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Future underground mining at LKAB Svappavaara: potential to combine caving and stoping methods

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Abstract

Two of LKAB's Svappavaara area open pit operations, Gruvberget and Leveäniemi, nestled between Kiruna and Malmberget SLC mines, have been initially considered for transition to underground mining using SLC or block caving methods. However, any underground mining operations at the Svappavaara site will be strongly influenced by external factors. For example, there are presently extremely tight constraints on ground deformation and land use, which are two factors that strongly discourage SLC and block caving methods. Therefore, it is necessary to investigate other alternative underground mining methods that can limit environmental disturbances while maintaining high productivity. Such alternatives may include combination of caving and stoping methods to create a form of hybrid method, with backfilling applied in this scenario. Such methods will decrease mining footprints associated with the cave mining methods. Hybrid mining methods and operations already exist but it is not well understood how they work and how they could be applied to suit more complex deposits. This paper considers the specific settings for the Svappavaara site and discusses how the concept of hybrid mining method can be applied in taking the Svappavaara orebodies underground.

Keywords: *hybrid mining method, low impact environment mining, complex orebodies*

1 Introduction

Depending on the type of the deposit and the mineral being mined, the mining industry is always looking for the most economic mining method. Large-scale, high productivity bulk mining methods do not usually fit small and medium sized deposits. Small and complex deposits are usually mined using more selective but more expensive and less productive stoping methods.

In general, mining methods can be divided into supported and unsupported methods. Supported methods can further be divided into pillar supported methods, where the mine workings are not filled, with open voids left in places where the mineral has been extracted. In artificially supported methods, the voids are filled with various kinds of backfills to provide passive support to prohibit caving of the surrounding rock volumes. In unsupported methods, the open voids are expected to be filled by caved material from above and the surrounding.

Mining method selection is usually conducted on the basis of the properties of the orebody and the host rock. Over the years different rather descriptive but systematic approaches for mining method selection considering technical and economic factors, besides the traditional ones, were proposed and used (e.g. Peele 1941; Lucas & Haycocks 1973; Thomas 1978; Boskhov & Wright 1973; Morrison 1976; Laubscher 1981; Nicholas 1981). Recently, complex fuzzy logic programming and artificial intelligence techniques utilise multi-criteria decision-making processes are used on mining method selection research (e.g. Bitrafan & Ataei 2004; Karadogan et al. 2008; Gupta & Kumar 2012; Namin et al. 2008).

For practical purposes the method proposed by Nicholas (1981) is widely used by the industry for the first step to mining method selection. Nicholas (1992) lists some of the parameters shown below as key inputs when choosing a mining method.

- Geometry and grade distribution of the orebody.
- Rock mass strength for the ore zone, the hanging wall, and the footwall.
- Mining costs and capitalisation requirements.
- Mining rate.
- Type and availability of labour.
- Environmental concerns.

Miller et al. (1995) developed the so-called UBC-system or method, which is a modified version of the Nicholas (1981, 1992) method. It follows the same procedure but makes some relative changes in how to rank some of the parameters, except for the geometry and grade distribution. Both Nicholas and Miller methods work by establishing the geometry and properties of the orebody and the type of production that is expected and then ranking the different mining methods based on their suitability for a given orebody. The mining method that yields the highest total score is thus the preferred mining method.

This paper applies the established methods and procedures for selecting the underground mining method for both the Gruvberget magnetite-hematite iron ore deposit and for the Leveäniemi magnetite-iron ore deposit at LKAB in Svappavaara in northern Sweden.

2 Background

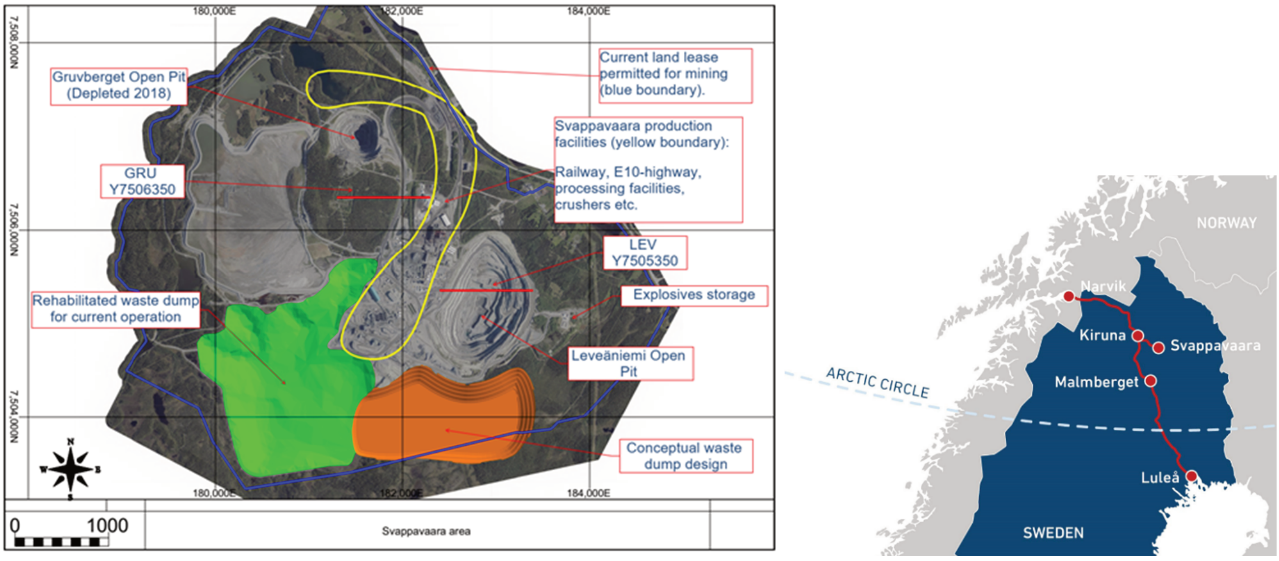
The Svappavaara site mining operations consist of the Leveäniemi open pit, which is currently in production, and Gruvberget open pit (magnetite), which has been depleted in 2018. Mertainen open pit mine (magnetite), located 15 km north from Svappavaara, is currently under care and maintenance.

Figure 1b shows the Svappavaara mining area, which is nestled between Kiruna and Malmberget, where LKAB's SLC operations are located. The two open pits (Leveäniemi & Gruvberget) assessed in this paper for future transition to underground are shown in Figure 1a.

Current ore reserves at Leveäniemi are approximately 86 Mt, of which 74 Mt is of proven category and approximately 11 Mt at probable category. Average iron ore grade reported is 47.2% Fe. The total mineral resource at Leveäniemi is approximately 162 Mt (90 Mt known, 58 Mt indicated, and 14 Mt inferred). The Leveäniemi mineral resources are divided into magnetite (90 Mt known, 58 Mt indicated, and 14 Mt inferred) and mixed magnetite-hematite (1 Mt known, 1 Mt indicated, and 0,07 Mt inferred) type mineralisation and add up to approximately 164 Mt in total.

The Gruvberget mineral resources are divided into magnetite (36 Mt known, 110 Mt indicated, and 68 Mt inferred), hematite (12 Mt known, 29 Mt indicated, and 53 Mt inferred), and mixed magnetite-hematite (7 Mt known, 19 Mt indicated, and 25 Mt inferred) type mineralisation and add up to approximately 359 Mt in total. Further, Gruvberget mineral resource is divided into open pit resource (approximately 170 Mt) and Underground resource (approximately 194 Mt and 5 Mt of 'must take', i.e. internal dilution material) (LKAB 2021). While the open pit reserves at Gruvberget have been depleted, the open pit operation at Leveäniemi is expected to continue until 2033 and the current stripping ratio based on the final pit design is approximately 0.63.

Gruvberget and Leveäniemi deposits are considered as large to medium in size, low value, and low-grade deposits with complex geology. Mining of these deposits requires a low cost, selective, and high productivity mining method that can be adapted according to the different geometries of the deposit.



(a) (b)

Figure 1 (a) Leveäniemi open pit (lower pit image) and Gruvberget (upper pit image). Rehabilitated waste dump for current operations is shown in green and a conceptual new waste dump in orange. The red straight lines mark the locations of the profiles in Figure 2. The yellow line encloses the area for production facilities and the blue boundary encloses the current land lease permitted for mining, (b) Svappavaara mining area relative to Kiruna and Malmberget mining areas

3 Mining method selection

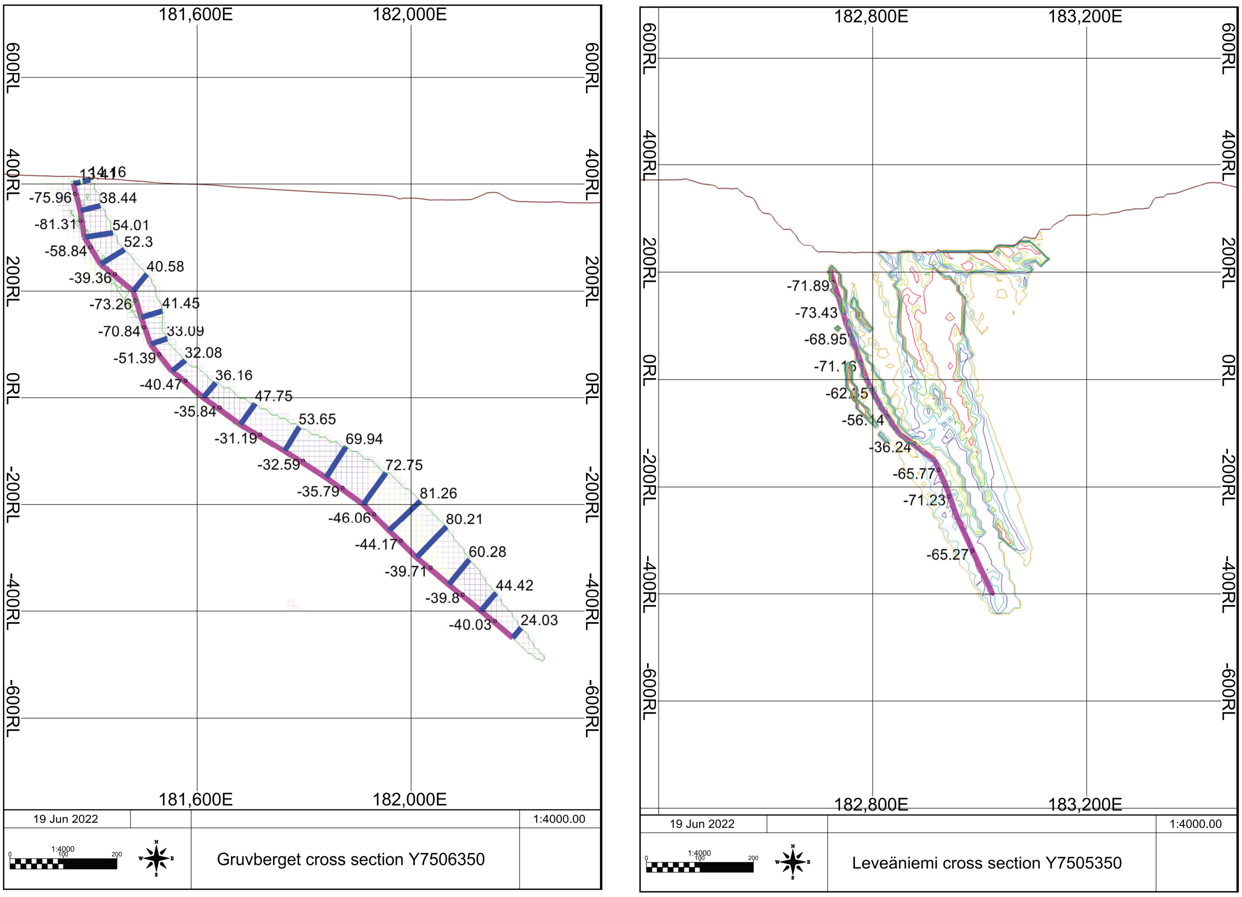
There are different approaches for selection of mining method for different types of orebodies. The UBC Method was used here for the study to rank the geometry and grade distribution for different mining methods for both Gruvberget and Leveäniemi orebodies. Geology, geometry, and grade information were included in the wireframes and resource block models obtained from the exploration department.

3.1 Geometric description of the orebodies

Figure 2 shows the complex geometry and geology of the two orebodies looked at Svappavaara. Figure 2a is a cross-section through the 40% grade shell at Y7506350 of the Gruvberget orebody. The contact between the 40% grade shell and the country rock is well defined and thus clearly shows significant variations in thickness, dip, and geology (magnetite, hematite, and mixed areas). Figure 2b is a cross-section through the Leveäniemi orebody at Y7506450 which cuts through different grade shells from 25 to 50%. The chosen grade shells have significant impact on the grade variation and geometry of the deposit.

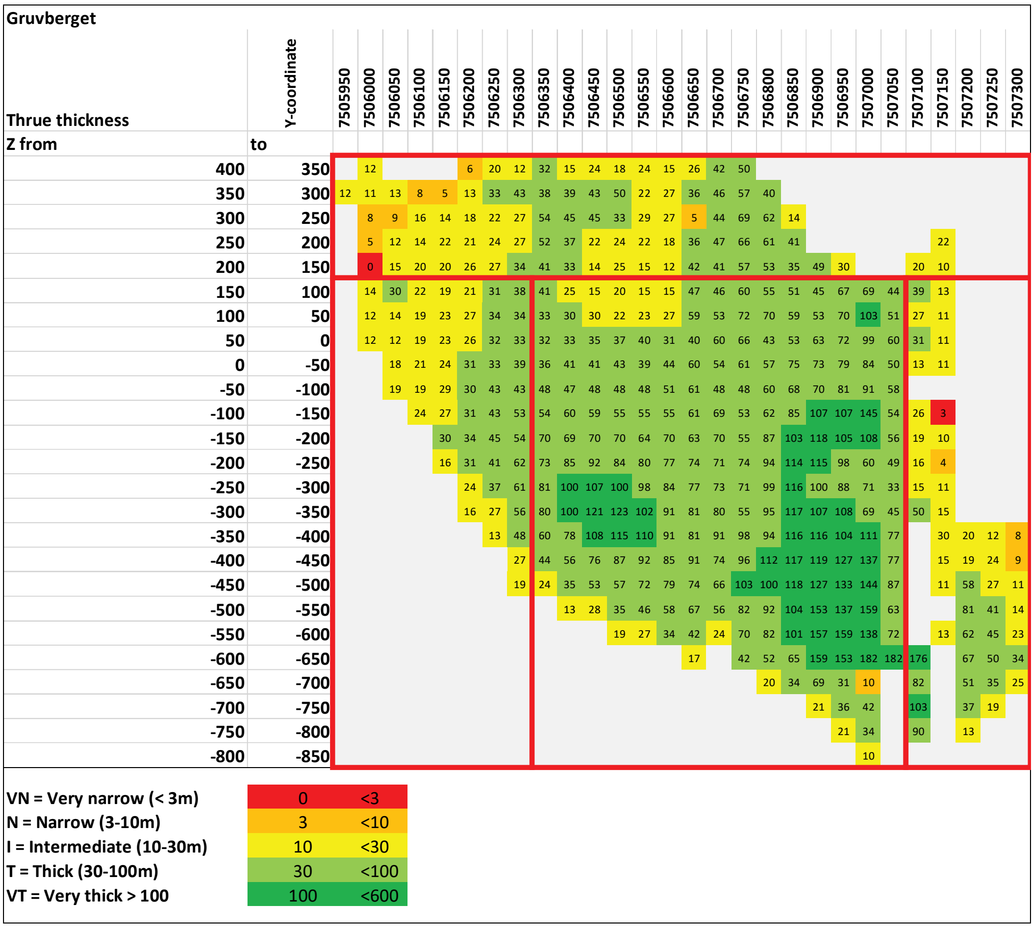
Instead of generalising the geometrical descriptions of the two orebodies by averaging the parametric values required in the UC Method, a more comprehensive approach was utilised. This was done by first creating sections and profiles through geological wireframes and grade shells with the most optimal grid sizes. Grids of 50 × 50 m cross-sections and profiles were created for both orebodies. The true thickness and dip are measured for all intervals and the data for the Gruvberget orebody is presented in Figure 3 and for the Leveäniemi orebody in Figure 4. The figures also include depths of the profiles and sections.

The general shapes of the orebodies are defined as massive (all dimensions are the same order of magnitude) if the true thickness was greater than 40 m, or as irregular (the dimensions vary over short distances) if the true thickness of the current level in the actual profile changed more than 50% from the previous level, otherwise the general shape is defined as tabular (two dimensions are many times the thickness, which does not usually exceed 100 m). Grade distribution was assumed to be uniform for both deposits (grade shells used). For depth calculations, a flat ground surface was assumed at 400 m asl.



(a) (b)

Figure 2 Cross-sections through (a) Gruvberget orebody showing the block model and grade shell at 40%; (b) Leveäniemi grade shells from 25% to 50%

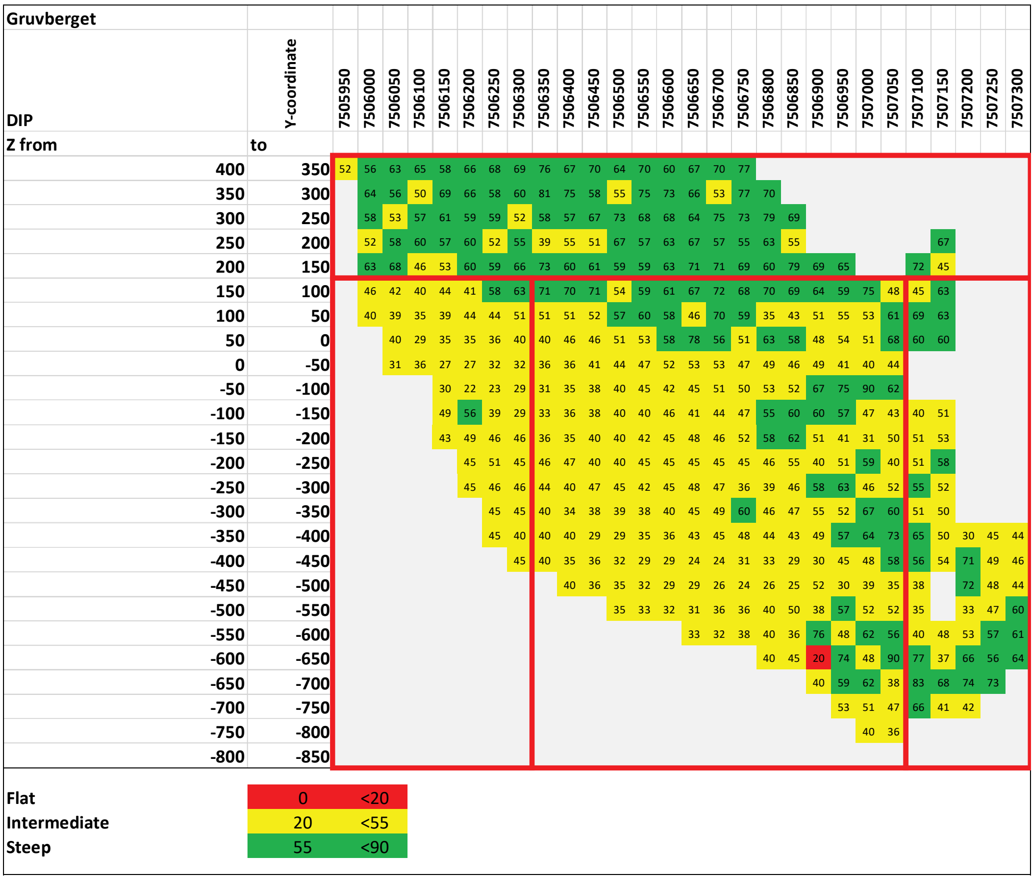


Gruvberget

Thrue thickness

Z from	to	7505950	7506000	7506050	7506100	7506150	7506200	7506250	7506300	7506350	7506400	7506450	7506500	7506550	7506600	7506650	7506700	7506750	7506800	7506850	7506900	7506950	7507000	7507050	7507100	7507150	7507200	7507250	7507300
400	350		12				6	20	12	32	15	24	18	24	15	26	42	50											
350	300	12	11	13	8	5	13	33	43	38	39	43	50	22	27	36	46	57	40										
300	250		8	9	16	14	18	22	27	54	45	45	33	29	27	5	44	69	62	14									
250	200		5	12	14	22	21	24	27	52	37	22	24	22	18	36	47	66	61	41						22			
200	150		0	15	20	20	26	27	34	41	33	14	25	15	12	42	41	57	53	35	49	30			20	10			
150	100		14	30	22	19	21	31	38	41	25	15	20	15	15	47	46	60	55	51	45	67	69	44	39	13			
100	50		12	14	19	23	27	34	34	33	30	30	22	23	27	59	53	72	70	59	53	70	103	51	27	11			
50	0		12	12	19	23	26	32	33	32	33	35	37	40	31	40	60	66	43	53	63	72	99	60	31	11			
0	-50			18	21	24	31	33	39	36	41	41	43	39	44	60	54	61	57	75	73	79	84	50	13	11			
-50	-100			19	19	29	30	43	43	48	47	48	48	48	51	61	48	48	60	68	70	81	91	58					
-100	-150				24	27	31	43	53	54	60	59	55	55	55	61	69	53	62	85	107	107	145	54	26	3			
-150	-200					30	34	45	54	70	69	70	70	64	70	63	70	55	87	103	118	105	108	56	19	10			
-200	-250					16	31	41	62	73	85	92	84	80	77	74	71	74	94	114	115	98	60	49	16	4			
-250	-300						24	37	61	81	100	107	100	98	84	77	73	71	99	116	100	88	71	33	15	11			
-300	-350						16	27	56	80	100	121	123	102	91	81	80	55	95	117	107	108	69	45	50	15			
-350	-400							13	48	60	78	108	115	110	91	81	91	98	94	116	116	104	111	77		30	20	12	8
-400	-450								27	44	56	76	87	92	85	91	74	96	112	117	119	127	137	77		15	19	24	9
-450	-500								19	24	35	53	57	72	79	74	66	103	100	118	127	133	144	87		11	58	27	11
-500	-550										13	28	35	46	58	67	56	82	92	104	153	137	159	63			81	41	14
-550	-600												19	27	34	42	24	70	82	101	157	159	138	72		13	62	45	23
-600	-650															17		42	52	65	159	153	182	182	176		67	50	34
-650	-700																		20	34	69	31	10		82		51	35	25
-700	-750																				21	36	42		103		37	19	
-750	-800																					21	34		90		13		
-800	-850																						10						

VN = Very narrow (< 3m)	0	<3
N = Narrow (3-10m)	3	<10
I = Intermediate (10-30m)	10	<30
T = Thick (30-100m)	30	<100
VT = Very thick > 100	100	<600



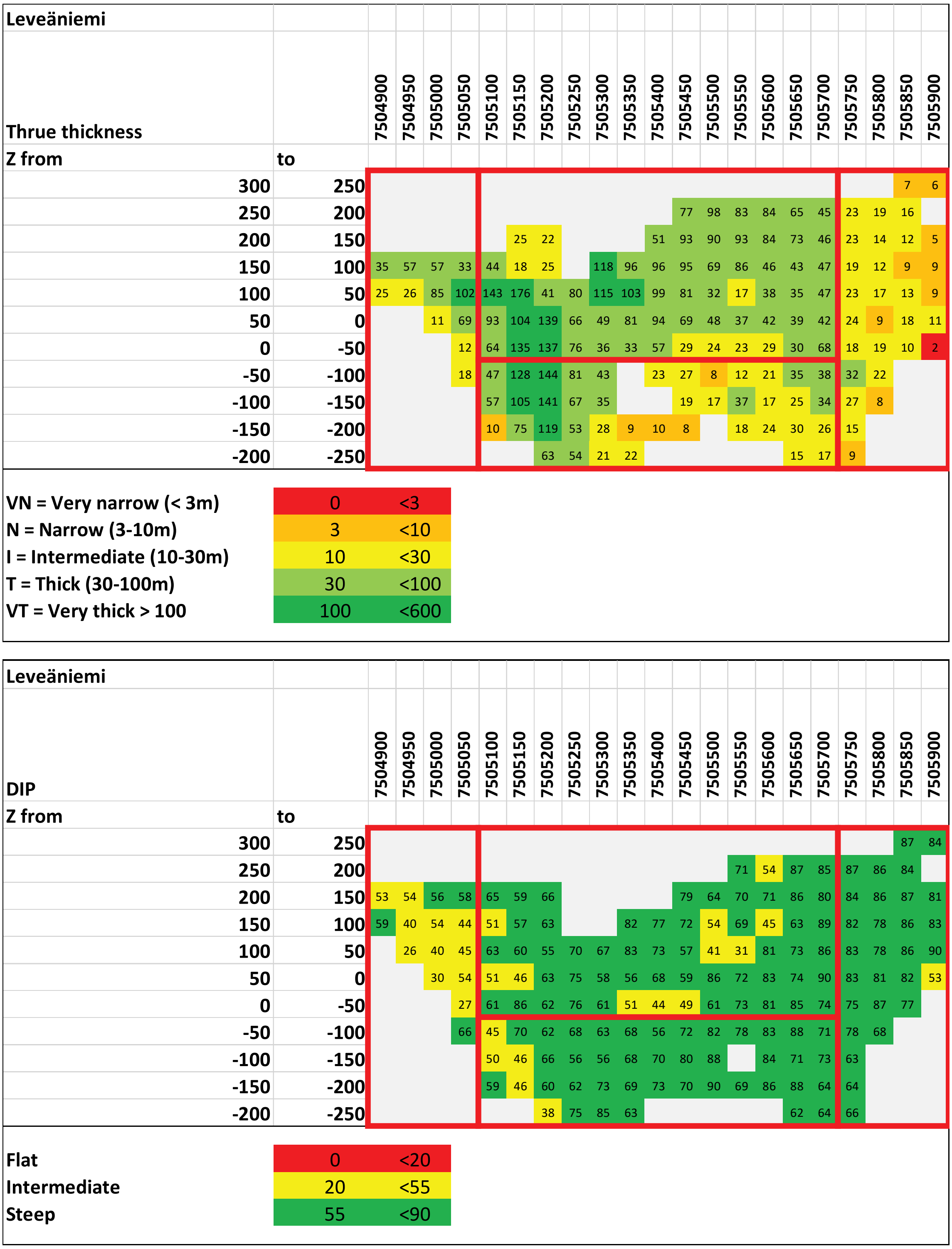
Gruvberget

DIP

Z from	to	7505950	7506000	7506050	7506100	7506150	7506200	7506250	7506300	7506350	7506400	7506450	7506500	7506550	7506600	7506650	7506700	7506750	7506800	7506850	7506900	7506950	7507000	7507050	7507100	7507150	7507200	7507250	7507300
400	350	52	56	63	65	58	66	68	69	76	67	70	64	70	60	67	70	77											
350	300		64	56	50	69	66	58	60	81	75	58	55	75	73	66	53	77	70										
300	250		58	53	57	61	59	59	52	58	57	67	73	68	68	64	75	73	79	69									
250	200		52	58	60	57	60	52	55	39	55	51	67	57	63	67	57	55	63	55						67			
200	150		63	68	46	53	60	59	66	73	60	61	59	59	63	71	71	69	60	79	69	65			72	45			
150	100		46	42	40	44	41	58	63	71	70	71	54	59	61	67	72	68	70	69	64	59	75	48	45	63			
100	50		40	39	35	39	44	44	51	51	51	52	57	60	58	46	70	59	35	43	51	55	53	61	69	63			
50	0			40	29	35	35	36	40	40	46	46	51	53	58	78	56	51	63	58	48	54	51	68	60	60			
0	-50			31	36	27	27	32	32	36	36	41	44	47	52	53	53	47	49	46	49	41	40	44					
-50	-100					30	22	23	29	31	35	38	40	45	42	45	51	50	53	52	67	75	90	62					
-100	-150					49	56	39	29	33	36	38	40	40	46	41	44	47	55	60	60	57	47	43	40	51			
-150	-200					43	49	46	46	36	35	40	40	42	45	48	46	52	58	62	51	41	31	50	51	53			
-200	-250						45	51	45	46	47	40	40	45	45	45	45	45	46	55	40	51	59	40	51	58			
-250	-300						45	46	46	44	40	47	45	42	45	48	47	36	39	46	58	63	46	52	55	52			
-300	-350							45	45	40	34	38	39	38	40	45	49	60	46	47	55	52	67	60	51	50			
-350	-400							45	40	40	40	29	29	35	36	43	45	48	44	43	49	57	64	73	65	50	30	45	44
-400	-450								45	40	35	36	32	29	29	24	24	31	33	29	30	45	48	58	56	54	71	49	46
-450	-500										40	36	35	32	29	29	26	24	26	25	52	30	39	35	38		72	48	44
-500	-550												35	33	32	31	36	36	40	50	38	57	52	52	35		33	47	60
-550	-600															33	32	38	40	36	76	48	62	56	40	48	53	57	61
-600	-650																		40	45	20	74	48	90	77	37	66	56	64
-650	-700																				40	59	62	38	83	68	74	73	
-700	-750																					53	51	47	66	41	42		
-750	-800																						40	36					
-800	-850																												

Flat	0	<20
Intermediate	20	<55
Steep	55	<90

Figure 3 The true dip and thickness Gruvberget orebody at 40% Fe cutoff grade – south is to the right



Leveäniemi

Thrue thickness

Z from	to	7504900	7504950	7505000	7505050	7505100	7505150	7505200	7505250	7505300	7505350	7505400	7505450	7505500	7505550	7505600	7505650	7505700	7505750	7505800	7505850	7505900
300	250																				7	6
250	200												77	98	83	84	65	45	23	19	16	
200	150						25	22				51	93	90	93	84	73	46	23	14	12	5
150	100	35	57	57	33	44	18	25		118	96	96	95	69	86	46	43	47	19	12	9	9
100	50	25	26	85	102	143	176	41	80	115	103	99	81	32	17	38	35	47	23	17	13	9
50	0			11	69	93	104	139	66	49	81	94	69	48	37	42	39	42	24	9	18	11
0	-50				12	64	135	137	76	36	33	57	29	24	23	29	30	68	18	19	10	2
-50	-100				18	47	128	144	81	43		23	27	8	12	21	35	38	32	22		
-100	-150					57	105	141	67	35			19	17	37	17	25	34	27	8		
-150	-200					10	75	119	53	28	9	10	8		18	24	30	26	15			
-200	-250							63	54	21	22						15	17	9			

VN = Very narrow (< 3m)	0	<3
N = Narrow (3-10m)	3	<10
I = Intermediate (10-30m)	10	<30
T = Thick (30-100m)	30	<100
VT = Very thick > 100	100	<600

Leveäniemi

DIP

Z from	to	7504900	7504950	7505000	7505050	7505100	7505150	7505200	7505250	7505300	7505350	7505400	7505450	7505500	7505550	7505600	7505650	7505700	7505750	7505800	7505850	7505900
300	250																				87	84
250	200														71	54	87	85	87	86	84	
200	150	53	54	56	58	65	59	66					79	64	70	71	86	80	84	86	87	81
150	100	59	40	54	44	51	57	63			82	77	72	54	69	45	63	89	82	78	86	83
100	50		26	40	45	63	60	55	70	67	83	73	57	41	31	81	73	86	83	78	86	90
50	0			30	54	51	46	63	75	58	56	68	59	86	72	83	74	90	83	81	82	53
0	-50				27	61	86	62	76	61	51	44	49	61	73	81	85	74	75	87	77	
-50	-100				66	45	70	62	68	63	68	56	72	82	78	83	88	71	78	68		
-100	-150					50	46	66	56	56	68	70	80	88		84	71	73	63			
-150	-200					59	46	60	62	73	69	73	70	90	69	86	88	64	64			
-200	-250							38	75	85	63						62	64	66			

Flat	0	<20
Intermediate	20	<55
Steep	55	<90

Figure 4 The true dip and thickness Leveäniemi orebody at 35% Fe cut-off grade – south is to the right

3.2 Rock mass geomechanical parameters of the orebodies

Rock mass parameters for the orebody and host rock are included in the UBC-ranking system. These parameters are namely, Rock Mass Rating (RMR) and Rock Substance Strength (RSS) for orebody and host rock footwall and hanging wall. The RSS is the ratio between UCS/σ_1. The UCS for the host rocks ranges from 80 to 150 MPa and for the orebodies it ranges between 50 and 60 MPa. The RMR'89 (Bieniawski 1989) ranges between 60 and 80 MPa for both the host rocks and the orebodies (which equates to a rock mass quality of fair to good).

3.3 Ranking of the different mining methods

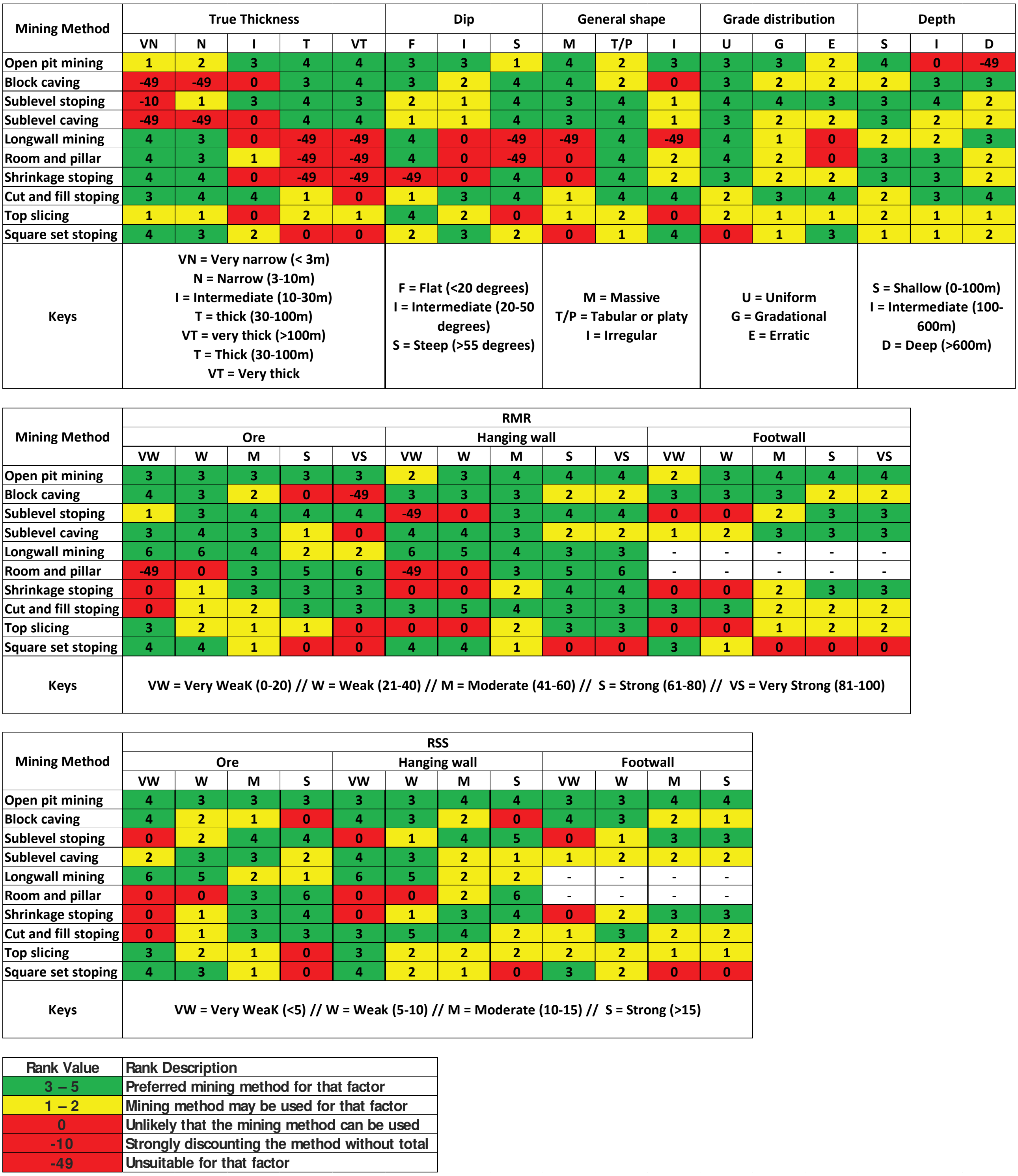
The UBC Method ranks various orebody parameters according to their suitability for different generic mining methods. For each parameter the mining method is ranked and ascribed a value according to the system shown in Table 1.

Table 1 Ranking system according to UBC Method

Rank description	Rank value
Preferred mining method for that factor	3–5
Mining method may be used for that factor	1–2
Unlikely that the mining method can be used	0
Strongly discounting the method without total elimination	-10
Unsuitable for that factor	-49

Figure 5 shows a matrix system for assigning scores to different mining methods based on the UBC Method. Collecting all parameters in a matrix enables calculation of the UBC-score value for each specific cell in the matrix that corresponds to specific block, level, and a profile in the deposit. Furthermore, the result matrix can be modified to show the highest ranked mining method for the specific block, or the matrix can be colour-coded to show which areas are most suitable to mining using a given mining method.

This system is suitable for identifying the most suitable mining method based on geometry and other parameters during scoping level or pre-feasibility level mining studies. This system also gives generic results and suggestions of mining methods that could be applicable for certain parts of the deposits. Moreover, a sensitivity analysis can be carried out by changing parameters where detailed data is not available.



Mining Method	True Thickness					Dip			General shape			Grade distribution			Depth		
	VN	N	I	T	VT	F	I	S	M	T/P	I	U	G	E	S	I	D
Open pit mining	1	2	3	4	4	3	3	1	4	2	3	3	3	2	4	0	-49
Block caving	-49	-49	0	3	4	3	2	4	4	2	0	3	2	2	2	3	3
Sublevel stoping	-10	1	3	4	3	2	1	4	3	4	1	4	4	3	3	4	2
Sublevel caving	-49	-49	0	4	4	1	1	4	3	4	1	3	2	2	3	2	2
Longwall mining	4	3	0	-49	-49	4	0	-49	-49	4	-49	4	1	0	2	2	3
Room and pillar	4	3	1	-49	-49	4	0	-49	0	4	2	4	2	0	3	3	2
Shrinkage stoping	4	4	0	-49	-49	-49	0	4	0	4	2	3	2	2	3	3	2
Cut and fill stoping	3	4	4	1	0	1	3	4	1	4	4	2	3	4	2	3	4
Top slicing	1	1	0	2	1	4	2	0	1	2	0	2	1	1	2	1	1
Square set stoping	4	3	2	0	0	2	3	2	0	1	4	0	1	3	1	1	2
Keys	VN = Very narrow (< 3m) N = Narrow (3-10m) I = Intermediate (10-30m) T = thick (30-100m) VT = very thick (>100m) T = Thick (30-100m) VT = Very thick					F = Flat (<20 degrees) I = Intermediate (20-50 degrees) S = Steep (>55 degrees)			M = Massive T/P = Tabular or platy I = Irregular			U = Uniform G = Gradational E = Erratic			S = Shallow (0-100m) I = Intermediate (100-600m) D = Deep (>600m)		

Mining Method	RMR														
	Ore					Hanging wall					Footwall				
	VW	W	M	S	VS	VW	W	M	S	VS	VW	W	M	S	VS
Open pit mining	3	3	3	3	3	2	3	4	4	4	2	3	4	4	4
Block caving	4	3	2	0	-49	3	3	3	2	2	3	3	3	2	2
Sublevel stoping	1	3	4	4	4	-49	0	3	4	4	0	0	2	3	3
Sublevel caving	3	4	3	1	0	4	4	3	2	2	1	2	3	3	3
Longwall mining	6	6	4	2	2	6	5	4	3	3	-	-	-	-	-
Room and pillar	-49	0	3	5	6	-49	0	3	5	6	-	-	-	-	-
Shrinkage stoping	0	1	3	3	3	0	0	2	4	4	0	0	2	3	3
Cut and fill stoping	0	1	2	3	3	3	5	4	3	3	3	3	2	2	2
Top slicing	3	2	1	1	0	0	0	2	3	3	0	0	1	2	2
Square set stoping	4	4	1	0	0	4	4	1	0	0	3	1	0	0	0
Keys	VW = Very WeaK (0-20) // W = Weak (21-40) // M = Moderate (41-60) // S = Strong (61-80) // VS = Very Strong (81-100)														

Mining Method	RSS											
	Ore				Hanging wall				Footwall			
	VW	W	M	S	VW	W	M	S	VW	W	M	S
Open pit mining	4	3	3	3	3	3	4	4	3	3	4	4
Block caving	4	2	1	0	4	3	2	0	4	3	2	1
Sublevel stoping	0	2	4	4	0	1	4	5	0	1	3	3
Sublevel caving	2	3	3	2	4	3	2	1	1	2	2	2
Longwall mining	6	5	2	1	6	5	2	2	-	-	-	-
Room and pillar	0	0	3	6	0	0	2	6	-	-	-	-
Shrinkage stoping	0	1	3	4	0	1	3	4	0	2	3	3
Cut and fill stoping	0	1	3	3	3	5	4	2	1	3	2	2
Top slicing	3	2	1	0	3	2	2	2	2	2	1	1
Square set stoping	4	3	1	0	4	2	1	0	3	2	0	0
Keys	VW = Very WeaK (<5) // W = Weak (5-10) // M = Moderate (10-15) // S = Strong (>15)											

Rank Value	Rank Description
3 – 5	Preferred mining method for that factor
1 – 2	Mining method may be used for that factor
0	Unlikely that the mining method can be used
-10	Strongly discounting the method without total
-49	Unsuitable for that factor

Figure 5 Matrix system for assigning scores for different mining methods based in the UBC Method

3.4 Orebody domains and mining method choices

3.4.1 Gruvberget geometric domains

The Gruvberget deposit can be divided into four different domains based on the geometry. The shallow, so-called open pit, parts of the orebody ranging from levels approximately 150 asl (corresponds to the bottom level of the depleted Gruvberget pit) up to the surface. In these areas, the thickness varies mostly from intermediate to thick and the dip is defined as steep (>55°).

The 'massive part' of the deposit from Y7506300 to Y750750 is located below Level 150 asl down to the bottom of the orebody. The true thickness in this part of the orebody is mostly intermediate with two subsets of areas that have the definition very thick. The dip ranks as intermediate, i.e. between 20° and 55°.

Tabular areas to the south (Y <7,506,300) and to the north (Y >7,507,100) exist down from Level 150 asl. Both the true thickness and the dip are intermediate for this part of the orebody as the mineralisation closes in.

3.4.2 Leveäniemi geometric domains

Similarly, Leveäniemi is divided also in four domains. The massive part of the orebody lies between Y7505150 and Y750700 and from Level -50 and up where the dip averages to 68° (steep), where the true thickness is thick. The bottom of the orebody below Level -50 asl is mostly steeply dipping with true thickness varying from thick (at southern part of the bottom) to intermediate towards the south. The deposit flattens out slightly towards south and has intermediate dip towards this end of the orebody. The true thickness is mostly intermediate pinching out towards the ends of the mineralisation both in the south and at depth. The north side of the orebody is steeply dipping, and the mineralisation is pinching out towards the end of the mineralisation where the true thickness goes down from intermediate to narrow.

3.5 Possible mining methods

3.5.1 Open pit potentials

The authors emphasise that possible open pit potential and the mineral resource discussed here are of conceptual nature following the guidelines for PERC. PERC stands for The Pan European Reserves and Resources Reporting Committee. PERC is a constituent member of the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) and is recognised by CRIRSCO as the National Reporting Organisation (NRO) for the Europe Region (https://percstandard.org/). The reasonable prospects for economic extraction are based on simplified economic models, high-level assumptions regarding processing capabilities and process recoveries and metal prices. Moreover, it is noted that the Gruvberget hematite is not currently a resource for mining and processing at Svappavaara.

3.5.1.1 Magnetite open pit at Gruvberget

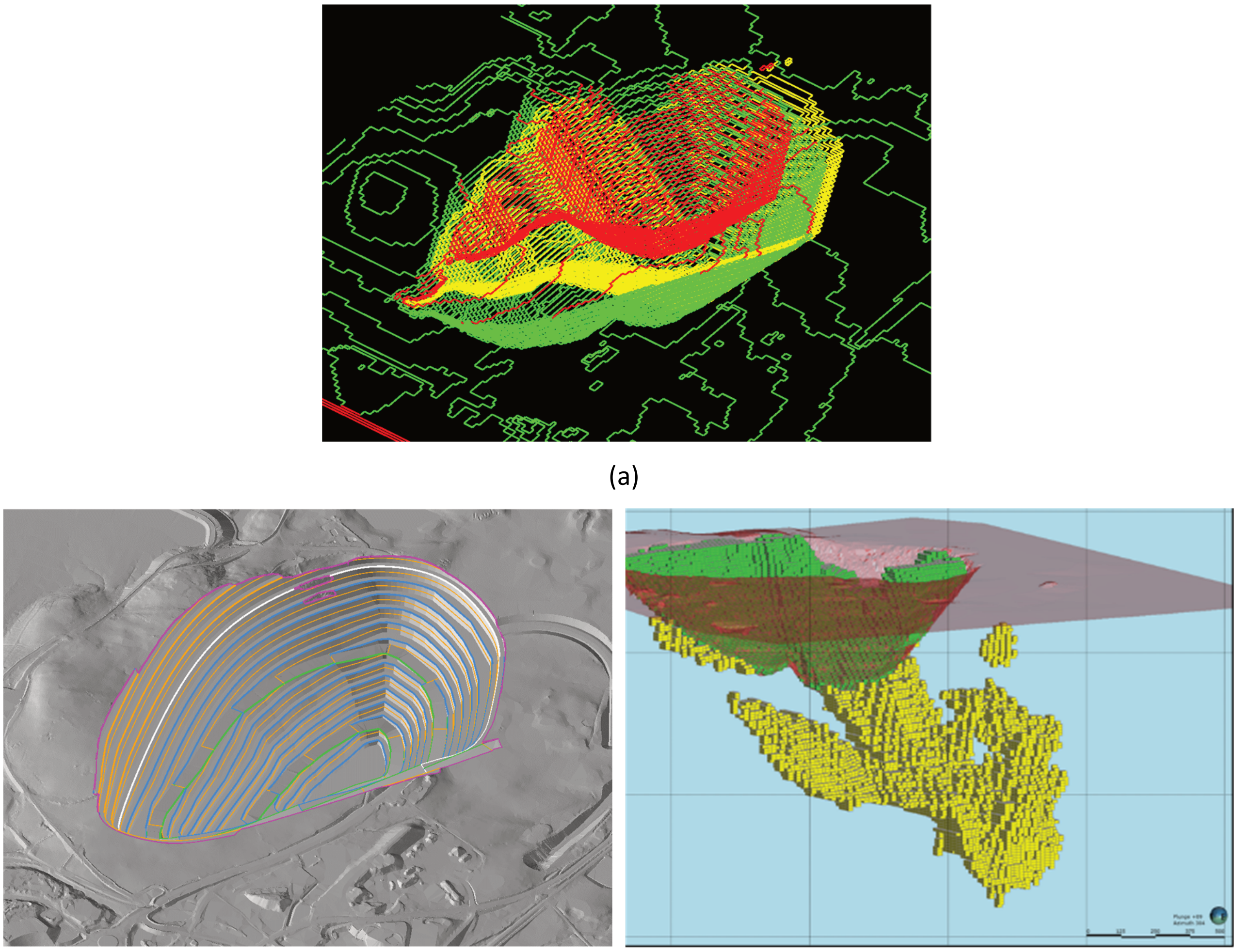
Pit optimisation indicates a pushback potential on the south side of the Gruvberget pit when only considering magnetite as a product. Preliminary layout and production schedule was discussed by Nensén et al. 2021. This pushback potential was written off due to potentially small impact on reserves (approximately 4.7 Mt magnetite), relative high stripping ratio, and intermittent ore production due to the limited size of the push-back.

3.5.1.2 Hematite open pit at Gruvberget

Similarly, pit optimisation indicates an open pit potential when considering only hematite as a product. The hematite deposit is outcropping and would require only little pre-stripping for accessing the hematite through open pit operation.

3.5.1.3 Combined magnetite and hematite open pit at Gruvberget

Naturally, assuming beneficiation and revenues from all material types mined results in the largest pit shell. Current open pit resource is based on the assumption that magnetite and hematite are processed separately and that the mixed material is processed as hematite. Resulting pit shells based on different revenue factors are shown in Figure 6a, with a conceptual design based on the resource shell shown in Figure 6b. This conceptual design contains approximately 300 Mt of waste rock and approximately 100 Mt ore (the word ore is used here to describe the different types of mineralisations subject to further processing). Both open pit resource and underground resource are shown in Figure 6c. The underground resource is based on stope optimisation performed at 40% cut-off grade.



(a)

(b)

(c)

Figure 6 (a) Resulting pit shells in red, yellow, and green at Gruvberget with revenue factor increasing respectively, (b) Conceptual pit design based on the resource shell; (c) Gruvberget open pit resource shown in green, and the underground stope resource shown in yellow

3.5.1.4 Leveäniemi open pit pushback

Similar open pit resource is reported at Leveäniemi. Possible expansions potential was indicated in the competent persons report (LKAB 2020) and further studied by Nensén et al. (2021). The scoping study concluded that an extension of the current Leveäniemi open pit would generate more waste that could be managed in the current permitted waste rock dump. Further, the push back would only have a limited effect on the life-of-mine (LOM) and the stripping required would exceed current operating capacity in the pit.

3.5.2 Possible underground mining methods

The UBC-ranking score for different domains of the different deposits and mining methods is shown Table 2, with the top three ranked mining methods highlighted in bold for each domain previously defined. The authors note that the above mining methods are generic, and that there are many variants to these generic methods (Saiang et al. 2020).

Table 2 Top three mining methods based on the UBC-ranking for each of the orebody domains

Mining method	Leveäniemi					Gruvberget		
	South	North	Massive	Bottom	Shallow	South	North	Massive
Open pit mining	-348	-450	-1455	-2235	**851**	53	-1231	-3490
Block caving	-88	-94	**544**	-32	457	329	225	**2851**
Sublevel stoping	**116**	**204**	**578**	**391**	**1186**	**489**	**519**	**2712**
Sublevel caving	-111	-122	**502**	-73	577	**346**	228	**2484**
Longwall mining	-991	-849	-4357	-3049	-7049	-895	-2643	-23148
Room and pillar	-987	-832	-4362	-3078	-4871	-596	-1593	-12776
Shrinkage stoping	-672	4	-2675	-709	-935	-517	-558	-10091
Cut-and-fill stoping	**160**	**244**	482	**524**	**1100**	**514**	**615**	2185
Top slicing	70	39	201	103	367	219	198	1255
Square set stoping	**95**	**126**	230	**276**	515	248	**315**	1115

3.5.2.1 *Stoping methods at Gruvberget and Leveäniemi*

Stoping methods (sublevel stoping, cut-and-fill stoping and square set stoping) rank among the top three alternatives for all the areas in both deposits. Square set stoping is an older mining method that is almost extinct and is considered inapplicable in this case. Cut-and fill-stoping works best in narrow to medium size orebodies and could be a preferred method for the south, north and bottom parts of Leveäniemi. Similarly, this could be the method for the south and north parts of Gruvberget.

3.5.2.2 *Caving methods for Gruvberget and Leveäniemi*

The massive part of the Gruvberget is mostly intermediately dipping and caving methods are included in the top three ranked mining methods. Likewise, the massive part of the Leveäniemi is predominantly steeply dipping or almost vertical, also indicating caving as the preferred mining method.

4 Discussion

The success of sublevel stoping relies on the stability of the stope walls and crowns and the stability of any fill masses exposed (Villaescusa 2014). This is also a disadvantage of the stoping method for bulk mining commodities such as iron ore. Pillars are needed for the hanging wall and stope wall stability to ensure safe working conditions, which results in ore losses reducing the ore recovery. Alternatively, backfill is placed in the stopes to provide artificial support. In this case a particular stoping geometry and sequence needs to be applied to allow for ore extraction and for the backfill to fulfil the support potential (Brady & Brown 2004).

At the Svappavaara area, the access to backfill material could become a hindrance for the method. Expected mass recovery at the cobbing plant varies depending on the feed grade (ROM-grade). The mass recoveries are discussed further in Section 4.1.2. The factors promoting stoping methods are of low environmental impact in terms of subsidence and modest ore dilution.

Caving methods are considered as low cost and high production mining methods, with disadvantages being significant ground deformation, side rock dilution and selectivity. The steeply dipping orebody at Leveäniemi provides an advantage when using caving methods. The parts of the intermediate dipping orebody at Gruvberget can be considered as a slight disadvantage for the application of caving methods.

4.1 Constraints

Before we can make any further conclusions on the mining method selection, we also must discuss the specific constraints that apply.

“Each orebody is unique; therefore, the approach of just adopting the same mining method for similar commodities was not always an effective or realistic approach” (Baloyi & Meyer 2020). The citation summarises well the shortcomings of the above ranking system. Similar conditions do not mean that a mining method can be transferred to another site; the site-specific criteria or a set of specific conditions are key for selecting the mining method.

4.1.1 Land use constraints

The Svappavaara industrial area shown in Figure 1a, and more specifically the waste dump facilities are limited by the land lease permitted for mining. The waste dump is limited by the tailings dam towards the north and by the industrial area towards the northeast. A small stream Liukattijoki to the west and north included in the Natura 2000 landscape acts as a natural boundary both for the waste dump and the industrial area.

Natura 2000 (https://ec.europa.eu/environment/nature/natura2000/index_en.htm) is a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types which are protected in their own right. The natural forest to the east and south of the waste dump is utilised as a migration route for the reindeer husbandry by the local Laevas Sami village (LKAB, internal documentation). The area to the west of the Leveäniemi Open Pit is occupied with a storage for explosives. The authors note that the conceptual waste dump design shown in Figure 1a is insufficient for the amount of waste rock that would result from open pit mining as described in Figure 6b. Similarly, the waste dump capacities would be insufficient for the screen waste resulting from mining the Gruvberget underground resources and Leveäniemi resource using underground mining methods.

4.1.2 Backfill constraints

Historical data from Leveäniemi and Gruvberget open pit suggests mass recovery of between 60–80% from the ROM-feed to pre-concentrate. Pre-processing is largely a dry process applying crushing, screening, and magnetic separators separating the waste rock dilution from the ROM. The process also upgrades the Fe-grade in the pre-concentrate prior the concentrating plant.

For stoping methods (selective mining method with moderate dilution) the resulting mass balance (waste tonnage minus ore tonnage) is negative, which means insufficient backfill material is available for filling the extracted stopes. For example, mining 300 Mt of material using underground stoping methods and assuming mass recovery of 70% results in 90 Mt of dry waste to be used as backfill material. Hence, external waste is required for the stoping methods to be technically feasible.

4.1.3 Subsidence and ground deformation

A major constrain for the Svappavaara deposits is subsidence and ground deformation associated with caving methods. The area where ground deformation should be avoided is fenced with a yellow colour in Figure 1a. This area contains the processing facilities and is situated in the hanging wall of the Gruvberget deposit. Other infrastructure, such as the main highway (E10), railway and material handling systems, is located on the north side of the Gruvberget deposit. Lake Syväjärvi is situated to the northeast of the deposit, only a couple of hundred meters away from the current pit.

Mining of the Leveäniemi deposit using caving methods is likely to cause significant ground deformation and subsidence on both the hanging wall and the footwall sides of the deposit due to steeply or almost vertically dipping orebody. In both cases, mining-induced ground deformation will certainly affect the infrastructure, industrial area, and the surrounding landscape.

4.1.4 Selective mining

The ore processing at Leveäniemi requires selective mining. Both pre-processing or cobbing (dry process) and concentrating plants rely on Low Impact Magnetic Separators (LIMS) when upgrading the ROM to be used in the following process. The process works well for strongly magnetic minerals. If the material is mixed with medium magnetic minerals like hematite, a different process is required. Generally, separating the Gruvberget magnetite from the Gruvberget hematite is difficult (LKAB 2016). Current hypothesis for Gruvberget is that magnetite, hematite, and mixed magnetite-hematite should be mined and processed separately without mixing the different ore types.

The grade variation at Leveäniemi could be described as gradational as the high-grade massive magnetite is often surrounded by lower grade areas. The current process does not handle big variations in the feed-grade and the low-grade ore needs blending with higher grades. The Leveäniemi magnetite also encompasses varying amounts of vanadium. The current open pit operation undertakes extensive grade control on both the vanadium and iron content, and selective loading is applied for each production blast to control the ROM-ore quality. Further, stockpiles are used to blend the right mix into the crushing and screening plant. Assuming the same requirements for the ROM-quality from any eventual underground operation requires the application of selective mining methods.

4.1.5 Permitting process

Undertaking a full environmental impact analysis is a major undertaking for any mining company with an uncertain outcome. One way of increasing the chances of approval for a mining project is to choose mining methods that minimise negative effects on the environment and local stakeholders. Mining methods that only have minor impact on the ground surface and that provide for waste management should be the preferred choice.

4.2 The mining methods

The evaluation carried out in this study shows that it is feasible to carry on mining the Svappavaara orebodies by the open pit method, or transition to underground and utilise the caving and stoping methods. The open pit mining will require a significant amount of waste stripping. The single most important constraint with this is the legal limit on storage capacity of waste dumps and land usage within the mining lease. This will also make the permitting process extremely difficult.

Cave mining, by sublevel caving and block caving, is the next feasible option for the Svappavaara orebodies. However, these methods will generate significantly large footprints (surface subsidence and deformation), which will affect the entire established mine infrastructure, the public infrastructure (main highway, main railway line, and village of Svappavaara) and surrounding protected areas (lakes and reservations).

The stoping methods are the next options for underground mining of the Svappavaara orebodies. These are largely low production methods, which will significantly limit the production levels desired by LKAB to sustain the operations. However, the main advantage of using these methods is that the surface footprints will be zero to minimal.

A question was therefore raised; is it possible to combine stoping and caving methods, taking advantage of each other's strengths, to have a productive mine and less environmental impact. And thus, the investigation to the so-called 'hybrid mining methods', which have become common in the last decade or so. Discussion of these methods are presented below. This approach of mining falls in the context of LKAB's vision for its future mines which is themed as 'invisible mines'.

4.3 Hybrid underground mining methods

There is no established definition of a hybrid mining method. In this paper we define a hybrid mining method as a method that combines two or several mining methods to take advantage of each other's strengths for the safe and efficient extraction of ore. It essentially means that one mining method provides the backbone for the other. The first hint of a possible hybrid mining method was proposed by Morrison (1976). Morrison proposed a scheme where the mining methods were grouped in to Group A – those requiring rigid pillars (supported), Group C – those that cave freely (unsupported), and Group B – those that allow controlled subsidence. Group B could essentially be defined as hybrid methods since Group A provides the backbone for Group C, where yielding pillars and backfills are engineered to constrain and control ground deformation and subsidence for bulk mining.

In fact, in the last decade or so a number of these hybrid mining methods have evolved, driven by demands for ground control and maximisation of recovery. Examples of these mines include a Chirano Mine in Ghana, where continuous mining is performed with a top-down SLC while continuously backfilling on top of the shrinking ore. This allowed for full extraction while allowing the hanging wall (and footwall) to deform in a controlled and predictable manner. Moreover, this method also allowed the mine to extract the ore in an SLC style with the layout of a stoping mine, which meant that infrastructure development typically necessary for a traditional SLC mine is not required. There are a few more examples of mines that use these mixed methods, for example Mt Wright (Australia), Lec des Iles (Canada) and Subika (Ghana). Nevertheless, the success stories (or even failure stories) are not published in the public domain and so part of this work is to try and document the workings of these hybrid methods.

5 Conclusion

The future mining of Svappavaara is likely to be a combination of Gruvberget magnetite-hematite open pit and Gruvberget and Leveäniemi underground operations using different underground mining methods.

- The pushbacks of Gruvberget magnetite and Leveäniemi have only limited effect on the LOM and are associated with both technical, economical, and environmental challenges and are not considered as viable alternatives. These options also contradict the specific land use constraint.
- The Gruvberget combined magnetite-hematite open pit has a positive effect on the LOM and significant potential to move mineral resources into mineral reserves. Thus, continued investigations are motivated if the specific land use constraint can be managed.
- Stoping methods alone are not considered as viable alternatives as the specific backfill constraint is contradicted.
- Caving methods alone are not considered as viable alternatives as the specific subsidence and the ground deformation constraints are contradicted.
- The hybrid mining method enables the specific land use constraints, backfill constraints, subsidence, and ground deformation constraints to be effectively controlled, and will aid in managing both the selective mining constraint and permitting process.
- An external source of rockfill (open pit) is required for the hybrid mining method.
- The need for rockfill for underground operations, together with economic analysis defines the size of the Gruvberget magnetite-hematite open pit.

For the Svappavaara orebodies it is obvious that the best alternative mining method would be to use the so-called hybrid mining method, where a stoping method can provide the backbone for SLC. This will address the most important constraint of ground deformation and subsidence on the one hand, and on the other the opportunity to increase productivity while reducing high infrastructure costs typical for traditional SLC operations. Thus, the method sought for Svappavaara orebodies have to meet LKAB’s demands for high production, low cost and minimum environmental footprint (Saiang et al. 2020).

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