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Supplementary Information for

Some Challenges of Deep Mining

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1. Early development of continuum mechanics

> … One must mention the great difficulty encountered in its [continuum mechanics'] development. Mathematical analysis in those days was built on the concept of continuous geometrical space in which it was possible to consider infinitesimal segments and to introduce the processes of differentiation and integration on this basis. The universally recognized Newtonian molecular theory of structure of bodies, on the other hand, represented them as discrete media composed of individual particles that are connected with each other by the forces of mutual attraction and repulsion. It proved to be very difficult to justify the applicability to such media of the apparatus of mathematical analysis, which was essentially connected with the concept of continuous functions capable of receiving indefinitely small (i.e., infinitesimal) increments, and with the possibility of passing to the limit in their summation, i.e., in their integration. On account of this, the first works on the mathematical theory of elasticity gave rise to much discussion; their validity was questioned. However, the fact that even an extremely small volume, presumably isolated from a body, contains a great number of molecules prompted investigators to appeal to the law of large numbers and to apply the method which was subsequently called statistical; this made it possible to bridge the gap between the continuous space of mathematical analysis and the solid body as a discrete medium. It became possible to apply the powerful apparatus of mathematics to the development of the new branch of physics.
>
> … doubts concerning the physical justification of the method of elasticity dealing, as it were, with a continuous solid medium gradually disappeared. From this point of view, it is sometimes said that the theory of elasticity is based on the hypothesis of the continuous structure of solids. ***It must be borne in mind, of course, that this hypothesis is but a working hypothesis; it is dictated by the adopted mathematical method of investigation and does not intrude into the branches of physics that are directly concerned with the problems of body structure.*** (Excerpted from the Introduction of *Theory of Elasticity* [1])

More recently, Trollope [2] has asserted that the continuum hypothesis has limitations with respect to rock masses: "In the field of geomechanics, granular media and block-jointed rock masses are obvious examples where the concept of the ideal physical continuum—one in which no gaps are formed—cannot be expected to apply."

2. Back analysis of ground control at Mount Tyell Mine, Tasmania

Fig. S1 is derived from Fig. 1 in Ref. [3]. This publication describes the ground conditions and excavation support systems as the depth and mining methods were changed over the 80 years of operation of the Mount Lyell mine, Tasmania.

It is proposed to assess how ground conditions at the Mount Lyell mine might have been predicted to change as the mining depth increased, and what extraction procedures recommended, given the information on the rock mass properties available at that time, but using DEM and SRM concepts. The results will be compared with the ground conditions observed, and mining procedures used, at the time. This analysis will serve to illustrate the value of the DEM procedure in assessing the dominant factors controlling the limits to mining depth for specific ground conditions.

The Prince Lyell mine has a rich history, commencing with open-pit mining in 1935, and transitioning to underground in 1972. Between 1972 and 2014, a total of 64 Mt was mined underground as the mine extended from 210 m to 1100 m below the surface (mbs). As the depth increased, three changes in the underground mining method were made to meet the changing geotechnical conditions, ore grade, mining costs, and metal prices. The first of these was open stoping with pillar recovery in 1972, followed by front caving and longitudinal sublevel caving (1995), and finally transverse sublevel caving (2004–2014).

The horizontal to vertical stress ratio is approximately 0.8:1, which means that at 1000 mbs, the pre-mining major principal stress state (σ_1) is around 51 MPa, or an increase of around 5 MPa for every 100 m of vertical increase in depth. As the depth increased, four stages of geotechnical behavior were observed.

(1) Onset of stress-induced excavation instability issues. The first significant stress-related damage was documented at 490 mbs (σ_1 = 25 MPa), where considerable ground control problems were experienced in the mining of primary stopes. This included crushing

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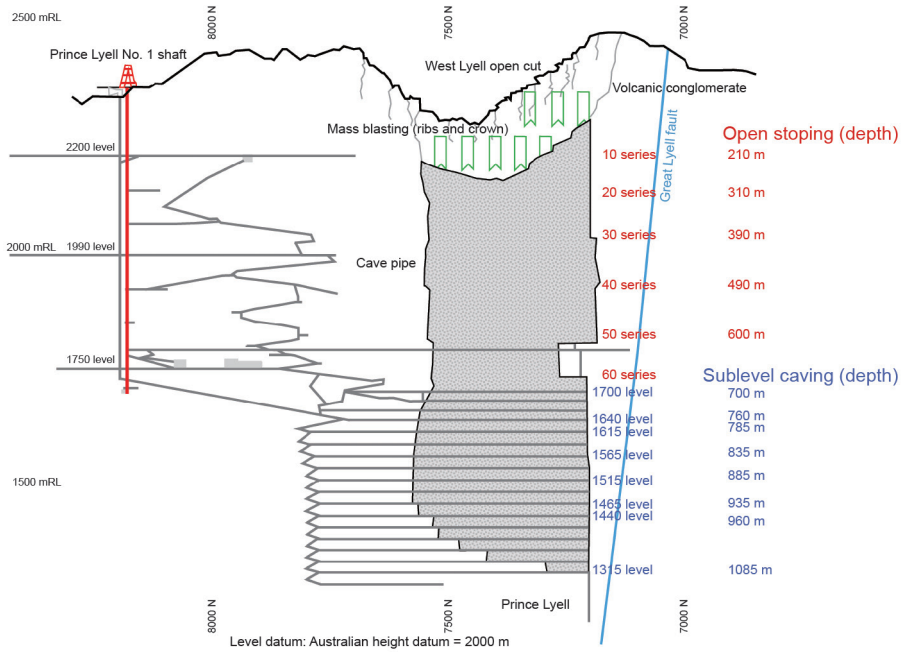


Fig. S1. Long-section view (looking north) of the Prince Lyell orebody and mining methods. (Modified after Fig. 1 in Ref. [3])

of large diameter drill holes, deformation of raise-bored shafts, and ring losses. Extensive stress-induced damage occurred in the extraction level drives.

(2) Increasing stress-induced excavation instability. In the 50 and 60 series stopes (600–700 mbs and σ_1 = 35 MPa), severe stress problems were experienced during extraction of the primary stopes. As a result, a destressing slot was mined across the strike extending 20 m in both the hanging wall and footwall directions, allowing for subsequent stopes to be mined in a relatively low-stress environment. The mining company, Copper Mines of Tasmania, commenced redevelopment of the operation as a transverse sublevel cave (SLC) retreat in 1995, below the 60 series on the 1700 level at a depth of 760 mbs (σ_1 = 39 MPa). The direction of the SLC retreat was changed with depth from longitudinal to transverse in order to help manage stress-induced damage ahead of the cave front in the tramming and access drives. The key factor controlling damage was the schist foliation, which—in the longitudinal layout—was oriented approximately parallel to the drive sidewalls. Stress-induced damage in the form of buckling on the foliation occurred in the walls of the extraction drives.

(3) Onset of time-dependent excavation behavior. On 1540 level (935 mbs or σ_1 = 48 MPa), time-dependent deterioration started to be noticed in the higher sericite schist. On the 1440–1315 levels (1085 mbs, or σ_1 = 55 MPa), several rock falls, occurred, the profile of the extraction drives was changed from a flat roof to arched. The introduction of this new ground support system improved excavation, and no rock falls were recorded in the newly supported production areas.

(4) Mobilization of faults leading to large seismic events. On the 1540 level (935 mbs or σ_1 = 48 MPa), both the quantity and magnitude of mining-induced seismicity increased substantially, especially during the slot initiation. Several large-magnitude seismic events, up to 2.4 local magnitude, were recorded. These large seismic events were attributed to slip on the Great Lyell fault, induced by stress interactions between the fault and SLC excavations. Ground support systems were adapted to mitigate falls of ground resulting from rockbursts, and re-entry protocols after blasting for seismically active areas of the mine were implemented.

Similar transitions in ground behavior have been experienced in many mining operations, highlighting the future issues that are likely to constrain or control underground mining. In some cases, such as Mt. Lyell, the behavior is well documented. In others, observations have been incorporated into empirical rules; in many cases it resides mainly in the minds of experienced engineers. All such sources, together with numerical modeling, are essential components of the rock engineering "laboratory."

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