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Geomechanical characteristics inferred from mine-scale rock mass behaviour

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Abstract

As with many other mining environments, the frequency of ground falls at Luossavaara-Kiirunavaara AB's Kiirunavaara Mine has increased with the progression of mining depth. These instabilities, which are unevenly distributed throughout the rock mass, have failure modes primarily including spalling, strainbursting, structurally controlled failure, and combinations thereof. Although caused in part by the mine-wide stress redistribution and geomechanical features of the rock mass, the exact manner in which these factors control the spatial distribution and characteristics of the ground falls not well understood. The objective of this paper is to describe the development of a geomechanical basis for how and why the distribution and characteristics of the ground falls differ throughout the rock mass.

Spatial and temporal characteristics of ground falls at the mine-scale were analysed using two main forms of data: 1) a database of ground fall events, and 2) laser imaging data. A methodology was developed specifically for the use of three-dimensional laser imaging data for mine-scale analysis of overbreak and falls of ground. In conjunction with geomechanical characterisation of the rock mass, these results can be used to assist with: identification of areas with higher risk of instabilities, production planning from an induced stress management perspective, location-based support system design in advance of drifting, evaluating the performance of drift development practice in different geomechanical conditions, and data collection and usage recommendations.

Keywords: *rockfalls, overbreak, geomechanical environment, laser imaging data, data collection*

1 Introduction

Meaningful correlations between the geomechanical environment and the spatial distributions of ground falls and overbreak can provide insight into expected problem areas in advance of drifting, enabling production planning from an induced stress perspective and location-based support system design. This has the potential to result in safer operations, while reducing costs associated with rehabilitation.

It is widely accepted that rock mass behaviour is correlated with geomechanical features and characteristics. Particularly large and/or damaging ground fall events are often individually analysed in detail, providing an improved understanding of the specific geomechanical characteristics that contributed to the event. However, this analysis is rarely expanded to the mine-scale, in particular for ground fall events, leaving little understanding of how geomechanically important features are spatially distributed. Often, data limitations in underground mining environments are not conducive to the statistical analysis required of databases that cover the mine, both spatially and temporally. The typical available data, databases of ground fall events, are often sparse and incomplete due to access restrictions and pressure from operations to rehabilitate the area in a timely manner. In surface applications, where data limitations are often less constraining, the spatial distribution of ground falls have been successfully analysed through the analysis of laser imaging data (e.g. Gigli et al. 2014; Abellán et al. 2010; Oppikofer et al. 2009), contributing immensely to the large-scale understanding of rock mass behaviour for particular sites. Some work using laser imaging has been completed in underground environments, such as Fekete et al. (2010), however, these applications have been limited to tunnels and have yet to be applied at the large-scale. Although currently uncommon in practice, analysis of mine-scale databases related to rock mass behaviour has the potential to improve the mine-scale understanding of which geomechanical features are of importance and how these features are spatially distributed.

Luossavaara-Kiirunavaara AB's (LKAB) Kiirunavaara Mine, in northern Sweden, exhibits behaviours typical of deep mining environments; seismicity, stress fracturing, and falls of ground. It is known that the falls of ground are unevenly distributed throughout the rock mass, however, the exact nature and the underlying causes of this uneven spatial distribution remain unidentified. Analysis of overbreak at the mine has not previously been completed at the mine-scale. This paper presents the analysis of traditional and non-traditional data sets regarding ground behaviour at the mine-scale. Correlations between these forms of behaviour and the geomechanical environment are postulated. The results contribute to a better understanding of rock mass behaviour at the Kiirunavaara Mine and demonstrate alternative methods for data collection and analysis that can have potential application in other underground environments.

2 Background and methodology

2.1 Kiirunavaara Mine

The Kiirunavaara Mine is located in northern Sweden. Producing approximately 28 million tonnes of iron ore per annum via sublevel caving, the mine is one of the largest underground mines in the world. The deepest active production level is currently Level 1051 m (approximately 820 m below surface). Along strike (Y-axis or the north–south axis in mine coordinates), the mine is divided into production areas called blocks (Figure 1). These blocks are used for production purposes and there is a name and coordinate change for levels deeper than Level 993 m, since production below this is passed to the newest main haulage level (Level 1365 m). The ratio of horizontal to vertical virgin stresses is approximately 1.28, and the virgin major principal stress is approximately horizontal and perpendicular to the strike of the orebody (refer to Vatcher et al. (2014) for more information on the stress field). The depth combined with the large induced stresses caused by sublevel caving of a 5 km long orebody and a heterogeneous, strong rock mass have resulted in seismicity and ground falls.

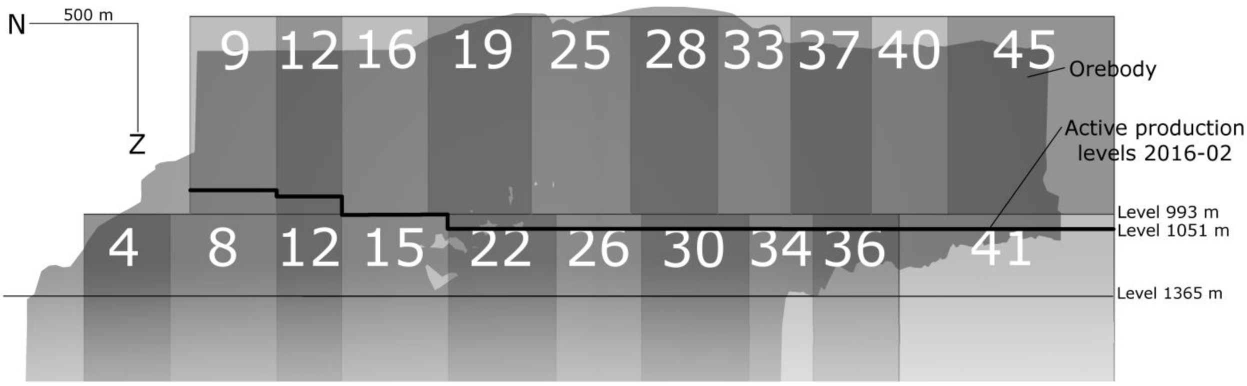


Figure 1 The Kiirunavaara orebody, seen from the footwall looking towards the hangingwall. Production blocks (based on mine coordinates) are shaded and labelled (numbers). The deepest active production level as of February, 2016 for each block is visible as a continuous thick black line along strike. The orebody has been extended along dip from the deepest orebody definition, as it is open at depth

2.2 Data

At the Kiirunavaara Mine, information regarding ground falls is available in two forms:

- The ground fall database.
- Laser imaging data of selected drifts.

Ground falls at the mine are defined as unplanned movements of rock that completely separate from the support system and excavation boundary. Usually they occur after development activities have ended, however, some falls of ground are from an unsupported face. The database (in Swedish) (LKAB 2016) consists of information on some ground falls at the mine. Larger ground falls are always included in the database, however, smaller rockfall events are occasionally not documented due to available resources. There is no official definition between large and small rockfall events at the mine; it is instead open for interpretation of the individual completing the documentation. Information in the database includes location of ground fall (occasionally coordinates, always production block), large/small classification, size (weight or volume), and failure mechanism/cause. Few ground fall events have complete information for all categories. The cause of each fall of ground is classified as one of five categories, which are translated below from Swedish (based on discussion with LKAB employees since written documentation does not currently exist):

- Seismically induced: This is the first cause that is evaluated for every fall of ground event. The seismic category is selected if a large seismic event was located near to the ground fall and close to the estimated time of the ground fall. The definition of 'nearby' is decided by the individual completing the documentation, and is specific to the area of the mine (for example, a wider search area is used in the southern portion of the mine). This is based on the past experience and knowledge of those completing the documentation. For those rockfall events listed as caused by seismic activity, the magnitude and location of the seismic event are usually found in the database. This means that the failure mechanism can include rockbursting (violent failure where the seismic source event is not at the ground fall location, including fault slip events), strainbursting (violent failure where the seismic source event is at the damage location), and dynamic shakedown of existing blocks. Moment tensor inversions are not routinely performed, and, therefore, are not part of the database.
- Related to geological structure(s): Pre-existing discontinuities are believed to have been the underlying cause of the ground fall. Due to practices related to identifying events associated with seismic activity, the vast majority of rockfall events that are classified as related to geological structures are time-dependent unravelling, rather than seismic shakedown.
- Stress related: Used to represent a variety of failure modes caused by stresses, where no related structures or seismicity can be identified. Failure modes include spalling (onion-like flaking around the surface of the opening), strainbursting, and rockbursting. It should be noted that the latter two of these failure modes are included as failure modes of stress related events, in addition to failure modes of seismic related events, since the seismic event may not have been identified. There is no distinction between high or low stress related failure modes.
- Blast related: This category is used when it is known that production or development blasting was the cause of the ground fall. The failure mechanism of the majority of events in this category is shakedown.
- Undecided: This category is used due to a number of potential reasons, including: unclear failure mechanism, occurring in an area outside of the coverage of the seismic system, and lack of available personnel resources for documentation.

The ground fall database contains data from 2008 and onwards. Ground falls are grouped into production blocks; each group consists of two production blocks, one of which is above Level 993 m and the other is below. For example, events from Block 33 (above Level 993 m) and Block 34 (corresponding block below Level 993 m) are grouped together in the database.

To isolate the influence of geomechanical environment, it is important that the database is comparable throughout time and space. For example, a good degree of comparability is retained throughout this database since the drift design remains unchanged. There are, however, some changes external to the ground fall database that may influence the data:

- Approximately in the middle of 2013, two additional personnel were hired to assist with data collection. This may increase the recorded number of events, since there are more resources devoted to data collection.
- The seismic system has undergone expansion, in particular in 2012 and 2013. This could lead to an increased number of events being classified as seismic, since the coverage of the seismic system improved.
- In 2010, the mine-wide support system was redesigned and implemented to accommodate more dynamic loading.

In addition to the database, there exists laser imaging data of some of the footwall drifts of the lower levels (Level 1070 m, Level 1165 m, Level 1252 m, and Level 1338 m). This data was obtained over a short time period (compared to the mining sequence), and only one model exists. The work was completed in connection with the development of the most recent main haulage level, Level 1365 m. The data spanned from Block 12 through Block 41 (Figure 2). Once processed (see Section 2.3), 8,275 m of drift data were available for analysis. There are some important features of note with respect to this data:

- Level 1070 m is a media drift (used for electricity, internet etc.) located in the footwall, has design dimensions of 8 m wide and 5.5 m high, and is located approximately 300 m horizontally from the orebody. For consistency with the mine’s terminology, design profiles are referred to as design profiles throughout this paper (Figure 2(b)). The remaining drifts (Level 1165 m, Level 1252 m, and Level 1338 m) are orebody access drifts from the footwall. Their design profile is 6 m wide and 5.5 m high, and are located on average 80 m horizontally from the orebody (Figure 2(c)).
- At the time of imaging (approximately at the end of 2010), the support system had already been installed (this includes bolts, mesh and shotcrete).
- At the time of imaging, areas that had experienced a fall of ground had already been rehabilitated.
- In general, all of the drifts are oriented with the local strike of the orebody. At the mine-scale, the strike of the orebody is north–south. However, there are slight changes in orientation at the block scale, as shown in the plan views of the media level (Level 1070 m), and a representative ore access drift (Level 1165 m) in Figures 2(b) and 2(c), respectively.
- The mine considers approximately 10% overbreak acceptable and expected (Quinteiro, pers. comm., 25 August 2016).

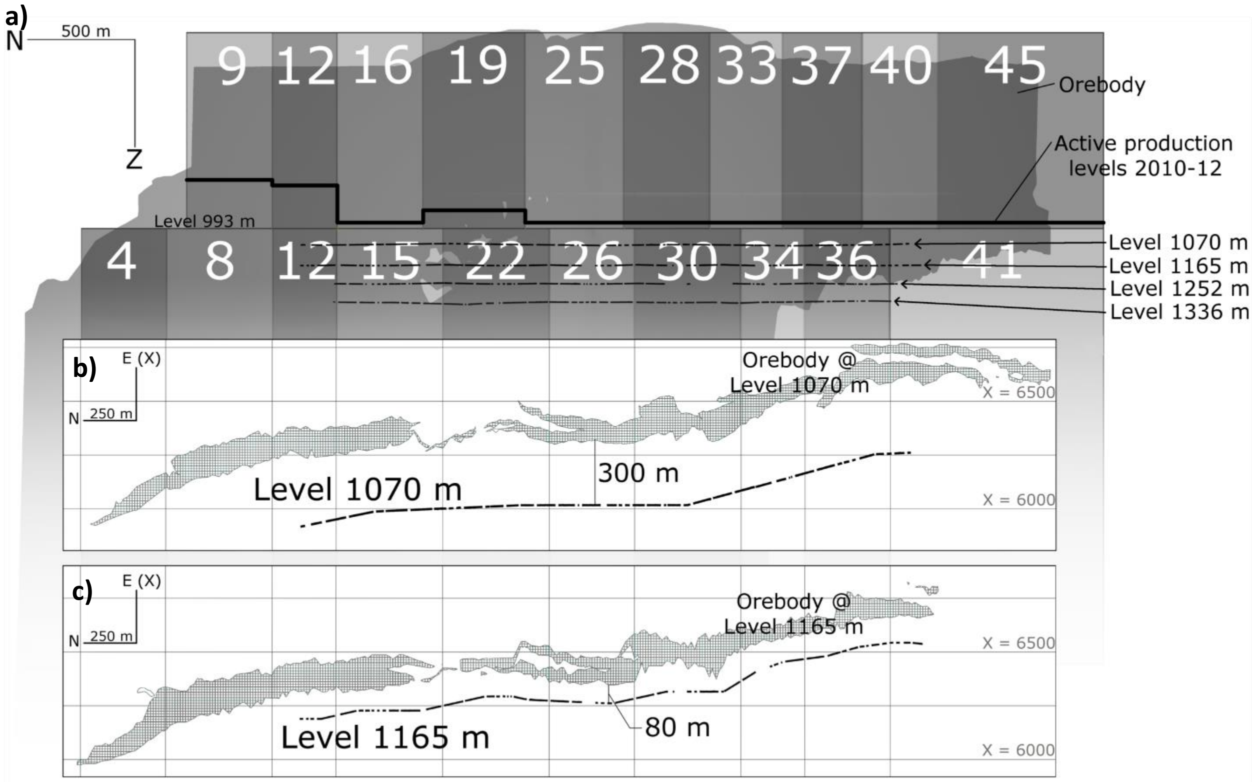


Figure 2 Views of the admissible drift data (laser imaging, black): (a) shows all 8,275 m of data from the footwall towards the hangingwall. The deepest production level for each block at the approximate time of imaging (end of 2010) is shown. Production blocks are labelled (numbers); (b) shows the data on the media drift, Level 1070 m, from above with a horizontal slice of the orebody at the same level; and, (c) shows the data on a representative orebody access drift (Level 1165 m), from above with a horizontal slice of the orebody at the same level

2.3 Methodology

The concept underpinning this methodology is to evaluate a large number of data, spatially and temporally spread throughout the mine, to isolate for the effect of geomechanical environment. For example, provided the data are comparable, areas in the rock mass that have more ground falls and overbreak provide information about the local geomechanical environment. This information can be a combination of rock mass characteristics as well as stress state during the time of the ground fall/overbreak. The importance of having sufficiently large databases for this type of analysis cannot be understated.

Both descriptive and inferential statistics were used to analyse the two forms of data. Fall of ground events from the database were evaluated by physical locations in the mine, by active production level at the time of the events, and for temporal patterns.

The laser imaging data of footwall drifts were divided into 5 m long sections along their three-dimensional (3D) centreline (Figure 3). This section length was intentionally selected as it is equivalent to round length at the mine, thereby equally distributing the shape caused by individual rounds across the database. Sections with planned geometry that veered from a standard drift pattern (such as drift intersections) were excluded from the analysis so that all data were comparable. The surface area of each 5 m section of laser imaging data was compared to the surface area of a 5 m length of the design (accounting for planned shotcrete thickness), and a percentage overbreak was calculated. Inferential statistics as well as spatial patterns in the data were analysed. The dataset is intentionally large so that underlying patterns in overbreak emerge, rather than focusing on the effects potentially caused by distinct mining crews, e.g. a specific crew's scaling techniques.

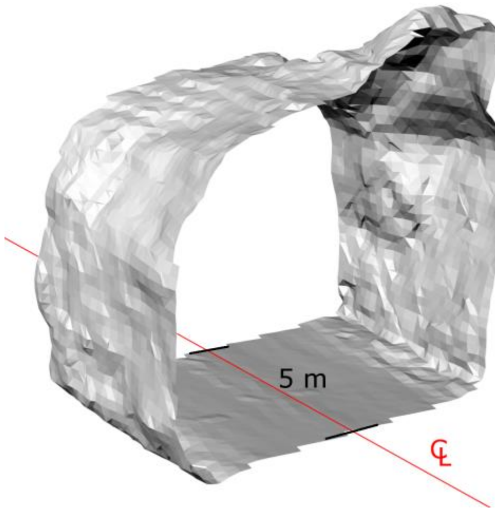


Figure 3 **Example of one processed data point from the laser imaging data. The scanned drifts are divided into 5 m sections (equal to round length) along the 3D centreline (line labelled ℄)**

3 Results

3.1 Ground falls

Of the 817 ground fall incidences in the database at the time of extraction, approximately half were considered to be small (Figure 4). This size distribution is relatively consistent throughout all production blocks in the orebody. However, the number of events throughout all production blocks is not evenly distributed. Figure 4 shows that there are fewer events near the margins of the orebody. Although this may in part be due to shallower production depth in the northern portion of the orebody, the southern margin also experiences fewer ground fall events despite having the same production depth as the central portion of the orebody.

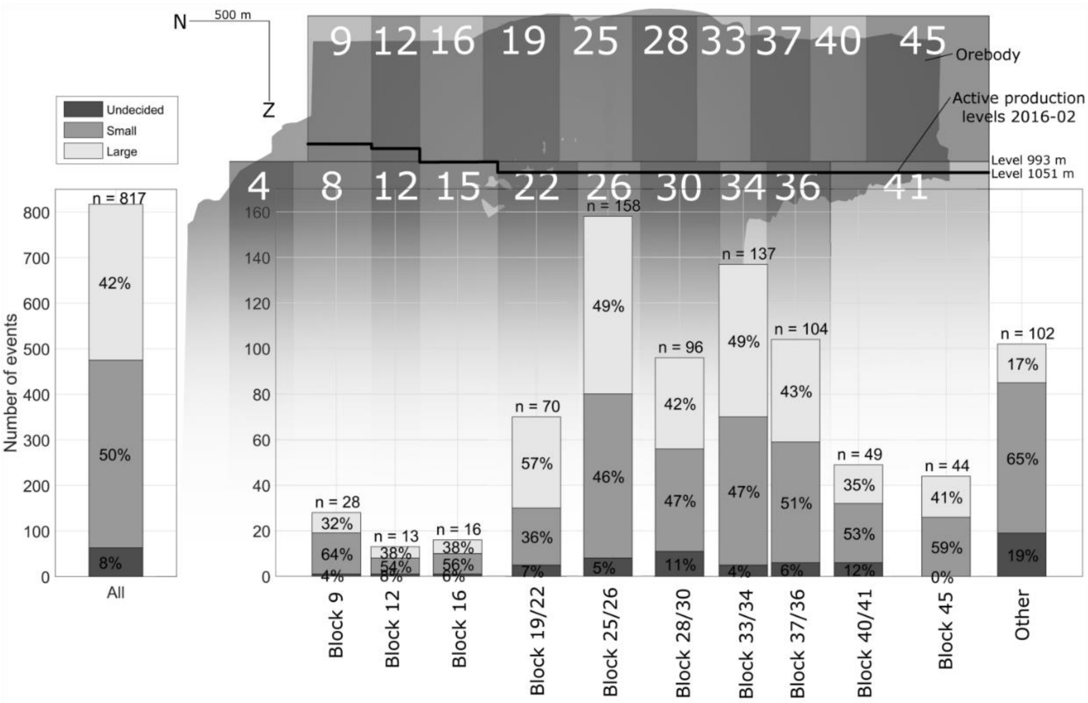


Figure 4 **Number of ground fall events by size (undecided, small or large) and production block overlaid on view of the orebody from the footwall towards the hangingwall. Note that location 'Other' refers to falls of ground in the main infrastructure area located away from and approximately in the middle of the orebody**

The number of ground fall events by category for the entire mine and each production block is shown in Figure 5. One of the most immediate realisations is that a large proportion of events across the mine have been categorised as undecided. The cause of this may be because the selection of category was unclear, multiple categories may have been appropriate, or the resources for documentation may not have been available. The results from the remaining categories are summarised as follows:

- There was a higher proportion of ground falls related to seismic activity in the inner portion of the orebody (Block 19/22 through Block 33/34) than the outer portions.
- There were relatively few ground falls related to geological structures. Those events that were, tended to be near the northern margin of the orebody (Block 9 and 12).
- Stress related falls of ground were more common in the inner portion of the orebody (Block 19/22 through Block 40/41) than the outer portions. These have a wider spatial variability than the events related to seismic activity.
- Few ground fall events were related to blasting. They were relatively evenly distributed across the mine.

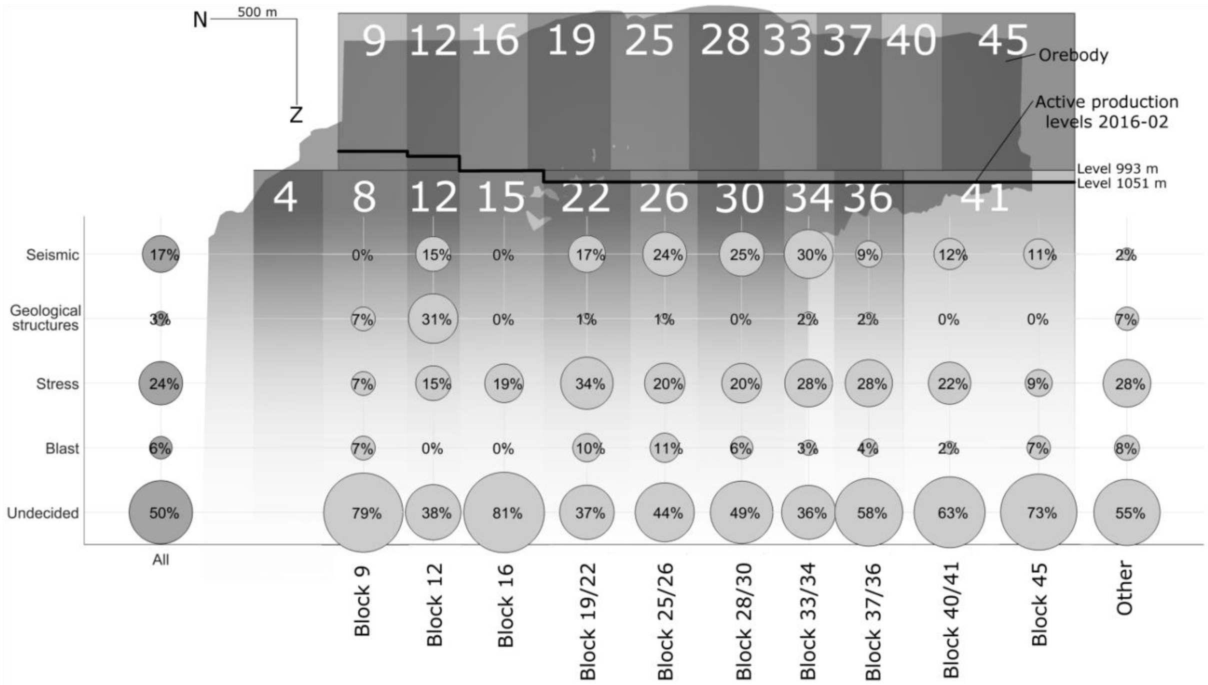
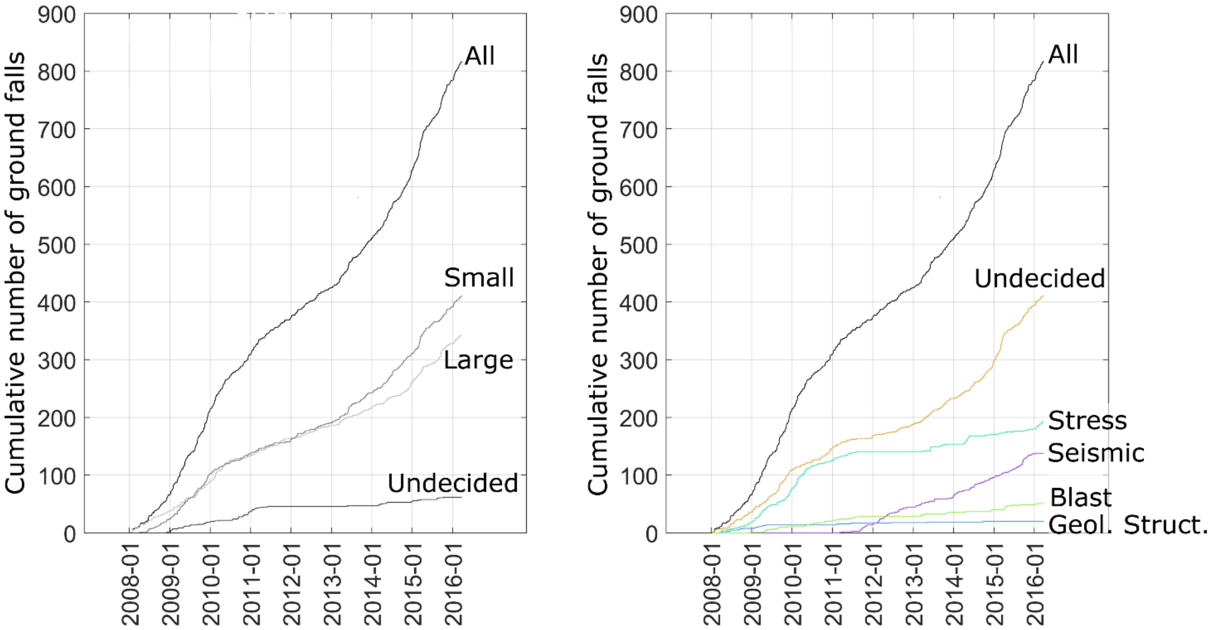


Figure 5 Number of ground fall events by category (seismic, geological structures, stress, blast or undecided) and production block. The size of each circle is proportional to the number of events (percentage of total events per column listed). Background shows view of the orebody from the footwall towards the hangingwall with production blocks and active production levels at the time of database extraction

In addition to considering location of ground falls, it is important to evaluate how the number of events changes over time. Figure 6 shows plots of the cumulative number of ground fall events throughout time. When considering the database as a whole ('All' in Figure 6, left and right), there are some distinct changes in the rate of ground fall events. Approximately in the middle of 2010, the rate of ground falls decreased and remained supressed until approximately the middle of 2013, after which the rate of events increased significantly. The initial decrease is likely due to the effectiveness of the new support system installed in drifts developed in 2010 and onwards. The increase in events in 2013 is likely due to a combination of 1) the mine is experiencing more events with increasing production depth, and 2) the availability of extra resources for documentation due to personnel commencing in mid-2013.



(a) (b)

Figure 6 Cumulative number of ground falls throughout time. The ground falls are divided into: (a) size category and (b) type category

The plot in Figure 6(a) separates the events based on their size category. Until 2013, the rate of large and small events was relatively similar (Figure 6(a)). However, during 2013 more small than large rockfall events began to be documented. This may be due to additional resources for documentation (more small ground fall events are recorded with extra personnel).

The plot in Figure 6(b) separates the events based on the categories describing the cause of the ground fall. Some significant changes in rockfall incidence rate exist when considering ground falls related to seismicity and stress induced events between 2011 and onwards. Near the beginning of 2011, the rockfall event rate related to stress declined significantly. In 2013 the rate of these rockfall events increased. Almost simultaneously in 2013, the number of ground falls related to seismicity increased. After that point, the rate of seismicity related rockfall events stayed relatively constant. This is likely related to expansions of the seismic network in 2013 as well as higher levels of seismicity due to an increased production depth. Ground fall events categorised as blast and geological structure related were few and relatively constant over time.

Supporting the hypothesis that the additional resources for documentation lead to the increase in the recorded number of small events in 2013 (Figure 6(a)), there was an increase in the number of ground fall events without a cause classification ('Undecided' in Figure 6(b)). These events with undecided cause had a greater proportion of smaller events than the entire database. This may indicate that the additional resources allocated to data collection increased the number of small events recorded, however, the cause was often not recorded, perhaps due to uncertainty and/or belief that it was inconsequential due to the ground fall size.

Separating the cumulative number of events by their production block reveals a similar pattern to that of the size and classification of the events; the central portion of the orebody behaves differently than the outer margins (Figure 7(a)). Block 19/22 exhibits a different pattern of cumulative rockfalls than the other blocks in the inner portion of the mine (Figure 7(b)). It has distinctly fewer events and does not exhibit the same patterns in changes of rockfall incidence rate as the other blocks. This is likely due to a lengthy pause in production in this block. The majority of the inner blocks, excluding Block 19/22, show a reduction in the rate of events around 2010. Block 33/34 does not show a definitive slowing this time. An increase in the number of events is experienced in all blocks except for Block 19/22 and Block 33/34 close to the beginning of production on Level 1022 m.

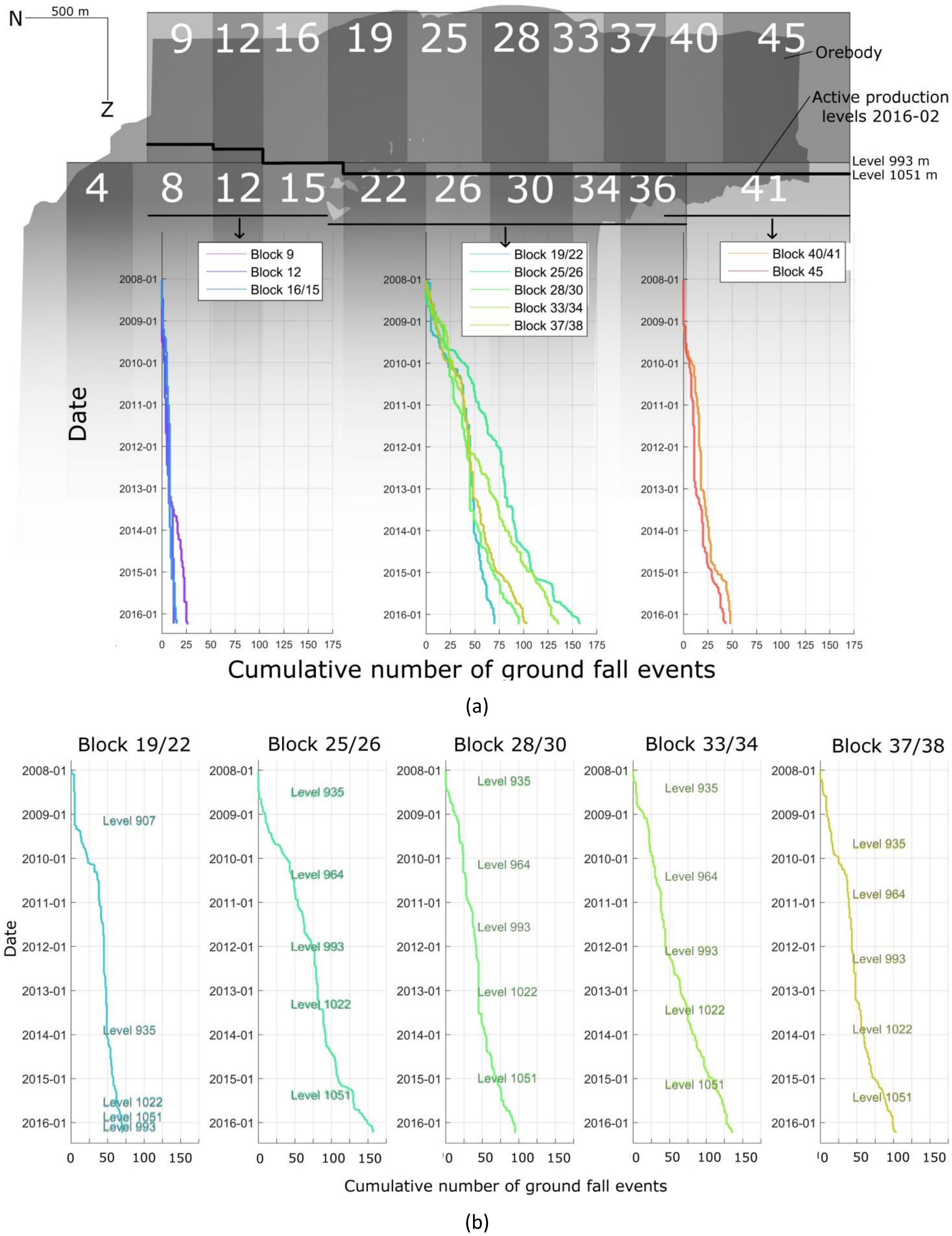


Figure 7 **Cumulative number of ground falls separated by production block for: (a) the entire mine (viewed from the footwall towards the hangingwall); and, (b) the inner portion. The date of the opening of each level for individual production blocks is overlaid on the cumulative ground fall data in (b)**

3.2 Overbreak

Histograms of the surface areas of the 5 m sections are shown in Figure 8, separated by level. The vast majority of the sections exhibit significantly larger profiles than the theoretical design profile (0% overbreak, shown as labelled vertical lines in Figure 8). From a percentage overbreak perspective, the media drift (Level 1070 m) has less overbreak than the orebody access drifts, despite having a larger theoretical design profile and being the shallowest. Level 1165 m was the nearest to the deepest active production levels at the time of imaging (approximately 200 m away to the deepest active production level in 3D), followed by Level 1070 m (250 m), Level 1252 m (280 m), and Level 1365 m (370 m). There does not appear to be a correlation between mean overbreak per level and minimum distance to the active production levels at the time of imaging. The majority of the drifts exhibit nearly normal distributions, with a mean value that is larger than the theoretical design surface area. The normal distributions indicate that the increased size of the drifts are likely due to the initial excavation process rather than rehabilitated areas caused by large induced stresses and geomechanical characteristics. The production drifts have more outliers to the right of the mean than the media drift (Level 1070 m), which likely represents areas which experienced ground falls (rehabilitated before the time of imaging). These results may indicate that the production drifts (located 80 m horizontally from the orebody) and the media drift (located 280 m horizontally from the orebody) are in different geomechanical environments.

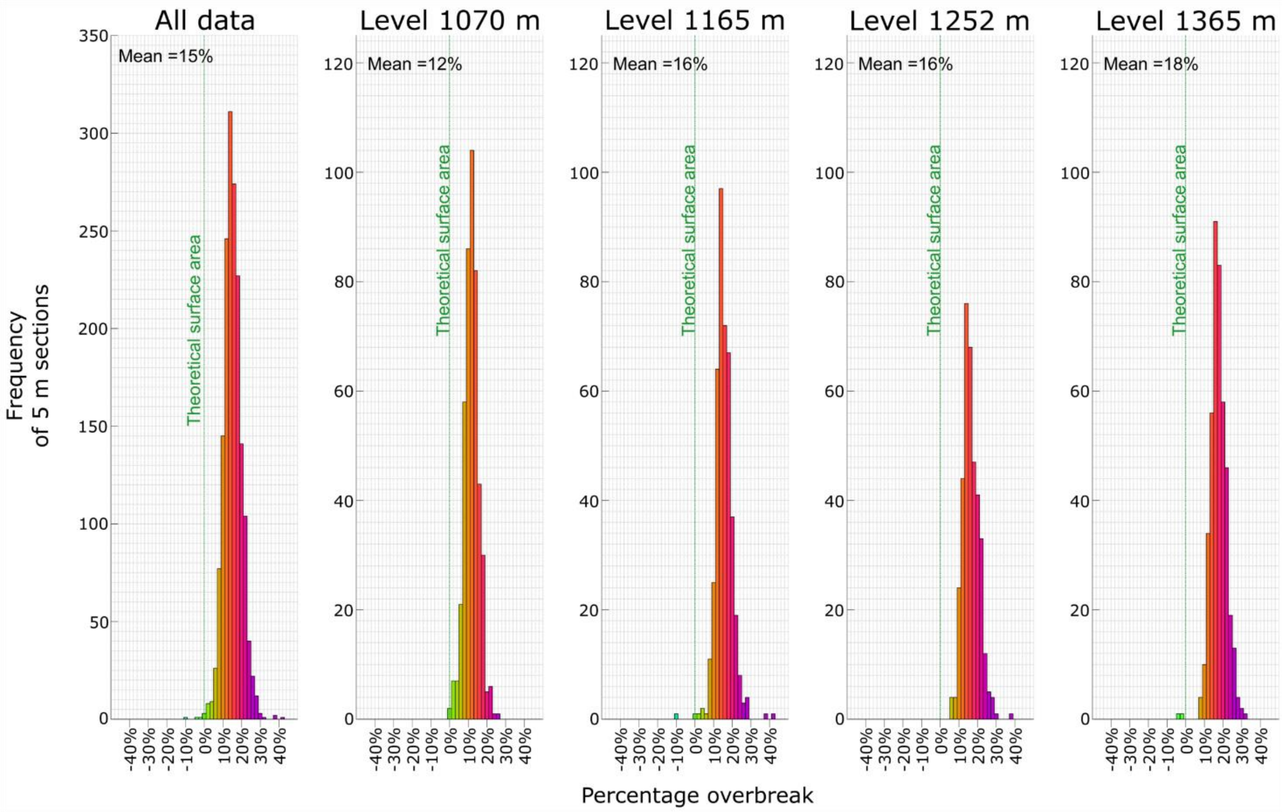


Figure 8 Distribution of surface area of laser imaged drift sections (5 m length) by level

Many levels and blocks have approximately normal distributions (skewness and kurtosis tests were performed on all data). Those blocks, divided by levels, with normal distributions are shaded in Figure 9(a). A close up of an example block, Block 34 if provided in Figure 9(b). Notably, in all cases except for one (Block 30 Level 1070 m), the non-normal datasets are skewed towards the right, meaning that there are an increased number of sections with larger overbreak (possibly ground falls, but clearly some difficulties due to ground conditions). Non-normal distributions did not correlate with the average surface area of the dataset; having a skewed dataset does not indicate a larger average overbreak. This is likely due to the smoothing nature of averaging; the mean overbreak should be interpreted as an indicator of the average rock mass quality, rather than indicative of the worst material in the area.

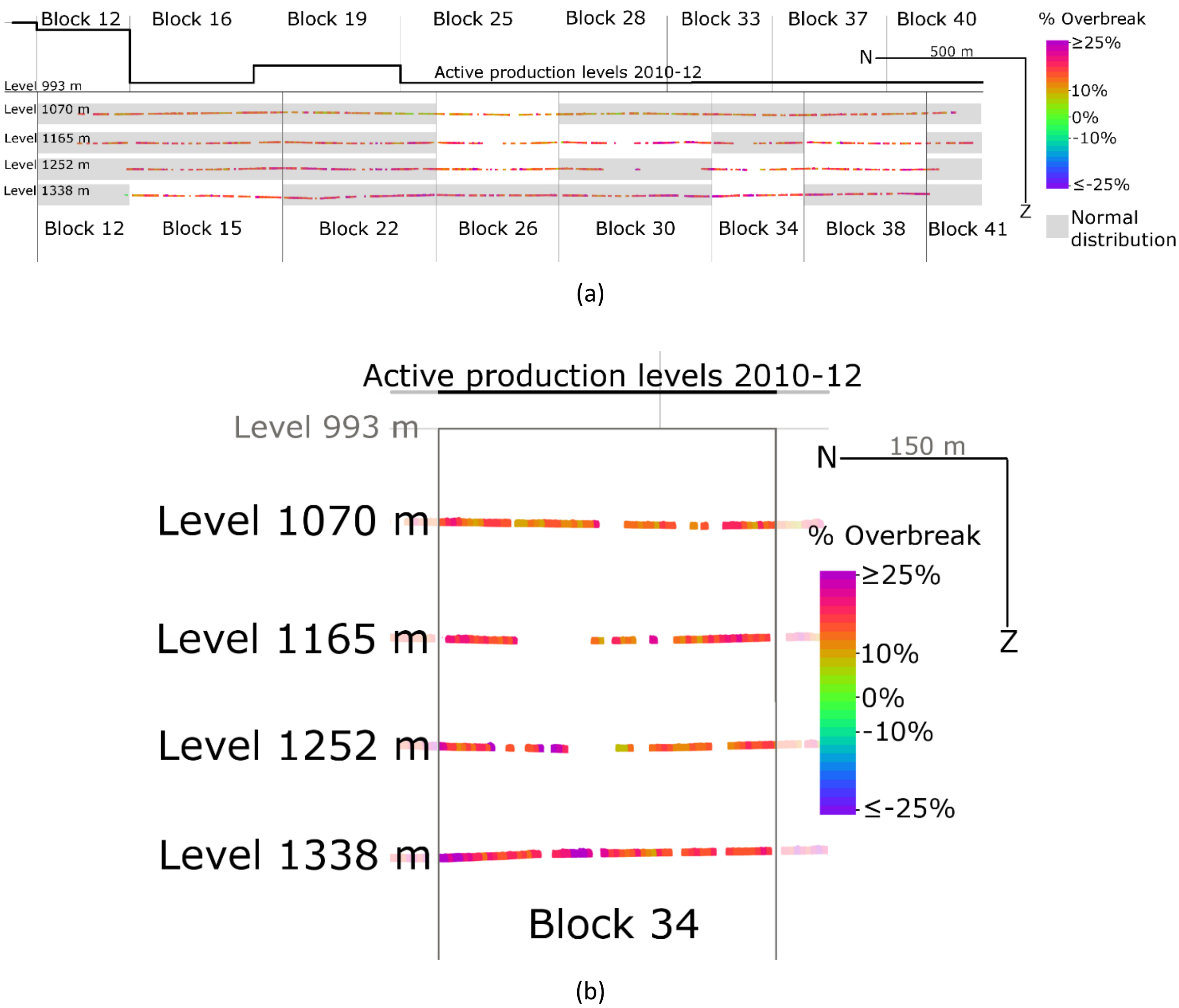


Figure 9 Laser imaged drift sections (5 m length) coloured by percentage overbreak, viewed from the footwall towards the hangingwall: (a) shows all data, where shaded areas, by production blocks and levels, have normal distributions; and, (b) shows the detail with a near view of data in Block 34

In general, more overbreak was experienced in the southern area of the orebody. That includes Block 26, Block 30, Block 34 and Block 38, but seemingly not Block 45, although data is more limited in this region. This is likely due to local changes in geomechanical environment. The small changes in drift orientation in this data do not appear to play a role in the spatial patterns of overbreak. Patterns of overbreak are, however, apparent at the block scale. Figure 10 presents an area, selected as an example, viewed from above. Confirming the histogram analysis, the media drift (Level 1070 m) has a distinctly different overbreak pattern than the orebody access drifts in the same area. Patterns in the breakout data are apparent when the access drifts are viewed from above; there are distinct areas approximately aligned with the block boundaries that consistently experience similar amounts of large overbreak. For example, in Figure 10, the orebody access drifts surrounding the block boundary between Block 30 and Block 34 have more overbreak than in the middle of either of those blocks.

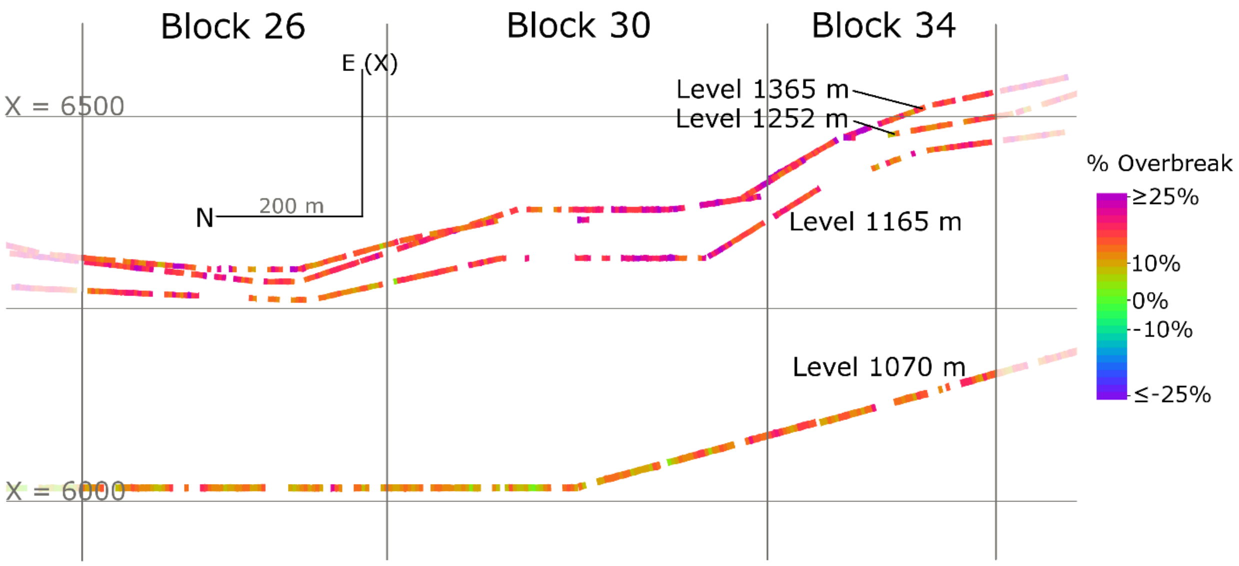


Figure 10 Laser imaged drift sections (5 m length) coloured by percentage overbreak in Block 26, Block 30, and Block 34. Viewed from above (approximately parallel to the E(X) axis)

4 Discussion

It is important to consider that the categories used for classification of events do not have individual nor distinct failure modes. For example, although an event may be classified in the database as seismic, rather than related to geological features, the underlying cause may actually be geological structures, which created blocks that were dynamically shaken down. The database in its current form does not capture the multiple failure modes of some events. This significantly limits the ability to correlate the mine's classification system to rock mass failure modes.

The location along strike and production depth appear to play an integral role in the distribution and characteristics of ground fall events at the mine. These characteristics may be due to induced stresses. An increase in the number of ground fall events occurred when production started on Level 993 m as well as Level 1022 m. Further illustrating the role of production depth, the period in which Block 19 had reduced production exhibited a decrease in the rate of ground fall events. The increased stresses due to depth may be accountable for these changes. Although the new support system installed after 2010 successfully reduced the number of ground falls for a number of production levels, in general the effect did not last beyond Level 1022 m. This may indicate that the combination of higher stresses and geomechanical environment has resulted in different behaviour modes, which the support system is not handling as efficiently as with the behaviour seen around Level 993 m. The vast majority of the events below Level 1022 m were classified as related to seismicity, however, their failure modes remain undefined. The expansion of the seismic system, which occurred in 2012 and 2013, would inevitably increase the number of ground fall events reported as being seismicity related, due to the nature of the current system documenting ground falls.

Regardless of production depth, there were distinctly more events near the inner portion of the orebody as opposed to near the margins. The vast majority of these events were categorised as related to seismicity or stresses. Additionally, the rate of the number of ground fall events was distinct between the inner and outer areas. Due to the large volume of caved material caused by the mining method (sublevel caving), the rock mass in the central portion of the orebody likely experiences less confinement than material near the margins of the orebody. Furthermore, due to the geometry of the central portion of the orebody compared to the outer margins, there are higher concentrations of stresses around the cave front in the central area.

It is noted that very few of the events in the database were classified as related to geological structures. Although this could be interpreted that discontinuities do not play a large role in ground fall events, based on experience of the authors and discussion with mine employees, this is likely due to a biasing of the data collection system. Underground, the authors have seen evidence that geological structures play a role in ground falls; distinct planes are visible after some of the ground fall events. Despite being imaged after rehabilitation, planar features are visible in the laser scanning data. With the data sets evaluated, it is not possible to identify the existence of seismic fault slip events, nor their contribution to ground falls. In the opinion of the authors, it is likely that ground fall events that are related to geological structures are classified under another category, such as seismically related or stress related. At this stage, the role of discontinuities in mine-scale behaviour cannot be quantified.

The rock mass near the middle to southern portion of the orebody had different overbreak characteristics than the northern part. The role of geological environment in overbreak is highlighted as these drifts were excavated well in advance of production. One potent example of this is Block 33/34, which had both unusual ground fall and unusual overbreak behaviour compared to neighbouring blocks. The rate of ground fall events in Block 33/34 did not slow with the new support system installed in 2010 and two of three of the orebody access drifts showed abnormal distributions of overbreak.

The media drift had less percentage overbreak, despite having a larger profile, than the orebody access drifts analysed. Mining induced stresses are not likely the cause of this due to distance to the active mining front, however, this should be confirmed using numerical modelling. Rather, this difference indicates that the media drift (300 m horizontally from the orebody) and the orebody access drifts (80 m horizontally from the orebody) are situated in different geomechanical regimes. It appears that the footwall material closer to the orebody is in worse condition than the footwall material further away from the orebody. This may have important implications to future work, for example numerical stress analysis.

The analysis of the laser imaging data highlighted an issue that is common to most underground mines; difficulty in controlling drift size. The proposed analysis method was an efficient and effective way to evaluate the amount of overbreak. Overbreak can be an expensive problem due to extra tonnage during development (especially when drifting long distances) and excess ventilation and support requirements due to larger drift size. Efforts to reduce drift size to the theoretical profile can significantly reduce the costs of development.

Despite being developed to document individual ground fall events, the ground fall database provided useful information to this study of the mine-scale behaviour. Evolution of the database alongside the development of new rock mass behaviour is, however, important. Evident from this analysis, the mine faces a classic problem that is common to many underground environments: difficulties identifying and recording failure modes, in particular, when they are mixed. Even with significant experience in damage mapping, these mixed failure modes are often challenging to unravel. This suggests that design of a classification system to capture this information is problematic.

The methodology behind the analysis of the laser imaging data showed that this type of data collection can provide valuable insights into mine-wide differences in rock mass behaviour. However, the analysis was limited by the data. At the Kiirunavaara Mine, development drifts are driven years in advance of production. The data available for this study was of development drifts that, at the time they were scanned, had not likely experienced maximum induced stresses from mining. Additional imaging data acquired at a later date could provide an opportunity to evaluate the effects of mining induced stresses. This could be useful information to validate numerical stress analysis models.

5 Conclusion

A new methodology was developed that enables analysis of non-traditional data to provide useful geomechanical information. Traditional and non-traditional data were analysed to evaluate spatial changes in geomechanical characteristics. The application of this methodology has shown that datasets, which are readily available in many mining and rock construction environments, can be successfully used to obtain a greater geomechanical understanding.

At the Kiirunavaara Mine, ground falls exhibit both spatial and temporal patterns. More ground falls occur near the inner portions of the orebody (as opposed to near the margins), and distinct mining levels appear to be associated with an increased rate of events (Level 993 m and Level 1022 m). Some exceptions exist, suggesting a change in geomechanical environment (Block 33/34, for example). Like ground falls, overbreak at the mine also exhibited distinct spatial patterns indicating changes in geomechanical environment. The drifts analysed that were nearer to the orebody experienced a larger percent overbreak than the drift located further away, despite all drifts being relatively remote from the mining front at the time of data acquisition. Particularly prominent in the southern portion of the orebody, non-normal distributions of overbreak data indicate areas that have consistently experienced more ground falls. Spatial patterns of overbreak are evident when viewed approximately perpendicular to the major principal stress. Changes in the underlying geomechanical environment are the likely cause of these spatial and temporal patterns of rock mass behaviour.

Non-unique failure modes posed a significant limitation to the ground fall analysis; compound failure modes are not represented in the database. This issue is likely of note in other mines as well, due to the difficulty in identifying the mixed failure modes while damage mapping. When damage mapping, one sees the final state of a failure and it is often difficult to unravel the failure mode components, which lead to that state. Creating a database and/or classification system in which multiple, compound failure modes can be recorded is not a trivial task, due to the difficulties of damage mapping such events.

This work has illustrated that laser imaging data is a promising addition to combat sparse data in the field of geomechanics. Spatial patterns and characteristics of overbreak provide information about the native geomechanical environment. Information about the stress field at the time of scanning may be present in this data, however, difficulties due to the heterogeneous nature of rock masses make extrapolation of the stress field unreliable in the many geomechanical environments.

This type of analysis can not only provide information about the underlying geomechanical environment, but also give an indication regarding support efficiency throughout mine life. Temporal analysis of ground behaviour (ground falls and overbreak) can give vital information about the vitality of (a) support system(s) as geological and mining induced stress conditions change. This information is critical for support design.

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