doi:10.36487/ACG_repo/2435_A-14

Pebble: New approach for planning and development unlocks value for a massive new block cave

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ABSTRACT

The Pebble Project is one of the world's largest, potential copper mines. Early concepts for underground mining at Pebble followed a typical path for Block Caving concepts in the early 2000's, which was to target the tallest possible draw columns. For an inclined, massive deposit this involved a single deep production level near the bottom of the deposit, inclusion of considerable waste and an assumption of high recovery of material, high in the columns. The challenges of this approach are that it is capital intensive and lengthens to the lead time to start of production. Such a design also increases the volume of waste, but reduction of waste is a goal for the Pebble team. An assessment was completed of an easier to start, higher grade, lower risk block caving concept, that considered emerging deposit knowledge. A staged concept, shaped to the deposit and the geotechnical conditions was developed that is a better techno-economic and environmental fit. The focus was staged exploration, development and impact. The following summarizes the workflow followed to develop the improved concept, including a description of the simulation techniques used to quantify the fit between deposit geometry and design.

1 INTRODUCTION

Pebble is a massive Tier 1 Cu deposit in Alaska, see Figure 1. It dips to the east from outcrop to a depth of between 530m below surface to 1,100 metres below surface, with a strike-length of 1,600m x 1,000m metres.

Figure 1 Pebble Project Location Map.

The near surface component of the deposit would be mined by open pit. Between 2008 and 2011, Pebble investigated the potential for underground mining the deeper, eastern section by block caving employing a deep 'large footprint' strategy. In this strategy, the mine would start and finish on the same deep horizon. The starter blocks on this deep horizon were to the east and sequential blocks were mined as strips alongside the starter blocks. The design also involved developing ± 1,200m deep metre shaft hoisting, service and ventilation complex before development of the footprint. This concept is shown in Figures 2 and 3.

A schematic section through the 2010 design is show in Figure 4, revealing some key design assumptions at the time.

For such a strategy, the inclined deposit means parts of the footprint must draw tall columns of low-grade material before drawing high grade into the cave. Further, the strategy assumes that the cave will indeed propagate favorably into the high grade at the top of those columns.

A plausible, adverse scenario for cave growth and break back for a deep, single block strategy in a massive, inclined deposit is shown at an intermediate stage of extraction in Figure 5. The Figure shows a common underbreak scenario, which directly leads to ore loss. The losses are also compounded because areas of the deep extraction level mined in the under broken zones preferentially draw waste.

Some elements of this scenario occur in all caving mines, and it is common that the effect is underestimated. Indeed, although the 2010 design was simulated using a coupled stress-strain flow model to assess stability of the footprint, the tools used to evaluate and 'optimise' the footprint elevation in 2010-11, and sometimes still used today, are not usually applied in a manner that accounts directly for the shaping of flow of waste and mineralized material by plausible cave shapes.

Further, many of the tools used in 2010-2011 for forecasting of recovery and dilution in caves assumed implicitly that caving would occur precisely as required throughout the target volume to deliver all the target mineralized material to the cave. Whereas probably the greatest single discount on performance in caves is likely mineralized material loss and dilution arising from adverse interactions between underbreak and flow, at the time almost all available software for recovery forecasting did not explicitly simulate any impact from underbreak.

The potential for overestimation of recovery is obvious. Less obvious is the impact from the resulting bias for deeper, larger footprints.

The cost of exploration, development and operation do not increase in direct proportion with depth, but rather parabolically, so a deeper first block will cost more per unit of capacity than a shallower block. This is often under-accounted for. The strategy also locks in a mining horizon and footprint location for not just the first block, but subsequent blocks which means collecting high resolution data for all the footprint at the deepest level before the project can 'gate' through the first production decision points.

The capital cost of delivering mineralized material handling and ventilation that will either provide or integrate with the life of mine needs up front, as implied for the access to a single, large block at the base of the footprint, is also immense. As the relationship between instability potential and stress is non-linear, delays from adverse geotechnical vents increases significantly with depth. This means a deeper project will experience disproportionately more risk of delay than a shallower one. It is common for deep block caves to have delays to start and ramp up of many years, and to contend with months or quarters of down time for repairs to damaged footprints. This is worse for large blocks, as long mining fronts make the management of stress-strain-structure interactions very challenging at depth.

Exploring a deeper footprint is slower and more expensive than a shallower footprint, and many deep block caves have found that gaining sufficient deposit knowledge during startup takes significantly longer than planned, excluding any development of underground infrastructure and deposit access timelines.

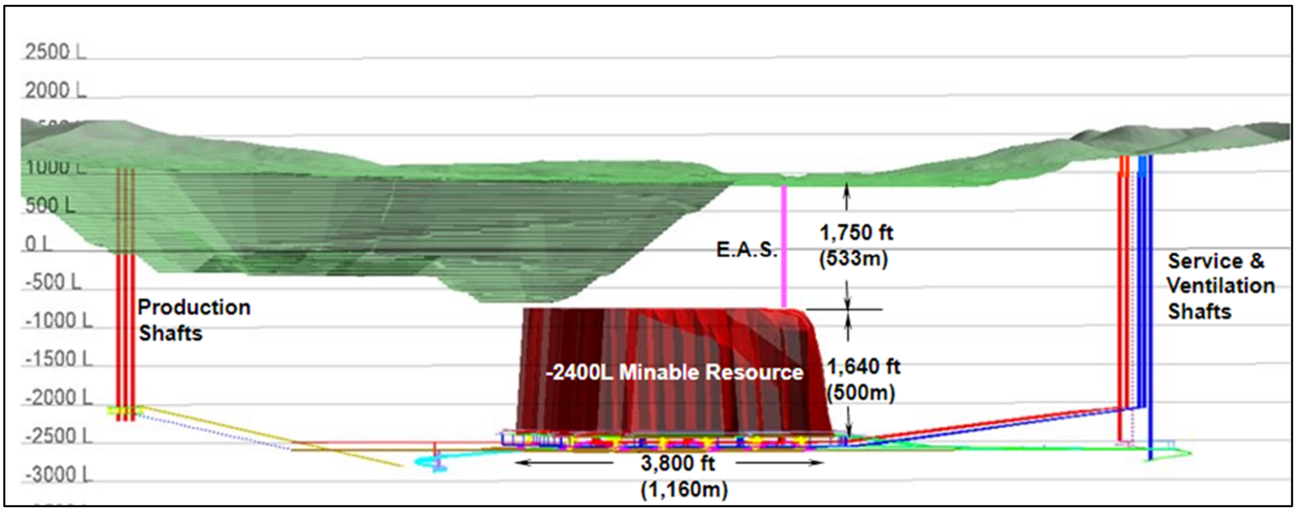

Figure 2 Dimensions of the Pebble "Old" Mine.

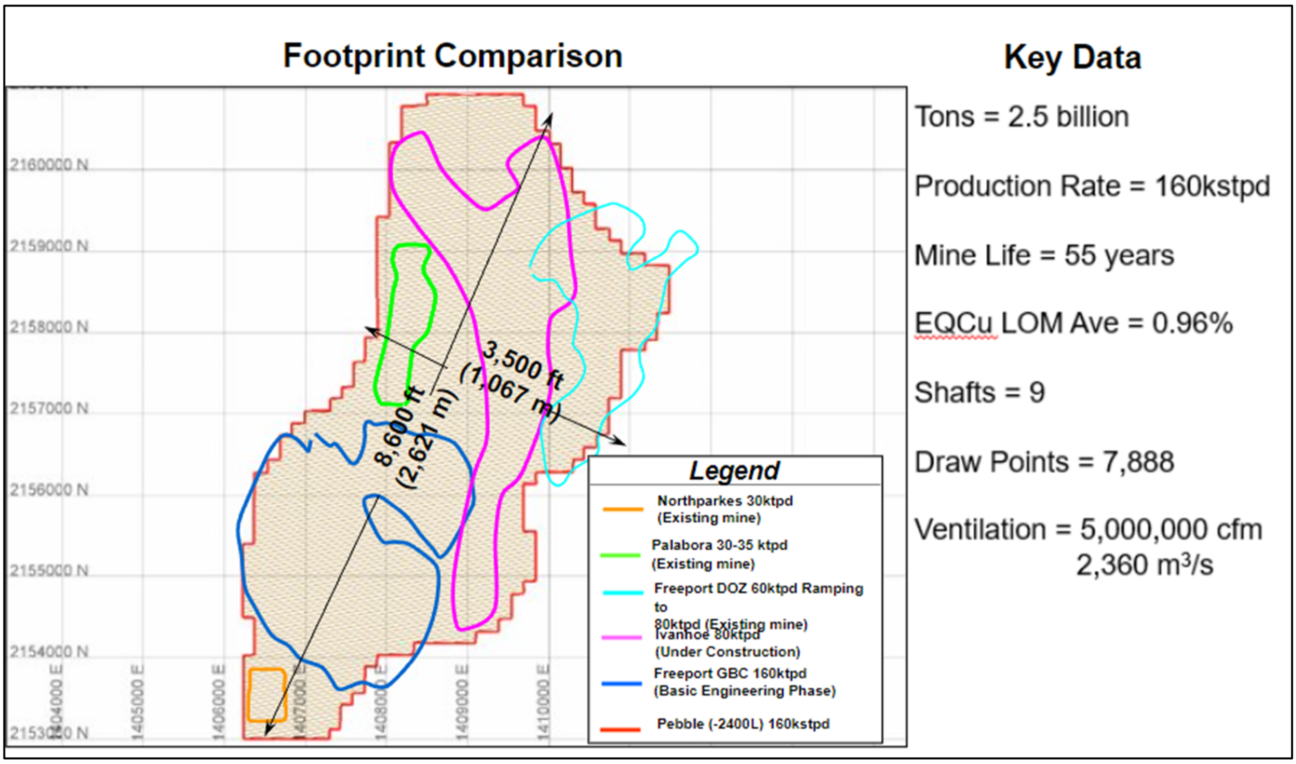

Figure 3 Footprint Comparison ("Old" Mine VS Other Caving Projects).

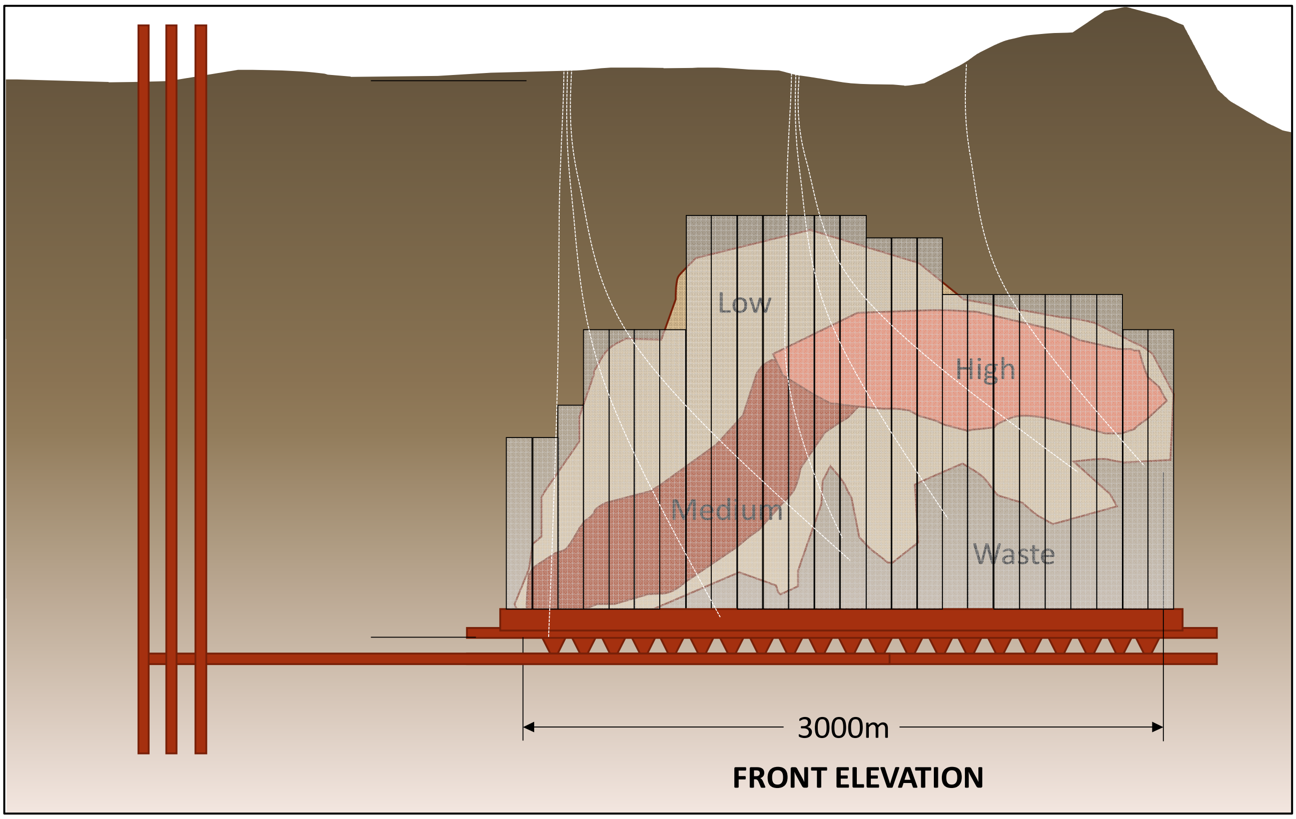

Figure 4 **Schematic section of the Pebble ~ 2010 large, deep footprint strategy versus the deposit.**

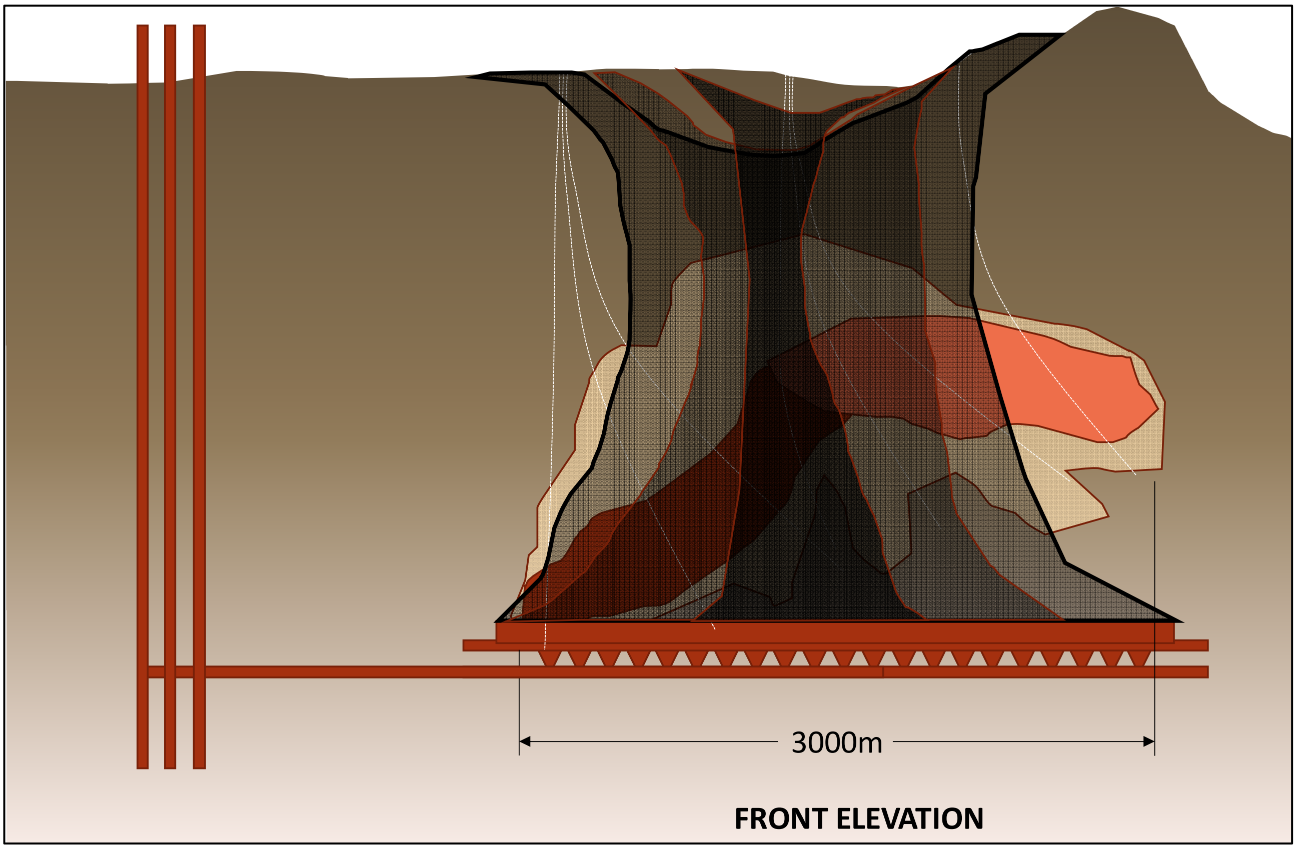

Figure 5 **An adverse scenario for cave growth and break back for a deep, single block strategy in a massive inclined mineralised deposit.**

In the case of Pebble, there is also an environmental imperative to minimize disturbance from emplacement of waste, which is not consistent with a single large footprint with areas that must draw hundreds of millions of tonnes of low-grade material to access high grade mineralized material.

2 AN ALTERNATIVE DESIGN

To meet capital, strategic and environmental goals, a staged project with less surface disturbance was required. Other essential tasks were to integrate the underground with an initial open pit, bring forward start-up and ramp-up times, and managing a complex and variable geotechnical environment. A reduction in up front capital and a levelling of capital expenditure is always implied, while developing a sustainable production build up.

The design intent was achieved by shaping the conceptual mine to match the plunging high grade core of the deposit with a sequence of blocks, as shown in the schematic in Figure 2. The strategy calls for successive exploration targetting, expansion of infrastructure and execution of the levels from shallowest to deepest along the plunge. In other words, permitting sequential in-fill exploration necessary for geotechnical and design optimization and decision making, development and sequential investment.

The footprint placement of the successive lifts is progressed in stages, as explained below.

- 1st pass – balance in column risk and value:
  - A block model was produced that computed the average value of the overlying column up to a maximum height of draw (tested 300m and 500m maximum heights of draw, with 350m reasonably assured, 500m less assured) and isosurfaces were plotted.

    The intent was to find targetable blocks that balance risk and value: if value sits high in a column, it is at higher risk. High value should be within a defendable height of the drawbell.

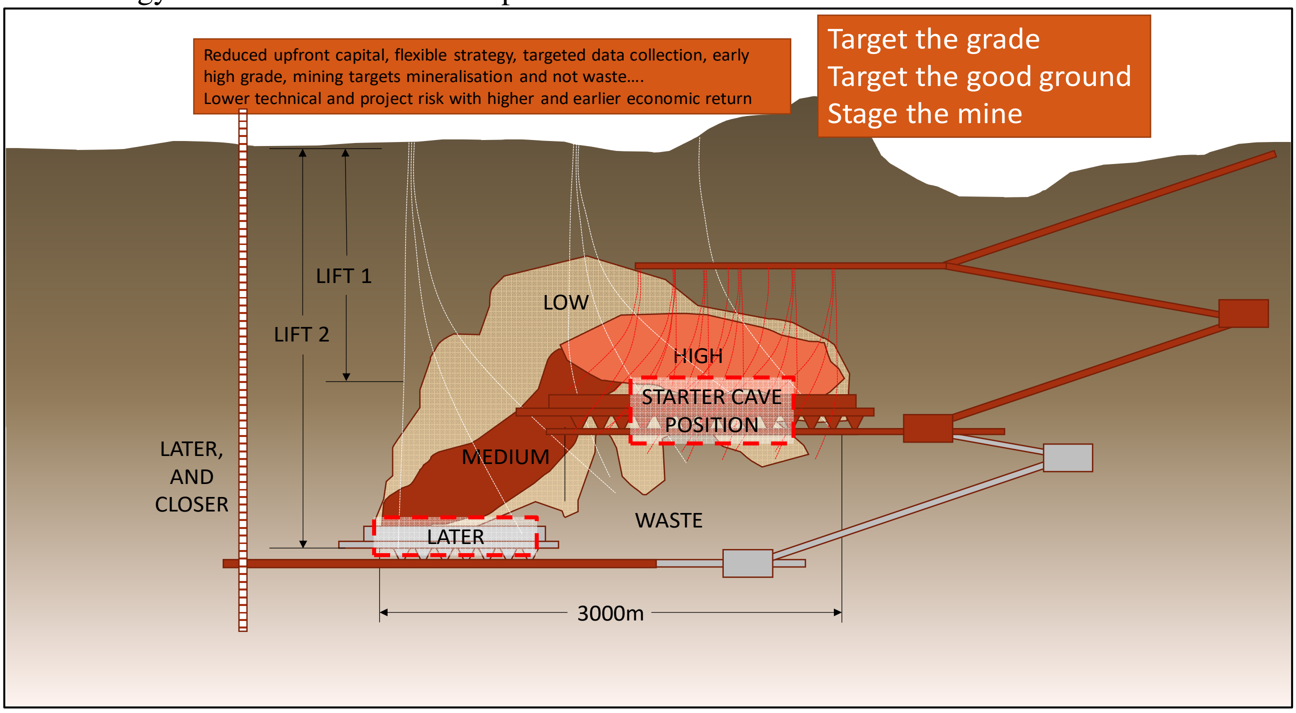

Figure 2 Schematic cross section through a staged design shaped to the deposit geometry.

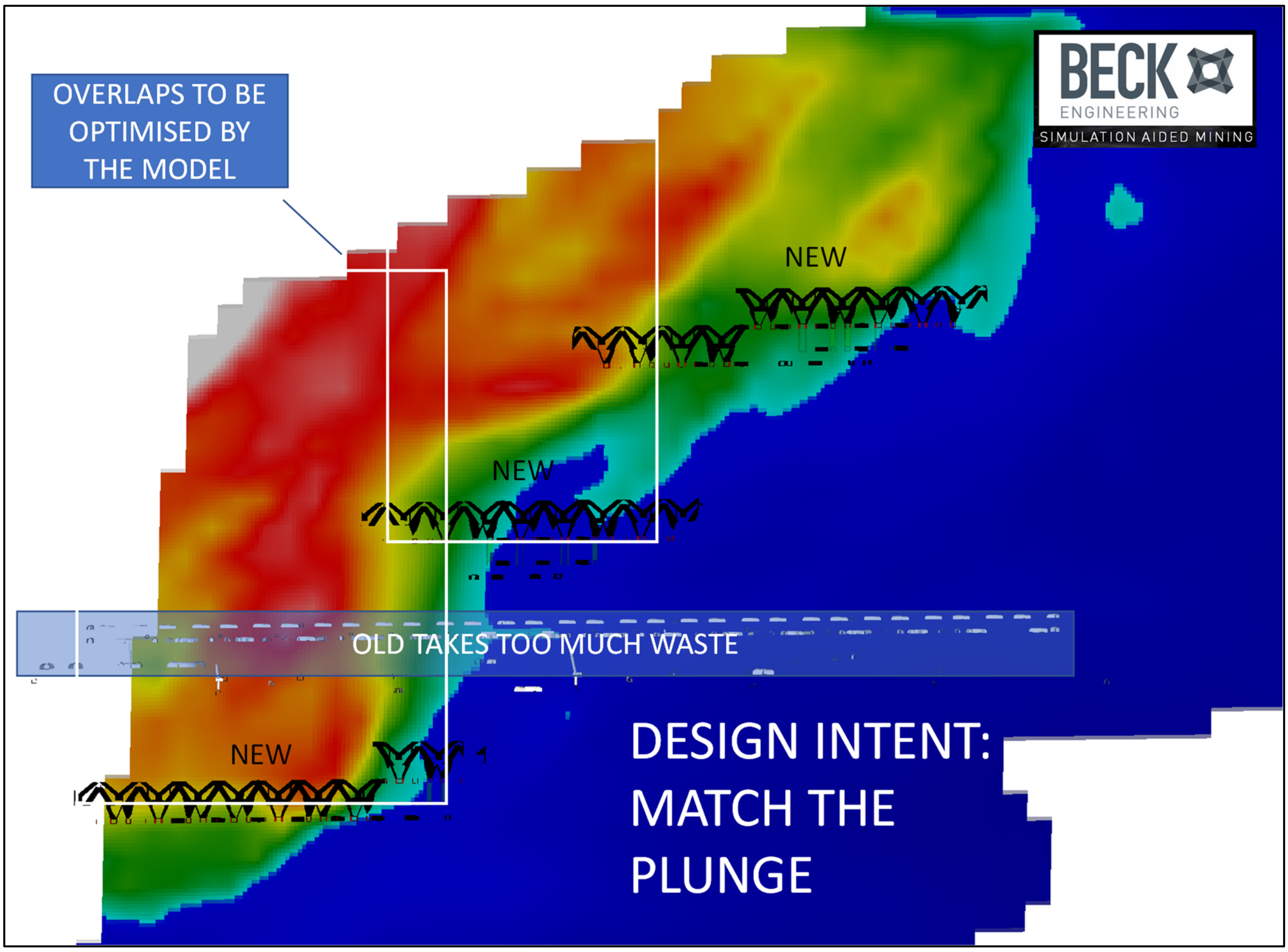

Figure 3 Section through the deposit showing the 'old' 2010 design and the alternative, staged design.

Ideally, the exercise will identify a target area which is insensitive to the main variables. For Pebble, it was found that there is a high value gradient at the base of the main high grade deposit core.

In other words, going too deep to 'chase' lower grade material simply lowers the average grade of the column, but puts at risk the higher-grade material higher up in the column.

This is demonstrated in Figure 3, which compares the old design and the first pass concept. Towards the west (right hand side) the old design went deep to scavenge low grade, but the likelihood of cleanly recovering the high grade in those columns was over estimated.

- 2nd pass – roughing in the footprints:
  - In the second pass practical footprints were fitted to this shape, spread across several levels. The basis for choosing the levels and block shapes was:
    - A minimum panel width of 200m (none were this narrow. This was a lower bound constraint).
    - Column heights not significantly exceeding 500m
    - Caveable shapes
  - This semi-automated process does not consider shape, access and sequence and can generate too many sub levels. By the end of the second pass, the precinct and target area for the future blocks is being constrained, so particular attention is paid to addressing any potentially unacceptable inter-block issues.

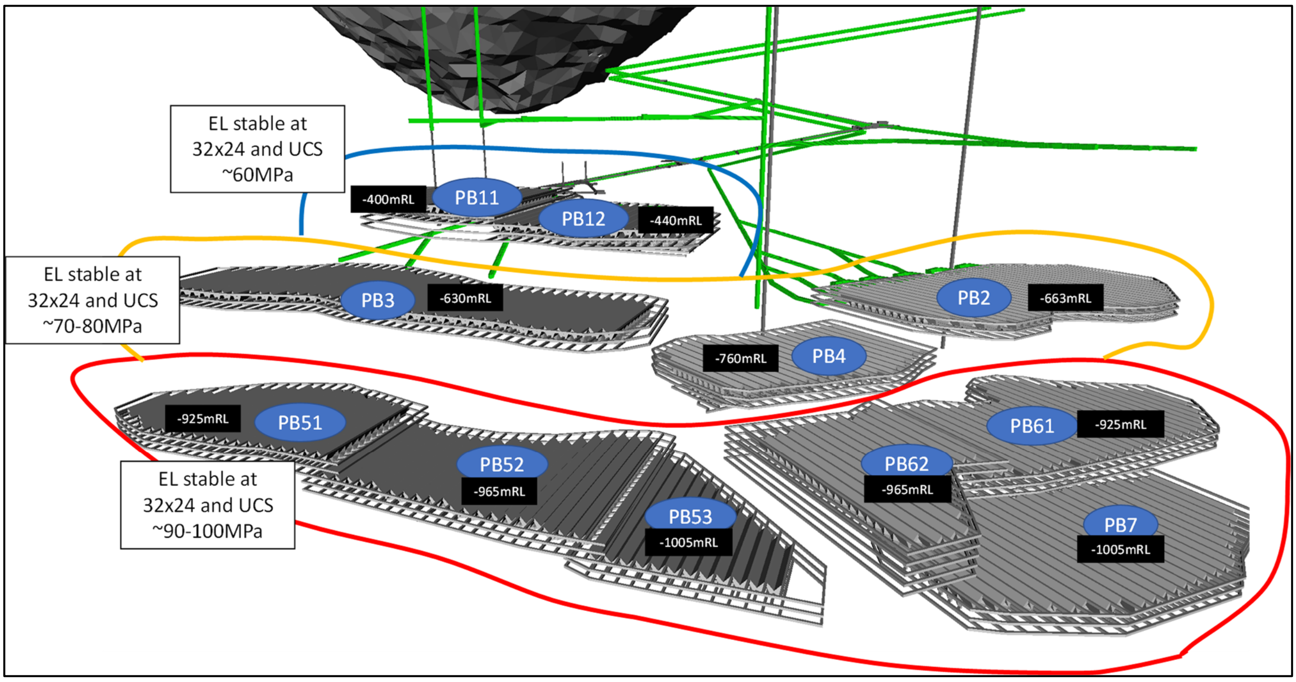

Figure 4 **Summary of the dependence on strength for sufficient stability.**

Production totals and RL for each block. Note that the design is preliminary, and changes to the detailed execution plan for each block to manage emerging geotechnical knowledge should be expected.

Table 1 **Production totals and RL for each block**

Name	**Production Tonnes_[kt]**	**Recovered_ [kt]**	**Recovered Au [kTroy Oz]**	**Recovered Mo_[kt]**	**Recovered Ag [kTroy Oz]**
PB11	73 300	356	458	18 200	4 360
PB12	118 000	409	1 170	21 600	2 940
PB20	414 000	1 780	3 440	92 700	13 000
PB30	278 000	1 350	1 810	67 700	12 800
PB40	243 000	1 030	1 680	47 000	8 710
PB51	206 000	1 030	1 120	63 300	8 140
PB52	213 000	1 290	1 850	56 000	8 990
PB53	116 000	611	1 140	22 700	4 690
PB61	415 000	2 170	2 030	123 000	18 000
PB62	186 000	1 020	1 260	44 400	8 180
PB70	334 000	2 000	1 320	101 000	15 300
TOTALS	**2 600 000**	**13 100**	**17 300**	**657 000**	**105 000**

- 3rd and 4th pass – refining the interactions between blocks:
  - In the 3rd and 4th pass, the shapes of each block were further adjusted in 3 dimensions to make them more practical to execute considering cost, access, fit to known geological structures, the RLs of adjacent blocks to share infrastructure and to 'chase value' where it is obvious that is possible.
  - This was an expert step. By the end of the 4th pass, access issues, mineralized

  material handling layout, stand-off and inter-block conflicts were being solved.

- 5th and 6th pass – final shaping of the blocks for sequencing, access and reliability:
  - In the 5th and 6th passes, the perimeter drives were laid out, the blocks divided to targetable sizes, applying constraints based on experiences, the global extraction sequence further developed and adjustments made to suit known poor ground.
  - The intent of these final design passes in a concept study was to arrive at a potentially executable design, fit for scheduling and simulation. This was also an expert step.

The 2021, alternative design is shown in Figure 4, which also shows a conceptual layout of the blocks, their horizon and the average strength required for reliable stability.

The essential elements of the concept are:

- A Prefeasibility Study (PFS) level design for a block needs explicit models of any rock mass defects passing through the block that approach the persistence of the block width. A knowledge of the general nature, trends and distribution of defects that approach a persistence of around 1/3 to half the block width is also required. For a PFS, for Pebble PB1 and PB2, estimated pierce points on the target footprint would be around 60m to 80m apart to complete this task.
- Ultimately, what is sufficient is driven by the complexity and should be guided by geologists to target resolution as described in Beck and Lilley, 2013.
- As it is the critical path, once PFS Exploration for PB11, PB12 and PB2 is authorized it should completed be as soon as possible via an exploration level, developed off the future conveyor decline. It is envisaged that the mining of the exploration declines and PB1 and PB2 exploration horizons, the drilling and the development of the improved resolution geological and structural models would take place as part of the PFS for these blocks.
- While diamond drilling of PB11 and PB22 is completed the conveyor decline would continue to the footprint for dewatering and to prepare for any trial mining tasks that may evolve from the conclusions of risk assessments in the PFS.
- At least some holes from PB1 exploration horizon would be extended to cover PB3 to assist in extending the major faults and as a start to improving the information there, but that is for Life of Asset planning. The majority of exploration efforts would be spent on PB1 and PB2.
- The exploration level for PB2 is mined off the conveyor decline below the turnout for PB1 exploration horizon, so PB2 would lag PB1. This lag needs to be scheduled, as it need only take place early enough to ensure PB2 is drilled out ready for PB2 studies. At present, we assume that the PB2 exploration horizon would be mined as soon as the horizon is accessed, and the diamond drilling would be prioritised just below PB11 and PB12 diamond drilling. PB2 starts some years after PB1 to stage investment and the overlap with the pit.
- As for PB1, the PB2 conveyor decline would continue to the footprint while PB2 PFS exploration is completed.
- Later, during production of PB1 and PB2, the respective exploration horizons would become a monitoring level used for placement of instrumented markers and observation holes.
- The PB2 exploration level can also be extended to cover PB4.
- The drill program will likely find major rock mass defects and variability that will lead to design modifications, so exploration for PB11, PB12 and PB2 is needed to develop sufficient resolution structural models and geological models to confirm the FEL2 design.

- Assuming PB11, PB12 and PB2 gate to production, they would be developed, and production would start.
- PB3 is the 3rd block, and sits just east, and below PB1. Given the gap between PB3 and PB1, it is suggested that most exploration could take place from crosscuts mined east from the PB1 footprint. Again, these crosscuts would serve as a monitoring level for PB3.

The same arrangement works for:

- PB6: its exploration level can be crosscuts mined east of PB2
- PB5: its exploration level can be crosscuts mined east of PB3.

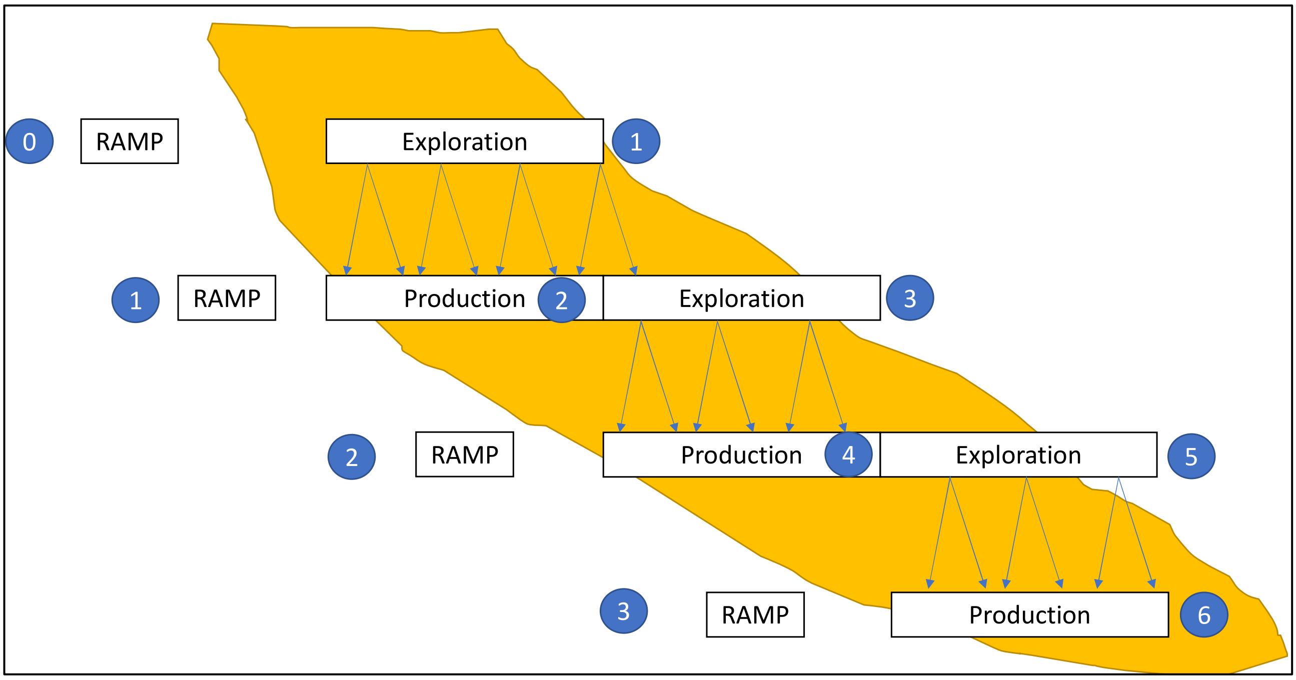

Figure 5 General outline of the exploration, development and mining sequence.

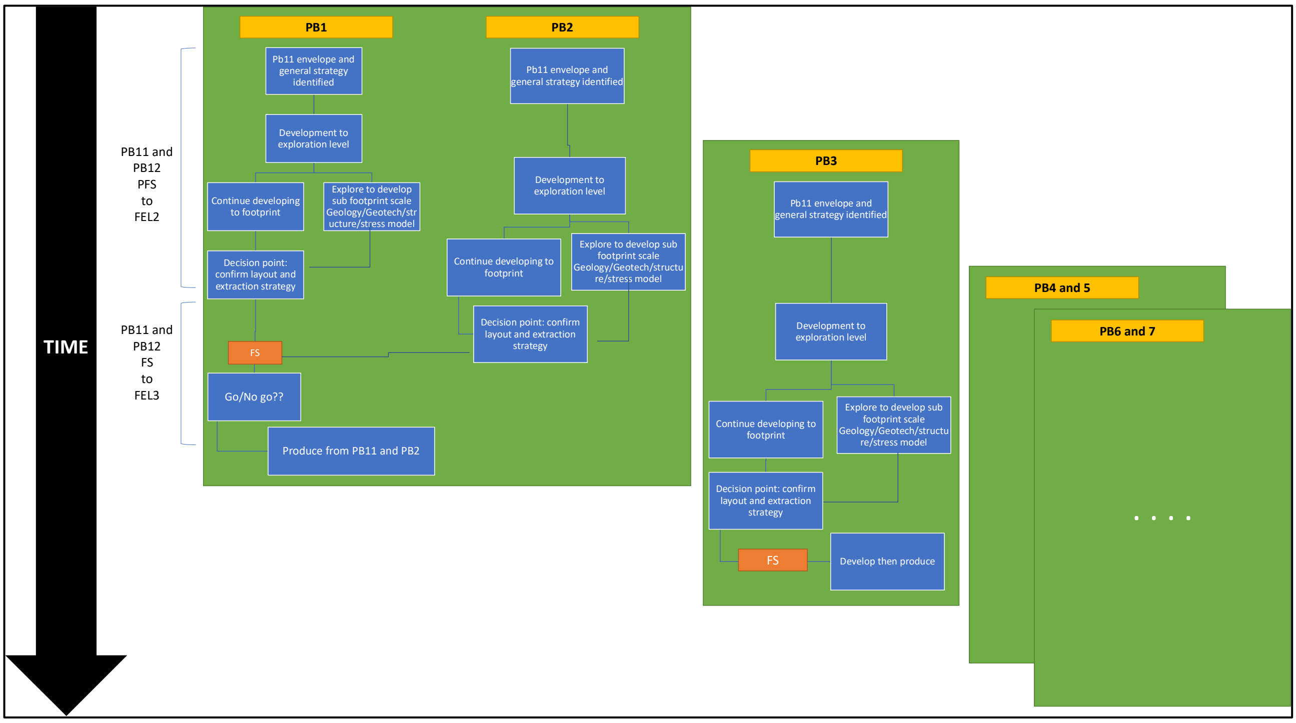

Figure 6 Sequence of proposed staging for studies, decision points, development, exploration and production.

A general outline and sequence for studies, decision points, development, exploration and production is shown in Figure 5 and Figure 6. Although implied above, the essential benefits to the approach are that it:

- Staged investment.
- Stages the in-fill exploration needed to finalise the design of each block

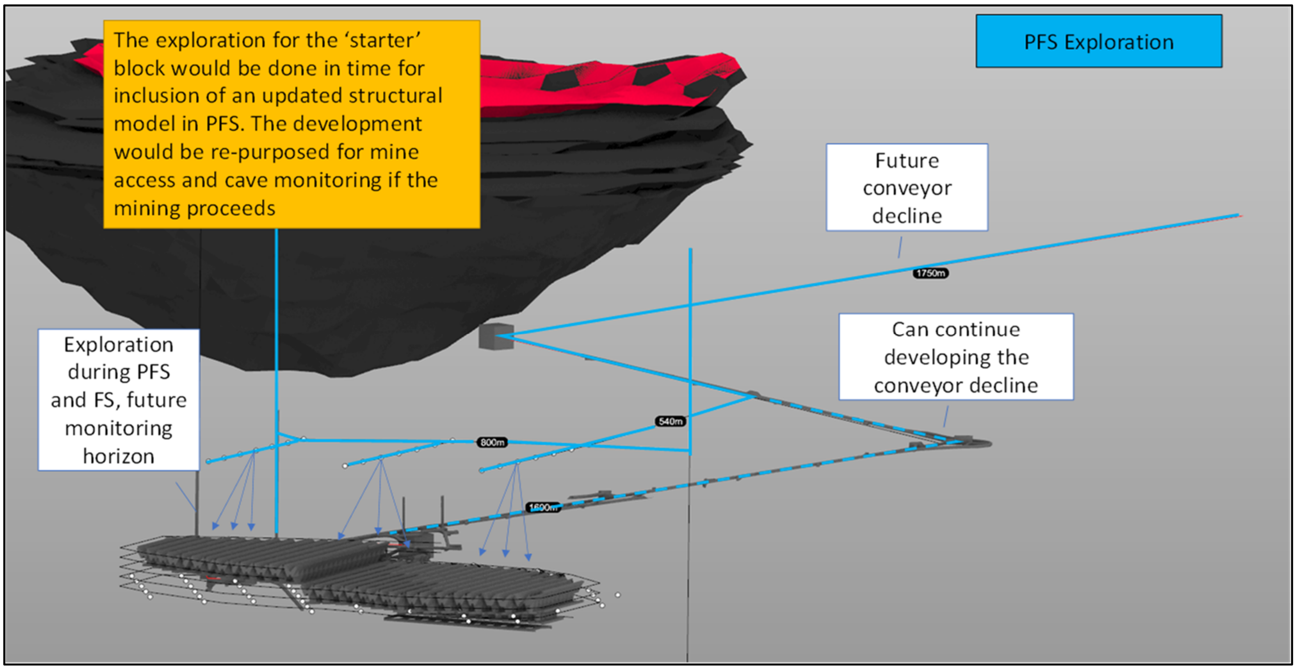

Figure 7 Exploration for PB11 and PB12

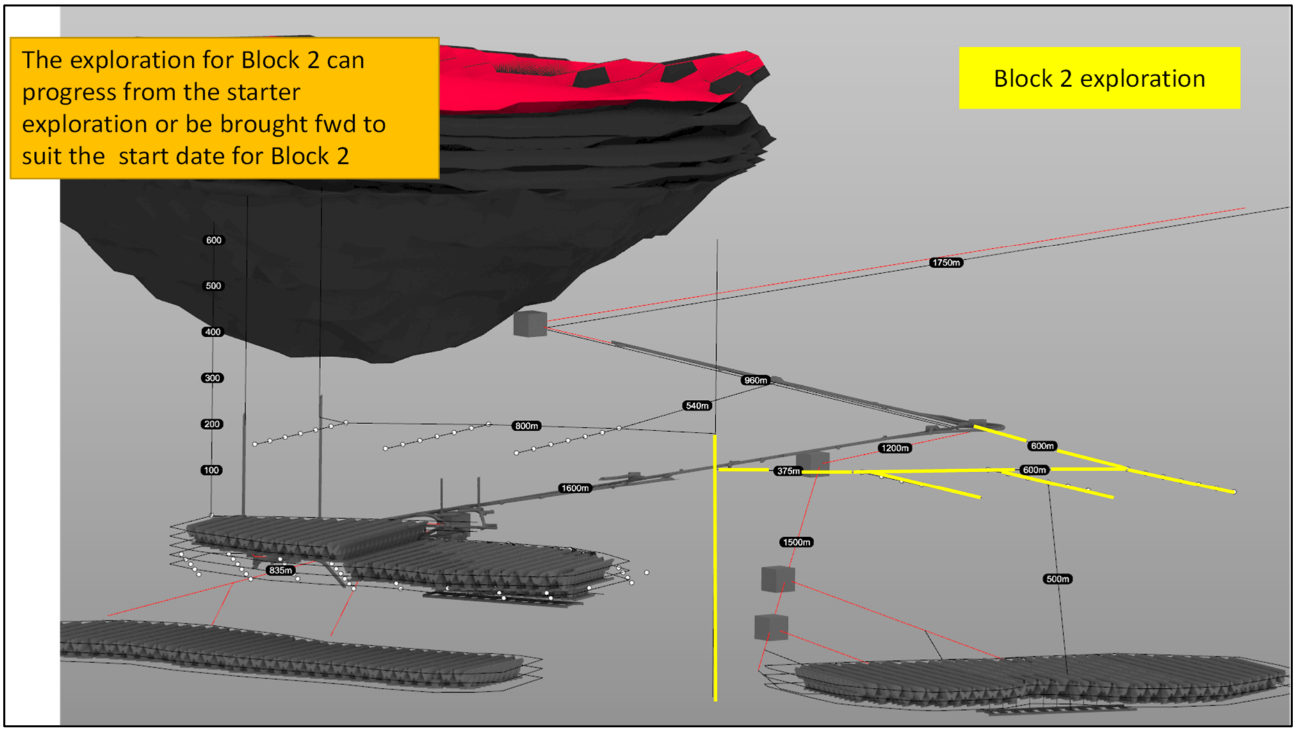

Figure 8 Exploration for PB2

- Permits an effective observational approach to manage environmental impacts arising from subsidence and drawdown.
- The assumptions and forecasts for each stage can be compared to measurements, and the reconciliation can be used to adjust and where

needed, re-permit subsequent stages or to not progress subsequent blocks or lifts.

- De-risks the impact of lower strength domains on reliability as the starter mine is shallower and therefore lower stress.
- Increases the grade
- Reduces the surface disturbance

3 CONFIRMING THE ALTERNATIVE DESIGN

The entire life of mine for the new plan has been simulated using an LR4-FS4 model (Beck Engineering, 2024). In this type of model the following elements are simulated:

- Draw of blasted material from the cave
- Flow of material inside the cave
- Changes in muckpile shape
- Loads and movement of rocks in the muckpile,
- Interaction between the caved rocks and the rock mass,
- Evolution of instability and cave growth, and
- Stress and strain outside the cave

The model has the following features:

1) the flow inside the cave is simulated by FS4 which is a Position Based Dynamics Discrete Element code.
2) the stress, strain and energy changes are simulated using LR4 which is a large strain, strain softening, dilatant discontinuum Explicit Finite Element model using only higher order elements
3) the coupling between the codes shared load, stiffness and stress information. This is described in Figure 9.
4) the transition from un-caved to caved is evaluated using acceleration and damage criteria.
5) the model includes the mines complete structural model and all relevant excavations, including passes, tunnels, drawpoints, drawbells and blasted rings
6) the entire life of mine has been simulated from beginning to end in steps small enough to sufficiently evolve the stress path.

Outputs that were evaluated include:

- Cave initiation and propagation
- Flow and the recovery of target and waste materials
- Stress and strain for all designed excavations
- Seismic potential, by evaluation of RER and increments of strain (Beck, 2022).
- Shaft deflection and strain
- Interaction with the open pit and preliminary evaluation of open pit stability.

The key differences in the 2021 simulation, apart from the design itself, is that the simulations are all cave shape constrained and can better capture the rilling and complex mixing that occurs at the leading edge of the advancing cave. This differs from past studies that did not consider cave shape when estimating recovery as described above.

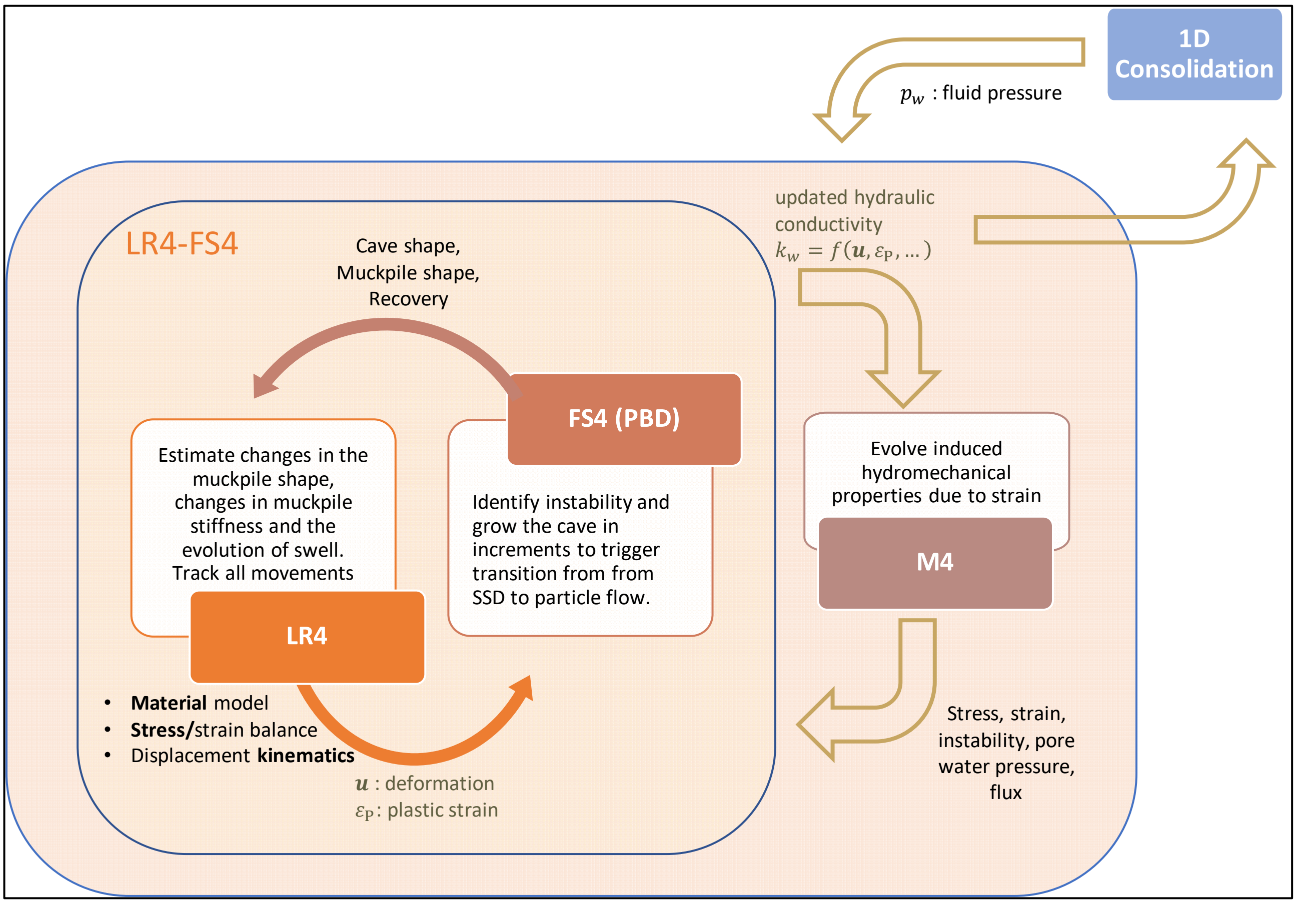

Figure 9 The coupling cycle for stress-strain-cave flow modelling using LR4-FS4

Several such models were run to optimise the draw strategy and to test a narrow range of cut-off grades.

It was noted that:

- Cell by cell metallurgical recovery was incorporated in these images, unless otherwise noted.
- The level-by-level plans of grade and recovered EqCu show that at least, in terms of footprint value, Pebble is a highly attractive prospect. There are higher grade mines, but the Pebble drawbells as designed are valuable.
- The first lift is economic on its own, paying for all access, exploration and production from lift 1 and the exploration and access to lift 2
- Lifts 2 and 3 are also preliminarily economic on their own, subject to current assumptions

The main vulnerabilities for the project are geotechnical, relating to stability, caveability and flow, and subsidence.

The rock strength estimates suggest a good rock mass on average but there are some very poor zones, and the strengths for all the geotechnical domains have a significant standard deviation. The size of the standard deviation alone suggests complexity which must be measured and managed by the design. To appreciate a range of potential outcomes a weak scenario was modelled and a case with average strengths to determine the strength requirements for stability in each lift. The results are summarised in Figure 4.

The analysis shows that for the new design, the footprint geometry is stable in lift 1 even for the weak case (UCS 60MPa). For subsequent lifts, feasibility of the layout and high performance depends on the average strengths being present and faults or poor domains being managed well. If the ground were poorer than expected or the poor zones more frequent, block transitions and pillars would be shaped around the poor zones, or partial recovery levels may be employed for more targeted alignment of sub block horizons.

4 CONCLUSION

A staged, multi-lift concept for Pebble has been developed based on numerous design and modelling iterations. The concept allows for a sequential development and sequential investment strategy. The shallowest blocks alone are likely to be viable as a stand-alone project.

The greatest uncertainties are similar to the uncertainties affecting all block caves at this stage of development: geology and rock strength. For Pebble, for at least PB1, which has been audited preliminarily, we think it is probable that a sufficient site investigation will show a more complex rock mass with more faulting and rock mass defects, but higher strengths.

The next steps are developing the exploration drift following the alignment of the proposed Lift 1 conveyor (after site investigation and subsidence analysis confirms the path), a level above PB1 and PB2 and essential ventilation rises. This would reduce the effort needed to collect the essential additional geotechnical and geological data to design the mine.

The critical path for the UG exploration program and the testing is also the critical path for starting the UG mine.

5 APPRECIATION

Thank you to the management of the Pebble Project for permission to publish this paper.

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