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Seismic response of large-scale to medium-scale geological structures in deep mines

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Abstract

Successful mining projects rely on three interconnected pillars: maintaining a safe working environment, achieving uninterrupted production at the required mining rate and ore grade, and managing costs effectively. A strong seismic response either during mine development or stope extraction constitutes a potential safety hazard and it can eventually affect the delivery of the mine plan. The anticipated rock mass behaviour around mine excavations depends on the effect of the in situ stress field on local rock mass conditions. Both are directly related to the geological and tectonic history of the deposit and regional environment. The geometry, strength and stiffness of large-scale structural features such as brittle faults, ductile shear zones and dykes have a direct and significant impact on the surrounding rock masses and local stress field. The Goldex and LaRonde mines in Canada, and the Kittilä mine in Finland, are deep underground seismically active mines in different geological settings. The seismic responses of medium to large-scale geological structures and dykes encountered at Goldex and select examples from LaRonde and Kittilä mines illustrate some of the lessons and ongoing work to assist in managing the seismic risk at these operations. The seismic response of large to medium-scale structures is challenging to anticipate and manage until actual mining has taken place and monitoring data is available. For instance, the seismic response associated with graphitic shears and jointing in the footwall at Rimpi, the milder-than-expected response of the diabase dykes and the stronger than expected response of the mylonitic ductile shears and brittle faults at Goldex were unforeseen. Even in a mature mine such as LaRonde, the understanding of the behaviour of the 700 Fault has taken some time to develop. The examples provided in this paper aim to demonstrate the benefits of integrating structural geology and improving the characterisation and modelling of the large to medium-scale structures from the earliest stages of a project. In mature mining camps, leveraging the geological and deformation history from regional geology and tectonic setting can help to anticipate potential alteration patterns and large-scale structural orientations and dykes. These structures should be included in early analyses and numerical modelling to guide the placement of mine infrastructure, strategic mine layout and mining sequence decisions.

Keywords: *geological structures, litho-structural model, seismic response, tectonic setting*

1 Introduction

Agnico Eagle Mines Limited (AEM) currently operates 11 mines on four continents. Five of the underground operations are seismically active and some of the developing projects are expected to become seismically active in the future. Seismic activity has a direct impact on operation safety and viability. Managing seismic risk is a multi-layered process that starts with the best available lithological, structural, and geotechnical models. Understanding the geological context and tectonic history of the mine's host rocks is key to anticipating and eventually managing the rock mass response throughout the mine life. During the excavation

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of mine development and stoping, the rock mass response will depend on several factors including; the strength and stiffness of the surrounding rock masses and geological structures, stiffness and strength contrasts, the local in situ stress regime and the mining footprint. The mining footprint affects the larger scale mine stiffness as well as the local stress orientation on structures. This paper focuses on the seismic response of medium (hectometres, mine-wide) to large (kilometres, regional) scale geological structures and dykes at three mines operating at depths of 700–3,200 m to present some findings that may be applicable to future projects.

From the earliest stages of a project, the regional geology and deformation history of a deposit can provide clues to the rock engineers as to the potential stress regime (compressive or extensional), expected rock properties (volcanics, intrusions, sediments, alteration types and intensity) and large-scale geological structures (brittle faults, ductile shear zones, dykes). To underline this aspect, the geological context and deformation history of the Goldex, LaRonde and Kittilä mines are briefly presented in the corresponding sections.

2 Geological context and deformation history – Abitibi Greenstone Belt

The LaRonde and Goldex deposits are located in the Neoarchean southern Abitibi Greenstone Belt (AGB) (2,795–2,695 Ma) (Monecke et al. 2017) of the Superior Province, Canada. The AGB covers an area of 500 km (east–west) by 300 km (north–south) and consists primarily of Archean metamorphosed volcanic rock sequences, intruded by several generations of intrusive rocks with meta-sedimentary rock basins located mostly along major deformation zones (Dubé & Mercier-Langevin 2020). Four phases of ductile deformation are recognised in the AGB. D_1 and D_2 deformation phases are associated with early folding of the volcanic rocks and are mostly recognised in the western part of the belt but are not well defined in the LaRonde and Goldex mines area. The main deformation event (D_3; ≤ 2,669 Ma ± 1.3 Ma) (Snyder et al. 2004) is associated to north–south shortening linked to a poorly- to well-developed sub-vertical foliation (S_3) and belt-scale ductile shear zones such as the Larder Lake-Cadillac and Destor-Porcupine deformation zones, as well as secondary ductile shear zones such as the Marbenite and Norbenite (Dubé & Mercier-Langevin 2020). D_4 is characterised mainly by late dextral transpressive/strike-slip ductile movement that is best developed in strongly schistose rocks such as the S_3 shear zones. Several late-stage brittle faults crosscut D_1 to D_4 structural features. Two main families of large-scale brittle faults are described around the Goldex and LaRonde deposits (D_5):

1. sub-vertical north–south to north-northwest–south-southeast with apparent dextral movement
2. sub-vertical east-northeast–west-southwest to north-northeast-south-southwest with apparent sinistral movement.

Three episodes of Proterozoic ultramafic to mafic dykes crosscut the AGB rocks and all the structural elements associated with the ductile and brittle deformation events. Despite being located less than 50 km apart from each other, Goldex and LaRonde deposits show contrasting styles of mineralisation, alteration, and host rock characteristics as they formed in different geological contexts and timeframes.

3 Goldex mine

3.1 Goldex mine background

The Goldex Mine is located on the western outskirts of the city of Val-d'Or, approximately 4 km from the downtown area. The low grade Goldex extension zone (GEZ) was discovered in 1989 and commercial production in the GEZ started in August 2008. The underground mining scenario was based on large-scale bulk mining at a target production rate of 7,000 tonnes per day (TPD). Production in the GEZ was prematurely halted in October 2011. Mining operations resumed in 2013 with the extraction of the satellite M and E zone deposits and progressed at depth with the Deep 1 zone (Deep 1) since 2017 (Figure 1). The mining method was converted from large-scale bulk mining to sublevel stoping with cemented paste backfill at a mining rate starting at 5,500 TPD and progressively ramping up to 7,500 TPD. Higher grade narrow orebodies (i.e. the South Zones,

Figure 1) were later discovered in the basaltic rocks in the footwall of the Goldex diorite. Their extraction was initiated in 2019. The life of mine plan includes the continuation of mining within the Goldex diorite in Deep 2 zone (Deep2) to a depth of 1,400 m, concurrently with the South Zones and the Deep 1 and M zones.

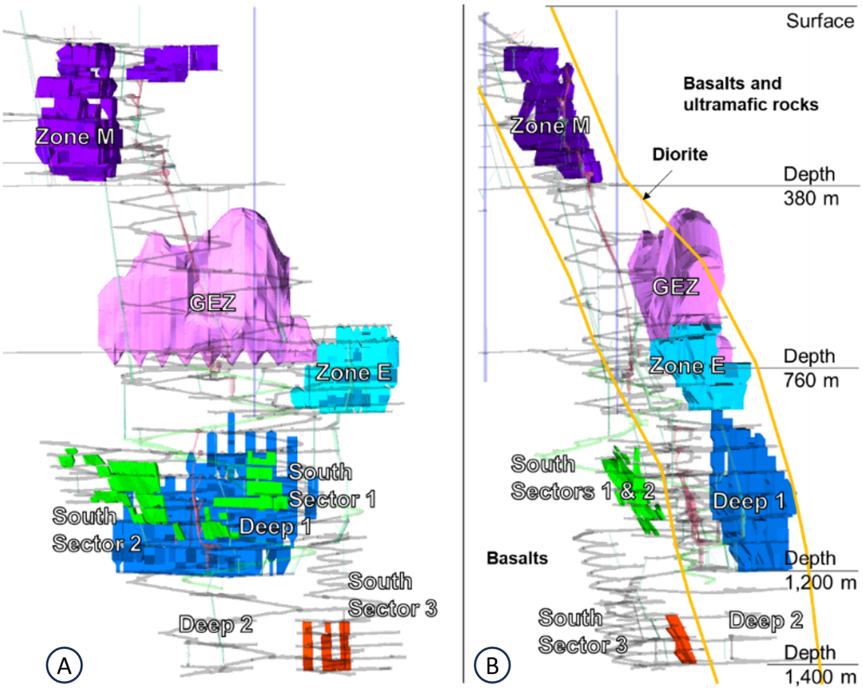


Figure 1 Mined stopes per mining zones, as of May 2024, at Goldex. (a) View looking north; (b) View looking west

3.2 Goldex local geology and structures

The Goldex deposit consists of a stockwork of gold-bearing quartz-tourmaline veins, with occasional pyrite-carbonate, associated with poorly developed proximal albite alteration and widespread weak to moderate chlorite-carbonate distal alteration (Munger 2019). The Goldex deposit is hosted within a syn-D1/D2 post-volcanic steeply north-northeast dipping intrusive rock of dioritic composition (i.e. Goldex diorite). The Goldex diorite is a homogeneous, stiff (Young's modulus: 60–70 GPa), very strong (UCS: 175–250 MPa), brittle, and mostly undeformed medium-grained intrusive rock unit with sparse discontinuous jointing.

The Goldex diorite is hosted in the Marbenite ductile shear zone, which is located ~2.5 km north of the crustal-scale Larder Lake-Cadillac deformation zone. As such, the Goldex diorite is bordered by multi-meter wide zones of strongly sheared and altered basalts and komatiites (ultramafic rocks), respectively transformed into chlorite-carbonate and talc-carbonate schists. Outside of the ductile shear zones, the basalts and komatiites are well preserved and undeformed.

The Goldex diorite is crosscut by several syn-D3 mylonitic ductile shear zones. The main Mylonite structure was well-known and modelled from the earliest days of mining at Goldex. The branches of mylonitic shear zones in Deep 1, however, are more subtle and were not identified until the zone was developed. These shears (named 'dylonites' at the mine) create planes of anisotropy within an otherwise homogeneous and strong rock mass (Figure 2). The dylonites are laterally extensive, sub-vertical and are trending west-northwest–east-southeast, similarly to the Goldex diorite. They are characterised by the recrystallisation of the constituent minerals of the Goldex diorite (i.e. mostly amphibole, chlorite, and feldspar), resulting in a drastic reduction of the grain size of the rock. The resulting rock is thus fine-grained and anisotropic with alternating millimetric to centimetric sub-vertical bands enriched in feldspar, amphibole and chlorite. Despite being of good quality, these decametric to metric structures represent weakness planes within the Goldex diorite. The width and intensity of deformation of the dylonite branches varies greatly between each other, but also laterally within a single structure.

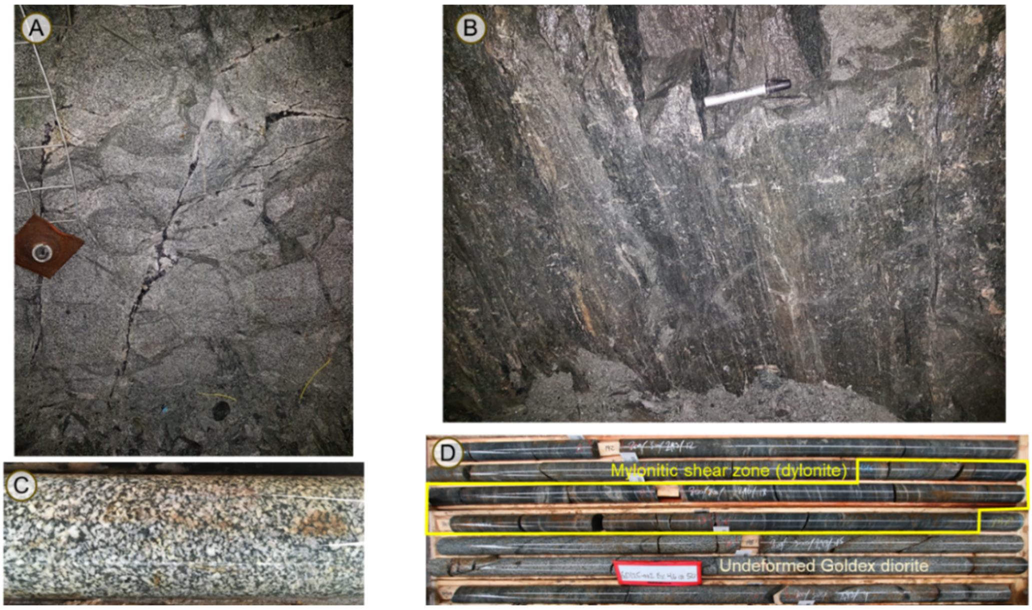


Figure 2 (a) and (c) Typical massive and undeformed Goldex diorite on level 115 and in drillcore; (b) and (d) Dylonite on level 105 in drift and on level 125 in drillcore

Two main families of laterally extensive syn-D_5 brittle faults are recognised at Goldex:

1. sub-vertical to steeply east-dipping north–south faults (Figure 3a)
2. sub-vertical east-northeast–west-northwest trending faults.

The characteristics of the brittle faults are spatially variable. They are generally identified as decametric to metric zones of strongly fractured rock that sometimes contains fault gouge. The fractured rock mass associated with the faults is locally epidote-altered and often crosscut by millimetric to centimetric gypsum-carbonate veinlets that are subparallel with the faults themselves.

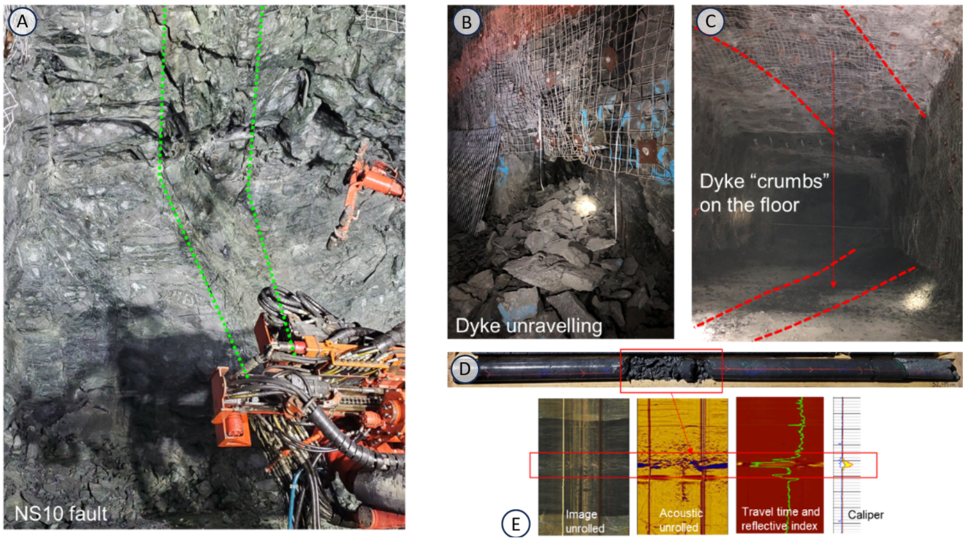


Figure 3 (a) North–south trending ‘NS10’ brittle fault in panel 105-133 development heading. (b) and (c) Proterozoic dyke (diabase) in excavations. (d) and (e) Images showing the correlation between amygdule-rich dyke centre, as seen in a televiewer survey, and crushed aspect in drillcore (triple tube drilling; both images are from the same dyke intersection)

Two families of late Proterozoic diabase dykes cut the Goldex diorite and host volcanic rocks; these dykes, of variable width and spacing, are typically decametric to metric in size, sub-vertical, and trend north–east to south–west and east-northeast–west-southwest, respectively. The quality of the dykes is highly variable but the nature and impacts of this variability has taken some time to unravel. The borders of the dykes are generally massive and of good quality, but the centre is sometimes more fractured and, in some cases, very weak. This feature is related to the fact that when the dykes intrude into older and colder host rocks, the magma cools much more rapidly on its borders (i.e. quenching) compared to its centre. Consequently, the gases trapped in the magma migrate and accumulate in the centre of the dyke, creating amygdules that are sometimes filled (or partially filled) with carbonate or other minerals. These amygdule-rich zones are much weaker than the quenched borders of the dykes and are preferentially fractured and crushed, when disturbed by drilling or mining (Figure 3b–e). The crushed/fractured centres in the dykes make them less suitable for accumulation of stresses and energy than the diorite. The width of the dykes seems to play a role in the presence/absence of the amygdule-rich centre.

3.3 Seismic response of geological structures and dykes

3.3.1 Mylonitic ductile shear zones

Mylonitic shears (dylonites) within the Deep 1 zone were first recognised and added to the litho-structural 3D model in fall 2019. At first, these structures were not considered as having a significant seismic potential based on their good rock mass quality and narrow thickness. At most, based on experience with the lower quality mylonite located between the GEZ and M zones, the expectation was that stope brows would recede and some overbreak may be encountered while mining in the vicinity of the dylonites.

The first seismic events with MW ≥ 2.0 outside of production blast periods (i.e. within 1 h of blast) occurred in September 2020 on the lowest levels of Deep 1 (levels 115 and 120). The magnitude of the events was unexpected at the relatively shallow depth (1,150 to 1,200 m deep) and small extent of the mining footprint. These events prompted a review of seismic sources, geological structures, mine layout geometry as well as ground support needs. A seismic event of magnitude MW2.1 that occurred on 20 December 2020, also brought to the forefront the seismic potential of the dylonites (Figure 4). The location (on a dylonite) and magnitude of the event, as well as the seismic moment tensor inversion (SMTI) analysis (ESG 2021), were consistent with a fault slip mechanism (Mercer 2021). It was concluded that the source of the event could be related to one of the dylonite branches, but the observed damages were largely attributable to the mine layout geometry, with a concentration of excavations and small pillars in the lower footwall (south) abutment of the mining zone, where stresses are concentrated because of the effect of the stress wrapping below the mining front (Figure 4).

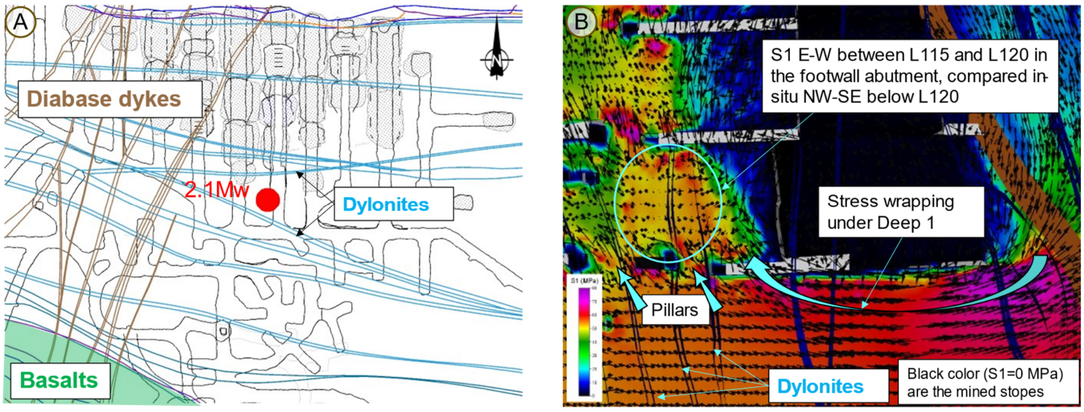


Figure 4 (a) Plan view of level 120 showing the approximate location of 20 December 2020, MW2.1 event (located between levels 115 and 120) compared to the dylonite branches. (b) Section looking west and parallel to panel 129 (location of 20 December 2020, event) showing the magnitude and orientation (arrows) of the major principal stress (S1). High stress wrapping as well as change in orientation of stress can be observed at the lower footwall abutment

Mining in Deep 1 retreats from north to south in a chevron pattern following a primary/secondary sequence. As mining progresses, stresses are therefore being pushed towards the south, where the dylonites crosscut the diorite (Figure 4a). The management of seismicity in the drawpoint development headings is described in Doucet et al. (2022). The excavation layout becomes more complex towards the south with drawpoint pillars, footwall drives and proximity to the main mine infrastructure as shown on Figure 4a. Above level 120, as the mining sequence expands the footprint in the north–south and east–west directions, the orientation of the local stress field in the footwall rotates progressively from the far-field northwest–southeast orientation to an east–west orientation, nearly parallel to the orientation of the dylonites (Figure 4b).

Since 2020, large events have continued to occur with mining in Deep 1. Analysis of the 23 events with MW ≥ 2.0 (i.e. time-space distribution of seismicity coupled with source mechanism analysis performed by seismic system provider ESG) have concluded that most events were of fault slip nature and located close to or within dylonite branches. A review of large magnitude events with and without damage to excavations has shown that the dylonites were contributors in 57% of cases and potential contributors, in combination with other factors such as pillar geometry and proximity to dykes, in 39% of cases. Only one of the large events (1/23) could not be related at all to the dylonites. These ductile shear zones thus present a significant seismic hazard as they have demonstrated several times their potential to store and release significant amounts of energy.

3.3.2 Brittle faults

In December 2015 and January 2016, two MW ≥ 2.0 events occurred in E zone and were associated with stope blasts next to the GEZ barrier pillar, as shown in Figure 5a. As the events occurred during blasts, there is considerable uncertainty in their location. Nevertheless, the lower magnitude seismicity recorded before and after the large events was concentrated between the muck-filled GEZ and the paste-filled E zone stopes, thus directly in the barrier pillar. A geological review of the area, after the large ground motion events, helped identify two east-northeast–west-southwest oriented brittle structures (abbreviated on figures as NE) with local gypsum infilling, shown in green on Figure 5b.

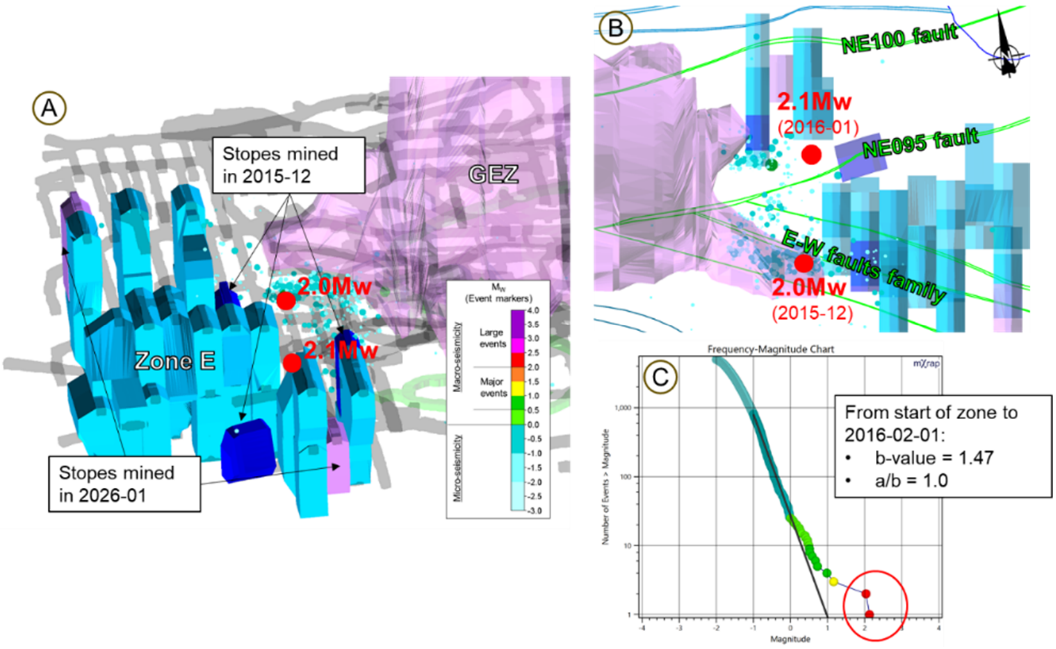


Figure 5 Stopes mined in E Zone close to the Goldex extension zone and location of the two large events recorded. (a) Isometric view looking southwest; (b) Plan view at elevation of large events; (c) Frequency–magnitude chart of the events from the beginning of zone E mining to the occurrence of the two large events

The east-northeast–west-southwest structures had been already mapped in the E zone drawpoints but were not interpreted and modelled prior to the large events. During the planning phase of E zone, it was recognised that the stress level would be elevated in the barrier pillar and seismic activity was anticipated. However, the large ground motion events were a clear departure from the seismic record since 2013 (as shown in the frequency–magnitude plot in Figure 5c) and were not expected. These events were categorised as related to the combination of continuous structures with locally unfavourable geometry and elevated stress in relatively small pillars; they highlighted the importance of recognising, interpreting, and modelling these medium-scale brittle faults.

The east-northeast–west-southwest trending family of brittle faults are located to the southeast of Deep 1 and, contrary to E zone, they have not intersected the stopes on the lower levels of Deep 1. However, because of their orientation and dip, they get closer to the mining front further up in the stoping pyramid. The brittle fault that has most affected mining in Deep 1 is the north–south oriented 'NS10' fault with a 70° dip towards the east. This fault was not recognised at first as it is parallel to most diamond drilling holes and developments. Two examples of the seismic response in panels where this fault is present are shown in Figure 6. Example 1 shows the seismicity associated with the excavation of the lead primary stope of the top level of Deep 1. The fault, which is located to the east of the mined stope, appears to act as a barrier for the propagation of seismic events. Seismicity is also more intense in the secondary panel crosscut by the fault than in the adjacent secondary panel to the west. Example 2 shows the seismic response in a secondary panel, from mining a lead stope in the adjacent primary panel. In this case, seismicity is concentrated west of the fault that crosscuts the secondary panel, whereas the seismic response is nearly absent on the eastern side of the fault. In this case, the seismic reaction was also exacerbated because the secondary panel's sequence was delayed, resulting in higher stress, with a favourable stress orientation for fault slip type events, on this structure.

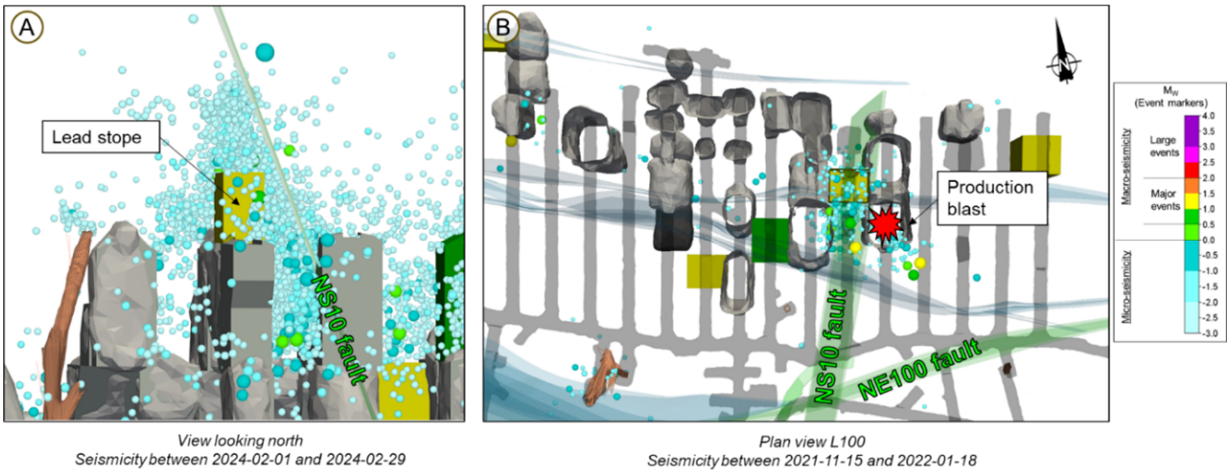


Figure 6 Seismicity associated with NS10 fault in Deep 1. (a) Example 1: seismicity is concentrated west of the fault, which acts as a seismic barrier. The secondary panel crosscut by the fault is also highly seismically reactive; (b) Example 2: seismicity is concentrated west of the fault that crosscut the secondary panel

3.3.3 Diabase dykes

During mining in the GEZ, the mine noted difficulties in maintaining the back stability of excavations at the western end of the deposit where diabase dykes intersected the excavations. Additionally, during later stages of mining the GEZ, seismic activity was observed to extend beyond the Goldex diorite northern contact into the hanging wall volcanics, correlating spatially with the diabase dykes. During the development phase of Deep 1, a consistent increase in seismic activity was noted as the development approached the dykes. The events were typically of small magnitude, but the response was consistent. Based on this empirical experience and the high intact strength (200–250 MPa) and stiffness of the diabase (60–75 GPa), the dykes were identified as potential seismic hazard in Deep 1. During drawpoints development on level 120 (1,200 m deep), it was observed for the first time that the core of the central dyke was crushed and could be easily excavated with a geology hammer. Around this weak core, the dyke was similar to previous exposures. This was in contrast with previous underground observations of the dykes and the general descriptions from geology logs where the dykes were generally described as massive and strong. Occasional damaged zones were attributed to drilling-induced damage. Concurrently, televiewer data from a surface site investigation program in 2018(an internal report) suggested that the crushed core of diabase dykes could be completely washed away during drilling, leading to a mischaracterisation as undamaged in core logs. An extensive televiewer investigation carried out in the upper part of Deep 1, however, provided evidence of the variable nature of the diabase dykes as described in Section 3.2.

Mining in Deep 1 confirmed that the diabase dykes are seismically active, as anticipated. However, the seismic hazard (defined as frequency and magnitude of large events) is lower than initially expected. Figure 7 shows a comparison of the seismic response with production in the western part of the mine where dykes are present, with the response in the east part where no dykes are present (Figure 8). Even though more tonnes overall are mined in the east than in the west, for the same tonnage mined, the graphs show that the rate of events MW ≥ 0.5 is higher on the east side. The cumulative energy release and deformation (seismic moment) are also significantly lower in the western part of Deep 1 compared to the east. Considering that the diorite is similar regardless of the presence of dykes, the difference in seismic response is attributed to the dyke swarm concentrated in the western part of the deposit. Where the dykes have a weaker centre, they can deform and crush thereby allowing a progressive release of stored elastic energy as stopes are mined. On the east side of Deep 1 the dykes are absent and the only discrete large-scale defects within the diorite consist of the brittle faults and mylonitic shears that were discussed in Sections 3.3.1 and 3.3.2.

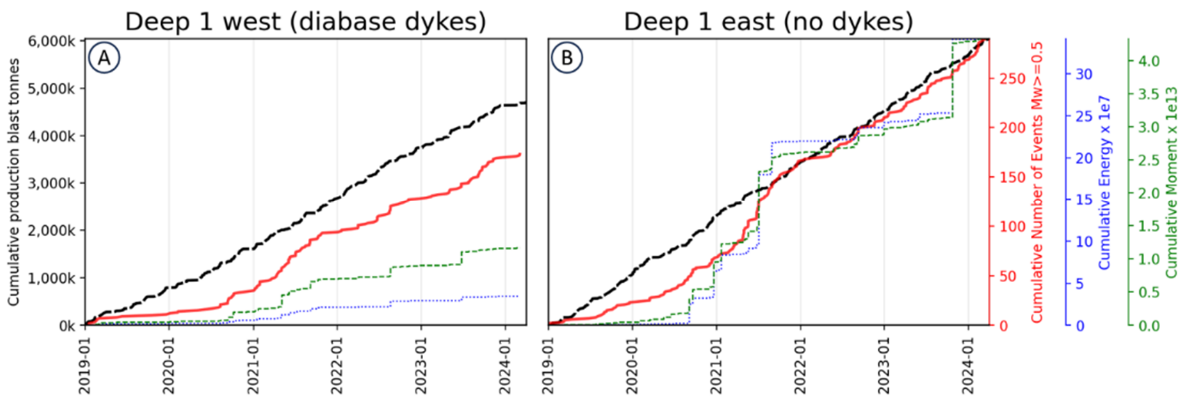


Figure 7 Comparison of seismicity between (a) the west (where the dykes are present) and (b) the east (where there are no dykes) of the Goldex Deep 1 zone

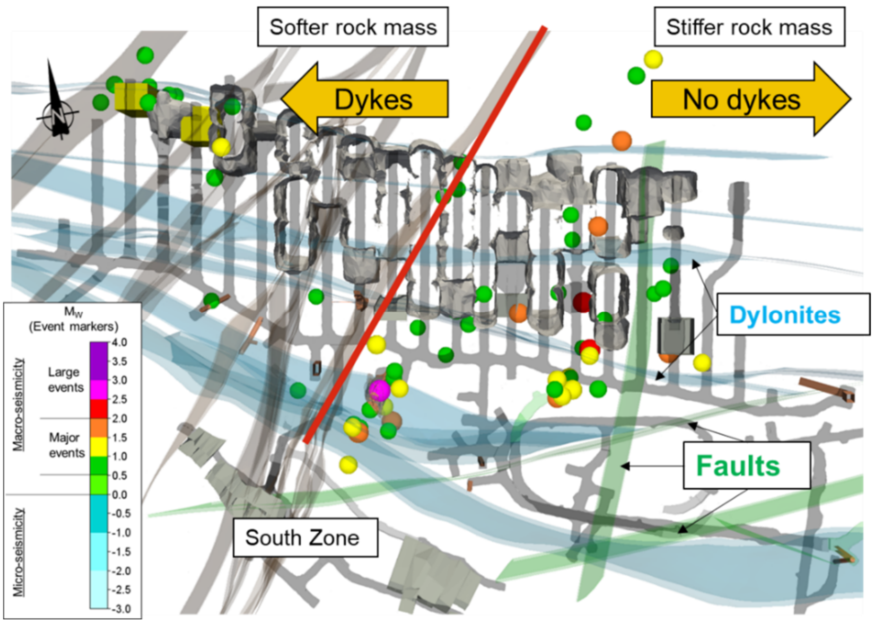


Figure 8 Plan view of level 100 with structural geological model and seismic events of MW ≥ 0.5 since 2019-01-01 (clipping plane +/− 25 m)

3.3.4 Structure interactions

As the Deep 1 pyramid matures and the footprint expands towards the southern contact of the diorite, structural interactions in the footwall are observed and can trigger large magnitude events. In-depth forensic analyses (documented in an internal report) were conducted by the Goldex team following a MW 2.7 event in October 2023, which occurred more than 5 hours after the final blast of a stope on the east part of the mine. The analyses included the seismic record, production and backfill history, damage locations, deformation changes from Lidar scans, SMTI analyses conducted by ESG (2023), and mine-wide numerical stress modelling results (data from Beck Engineering (2022) analysed by Goldex). The blasted stope was located in panel 133 between levels 105 and 110 (50 m high stopes). Several structures are present in the footwall including the sub-vertical east–west oriented 'NE100' fault and a branch of the dylonite. The 'NS10' fault identified in Figure 6 is also present in panel 133 and crosscuts the other structures.

The detailed analyses have shown that the initial seismic reaction following the final stope blast was associated with the 'NS10' fault and was deemed normal based on the previous record. The post blast seismic activity was clustered in the drawpoint pillars near the footwall drive and the intersection of the 'NS10' fault and a dylonite branch. The next secondary pillar, panel 135 was also active with seismicity above level 105. The large magnitude event occurred after the initial seismic response had returned to background. The numerical model results suggest that the maximum principal stress at the location of the event has progressively rotated from the initial inclined northwest–southeast orientation to a more horizontal east–west direction, which favours slip by increasing the shear stress on the sub-vertical east–west oriented 'NE100' fault or potentially the dylonite branch (Figure 9a). As the stoping pyramid progresses vertically and towards the footwall, it also lowers the confinement (normal stress) on the footwall structures.

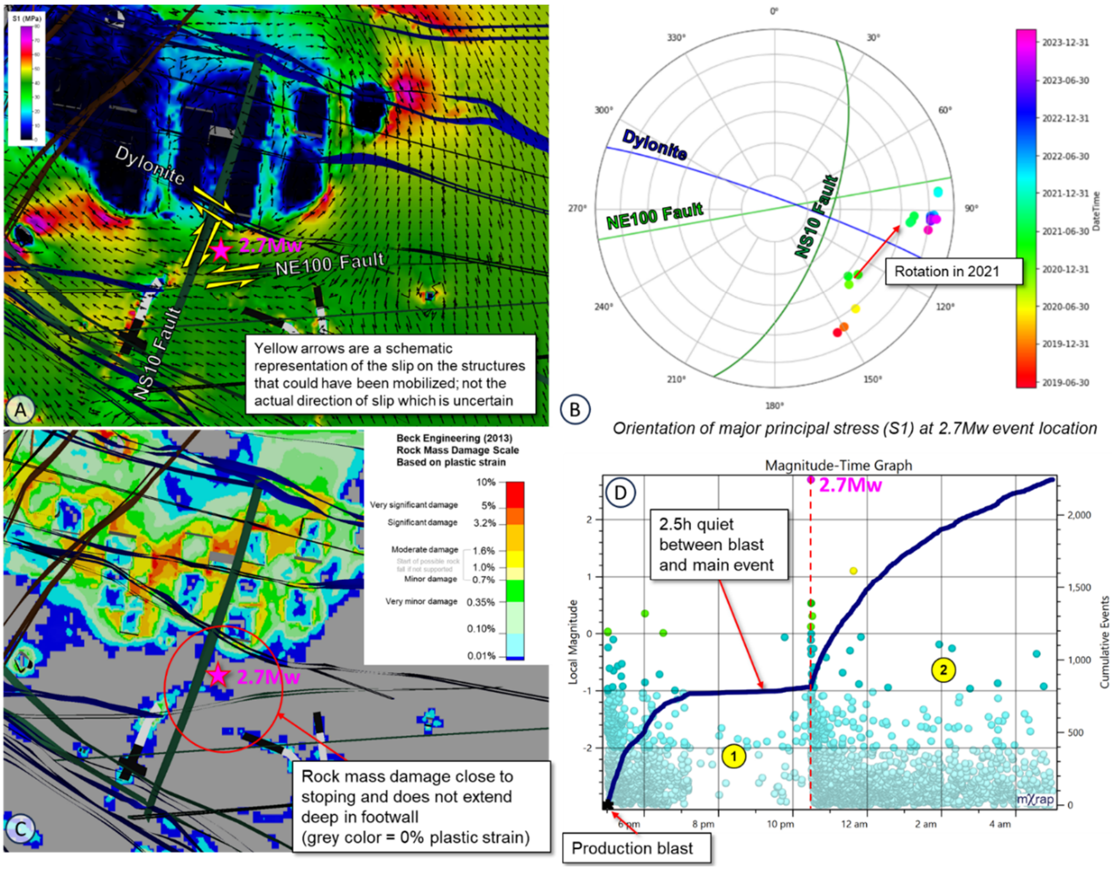


Figure 9 Interaction of multiple structures and elevated stress in the footwall abutment around the time of the MW2.7 event in October 2023. (a) S1 state on level 100; (b) Change in principle stress orientation over time at event location; (c) Modelled rock mass damage close to stoping, based on plastic strain (Levkovitch et al. 2013); (d) Magnitude-time graph of seismic activity before and after the event

Some lessons from this event and the analyses conducted include:

- As mining advances towards the footwall and stresses rotate, different defects (structures) can be activated. The response on structures can occur with a delay after the typical post stope blast activity has ended.
- Within a very strong sparsely jointed rock mass such as the diorite, the extent of damage and yield around the stope is limited in distance. Away from stoping, the rock mass maintains its capacity to store strain energy that can be released suddenly by failure on large-scale defects when these are affected by mining-induced stress rotation (increase in shear) and confinement reduction.
- Large magnitude events typically have large source radii that may encompass multiple large-scale structures.
- Structures may be sequentially or simultaneously activated.
- The multi-disciplinary analyses such as those conducted by the Goldex team provide invaluable insight that cannot be obtained from any single type of analysis alone.

4 LaRonde mine

The LaRonde mine is a world-class polymetallic deposit that has produced over 8 M ounces of gold since its inauguration in 1988. Current mining is at 3.2 km below the surface with plans to reach 3.4 km. Details of the mine geometry and mining method are presented in Sasseville et al. (2022). Over the past decade, mining-induced seismicity under high-stress conditions has intensified at LaRonde, with geological structures posing seismic risk management challenges. This section discusses the seismic response of one of the larger geological structures that has interacted with mining operations since 2018.

4.1 Geological context

The LaRonde deposit is a gold-rich volcanogenic massive sulphide deposit that formed prior to regional deformation and metamorphic events (±2,698 Ma)(Mercier-Langevin et al. 2007). The deposit is formed of several sheetlike massive to semi-massive stratabound sulphide lenses hosted in a steeply south-dipping sequence of mafic to felsic volcanic, volcaniclastic and subvolcanic intrusive rocks (Dubé et al. 2007). The deposit is strongly deformed and transposed by D_3. Around the ore zones, the strongly silicified and sericite-altered host rocks are moderately to strongly foliated (S_3) within a wide zone of pervasive deformation. S_3 is steeply west-southwest-dipping with a west-northwest–east-southeast orientation, as is the stratigraphic sequence. Although no clear evidence of regional D_4 movements is documented there are some indications of dextral movements on the 700 Fault which is the structure discussed in the next sections.

4.2 700 Fault zone

The 700 Fault zone is a sub-vertical west-northwest–east-southeast (275–95°) trending geological feature that crosscuts the host rocks of the LaRonde mine. This structure has been observed in diamond drillholes and mine developments from a depth of ~1,370 to ~3,700 m below surface. However, the complete vertical and lateral extents of this structure are not known. As it is discordant to the regional lithologies, the 700 Fault and its associated damage zone (modelled as low RQD zone) crosscut the lithological units both vertically and laterally. Due to the dip of the steeply south-dipping underlying geology and the near vertical dip of the 700 Fault; the distance between the fault and the main zone 20 orebody increases with depth (Figure 10).

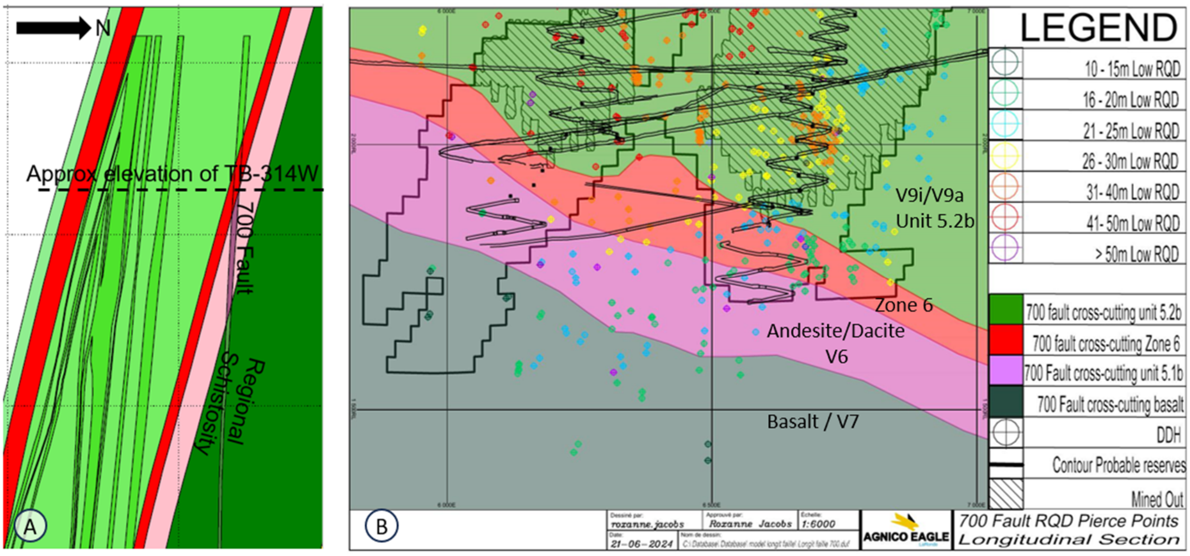


Figure 10 **(a) Vertical section looking west, showing the sub-vertical 700 Fault crosscutting the steeply dipping lithology; (b) Longitudinal view north in the plane of the 700 Fault showing the lithologies that are crosscut by the fault. The black outline indicates the extent of the reserve in the West and East mine sectors**

The character of the fault and its damage zone are strongly related to the properties of the lithologies that it crosscuts (Figure 11). Where the 700 Fault occurs in the rhyolites and rhyodacites of unit 5.2b – these lithological units are characteristically moderately to strongly foliated with pervasive silica and sericite alteration – the fault zone can be up to 50 m in width. The fault zone in these sectors comprise several fault planes with observed fault gouge, alternating with moderately to intensely sheared zones. Where the 700 Fault crosscuts the mineralised zone 6, there is moderate to strong shearing on the northern and southern margins of the 700 Fault zone. Between the massive sulphide lenses, where the sulphide percentage is less than 30%, the 700 Fault is observed as intervals of lost core and strong to intense deformation with shearing and kink bands. At the depths where the 700 Fault crosscuts the basalt, which is a more massive and less altered unit compared to the rhyolite, the fault zone is generally limited to a width of 15 m and presents as a strongly altered zone with quartz-carbonate breccias around the fault plane.

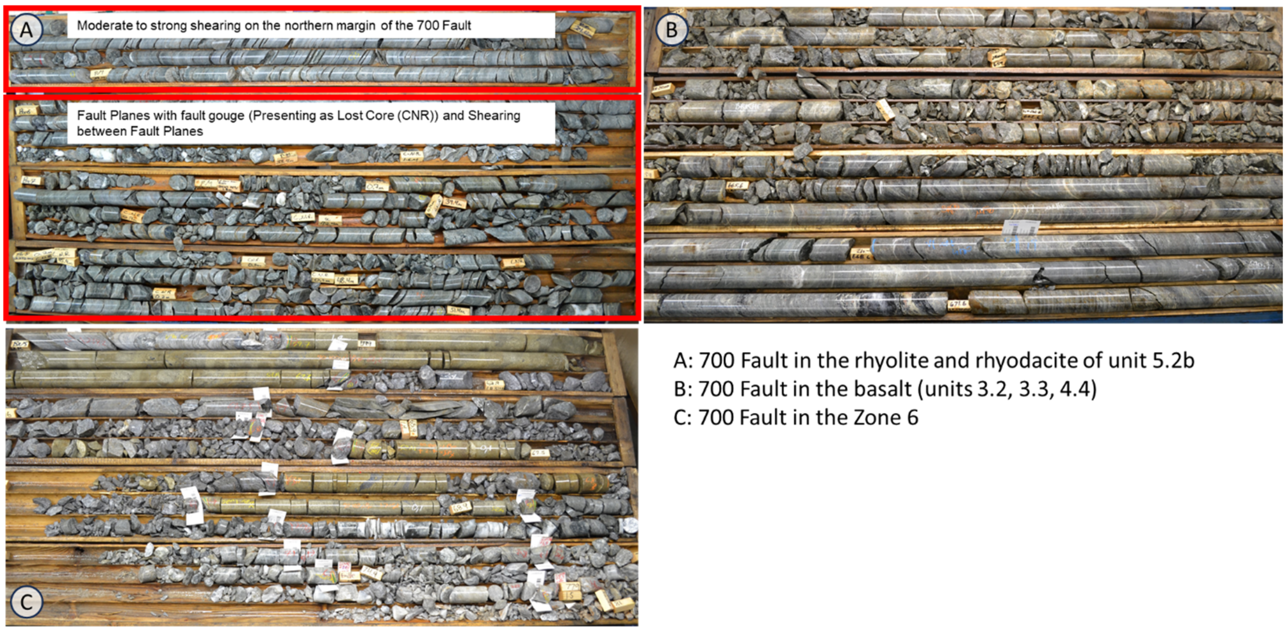


Figure 11 **(a) The 700 Fault as observed in the rhyolite/rhyodacite of unit 5.2b in DDH core from level 278. (b) The 700 Fault as observed in the basalt; (c) The 700 Fault crosscutting the Zone 6**

4.3 Seismic response of the 700 Fault in the East mine sector

Since 2018, the LaRonde mine has experienced 31 seismic events with a Richter magnitude MR > 3 recorded by the Regional Seismic Network. Of these, 21 occurred in the hanging wall, away from any excavation. Five events were located near or on the geological structure known as the 700 Fault, and two of these were the largest events recorded, each reaching MR3.8. The first MR3.8 event was recorded on December 20, 2018, behind the western abutment of the east mine, just below level 287 (2,870 m below surface), where the underhand and overhand mining sequences merged. Ollila & Brown (2022) present the details of the mining sequence and comment on the fact that the largest seismic event during mining of the sill was recorded on the 700 Fault 180 m into the footwall of the stopes. Their analysis shows that the evolution of the seismicity in the sill (merge) area is consistent with a transition from a stiffer loading system (intact sill pillar) to a softer loading system (yielded and partially extracted sill pillar). The large event on the fault may be explained by unclamping or reduction in confinement on the fault with sill pillar failure and mining.

Figure 12 illustrates the evolution of the mining footprint in the east mine sector with seismicity along the 700 Fault. The figure displays the locations of seismic events with Richter magnitude, MR > 1 within 40 m on either side of the 700 Fault surface, as currently modelled, and the mining footprint at three key dates:

- 1 January 2019 (Figure 12a)
- 1 January 2022 (Figure 12b)
- 1 January 2024 (Figure 12c).

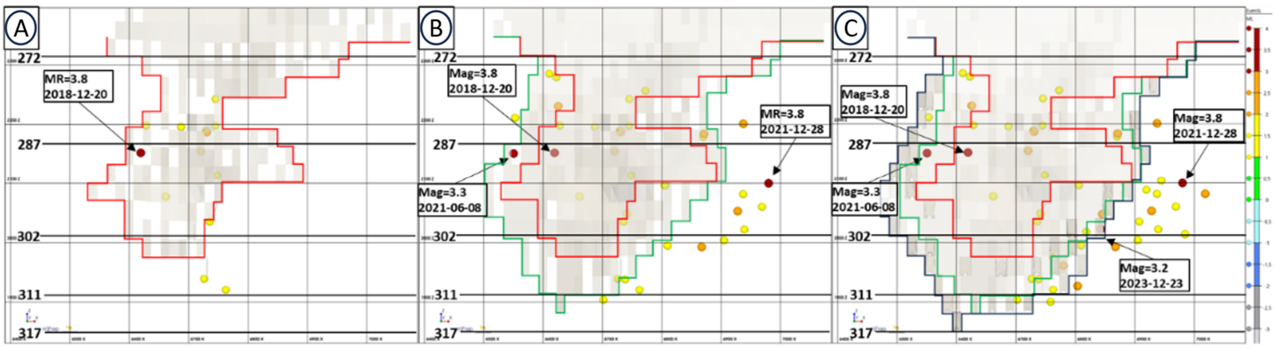


Figure 12 Longitudinal view looking north of seismic events of MR > 1 located 40 m on either side of the 700 Fault and the mining footprint of the East mine from 2018-01-01 to (a) 2019-01-01, (b) 2022-01-01, and (c) 2024-01-01

Figure 12a shows the first MR3.8 event recorded on 20 December 2018, on the 700 Fault. This event occurred at the edge of the mining-induced stress wrap-around in the footwall and triggered seismic activity further into the footwall. As the mining footprint progressed deeper and broader over time, seismic activity patterns shifted. In Figure 12c, depicting the scenario on 1 January 2024, major seismic events along the fault tend to cluster at the extremities of the mined footprint. It is suspected that expanding the footprint induces shear stress on the fault while mining secondary stopes allows convergence, thereby reducing confinement on the fault and allowing slip on the structure.

Another particularity of the 700 Fault and the low RQD zone around it, is the lack of seismicity observed in this region. This is in stark contrast to the seismic response observed at LaRonde and is referred to here as the 'seismic gap'. Figure 13a shows the progression of the seismic front with stoping in the east mine. The lack of activity near and along the 700 Fault is noticeable. Figure 13b illustrates the seismic gap during the development of levels 317, 320 and 323. Deformation monitoring is envisaged to monitor aseismic deformation.

The physical characteristics and geomechanical properties of the fault itself and surrounding fracture zone are variable, as described in Section 4.2. The mining front at depth is just reaching where the 700 Fault starts to move out of the 5.2B geological unit, into the more competent zone 6 and eventually andesite units.

The fault also moves away from the ore zone at depth. These changes are expected to affect the seismic response as the mine extends deeper.

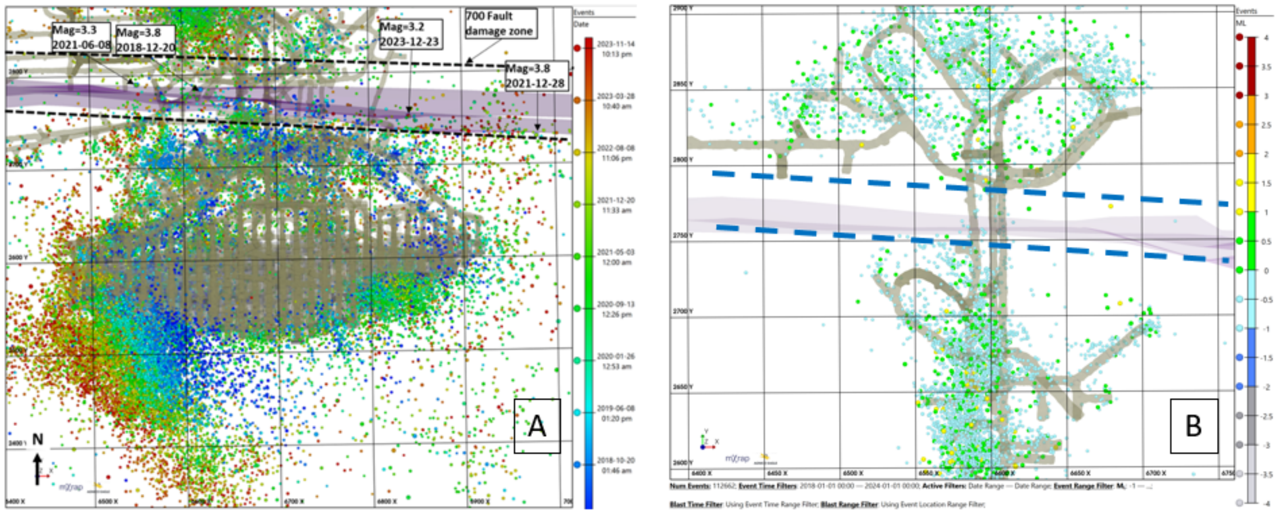


Figure 13 (a) Plan view of the seismic front progression towards the 700 Fault in the East mine from 2018-01-01 to 2024-01-01. Seismic events with moment magnitude MW > −1 located between levels 287 and 311 are coloured by date; (b) Plan view of levels 317 to 323 for the same time period with events coloured by magnitude. The seismic gap around the 700 Fault is highlighted

As observed at LaRonde mine and reported elsewhere (Ollila & Brown 2022; Blake & Hedley 2001; Ortlepp & Stacey 1994; Lenhardt 1992), the largest mining related events tend to be fault related. The complexity and seismic hazard associated with these major geological structures necessitate a thorough study of their geological and geomechanical characteristics from the earliest stages of a project and throughout the mine life and of the evolution of their behaviour, to manage the associated seismic risk.

5 Kittilä mine

5.1 Kittilä mining history

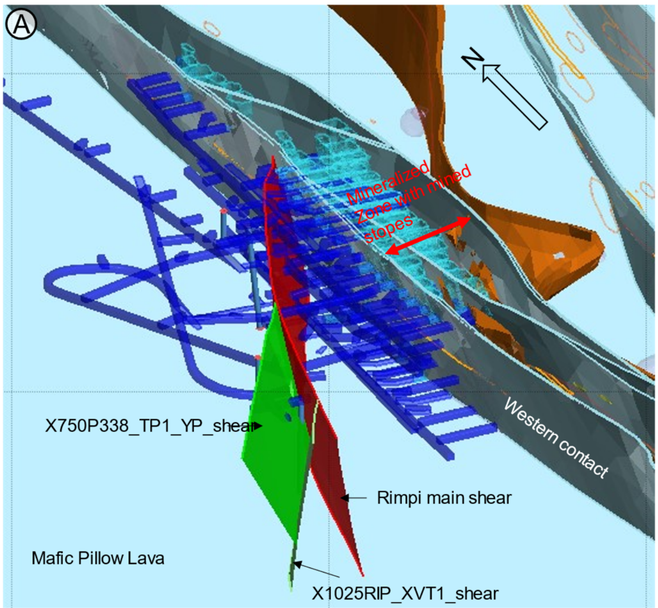
The Kittilä mine is located in the Central Lapland of northern Finland, 150 km north of the Arctic Circle. The current mining rate is 2.0 Mt per year from different ore zones, including Etelä, Suuri, Roura, and Rimpi, within the Suurikuusiko gold deposit. The mine extends over a strike length of 3.5 km in the north–south direction, and from surface to the current depth of 1,025 m. At the present time, mining reserves extend to 1,500 m and resources extend deeper. The orebody consists of multiple parallel lenses of varying thickness in the east–west direction. Details of the mine, the mining method and the challenges related to sill pillar mining are presented in Pyy & Falmagne (2019). The rationale for early installation of a seismic system in the Rimpi orebody are detailed in Pyy et al (2022). The work presented here focuses on the Rimpi orebody.

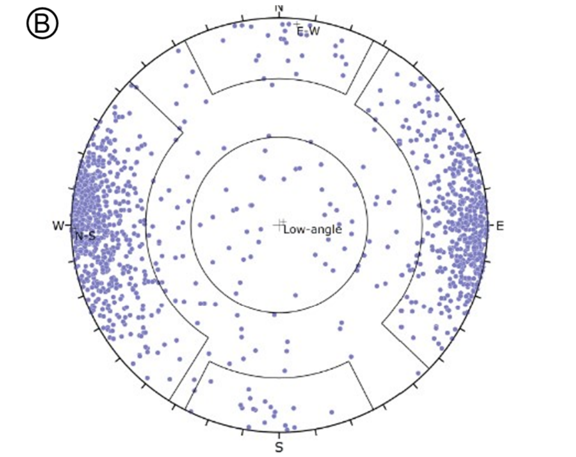
5.2 Geological context and deformation history

A description of the geological and structural context of the Suurikuusiko gold deposit is summarised from Häkkinen (2021) as follows. The Paleoproterozoic Central Lapland Greenstone Belt (CLGB) is divided into five lithostratigraphic groups. The youngest of these, the 2.0-billion-year-old Kittilä group, hosts the Suurikuusikko gold deposit. This deposit is situated along the north-northeast–south-southwest trending Kiistala shear zone (KiSZ), which marks the contact between two thick mafic volcanic sequences. The western sequence comprises massive mafic and pillow lavas, while the eastern sequence includes mafic lavas interspersed with minor pyroclastic materials. Mineralisation is predominantly found on the eastern side of this sheared contact, hence the designation ‘the western contact’ at the mine site. The evolution of the KiSZ has been interpreted and detailed by Sayab et al. (2019) and is not repeated here but provides useful insights for geotechnical interpretation.

5.2.1 Local geology and structures

A key structural feature of the Suurikuusiko deposit is the western contact which is traced over the entire strike length of the deposit from north to south. This intensely sheared contact (Figure 14a) marks the juxtaposition of the massive and strong mafic pillow lavas (MPL), with often well preserved pillow texture to the west, and the mixed volcanic package hosting the orebodies to the east. The mine infrastructure (ramp, ventilation raises, pump stations) and the footwall haulage drives in Rimpi are located in the typically good rock mass quality MPL. The mineralised zone is crosscut by graphitic shears and consists of a deformed package of variable width with relatively lower strength and stiffness compared to the footwall and hanging wall rocks, and is bound by weak contacts (the western contact to the west and another shear zone to the east).





Fracture set	Mean orientation (dip/dip direction)
N-S subvertical set	88°/089°
E-W subvertical set	87°/185°
Low angle set	2°/235°

Figure 14 (a) 50 m slice with oblique view of the mineralised zone, mined stopes and structural model as of April 2024; (b) Interpreted fracture sets from the geotechnical drilling in Rimpi (Mattila & Valli 2023)

Since the start-up of the mine, geological mapping efforts have been concentrated on the mineralisation with a much-reduced focus on non-mineralised areas such as the footwall development. The structural model of the footwall areas has therefore lagged but is progressing. A continuous shear zone identified as Rimpi main shear has been traced and modelled in the MPL (Figure 14a). Two other potential shear zones labelled on Figure 14 have recently been identified but are less certain. The shear zones in the footwall rocks are variable in width and in strength/competency as well as along their length. Some areas are strongly graphitic and others are well-healed.

The jointing pattern in Rimpi consists of a main north–south sub-vertical set, an east–west sub-vertical set and a low angle set (Mattila & Valli 2023). Some random jointing is also observed. The east–west and low angle sets are more widely spaced than the north–south set aligned with the foliation (Figure 14b).

5.3 Seismic response

5.3.1 Shears in MPL footwall

The seismic monitoring system was installed in Rimpi during the early stages of development in 2017. The seismic monitoring data combined with damage observations, provided insights into the first major seismic event recorded at the mine on 13 November 2019 (Pyy et al. 2022). The vicinity of the Rimpi main shear within the MPL footwall rocks has been seismically active since 2019. Pyy et al. (2024) describe two events that occurred in June 2022 and March 2024. Their analysis indicates that small events along planar features, such as the Rimpi shear, tend to be more shear slip type events but the damage is associated with crush type events and unfavourable local geometry of excavations and small pillars in the footwall

5.3.2 *Interactions with fracture sets*

Pyy et al. (2022) reported on the identification of low angle planar features outlined by seismic clusters of very small events in the footwall at Rimpi. A review of the data shows that the drill hole also intersected the Rimpi main shear as shown in Figure 15a. The graphitic shear feature had not been traced at the time and was not considered unusual or significant. The planar trend labelled as 'Plane ac' (Pyy et al. 2024) in Figure 15b has continued to be active with mostly small events until 2023 but a similar trend seems to be developing higher up in the footwall as mining progresses upwards. The exact relationships between of the weak graphitic defects and the seismically active planes is still unclear but may be related to low angle fractures.

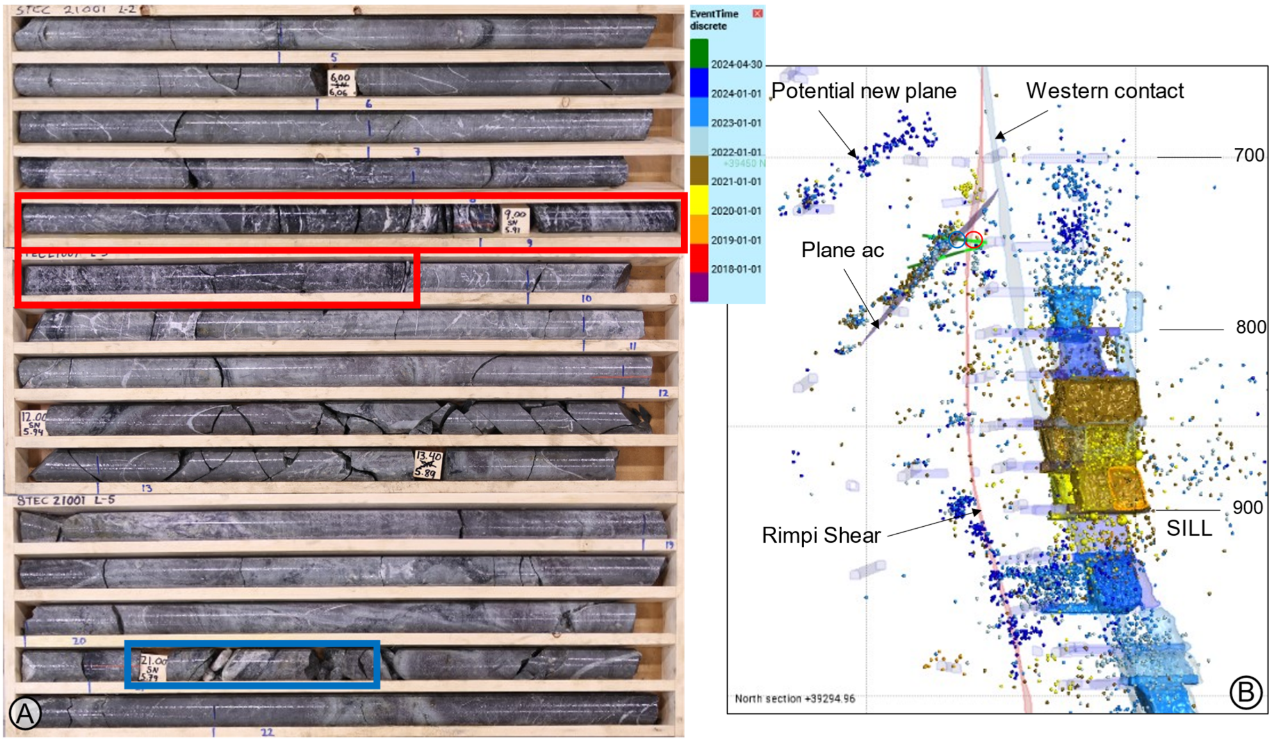


Figure 15 (a) Drillcore from investigation hole to test 'Plane ac' identified from small seismic events. The blue outline reported in Pyy et al. (2022) fits with 'Plane ac'. The red outline shows the aspect of the Rimpi main shear in core; (b) Vertical section looking north. Events within 25 m of 39295 N are coloured from 2017 to April 2024 as per the legend.

5.3.3 *Impact of local mine geometry*

The mine infrastructure in Rimpi was advanced at a rapid pace based largely on the mine's experience at Suuri and Roura, and the known continuity of the orebody. The main ramp, footwall drives, sumps and ventilation infrastructure were designed to be operationally functional and efficient based on experience. The lack of detailed information for positioning the footwall development leads to unfavourable geometries with small pillars both on the levels and with vertical raises where present. Pyy et al. (2024) describe the damage from a MW1.0 event. The high 'local extraction ratio' and small pillar geometry with a weak structure crosscutting it, all contributed to the observed failure.

6 Observations and lessons

Common observations and lessons from the experience presented above are summarised in this section.

6.1 Litho-structural modelling for geotechnical applications

Experience from three deep seismically active mines highlights the critical importance of developing the best possible litho-structural model as early as possible in a project's lifecycle, when high impact decisions such as the placement of mine infrastructure and level development are made, and strategic mining rate and mining sequence decisions are taken. The regional geology and deformation history of the deposits provide important clues as to the lithologies, alterations and structural families, as well as some insight into the potential stress regime that may be anticipated. The exploration geology teams are an essential source of knowledge during the early stages of a project (Scoping to Feasibility). However, as the project moves into construction and operation, mine geology teams often shift their focus to mineralisation and grade control, with less emphasis on geological characterisation of structures and barren lithological units. Integrating geologists into the ground control and geotechnical project development groups facilitates the transition and continuity of geological knowledge from exploration to production.

The seismic response of large to medium-scale structures is challenging to anticipate and manage until actual mining has taken place and monitoring data is available. For instance, the seismic response associated with graphitic shears and jointing in the good quality footwall rocks at Rimpi, the milder-than-expected response of the diabase dykes and the stronger than expected response of the mylonitic ductile shears and brittle faults at Goldex were unforeseen. Even in a mature mine such as LaRonde, the understanding of the behaviour of the 700 Fault has taken some time to develop. The examples provided in this paper aim to demonstrate the need to integrate structural geology and improve the characterisation and modelling of the large to medium-scale structures from the earliest stages of a project. These structures should be included in early analyses and numerical modelling to guide evaluations of the placement of mine infrastructure, strategic mine layout and mining sequence decisions.

6.2 Mining geometry and seismic response

The three mines described in the previous sections present different geological settings, age, and genesis. Nonetheless, from a geotechnical perspective some similarities can be identified. In the hard, stiff, and sparsely jointed diorite at Goldex and MPL at Kittilä, the mining-induced accumulated strain energy is preferably released through deformation of pre-existing structures. The strength and orientation of these structures or defects (single or multiple, such as the diabase dyke swarm at Goldex) relative to the local stress field control the timing and magnitude of the seismic response. Activating shear along one structural orientation can potentially trigger a response on cross cutting fractures (shallow dipping planes at Kittilä) or other large-scale faults or shears (Goldex). Wide, weak faults may deform aseismically as observed at LaRonde. When released, the accumulated strain on and near the fault can generate large events with broad stress redistribution potentially activating the next weakest or critically loaded structure(s).

Seismic events associated with large to medium-scale structures tend to be of greater magnitude compared to previous records. However, excavation damage tends to be more closely associated to mining layout factors, such as a high local extraction ratio with multiple excavations and small pillars.

6.3 In situ stress and measurements

Measurements of the in situ stress field was not discussed here due to space limitations. This is a critical input parameter for geotechnical design that is generally under-measured due to the associated high cost and the frequently variable and difficult to interpret results. The litho-structural model and geological deformation history of the deposits provide clues to the anticipated stress field and potential explanations for measured variability which would encourage more measurements of this important parameter.

7 Conclusion

The occurrence of seismicity and strong ground motions that can be anticipated over the life of mine are a function of stress, strain, and strength of the rock mass and geologic structures. From the earliest stages of a mining project, the available litho-structural geology model forms the basis for the construction of a geotechnical model. When high stress-to-strength ratios are anticipated, excavation and ground support designs are developed to manage these conditions. Typically, the litho-structural model of mineralised zones is the focus of the first refinements, while geological mapping and modelling in waste often lag behind or are neglected. This is unfortunate, as most of the mines' permanent infrastructures and developments are typically in non-mineralised areas. Consequently, it becomes more challenging for the ground control teams to identify areas that should be avoided or require specific control measures and enhanced ground support, until the seismic record can be interrogated.

Experience at the three sites has shown that control measures that are typically successful for stope blasting induced events may not be adequate when large geological structures are triggered as a delayed response due to stress redistribution in the rock mass. Such events can, in turn, generate broad stress redistribution that can cause widespread damage. Furthermore, it was shown that, on several occasions, the observed rock mass damage resulted from unfavourable mine layout geometries, such as a high local extraction ratio and small pillars. The documented cases demonstrated that the seismic response was a function of the physical (thickness, spacing, continuity) and geotechnical properties (strength, stiffness) of both the structures and the host rock mass. Therefore, geology and geotechnical efforts should be allocated sooner than later to refine the litho-structural model of the non-mineralised areas and conduct investigations to characterise large-scale structures, in addition to the typical rock mass domaining, which focuses more on rock mass fabric and strength.

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