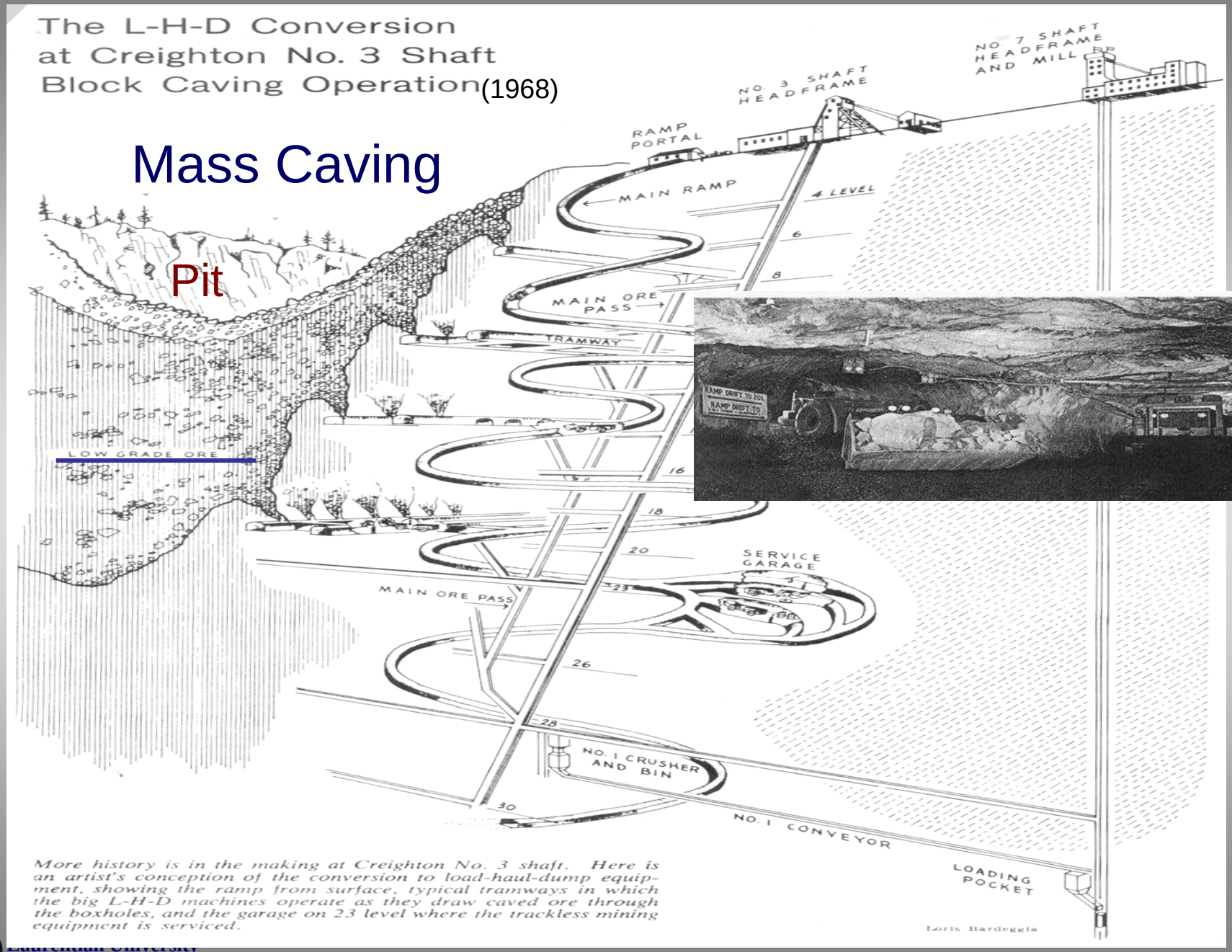
15 Km
←Haulage→

General cross section



Typical mining sequence for a caving panel

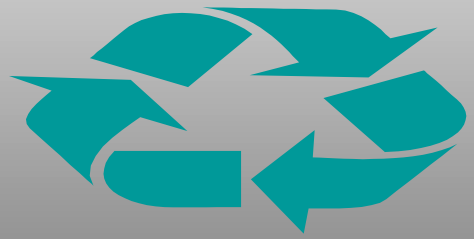
Mass Caving



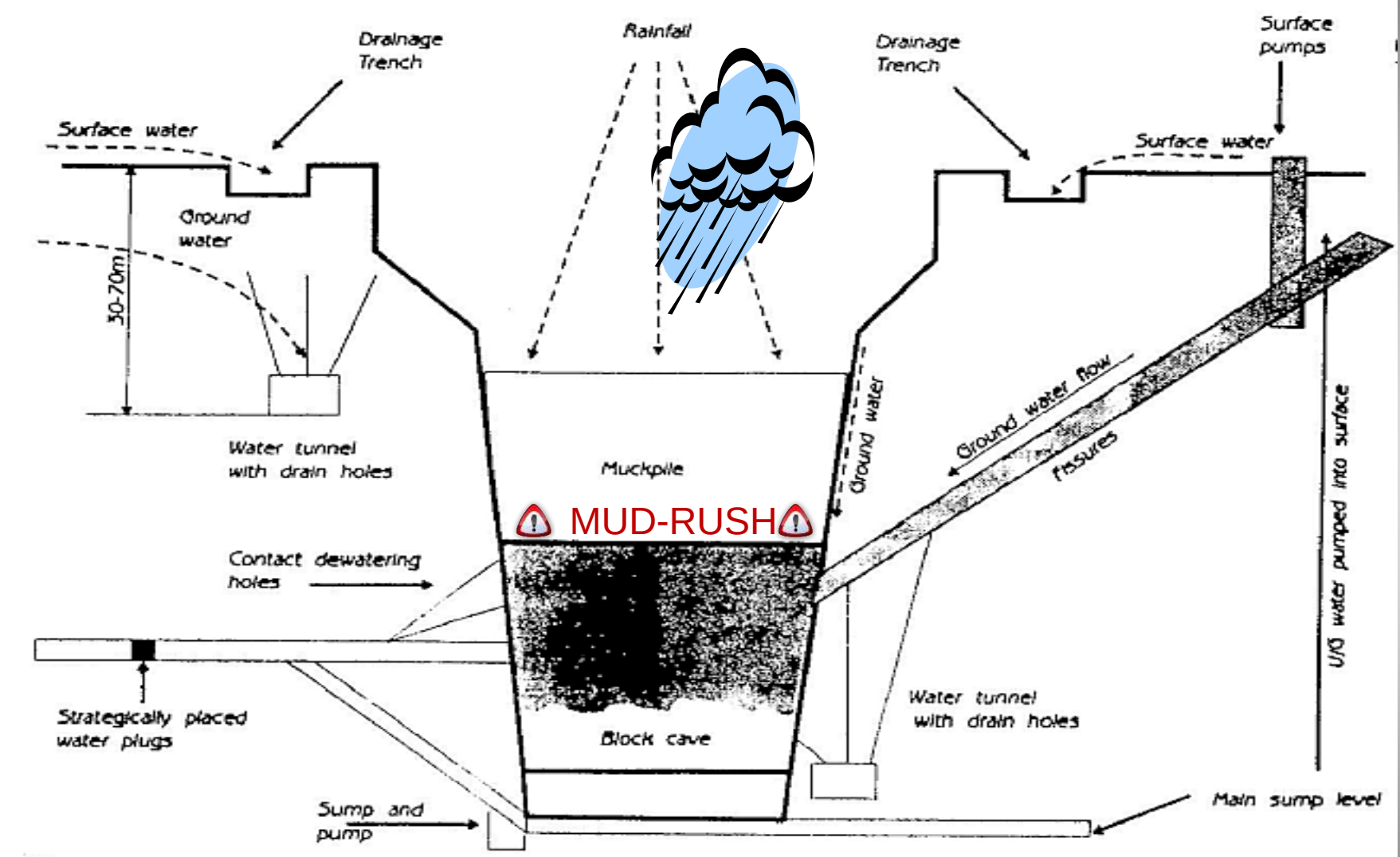
More history is in the making at Creighton No. 3 shaft. Here is an artist's conception of the conversion to load-haul-dump equipment, showing the ramp from surface, typical tramways in which the big L-H-D machines operate as they draw caved ore through the boxholes, and the garage on 23 level where the trackless mining equipment is serviced.

Block Caving Cycle of Operations

- Development *(drill, blast, load, haul)*
  Levels, crosscuts, draw bells, cones, fingers, passes
- Undercutting (fan drilling & blasting)
- Cave - Secondary blasting (<50% rule)
- Mucking (gravity flow & chute control)
- Hauling
- Crushing
- Hoisting or hauling



Water inflow management (mud-rush danger!)



Water inflow in a block caving operation (Butcher, 2000)

Block Caving Design parameters

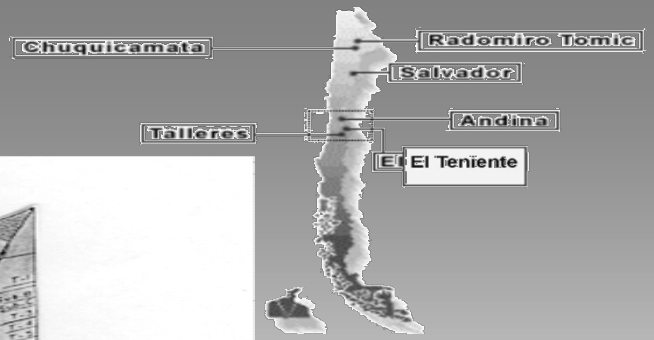
- Production Requirmnts
- Cavability
- Primary Fragment.
- Drift spacing
- Drawpoint interaction
- Draw zone spacing/pillar
- Drilling & blasting
- Hauling
- Crushing
- Layout
- Logistics
- Excavation stability
- Method of Draw
- Draw heights
- Sequence – rate of draw
- Ventilation
- Undercutting sequence
- Tonnage drawn
- Fragmentation size range
- Rockburst potential
- Induced stresses
- Support & rehabilitation drawpoint/drift/pass
- Ore extraction – dilution
- Ground subsidence
- Adjacent openings
- Water management

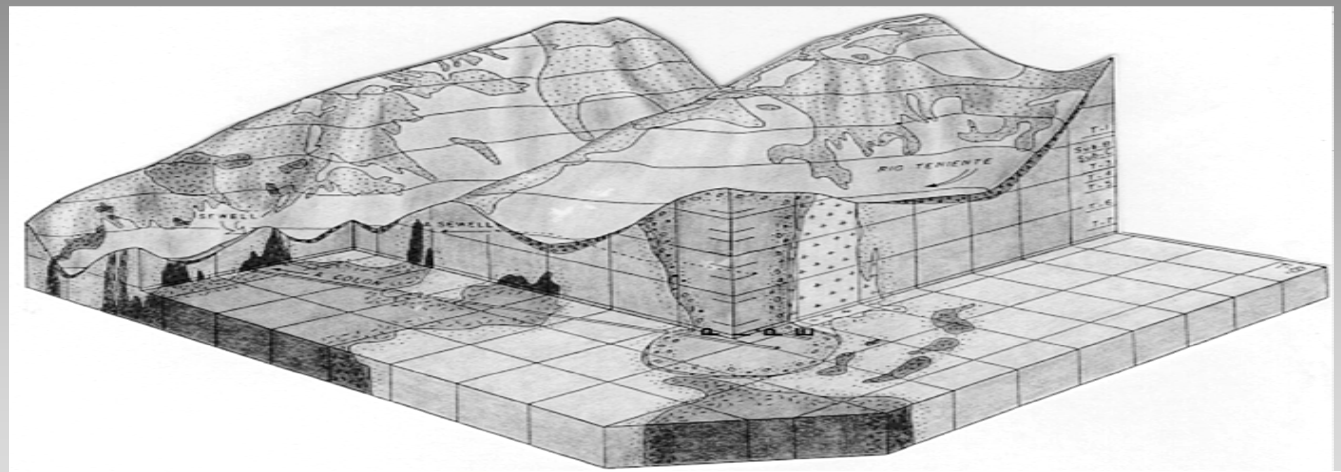
(Laubscher, 2001)

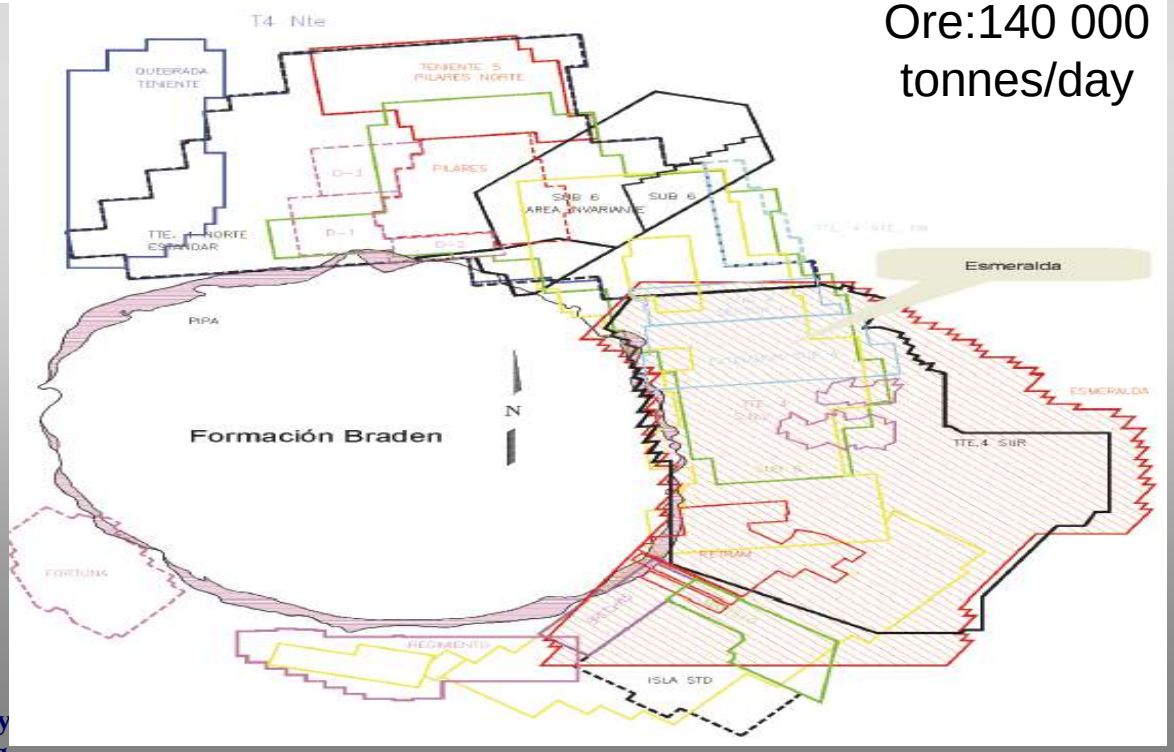
Block Caving Operating problems

- Operating complexity
- Air blasts
- Hang ups - premature collapses (U/C, draw point, ore pass)
- Oversize - secondary blasting requirements
- Caving & fragmentation prediction & control
- Recovery
- Dilution
- Water inflow
- Stresses/Displacmnts
- Rockbursts - seismicity
- Support-Rehabilitation
- Orepass, Drift, Drawpoint, Grizzly integrity
- Equipment performance
- Operating control
- Subsidence
- Mud/muck rushes
- Ventilation air loss
- LHD fleet management

El-Teniente Mine



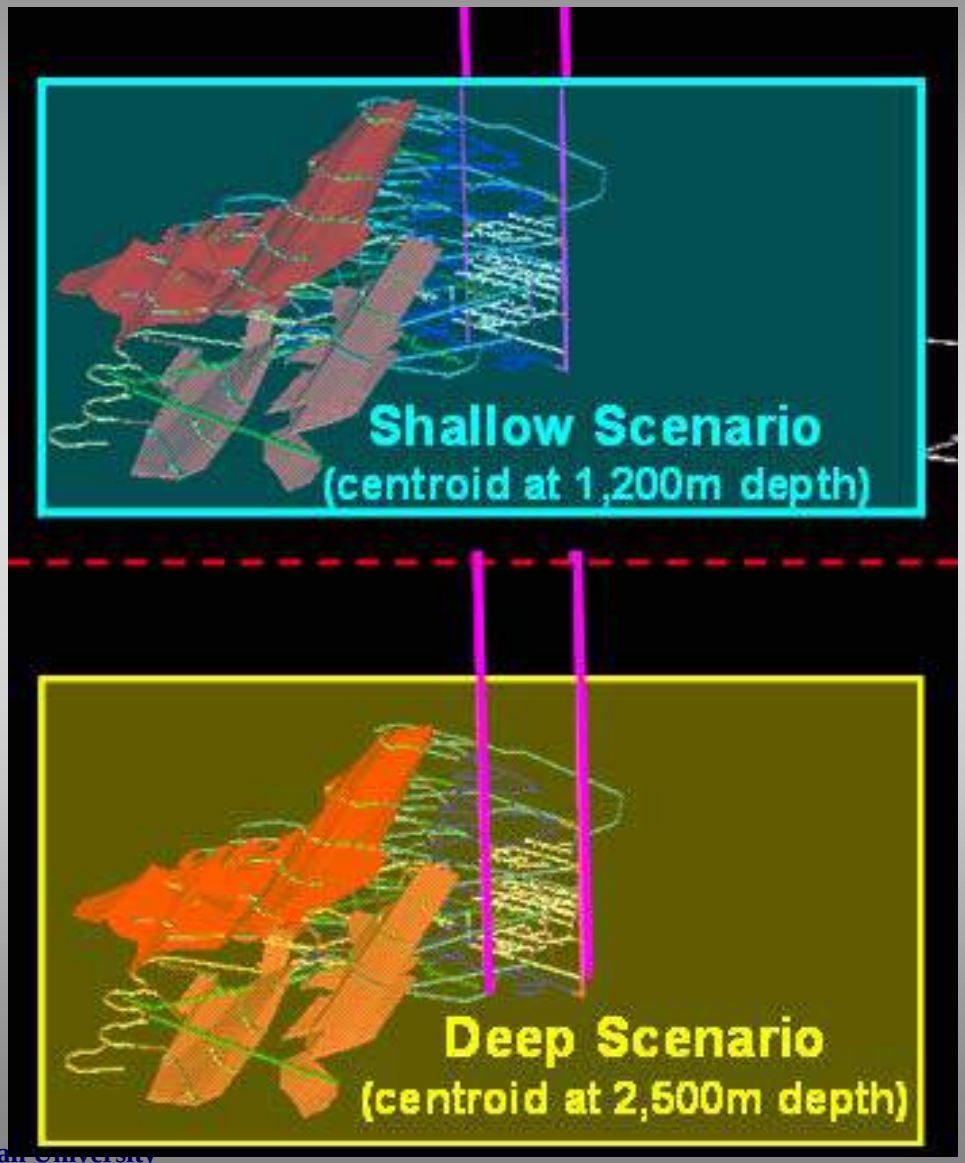




Ore:140 000 tonnes/day

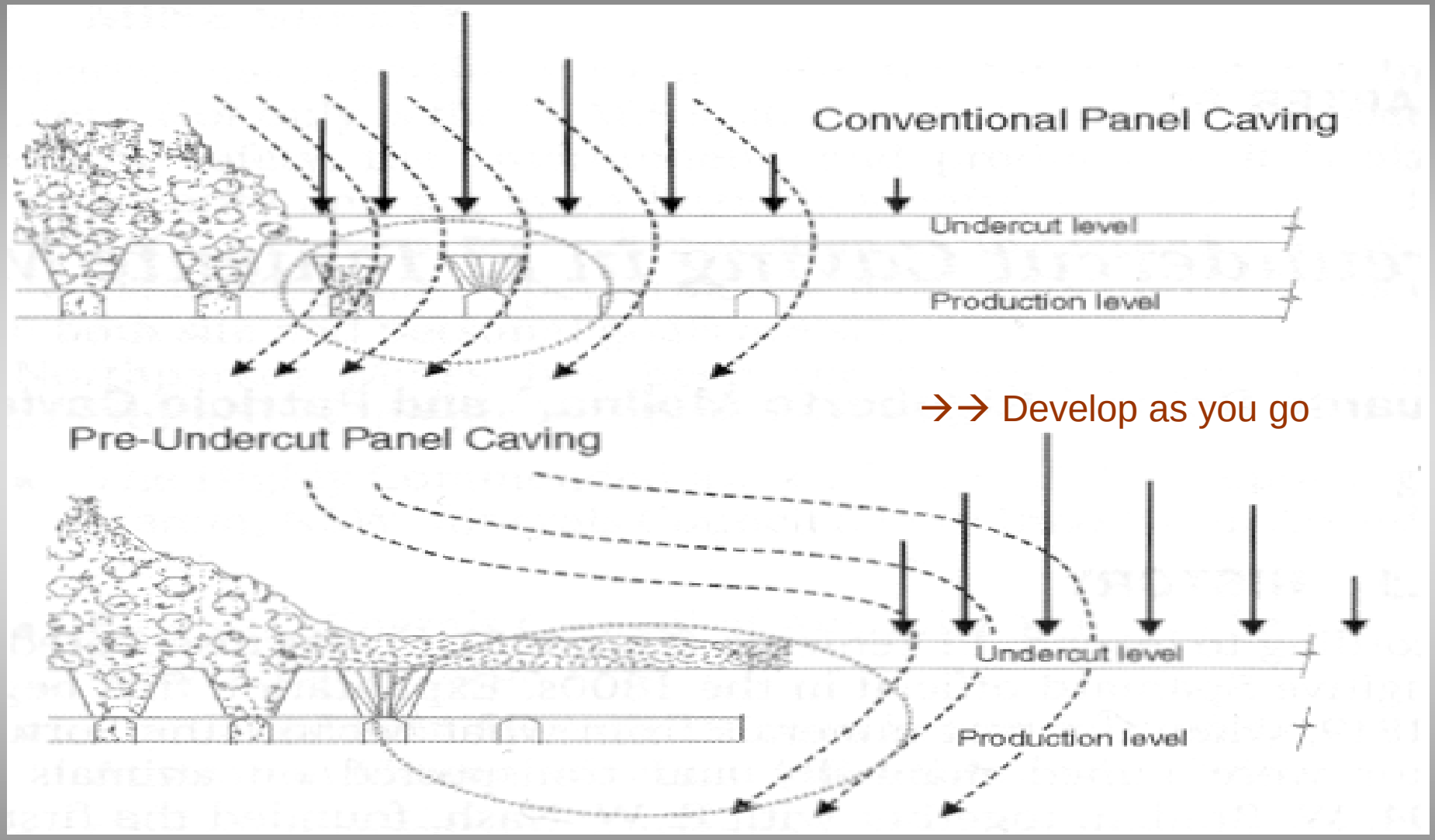
DEEP MINING

Operating Challenges



- Access
- Depth – ground conditions
- Seismicity
- Heat Stress and ventilation
- Cost – capex, operating delays & logistics in BFS

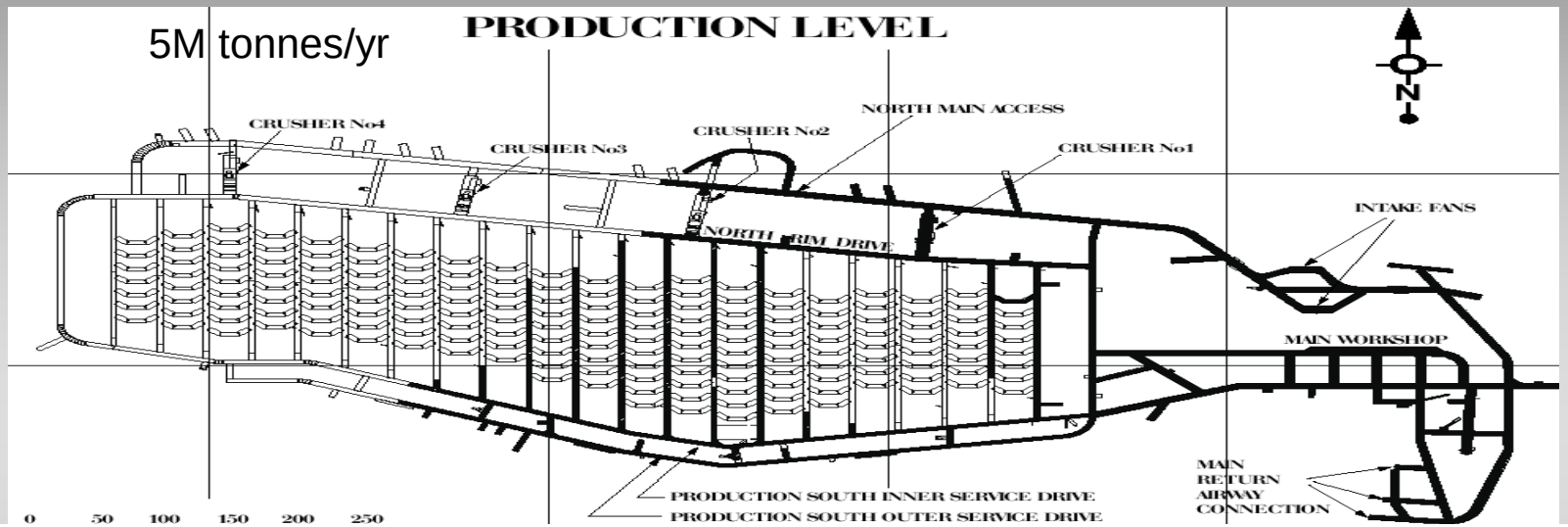
Evolution of U/C design at El-Teniente Mine

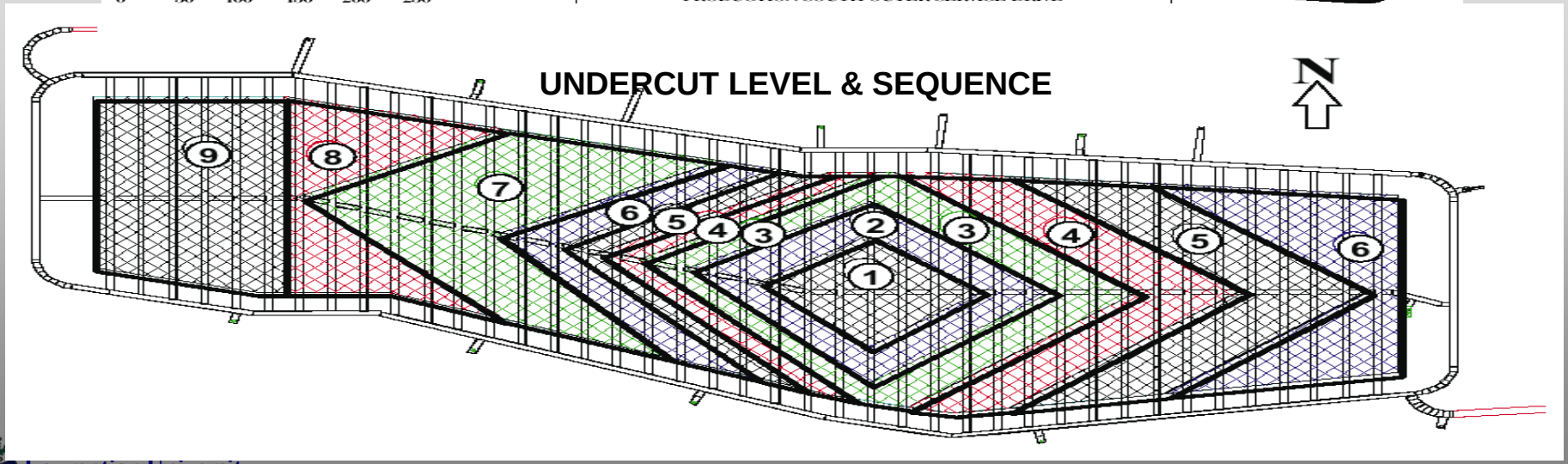


High regional stresses, large displacements, rock bursts

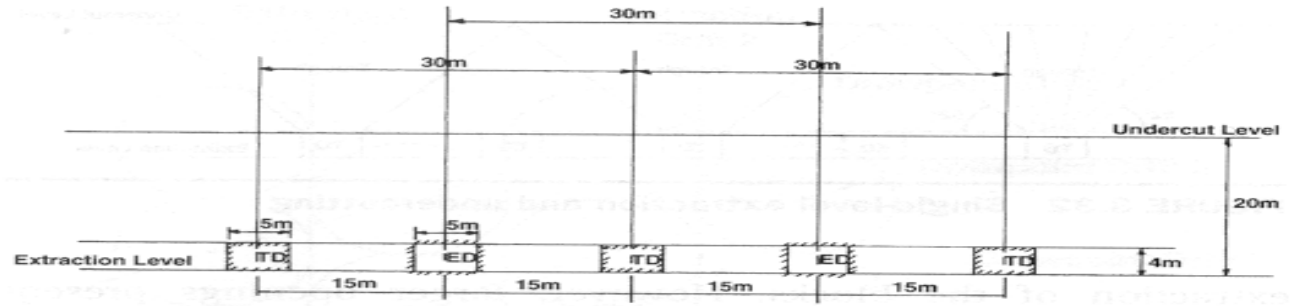
Mining sequence at Henderson Mine

GLORY HALL

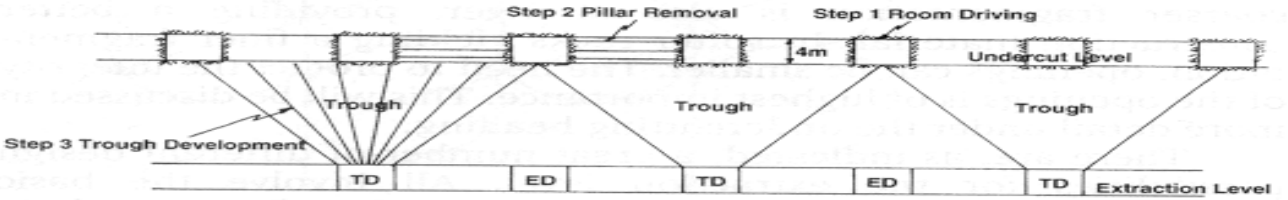




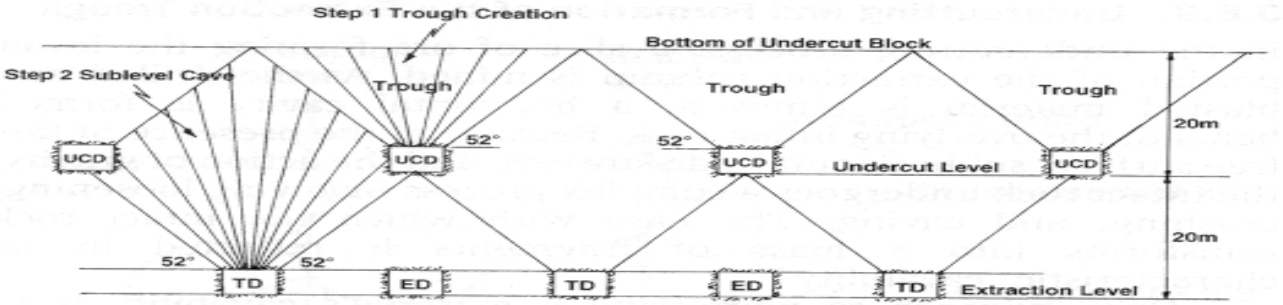
UNDERCUTTING METHODS



Separate level undercutting and extraction



Undercutting and trough development



Two-level undercutting

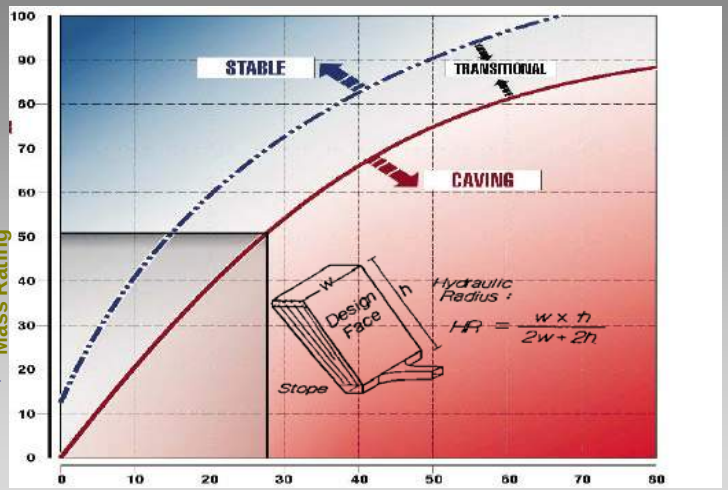
When will it cave?

Cavability as a function of
rock mass conditions &
hydraulic radius

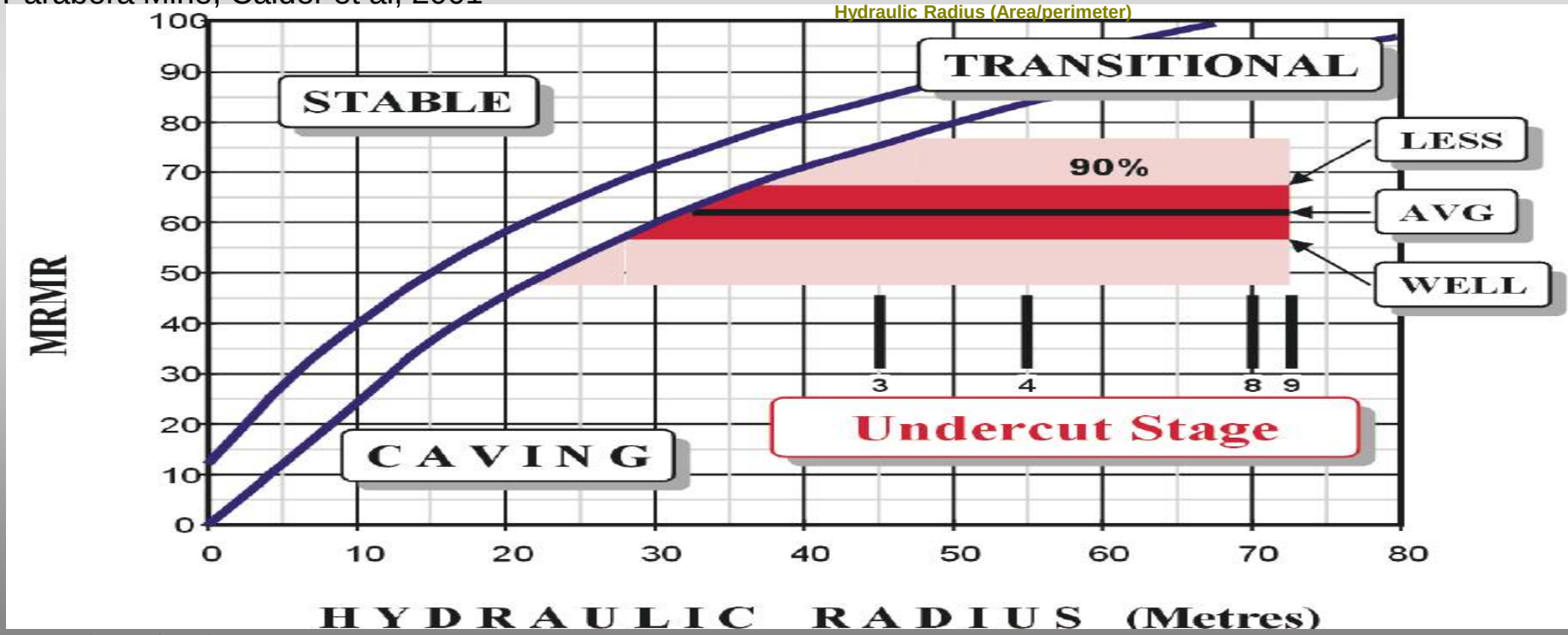
Example

$$HR = \frac{w \times h}{2w + 2h}$$

Stability Diagram (Laubscher, 1994)



Parabora Mine, Calder et al, 2001



Contents

A. Principles

B. Variations & Examples

C. Design Issues (safety + environmental + regional stewardship)

D. Operating Issues

E. Optimization

- o Design
- o Operating
- o Economics
- o Bottom line

F. Delay-impact Example

G. Video

i. Recovery
ii. Dilution
iii. Grade
iv. Tonnage
v. Cost
vi. Time
vii. Resources utilization
viii. Delay impact
ix. Return on investment, $, %
x. Flexibility/robustness/risk
xi. Contingency

Criteria for decision making in project valuation & optimization

Optimization, Risk Mitigation & Risk Management under uncertainty

Environmental issues

Design issues

Operating issues

Economic issues

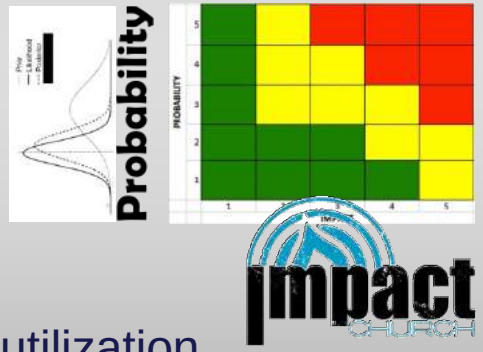
DEBOTTLENECKING
LIFE CYCLE REDUCTION

Production Planning needs

- Geological model
- Geomechanics model
- Fragmentation model
- Reconciliation model

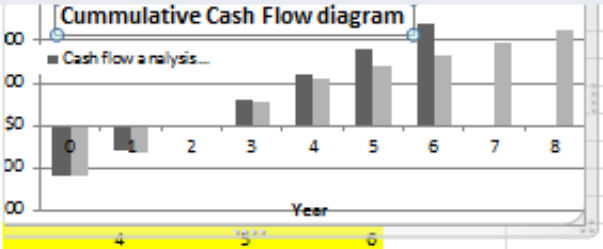
Consider the impact of risk on:

i. Recovery
ii. Dilution
iii. Grade
iv. Tonnage
v. Cost
vi. Time
vii. Resources utilization
viii. Delays
ix. Return on investment, $, %
x. Flexibility/robustness/risk
xi. Contingency



Delays - Impact Example

FIXED COST			7000000									
VARIABLE COST/ton			80									
REVENUE/ton			130									
OREBODY SIZE (tons)			6000000									
inflation			9%									
Discount rate %			12%									
Cashflow analysis #1												
PRODUCTION RATE (t/yr)				1.000.000	1.000.000							
		year	0	1	2	3	4	5	6			
revenue($)				141700000	154453000	168353770	183505609	200021114	218023014			
fixed costs($)				7630000	8316700	9065203	9881071,3	10770368	11739701			
variable costs($)				87200000	95048000	103602320	112926529	123089916	134168009			
net operating income($)				46870000	51088300	55686247	60698009	66160830	72115305			
CCA (straight line depreciation)				13333333	13333333	13333333	13333333	13333333	13333333			
taxable revenue				33536667	37754967	42352914	47364676	52827497	58781971			
taxes @40%				13414667	15101987	16941165	18945870	21130999	23512789			
after tax profit				20122000	22652980	25411748	28418806	31696498	35269183			
cashflow(current)			-80000000	33455333	35986313	38745082	41752139	45029831	48602516			
cashflow(const.)			-80000000	30692966	30288960	29918312	29578268	29266301	28980092			
cummul cash flow			-80000000	-49307034	-19018074	10900238	40478506	69744807	98724899			
NPV=			$42.932.097									
IRR=			30%									
cashflow analysis #2												
PRODUCTION RATE (t/yr)				1.000.000	1.000.000	1.000.000	1.000.000	500.000	500.000	500.000	500.000	
		year	0	1	2	3	4	5	6	7	8	
revenue				141700000	154453000	168353770	183505609	100010557	109011507	118822543	129516572	
fixed costs				7630000	8316700	9065203	9881071,3	10770368	11739701	12796274	13947938,5	
variable costs				87200000	95048000	103602320	112926529	61544958	67084004	73121565	79702505,7	
net operating income				46870000	51088300	55686247	60698009	27695231	30187802	32904704	35866127,6	
CCA (straight line depreciation)				10000000	10000000	10000000	10000000	10000000	10000000	10000000	10000000	
taxable revenue				36870000	41088300	45686247	50698009	17695231	20187802	22904704	25866127,6	
taxes @40%				14748000	16435320	18274499	20279204	7078092,5	8075120,8	9161881,7	10346451	
after tax profit				22122000	24652980	27411748	30418806	10617139	12112681	13742823	15519676,5	
cashflow			-80000000	32122000	34652980	37411748	40418806	20617139	22112681	23742823	25519676,5	
cashflow (const)			-80000000	29469725	29166720	28888734	28633701	13399726	13185069	12988137	12807465,1	
cummul cash flow			-80000000	-50530275	-21363555	7525178,7	36158880	49558605	62743674	75731811	88539276,5	
NPV=			$33.654.674									
IRR=			26%									



Block Caving Video

A visualization of the block caving method of underground mining

http://www.miningaustralia.com.au/news/catlaunchesnewblockcavingorehandlingsystem

http://www.infomine.com/library/videos/3375c0/block_caving.aspx

http://www.ukessays.com/essays/management/the-block-cave-mining-method-management-essay.php

→ BC optimization of the KSM project
https://www.youtube.com/watch?v=oYc47CLOnGs

DEBOTTLENECKING & OPTIMIZATION:
http://www.stratusengr.com/Articles/DebottleOptions.pdf