Literature Review to Identify Techniques for Mining Method Selection
Resolution Copper EIS

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Introduction

- A literature review was conducted to identify classical references for mining method selection in response to action item #GS-3 (Resolution Geology/Subsidence Working Group Meeting 2/11/2020).
- Selection of a feasible mining method requires the comparison of the characteristics of the deposit with those essential for different mining methods
- In general, most selection techniques deal primarily with:

1. The physical and geologic characteristics of the deposit
2. The ground conditions of the hanging wall, footwall and ore zone

Selection Method Techniques

- A literature review was performed to identify techniques for mining method selection
- The following are common classical references for mining method selection:

1. Boshkov and Wright
2. Hartman
3. Morrison
4. Laubscher
5. Nicholas
6. KDI & KMI

Boshkov and Wright

- The classification system proposed by Boskov and Wright (1973) is one of the first qualitative classification schemes developed for underground method selection. Therefore, their system assumes that the possibility of surface mining has already been eliminated.
- The results of this classification scheme results in four methods that may be applicable.

Table 23.4.1. Applications of Underground Mining Methods

Type of Ore Body	Dip	Strength of Ore	Strength of Walls	Commonly Applied Methods of Mining
Thin beds	Flt	Stg	Stg	Open stopes with casual pillars Room and pillar Longwall
		Wk or Stg	Wk	Longwall
Thick beds	Flt	Stg	Stg	Open stopes with casual pillars Room and pillar
		Wk or Stg	Wk	Top slicing Sublevel caving
		Wk or Stg	Stg	Underground glory hole
Very thick beds				Same as for masses
Very narrow veins	Stp	Stg or Wk	Stg or Wk	Resuing
Narrow veins (widths up to economic length of stull)	Flt Stp	Stg	Stg	Same as for thin beds Open stopes Shrinkage stopes Cut and fill stopes
			Wk	Cut and fill stopes Square set stopes
		Wk	Stg	Open underhand stopes Square set stopes
			Wk	Top slicing Square set stopes
Wide veins	Flt Stp	Stg	Stg	Same as for thick beds or masses Open underhand stopes Underground glory hole Shrinkage stopes Sublevel stoping Cut and fill stopes Combined methods
			Wk	Cut and fill stopes Top slicing Sublevel caving Square set stope Combined methods
		Wk	Stg	Open underhand stopes Top slicing Sublevel caving Block caving Square set stopes Combined methods
			Wk	Top slicing Sublevel caving Square set stopes Combined methods
Masses		Stg	Stg	Underground glory hole Shrinkage stopes Sublevel stoping Cut and fill Combined methods
		Wk	Wk or Stg	Top slicing Sublevel caving Block caving Square set stopes Combined methods

Wk = weak; stg = strong; flt = flat; stp = steep.
Source: Boshkov and Wright, 1973 (permission: Society for Mining, Metallurgy, and Exploration, Inc.).

Hartman

- Hartman (1987) developed a flow chart selection process to identify the mining method based on the geometry of the deposit and the ground conditions of the ore zone. This system is similar to the Boshkov and Wright method but is aimed at more specific mining methods.

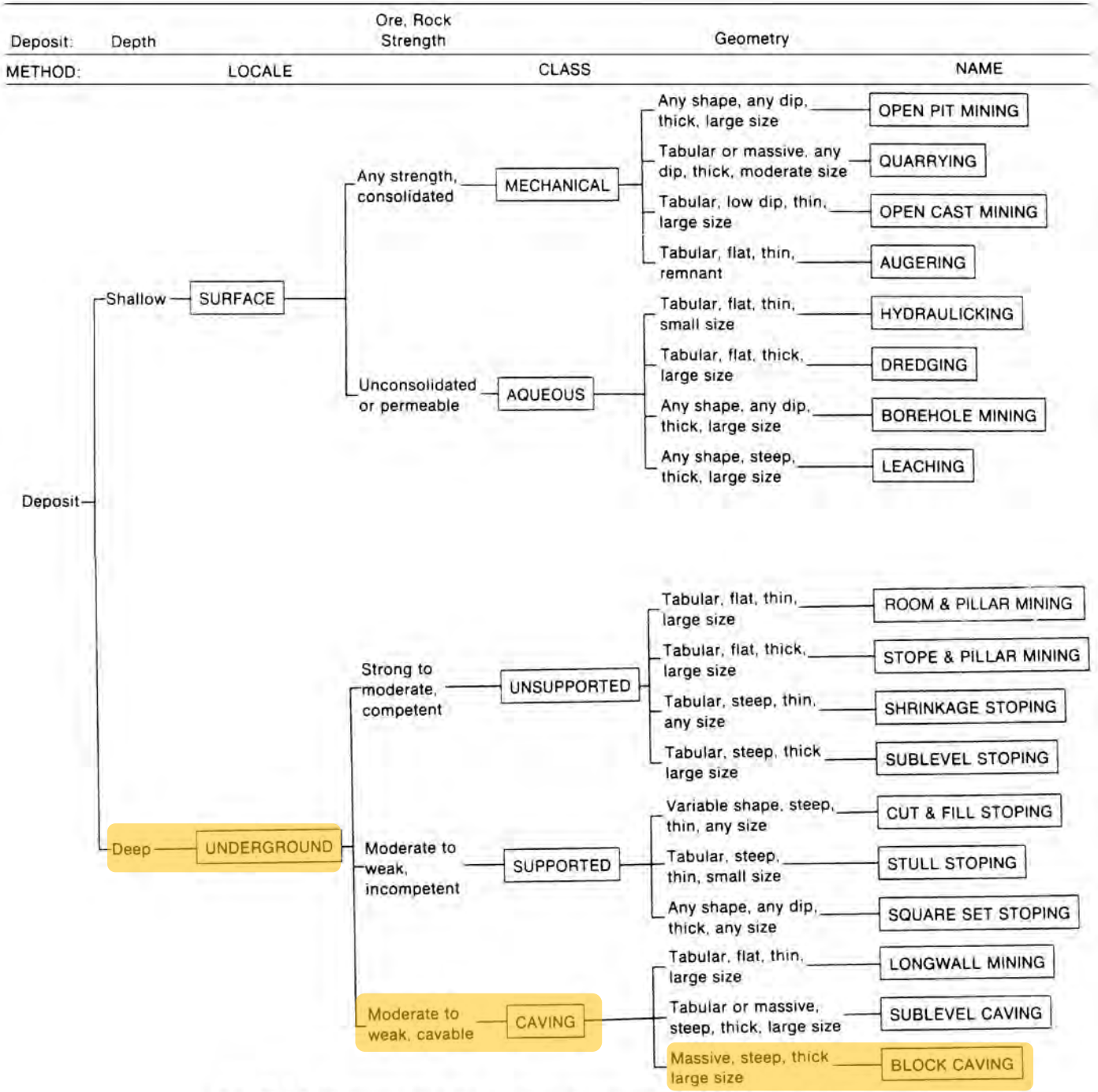


Fig. 23.4.1. Hartman's chart for selection of a mining method (Hartman, 1987).

Morrison

- Morrison (1976) developed a system using general definitions of ore width, support type and strain energy accumulation

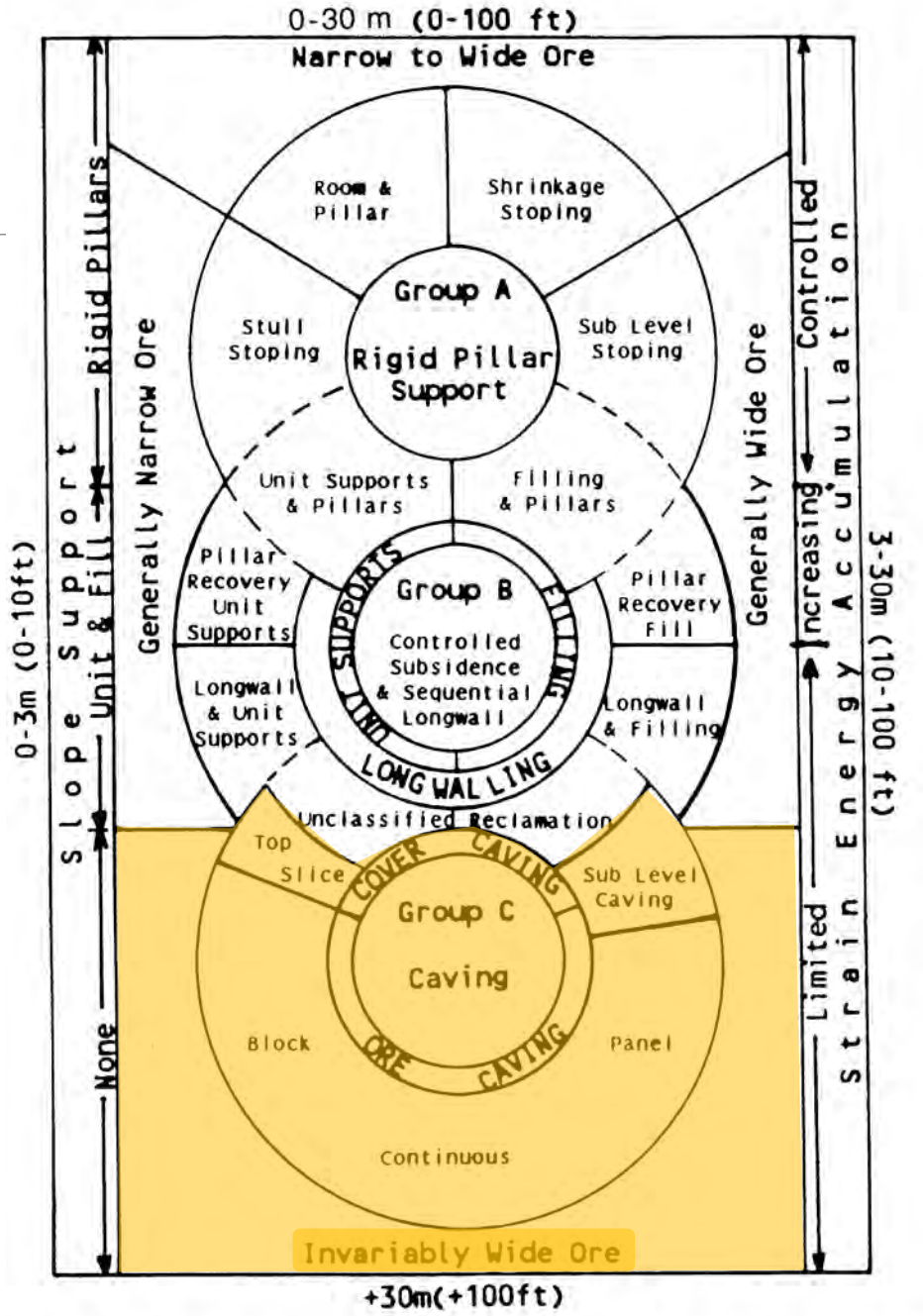
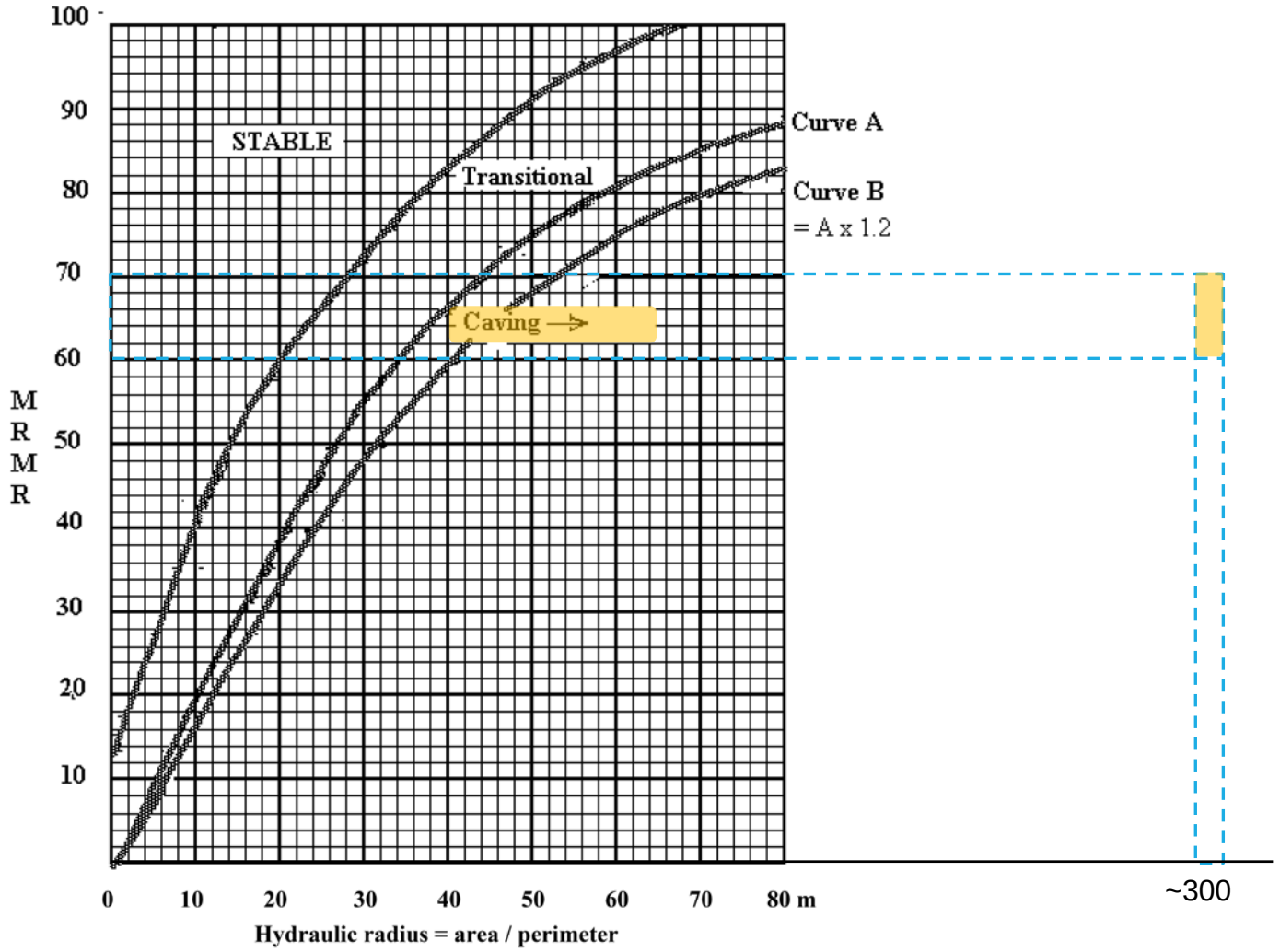


Fig. 23.4.2. Morrison's chart for selection of a mining method (Morrison, 1976).

Laubscher

- Laubscher (1981, 1990) developed a selection process based on his rock mass classification system. Laucher's scheme is aimed at mass mining methods, primarily block caving vs stoping, with his main emphasis being on caveability.



Nicholas

- Nicholas (1981) developed a quantitative classification system. The system relies on a series of steps that classify:

1. The ore geometry and grade distribution
2. The rock mechanics characteristics of the ore zone, HW and FW
3. Numerical ranking based on addition of scores
4. Using a weighting factor of the categories

Table 23.4.2. Definition of Deposit Geometry and Grade Distribution

1) *General Shape/Width*		
	equi-dimensional	all dimensions are on the same order of magnitude
	platy—tabular	two dimensions are many times the thickness, which does not usually exceed 325 ft (100 m)
	irregular	dimensions vary over short distances
2) *Ore Thickness*		
	narrow	<30 ft (<10 m)
	intermediate	30–100 ft (10–30 m)
	thick	100–325 ft (30–100 m)
	very thick	>325 ft (>100 m)
3) *Plunge*		
	flat	<20°
	intermediate	20°–55°
	steep	>55°
4) *Depth Below Surface*		
	provide actual depth	
5) *Grade Distribution*		
	Uniform. The grade at any point in the deposit does not vary significantly from the mean grade for that deposit.	
	Gradational. Grade values have zonal characteristics, and the grades change gradually from one to another.	
	Erratic. Grade values change radically over short distances and do not exhibit any discernible pattern in their changes.	

Source: Nicholas, 1981.

Table 23.4.3. Rock Mechanics Characteristics

1) *Rock Substance Strength* (uniaxial strength/overburden pressure)			
	weak	<8	
	moderate	8–15	
	strong	>15	
2) *Fracture Frequency*			
	No. of Fractures per (ft)	(m)	% RQD
	very close	>5	>16	0– 20
	close	3–5	10–16	20– 40
	wide	1–3	3–10	40– 70
	very wide	<1	<3	70–100
3) *Fracture Shear Strength*			
	weak	clean joint with a smooth surface or fill with material with strength less than rock substance strength	
	moderate	clean joint with rough surface	
	strong	joint is filled with a material that is equal to or stronger than rock substance strength	

Sources: Nicholas, 1981.

Nicholas cont'd

Table 23.4.4. Ranking of Geometry/Grade Distribution for Different Mining Methods

Mining Method	General Shape			Ore Thickness				Ore Plunge			Grade Distribution		
	M	T/P	I	N	I	T	VT	F	I	S	U	G	E
Open Pit Mining	3	2	3	2	3	4	4	3	3	4	3	3	3
Block Caving	4	2	0	−49	0	2	4	3	2	4	4	2	0
Sublevel Stoping	2	2	1	1	2	4	3	2	1	4	3	3	1
Sublevel Caving	3	4	1	−49	0	4	4	1	1	4	4	2	0
Longwall Mining	−49	4	−49	4	0	−49	−49	4	0	−49	4	2	0
Room and Pillar Mining	0	4	2	4	2	−49	−49	4	1	0	3	3	3
Shrinkage Stoping	2	2	1	1	2	4	3	2	1	4	3	2	1
Cut and Fill Stoping	0	4	2	4	4	0	0	0	3	4	3	3	3
Top Slicing	3	3	0	−49	0	3	4	4	1	2	4	2	0
Square Set Stoping	0	2	4	4	4	1	1	2	3	3	3	3	3

M = Massive
T/P = Tabular or Platy
I = Irregular

N = Narrow
I = Intermediate
T = Thick
VT = Very Thick

F = Flat
I = Intermediate
S = Steep

U = Uniform
G = Gradational
E = Erratic

ing of Rock Mechanics Characteristics for Different Mining Methods

5b: Hanging Wall

Mining Method	Rock Substance Strength			Fracture Spacing				Fracture Strength		
	W	M	S	VC	C	W	VW	W	M	S
Open Pit Mining	3	4	4	2	3	4	4	2	3	4
Block Caving	4	2	1	3	4	3	0	4	2	0
Sublevel Stoping	−49	3	4	−49	0	1	4	0	2	4
Sublevel Caving	3	2	1	3	4	3	1	4	2	0
Longwall Mining	4	2	0	4	4	3	0	4	2	0
Room and Pillar Mining	0	3	4	0	1	2	4	0	2	4
Shrinkage Stoping	4	2	1	4	4	3	0	4	2	0
Cut and Fill Stoping	3	2	2	3	3	2	2	4	3	2
Top Slicing	4	2	1	3	3	3	0	4	2	0
Square Set Stoping	3	2	2	3	3	2	2	4	3	2

Key:

Rock Substance Strength
W = Weak
M = Moderate
S = Strong

Fracture Spacing
VC = Very Close
C = Close
W = Wide
VW = Very Wide

Fracture Strength
W = Weak
M = Moderate
S = Strong

Nicholas cont'd

5a: Ore Zone

Mining Method	Rock Substance Strength			Fracture Spacing				Fracture Strength		
	W	M	S	VC	C	W	VW	W	M	S
Open Pit Mining	3	4	4	2	3	4	4	2	3	4
Block Caving	4	1	1	4	4	3	0	4	3	0
Sublevel Stoping	−49	3	4	0	0	1	4	0	2	4
Sublevel Caving	0	3	3	0	2	4	4	0	2	2
Longwall Mining	4	1	0	4	4	0	0	4	3	0
Room and Pillar Mining	0	3	4	0	1	2	4	0	2	4
Shrinkage Stoping	1	3	4	0	1	3	4	0	2	4
Cut and Fill Stoping	3	2	2	3	3	2	2	3	3	2
Top Slicing	2	3	3	1	1	2	4	1	2	4
Square Set Stoping	4	1	1	4	4	2	1	4	3	2

5c: Footwall

Mining Method	Rock Substance Strength			Fracture Spacing				Fracture Strength		
	W	M	S	VC	C	W	VW	W	M	S
Open Pit Mining	3	4	4	2	3	4	4	2	3	4
Block Caving	2	3	3	1	3	3	3	1	3	3
Sublevel Stoping	0	2	4	0	0	2	4	0	1	4
Sublevel Caving	0	2	4	0	1	3	4	0	2	4
Longwall Mining	2	3	3	1	2	4	3	1	3	3
Room and Pillar Mining	0	2	4	0	1	3	3	0	3	3
Shrinkage Stoping	2	3	3	2	3	3	2	2	2	3
Cut and Fill Stoping	4	2	2	4	4	2	2	4	4	2
Top Slicing	2	3	3	1	3	3	3	1	2	3
Square Set Stoping	4	2	2	4	4	2	2	4	4	2

Table 23.4.6. Weighting Factors

Ore Geometry	1.0	1.0	1.0
Ore Zone Ground Conditions	1.33	0.75	1.0
Hanging Wall Ground Conditions	1.33	0.6	0.8
Footwall Ground Conditions	1.33	0.38	0.5

Nicholas cont'd

Mining Method	Geometry/Grade Distribution	Rock Mechanics Characteristics									Total un-weighted			**Grand Total**		
		Ore			HW			FW								
Open Pit Mining	14	10	to	11	10	to	11	10	to	11	44	to	47	**37**	**to**	**39.3**
Block Caving	16	10	to	7	9	to	7	8	to	9	43	to	39	**37.2**	**to**	**33.1**
Sublevel Stoping	12	-46	to	6	-46	to	6	3	to	5	-77	to	29	**-69.3**	**to**	**25.3**
Sublevel Caving	15	6	to	9	8	to	7	5	to	7	34	to	38	**29.9**	**to**	**33.1**
Longwall Mining	-143	7	to	4	9	to	7	9	to	10	-118	to	-122	**-124.3**	**to**	**-128.4**
Room and Pillar Mining	-46	4	to	7	4	to	7	6	to	8	-32	to	-24	**-35.8**	**to**	**-29.4**
Shrinkage Stoping	12	6	to	8	9	to	7	7	to	8	34	to	35	**28.7**	**to**	**29.6**
Cut and Fill Stoping	7	8	to	7	8	to	7	10	to	8	33	to	29	**26.4**	**to**	**23.6**
Top Slicing	13	6	to	7	9	to	7	7	to	8	35	to	35	**29.7**	**to**	**29.6**
Square Set Stoping	7	9	to	6	8	to	7	10	to	8	34	to	28	**27.4**	**to**	**22.6**

KDI & KMI

- Nieto (2010) developed a selection method based on defined field key deposit indicators (KDI) and comparing them to the KDIs that are favorable to a series of mining methods considered.
- Key mining method indicators (KMI) are used to further complement KDI rankings by analyzing every method's KMI performance based on the expected productivity of the mining operation being considered.
- This method was modified after Harmann and Mutmansky, 2002)

Table 1 — Ore strength KDI definitions (Hartmann & Mutmansky).

Relative strength	Example material	Compressive strength (psi)	KDI value
Very weak	Coal	< 6,000	1
Weak	Weathered sandstone	6,000 – 14,500	1-2
Moderate	Limestone	14,500 – 20,000	2
Strong	Granite	20,000 – 32,000	3
Very strong	Quartz	> 32,000	4

Table 2 — Deposit shape KDI definitions.

Deposit Type	Shape	Width	Extent	KDI Value
Tabular	Flat	Thin to moderate	Horizontal	1
Lenticular	Flat, elliptical	Thin to moderate	Horizontal	2-3
Massive	Any	Thin to thick	Horizontal & vertical	4

Table 3 — Deposit orientation KDI definitions.

Inclination Category	Dip Angle	KDI value
Low	0-5°	1
Moderate	5-25°	2
Fairly steep	25-45°	3
Steep	45-90°	4

KDI & KMI cont'd

Table 4 — Deposit size KDI definitions.

Deposit Size	KDI Value
Thin (small)	1
Moderate	2
Fairly Thick	3
Thick (large)	4

Table 5 — Ore grade KDI definitions.

Ore grade	KDI value
Low	1
Moderate	2
Fairly High	3
High	4

Table 6 — Ore uniformity KDI definitions.

Ore uniformity	KDI value
Variable	1
Moderate	2
Fairly Uniform	3
Uniform	4

Table 7 — Deposit depth KDI definitions.

Deposit depth	KDI value
Shallow	1
Moderate	2-3
Deep	4

Table 24 — Key mining indicator (KMI) performance in underground mining methods.

Key Mining Indicators (KMIs)	unsupported					supported	caving		
	room-and-pillar	stope-and-pillar	shrinkage stoping	sublevel stoping	VCR	cut and fill	longwall	sublevel caving	block caving
Operating Cost	moderate	low	high	moderate	moderate	Highest	low	low	low
Capital Investment	high	moderate	low	moderate	moderate	moderate	high	moderate	high
Development	moderate	moderate	high	high	moderate	low	high	high	high
Dilution	moderate	low	low	moderate	moderate	low	low	moderate	high
Subsidence	moderate	low	low	low	low	low	high	high	high
Production Rate	high	high	moderate	high	high	moderate	high	high	high
Productivity	high	high	low	high	high	moderate	high	moderate	high
Development Rate	rapid	rapid	rapid	moderate	moderate	moderate	moderate	moderate	slow
Depth Capacity	limited	limited	limited	moderate	moderate	high	moderate	moderate	moderate
Selectivity	low	high	moderate	low	low	high	low	low	low
Recovery	moderate	moderate	high	moderate	moderate	high	high	high	high
Flexibility	moderate	high	moderate	low	low	high	low	moderate	low
Stability of openings	moderate	high	high	high	high	high	high	moderate	moderate
Health and safety	good	good	good	good	good	moderate	good	good	good
Mechanization	high	high	low	high	high	high	high	high	high
Ventilation	good	fair	poor	good	good	poor	fair	fair	good
Continuous	yes	no	no	no	no	no	yes	no	no
Gravity-Assist	poor	fair	good	good	good	good	poor	fair	good

Sources: Modified after Hartmann & Mutmansky, 2002

KDI & KMI cont'd

Table 26 — Key Deposit Indicator (KDI) attributes favorable to underground mining methods (modified after Hartman and Mutmansky, 2002).

Key Deposit Indicators (KDIs)	Field Data KDI's	unsupported								supported		caving									
		room-and-pillar favorable KDI Value		stope-and-pillar favorable KDI Value		shrinkage stoping favorable KDI Value		sublevel stoping favorable KDI Value		VCR favorable KDI Value		cut and fill favorable KDI Value		longwall favorable KDI Value		sublevel caving favorable KDI Value		block caving favorable KDI Value	
Ore strength	1-2	weak to moderate	1,2	moderate to strong	2,3	strong	3	moderate to strong	2,3	moderate to strong	2,3	moderate to strong	2,3	any	1,2,3,4	moderate to fairly strong	2,3	weak to moderate, cavable	1,2
Rock Strength	1-2	moderate to strong	2,3	moderate to strong	2,3	strong to fairly strong	3,4	fairly strong to strong	4	fairly strong to strong	4	weak to fairly weak	1,2	weak to moderate, cavable	1,2	weak to fairly strong, cavable	2,3	weak to moderate, cavable	1,2
Deposit shape	4	tabular	1	tabular, lenticular	1,2,3	tabular, lenticular	1,2,3	tabular, lenticular	1,2,3	tabular, lenticular	1,2,3	tabular to massive	1,2,3,4	tabular	1	tabular or massive	1,4	massive or thick tabular	1,4
Deposit dip	4	low	1	low to moderate	1,2	fairly steep	3,4	fairly steep	3,4	fairly steep	3	moderate to fairly steep	2,3	low	1	fairly steep	3,4	fairly steep	3,4
Deposit thickness size	4	thin	1	large, moderate, thick	1,2,3,4	thin to moderate	1,2	fairly thick to moderate	2,3	fairly thick to moderate	2,3	thin to moderate	1,2	thin	1	thick	4	very large, thick	4
Ore grade	1	moderate	2	low to moderate	1,2	fairly high	3,4	moderate	2	moderate	2	fairly high	3,4	moderate	2	moderate	2	low	1
Ore uniformity	3	fairly uniform	3	variable	1	uniform	4	fairly uniform	3	fairly uniform	3	moderate, variable	1,2	uniform	4	moderate	2	fairly uniform	3
Depth	4	shallow to moderate	1,2	shallow to moderate	1,2	shallow to moderate	1,2,3	moderate	2,3	moderate	2,3	moderate to deep	2,3,4	moderate to deep	2,3	moderate	2,3	moderate	2,3
Total hits	7		2		4		1		3		2		4		2		5		7

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Summary

	Open Pit	Top Slicing	Block Caving	Sublevel Caving	Sublevel Stoping	Shrinkage Stoping	Square Set Stoping
Boshkov and Wright		X	X	X			X
Hartman			X				
Morrison		X	X	X			
Laubscher			X				
Nicholas	X		X	X			
KDI & KMI			X				

All of the mining method techniques arrived at similar conclusions, with Block Caving as the preferred mining method.

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Donna Morey

From: Peacey, Victoria (RC) <Victoria.Peacey@riotinto.com>
Sent: Wednesday, March 18, 2020 12:51 PM
To: Rasmussen, Mary C -FS
Cc: Chris Garrett; Donna Morey
Subject: Response to Action Item #GS-3 - Geology/Subsidence - Literature Review
Attachments: Literature Review Mining Method Selection.pptx

Hello Mary,

In partial response to action item GS-3, please see the attached literature review on mining method selection conducted by Itasca. I will submit the remaining GS-3 action items separately (information on health and safety, Magma Copper operations, etc…).

Thanks,

Vicky Peacey
Senior Manager Permitting and Approvals

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